Annual Report
2009

Association
EURATOM / IPP.CR

INSTITUTE OF PLASMA PHYSICS, v.v.i.
ACADEMY OF SCIENCES OF THE CZECH REPUBLIC

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PREFACE

This report summarizes the main activities and achievements of the Association EURATOM/IPP.CR in 2009. The Association participates in the joint European effort in mastering controlled fusion by carrying out relevant plasma physics and technology R&D, including participation in JET and other European devices and activities related to the international fusion experiment ITER.

The Association was founded on December 22, 1999 through a contract between the European Atomic Energy Community (EURATOM) represented by the European Commission, and the Institute of Plasma Physics, v. v. i., Academy of Sciences of the Czech Republic (IPP). Several other institutions have been included in the Research Unit to contribute to the work programme in physics and technology research:

- Faculty of Mathematics and Physics, Charles University in Prague
- Institute of Physical Chemistry, v. v. i., Academy of Sciences of the Czech Republic
- Faculty of Nuclear Science and Physical Engineering, Czech Technical University
- Nuclear Physics Institute, v. v. i., Academy of Sciences of the Czech Republic
- Nuclear Research Institute in Rez, Plc
- Institute of Applied Mechanics, Brno, Ltd
- Institute of Physics of Materials, v. v. i., Academy of Sciences of the Czech Republic

Measured in person years, the effort expended on the Association's fusion research has slightly decreased, compared to the previous year, to about 81 py (from 48 py). This reflects the increase of manpower in connection with the COMPASS project. The overall 2009 expenditure was about 2.8 M€.

With the tokamak COMPASS transferred from UKAEA in 2007, most of our efforts were invested this year into the re-installation of this unique facility. The tokamak officialy started operation on 19th February 2009. In this respect we also experienced considerable increase in the interest of media and general public in our research, as well as calls for lectures and general collaboration from several Universities.

However, this Annual report demonstrates that our research scientists also pursued an important number of underlying fusion-relevant plasma research, oriented both to preparation of the scientific programme for the COMPASS tokamak and to our traditional topics, e.g. the study of phenomena at the plasma edge, wave-plasma interaction and diagnostics development. The research was performed in close collaboration with many of the other EURATOM Associations and EFDA JET (as mentioned in the reports).

Under the label of "emerging technologies" supported by the "new" EFDA, several tasks in the area of fusion materials have been addressed. We hope that with a more massive support of technology work by Fusion for Energy (European Joint Undertaking for ITER and Development of Fusion Energy), we will be able to build upon the expertise acquired under EFDA and exploit the existing facilities (the cyclotron, the fission reactor, thermal fatigue testing facility etc.) to further contribute to the R&D in areas such as Vessel/In Vessel or Tritium Breeding and Materials.

Pavol Pavlo
Head of Research Unit
Association EURATOM/IPP.CR

I RESEARCH UNIT

1 Association EURATOM/IPP.CR

Composition of the Research Unit in 2009

IPP **Institute of Plasma Physics, v.v.i., Academy of Sciences of the CR**
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Fax: +420 221 912 332
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FNSPE **Faculty of Nuclear Science and Physical Engineering, Czech Technical University**
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Fax: +420 222 320 862
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NRI **Nuclear Research Institute Plc., Řež**
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Tel: +420 5 322 90 379
Fax: +420 5 412 18 657
Contact person: Tomáš Kruml
e-mail: kruml@ipm.cz

Steering Committee

EURATOM

Douglas Bartlett,Unit J4, DG RTD
Steven Booth, Unit J4, DG RTD
Eduard Rille, Unit J3, DG RTD

IPP.CR

Ivan Wilhelm (Ministry of Education, Youth and Sports)
Petr Křenek (Institute of Plasma Physics)
Pavel Chráska (Institute of Plasma Physics)

Head of Research Unit

Pavol Pavlo

Secretary of the SC

Jan Mlynář

International Board of Advisors of the Association EURATOM/IPP.CR

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Prof. Guido Van Oost	Ghent University, Gent, Belgium
Dr. Henri Weisen	EPFL, Lausanne, Switzerland
Dr. Sandor Zoletnik	RMKI KFKI, Budapest, Hungary

The Board was established to help with the formulation of scientific program, and to assess the scientific achievements of the Association EURATOM-IPP.CR.

Representatives of the Association IPP.CR in Committees and Bodies

Consultative Committee for the EURATOM Specific Programme on Nuclear Energy Research - Fusion

Pavel Chráska	Institute of Plasma Physics, Academy of Sciences of the Czech Republic
Milan Tichý	Faculty of Mathematics and Physics, Charles University, Prague

EFDA Scientific and Technical Advisory Committee

Jan Stöckel	Institute of Plasma Physics, Academy of Sciences of the Czech Republic

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Pavol Pavlo	Institute of Plasma Physics, Academy of Sciences of the Czech Republic
Radomír Pánek	Institute of Plasma Physics, Academy of Sciences of the Czech Republic

Governing Board of Fusion for Energy

Pavol Pavlo	Institute of Plasma Physics, Academy of Sciences of the Czech Republic
Jan Kysela	Nuclear Research Institute pls., Řež

2 Manpower and Budget

Manpower Analysis of the Association EURATOM/IPP.CR in 2009

Institution	STAFF, PY	STAFF, Person					
		Female	Male	Prof.	Non-Prof.	TOTAL	Total, %
IPP	39.178	10	57	47	20	67	**83.0**
FMP	0.850	1	3	4	0	4	**5.0**
JHIPC	1.600	0	2	2	0	2	**2.0**
FNSPE	0.700	0	2	1	1	2	**2.0**
NRI	2.500	1	5	4	2	6	**7.0**
NPI	0.000	0	0	0	0	0	**0.0**
IPM	0.000	0	0	0	0	0	**0.0**
IAM	0.000	0	0	0	0	0	**0.0**
TOTAL	**44.828**	**12**	**69**	**58**	**23**	**81**	**100.0**
Total, %	**100.0**	**15.0**	**85.0**	**72.0**	**28.0**	**100.0**	

Expenditures in 2009

	Euro
Physics	1 500 333
JET Notifications	0
Operational cost of major facilities	198 034
Coordination, in the context of a keep-in-touch activity, of the Member State's civil research activities on Inertial Fusion Energy	9 887
Sub-total	**1 708 254**
Large Devices	**900 000**
Specific Co-operative actions 8.2a	94 742
Specific Co-operative actions 8.2b	79 239
JET S/T Task (EFDA Art. 6.3)	4 565
Fellowship contracts	36 536
Sub-total	**120 340**
TOTAL	**2 728 594**
Mobility Actions	**85 842**

The COMPASS tokamak officially started its operation on February 19th 2009. This event triggered major interest of media; two plasma discharges were demonstrated „live“

Laser systém and fast analog-digital converters for Thomson Scattering on COMPASS were procured in 2009

II OVERVIEW

The main areas of the research undertaken in the Association EURATOM/IPP.CR in 2009 were as follows:

1. Provision of Support to the Advancements of the ITER Physics Basis
2. Development of Plasma Auxiliary Systems
3. Development of Concept Improvements and Advances in Fundamental Understanding of Fusion Plasmas
4. Emerging technologies

Here, the most important results, activities and achievements are briefly summarised; detailed reports are available in Part IV. Notice that the major part of the Association activities in Physics relies on broad collaboration with other EURATOM Associations. Besides, in Part V we provide information on work in the Association for ITER and F4E.

1. Provision of support to the advancement of the ITER Physics Basis

1.1 Development of candidate operating scenarios

Statistical comparison of ELMing H-mode with advanced regimes on JET tokamak.
Principal Investigator: I. Duran
The development of discharge scenarios with weak and strong internal transport barriers is one of the primary goals of research at JET. Such scenarios are the key to non-inductive, steady-state operation in future devices and are being developed as ITER candidate scenarios. Two types of study are possible: the detailed investigation of individual discharges, including numerical fluid code modeling and a statistical approach in which a large number of edge and core plasma quantities are compared across a large discharge database to assess the level of similarity in the edge plasma of each type of scenario. We have followed the latter, statistical approach, compiling a database of more than 80 relevant quantities which characterize plasma geometry, basic plasma parameters including profiles of Te, ne, Ti, and all edge and SOL properties which are currently measured on JET.
In the 2009, the further progress in this activity was hampered by the loss of the key contact person on JET for this task - Richard Pitts (CRPP, Switzerland) – who joined ITER IT. Without his coordinating role, there was found not enough expertise and inertia within IPP.CR to carry on this complex task further, and gradually it was decided to stop this activity. Additionally, decreasing of the priority for this task was also caused by the fact that the variability of JET operational parameters will be strongly limited within the next few years during commissioning and the first years of operation of the ITER-like wall. Large variability in operational parameters is a key prerequisite for successful employment of statistical 'database approach'. It is foreseen, that the resources within IPP.CR, originally dedicated to this task, will be directed to other JET related activities in 2010.

1.4 Power and particle exhaust, plasma-wall interaction

Modelling of heat loads of divertor plates on ITER during transient events.
Principial Investigator: R. Dejarnac

Co-worker: M. Komm
The plasma deposition in narrow gaps between tiles of ITER plasma facing components during ELMs has been simulated by means of particle-in-cell technique. The particle and power loads onto and between the divertor tiles are estimated for a multi-species plasma. We simulated an equal mixture (50%-50%) of deuterium and tritium for the main plasma with one impurity, the carbon (3%). The aim of this study was to know whether the carbon ions can enter the narrow gaps between tiles and with which energy. Due to its radioactivity, the tritium deposition in the gaps is also of high interest and has been estimated. The global penetration of the two hydrogen species into the gap is in the order of the gap width (~0.5 mm) with the tritium representing 35 to 40% of the total particle deposition in the gap. The contributions of the hydrogen species on the total heat flux to the gap sides follow the same percentages. The main impurity penetrates into the gap in between 50 to 70% of the total plasma deposition length but with a power deposited representing less than 1% of the total deposited power, as well as for the particle deposition. These results have been presented in the 23rd Symposium On Fusion Energy in San Diego, California, June 2009 (Poster no. SP3C-28) and will be published in a special issue of the peer-reviewed journal IEEE Transactions on Plasma Science [23].
In order to validate experimentally our gap simulations, we plan to build (2010) a special probe, so-called "sandwich probe", that recreates a gap with insulated segments in the radial direction in order to measure plasma deposition distributions. The design chosen for the segments involves the deposition of metallic, conducting layers on a ceramic substrate. In collaboration with the Material Department of our Institute, as preliminary tests, we have deposited thin metallic layers of different metals on Boron Nitride (BN) samples using two techniques 1) Plasma Spray and 2) Coating. Conclusions of these tests are that both techniques are not suitable for elaborating the conducting parts of the sandwich probe. Ref.: [23]

1.5 Physics of plasma heating and current drive

Understanding of gas puff ionization and fast beam generation by LH waves in ITER relevant SOL.
Principal Investigator: V. Petrzilka
Collaboration: M. Goniche, A. Ekedahl (CEA Cadarache, Fr) J. Mailloux, M.L. Mayoral, G. Corrigan, V. Parail, P. Jacquet (JET, UK), P. Belo (IST, Portugal), T.M.Biewer (ORNL, USA), J. Ongena (RMA, Belgium)
During lower hybrid (LH) wave heating, a reduction of saturation current variations with ELMs and a corresponding reduction in the plasma density variations was found by numerical modeling: The LH wave ionizes the SOL (Scrape-off-layer) even before the ELM arrives, and there remains less neutrals for ionization by the ELM. This explains the reduction in variations of the LH wave reflection coefficient observed experimentally in ELMy plasmas, when the LH power is increased. In addition, LH wave scattering on self-consistent plasma density modulations produced by ponderomotive forces was also modeled: The wave scattering results in electron acceleration process in SOL, what can possibly explain fast electrons observed experimentally at a rather large distance of several cm from the LH grill mouth. We also participated in dedicated experiments, in which fast electrons were observed on JET and on Tore Supra: For the first time, fast electrons generated by a PAM (Passive-active module) type LH grill were observed. The energy distribution of the fast beam and its radial width was explored for the PAM grill, too.
Ref.: [1, 2, 4, 22, 30, 31, 32, 45, 46,47, 48, 49, 50, 52, 80, 121]

1.6 Energetic particle physics

Analyses of spatial and spectral characteristics of neutron emissivities at JET.
Principal Investigator: J. Mlynar
Collaboration: Bonheure G., Association EURATOM-Etat Belge, ERM, Belgium Tsalas M., Association EURATOM-Hellenic state, NCSR "Demokritos", Greece Murari A., Association EURATOM-ENEA, Consorzio RFX, Padova, Italy
In 2009, major efforts were dedicated to statistical analyses of Neutron profile monitor data, in particular to studies of spatial characteristics of neutron emissivities after tritium puff using Minimum Fisher Regularisation, which has allowed for fuel transport studies. In correlation studies, dependence of spatial properties on amount of puffed tritium and on plasma density was clearly indentified. Assessment of these results lead to improvement of the statistics by using more pulses from the trace tritium campaign (TTE) and some preliminary studies of tritium beam blip instead of puff were done. A new, more detailed version of the proposed article on the observed 2D characteristics of tritium fuelling was broadly discussed and prepared for the JET pinboard.
The TTE data were also closely analysed for a possibility to detect core fuelling by neutral atoms. Although data seemed promising in 50ms time resolution, detailed statistics of 10ms time resolution proved negative, i.e. within the resolution of the Neutron profile monitor no fuel atoms are present in the plasma core.
A new user-friendly code has been developed that supports the neutron data analyses for a long term shot to shot comprehensive study from various neutron diagnostics systems. As a side-product of this collaboration on neutron data, the geometric matrix for the Soft X ray diagnostics at JET was successfully implemented into Minimum Fisher Regularisation, leading to a new EFDA task proposal.
Ref.: [14, 15, 19]

1.7 Theory and modelling for ITER

Interaction of particles with a system of an ergodic layer of magnetic islands and electrostatic turbulence.
Principal Investigator: L. Krlin
Co-workers: M. Kurian, P. Cahyna, R. Pánek
For the system of an ergodic layer and an edge plasma turbulence, where the effect of both topics on test particle dynamics was considered, first numerical results were obtained . We found that for usual level of magnetic perturbation, forming the ergodic layer and for a model of an electrostatic turbulence, presented by an egg-crac potential [75] with parameters , usually considered and for carbon ions, the effect of the electrostatic turbulence dominates the effect of the ergodic layer. The discussion of this phenomenon for other plasma particles (e.g. protons, electrons and alpha particles) and the meaning of it for real experiments is in a run.
Ref.: [75]

Investigation of interactions of perturbation field with plasma.
Principal Investigator: P. Cahyna
Collaboration: E. Nardon, A. Kirk, G. de Temmerman, Association EURATOM-CCFE
Resonant magnetic prerturbations are being proposed as a tool to suppress type-I ELMs in ITER. Their interaction with plasma is still mostly unknown. One means of interaction is the creation of eddy currents in the plasma which may screen the external perturbation. We have developed a code to calculate the screening currents and their field in order to provide

predictions which can be tested in experiments. We focused mainly on predicting the impact of screening on the divertor footprints created by the perturbation. We have found that if the external perturbation is screened inside the plasma, the footprints are strongly reduced. The lack of observations of footprints in MAST H-mode discharges [26] may provide an experimental support for this finding.
Ref.: [6, 25, 26]

2. Development of plasma auxiliary systems

2.1 Heating and current drive systems

LHCD for COMPASS.
Principal Investigator: V. Fuchs
Co-worker: F. Žáček
Collaboration: M. Goniche, J. Hillairet, M. Freynac, Association EURATOM-CEA, France
R. A. Cairns, University of St. Andrews, Scotland
COMPASS is presently considering two different options for a lower hybrid heating and current drive system: the “old” LH system (1.3 GHz) inherited from Culham, and a “new” LHCD system (3.7 GHz) based on 2 to 3 klystrons going to be made available to us by CEA Cadarache. There are several advantages and disadvantages of the two systems, which we enumerate in the main Report. The the main differences between the present 1.3 GHz “simple” waveguide grill, and a projected multi-junction antenna for the 3.7 GHz system is superior antenna directivity and reflectivity of the 3.7 GHz system.
Concerning lower hybrid current drive, attempts to benchmark our lower hybrid module of ACCOME using the Cadarache code LUKE/CP3O failed, because of the restriction of using only one ray in LUKE. For the COMPASS antenna, be it 1.3 or 3.7 GHz, since the main spectrum width is very wide: of the order of 2 in N// space, one ray is insufficient for tracing the LH wave powerflow.
We are therefore still hoping to be able to use the code CQL3D for benchmarking. Installation of CQL3D on our SUN system is completed, we are waiting for a execution tutorial from Dr R Harvey, the CQL3D administrator.
Furthermore, with Dr R A Cairns we have progressed with developing a full wave approach to LH wave propagation for COMPASSD. A paper was submitted to Nuclear Fusion. Ref.: [27, 29]

Preparation of installation of the NBI on COMPASS.
Principal Investigator: J. Stockel
Co-worker: J. Mlynář
Collaboration: A.A. Ivanov, Budker Institute, Novosibirsk, Russian Federation
Two Neutral Beam Injectors (NBI) will be used for additional plasma heating on the COMPASS tokamak. The beam energy is 40 keV and the total power 2x300 kW. The NBIs are manufactured at the Budker Institute, Novosibirsk, Russian Federation. During the year 2009, the design of NBIs and their connection to the COMPASS tokamak was finalized. Furthermore, some preparatory work had to be done. The design of the beam duct was modified taking into account the final geometry of the NBI and of the supporting structures of the COMPASS tokamak. The vacuum system was designed and refrigerators for cryopumps were purchased. Furthermore, additional equipment required for NBI operation, such as the

cooling and gas handling systems were specified. The NBIs will be delivered to IPP Prague in the mid of 2010 to perform the first tests.

2.2 Plasma diagnostics

Probe measurements on COMPASS.
Principal Investigator: J. Stockel
Co-workers: J. Adamek, J. Brotankova, R. Dejarnac, J. Horacek, M. Komm
Collaboration: Ts. Popov. Association EURATOM-INRNE/Faculty of Physics, Sofia, Bulgaria, J. Gunn, Association EURATOM-CEA Cadarache, France, M. Spolaore, Association EURATOM-ENEA/RFX, Padova, Italy, C. Hidalgo, Association EURATOM/CIEMAT, Madrid, Spain
An array of Langmuir probes embedded to a divertor plate was commissioned and first experimental results are promising. A new probe head for measurements of current filaments in the SOL is being designed. Two reciprocating probes, located at different poloidal and toroidal positions are almost commissioned. A significant progress was achieved in numerical modeling of probe performance.
Ref.: [8, 9, 109, 134]

Development of fast tomography systems based on fast bolometric and SXR arrays for COMPASS.
Principal Investigator: V. Weinzettl
A basic functionality of the first complex port plug (upper angular port) combining detection systems for fast bolometry, soft X-ray and visible light observations taken into account a strongly limited available space, a heat protection and a shielding during a cleaning glow discharge was successfully tested (without VIS optics) under real plasma conditions. Additionally, new electronic parts (signal amplifiers, a local temperature control connected to the baking modules) were developed. The system is fully compatible with ultra high vacuum in the tokamak and survives both a cleaning glow discharge and baking of the vessel. An experience gained from the first tests was considered in minor improvements, namely, of the cable spacer made from VESPEL SP1 material, the connection of the vacuum feedthrough and the detector socket, and of the slit holder. These parts with a better performance were constructed and installed to the second port plug (angular lower port) equipped with the same detectors. Moreover, a design of both the third and fourth plugs for vertical ports located in the same poloidal cut was finished and corresponding parts were manufactured.
Ref.: [11, 12, 122]

Installation of the BES system on the COMPASS tokamak.
Principal Investigator: V. Weinzettl
Co-workers: J. Havlicek, J. Urban, M. Stransky, J. Stockel, P. Hacek, O. Hronova, J. Horacek, I. Duran, M. Hron, V. Piffl
Collaboration: G. Veres, M. Berta, G. Anda, S. Tulipan, T. Ilkei, D. Dunai, D. Nagy, A. Bencze, S. Zoletnik, Association EURATOM – HAS
The stray magnetic field calculations and direct measurements using Hall probes necessary for an estimation of the diagnostic beam magnetic shielding back-influence on plasma were realized on the COMPASS tokamak. A real status of the diagnostic ports for BES/ABP

detections and installation possibilities were examined and important dimensions for BES/ABP were re-measured. The design of the vacuum interface allowing BES/ABP diagnostics was finalized, manufactured and installed on the COMPASS tokamak and the prototype of the ABP detector was mounted there. Tests of electromagnetic compatibility of the high-voltage source for the diagnostic beam were also successfully realized. However, a delivery of the diagnostic beam manufactured by Association EURATOM - HAS is delayed and the beam was not transferred to Prague yet.

Development of fast digital video camera system for machine control, plasma overview and turbulence measurements.
Principal Investigator: V. Weinzettl
Co-worker: D. Sestak
Collaboration: M. Berta, G. Veres, T. Szilveszter, A. Szappanos, S. Zoletnik, Association EURATOM – HAS
A new camera system 'Event Detection Intelligent Camera' (EDICAM) is being developed by the Hungarian Association and has been installed on the COMPASS tokamak during February 2009. The standalone system contains a data acquisition PC and a prototype sensor module of EDICAM. Appropriate optical system have been designed and adjusted for the local requirements, and also a special mechanical holder that keeps the camera out of the magnetic field. The fast camera contains a monochrome CMOS sensor with advanced control features and spectral sensitivity in the visible range. A special web based control interface has been implemented using Java Spring framework to provide the control features in a graphical user environment. The whole camera system was successfully tested under real plasma conditions in spring and summer campaigns. The basic processing software programmed in the MATLAB environment was installed on the new data server, where all data from the camera will be stored. However, only a prototype of the camera connected with the driving PC using electrical cables, instead of optical fibres, was delivered to IPP Prague. Also an improved camera firmware allowing a continuous monitoring of the intensity of predefined image areas and trigger signal generation for machine protection was not installed yet.
Ref.: [13]

Development of multichannel diagnostics in visible light for COMPASS.
Principal Investigator: D. Naydenkova
Co-workers: V. Weinzettl, D. Šesták, J. Vlček, R. Melich, D. Jareš
Two wide-angle optical systems for visible plasma radiation collimation were produced. Nowadays the optics is under tests. Optical cable systems were purchased. The endconnectors between the optical cable and the photodiode array detectors and the objective were manufactured. Amplifier of signals was tested. The first measurements of the most intensive lines were done and main impurity lines were identified. An attempt to describe different tokamak regimes in terms of visible radiation was done.
Ref.: [12, 41, 42, 78, 111, 122]

Comparative measurements of the electron temperature on ASDEX Upgrade in ELMy H-mode by using the Ball-pen and fast swept Langmuir probe.
Principal Investigator: J. Adamek
Co-workers: J. Horáček, J. Stöckel, V. Weinzettl, M. Peterka

Collaboration: H.W. Müller, V. Rohde, Max-Planck-Institut für Plasmaphysik, EURATOM Association, D-85748 Garching, Germany, R. Schrittwieser, C. Ionita, F. Mehlmann, Association EURATOM/ÖAW, Univ. Innsbruck, Austria

In collaboration of the association EURATOM-IPP.CR, EURATOM-IPP and EURATOM-ÖAW on ASDEX Upgrade tokamak in April 2009 the joint experiments has been performed on the comparative measurements of the electron temperature by the ball-pen probes (BPPs), swept Langmuir probe and Thomson scattering. The BPPs and LP have been mounted on the mid plane manipulator and used for the direct measurements of the plasma and floating potential and the I-V characteristics (swept LP probe, 130kHz) in L-mode and ELMy H-mode. The BPP/LP operating in DC regime provides the electron temperature with high temporal resolution and the first results were presented and published on 36EPS(2009). The comparison of the radial profile of the electron temperature obtained by the BPP/LP, swept LP and Thomson scattering during L-mode were presented on IWEP 2009 in Innsbruck and be published in 2010. The results shows a good agreement between BPP/LP and Thomson scattering, which confirm that the BPP can be used for the simple and fast measurements of the electron temperature with high space resolution in SOL on large fusion devices. The fast measurements of the electron temperature using the BPP/LP and fast swept LP indicate a systematic agreement of the achieved results during ELM's. The inter-ELM part can not be compared because the fitting procedures used for fast swept LP are limited by the minimum electron temperature ~8eV in this case.

Moreover, the further analysis show a very good agreement of the radial electric field measurements by the BPP (gradient of the plasma potential profile) and the Doppler reflectometry (results will be also included in Annual Report 2009 of IPP and also published in 2010).

Ref.: [43, 44, 56, 59]

Comparative measurements of the electron temperature on TEXTOR tokamak by using the Ball-pen probe and triple probe technique..

Principal Investigator: J. Adamek

The project was canceled due to the technical problems and The scientific part were substituted for the comparative measurements by Thomson and BPP on ASDEX Upgrade (see more at the executive summary for ASDEX Upgrade).

Ultrasoft x-ray spectroscopy using multilayer mirrors on COMPASS-D.

Principal Investigator: V. Piffl

The negotiation on USX Spectrometer transfer to IPP Prague was successfully finished. The spectrometer body and vacuum interface was transported in the beginning of 2009 year in Prague.

The application of the “Ultrasoft x-spectroscopy using multilayer mirrors on COMPASS-D” has been however deferred due to the lack of financial means for the necessary technical improvement of the USX spectroscopy diagnostic system.

Thomson scattering design for COMPASS.

Principal Investigator: P. Bikova

Co-workers: P.Bohm, M.Aftanas, R.Melich, D.Sestak, W.Weinzettl

Collaboration: M. J. Walsh, R. Scannell, G. Naylor and M. Dunstan, Association EURATOM, CCFE, Culham Science Centre, Abingdon, Oxfordshire, OX143DB, UK

The COMPASS Thomson scattering (TS) diagnostic has been developed to a conceptual design, which comprises choice of particular components (laser system, polychromators, detectors, optical fibers, data acquisition system) and to a detailed design of particular components and specification of required parameters. The design was developing under the effective collaboration with the CCFE team. Particularly, the design of polychromator developed on MAST, CCFE has been used and adapted to meet COMPASS needs.
Ref.: [12, 63, 64, 124, 125, 126]

Magnetic diagnostics
Principal Investigator: J. Havlíček
Co-workers: F. Žáček, F. Janky, J. Horáček, I. Ďuran, J. Brotánková, O. Bilyková
A full set of the magnetic diagnostic coils was delivered together with the tokamak from Culham Science Centre. The cabling, rack cabinets and data acquisition system are new - refurbishment was required.
Because of the limited number of available data acquisition channels only a few basic diagnostic coils were used for initial COMPASS campaigns.The set of ~ 70 magnetic diagnostics coils was calibrated and prepared for use at the end of the year.
First attempts to plasma position reconstruction and subsequently an extensive analysis of magnetic coils combination suitable for vertical and horizontal plasma position reconstruction were perfomed.
Ref.: [57, 76]

Development of millimeter-wave reflectometry system for the measurement of edge piedestal plasma in tokamak COMPASS.
Principal Investigator: J. Zajac
Co-workers: F. Zacek, J. Vlcek
Collaboration: M. Manso, A. Silva, P. Varela, L. Cupido, Association EURATOM- Instituto Superior Technico / Centro de Fusão Nuclear, Lisbon, V. Kiseliov, Institute of Radiophysics and Electronics-Dep. of Quasioptics, Kharkov, Ukraine
The reflectometry system for Compass was mainly designed to perform the relevant plasma density profile measurements in the pedestal region. The additional requirement is using of the reflectometers as well as an experimental diagnostics for studies of the plasma turbulence. The reflectometry system consists of two parts which are developed separately. The first part are the microwave electronics and data aquisition which will be provided by IST/CFN. The procurement of the microwave electronics in IST/CFN has not been finished in 2009. The provider of the second part (band-combiners and the quasi-optical antennas - BCA) is the Institute of Radiophysics and Electronics NAS of Ukraine (IRE NASU). The developement of BCA was started successfuly in August and there have been no indications of problems so far.

Microwave interferometer for Compass.
Principal Investigator: J. Zajac
Co-workers: F. Zacek
Collaboration: Gennadiy Ermak, Anton Varavin, Institute of Radiophysics and Electronics, Kharkov, Ukraine
This is for the Annual Report 2009, part of Microwave interferometer for Compass tokamak. The 2-mm interferometer for the density measurement was designed in years about 1990 in Culham. The interferometer has been re-installed on Compass in IPP Prague. Some suitable

modifications were proposed with the help of specialists from the Institute of Radiophysics and Electronics NAS of Ukraine (IRE NASU). Two actions realized in 2009 improved the interference between oscilators inside the intereferometer box. The new phase detectors controlled by microprocesor will be implemented soon.

Development of a new ion temperature probe for the Tore Supra Scrape-off layer.
Principal Investigator: R. Panek
The STP probe has been developed and installed at TORE SUPRA tokamak in 2008. We have also participated in the first tests and measurements in the second half of 2008, which proved the probe performance. In 2009, due to other priorities connected to the commissioning of COMPASS tokamak, we did not participated in the measurement with STP at the TORE SUPRA tokamak.

2.4 Real Time Measurement and Control

COMPASS control, real time feedback, data acquisition, and communication.
Principal Investigator: M. Hron
The COMPASS CODAC and allied systems commissioning was ongoing during 2009:
a) tests and improvements of the tokamak power supplies and namely of the operator interface continued [51], at present the power supply system is in full operation;
b) commissioning of the machine operation systems – vacuum pumping, temperature measurement and vacuum vessel baking, gas handling and glow discharge, and gas puffing systems was finished [81, 84];
c) hardware part of the CODAC system consisting of ATCA telecommunication standard crates and I/O modules developed at IST [54] was built;
d) an operator interface – node for subsystem control called FireSignal [82] was installed;
e) implementation of diagnostics into the CODAC, namely the atomic beam probe and fast visible camera [13], is ongoing;
f) real-time software for the plasma control was developed [83];
g) plasma position control (feedback) and fast amplifiers construction was ongoing: a model based on the transfer function was developed, two modules of the fast feedback amplifiers were built and tested in laboratory conditions, and installed in the COMPASS site;
h) personnel protection system, a separate system which output enters the machine control, was installed and successfully tested [65].
Several of these subsystems were built in a close collaboration with the Associations EURATOM/IST and HAS.
Ref.: [13, 51, 54, 65, 81, 82, 83, 84]

3. Development of concept improvements and advances in fundamental understanding of fusion plasmas

3.1 Optimization of operational regimes for improved concepts

Preparation for experiments with RMP coils of COMPASS.
Principal Investigator: P. Cahyna

Co-workers: R. Pánek, J. Havlicek
Collaboration: E. Nardon, Association EURATOM-CCFE, M. Becoulet, Association EURATOM-CEA
In the future experimental programme of COMPASS we plan to focus on studies of resonant magnetic perturbations (RMPs), especially in view of their application as an ELM control mechanism and their planned use in ITER. We will use the existing saddle coils which have the maximum toroidal mode number n=2 and we plan to extend them with new coils to be able to produce a higher toroidal mode number up to n=4 for studies of the influence of the mode number. We calculated the spectra of the existing coils and determined the configurations in which they produce significant edge perturbations [5]. Material for the new coils have been procured and first tests of a prototype amplifier for powering the coils were performed. We also modelled effects of coils and the plasma response which can be observed by diagnostics [7]. Especially promising are observations of the divertor footprints which can use the existing set of Langmuir probes and would benefit from an IR camera. Commisioning of the magnetic diagnostics which will be used (among others) for the RMP experiments is in progress [76].
Ref.: [5, 7, 76]

3.2 Understanding of plasma characteristics for improved concepts

ELM pacing: further exploring edge biasing as potential new tool.
Principal Investigator: V. Weinzettl
Collaboration: H.W. Muller, V. Rohde, M. Wischmeier, Association EURATOM – IPP
The proposed effect of the ELM pacing by the edge plasma biasing was investigated in details on the existing data measured in 2008 with the aim to confirm or definitely reject its explanation via induced electric fields. At least for the used small-area probe tips and driven currents bellow 1 A, the effect of the ELM triggering by edge plasma biasing did not work or is minor, and is probably superimposed by impurity erosion effects from the probe body. However, for the measured data of the ELM pacing campaign with the high-heat flux head mounted on the midplane manipulator the processing routines were prepared that valuable information on the ELM fine structure was mined.

3.3 Other experimental activities

Tests and exploitation of Hall probe based systems on tokamak JET (EP2 project) and on stellarator TJ-II..
Principal Investigator: I. Duran
Co-worker: K. Kovařík
Collaboration: I. Bolshakova, R. Holyaka, V. Erashok, Magnetic Sensors Laboratory, Lviv Polytechnic National University, Lviv, Ukraine, A. Quercia, Association EURATOM ENEA/CREATE, Naples, Italy
Use of various configurations of flux loops for measurement of magnetic field in fusion devices is inherently limited by the pulsed operation of these machines. A principally new diagnostic method must be developed to complement the magnetic measurements in true steady state regime of operation of fusion reactors. One of the options is the use of diagnostics based on Hall sensors. Two experiments dedicated to testing of various types of Hall probes were undertaken on JET and TJ-II with participation of IPP.CR.

1. The system of two sets of three 3D ex-vessel Hall probes is being commissioned on JET within EP2 project. IPP.CR participated on high level commissioning of the system and on evaluation of its performance. The aim of this JET upgrade is to test ITER candidate steady state magnetic sensors under fusion neutron spectrum during JET DT campaigns and also to improve the magnetic reconstruction by improving spatial resolution of ex-vessel magnetic field monitoring.
2. On TJ-II, commissioning of the combined probe; containing coils, Hall sensors and oriented Langmuir probes; continued in 2009 by design and installation of a new cabling system, compatible with magnetic diagnostics, in upper reciprocating probe drive manipulator. Besides the tests of used Hall probes, this new diagnostic is expected to shed additional light into complex picture of electrostatic and magnetic modes and their interaction on TJ-II [67].
Ref.: [67]

Experiment vs. modelling of outboard SOL turbulence.
Principal Investigator: J. Horacek
Co-worker: J. Adamek, J. Seidl, E. Havlickova
Collaboration: H.W. Muller, V. Rohde, Max Planck Institut fur Plasmaphysik, EURATOM Association, Garching, Germany,, F. Mehlmann, C. Ionita, Association EURATOM/OAW, Institute for Ion Physics and Applied Physics, University of Innsbruck, Austria, A.H. Nielsen, Association Euratom Risø DTU, Risoe National Laboratory for Sustainable Energy, DK-4000 Roskilde, Denmark
1. ESEL simulation of ITER cancelled because ITER SOL collisionality is actually outside ESEL capabilities.
2. plasma-wall interaction computation: cancelled because current ESEL version doesn't take into account ion temperature that is necessary for PWI computation. Ongoing project of coupling ESEL with SOLF1D parallel transport code will add this feature within a year
3. external transport barrier - Completed by presentation [J. Seidl, J. Horacek etal. EU-US TTF Workshop, Copenhagen 2008].
4. SOLF1D parallel transport code coupled with ESEL: ongoing project. It's part of PhD thesis [77] and [58,60] presentations, compared with B2 model. The coupling will enhance the 2D ESEL code into a quasi-3D code of SOL plasma electrostatic interchange turbulence.
5. Quality experimental data of fast and local SOL parameters were measured at Asdex [on mobility], presented in [55,56,59] and summarized in paper submitted to Nuclear Fusion in March 2010.
6. Modelling of probe heating during reciprocation: completed without a publication.
7. New topic: attempt to explain suprathermal electron generation too far from LH grill on ToreSupra by the ESEL model, presented as [30, 32].
8. Lots of effort was put in 2010 in reinstallation of two reciprocating probes on Compass tokamak under EFDA Priority support WP08-TGS-01-06. Lots of vacuum components were built in our workshop or purchased, then installed on the vacuum vessel. The probes are ready for plasma operation since March'10 and May'10, respectively.
Ref.: [30, 32, 44, 55, 56, 58, 59, 60, 77]

3.4 Theory and modelling

EBW simulations for WEGA
Principal Investigator: J. Preinhaelter
Co-worker: J. Urban
Collaboration: H.P. Laqua, Association EURATOM-CEA Cadarache, France

The WEGA experiment in IPP Greifswald presently carries out unique experiments with EBW heating and emission. Overdense plasma for 28 GHz second harmonic heating can be achieved and subsequently sustained exclusively by O-X-EBW heating. EBW emission is also detected during these discharges, enabling detailed EBW studies in quasi-stationary conditions. These experiments are supported by our modelling using the AMR code. The simulations of the O-X-EBW heating are consistent with the experiments. On the other side, a very intense EBW emission is experimentally detected and cannot be explained by the present models. More detailed studies are thus needed to give an explanation for this phenomenon. Ref.: [17, 36, 38, 40, 53]

MAST EBW studies
Principal Investigator: J. Preinhaelter
Co-worker: J. Urban
Collaboration: V. Schevchenko and M. Valovič EURATOM/CCFE Association , Culham, UK
The EBW emission from MAST detected by the rotating mirror was simulated with our AMR code. We compared the results of the simulation with the experiment but we do not obtain good fit. We concluded that the EFIT equilibrium, used in AMR code for the determination of magnetic configuration, does not describe by adequately profile of the intensity of magnetic field in the transport barrier.
Ref.: [33, 62]

EFIT++ development.
Principal Investigator: J. Havlicek
Co-worker: J. Urban
Collaboration: L. Appel, EURATOM/CCFE Fusion Association, United Kingdom
The EFIT++ code development consists of implementation of a computational model to represent the induced currents in the passive structures of the tokamaks. The status of the induced currents model is that the model was implemented into C++ and incorporated into the EFIT++ code. The model is in the testing phase. The comparison of currents computed by this model with previously used INDUCTION module shows several discrepancies. Work remains to complete benchmarking against the INDUCTION code, and to optimise its operation.

Quasineutral particle-in-cell code (QPIC) for description of SOL plasma.
Principal Investigator: V. Fuchs
Co-worker: V. Petržílka
Collaboration: J. P. Gunn, M. Goniche, A. Ekedahl, N. Fedorczak, J. Hillairet
Association EURATOM-CEA, France
We modified our quasi-neutral particle-in-cell code (QPIC) by introducing the effect of collisions using a Bhatnagar-Gross-Krook collision operator in Monte-Carlo form. This allows more rigorous analysis of phenomena associated with flows originating from extraordinary particle sources in the SOL, such as lower hybrid power and/or ELMs. Tests of the QPIC code with the collision operator are still in progress. Our principal task, in view of the planned (and in fact materialized) start in November 2009 of Tore Supra operation with the new PAM (passive-active multi-junction) C4 antenna, was to continue a study, started in 2008, of the phenomenon of fast electrons observed all the way from the grill mouth to the last closed flux surface during operation with the C2 antenna. This observation contradicted previous PIC studies which predict interaction widths of up to about 5 mm. We first analysed the fast electron measurements from 2007 and 2008 campaigns in the light of data from edge

turbulence measurements in order to show that the fast electrons are correlated with a special kind of turbulence, with "blobs" detached from the main body of the plasma. We carried out test electron simulations with electric field files from the ALOHA antenna code at conditions of Tore Supra shot 39547, to investigate SOL conditions for weak Landau damping, which would allow penetration of the injected lower hybrid spectrum to radial positions sufficiently close to the last closed flux surface before being strongly damped by a dense and hot blob. Ref.: [22, 30, 31, 32, 45, 49]

EBW Fokker-Planck modelling.
Principal Investigator: J. Urban
Co-worker: J. Preinhaelter
Collaboration: J. Decker, Y. Peysson Association EURATOM-CEA Cadarache, France
G. Taylor Princeton Plasma Physics Laboratory, NJ, USA
Our AMR (Antenna, Mode-conversion, Ray-tracing) code is specifically suited for electron Bernstein wave (EBW) simulations. It has been recently coupled with the LUKE Fokker-Planck solver to enable quasilinear damping and current drive calculation. The coupling is two-way, i.e., AMR can use LUKE and vice versa, providing all plasma parameters are consistent. Batch processing of different cases is easily possible using the AMR driver script. The AMR-LUKE suite is presently used for predictive modelling of EBW heating and current drive on spherical tokamaks, particularly NSTX, MAST and their envisaged upgrades. Promising results have been found that show efficient EBW current drive over the whole tokamak radius.
Ref.: [20, 21, 33, 34, 35, 37, 61, 114]

Detection of EBW emission on COMPASS.
Principal Investigator: J. Preinhaelter
Co-workers: J. Urban, J. Zajac, F. Žáček
Our 16-channel radiometer was completed and we absolutely calibrated. Two antenna systems for oblique electron Bernstein waves (EBW) detection, both with steering mirror, are prepared for two ports of COMPASS. Preliminary testing shots with underdense, highly non-thermal plasma with large portion of runaway electrons do not allowed to study EBW emission so we measured only direct perpendicular emission of O-mode from fundamental harmonic.
Ref.: [39]

4. Emerging Technologies

4.1 Development of Materials science and advanced materials for DEMO

Development of Hall sensors for use within magnetic diagnostic of fusion reactors..
Principal Investigator: I. Duran
Co-worker: K. Kovařík
Collaboration: L. Viererbl, Z. Lahodová, Nuclear Research Institute, plc., Association EURATOM IPP.CR, Řež, Czech Republic M. Oszwaldowski, J. Jankowski, S. El-Ahmar, Faculty of Technical Physics, Poznan University of Technology, Association EURATOM/IPPLM, Poznan, Poland
Magnetic diagnostic based on radiation hard Hall probes is a promising concept for measurement of almost DC magnetic fields on ITER tokamak and future fusion reactors. Good progress has been achieved in development of such sensors based on specially doped semiconductor materials for ITER ex-vessel steady-state magnetic diagnostic. The main open

issue at present is achieving of sufficient thermal resistance in combination with already achieved radiation-resistance i.e. develop sensors with survival temperature around 300 degC. In this respect two lines of research were persuaded in 2009. First one aims at achieving survival of conventional InSb Hall sensors by protecting the semiconductor sensing layer by SiOx protective layer. Such sensors were recently developed by Poznan University of Technology, Poland and their irradiation tests were performed at IPP.CR on LVR-15 fission reactor in several steps up to the total neutron fluence of 10^18 cm^-2. The second approach relays upon the expected higher radiation and thermal resistance of metal Hall sensors compared to their semiconductor based counterparts. In this case, we performed initial feasibility study, we enhanced our test equipment to allow characterization of metal Hall sensors which feature low sensitivity, and we searched for the most suitable technology for production of such sensors.
Ref.: [67, 72, 73, 74, 75]

Irradiation and characterization of fusion-relevant materials.
Principal Investigator: J. Matejicek
Co-worker: L. Viererbl, Nuclear Research Institute, Rez, Czech Republic
Irradiation of the materials was concluded and their activity measured. Transportation of the samples for external characterization as well as in-house characteriation are underway.

Development of W/Fe functional gradient materials using laser deposition..
Principal Investigator: J. Matejicek
Co-worker: H. Boldyryeva
Collaboration: P. Ambrož, Czech Technical University in Prague (ČVUT), Prague, Czech Republic
Laser cladding experiments continued with different scanning regimes, to achieve different cladding thickness and composition. Additional treatment included re-heating by laser itself and furnace annealing, both resulting in increased thermal conductivity.

5. Training and career development

5.1 Collaboration with the Universities in training in fusion research

Collaboration of tokamak COMPASS with the Universities in postgraduate and undergraduate training in fusion research.
Principal Investigator: J. Mlynar
Co-workers: I. Ďuran, J. Stöckel
In 2009, 15 doctoral and 19 undergraduate students were involved in the work of the the tokamak department (COMPASS). IPP staff participated in the winter school of Faculty of Nuclear Sciences and Physical Engineering CTU (FNSPE) for MSc students (which took place in the IPP premises), organised 6 courses, a seminar course and one practica for the FNSPE and one course for the Faculty of Mathematics and Physics, Charles University. In total in 2009 our staff taught more than 200 hours of lectures. Besides we participate in the EURATOM CSA in education (FUSENET) and although this is a marginal activity, the regular SUMTRAIC course (see separate report) clearly benefited from this coordinated action.
Doctoral students played a key role in COMPASS commissioning and several foreign students visited COMPASS, in particular from Belgium and France.

The amount of proposed BSc and MSc thesis was kept on sufficient level (8 new topics in total) - slightly higher than the number of potential candidates so that the students can choose according to their preferences.
Situation in the University education in fusion related fields, including collaboration with IPP, was detailed in the recent issue of the Czechoslovak Journal of Physics (in Czech). Ref.: [18, 136, 137, 138]

Undergraduate training in Fusion at Faculty of Mathematics and Physics (FMP), Charles University and at Faculty of Nuclear Sciences and Physical Engineering (FNSPE), Czech Technical University in Prague.
Principal Investigator: V. Svoboda
Co-workers:, D. Břeň, M. Tichý , R. Hrach
The Faculty of Nuclear Sciences and Physical Engineering, Technical University in Prague (FNSPE) successfully continued the MSc curricullum "Physics and Technology of Thermonuclear Fusion". In February, in collaboration with IPP, FNSPE organised the joint workshop (one week winter school) for all students of the curricullum. FNSPE also takes an important part in the FUSENET consortium. However, the main achievement of FNSPE since last Report was the successful reinstallation of the GOLEM tokamak at the faculty (former CASTOR) which is foreseen as the main practica tool for the MSc students. The GOLEM facility had first plasma on 8th July 2009 and took part in the SUMTRAIC summer school.

The Faculty of Mathematics and Physics, Charles University (FMP) is focused on post-graduate (doctoral) level in the fusion education. In this respect, FMP participates in FUSENET and also took part in the consortium (lead by University of Ghent) that applied for the Erasmus Mundus support for European Doctoral course in fusion. FMP also hosted the 2009 summer school “Plasma Physics in Science and Technology”, organised by the University Greifswald in Prague.
Ref.: [18, 135, 136, 137, 138, 139, 140]

5.2 Training in laboratory experience, principles of data validation, analyses and interpretation, and presentation of results

Summer Training Course on the COMPASS tokamak.
Principal Investigator: J. Stockel
Co-workers: J Brotánková, R Dejarnac, J Havlíček, J Horáček, M Hron, J Mlynář. D Naydenková, R Pánek, V Weinzettl, J Zajac
Collaboration: G. Veres, M. Berta, Association EURATOM-HAS, Hungary
The 7th Summer Training Course (SUMTRAIC 2009) was organized for the first time on the COMPASS tokamak in collaboration with the Association EURATOM/HAS in the period 26.8.08 - 4.9.2009. Before practical training, several introductory lectures have been presented. The Course was attended by 13 students from five countries. Students were divided to five experimental groups supervised by local and Hungatian supervisors. Four days was devoted to experiments on COMPASS, the remaining time was spent by data processing and preparation of presentation at the closing workshop. The next SUMTRAIC will be held in the period 23. August - 4. September 2010.

5.3 EFTS

Conduct training of two young engineers within EODI and ENTICE projects..
Principal Investigator: I. Duran
Training of two young engineers continued in IPP.CR within the formal framework of FP6 EFTS projects ENTICE and EODI. Training of Alena Krivska (ENTICE) successfully continued along her carrier development plan. She finished her training period in IPP Garching followed by one month stay in Spinner company. In June, she started her last long term stay within the program in UKAEA. There, she was further enhancing particularly her modeling skills of ICRH antennas and interaction of ICRH waves with edge plasma using several applicable codes.
Training of David Sestak (EODI) also successfully continued along his carrier development plan. He spent 3 months in total in ITER IT where he engaged in design of Thomson scattering equatorial port plug. In IPP Prague he participated in various diagnostics development tasks with emphasis on optical diagnostics and design of high resolution Thomson scattering system for COMPASS.
Ref.: [12, 39, 85, 86]

6. Other activities in magnetic confinement fusion

6.1 Public information

Public Information activities in Association IPP.CR.
Principal Investigator: M. Řípa
Co-worker: Jan Mlynář
In 2009 the Public Information in IPP Prague was very productive due to combination of three media attractive conditions: The official start of COMPASS operation in April, Czech Presidency in the EU and 50th Anniversary of the Institute of Plasma Physics. As a result, the number of media coverage was extraordinary last year, with spots on main TV and radio broadcasts, several tens of articles in main newspapers and even several reports in foreign media. Tokamak COMPASS also hosted several VIPs last year, in particular Members of European Parliament, and hundreds of public visitors on regularly organised excursions to the COMPASS facility. The tradition of public lectures on fusion energy also continued with considerable success. For audience interested in physics, a special issue of the Czechoslovak Journal of Physics was printed in collaboration with our institute.
Ref.: [16, 18, 79, 80]

7. Coordination, in the context of a keep-in-touch activity, of the Member State's civil research activities on Inertial Fusion Energy'

7.1 Scientific Developments

Laser radiation coupling to laser-accelerated foil targets..
Principal Investigator: J. Ullschmied
Co-workers: Eduard Krouský, Karel Mašek, Miroslav Pfeifer, Jiří Skála
Collaboration: A. Kasperczuk, T. Pisarczyk, S. Borodziuk, J. Badziak, T. Chodukowski, Association EURATOM-IPPLM, Warsaw, Poland, J. Limpouch, FNSPE CTU Prague, K. Rohlena – Institute of Physics, ASCR, v. v. i.

Experiments on laser interaction with foil targets were performed by a group of PALS (IPP-CZ) and IPPLM-PL physicists at the PALS infrastructure during a cooperative experimental campaign supported by LASERLAB-EUROPE in the period February-March 2009 [102, 105]. They resulted in proposing a novel method of acceleration of macroparticles to high velocities, based on exploiting the pressure and radiation of the hot plasma produced by laser on a massive auxiliary target. This reversed scheme acceleration (RAS), the advantages of which were demonstrated in [102,105], was further improved by providing the auxiliary target with a cavity [127] . The new concept called the Laser Induced Cavity Pressure Acceleration (LICPA) makes it possible to accelerate both light and heavy macroparticles in arbitrary direction, with the acceleration efficiency far exceeding that achieved up to now by using the classic ablative acceleration scheme.
Ref.: [102, 105, 127, 128, 129]

7.2 Coordination Activities

Coordinated investigations of laser-produced plasma jets for the fast ignition concept of ICF target.
Principal Investigator: J. Ullschmied
Co-workers: Eduard Krouský, Karel Mašek, Miroslav Pfeifer, Jiří Skála
Collaboration: J. Badziak, T. Pisarczyk, T. Chodukowski, A. Kasperczuk, P. Parys, M. Rosinski, J. Wolowski, Association EURATOM-IPPLM, Warsaw, Poland
A large set of experimental data on electron density distributions and ion currents in different expansion stages of the plasma-jets produced by focused laser radiation on solid target of different materials, collected during cooperative experiment at the PALS infrastrucutre, have been used for setting up numerical simulation models of the plasma jet formation. The combined experimental and simulation results on the jet formation are being published in a series of conference contributions and articles, such as [103, 104, 107].
Ref.: [103, 104, 107, 128, 129]

7.4 Maintain a watching brief on inertial confinement civil research activities

Inform the wider fusion community of developments in IFE.
Principal Investigator: J. Ullschmied
Contributions to the Annual Report 2008 of IFE-WG on the IFE Keep-in-Touch Activities have been completed, Jiri Ullschmied (IPP-CZ) and Jerzy Wolowski (IPPLM Warsaw) being the rapporteurs for the Laser Plasma Interaction and Plasma Diagnostics parts. The complete Annual Report was presented by Sylvia Jacquemot (LULI) at CCE-FU meeting on 11. 6. 2009. The full report is available at http://www.luli.polytechnique.fr/pages/IFE-KiT/watching2008.pdf .

III GENERATED INFORMATION AND INTELLECTUAL PROPERTY

1. Generated information

List of 2009 research publications of the Association EURATOM / IPP.CR follows. For overview of Public Information activities please refer to the report in Part IV, section 7.

[1] A. Ekedahl, K. Rantamäki, M. Goniche, J. Mailloux, V. Petrzilka, G. Granucci, B. Alper, G. Arnoux, Y. Baranov, V. Basiuk, P. Beaumont, G. Calabrò, V. Cocilovo, G. Corrigan, L. Delpech, K. Erents, D. Frigione, N. Hawkes, J. Hobirk, F. Imbeaux, E. Joffrin, K. Kirov, T. Loarer, D. McDonald, F. Nave, I. Nunes, J. Ongena, V. Parail, F. Piccolo, E. Rachlew, C. Silva, A. Sirinelli, M. Stamp, K-D. Zastrow and JET EFDA contributors: Effect of gas injection during LH wave coupling at ITER-relevant plasma–wall distances in JET. *Preprint EFD-P08-018, Plasma Phys. Control. Fusion 51 (2009) 044001 (17pp), on JET pinboard.*

[2] M.Goniche, A.Ekedahl, J.Mailloux, V.Petržílka, K.Rantamäki, P.Belo, G.Corrigan, L.Delpech, K.Erents, P.Jacquet, K.Kirov, M.-L.Mayoral, J.Ongena, C.Portafaix, M.Stamp, K.-D.Zastrow and JET EFDA contributors: SOL characterisation and LH coupling measurements on JET in ITER relevant conditions. *Preprint EFD-P08-017, Plasma Phys. Control. Fusion 51 (2009) 044002, on JET pinboard*

[3] J. Marki, R.A. Pitts, J. Horacek, D. Tskhakaya and The TCV Team: ELM induced divertor heat loads on TCV . *Journal of Nuclear Materials 390-391 (2009) 801-805* http://dx.doi.org/10.1016/j.jnucmat.2009.01.212

[4] K. K. Kirov, M L. Mayoral, J. Mailloux, Yu. Baranov, L. Colas, A. Ekedahl, K. Erents, M. Goniche, P. Jacquet, A. Korotkov, P. Morgan, V. Petrzilka, J. Ongena, K. Rantamäki: Effects of ICRF induced density modifications on LH wave coupling at JET. *Preprint EFD-P07-064, Plasma Phys. Control. Fusion 51 (2009) 044003 (20pp)*

[5] Cahyna P., Pánek R., Fuchs V., Krlín L., Bécoulet M., Nardon E., Huysmans G.: The optimization of resonant magnetic perturbation spectra for the COMPASS tokamak. *Nuclear Fusion* 49 (2009) 055024

[6] Nardon E., Kirk A., Ben Ayed N., Bécoulet M., Cahyna P., Evans T.E., Huysmans G., Koslowski H.R., Liang Y., Saarelma S., Thomas P.R., JET EFDA Contributors: ELM control by resonant magnetic perturbations on JET and MAST. *Journal of Nuclear Materials* 390-391 (2009) 773

[7] Cahyna P., Pánek R., Fuchs V., Havlíček J., Krlín L., Bécoulet M., Nardon E., Huysmans G.: Planning of RMP experiments on COMPASS. *4th International Workshop on Stochasticity in Fusion Plasmas*

[8] Tsv. K. Popov, P. Ivanova, J. Stöckel, R. Dejarnac : Electron energy distribution function, plasma potential and electron density measured by Langmuir probe in tokamak edge plasma. *Plasma Phys. Control. Fusion* 51 (2009) 065014 (15pp

[9] Nanobashvili, I; Devynck, P; Gunn, JP, Stockel J, Van Oost G. : Comparative analysis of intermittent burst temporal characteristics at the edge of the CASTOR and Tore Supra tokamaks . *Physics of Plasmas* 16(2) 022309,2009

[10] J. Brotankova, J. Adamek, E. Martines , J. Stockel, M. Spolaore, R. Cavazzana, G. Serianni, N. Vianello, M. Zuin: , Measurements of plasma potential and electron temperature by ball-pen probes in RFX-mod. *Problems of atomic science and technology* 2009. № 1. Series: Plasma Physics (15), p. 16-18

[11] Vacha M. (supervised by Weinzettl V.): Detection systems for measurements of high-temperature plasma radiation on the COMPASS tokamak by fast bolometers and soft X-ray detectors. *Diploma thesis* Faculty of Mathematics and Physics of the Charles University in Prague, 2009

[12] Sestak D., Weinzettl V., Bilkova P., Bohm P., Aftanas M., Naydenkova D.I., Stockel J., Duran I., Walsh M.J.: Design and engineering of optical diagnostics for COMPASS. *Fusion Engineering and Design* 84 (2009) 1755-1758

[13] Szappanos A., Berta M., Hron M., Panek R., Stockel J., Tulipan Sz., Veres G, Weinzettl V., Zoletnik S.: EDICAM Fast Video Diagnostic installation on the COMPASS tokamak. *IAEA-TM2009/118 and accepted for press in Fusion Engineering and Design*

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2. Intellectual property

No intellectual property was reported to be generated in the Association EURATOM/IPP.CR in 2009.

Regarding the intention from 2008 to file a patent **„The construction of the ball-pen probe (BPP) head for the direct measurements of the plasma potential on fusion devices with magnetic confinement“** announced by Dr Jiri Adamek, IPP, the proposal was still under investigation of the Patent office at the end of 2009. The subject of the patent is a novel and so far unpublished solution of this type of probe consisting in an additional carbon shield used in order to protect the front part of the boron nitride of the BPP from the radiation and also heat flux.

IV REPORTS

1. Provision of support to the advancement of the ITER Physics Basis

Detailed Particle and Power Fluxes into ITER Castellated Divertor Gaps during ELMs

R.Dejarnac, M. Komm

Plasma deposition in narrow gaps between tiles of ITER plasma facing components during ELMs is simulated by means of particle-in-cell technique. The particle and power loads onto and between the divertor tiles are estimated for a multi-species plasma. The aim of this study is to know whether the impurity ions, here carbon, can enter the narrow gaps between tiles and with which energy. Due to its radioactivity, the tritium deposition in the gaps is also of high interest and an estimation of trapped T into ITER divertor due to 4MJ ELMs during 1 discharge is given. Moreover, a special probe to measure plasma deposition into gaps, for validation purposes, is under design and first tests of the conducting part have been performed.

Kinetic calculations, using particle-in-cell (PIC) technique, of plasma deposition in the gaps between ITER divertor tiles have been performed in order to estimate particle and power fluxes that fall in the gaps due to ELMs. We have investigated hydrogen plasmas with a 50-50% mixture of deuterium/tritium and with 3% of carbon as a main impurity. The two basic orientations of the gap with respect to the magnetic field, poloidal (PG) and toroidal (TG), have been studied. The code used for this purpose, SPICE, has been developed at the IPP Prague and is adapted to such a tile gap geometry [1,2,3,4]. The gaps simulated here correspond to the ones in ITER's divertor plates and have a width of 0.5 mm. The inclination angle of the magnetic field lines is taken at $\alpha = 4^o$ with a magnitude for the toroidal field of $B = 7\ T$. The plasma density and temperature of the different species are the results of kinetic simulations of the parallel transport in the ELMy SOL [5,6] with ITER conditions. The simulated ELM has an energy of 4 MJ with pedestal density and temperature $n_{ped} = 6.10^{19}\ m^{-3}$ and $T_{ped} = 5\ keV$, respectively.

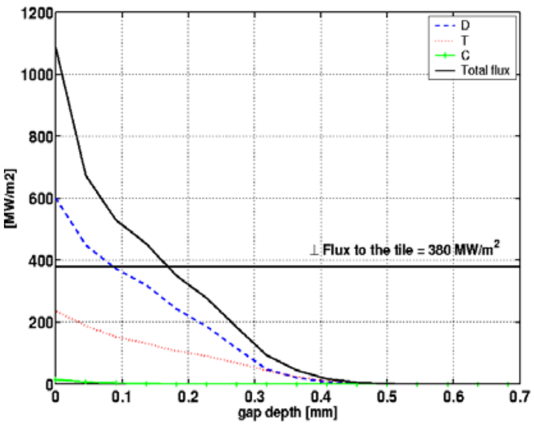

Figure 1: Power flux profiles of D, T and C along a PG (left) during a 4MJ ELM. The unperturbed perpendicular flux falling to the tile surface far from the gap is also represented.

We observe that the deposition is strongly asymmetric. Only one side of the gap is wetted by the plasma in both PGs and TGs. In the case of PGs, the wetted side is the plasma facing side and in the case of TGs, the wetted side is the one favored by the *ExB* drift. The total peak value at the entrance of the gap is ~3 times the incoming, unperturbed heat flux in PGs (see Fig. 1) and ~2 times in TGs. The total deposition of the plasma in the gaps is found to be of the same order than the gap width, i.e. ~0.5 mm.

Going into details, we observe that the D carries most of the flux (70% of the total flux deposited inside the gap). However, the D and the T are deposited on the same distance which corresponds to the total deposition length of the plasma.

Concerning the carbon deposition in the gap, we observe a smaller penetration (0.25−0.35 mm) but with very low power (see Fig. 1) that corresponds to less than 1% to the total heat flux inside the gap in PGs and TGs. The rate of C ions falling on one gap (either on a PG or a TG) integrated over the radial direction is $\sim 1.35*10^{18}\ C\ m^{-1}.s^{-1}$. Assuming now that 100% of the incoming C ions combine with the incoming T (which have a higher rate $\sim 4.2*10^{19}\ T\ m^{-1}.s^{-1}$) in a 1 : 1 co-deposition process and are trapped at the surface, we find a deposited mass rate of $\mathbf{6.7*10^{-6}\ g.m^{-1}.s^{-1}}$ for the T to be retained in a PG or in a TG during a 4MJ ELM. As an estimation, for typical ITER divertor tiles of dimensions 19.5 x 30 mm^2, and by extrapolating to the part of the entire divertor, which is wetted by the plasma during an ELM (~6.5% of 110 m^2 [7]), we find that the plasma deposits ***0.04 g*** of T per discharge only due to ELMs (assuming 10s of ELMs per ITER 400s long discharge [8]).

In order to validate experimentally our gap simulations, we plan to build (2010) a special probe, so-called "sandwich probe", that recreates a gap with insulated segments in the radial direction in order to measure plasma deposition distributions. The design chosen for the segments involves the deposition of metallic, conducting layers on a ceramic substrate. In collaboration with the Material Department of our Institute, as preliminary tests, we have deposited thin metallic layers of different metals on Boron Nitride (BN) samples. We used two techniques 1) Plasma Spray and 2) Coating.

1) Using the former technique, we sprayed tungsten and stainless steel on BN substrates with acceptable thicknesses (~100 microns) for our purpose. However, the surface of the metallic layers obtained by plasma spray on BN is not homogeneous and strongly granular. Moreover, the layers do not stick to the BN substrate and tend to peel off by plates very easily, which is of course not acceptable.

2) using the latter technique, thin layers of carbon and gold have been coated to two BN samples with good conditions for our purpose. Indeed, the layers are homogeneous and do not peel off. However, the thickness achieved is far from fulfilling our requirements. The maximum thickness of coated layers achieved is ~1 micron and we need layers from 50 to 100 times thicker to survive the extreme plasma conditions. This method seems to be also non suitable for our purpose.

As a conclusion, we can say that the two techniques available in our Institute for deposition of thin metallic layers on ceramic substrates are not suitable for elaborating the conducting parts of the sandwich probe. We need to find alternative techniques (vapor coating, electron beam, magnetron sputtering, galvanization, etc..) and make new tests in order to choose the appropriate technique for the sandwich probe conception.

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Scrape-off-layer variations during Lower Hybrid ionization and ELMs

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It is known that lower hybrid (LH) wave increases the Scrape-off-Layer (SOL) density by direct ionization of the SOL due to parasitic LH wave energy absorption [1]. Similarly, also ELMs bring energy into the SOL, the SOL temperature is increased and the SOL ionization is enhanced. In this paper we present a modeling study of modifications in time of the JET SOL due to ELM events *and* direct SOL LH ionization. The modeling uses the fluid code EDGE2D, upgraded to include direct SOL ionization by the LH wave [1] and the effect of the limiters near the LH grill [2] simulating the LH grill private space. The ELM is modeled by a standard option available in EDGE2D, which consists in enhancing transiently the transport coefficients on the low field side in a region near the separatrix. In the computations presented, the diffusion coefficient D is five times enhanced for 5 ms in the interval $-0.02 < R\text{-}R_{sep} < 0.04$ m. The diffusion coefficient is assumed to grow linearly between 0 – 2.5 ms, and then it again returns to its previous value between 2.5 and 5 ms. The initial value of D is chosen [1] as 0.1 m^2/s for $R\text{-}R_{sep} < 0.03$ m, and 1 m^2/s for $R\text{-}R_{sep} > 0.03$ m. It is assumed that the parasitic LH absorption takes place in the outer SOL, with the radial profile illustrated in Figures. The amount of the dissipated power was tuned to 50 kW [1] in front of the grill to fit the j_{sat} measurements without taking into account ELMs in the modeling. We concentrate on ITER like shots with wide SOL, shot number # 66972 and other shots from this series. As the computations show, plenty of the SOL neutrals are ionized by the LH parasitic dissipation before the ELM arrives, so that any additional contribution to the ionization of the SOL due to ELMs can only be small, cf. Fig. 1 for the ionization source without and with LH heating.

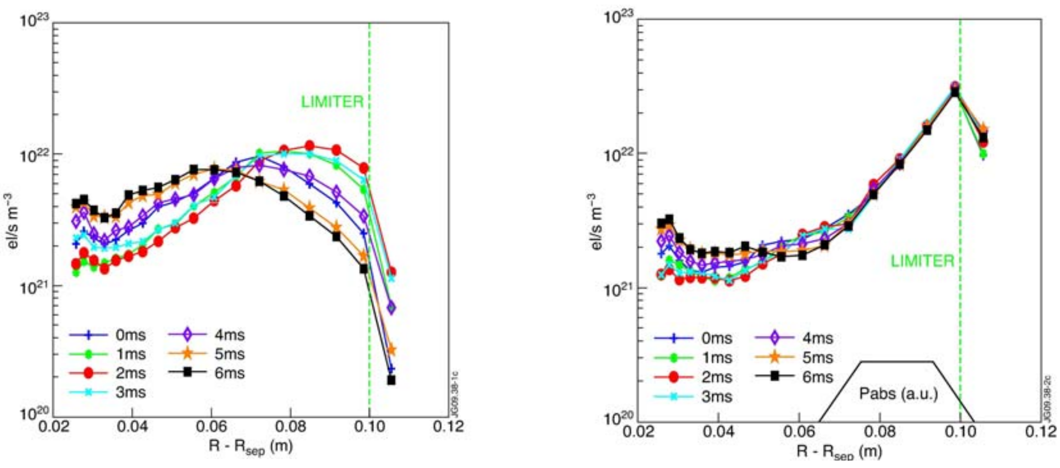

Fig 1. Ionization source during an ELM in 1 ms intervals, left: LH "off", right: LH "on".

The modeled j_{sat} variations due to ELMs and LH ionization are shown in Fig. 2. It follows from the modeling that the SOL saturation current j_{sat} (and the plasma density) in the far

SOL in front of the grill is higher during LH due to the direct LH SOL ionization, but the additional j_{sat} variations corresponding to ELMs are lower in front of the LH grill, where the LH power is dissipated. The reduction of j_{sat} variations with ELMs and corresponding reduction in the plasma density variations explains the reduction in variations of the LH wave reflection coefficient observed experimentally in ELMy plasmas, when the LH power is increased. The modeled j_{sat} with LH "on" is confined between the red curve with full circles and the black curve with full squares during ELMs. The blue dashed lines bound the region of the modeled j_{sat} during ELMs without LH. The measurements of j_{sat} [1] are also compared with the modeling.

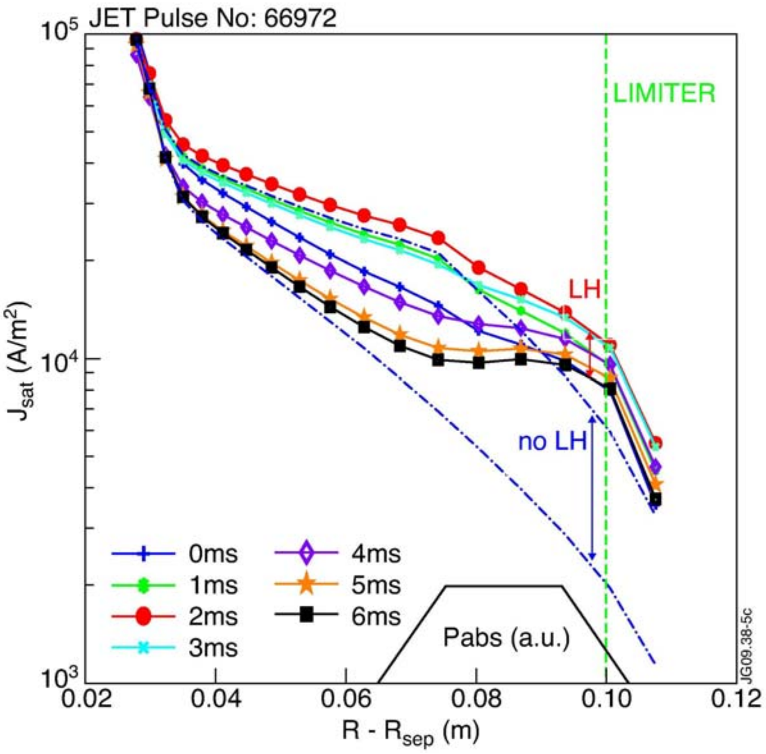

Fig 2. Saturation current j_{sat} density during an ELM in 1 ms intervals, LH on, and modeled saturation current j_{sat} density limits during an ELM, LH "on"- red curve with full circles and the black curve with full squares, LH "off" - blue curves, dash and dot.

In conclusion, the modeled j_{sat} is in a good agreement with the RCP measurements during LH on and ELMs. The modeled j_{sat} features explain the reduction of the LH wave reflection coefficient oscillations at enhanced LH power. In addition, some insight into the SOL ionization by common action of ELMs and parasitic SOL LH wave dissipation was obtained: The LH ionizes the SOL even before the ELM arrives, and there remains less neutrals for ionization by the ELM.

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Fast electron generation by LH waves scattered on ponderomotive density modulations in front of LH grills

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Lower hybrid (LH) wave scattering on self-consistent plasma density modulations produced by ponderomotive forces is explored, using the model developed in [1]. A long grill in the poloidal (y) and toroidal (z) directions is assumed; only the basic mode is considered in waveguides with thin walls. For simplicity, we choose a step and ramp profile for the unperturbed plasma density, $n_0(r) = n_b+n_c\, r/L_n$, where n_b is the boundary density and n_c is the cut-off density (for which the plasma frequency equals the frequency of the LH wave). In the presence of LH power, the density $n_0(r)$ is modified and reads $n(r,z) = n_0(r)\exp(-\delta(r,z))$, $\delta(r,z) = \varepsilon_0\, |E|^2 / 4n_cT$, ε_0 being the permittivity of the vacuum, E is the electric field of the wave and $T = T_e+T_i$ is the temperature. Computed n(r,z) in front of the grill for typical Tore Supra parameters is shown in Fig.1. The electric field of the wave is assumed to be in the form $E_z(r,z) = \Sigma_s\, (E_s^+(r) \exp\,(isk_zz)+E_s^-(r)\exp(-isk_zz))$. The individual Fourier components create standing waves. The launched wave then scatters on the density ripple, which it produces. The equations for $E_s^+(r)$ and $E_s^-(r)$ are solved numerically with the following boundary conditions: for the first harmonic, the value of the field and its derivative is chosen deep enough inside the plasma where the ponderomotive effects are negligible.

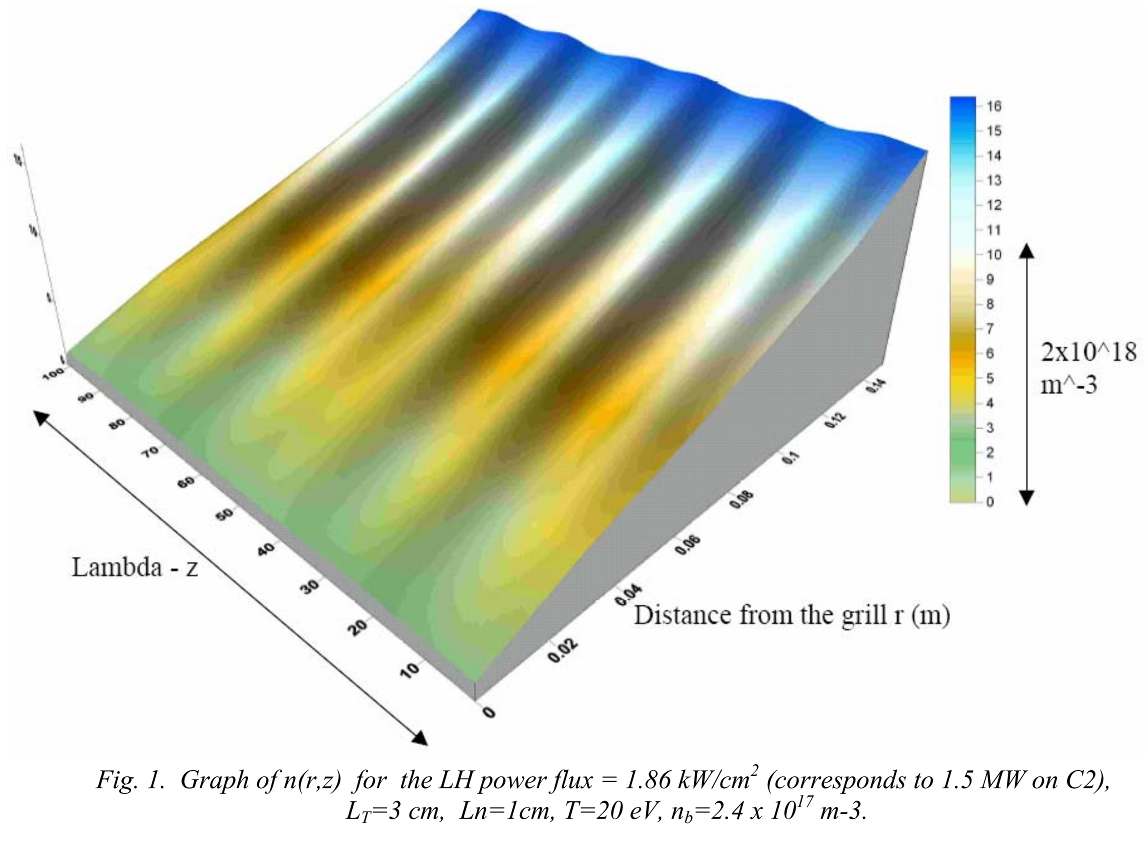

Fig. 1. Graph of n(r,z) for the LH power flux = 1.86 kW/cm^2 (corresponds to 1.5 MW on C2), L_T=3 cm, Ln=1cm, T=20 eV, n_b=2.4 x 10^{17} m-3.

Because of the higher temperature there, ponderomotive forces can be neglected and the wave propagation is described by the linear theory. For higher harmonics, the first boundary condition is the radiation condition inside the plasma. As we want to explore higher harmonics generation from the main wave, so as the second condition it is assumed that no higher harmonics are radiated by the grill. The detailed numerical procedure is described in [1]. The energy flux in the k-th harmonics is proportional to $1/k^2$. The LH wave frequency, the LH power density and plasma parameters correspond to the Tore Supra C2 and C3 launchers. Amplitudes of higher spatial harmonics of the scattered wave, which higher harmonics can produce the electron acceleration near the grill mouth [2], are derived up to the 25th harmonics. It is shown that the SOL (Scrape-off-layer) electrons with velocities along the magnetic field higher or equal to the velocity corresponding to energy of about 80 eV can be accelerated in the field of the scattered

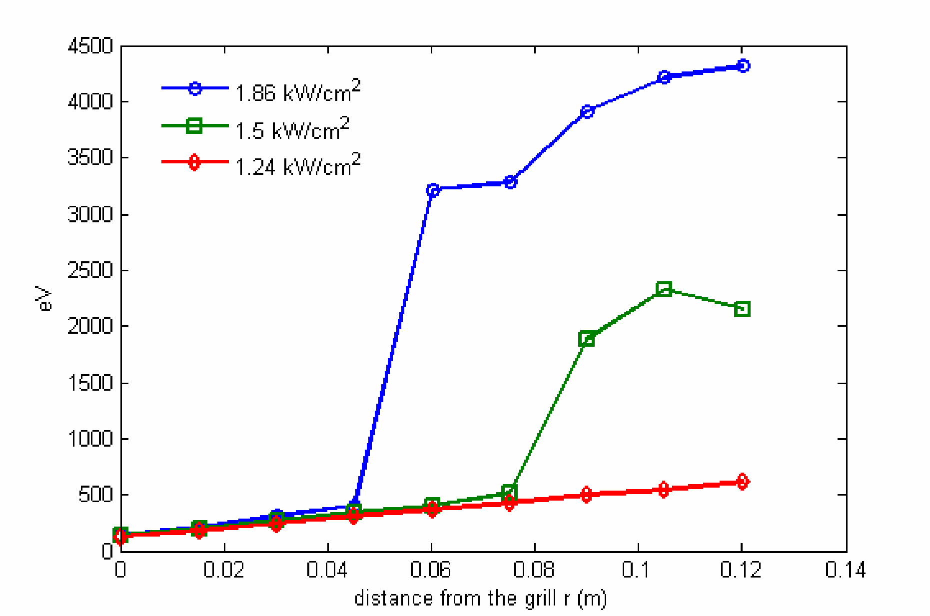

Fig. 2. Acceleration of electrons in the scattered field as a function of radius for varying LH power flux from 1.24 to 1.86 kW/cm² (corresponds to 1 - 1.5 MW on C2), L_T=3 cm, Ln=1cm, T=20 eV, n_b=2.4 x 10^{17} m^{-3}, the initial electron energy is 80 eV.

wave up to an energy of several keV, cf. Fig 2. The maximum amplitude of the higher harmonic waves peaks at a certain radial distance from the grill mouth, and therefore the maximum energy and number of the accelerated electrons also peaks several cm from the grill mouth, depending on the LH wave power density and other parameters. Let us note that the above described wave scattering and resulting electron acceleration process can possibly be at play in producing fast electrons observed experimentally at a distance of several cm from the grill mouth [3]. The higher harmonics launched by the grill and generating accelerated electrons in the SOL [2] are dissipated in a few mm distance from the grill mouth [4], and their presence can not explain the observed [3] radially several cm wide fast electron layer. However, for a detailed comparison with experiment, the launched grill field and its nonlinear modification should be accounted for much more precisely, e.g. by a 3D coupling code, which would be able to take into account the toroidal density ripple.

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Analyses of spatial and temporal characteristics of neutron emissivities at JET for fuel transport studies

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Previous work [1] demonstrated clearly that tomography based on Minimum Fisher Regularisation (MFR) can substantially contribute to tritium transport studies, when combinted with thel ratio method and applied on the Neutron profile monitor data from the tritium puffs in the JET TTE campaign. In 2009, major efforts were therefrom focussed on completion of these novel data-oriented transport studies. A new article detailing 1-D fuel transport as a function of dimensionless quantities was finalised and published [2]. The noteworthy work in this article is the Monte Carlo simulation of the noise (statistical error) transmission in the neutron emissivity reconstruction followed by derivation of the transport coefficients. Although the above references are based on 1D (poloidally averaged) values, a major challenge posed by these studies is set by the fact that the 2D reconstruction identified systematic poloidal assymetries. These spatial characteristics were quantified [3]. Due to these results, the database of the analysed tritium puff discharges was extended, a new user-friendly and general data analyses tool was prepared and several possible interpretations of the observed poloidal assymetries were analysed.

Fuel transport properties after tritium puff are derived as follows: (i) MFR tomography determines evolution of D-T fusion 14.1 MeV neutron emissivities after T puff (ii) MFR tomography determines D-D fusion 2.5 MeV neutron emissivity just before the T puff (iii) fuel transport coefficients (diffusion and the pinch velocity) can be found by fitting the evolution of the ratio profile. Notice that the initial emissivity reconstruction must be 2D due to effects of fast (beam) trapped particles that cause higher emissivities on the low field side, see Fig. 1.

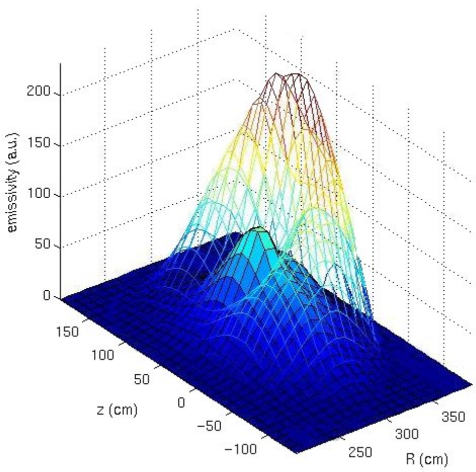

Fig. 1. Tomography reconstruction of DD (solid) and DT (transparent) emissivities in JET #61174, shortly before and after T puff, respectively. Notice the increased emissivity on the low field (higher R) side.

However, it is observed systematically that the poloidal assymetries do not cancel out completely in the ratio after the T puff, except for low density low puff discharges. Therefore, we pursued detailed studies in order to quantify these spatial characteristics of the fuel transport [3]. Correlation analyses were applied to 17 JET discharges with T puff. Radial decay of the 2D assymetries was measured via radial shift of the centre of mass of the emissivity ratio, see figure 2. Clearly, the decay takes longer time if higher amount of tritium is puffed, possibly indicating the role of recycling. The correlation analyses also revealed strong link to plasma density – the higher plasma density, the bigger the initial offset of the centre of mass of the emissivity ratio. Next, decay of poloidal structures in the emissivity was analysed by evolution of standard deviation in the emissivity ratio in poloidal direction. The most important result is shown in figure 3. With higher amount of tritium puff, there are more poloidal structures and they decay faster. Interestingly, linear fit in Fig. 3 extrapolates to full poloidal symmetry in case of zero amount of puffed tritium.

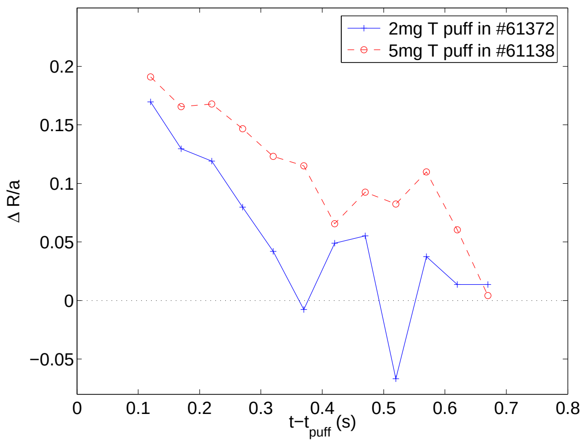

Fig. 2: Evolution of radial assymetry of the DT/DD emissivity ratio in two almost identical JET discharges after different level of tritium puff.

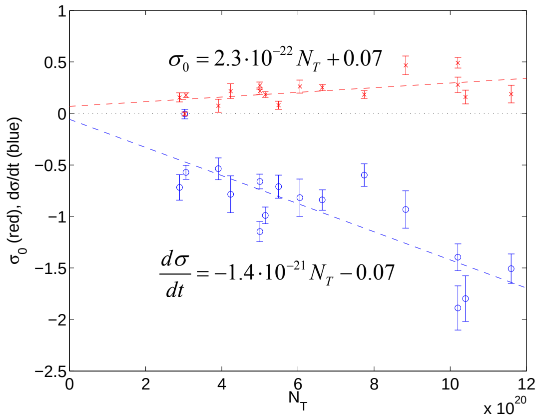

Fig. 3: Initial offset (in red) and time derivative (in blue) of the standard deviation of the poloidal component of the emissivity ratio as a function of the amount of puffed tritium. Notice that linear fits (dashed lines) extrapolate to zero at zero puff.

The ongoing work is focused on improving the data statistics and clarifying the interpretation of the observed spatial characteristics of the fuel transport. Besides the possibility of systematic artefacts due to sparse data – which has been to a substantial degree eliminated – and the influence of wall recycling, spatial assymetries can be possibly attributed also to the effects of turbulent transport as predicted in [4].

In support of this work, a systematic code was developed that allows for a long term shot to shot comprehensive study of the neutron data from various diagnostics systems, including integral volume flux measurement systems (fission counters, silicon diodes and foil activation), neutron profile cameras (liquid and plastic scintillators) and neutron spectrometers (NE213 and Stilbene). The new code is built as a massive data processor that can search for valuable information in the JET data depository, e.g. to uncover synergies between particular diagnostics and plasma scenarios or identify occasional system malfunction.

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Dynamics of particles in the ergodic layer of a system of magnetic islands under the influence of the edge tokamak plasma electrostatic turbulence

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An ergodic layer, produced in a tokamak by an external system of magnetic coils and creating two rows of magnetic islands, can be used as an ergodic divertor, as well as for the suppression of edge localized modes (ELM). The ergodic layer, based on the intrinsic stochasticity of such system is formed by a very delicate chaotic system of magnetic lines. It is expected that this layer influences the particles trajectories, changing their regular motion into the chaotic ones.

Additionally, it could be expected that an electrostatic edge potential turbulence might appear inside the ergodic layer, thus creating an additional mechanism affecting the particles´ dynamics. It is therefore of some interest to compare the effect of the ergodic layer and the effect of the potential turbulence.

In our model, discussing this problem, the edge potential turbulence is modeled by means of an egg - crate potential structures, decribed by us e.g. in [1]. Particle dynamics is determined by the corresponding Hamiltonian, which - besides the vector potential of the main magnetic field – includes the vector potential, creating the ergodic layer, and a time-independent, spatially periodic potential.. We solve the dynamics of ions and of electrons.

We have already obtained first numerical results. We considered a typical level of the magnetic pertubation (creating the system of magnetic islands and the ergodic layer itself) with the strength of 10^{-3} of the main (toroidal) magnetic field; typical distances of chaotic potential blobs $10^{-3} - 10^{-2}$ m; and carbon ions with total energy of $50\,eV$. For this case, we discovered that for amplitudes of the potential up to $1\,V$, the efect of the potential is not measurable. However, in the case of the amplitudes of about $10\,V$, the effect of the potential suppresses all other factors, thus being the dominant factor influencing particle motion. (We expect the potential to have a similar influence on the electrons).

The paper will discuss the real meaning of this phenomenon for the tokamak experiments and the limits given by our model of the turbulent potential.

References:

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Investigation of interactions of perturbation field with plasma

P. Cahyna

In collaboration with:
E. Nardon, A. Kirk, G. de Temmerman, Association EURATOM-CCFE

The resonant magnetic perturbations which successfully suppress Type-I ELMs on DIII-D and are planned for this purpose on ITER are expected to strongly interact with the plasma by various means. Those include:
- creation of screening currents inside the plasma which modify the perturbating field. If this effect is strong it may invalidate the vacuum field approach used until now to analyze the experimental results and proposed ITER coil designs. Only very recently diamagnetic effects started to be taken into consideration, which may lead to much stronger screening currents that had been previously thought [1],
- influencing the plasma rotation by means of the screening currents and the Neoclassical Toroidal Viscosity (NTV) [2],
- creation of electrostatic perturbations which may produce enhanced particle transport and be responsible for the ELM suppression effect itself.
A lot of questions about the interaction of perturbations with plasma remain open and their resolution is essential for application of this technique on ITER.

We developed a code for determining the screening currents generated inside plasma in a response to the perturbations from coils. Using the assumption that the perturbation is screened, our code can determine their amplitude and the resulting total magnetic field. The calculation is done in a realistic geometry and it includes the geometric coupling of harmonics between resonant surfaces, which results in different screening currents than those which would be predicted by simplified models using toroidal geometry. The magnetic field prediction can then be checked for agreement with the experimental data to prove or refute the original assumption.

One consequence of resonant magnetic perturbations are spiraling patterns of the heat flux on the divertor plates (divertor footprints), which can be observed with infrared cameras as zones of increased temperature. Using a line-tracing code we determined the shape of divertor footprints for JET and MAST. By coupling the code with the code for magnetic field of the screening currents we were able to compare the footprints created by the vacuum field against those in the screened field. Our results show that the screening significantly reduces the footprints (Fig. 1). This provides the opportunity of detecting the screening currents by comparison with the observed footprints.

On MAST the footprints have been observed only in L-mode discharges, not in H-mode discharges with applied resonant magnetic perturbations. It is remarkable that the perturbations don't have significant effect in H-mode discharges [3], especially they don't affect type-I ELMs, unlike on DIII-D where one can also observe divertor footprints. It is thus possible to conjecture that on MAST the perturbations in H-mode are strongly screened by plasma and this might be the reason of failure of ELM control.

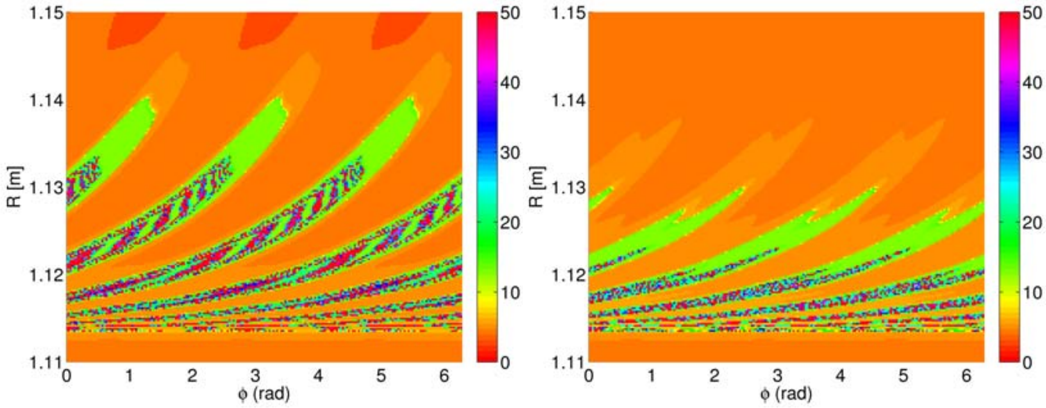

Fig. 1. Map of connection length of the field lines reaching the outer divertor plate of MAST for an example vacuum (left) and screened (right) perturbation. Field lines with high connection length reach the interior of the plasma and should correspond to hot areas of the divertor.

The calculation of the screening currents and field has also other possible applications: comparison with signals from magnetic diagnostics, use as input for neoclassical toroidal viscosity calculations and validation of cylindrical MHD models which don't include geometry effects.

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[1] E. Nardon et al., *Nuclear Fusion* 50 (2010) 034002

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[3] E. Nardon et al., *Plasma Phys. Control. Fusion* 51 (2009) 124010

2. Development of plasma auxiliary systems

Lower hybrid current drive for COMPASS

V. Fuchs, F. Žáček

In collaboration with:
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R. A. Cairns, University of St. Andrews, Scotland

COMPASS is presently considering two different options for a lower hybrid heating and current drive system: the "old" LH system (1.3 GHz) inherited from Culham, and a "new" LHCD system (3.7 GHz) based on 2 to 3 klystrons going to be made available to us by CEA Cadarache. There are several advantages and disadvantages of the two systems, which we enumerate herein. We briefly describe the main differences between the present 1.3 GHz "simple" waveguide grill, and a projected multi-junction antenna for the 3.7 GHz system. The 3.7 GHz LH system is superior in terms of antenna directivity and reflectivity. We also mention some issues concerning LHCD modeling.

Some arguments in favor of a higher frequency (3.7 GHz) with respect to a lower one (1.3 GHz) for the lower hybrid current drive and heating are the following:

a) More power density can be transmitted through the antenna (ideally the antenna power density increases with the source frequency f_{LH}, experimentally as $f^{0.67}$, (see e.g. Ref [1], describing PAM tests on FTU)

b) There is less risk of arcing at the waveguide mouth, because of the lower electric field for the same power. The antenna reflectivity is substantially lower, and directivity higher.

c) Weaker interaction with edge turbulence. Such interactions increase approximately as $(\omega_{pe}/\omega)^2$ and can effect the wave spectrum through linear and/or non-linear phenomena.

d) Possibility of direct comparison with other important LH experiments in Europe which use the same frequency (JET, Tore Supra, possibly ASDEX) and closer to ITER frequency (= 5 GHz).

e) Weaker interaction of grill spectrum with edge electrons, which depends on electron quiver velocity $\approx 1/\omega_{LH}$.

On the other hand, the disadvantages are the following:

a) More expensive grill and also all the support equipment for the transmission lines.

b) Possible problems with the coupling, since the optimum density in front of the grill is 2-3 times the cut-off frequency, which goes as f_{LH}^2. For 3.7 GHz $n_{cutoff} = 1.7\text{x}10^{17}\ m^{-3}$.

Apart from cost, the technical advantages of the 3.7 GHz system clearly outweigh its disadvantages with respect to the present 1.3 GHz system.

J. Hillairet and M. Freynac proposed two separate designs of a multi-junction for a COMPASS-compatible antenna with 3.7 GHZ klystrons. The two designs are optimized for two different values of the radiated fundamental peak, specifically, $n_{//}$=2.0 and $n_{//}$=2.5. Figure 1 shows the reflectivity, R, and directivity, D, for a multi-junction design with N=6 waveguides per module (principal spectrum peak at $n_{//}$=2.0), 2 modules per row. Results for a design with 8 wave-guides per module (with principal peak at $n_{//}$=2.5) are similar.

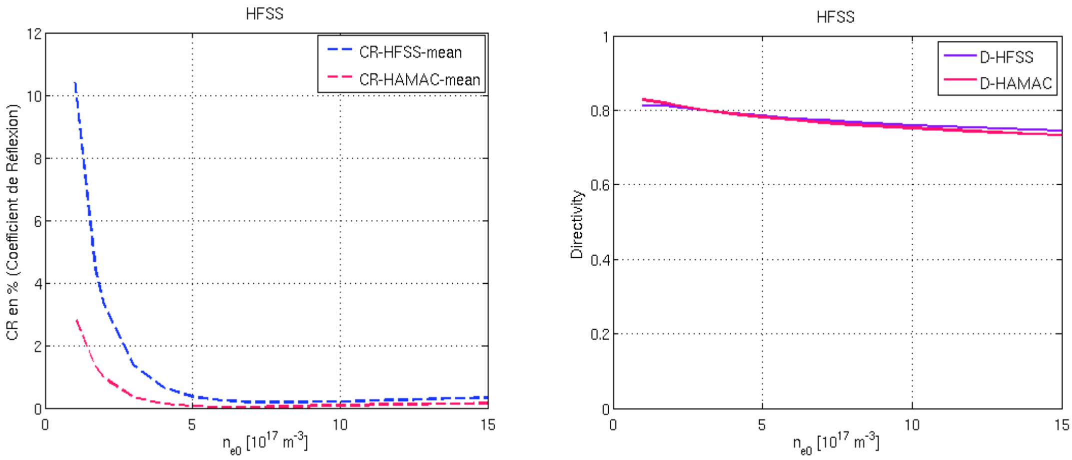

Fig. 1 Reflection coefficient a directivity of a N=6 multi-junction COMPASS antenna as a function of electron density. HAMAC is the ALOHA code scattering matrix solver, HFCC is a commercial solver.

Figure 2 shows power spectra for the multi-junction and "standard designs. The much reduced directivity of the "standard" design, which also applies to the present 8-waveguide COMPASS antenna, can be attributed to the excess of power in the $n_{//}$<0 range.

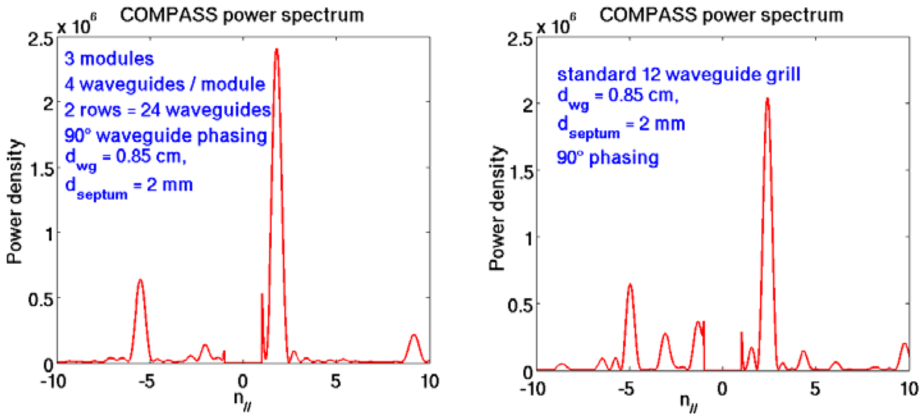

Fig. 2 Comparison of power spectra for a multi-junction and standard grill designs. Note the predominance of negative $n_{//}$ spectral peaks in the "standard" case.

Turning now to LHCD simulations with the new multi-junction 3.7 GHz spectra, we note that these face the same difficulty as did LHCD simulations with the present 8-waveguide standard grill, which is a very wide main spectral peak, specifically $\Delta n_{//}/n_{//} \approx 1$, practically invalidating the standard ray tracing approach for determining LH wave power-flow and power deposition. We therefore developed a simplified full wave approach [2], which can make use of the available and well-known ray tracing techniques.

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[2] R. A. Cairns and V. Fuchs, submitted to Nuclear Fusion.

Neutral beam injectors for COMPASS

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Two Neutral Beam Injectors (NBI) will be used for additional plasma heating on the COMPASS tokamak. The beam energy is 40 keV and the total power 2x300 kW. The NBIs are manufactured at the Budker Institute, Novosibirsk, Russian Federation. During 2009, the design of NBIs and their connection to the COMPASS tokamak was finalised. Next, preparatory work had to start in IPP Prague. The design of the beam duct was modified taking into account the final geometry of the NBI and of the supporting structures of the COMPASS tokamak. The vacuum system was designed and refrigerators for cryopumps were purchased. Furthermore, additional equipment required for NBI operation, such as the cooling and gas handling systems were specified. The NBIs are expected for delivery to IPP Prague in the mid of 2010 to perform the first tests.

Two Neutral Beam Injectors (NBIs) will be used for additional plasma heating on the COMPASS tokamak. The beam energy is 40 keV and the total neutral beam power 2x300 kW. The NBIs are manufactured at the Budker Institute, Novosibirsk, Russian Federation. After the successful tender, the contract with the winner (ČKD Elektrotechnika) was signed at the beginning of 2009. Two groups from the subcontracting institution (Budker Institute, Novosibirsk) visited IPP Prague to finalise experimental arrangement for NBI Heating on COMPASS. Several technical issues were discussed and specified:

- Location of the NBI and the beam duct: The design of the NBI was finalised. Because of a rather short focusing length (1,8 m), the NBI need to be closer to the tokamak than expected. The Budker Institute also proposes a new beam duct, which will be shorter and broader than our original design. Therefore, the danger of beam blocking will be further reduced. However, this new design requires a substantial modification of supporting structures of COMPASS, see Fig. 1.

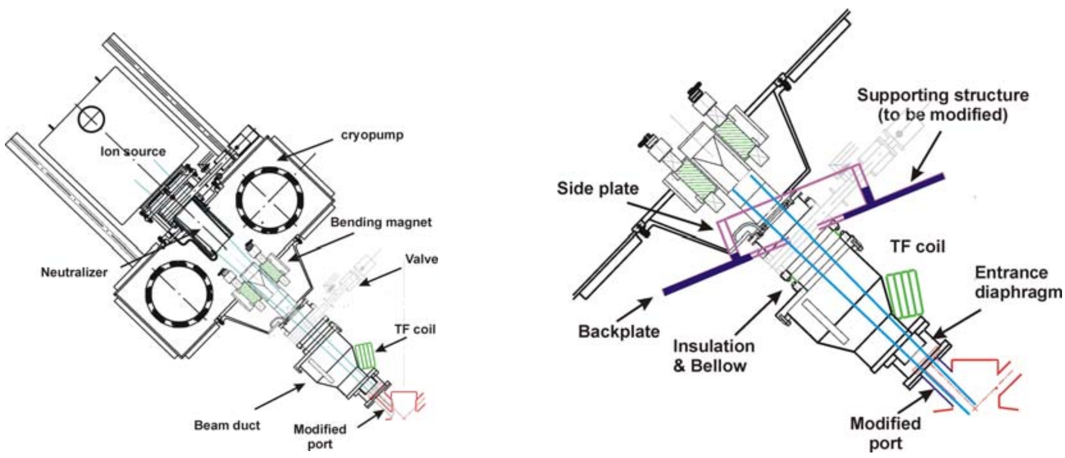

Fig. 1. Left: Location of the NBI on COMPASS. Right: Detail of the beam duct. Parts of the supporting structure to be removed (cut) are shown in pink colour.

- Power supplies for NBI: Location of cubicles for power supplies (PS) was fixed (at the right-hand side of the ground floor of the COMPASS building). Majority of cubicles will be produced in Budker Institute, a few of them by the ČKD Elektrotechnika.

Design of ČKD cubicles was approved by the Budker Institute. The length of the high voltage cables connecting the cubicles and the NBIs was specified. The high voltage transformer for NBI was tested on the artificial load by ČKD on the request of the Budker Institute, which is satisfied with achieved results. The design of PS is finished and first parts are being manufactured.

- Vacuum system for NBI: Pumping of NBIs will require two different pumping systems. The turbomolecular pumps (one for each NBI) are available. Dry for-vacuum pumps have to be purchased. This pumping system has to be in operation immediately after delivery of NBIs to IPP Prague and will be used during the testing phase. The second pumping system - cryopumps - will be used after connection of NBI to COMPASS. It was decided that so called cryocoolers will be used to cool cryopanels inside the NBI to the liquid helium temperature. The cryocoolers, which are available on market, will significantly reduce the operational costs of NBI, because the liquid Helium is not required. The most suitable type (SUMIMOTO 4K-1.5W closed refrigerator system SRDK415D-F50H) was selected. Two cryocoolers were already purchased. The remaining two cryocoolers will be purchased at the beginning of 2010.
- Cooling system: the NBIs require an active cooling of various elements by demineralised water. The conceptual design of the cooling system is completed and shown in Fig. 2.

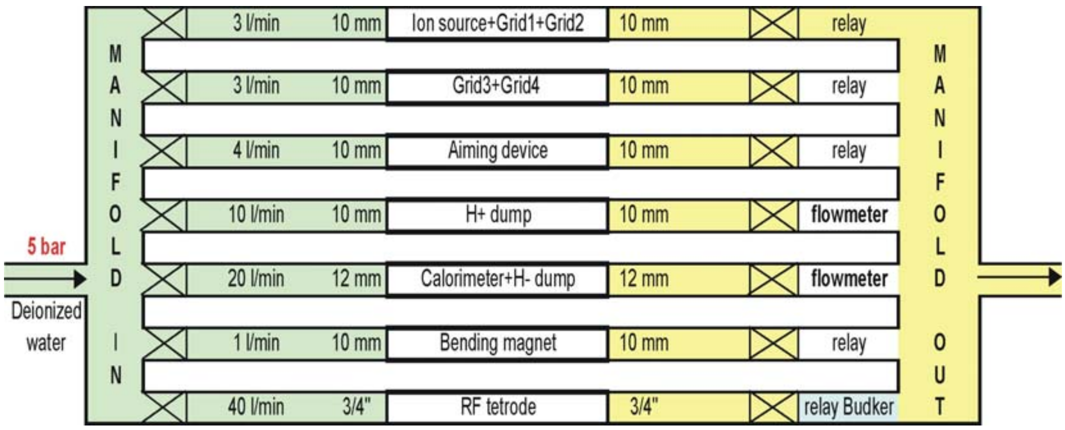

Fig. 2. The water - cooling system for a single NBI

As a source the existing station of the deionised water will be exploited.

- Gas-handling system: the NBI also requires a system allowing to inject the working gas (H_2, D_2) into the injector. The conceptual design of the gas-handling system is completed.

The NBIs will be delivered to IPP Prague in the mid of 2010 to perform the first tests. Their connection to tokamak and the first experiments are expected in the fourth quarter of 2010.

Probe measurements on the COMPASS tokamak

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An array of Langmuir probes embedded to a divertor plate was commissioned and first experimental results are promising. A new probe head for measurements of current filaments in the SOL is being designed. Two reciprocating probes, located at different poloidal and toroidal positions are almost commissioned. A significant progress was achieved in numerical modeling of probe performance.

Divertor probes

The array of Langmuir probes (with 39 pins) embedded in the divertor tiles of the COMPASS tokamak was commissioned and equipped with new pre-programmed power supply manufactured in the Association EURATOM/INRNE, Bulgaria. En example of the experimental data is shown in Fig. 1.

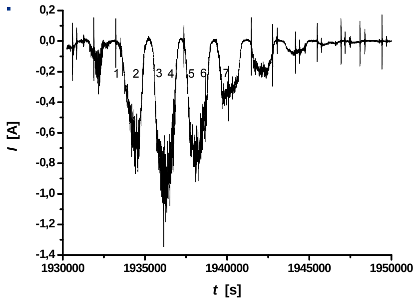

Fig. 1. Evolution of the probe current of the probe No. 4 in the discharge #889.

The I-V characteristics are constructed and compared with the method described in [1], which allow determining the electron temperature, the plasma potential and the electron distribution function. Results of comparison are shown in Fig. 2

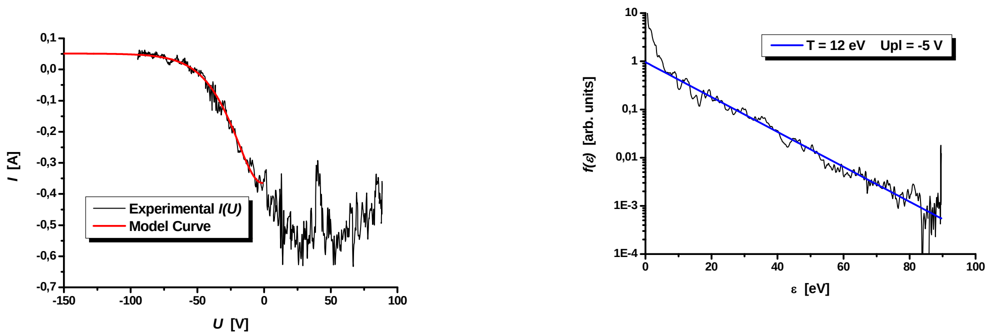

Fig. 2. Left - the IV characteristic, right - the corresponding electron distribution function.

The electron distribution function is found to be Maxwellian and the electron temperature is typically in the range of 8-20 eV.

Modelling of probe performance

Numerical calibration of the tunnel probe was performed with the SPICE2D code. The existing model was refined to the probe geometry and first calibration curves were generated for COMPASS as well as for Tore Supra. Furthermore, the ion sensitive probe was modelled by means of the 3-dimensional kinetic code SPICE3D. Using this code, potential structure at the entrance of the probe was identified. This structure produced ExB drifts, which push electrons into the shielded space. A stream of electrons hitting the collector was observed for various potentials of the collector. Simulations revealed that electrons can penetrate inside the geometrical shadow in all studied cases but when the potential of the collector is equal to the potential of the tube, they do not reach the collector [2].

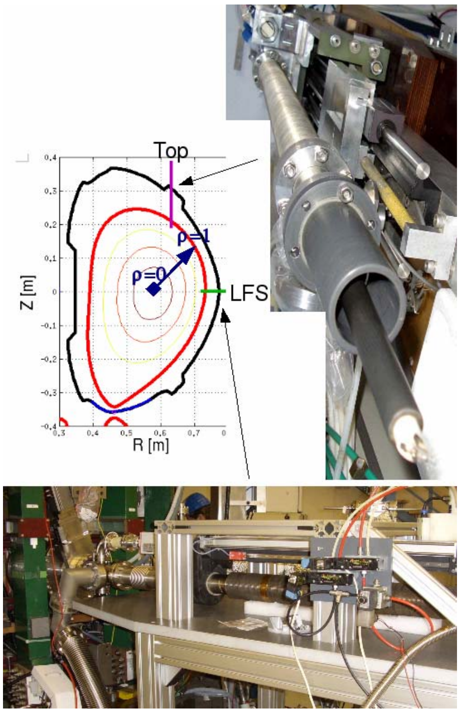

Fig.3. Position and pictures of the two reciprocating probes.

Reciprocating probes

Two reciprocating manipulators (the first horizontal and the second vertical) are envisaged for installation on the COMPASS tokamak. Their position is shown in Fig. 3.

The horizontal reciprocating manipulator (completed from existing parts from Culham Laboratory) is already connected to the tokamak and first measurements will start soon. The attachment element at the end of the manipulator is designed to be possible to use various probe heads exploited on the ASDEX – Upgrade. The maximum possible number of the probe tips is 18.

The vertical reciprocating manipulator (received from CRPP Lausanne) is being commissioned. For first experiments, the existing probe head from the TCV tokamak will be exploited.

Design of the U-probe

A new probe head, baptized as the U-probe is being designed for the COMPASS tokamak to measure current filaments and vorticity in the SOL. The probe is developed in cooperation with the Consorzio RFX in Padova, and Ciemat in Madrid.

The probe will consist of two poloidally spaced fingers, immersed to the SOL from the LFS. Each of the fingers contains three radially distributed magnetic coils measuring the toroidal, poloidal, and radial components of the magnetic field. The fingers will be equipped with a set of electric probes (Langmuir tips and the Ball-pen probe for measurements of plasma parameter in the SOL and their fluctuations. A sketch one of the fingers is shown in Fig.4.

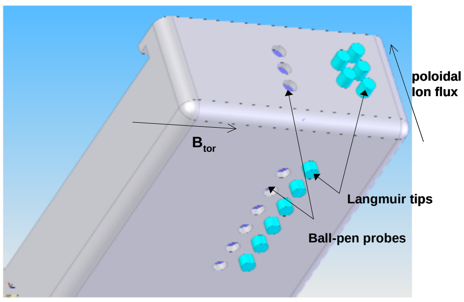

Fig.4. One of the fingers of the U-probe as seen “by the plasma“

References:

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[2] Komm M. et al: Particle-In-Cell simulations of the Ball-pen probe. Accepted for publication in *Contrib. Plasma Phys.*

Beam Emission Spectroscopy system for COMPASS and Atomic Beam Probe system for COMPASS

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In collaboration with:
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Association EURATOM – HAS

The new Beam Emission Spectroscopy (BES) diagnostic for edge density measurements on the COMPASS tokamak is under development by the Association EURATOM – HAS in a framework of the bilateral agreement between IPP Prague and KFKI RMKI. The BES system will consist of the Li beam injector and the detection part based on an array of avalanche photo diodes and/or a fast camera. An extension of this system designed in parallel to BES is the Atomic Beam Probe diagnostic (ABP) for edge current measurements by collecting the ions stemming from beam ionization, the project covered by the EFDA task No. WP08-TGS-01a-02 (III-3-a).

Beam Emission Spectroscopy using accelerated neutral particle beams become a routine technique for the determination of electron density profiles in fusion plasmas, see Fig.1. The method is based on the fact that light emission from the neutral beam penetrating the plasma depends on plasma parameters. In the case of certain beam species, e.g. Li, Na, sensitivity on the electron temperature is small, thus the electron density profile primarily determines the beam light emission.

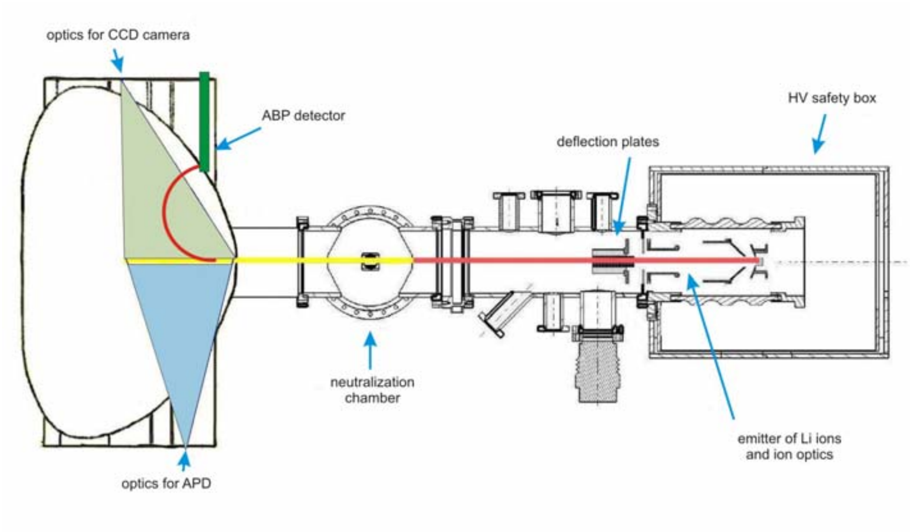

Fig.1: Set-up of the diagnostic beam and beam diagnostics (BES and ABP).

A magnetic field reconstruction is a crucial part of the BES/ABP project allowing a plasma parameters mapping and a prediction of trajectories of ionized beam particles. To get the most probable magnetic configurations, the EFIT code originating from Culham was used. An important issue for the beam source is also presence of the stray magnetic field around the torus and its interference with a beam source shielding. The stray magnetic field on the COMPASS tokamak was computed using a numerical integration of the Biot-Savart law in an approximation of infinitely thin wires. Fig. 2a shows the computed profile of the stray magnetic field at midplane. Later, temporal computations of the stray magnetic field in 2-D, see Fig.2b, were done for a comparison with direct magnetic field measurements that were performed using 3 perpendicular Hall detectors placed stepwise at different radii from the tokamak axis (R~2-3 m) and at several different heights (-1 m <Z< 1 m), see Fig3.

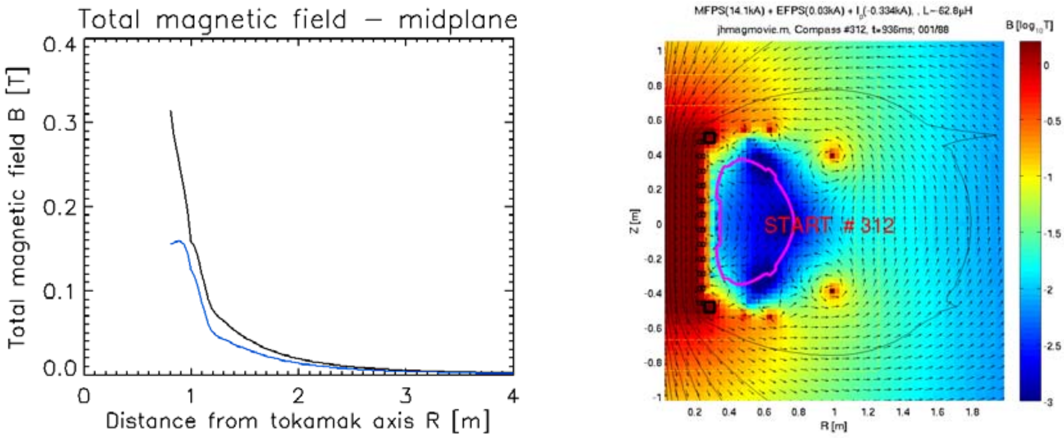

Fig.2: (a - left figure) Stray magnetic field computation with and witout plasma.
(b – right figure) Time slice of 2-D temporal computations of the stray magnetic field.

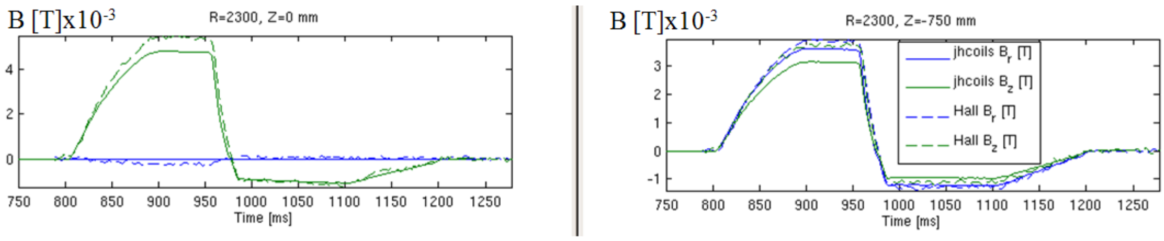

Fig.3: Temporal evolution of measured (dashed line, bottom) and simulated (solid line, bottom) radial and vertical components of the stray magnetic field for standard (left) and vacuum (right) shots.

According to the magnetic field and heat flux computations, installation possibilities for the beam and both beam diagnostics were examined. The design of the vacuum interface allowing BES/ABP diagnostics was created. All parts were manufactured, put together and installed on the COMPASS tokamak and the test ABP detector was mounted there, see Fig.4. The first tests of the system will be done in spring 2010.

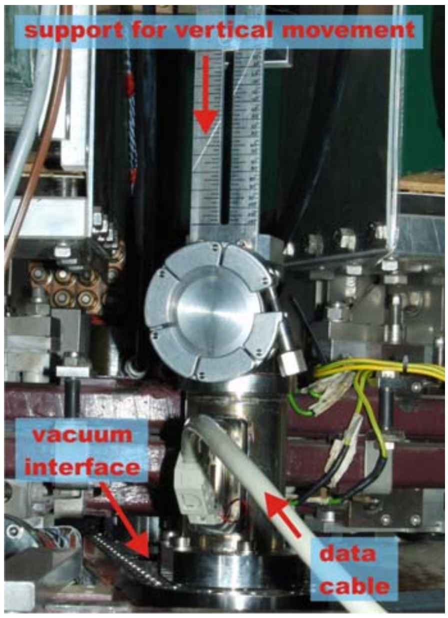

Fig.4: Test ABP detector installed on the COMPASS tokamak.

Development of fast digital video camera system for machine control, plasma overview and turbulence measurements

V. Weinzettl, D. Sestak

In collaboration with:
M. Berta, G. Veres, T. Szilveszter, A. Szappanos, S. Zoletnik, Association EURATOM – HAS

The camera system 'Event Detection Intelligent Camera' (EDICAM) is being developed by the Hungarian Association and has been installed on the COMPASS tokamak. The standalone system contains a data acquisition PC and a prototype sensor module of EDICAM. Appropriate optical system have been designed and adjusted for the local requirements, and a special mechanical holder that keeps the camera out of the magnetic field. The fast camera contains a monochrome CMOS sensor with advanced control features and spectral sensitivity in the visible range. A special web based control interface has been implemented using Java Spring framework to provide the control features in a graphical user environment. The whole camera system was successfully tested under real plasma conditions. The basic processing software programmed in the MATLAB environment was installed on the new data server, where all data from the camera will be stored.

EDICAM [1] is a fast video camera system developed for a use with plasma physical experiments, considering triggering and frame rate requirements of such measurements. A fully functional prototype of the camera mounted with especially designed optics on a newly constructed holder has been operating on the COMPASS tokamak since February 2009, see Fig.1. Later, both temperature monitoring and air-cooling of the camera optics were installed there to protect the system during the baking procedure of the tokamak vacuum vessel.

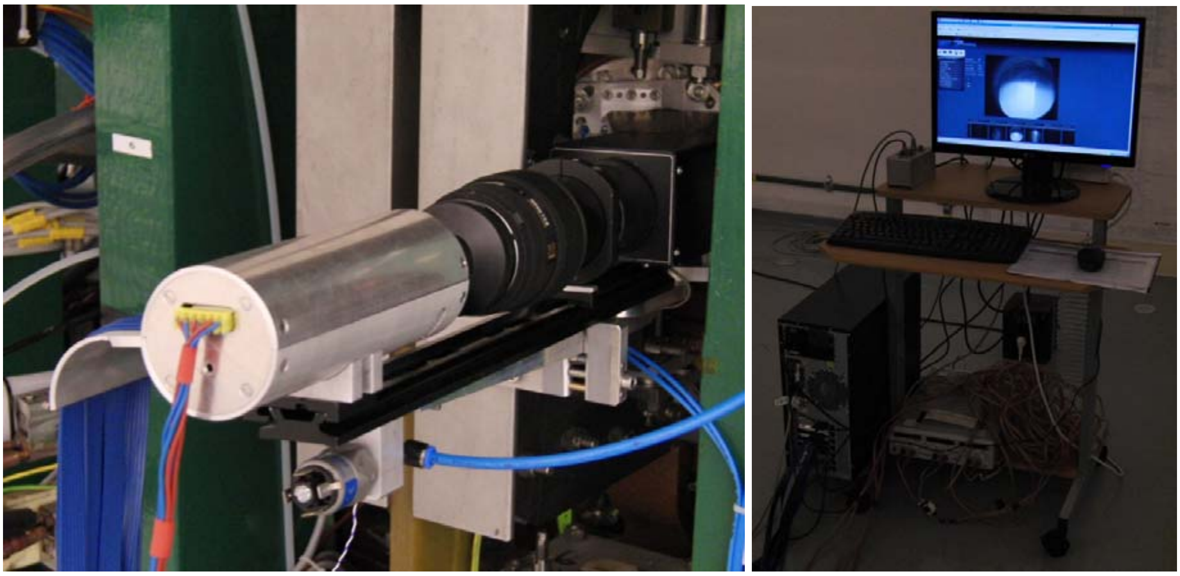

Fig. 1. The EDICAM system. The prototype of the camera mounted on COMPASS (left). The driving PC with one frame collected during the discharge on the screen and the power source for the camera (right).

A new MySQL database at the data acquisition PC was established for the camera data, which are automatically stored right after every shot. The data access scripts were written in the MATLAB environment enabling image post-processing.

A typical camera frame resolution is 1280x1024 pixels at milliseconds time scales, however, the resolution can be decreased up to 16x16 pixels, if extremely fast frame rates of 100 kHz are required.

The camera system viewing a plasma column tangentially is commonly used to monitor plasma-wall interaction, see Fig.2, leading to optimization of discharge scenarios. However, its speed also allows getting information on physical processes expressing via radiation in visible light that take place during plasma discharges, see Fig.3.

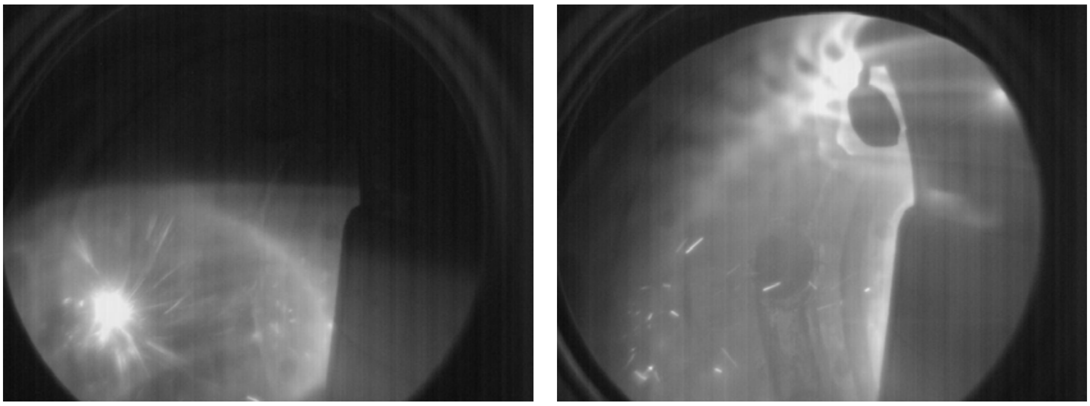

Fig. 2. Plasma-wall interaction seen by the fast camera during COMPASS tokamak discharges #310(left) and #312 (right). Frames size is 800x600 pixels, exposition time is 0.6 ms.

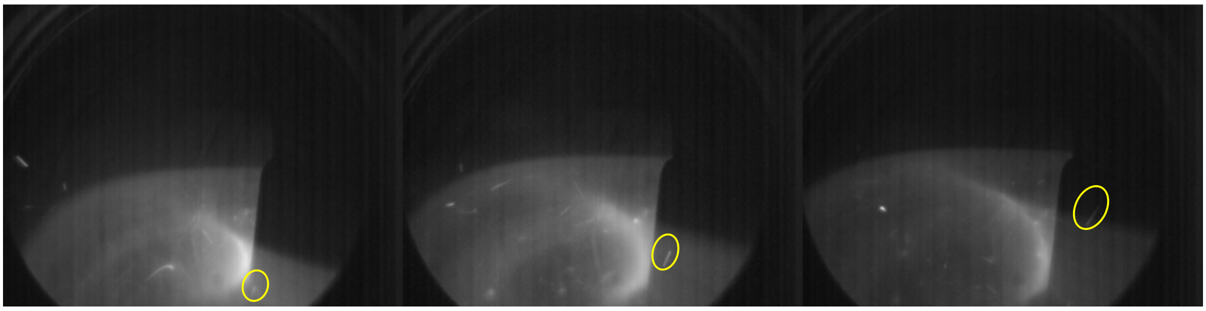

Fig. 3. Formation of circular plasma at 6th ms in the discharge #323 and a dust particle tracking demonstrated on three consecutive camera frames of 800x600 pixels spaced in time by 1.475 ms.

References:

[1] Szappanos A., Berta M., Hron M., Panek R., Stockel J., Tulipan Sz., Veres G, Weinzettl V., Zoletnik S.: EDICAM Fast Video Diagnostic installation on the COMPASS tokamak. IAEA-TM2009/118

Development of multichannel diagnostic for measurements of visible plasma radiation for COMPASS tokamak.

D. Naydenkova, V. Weinzettl, D. Šesták, J. Vlček, R. Melich, D. Jareš

The COMPASS tokamak will be equipped with fast multichannel diagnostics of visible light allowing both high temporal and spatial resolutions. It will be a key diagnostic tool for MHD physics studies. The first measurements of the most intensive lines were done and main impurity lines were identified.

The two identical visible light diagnostic systems rely on a light transmitted through the focusing lens-based objective located inside the radially viewing upper and lower angular diagnostic ports at the poloidal cross-section 6/7. The unique design of the wide-angle optical system for visible plasma radiation collimation was developed in the Department of Optical Diagnostics of IPP in Turnov. The objective consists of three parts that are optimized as a unit and compensate their optical aberration. The first part, an ultra wide-angle objective achieving 114° field of view, transmits an image of one half of the plasma column into infinity. The second part is an infinite-finite distance objective that creates a real image. The third part is a system of relay lenses reimaging it onto a linear set of optical fibers directly or through an interference filter. Nowadays the objectives are tested in the laboratory. The objective is connected to the detector by silica/silica fibers of 200 μm core. Each fibre represents one spatial point on the plasma.

Fig. 1. "Detector side" endpiece. It consists of the 35-channel connector equipped with a protection shielding and 50 cm optical cables with SMA connectors at the ends.

Fig. 2. An assembly view of the amplifier with detector two arrays plates.

High flexibility of the fiber set-up is reached using exchangeable endpieces that allow for fiber reconnection penalised by a few per cent loss of light. Two types of optical fibres end-connectors were designed to fulfil our requirements for a light registration. The "tokamak side" 35-channels optical fibre connectors were designed to be mounted directly into the objectives. The „detector side" 35-channels optical fibre connectors were designed to transmite light between optical cables and detectors with negligible overlap of channels, see Fig.1. Twenty meter long optical cables are led - depending on purpose of the measurement – either to the 35-channel detector S4114-35Q manufactured by Hamamatsu, or to minispectrometers HR2000+ from Ocean Optics with spectral coverage 248-472 nm and 457-663 nm with approximate spectral resolution of 0.15 nm, see Fig.3. The minispectrometers are capable for recording spectra with up to 1 kHz temporal resolution.

Two stage 70-channels amplifier with amplification ratio ~$5 \cdot 10^5$ was designed and manufactured in our laboratory for signal registaration in the range of 0-5V. The connectors between the optical cables and the detectors were designed as a part of the amplifier's box with a possibility to optimize the fibres position relatively to detectors in the arrays. Temporal resolution of the amplifier is limited approximately to 1 MHz. Level of noise after amplification was registrated as 2mV.

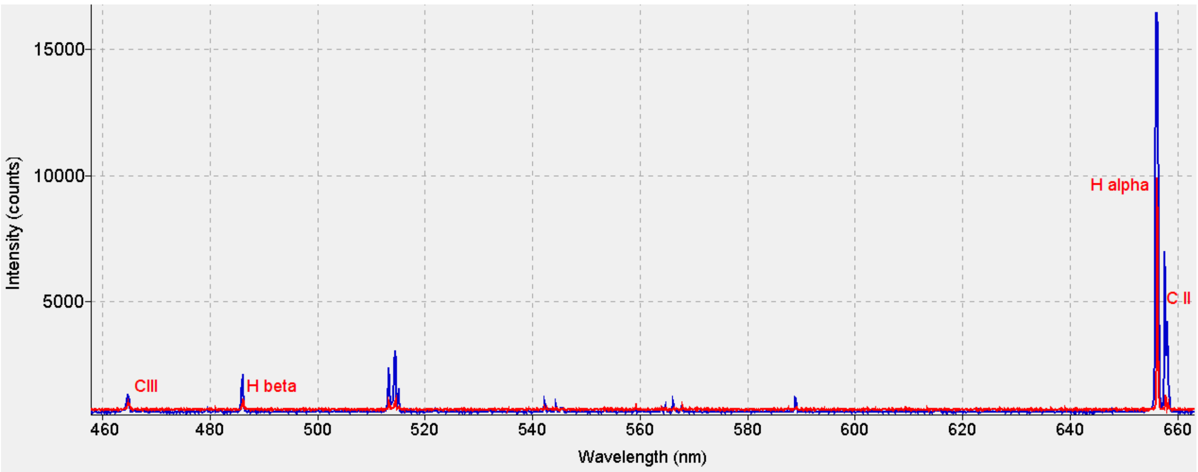

Fig.3 – Visible spectra measured during typical discharges (#864 and #987) in tokamak COMPASS in toroidal (red) and poloidal (blue) directions corespodenly.

The unique integrated spectroscopic system allowing for tomographic reconstruction at a few microseconds time base with spatial resolution of about one centimeter was developed. In combination with other diagnostics on the COMPASS tokamak it will serve for a characterization of plasma structures responsible for anomalous transport.

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[3] Naydenkova D.I., et al., WDS 2009, Prague, Czech Republic, 2th June - 5th June, 2009, Proceedings of Contributed Papers Proceedings of the 18th Annual Conference of Doctoral Students - WDS 2009, Part II, pp. 158–162.

Feasibility of the Charge Exchange Recombination Spectroscopy on COMPASS experiment

V.Piffl

During the nineties, almost all the experimental devices were equipped with Charge Exchange Recombination Spectroscopy (CXRS) diagnostic systems, which allowed the detailed study of transport and heating processes of the ion component in the core and edge of high temperature plasma.

To install a similar diagnostics in the COMPASS IPP tokamak in next future, supports just the fact that such CXRS diagnostic was active used on the COMPASS-D during the initial operation period in the original laboratory, UKAEA, England.

At COMPASS in IPP, two tangential heating beams will be installed. The particles that can be injected are H and D. Each of the NBI's launches a maximum power of 0.25-0.3 MW into the plasma at a maximum energy of 40 -50 keV/amu. The duration of the beam pulse can be as long as 0.5 sec, modulated at the frequency of 50-100 Hz .

CXRS diagnostic looks at emission lines from impurity ions that have captured electrons from the neutral beam particles and is mostly optimized for CVI (n=8->7) carbon impurity transition at 5291 Å. With the respect to the heating beam trajectory in the chamber, the central port in the equatorial plane is proposed as most suitable for installation of the compact optical observation system including mirrors and lenses for collecting CX radiation. The light collected by the system is transmitted by optical fibres to the input of the high resolution astigmatically corrected spectrometer. Such arrangement allows to measure the toroidal plasma rotation speed, the local ion temperature and impurity density profile (dominantly in so call "gradient hot core plasma"). To increase the credibility and accuracy of spatial measurements, we assume to arrange a two-three fans of line-of-sight-rays. Such rays' configuration calls for non trivial technical solution of inner mirrors installation and consequently the occupation of the access flange.

The obvious weakness of the now days CXRS system is a relatively low time resolution, in the range of 10^{-4} sec. The CX signal is regularly composed by the active CX emission where the line-of-sight crosses the neutral beam and the passive signal component which is caused be neutral particles at the edge. The power modulated heating beam installed on COMPASS can avoid the effect of passive emission. The useful signal is the result of not simple processing: time integration, subtraction of both low level detected emissions. The achieved up to date time resolution is sufficient to monitor processes in quasi-stationary plasma regimes, but is insufficient to follow the much faster turbulence processes.

According to the our brief analyse, there are technical preconditions and enough experimental experiences to develop and successfully realise the CXRS diagnostic system in COMPASS team.

The motivation to install CXRS system should be the possibility to open the way to the new research area in plasma transport physics on COMPASS.

There is an example. According to the observations in the COMPASS type experiments, the plasma density profile peaking by added heating is accompanied by observable carbon density profile changes – from peaked to hollow profile. Note that the behaviour of profiles of other impurities is not yet known in such conditions.

The study of the impurity transport character remains important and promising for predicting the fusion performance of a tokamak reactor. From this point of view, CXRS diagnostic together with BES and X-ray diagnostic systems, gradually putting into operation at COMPASS, has a potential to produce attractive physical results.

A novel design of the emissive probe

M. Tichý, P. Kudrna

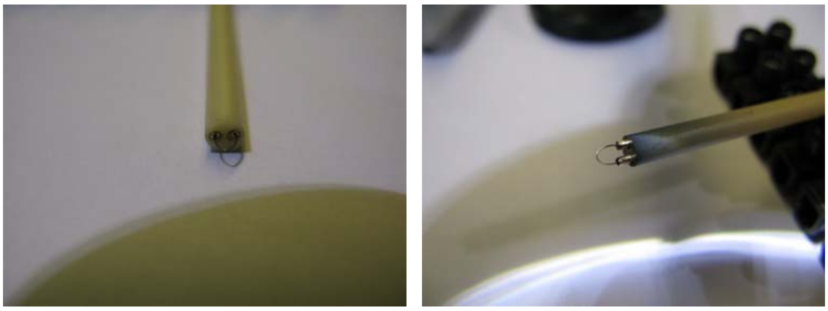
A simple and reliable construction of the emissive probe has been developed. Vital part of the emissive probe are the contacts between the electric leads to the tungsten/thoriated-tungsten wire loop. The suggested construction uses copper wires with 1mm^2 cross section as the current leads and crimping as the contact method.

The commonly used method how to construct the electric-current-heated emissive probe is to use the litz wire (braid of thin - 0.05 mm in diameter - copper wires) wound around the typically 0.2 mm in diameter (optionally thoriated) tungsten wire used for the emissive probe loop. This system works and has been used many times; however, the winding of the braid of tiny copper wires around the thin tungsten wire is not easy and also, this method does not guarantee a reliable contact between the copper and tungsten in all cases. We have developed a method that is very sturdy, reliable and comparatively easy from the point of view of mechanical construction.

The idea is to use as electric current leads a single copper wire with the cross section capable of carrying the requested current (with 0.2 mm in diameter tungsten around 7 amps). The 1mm^2 copper wire satisfies this requirement with reserve. Such copper wire is routinely available in shops selling equipment for electricians. As a method of creating the copper-tungsten joint we have used crimping. However, to drill 0.2 mm in diameter hole into the copper wire is difficult. We have found a way around this problem by using copper tubes regularly available from the Goodfellow company under item No. CU007100. These tubes have 0.22 mm inner diameter and 0.5 mm outer diameter. When slipped over the 0.2 mm tungsten wire they create copper surface with diameter 0.5 mm. Hence, the hole needed in the copper lead can be of 0.5 mm in diameter that is manufactured much more easily. The contact is then made by inserting the tungsten wire with the slipped-on copper tube into the bored copper lead and by crimping all materials together.

The emissive probe holder is made of the Frialit-Degussit double-bore tube available from the Friatec company under item No. 143-11040-1. This tube has outer diameter 4 mm and inner diameter of each of the holes 1.2 mm. Since the outer diameter of the 1 mm^2 copper wire is 1.12 mm it fits to the tube bore tightly but with sufficient clearance to insert the lead easily. The sticking out sturdy leads on the other end of the probe enable also comfortable fixing of the wires from the power supply used for heating the emissive probe tungsten loop.

The figures given below give sufficient notion about the construction of the emissive probe tip (left panel) and on the crimped contacts (right panel). Preliminary tests proved exceptional reliability of the contacts made in the described manner. The massive copper leads also serve as excellent heat-transferring media so that the emission occurs only from the probe tip. Application for a registered design is in progress.



Ball-pen probe measurements in H-mode on ASDEX Upgrade

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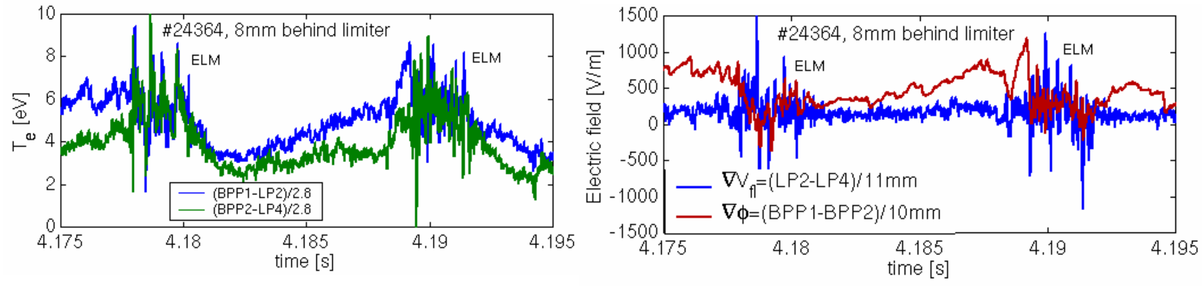
Experimental investigations of the plasma potential, poloidal electric field and electron temperature during L-mode and ELMy H-mode were performed on ASDEX Upgrade by means of a probe head containing four ball-pen probes and four Langmuir probes. This allows measuring simultaneously the floating and plasma potential at the same time, which are related through the electron temperature. Thus a combination of ball-pen probes and Langmuir probes offers the possibility to determine the electron temperature directly with good temporal resolution. This novel method for temperature measurement is compared to standard techniques using swept Langmuir probes. The influence of the electron temperature on the usual calculation of the poloidal electric field from the gradient of the floating potential is determined by a comparison to the poloidal electric field derived from the plasma potential.

The ball-pen probe (BPP) [1] for direct measurements of the plasma potential Φ_{pl} was developed in the Institute of Plasma Physics in Prague. Here we compare and combine BPP data with measurements with standard Langmuir probes (floating, V_{fl}, and swept) located on the same probe head and mounted on the reciprocating midplane manipulator on ASDEX Upgrade. These two probe techniques allow a comparison of the poloidal electric field $E_{pol} = -\mathrm{grad}\Phi_{pl}$ with the standard approximation $E_{pol} \cong -\mathrm{grad}V_{fl}$ and to derive the electron temperature T_e during ELMy H-modes.

The probe head consists of four BPPs with the retraction depth ($h < 0$ mm) of their collectors and four Langmuir probes (LP1, LP2, LP3, LP4), as shown in Fig. 1. This arrangement was used during the experimental campaign in 2009 on ASDEX Upgrade. The BPP-collectors are made of stainless steel with diameters of 4 mm, fixed inside the ceramic (boron nitride) shielding tubes. In ELMy H-mode shots, measurements were performed positioning the probe head about 8 mm behind the limiter with a neutral beam injection (NBI) power of 10 MW, toroidal magnetic field $B_T = 2.5$ T, plasma current $I_P = 1$ MA and line-averaged density $n_e = 8.5 \cdot 10^{19}$ m^{-3}.

Fig.1. Picture of the quadruple ball-pen probe used in AUG during the campaign in 2009. The probe head has four BPPs with conical tips retracted into the boron nitride screen. In addition, there are four graphite Langmuir probes.

Assuming the influence of T_e on the BPP collectors to be negligible, on a short time scale the evolution of T_e can be investigated [2] if the energy distribution is Maxwellian: $T_e = (\Phi_{pl} - V_{fl})/2.8$. It is measured by a neighbouring BPP and LP (BPP1, LP2 or BPP2, LP4, respectively) during ELM events and plotted in Fig. 2a.



(a) *(b)*

Fig. 2. (a) Two temporal evolutions of T_e obtained by BPP1& LP2 and BPP2&LP4. The data are processed in the frequency range f < 40kHz. (b) Poloidal gradient of the floating potential (blue line) and plasma potential (red line) (f < 40 kHz).

The evaluated data are averaged over 25µs (f < 40 kHz) to minimize the influence of the time shifts between probe signals (due to different probe locations) and the space averaging (different probe dimensions). The derived value of T_e is strongly fluctuating during ELMs. The poloidal gradients of floating potential and plasma potential, calculated from V_{fl} (LP2, LP4) or Φ_{pl} (BPP1, BPP2), are plotted in Fig. 2b (data are averaged over 25 µs). It is seen that the poloidal gradient of V_{fl} fluctuates more than that of Φ_{pl}. This might be caused by T_e being out of phase or different in amplitude for LP2 or LP4, respectively, during ELMs and also in between ELMs. For comparative measurements of T_e during ELMy H-mode shots [3] a combination of BPP and LP, and a fast swept LP were used. The probe head was located at 5.5 cm distance from the separatrix just at the position of the outer limiter. LP1 was operated in fast swept mode. The fast single probe was swept with a frequency of f_{sweep} = 101 kHz. In or order to derive T_e BPP3 with the most retracted pin and therefore most reliable for the determination of Φ_{pl} was used. Thus, the electron temperature T_e is derived using floating probe LP4 and the formula $\Phi_{pl} = V_{fl} - \alpha T_e$ with $\alpha = 2.8$. The time resolution was reduced to 25 µs to account for the size of the two-pin arrangement. In Fig. 3 this value of T_e is compared to the values obtained by the fast sweeping pin. As an ELM monitor the current of LP1 is plotted in black for U < 30 V which is roughly I_{sat}. The T_e from BPP/LP is plotted in blue. The T_e data from the fast swept probe are shown in red. All individual characteristics were analyzed and data with beta > 30 removed. Afterwards the data were smoothed by a median to reach a similar time resolution as the BPP data. During ELMs both measurements show $T_e \approx 10 - 12$ eV and agree quite well. In between ELMs the BPP-T_e is significantly higher than the swept probe-T_e. The fast swept probes cannot measure low T_e reliably. This does not affect the median values of the ELM interval but strongly influences the inter-ELM measurement.

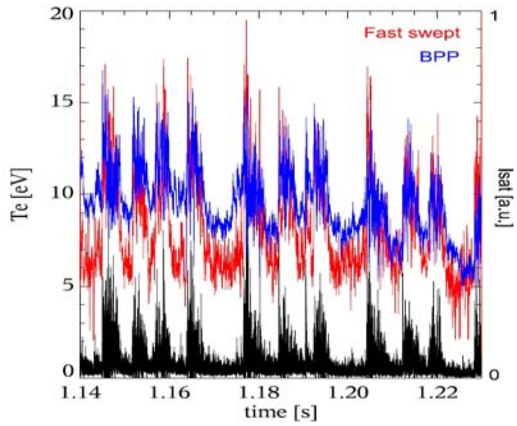


Fig. 3. I_{sat} (black) and T_e during ELMy H-mode. Mean value of T_e of fast swept single probe (red), and T_e as determined from BPP/LP (blue) [3].

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Thomson scattering design for COMPASS

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The COMPASS Thomson scattering (TS) diagnostic has been developed to a conceptual design, which comprises choice of particular components (laser system, polychromators, detectors, optical fibers, data acquisition system) and to a detailed design of particular components and specification of required parameters. The design was developing under the effective collaboration with the CCFE team. Particularly, the design of polychromator developed on MAST, CCFE has been used and adapted to meet COMPASS needs.

The scientific programme of the COMPASS tokamak [1] is focused on the H-mode and on pedestal region studies. Therefore, the role of TS diagnostic system is to measure electron temperature and electron density during physical events across the plasma with emphasis on coverage of pedestal region. The new TS system on COMPASS consists of two diagnostic sub-systems, the core TS system and the edge TS system. The core TS system will measure at 24 spatial points with spatial resolution about 10 mm while the edge TS system will measure at 32 spatial points with spatial resolution in the range of 3 mm to 5 mm. Demanding value of spatial resolution of 3 mm is planned to be achieved by a combination of challenging designs of collection optics and polychromators.

A critical part of TS system is the laser source. To achieve the specified requirements, a multi-laser solution is utilized. Two 30 Hz 1.5 J Nd:YAG laser systems are set to be located outside the tokamak area at a distance of 20 m from the tokamak. To allow easy and safe performance tests, a mimic (test) path of the same optical length as the main laser beam path was built. The laser system will be used in two typical modes, one where the laser beams are overlapped in time and the second where they are separated in time. Tunable time separation in the latter case enables a possibility to observe physical events– for example fast plasma filaments [2] and magnetic islands need time separation in the range of microseconds while time separation of hundreds of microseconds allows to measure pedestal evolution [3].

Scattered light will be collected by two separate objectives. The objective for core TS system collects light from the central and upper part of plasma (-30 – 210 mm above the mid-plane) and focuses it to 24 inputs of optical fibre (polymer cladding silica, NA=0.286) bundles. The bundle input is of rectangular shape, 1.23 mm x 2.65 mm, i.e. 6 x 11 fibers (0.21 mm core, 0.23 mm core and cladding). The objective for edge TS system collects light from 200 to 300 mm above the midplane and focuses it to 32 inputs of optical fibre bundles. The bundle input is of rectangular shape, 2.42 mm x 1.23 mm, i.e. 10 x 6 fibers. Fibers are packed in a hexagonal package to ensure efficient collection of light. The fibre bundle outputs are circular (diameter of 3 mm to fit into the input of polychromator) with randomized fibres. Because of budget constraints, a duplexing technique was used to reduce number of polychromators by a factor of 2. The light form two adjacent spatial points is led to a single polychromator via two fibre bundle arms of different length connected at the end (polychromator input). The length difference between both arms is 13 m (delay between scattered signals coming from adjacent spatial points is 64 nm).

The light coming to polychromator is spectrally resolved by a set of spectral filters that have been designed regarding to expected COMPASS plasma parameters. The set of spectral filters for the core TS allows to measure temperatures in the range of (100 – 5000) eV with the error below 10%. The set of spectral filters for the edge TS is ready to measure temperatures from 30 eV – 1000 eV with error up to 10%. This range could be extended towards the lower temperatures (10 eV with the error of 12%). The light is detected by Avalanche photodiodes (APDs with enhanced infrared sensitivity). Outcoming signals are digitized by fast sampling (GS/s) 8-bit analog digital converters.

The design of TS diagnostic on COMPASS has been described in [4].

References:

[1] R. Pánek, Czech J Phys. 56 (Suppl. B) (2006) B125-B137
[2] R. Scannell et al., Plasma Phys. Control Fusion 49, 1431446 (2007)
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[4] P.Bilkova et al., Nuclear Instruments and Methods (A), submitted in December 2009

Magnetic diagnostics

J. Havlíček, F. Žáček, F. Janky, J. Horáček, I. Ďuran, J. Brotánková, O. Bilyková

The COMPASS tokamak is equipped with 440 magnetic diagnostics coils. These coils are distributed all over the vacuum vessel (see Figure 1) and were transported in a functional state from Culham. Refurbishment of the cabling was required because of different layout of the magnetic cubicles with integrators. These cubicles are located outside of the tokamak hall in a separate technological room dedicated to data acquisition.

During COMPASS reinstallation in Prague all diagnostic coils were checked for short circuit with vacuum vessel; it was found that several of them are functionless. Cables going from tokamak hall to CODAC room with data acquisition were laid and equipped with connectors. Because of the limited number of available data acquisition channels only several basic diagnostic coils were used for first COMPASS campaign in December 2008.

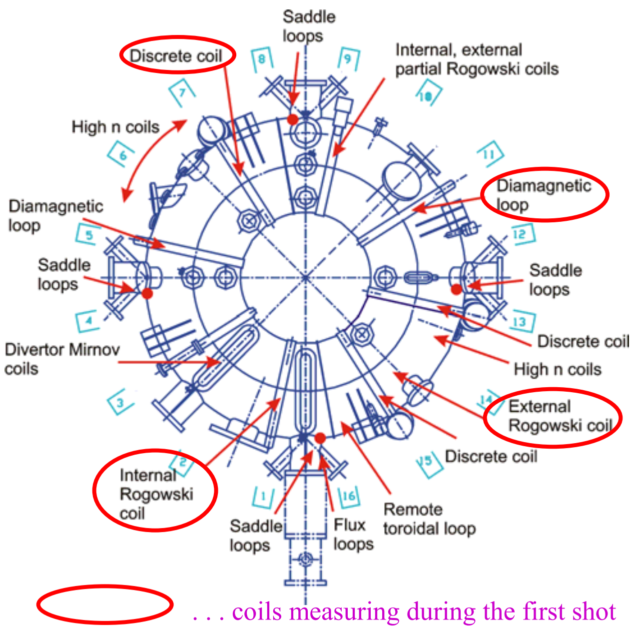

Fig. 1. Top view of the COMPASS tokamak with all magnetic diagnostics coils.

The set of ~ 70 magnetic diagnostics coils was calibrated and prepared for use at the end of the year:

– 24 Discrete Mirnov coils - measurement of poloidal B

– 16 Internal Partial Rogowski coils - measurement of averaged poloidal B

– 8 flux loops (integrated signal) – measurement of ?

– 8 flux loops (raw signal) – measurement of loop voltage

– 6 commercial Rogowski coils MFC 150 – measurement of PF coils currents

– External and Internal Rogowski coil - measurement of plasma and vessel current

– diamagnetic loops

A few attempts to use diamagnetic coils to measure plasma energy were made but the noise completely overlaps the physical data. It is proposed to use analogue amplification closer to the tokamak to suppress the noise.

Both vertical and horizontal positions of the plasma column were not stabilized during initial campaigns. This stabilization can be done by using horizontal and vertical magnetic field to counter the positional instability of the plasma, but the fast field power supplies were not available at that time. First attempts to plasma position reconstruction are described in the following text.

The plasma position was estimated utilizing Mirnov coils located at top, bottom, HFS (high field side) and LFS (low field side) positions. The algorithm for plasma position reconstruction assumed circular shaped plasma with minor radius limited by the nearest vessel surface and with centre coordinates R and Z being determined by the algorithm. The measured values of magnetic field at the top, bottom, HFS and LFS positions were compared with values computed for various centre coordinates R and Z to determine the actual position of the plasma column.

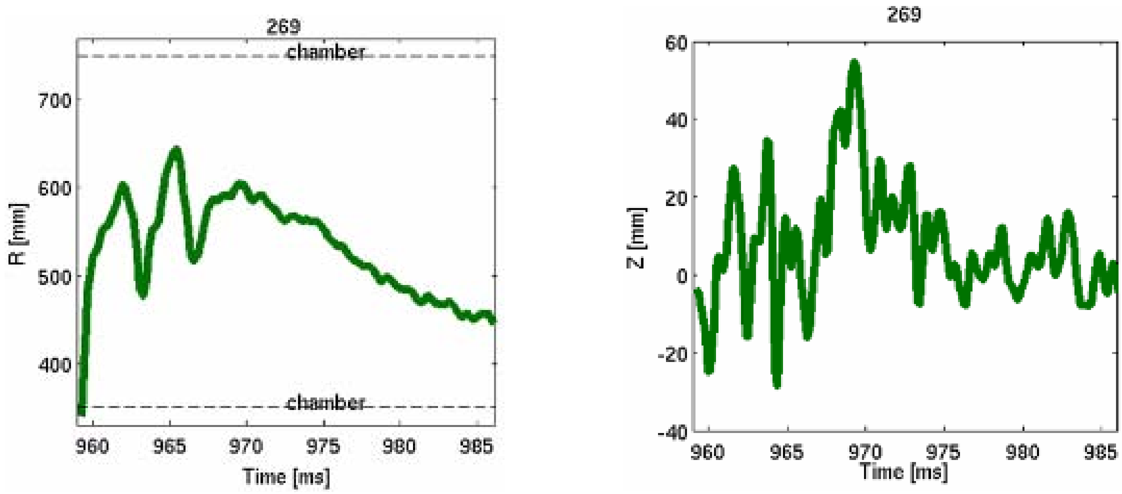

Fig. 2: Preliminary plasma position reconstructions using Mirnov coils.
Left: horizontal plasma position, right: vertical plasma position.

Figure 2 shows plasma position during the shot #269. The left panel (position in the horizontal dimension) shows that the plasma was ignited on the high field side (HFS) of the vacuum vessel. Two quick changes of the position in the direction to the vessel centre were probably caused by a shard of the limiter tiles loosened to the plasma which temporarily decreased the plasma current which resulted into EFPS magnetic field pushing plasma column inwards. The right panel (position in the vertical dimension) shows plasma oscillating around the midplane.

An extensive analysis of magnetic coils combination suitable for vertical and horizontal plasma position reconstruction was performed. Insensitivity on the plasma parameters such as elongation, plasma shape and plasma current distribution as well as high sensitivity on plasma position were optimized parameters. An example of the result is given in Figure 3 – a signal from four Internal Partial Rogowski Coils (3*IPR#5 + IPR#3 – 3*IPR#13 – IPR#15) seems to be a good combination for plasma vertical position reconstruction.

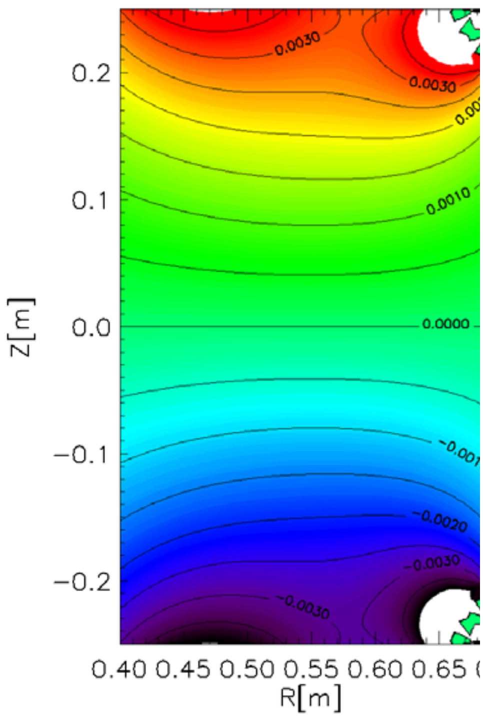

*Fig. 3: Dependency of signal [T/kA] measured in the Internal Partial Rogowski Coils (3*IPR#5 + IPR#3 – 3*IPR#13 – IPR#15) on the plasma center position (circular plasma).*

References:

[1] R. Pánek et al., *Czechoslovak Journal of Physics*, 56(2) (2006) B125

[2] J. Havlicek et al., *WDS'09 Proceedings of Contributed Papers*, (2009) 148

Development of millimeter-wave reflectometry methods for the measurement of edge piedestal plasma in tokamak COMPASS-D

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The reflectometry system for Compass was mainly designed to perform the relevant plasma density profile measurements in the pedestal region. Five individual reflectometers are supposed to measure the plasma density profile which correspondes to the frequency range 18-90 GHz. The additional requirement is using of the reflectometers as well as an experimental diagnostics for studies of the plasma turbulence. The realization of the reflectometry system was divided in two phases. The phase A, which involves three reflectometers of the K and Ka bands, is realized in the frame of EFDA Task WP08-TGS-01-06: Role of turbulence and long-range correlations during the development of edge transport barriers.

The reflectometry system consists of two parts which are developed separately. The first part are the microwave electronics and data aquisition which will be provided by IST/CFN. The second part are band-combiners and quasi-optical antennas which are necessary to transmit and receive all five microwave channels (O-mode K, Ka, U and E frequency bands and one X-mode Ka frequency band). The provider of the band-combiners and the quasi-optical antennas is the Institute of Radiophysics and Electronics NAS of Ukraine (IRE NASU).

In February 2009 the meeting was held in IPP Prague with the participation of M. Manso, A. Silva from IST/CFN Lisboa and V. Kiselov from IRE NASU Kharkov. The system arrangement was agreed in detail including the time schedule. V. Kiselov introduced the concept of the Reflectometer Band Combiners with Antennas (BCA), which will be designed in IRE NASU. The system was found to be promising by all participants. Its installment on COMPASS is possible to expect in summer 2010.

V. Kiselov recommended utilizing the possibility to make the contract between IPP Prague and IRE NASU through the STCU - Scientific and Technology Center of Ukraine. The IPP/STCU/IRE partnership was signed in July 2009. The yearly project of BCA officialy started in August 1st, 2009. J. Zajac from IPP Prague visited IRE NASU Kharkov in August 2009. The developement of BCA was started successfuly and there have been no indications of problems so far.

It was recquired that two people from IPP would take part in designing and manufacturing of the electronical and mechanical parts of the system in CFN/IST home laboratory for 60 days. Because the procurement of the electronics has not been finished in 2009, the participation is delayed. During the visit of J. Zajac and J. Vlcek in IST/CFN (Oct. 2009) parties settled the technical details of the construction of the reflectometry system at the Compass tokamak site. The topics included namely the mechanical design of the support structure for the reflectometry system and the connections between different parts of the system.

The vacuum window for the reflectometer antennas and the protective shutter of the window were purchased by IPP. The quartz window will be installed in tokamak port in April 2010. The layout of the support structure for the reflectometry system is on Fig. 1. The commercial

Building Kit System will be used. The realization of the support structure is planned in IPP in April 2010.

Use of Mobility in 2009:

Jaromir Zajac / 14 days in CFN/IST Lisbon / Participation on the developement and contruction of the reflectometers

Jiri Vlcek / 14 days in CFN/IST Lisbon / Participation on the developement and contruction of the reflectometers

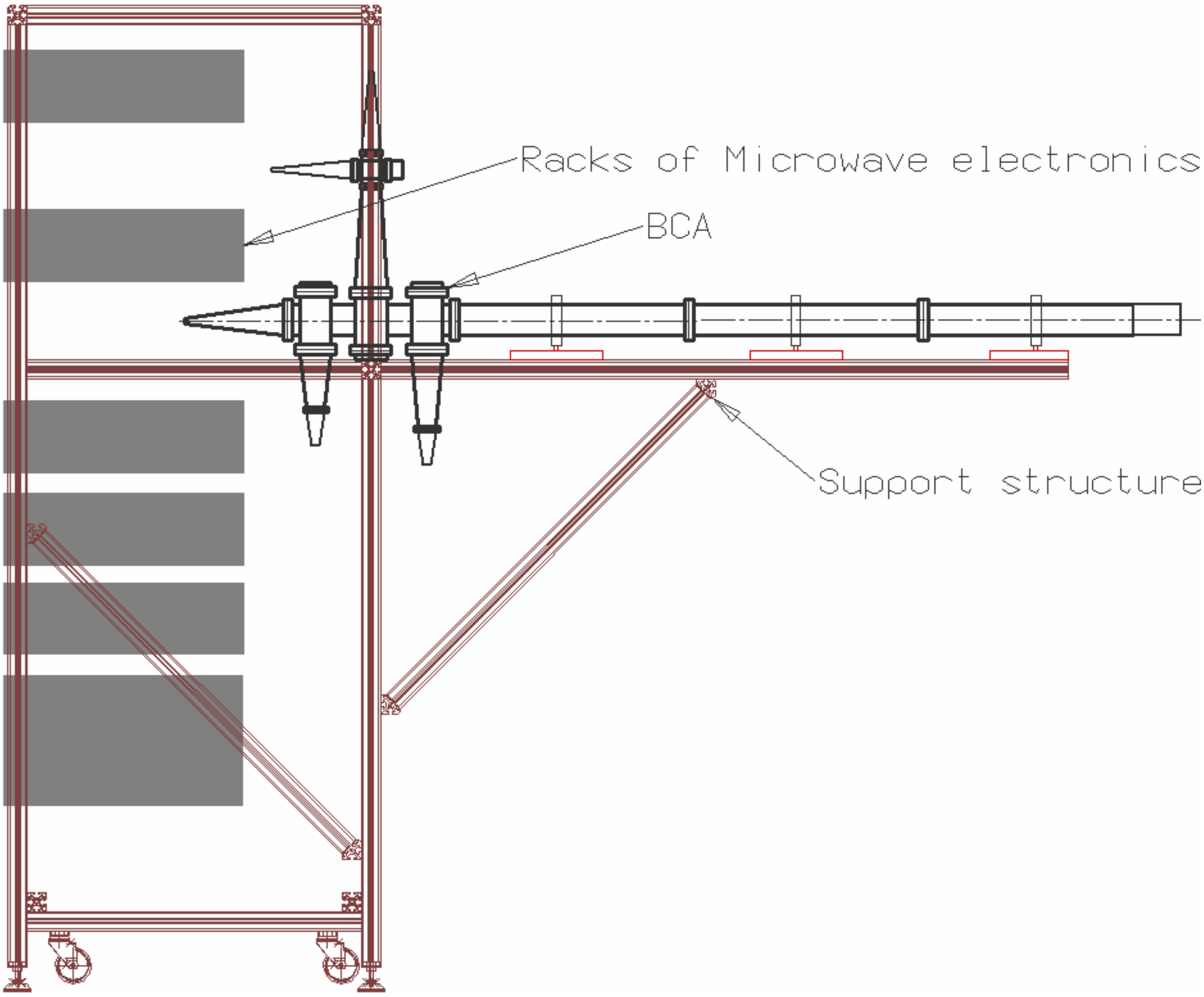

Fig. 1. Design of support structure in side view

Microwave interferometer for Compass

J.Zajac, F.Zacek

In collaboration with:
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The 2-mm interferometer for the density measurement was designed in years about 1990 in Culham. The interferometer has been re-installed on Compass in IPP Prague. The case with microwave components was put inside the thermally stabilized cabinet. The perfomance tests on Compass showed that the density measurement is not accurate enough. Therefore some suitable modifications, leading to the better dynamic range and stability, were proposed. The upgrade was considered with the help of specialists from the Institute of Radiophysics and Electronics NAS of Ukraine (IRE NASU).

The interference between oscilators was implicating the modulation of the output signals of the interferometer. The problem arized inside the interferometer when signals of two microwave oscillators 131 GHz and 133 GHz penetrate to the signal paths of each other and cause the spurious interference. Two improvements were realized in 2009. Firstly the purchasing of new microwave insulators (developed in IRE Kharkov) for a better signal filtering and, secondly, the filling of the free space in the interferometer case (in between microwave components) with the material absorbing the micowave energy. Now the signal ripples are lower than 50% of the previous value. The difference is demonstrated on Fig. 1. Two plasma shots with a similar plasma density course were chosen for the comparison. In the older shot (blue line) the signal modulation caused by the interference is clearly seen. In the newer shot (green line) the effect has a tolerable level.

J. Zajac from IPP Prague visited IRE NASU Kharkov in August 2009 to discuss further improvements of the interferometer, namely the design of phase detectors. The new detectors, developed in IRE NASU, will have a better dynamic range than the original phase detectors used in the interferometer, which is good for the prevention of the signal breaks when the plasma is unstable. Moreover the new detectors will be equiped by the microprocessor which will enable the real time removing of the systematic errors (e.g. the DC component) and the control of the gas puffing as a plasma density feedback. The special SW for the new detectors has to be developed in IRE NASU. The SW and detectors were ordered and the SW was delivered by the end of 2009. The final testing of detectors in IRE NASU was delayed because of problems with the instrumentation. The implementation of detectors into the interferometer on Compass is planned at the beginning of 2010.

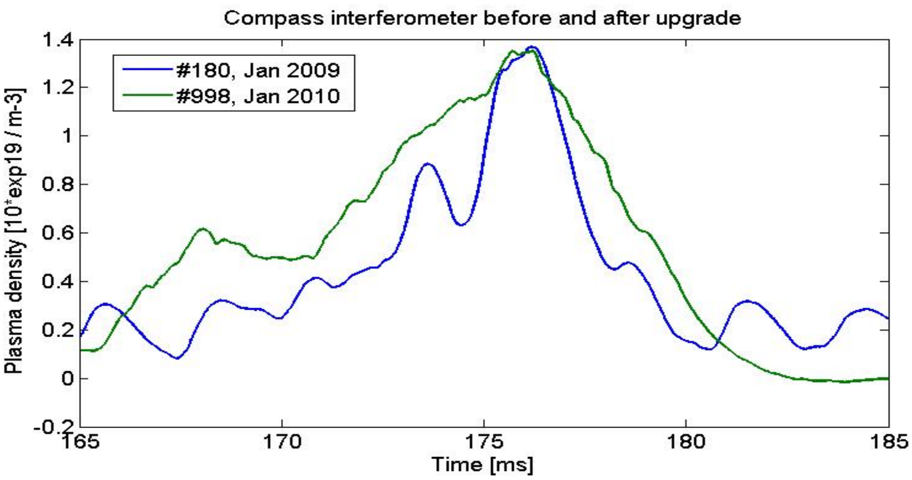


Fig. 1. Comparison of plasma density measurements before and after interferometer upgrade

COMPASS control, real time feedback, data acquisition, and communication

M. Hron

The CODAC system was installed at the COMPASS site in a close collaboration with the Association EURATOM/IST during 2009. The system uses two telecommunication standard crates called ATCA and includes in total 14 I/O modules. The modules were developed at IST, each module includes:
32 analog inputs (18-bit @ 2 Msamples/s);
4 analog outputs (16-bit @ 50 Msamples/s);
8 digital input/output channels connected to a processor;
Xilinx Virtex-4 FPGA;
512 MB DDRII SDRAM;
11 Aurora fast serial links (for other DGP cards);
8 RS-485 slow serial links (external devices);
1 SFP optical transceiver for the real-time event network connection;
– Firmware stored on Compact Flash card.
Most of these boards are installed on the COMPASS site and in use at present, two boards are used for further tests at IST.

Data acquisition

The data acquisition uses the analog inputs of the ATCA I/O modules described above. It includes in total 448 A/D converters, from which:

a) 64 data acquisition channels are connected to an FPGA (field programmable gate array) and a DSP (digital signal processor), used at sampling rate 20 kHz and utilized for real time data manipulations. These channels are connected to the real time feedback loop, it is a full number of needed channels with a good reserves for possible future increase of the number of input channels in the feedback loops;
b) 320 channels (out of 384 channels planned in total) are used for fast data acquisition (at 2 MHz).

Programming of the hardware drivers for the real time control is ready for connection to the fast amplifiers The tests of the data acquisition are ongoing as well as programming of the hardware drivers for the real time control.

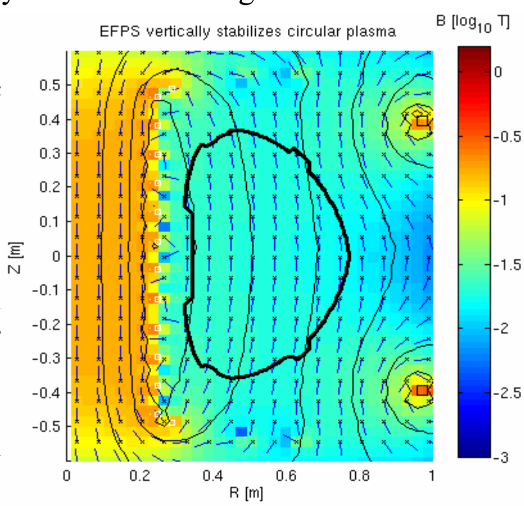
Data storage and data access

The experimental data are stored on a distributed cluster system. The existing matlab and IDL routines allow an easy access to the data in the database using a java bridge and so called SDAS layer. In addition, a dedicated IDL routine was developed for selection of sets of signals to be displayed. Moreover, the data can be accessed also from Octave.

Plasma position control (feedback) and fast amplifiers construction

The development of the plasma position control algorithms is ongoing. A model based on the transfer function of the system (power supplies, coils, plasma, sensors) was developed.

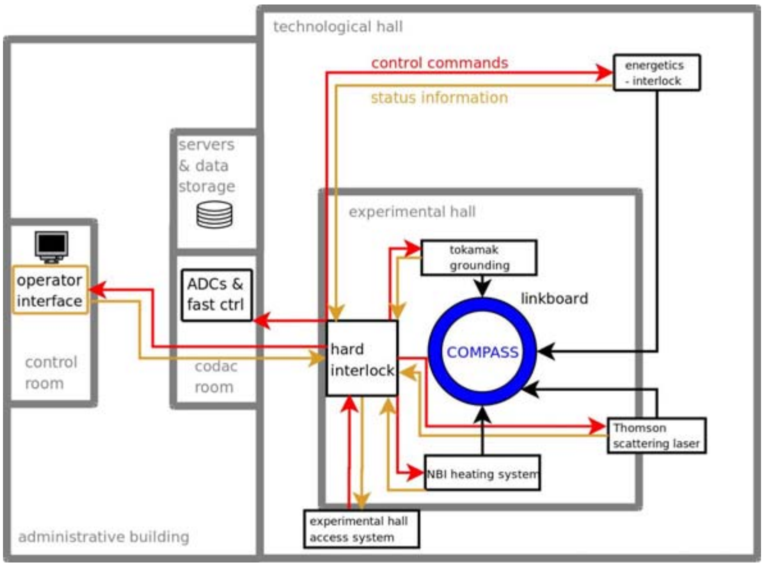
The figure shows the magnetic field inside the vacuum chamber. The circular plasma column is vertically stable while horizontal stability is not controlled. As the plasma pressure was equilibrated by pre-programmed vertical



Magnetic field inside the vacuum chamber

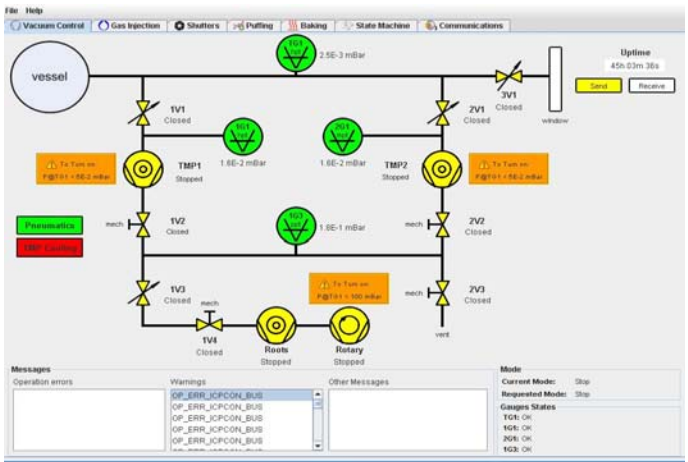
field EFPS in this case, a strong horizontal movement appeared.
Two modules (1 kA each) of the fast amplifiers for fast feedback control of the plasma position were built in collaboration with the Association EURATOM / IST. The modules were tested in a laboratory conditions and installed in the COMPASS site, the tests are planned for January 2010.

Personnel protection system
The personnel protection is a separate system, which output enter the machine control. Therefore, its status is note here as well. The construction of the personnel protection system was finished and the system was successfully tested. Basic elements of the machine protection system are operational at present. The system is ready for the extensions: a) the high power laser for Thomson scattering and b) the neutral beam heating.
The scheme shows links between the elements of the protection system. The core of the system is created by so called hard interlock, the PLC which evaluates all input signals. The outputs are directed to the operator and to all potentially dangerous systems.



Interconnection of the personnel protection elements

Vacuum and related systems control
The control of the vacuum pumping, temperature measurement and vacuum vessel baking, gas handling and glow discharge, and gas puffing systems were built within the IPP Prague in a collaboration with IST Lisbon. The commissioning of these systems was finished during 2009. The figure shows the control panel of the vacuum vessel pumping as an example the displayed interfaces. The measured pressure, status of the vacuum pumps, valves etc. is shown in the figure. The pumps and valves can be controlled using the interface.



Operator interface of the vacuum system

Implementation of new diagnostic systems
CODAC requirements for Thomson scattering control, timing, and data acquisition were specified in the Calls for Tenders. The implementation of the atomic beam probe and fast visible camera is ongoing in a collaboration with the Association EURATOM / HAS. Development of control of the reciprocating probe manipulators is ongoing.

3. Development of concept improvements and advances in fundamental understanding of fusion plasmas

Preparation for experiments with RMP coils of COMPASS

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The base operating scenario of the ITER tokamak will be accompanied with large periodic instabilities known as edge localized modes (ELMs), incompatible with the first wall components due to the high thermal loads that the first wall would have to sustain during the ELMs. One promising method to eliminate or mitigate the ELMs are the resonant magnetic perturbations (RMPs) imposed by external coils. The COMPASS tokamak in IPP Prague is equipped with a set of saddle coils for producing controlled resonant magnetic perturbations. In the future experimental programme of COMPASS we plan to focus on studies of RMPs, especially in view of their application as an ELM control mechanism and their planned use in ITER.

The saddle coils of COMPASS cover most of the vacuum vessel and can produce perturbations with the toroidal mode number n=1 or n=2. Due to the great number of independently connectable coils it is needed to determine the optimal configuration, especially because some coil segments are movable and because of access difficulties it is preferable to fix them once in the optimal position to avoid the need of further adjustments. This optimization has been performed with the goal of maximum resonant components at the plasma edge, which are believed to be responsible for the ELM suppression effect, possibly through the formation of magnetic islands and stochastic regions. The optimal configuration depends on the plasma equilibrium, so we chose representative equilibria with a toroidal field of 1.2 T and 2.1 T and a single-null geometry, either with low triangularity (labeled SND) and high triangularity (labeled SNT) [1]. For all the four possible combinations of toroidal field and triangularity the same coil positions can be used, so coil adjustement will not be required between shots. Only the polarity of their currents will need to be adapted by changing the wiring of the linkboard. For all the equilibria we found a configuration yielding significant resonant components [2].

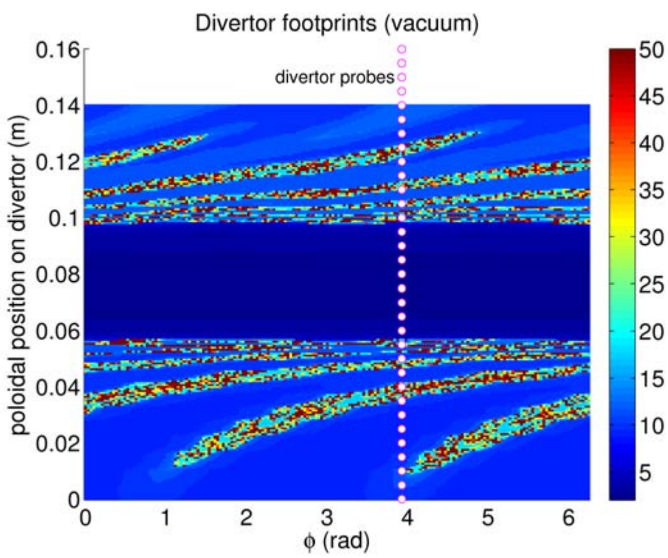

Fig. 1. Map of connection length on the divertor of COMPASS. Areas with high connection length are supposed to receive high thermal fluxes.

To prepare for future experiments we performed calculations of several effects linked to the resonant magnetic perturbations of the saddle coils. One known effect is the splitting of divertor strike points which produces spiralling patterns of high heat flux, known as the divertor footprints. Those can be observed with an infrared camera. Fig. 1 shows a prediction of the footprints caused by the saddle coils on the divertor of COMPASS. In the divertor tiles there is an embedded row of Langmuir probes (their positions are shown as white circles), which could also detect the increased temperature in the footprints. It can be seen that the resolution of the probes is sufficient to detect the structure of the footprints.

Another structures expected to be created by the perturbation are the magnetic islands at the edge. Similar structures at the edge of the TEXTOR tokamak have been observed by visible camera [3]. On COMPASS we have a visible camera with a tangential view of the plasma and we have verified that the islands (Fig. 2) would be in the field of view of this camera.

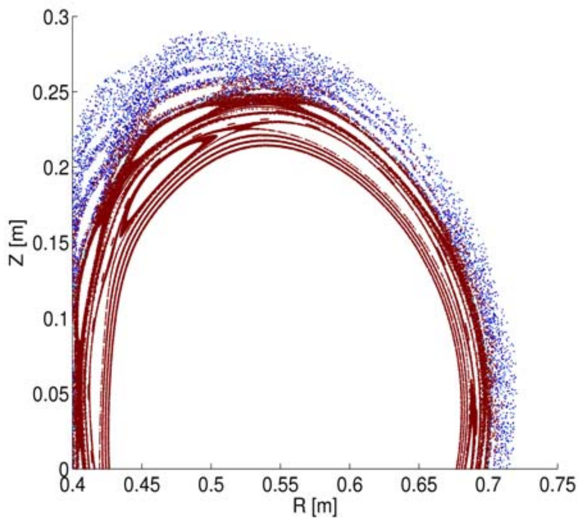

Fig. 2. Poloidal section through the field lines of the perturbed magnetic field, showing the islands at the edge.

The perturbation could induce screening currents inside the plasma which would reduce the magnetic islands. The magnitude of this effect is still an open problem. The screening currents would lead to a reduction of the divertor footprints, as well as a magnetic signal which can be in principle measured by magnetic diagnostics [4]. COMPASS is equipped with a rich magnetic diagnostics, especially the saddle loops. We calculated the integrated signal on one saddle loop resulting from the presence of a screening current in the plasma. The signal is of the order of 3.10^{-6} V.s which is very low, but can be improved by connecting multiple coils with a similar expected signal in series.

As the structures created by the perturbations are 3D and the diagnostics usually look only at one poloidal location, it is helpful for the observation of the structures to be able to rotate them in front of the diagnostics. For this time-varying currents in the coils are required. The maximum frequency is below 1 kHz, which is the time constant of field penetration through the vacuum vessel. To rotate the perturbations in front of the diagnostics a low frequency amplifier (tens Hz) will be sufficient.

Work on the coil hardware was begun: a prototype amplifier based on the MOSFET technology has been tested. The cables to connect the coils to the amplifiers have been procured. An interesting possibility for improving the current coil system is to add new coils to produce n=4 perturbations, which would allow more extensive studies of the significance of the mode number. The material for the new coils was procured.

Our results indicate that the magnetic perturbations on COMPASS may produce measurable effects which can reveal some details about the interaction of perturbations with plasma. We identified the requirements on the coil system and diagnostics (e.g. the need of having an infrared camera) and the preparation of the coil hardware is in progress.

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ELM pacing: further exploring edge biasing as potential new tool and ELM structure investigation

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The proposed effect of the ELM pacing by the edge plasma biasing was investigated in details on the existing data measured in 2008 with the aim to confirm or definitely reject its explanation via induced electric fields. At least for the used small-area probe tips and driven currents bellow 1 A, the effect of the ELM triggering by edge plasma biasing did not work or is minor, and is probably superimposed by impurity erosion effects from the probe body. However, for the measured data of the ELM pacing campaign with the high-heat flux head mounted on the midplane manipulator the processing routines were prepared that valuable information on the ELM fine structure was mined.

Experiments realized on several tokamaks have shown an ability of the edge plasma biasing to stabilize plasma turbulences via the mechanism of E × B velocity shear. The intention of this explorative approach was to establish a well defined "perturbation" by pulsed edge biasing and to search for correlations with an ELM behavior. A temporarily and spatially well defined perturbation caused by probe tips biasing was used to change an ELM pattern in H-mode on the ASDEX-Upgrade tokamak, see Fig.1. Short insertions (about 100 ms) of the midplane manipulator (MEM) equipped with the high-heat flux head, biasing of the probe tips and observations of the effect on the ELM pattern were realized at different insertion depths and for different applied voltages.

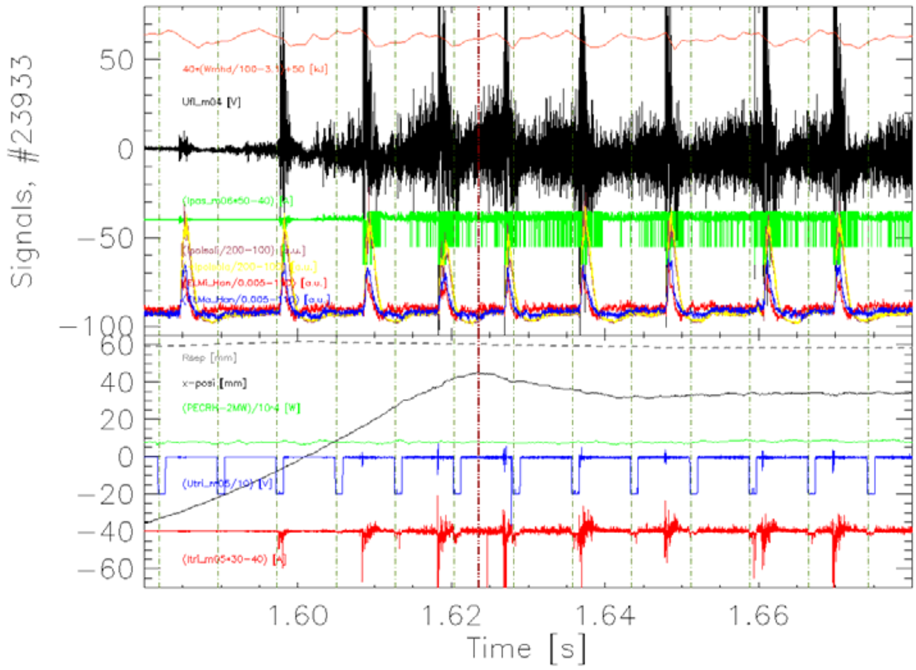

Fig. 1. Time line of the most interesting parameters during the probe insertion of the shot #23933. The bottom part of the picture shows biasing voltage and current (blue and red) together with a position of the probe (solid black) and separatrix (dashed black) and a minor modulation of ECRH power (green). The rising edges of the biasing pulses are indicated by vertical dash-dot lines. The upper part of the picture visualizes ELM occurrences via H_α and I_{polsol} signals from LFS and HFS (blue, red, yellow, brown), stored energy in plasma WMHD (upper red), floating potential of one probe tip (black) and shunt current of another probe tip.

A typical observation of the ELM pattern response on the local perturbation caused by pulse biasing of the probe head located close enough to separatrix was that the averaged ELM frequency is partially changed during the probe head insertion, however, a full synchronization of ELMs with the biasing pulses is not reached. In this situation, it was crucial to confirm or reject the proposed effect and search for an explanation of the observed experimental data. Therefore, all shots and realized strokes were reviewed but no evidence of clear triggering was found across different insertions for both biasing polarities and all biasing frequencies. At least for the used small-area probe tips and driven currents bellow 1 A, the effect of the ELM triggering by edge plasma biasing did not work. Possible ELM pacing for deeper insertions was probably caused by local density perturbation connected with impurity erosion from the probe tips.

ELMs and their propagation towards the first wall are the critical topics for ITER and future power plants. Experiments realized worldwide show a complex temporal and spatial behavior of ELMs. A similar edge plasma structure evolution was proposed by gyro-fluid simulations of the ESEL code, used in IPP Prague for blob dynamics simulations, showing more details than observed in present experiments, such as a mushroom-like propagation and different density, temperature and potential behaviors. In the above-mentioned experiments with an ELM pacing, some basic measurements of ELM type-I structure (filaments) using few independent probe tips located stepwise at different distances from the separatrix were realized.

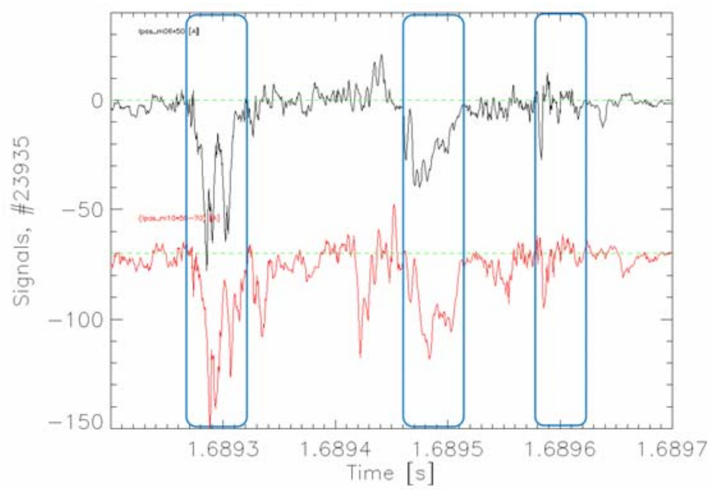

Fig. 2. Black and red traces show an evolution of passive current signal on two different probe tips during the ELM type I event. A fine structure is shown and three regions with the same behavior on both tips are marked.

Searching for the ELM structure was done using passive currents that were measured by the edge probe tips. ELM movement across the probe head was confirmed by a very high cross-correlation between these signals and the averaged ELM velocity was estimated from the time lag at maximum of about 3 μs. Temporal width of the averaged fine ELM segment was estimated from cross-correlation peak width and it ranges about 50 μs. Consequently, segments of this width were found inside ELMs, see Fig.2. Their speed is similar to the averaged ELM movement but slightly differs from segment to segment (corresponding to 3.3, 3.8 and 2.9 μs). The segments can be identified as ELM filaments. However, they are often composed from few finer peaks of about 5-10 μs width supporting hypothesis that they represent different parts of the same ELM filament of non-uniform charge distribution.

Development and tests of Hall probe based diagnostic system on tokamak JET (EP2 project)

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Use of various configurations of flux loops for measurement of magnetic field in fusion devices is inherently limited by the pulsed operation of these machines. A principally new diagnostic method must be developed to complement the magnetic measurements in true steady state regime of operation of future fusion reactors. One of the options is the use of diagnostics based on Hall sensors. The system of two sets of three 3D ex-vessel Hall probes was designed, installed, and it is now in the final stage of commissioning on JET within EP2 project. The aim of this JET upgrade is to test ITER candidate steady state magnetic sensors under fusion neutron spectrum during JET DT campaigns and also to improve the magnetic reconstruction by improving spatial resolution of ex-vessel magnetic field monitoring. IPP.CR is participating on high level commissioning of the system and on the evaluation of its long-term performance.

The Hall probes are one of the most perspective options for measurement of quasi steady state magnetic fields on future fusion devices. Lack of experience with usage of the Hall sensors on present-day pulsed devices implies the necessity of testing of these sensors in real tokamak environment. Such tests were approved on the largest existing fusion device JET in formal frame of EP2 project. JET tokamak is the closest-to-ITER present day equivalent in term of general complexity of environment for diagnostics. Several commercially available Hall sensors were tested on JET already within EP1 project with the aim to investigated properties of JET iron core saturation and remaining magnetization [1]. Meantime, the market survey

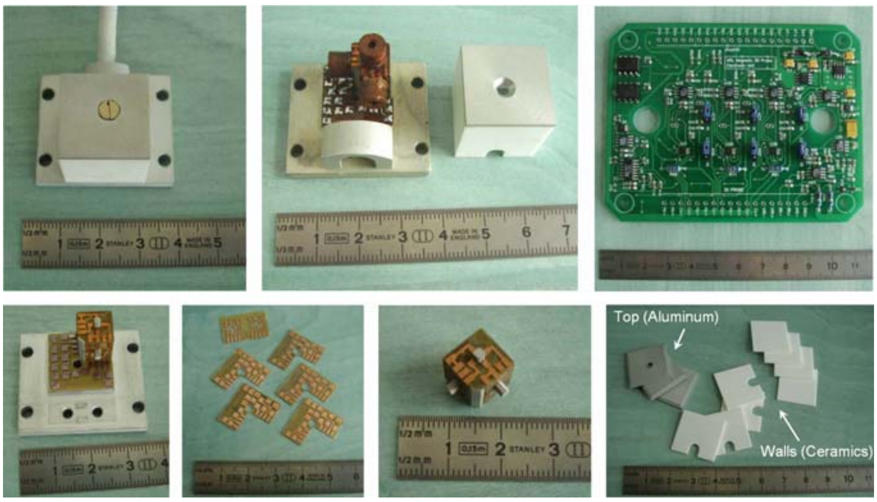

Fig.1. One of the six RHP probe heads in various stages of manufacturing process and assembling.

and investigation of radiation hardness of commercially available Hall sensors [2] demonstrated that the special Hall sensors developed by Magnetic Sensors Laboratory (MSL) provide the most stable performance under ITER relevant neutron loads. These sensors were identified as the most promising candidates for ITER steady state magnetic diagnostics. Further on, despite a reasonable radiation stability of the MSL Hall sensors, some kind of in-situ recalibration procedure seems to be necessary to ensure long term satisfactory performance of these sensors on ITER over the full life time of the machine. This can be achieved for example by integration of Hall sensors with micro-solenoids which provide a source of test magnetic field when biased by defined current waveform. Additionally, these micro-solenoids serve for test purposes as an additional reference magnetic field detector located very close to each Hall sensor. Performance evaluation of this approach to periodic in-situ recalibration of Hall sensors on large scale fusion experiment was one of the major drivers behind the EP2 Radiation-hard Hall probe (RHP) project. Additional motivation was to test MSL Hall sensors under neutron fluxes with closest to ITER neutron spectrum during JET DT campaigns.

As a result, a set of six 3-dimensional combined probes, consisting of 3 Hall sensors and 3 coils each arranged perpendicularly to each other, were designed, manufactured, and delivered to JET by MSL, Ukraine. The procurement included also the control electronic circuits that serve for various purposes including biasing of the Hall probes, amplification of the output voltage, in-situ auto-calibration, monitoring of temperature inside each probe head, etc. Inner structure of one probe head in various stages of manufacturing process is depicted in figure 1. In the mid-2009, the probes were fixed onto their support structures, developed by ENEA, and the both probe assemblies (see figure 2, left panel) were installed at two ex-vessel locations of JET tokamak. Both probe assemblies are ex-vessel located at the bottom part of the JET device, in-between the toroidal field coils in octants 5 and 8 (see figure 2, right panel). Fully automated algorithm for periodic in-situ auto-calibration of each Hall sensor before each discharge was implemented into JET CODAC system. The whole system was put in routine operation and the data were collected for over 1500 JET pulses. Measured evolutions of magnetic field components were compared to the results of modelling achieving a very good agreement. Sensors showed stable and reliable performance over the time interval of several months until the end of JET 2009 experimental campaigns. Stability of the sensors performance will be continuously analyze also in future years focussing on performance under fusion neutron fluxes during the envisaged JET D-T campaigns

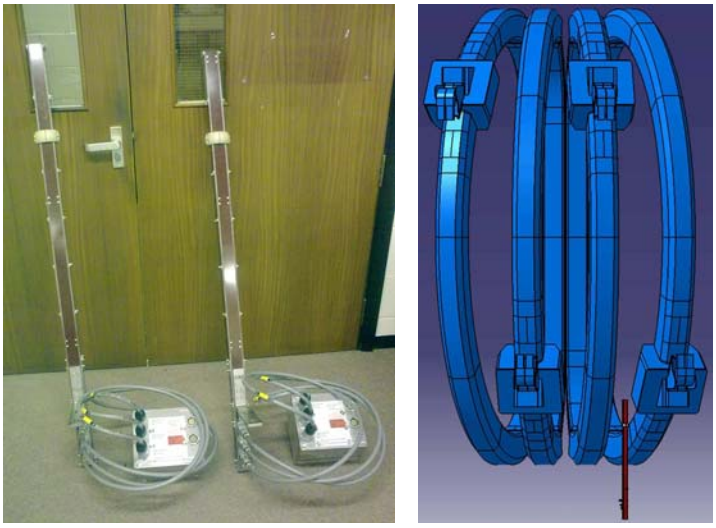

Fig.2. Left panel – two manipulators, each containing 3 probe heads, with control electronic boxes shortly before installation on JET. Right panel – location of one of the manipulators at the bottom part of JET in between the two toroidal field coils.

References:

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Experiment vs. modeling of outboard SOL turbulence

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We focused on interpretation of experimental data from ASDEX Upgrade reciprocating manipulator, yielding fast plasma density, potential and electron temperature. Spatial and temporal scales are found consistent with expectations based on interchange-driven turbulence model ESEL. Conditionally averaged signals found for both potential and density are also consistent, however, those for temperature show unexpected short drop at the very centre of a blob. These results are submitted to Nuclear Fusion.

In Spring 2010, we performed experiments with reciprocating manipulator probing edge plasma in tokamak ASDEX Upgrade, using both Ball-pen and Langmuir probes. Combining those probes yields very fast (0.5μs) and local (2-4 mm) measurement of plasma potential, density and electron temperature. So fast measurement of plasma potential and temperature is quite unique. Our main effort focused on interpretation of the data, whether they are reasonable and in accordance with theoretical expectations, based on model of interchange turbulence driven by radial gradient of plasma pressure and toroidal magnetic field. In general, so called blobs are generated in this type of turbulence.

Time-averaged values and relative fluctuation levels are shown in Figure 1 for all derived quantities: plasma potential, electron temperature, density and floating potential. Expected exponential decrease is clear in the SOL, as well as in the wall shadow region (radius behind 50mm) with expected change in slope determined by change in collisionality. Relative fluctuation levels are as expected, except from surprisingly small level of plasma potential fluctuations.

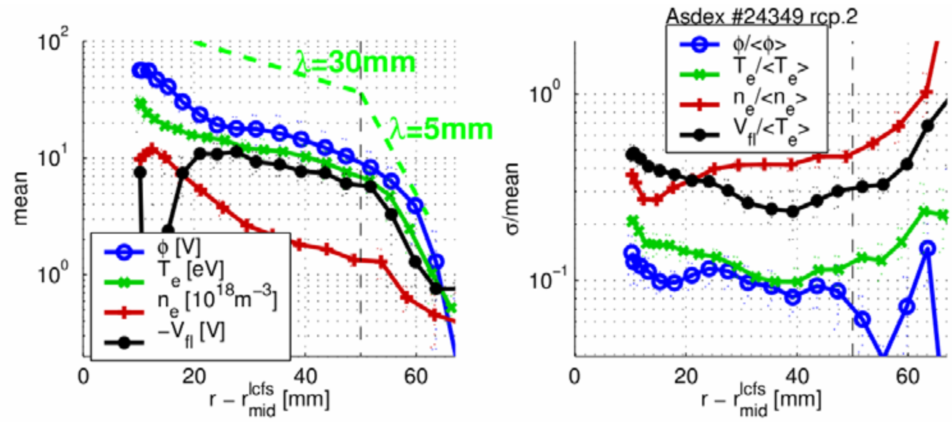

Figure 1: Radial profiles (wrt. distance from midplane separatrix) of time-averaged mean and relative fluctuation level of plasma potential, electron temperature, density and (inversed) floating potential.

We used a relatively simple technique to measure characteristic length in space and time of the turbulent structures. We derive theoretical expectations for their relations, such that spatial scales of potential should excess those of both temperature and density, and that all quantities should propagate with the same speed. All those expectations are successfully verified by the experimental data in Figure 2.

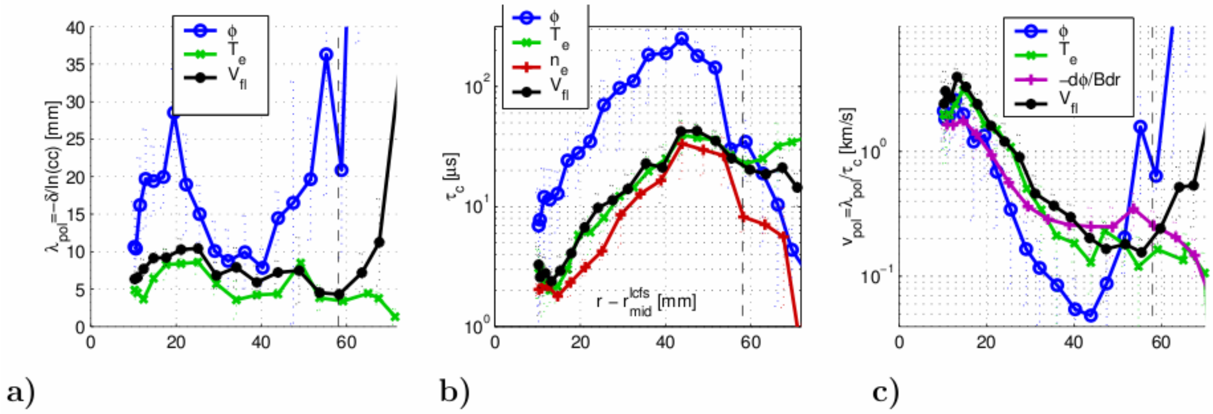

Figure 2: Data analysis yields radial profiles of a) poloidal spatial dimension (where λ=5 or 10 mm), b) auto-correlation time τ_c and c) poloidal velocity, v_{pol}. Note that in a) and c) measurement is not available for density.

At last, a picture of a blob in the dimensions of space and time of a "typical" blob is constructed by means of conditionally-averaged waveforms of all measured quantities. They behave as expected theoretically and within general experimental consensus, namely that both density and temperature increases when a blob passes across our probes, see Figure 3. Surprisingly, however, temperature seems to drop a bit for couple of microseconds at the very center of a blob, which is clearly result of so fast temperature measurement that is quite unique. This temperature drop is, however, theoretically unexplained.

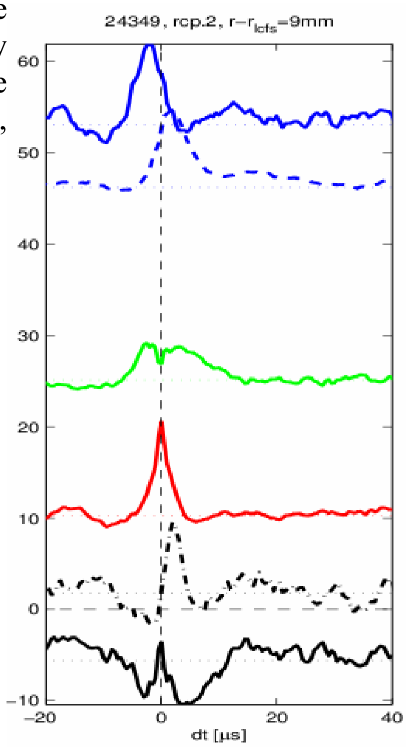

Figure 3: Conditionally-averaged blob passing across the probe head, triggered by peak in I_{sat} signal. Position closest to LCFS is shown. Local mean values are shown by the dotted lines.

EBW simulations for WEGA

J. Preinhaelter, J. Urban

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The WEGA experiment in IPP Greifswald presently carries out unique experiments with EBW heating and emission. Overdense plasma for 28 GHz second harmonic heating can be achieved and subsequently sustained exclusively by O-X-EBW heating. EBW emission is also detected during these discharges, enabling detailed EBW studies in quasi-stationary conditions. These experiments are supported by our modelling using the AMR code. The simulations of the O-X-EBW heating are consistent with the experiments. On the other side, a very intense EBW emission is experimentally detected and cannot be explained by the present models. More detailed studies are thus needed to give an explanation for this phenomenon.

The most interesting and physically challenging experimental results on the WEGA stellarator in IPP Greifswald are presently achieved with a new 28 GHz heating system. The magnetic field for these experiments is ~0.5 T. Under specific experimental conditions, particularly well conditioned vacuum chamber with low impurities and well performing heating systems, a plasma, which is overdense for 28 GHz (i.e., with electron density above 10^{19} m^{-3}), can be reached. Furthermore, such plasma can be confined exclusively by 28 GHz O-X-EBW heating. This is presently a unique feature of the WEGA stellarator.

The 28 GHz O-X-EBW heating scenario was simulated using our AMR (Antenna—Mode-conversion—Ray-tracing) code, which is able to calculate the O-X-EBW conversion efficiency by a full-wave solver and the power deposition by an electrostatic ray-racing. Calculations of the mode conversion show that almost 100% conversion can be achieved, providing correctly adjusted polarization and aiming of the antenna output beam. The angular window, in which the conversion is above 90 %, is rather broad because of the anticipated relatively steep density gradient. The conversion takes place at the toroidal position with the highest flux surface density on the outboard side and hence also with the steepest density gradient. The power deposition calculations are consistent with the experimental results. A localized deposition close to the magnetic axis is found with the optimum toroidal magnetic field of 0.48 T. There is also almost no current drive predicted because of the oscillating and low $N_{||}$.

Very unexpected results are obtained from EBW emission (EBE) measurements. An extremely high radiation temperature of typically 10 – 50 keV is detected at frequencies close to the heating frequency (which is, however, filtered out from the received signal). The emission spectrum is quite narrow—the radiation temperature drops by two orders of magnitude at 27 and 29 GHz. The origin of such high emission level can possibly be in fast electrons, which are also detected by soft X-ray measurements.

We have therefore performed simulations of the EBE spectra under various plasma parameters and viewing position (on/off-axis, low/high-field side etc.), including a population of fast electrons. This was done similarly to the 2.45 GHz case, where we assumed a bi-Maxwellian plasma with two electron temperatures and densities [1]. Similarly to the experiment, a low radiation temperature at the low frequency part of the EBE spectrum (≤ 27 GHz) is found in the simulations because the emission originates at cold edge regions, see Fig. 1. A significant increase of the radiation temperature at ~28 GHz is also present in the simulations, although with much lower level, typically around 1 keV. The reason why the thermal emission is not higher is principal. The wavelength of the EBW is given by the

Larmor radius of the cold bulk plasma ($k\rho_L \approx 1$ for EBWs). Consequently, the interaction of the fast electrons with large Larmor radius with the short wavelength EBWs is very weak and the emission comes mainly from the bulk electrons. Relativistic effects play also a role here.

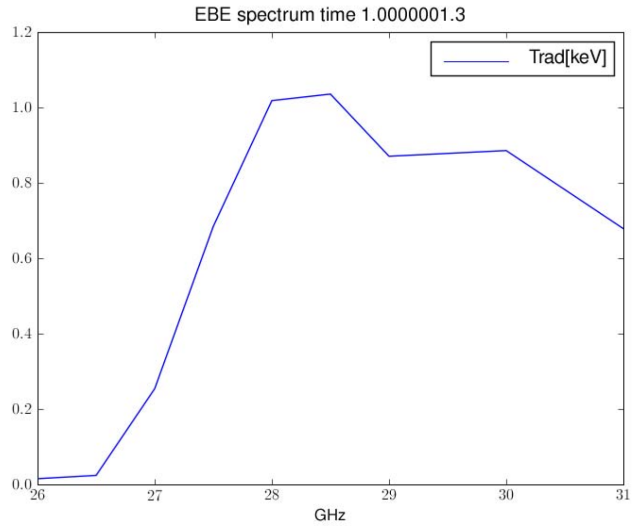

Fig. 1. Simulated EBW emission spectrum for typical WEGA parameters (B_0=0.48 T, $n_{e0}=2\times10^{19}$ m^{-3}, bulk T_{e0}=0.1 keV, suprathermal T_{e0}=10 keV).

Other mechanisms, e.g., non-thermal emission, must be probably taken into account to understand the results. Further simulations and experiments, which should bring a better insight into this problem, will be carried out.

References:

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MAST EBW studies

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The EBW emission from MAST detected by the rotating mirror was simulated with our AMR code. We compared the results of the simulation with the experiment but we do not obtain good fit. We concluded that the EFIT equilibrium, used in AMR code for the determination of magnetic configuration, does not describe by adequately profile of the intensity of magnetic field in the transport barrier.

We developed short FORTAN code, which produced position of waists, the directions of the incident central rays during rotation of mirror and the angular divergence of antenna beam. These quantise form part of input of AMR code, which computes the simulation of EBW emission from MAST. The same code can be used for the proper positioning of antenna and mirror so the optimum conditions could be achieved.

In Fig. 1 we depicted how the direction of the incident wave vectors develops during the mirror rotation and in Fig. 2 we show the intersection of the central rays with window plane during the mirror rotation. This intersection is well centred on the window centre.

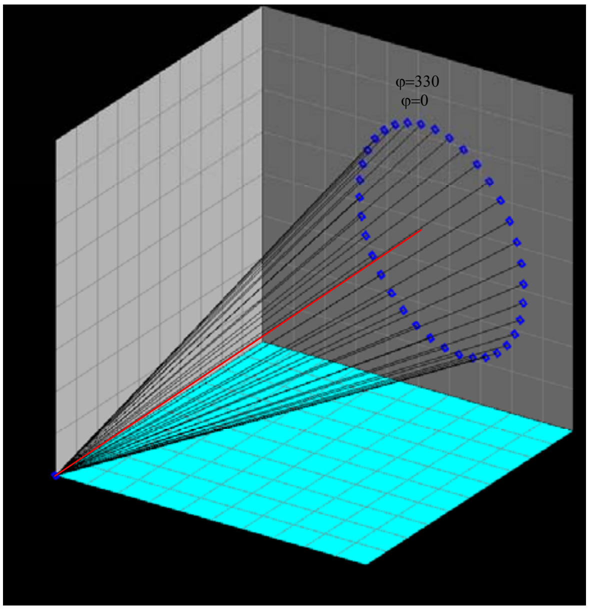

Fig 1 Incident rays of rotating mirror antenna

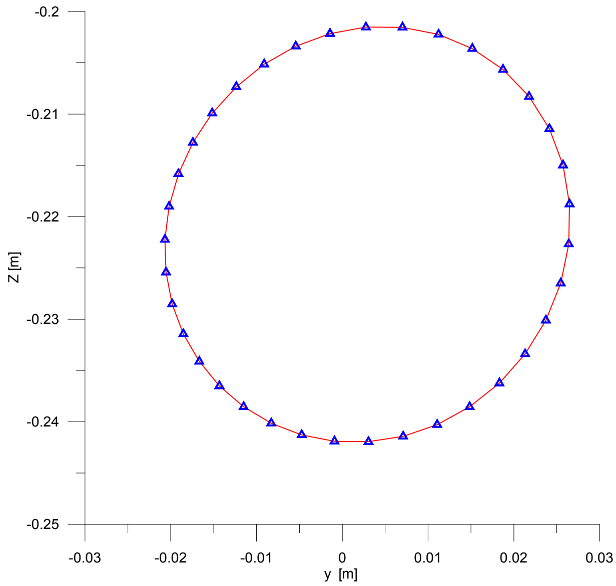

Fig. 2 Intersection of incident central rays of rotating mirror antenna with window surface

We run the simulation for shot 21896 where for t=0.32-0.38s H-mode was established and EBW emission was detected. During time interval studied the plasma parameters do not changed substantially so for simulation we take these values fixed at t=0.36s and the time scale can be substituted by the angel of rotation. Fig. 3 represents one full cycle of rotation of antenna.

We compared results of simulation with experiment (se Fig. 3) but we do not obtain good fit. Main reason is that in the simulation we determine the direction of the magnetic field from EFIT. In the transport barrier, where the O-X-EBW conversion take place, contemporary EFIT does not describe the magnetic field properly. At present, MSE diagnostic was installed which determines the direction of magnetic field directly and this new information will be incorporated into EFIT as new constrain. We hope that such an approach can improve the agreement between detected and simulated EBW signal.

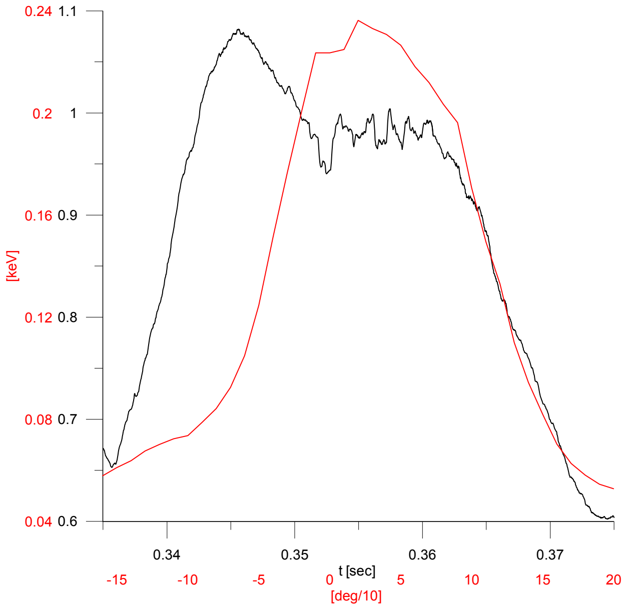

Fig. 3 Development of the measured EBW emission signal (black) and simulated signal (red).

We also placed the code on UKAEA cluster in /projects/codes/other/amr directory so it will be available for Culham scientific community. Now we are writing the manual enabling to use code for other users.

The same code is also placed on Aethelwolf cluster. Here we also instated complete Python, which is needed for proper performance of code. At present, on both clusters code run on one processor (PBS protocol, which we use in Princeton will be available in near future and it allow to use parallel computing in AMR code).

EFIT++ development

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The EFIT++ code development carried out by IPP Prague consists of implementation of a computational model to represent the induced currents in the passive structures of the tokamaks. These may be coil cases and the vessel or other structural elements. The modelling is restricted to axisymmetric currents as the EFIT++ code is itself assuming axisymmetry. The model is written entirely in C++ as a consistent set of objects utilizing freeware scientific libraries such as GSL.

During the year 2008 all data structures necessary for actual computation of induced currents (matrices of self- and mutual inductances) were prepared. During the year 2009 the development of the model continued by coding and testing of C++ method "computeInducedCurrents" which wraps all previously prepared structures into one working model usable within the EFIT++ to compute currents in the passive structures.

The first (inactive) version of the induced currents model was incorporated into the EFIT++ code and a number of options to control the model were added into the xml input file.

A new C++ class called InducedCurrentsModelOptions holds the options for the induced currents model. These options allow to control whether the model is used or not, whether to compute response matrices for the model, time when the induced currents are computed and time step desired during computation, spatial resolution which should be used to compute mutual and self-inductances of tokamak toroidal conductive structures (passive structures – vacuum vessel and poloidal field (PF) coils casings, PF coils and computational grid for plasma current) and parameters for description of the plasma current profile used for induced currents computation. The plasma current is represented by a user-defined profile scaled to the measured current. The induced currents model has been implemented in a way that allows the future use of EFIT++ generated plasma current distributions.

An extended validation of the new induced currents model against existing INDUCTION code was performed.

There is a number of fundamental differences between these two codes although the computed induced currents should be similar. The INDUCTION code is written in Fortran language while new model is written in C++ language. The induced currents model is based on the model described in the article of G.J. McArdle and D. Taylor [1]. The new code uses a variable transformation, which allows to avoid numerical differentiation of the PF coils currents and the plasma current. The new model also uses eigenvalue decomposition to separate the variables in the set of the ODEs describing the induced currents.

The validation of the new model against the INDUCTION shows that there is a number of differences between the results from these codes that still need some work to resolve. At present the status of the validation is this:

1) It has been shown that the mutual and self couplings in the INDUCTION code are computed incorrectly. This may result in non-negligible errors of mutual couplings for closely located coils of finite area. The self-inductances of passive structures with dimensions comparable to the radius of the passive structure are also incorrect (up to 25% self inductance error for inconel on the central column in the MAST tokamak).

2) It was found out that there is a significant difference between the new code and INDUCTION in the level of the induced currents noise. The MAST induced currents computed by the INDUCTION module showed much smaller noise than the new induced currents model (~10% noise). This is because of the smoothing scheme applied in INDUCTION that is not present in the new induced currents model.

Investigation shows that the noise observed in both codes (after temporary removal of smoothing from INDUCTION) is due to bit noise created during the PF coils power supplies ADC sampling. The noise in the induced current elements is amplified and is much larger than one would expect - around 10% of the (peak) induced current.

The noise is coherent between passive structures, so it could be potentially catastrophic for equilibrium interpretation. A recommended course of action to remove the noise source is to increase the AD converters bit resolution. There already were plans to upgrade MAST AD converters from 12bits to 16bits.

3) A bug was found and fixed in the new induced currents model code. An implicit integration scheme was incorrectly implemented.

There are still several issues remaining to be solved before the new model can be declared ready for use. These issues are:

1) There are small (<1%) spikes in computed induced currents in the new induced currents model. Induced currents are computed with a finer time step (usually dt=1.10-5 s) than input PF coils currents (sampling rate 2.10^{-4} s) and the spikes are in observed only during approximately $2\text{-}4.10^{-5}$ s after the new sample of PF coils current is supplied. These spikes are unphysical and must be removed by finding and repairing the reason for them in the new code.

2) There is a huge difference (~10%) in the computed induced currents between the two codes during plasma breakdown and during plasma collapse at the end of the plasma ramp-down phase. This must be explained.

3) There is a significant difference during plasma current ramp-up and ramp-down phase. It was found that this difference is present only when plasma current is used during computation of the induced currents. Therefore the problem is in the addition of the plasma current influence to the induced currents. This problem remains to be solved.

The milestones in the Work Plan were not fully fulfilled even though a good deal of a progress to their fulfillment was achieved. The reason is that the amount of work necessary to complete verification of the new induced currents model against the INDUCTION code was seriously underestimated when the Work Plan was prepared.

Work remains to complete benchmarking of the new induced currents model code, and to optimize its operation.

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1D SOL fluid modelling and coupling to turbulence

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In collaboration with:
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The work contributes to edge plasma transport modelling. The one-dimensional fluid code SOLF1D has been used for modelling plasma transport in the scrape-off layer (SOL) along magnetic field lines. Parallel plasma transport has been studied both in steady state and under transient conditions that arise due to plasma turbulence. The main motivation of the work was to analyze parallel losses of particles and energy to divertor targets in order to improve the description of parallel transport in the turbulence code ESEL, with the future aim to couple ESEL and SOLF1D into a quasi three-dimensional model.

The ESEL code has been previously used to simulate plasma turbulence in the edge/SOL of TCV and JET tokamaks with a certain success [1]. However, the results obtained in [2] indicate that it is desirable to include parallel dynamics into the code and to couple ESEL with SOLF1D, a 1D model of the SOL based on Braginskii equations [3].

Parallel damping of the density and electron temperature calculated in SOLF1D was compared in steady state with the approximate model used in ESEL which is based on subsonic plasma advection and classical Spitzer-Härm diffusion and the assumption of steady-state simple SOL. Discrepancies have been pointed out and discussed. Further, we studied plasma transport along the magnetic field in a time-dependent way and investigated how turbulence dynamics at the outboard midplane influence plasma and heat tranport in the parallel direction. A simple transient event simulating a blob passing across the flux tube at the outboard midplane was analyzed. The parallel dynamics reveal a complex structure compared to the simple approach used in ESEL. Plasma and energy is carried to the target on two distinct time scales, corresponding to ion sound speed and electron thermal speed. This appears in Fig. 1 as two density maximums at the boundary.

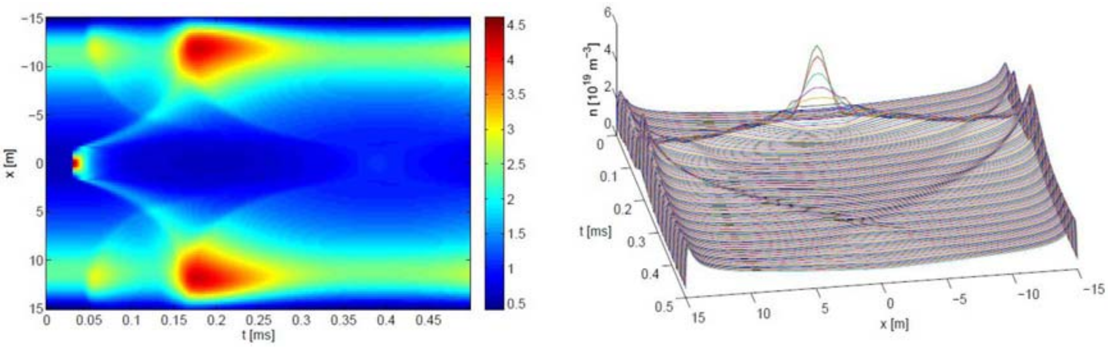

Fig. 1. Time evolution of the plasma density n [10^{19} m^{-3}] along the SOL between two targets.

SOLF1D was further applied on time-dependent data provided by ESEL to analyze the strength of parallel losses of intermittent blob structures to targets (Fig. 2) and to see how plasma fluctuations propagate along the magnetic field (Fig. 3). A comparison of SOLF1D and ESEL for series of plasma fluctuations shows missing elements in ESEL and confirms that the ESEL parallel model is insufficient, resulting in weaker parallel damping of the density and temperature. Better agreement of ESEL simulation with experiment is anticipated from the improved approach.

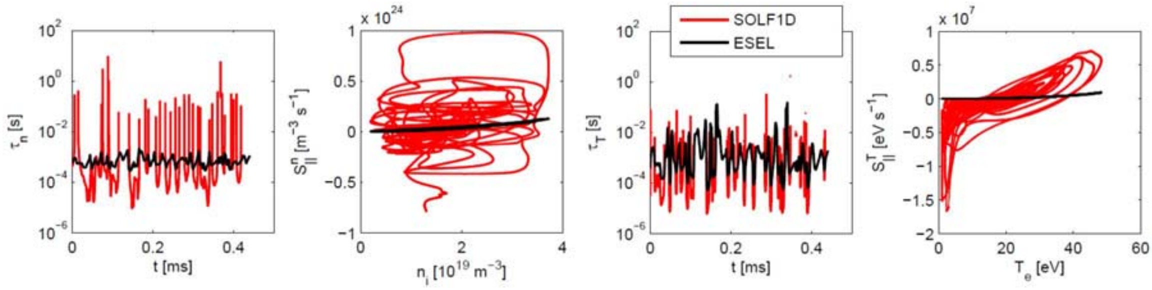

Fig. 2. Comparison of parallel loss times τ and total parallel losses for ESEL and SOLF1D.

Steady-state SOL transport solvers neglect plasma fluctuations and use average values of fluctuating plasma parameters, often aiming to fit simulation results with statistically averaged experimental profiles. This can lead to a misrepresentation of the dynamics between the different physical quantities. We estimated the possible effect from data calculated by ESEL at the outer midplane for various radial positions (Tab. 1) and SOLF1D code will be used to calculate the effect along the SOL and show the impact of time-dependent description on target plasma parameters.

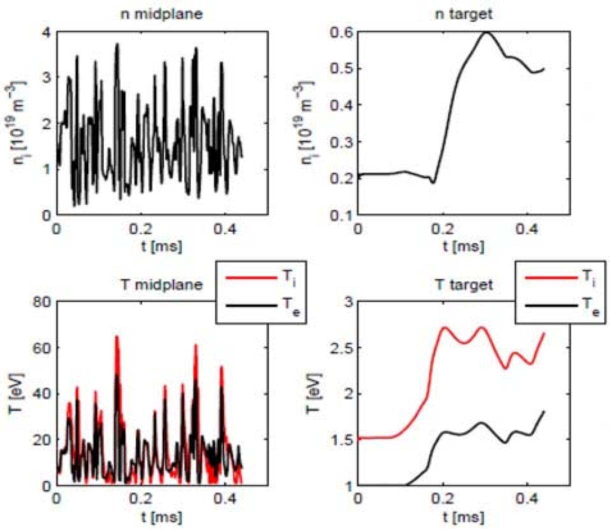

Fig. 3. Plasma fluctuations at the outer midplane and the response at the target calculated in SOLF1D

References:

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	$\rho = 0.04$	$\rho = 0.20$	$\rho = 0.38$	$\rho = 0.54$
average values				
$\langle n \rangle$	1.84E19	1.51E19	1.17E19	8.59E18
$\langle T \rangle$	18.6600	12.8251	8.48266	4.78630
level of fluctuations				
$\langle n^2 \rangle^{\frac{1}{2}} / \langle n \rangle$	1.07140	1.11580	1.19118	1.25669
$\langle T^2 \rangle^{\frac{1}{2}} / \langle T \rangle$	1.12924	1.24299	1.46603	1.77295
errors connected with averaging $\langle f(n,T) \rangle / f(\langle n \rangle, \langle T \rangle)$				
$f = T^{\frac{5}{2}}$	1.5454	2.1650	3.7262	6.9027
$f = T^{\frac{7}{2}}$	2.5356	5.0111	13.347	40.157
$f = nT$	1.1939	1.3490	1.6615	2.0252
$f = n\overline{\sigma v}_{\mathrm{ION}}$	1.2510	1.2633	1.8077	5.3897
$f = n\overline{\sigma v}_{\mathrm{CX}}$	1.0334	1.0540	1.0887	1.1150

Tab. 1. Averaging of plasma fluctuations.

Upgrading the SPICE code

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In collaboration with:
J.P. Gunn, Association EURATOM-CEA, Cadarache, France

2D Particle-In-Cell carthesian code SPICE has been successfully used to model the plasma-solid interaction of the tokamak divertor wall. Its principal component, the Poisson equation solver, has been implemented using a direct numerical method in order to boost its efficiency compared to the iterative solver.

The code has been extended into 3D to model setups with lesser symmetry, such as the Katsumata probe. In order to cope with substantial increase in computation time, the direct solver was augmented with a multigrid-based iterative method [1]. Preliminary results indicate new insight into behavior of magnetized plasma in presence of complex solid bodies (Fig. 1).
Ongoing work aims to extend the capabilities of the model and solver, such as more general boundary conditions, ability to rapidly process varying potential on the solid surface ("floating potential"), optimizing numerical precision and general computational efficiency.

Another evolution branch of the SPICE code introduces cylindrical coordinates into the 2D model with the goal of rapidly modeling plasma systems with rotational symmetry. Recently the direct solver was successfully formulated for this type of problems as well, which enables more complex and larger geometries to be modeled in a reasonable timeframe.

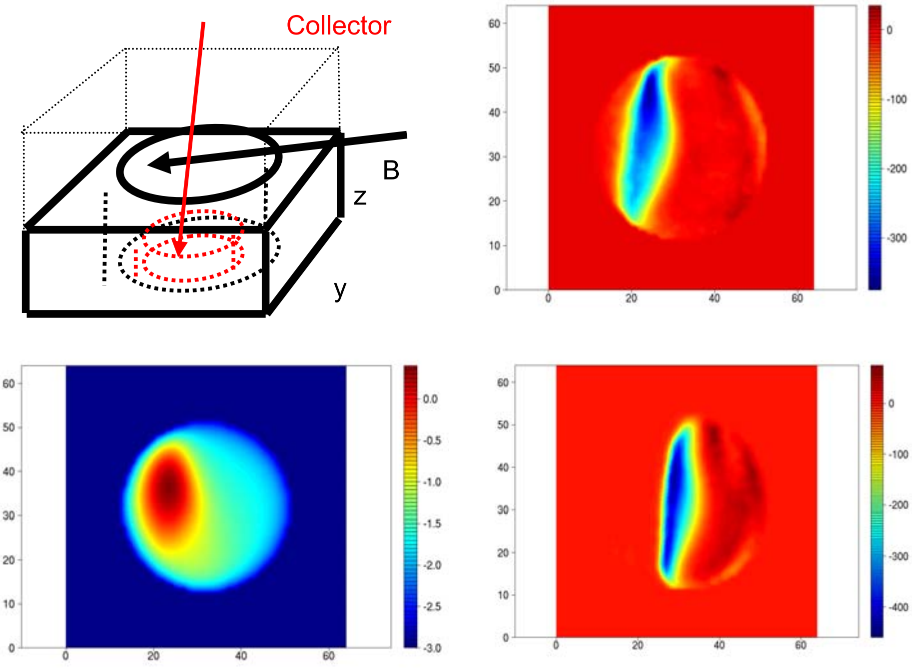

Fig. 1. Top left: layout of the plasma probe with the magnetic field introducing asymmetry. Bottom left: potential structure at the layer z=35. Top right: electron Vz velocities at z=35. Bottom right: electron Vz velocities at z=30.

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Particle-in-cell studies of fast electrons in the tokamak SOL

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We modified our quasi-neutral particle-in-cell code (QPIC) by introducing the effect of collisions using a Bhatnagar-Gross-Krook collision operator in Monte-Carlo form. This allows more rigorous analysis of phenomena associated with flows originating from extraordinary particle sources in the SOL, such as lower hybrid power and/or ELMs. Tests of the QPIC code with the collision operator are still in progress. Our principal task, in view of the planned (and in fact materialized) start in November 2009 of Tore Supra operation with the new PAM (passive-active multi-junction) C4 antenna, was to continue a study, started in 2008, of the phenomenon of fast electrons observed all the way from the grill mouth to the last closed flux surface during operation with the C2 antenna. This observation contradicted previous PIC studies which predict interaction widths of up to about 5 mm [1]. We first analysed the fast electron measurements from 2007 and 2008 campaigns in the light of data from edge turbulence measurements in order to show that the fast electrons are correlated with a special kind of turbulence, with "blobs" detached from the main body of the plasma. We carried out test electron simulations with electric field files from the ALOHA antenna code at conditions of Tore Supra shot 39547, to investigate SOL conditions for weak Landau damping, which would allow penetration of the injected lower hybrid spectrum to radial positions sufficiently close to the last closed flux surface before being strongly damped by a dense and hot blob.

Recent experimental results from retarding field analyzer (RFA) measurements on Tore Supra have indicated the existence of fast electrons as far as a few centimeters from the grill mouth. The observed fast electrons causing hot spots can be divided into two distinct classes. To the first class belong fast electrons generated very near the grill, characterized by electric probe signals, which persist for the duration of LH power. The second class of electrons causing spots on target components further away from the grill mouth - of the order of cm - exhibit temporal intermittency at a rate comparable with the detachment rate of relatively hot and dense plasma filaments -"blobs" - from the main body of the plasma [2,3].

The blobs, driven by the interchange instability, are ejected at the last closed flux surface (LCFS) around mid-plane from the low field side of the torus and are observed, in experiment as well as in ESEL simulations, on a number of tokamaks [4]. These blobs move toward the plasma edge, maintaining a radial extent of typically 1-2 cm. As a blob moves radially outwards, simultaneously extending in the parallel direction along B-field lines, its temperature and density gradually decreases. This essentially leaves a tenuous and relatively cold SOL between blob events. If under such conditions the background density exceeds the slow wave critical coupling value ($n_e \geq 1.7 \times 10^{17}$ m^{-3} for f_{LH}=3.7 GHz), the wave will propagate inward and experience very weak damping. It is only when the wave encounters a relatively dense and hot incoming blob, that the damping becomes appreciable.

Given what we know about Landau damping, and given the fast electron characteristic burst rate, we propose a model in which stochastic electron acceleration is triggered locally and intermittently far from the grill. This implies that conditions must arise by which relatively low $n_{//}$ ($15 \leq n_{//} \leq 60$) components, which carry a high proportion of the LH power, successfully propagate to deep radial positions without being absorbed, until they encounter the correct range of plasma parameters, for example a hot and dense plasma "blob".

We examined the consistency of experimental observations with the hypothesis of fast electron generation away from the grill mouth by Landau damping of the LH spectrum on blobs. A fundamental concept in this respect is the duty cycle [2,3] of supra-thermal electrons, defined as the fraction of the observation time during which they are detected by the probe. The duty cycle was observed to decrease with distance from the grill mouth as shown below in Figs 1a,b. Figure 1a is a compilation of 2-D fast electron data. We see, for example, that the duty cycle equals about 0.05 near the LCFS, i.e. about 6 cm from the grill mouth. This means that about 5% of the time fast electrons were observed near the LCFS. This also means that the antenna high-$n_{//}$ spectral components are weakly damped on the background electrons so that the background T_e must be relatively low. Fluctuations of temperature and density

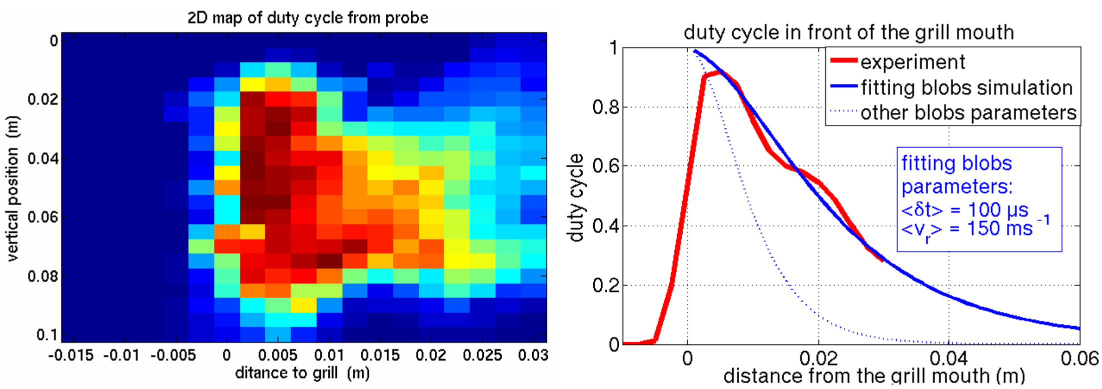

Fig. 1a) Duty cycle plotted as function of radial distance taken from a 2D map of fast electron current. 1b) Shown is a fit of the radially decaying part using a model of propagating blobs.

deduced from ion saturation current time trace fluctuations allow estimating that the background temperature will fall below 12 eV about 5% of the time. This agrees with the value of duty cycle near the LCFS.

We can therefore carry out a meaningful simulation of Landau damping at 10 eV. In order to assure good LH wave coupling and propagation we set the density at twice critical, i.e. at $n_e=3.5\times10^{17}$ m^{-3}. Two crucial properties of the LH spectrum Landau damping process act to non-linearly and self-consistently establish the interaction zone between the LH spectrum and the edge electrons. First, the generated hot electron population modifies the damping itself, and, second, the high-$n_{//}$ components are progressively removed from the spectrum as the wave propagates inwards – i.e. the SOL electrons act as a low-pass filter on the spectrum. We therefore find a self-consistent state by iterating between the distribution function, which depends on the antenna electric field from the ALOHA code [5] and the damping, which in turn depends on the concentrations and temperatures of the background and supra-thermal components of the electron distribution function. An example of a computed electron distribution function at the grill mouth is shown in Fig. 2. We clearly recognize the cold and the supra-thermal components.

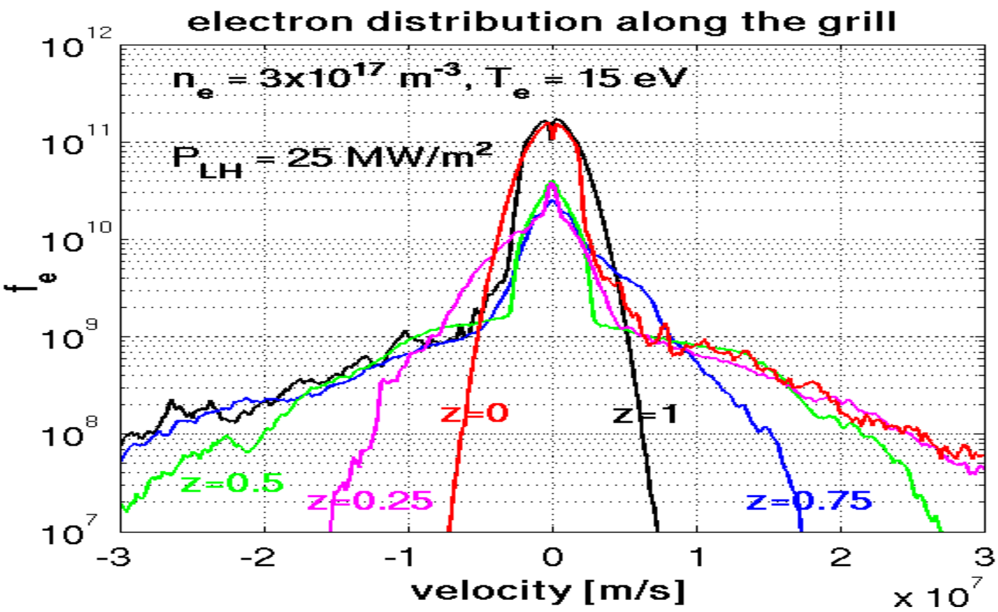

Fig. 2. Electron distribution function from a test electron simulation, for a few positions along the grill. The toroidal coordinate z is normalized to the grill length, so that z=0,1 refer to the grill ends.

To determine the suprathermal electron temperature and concentration needed in the LH wave dispersion relation, we use a Maxwellian fit to the computed suprathermal component. Selected results from solving the dispersion relation are shown in Fig. 3.

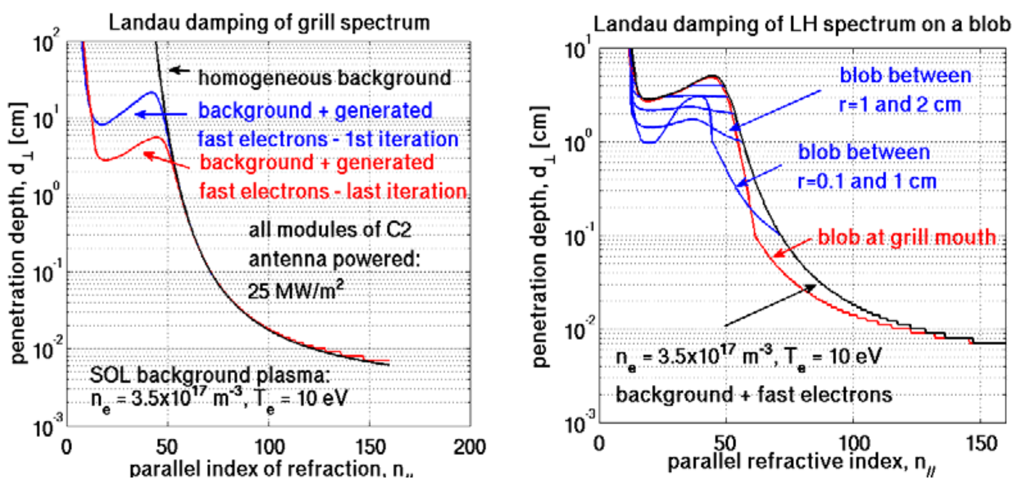

Fig. 3a) The penetration depth $d_\perp(n_{//})$ for 90% absorption of the LH grill spectrum in a homogeneous plasmas at density $ne=3.5x10^{17}$ m^{-3} and temperature T_e = 10 eV. 3b) Penetration depth in the SOL background of Fig. 3a), but with a blob at the specified radial positions. Blob T_e and n_e are assumed equal to T_e and n_e values measured in Tore Supra shot 39547 and given in Table 1 of Ref [6].

The 90% LH power penetration depth $d_\perp(n_{//})=2/Im[k_\perp(n_{//})]$, where $k_\perp(n_{//})$ is the solution of the LH electrostatic dispersion relation. We note that the last iteration of Fig. 3a – the self-consistent state between the electron distribution function, the damping rate, and the antenna electric field filtered by the Landau damping- will allow penetration to radial positions around 5 cm away from the grill mouth. Background temperatures higher than 10 eV are bound to be more restrictive.

Figure 3b indicates what happens to spectrum penetration when a blob intervenes. Clearly contrasted is the weak damping in the background against the strong damping in the blob. The penetration depth in a blob, whose radial extent is about 1 cm, is very small – less than 1 mm - so that an appreciable range of lower-$n_{//}$ gets completely absorbed by the blob.

In summary, we have developed a computational procedure for self-consistent modelling of lower hybrid power deposition in the tokamak SOL and shown that a blob detached from the LCFS due to the interchange instability and propagating outwards will efficiently absorb LH power with subsequent generation of fast electrons at any radial position, provided no other blob lies between that position and the grill mouth.

Conceptually, the principal part of this work, apart from the hypothesis that LH generated fast electrons are observed away from the grill mouth because of LH spectrum interaction with blobs, is the demonstration of positive correlation between the observed intermittency of hot spots caused by the fast electrons and the blob fluctuation statistics.

Technically, the most important result established here is that the LH spectrum can propagate towards the LCFS in a realistically tenuous and cold SOL background associated with weak enough slow wave damping to allow the spectrum to be eventually intercepted and damped by an incoming dense and hot blob.

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EBW Fokker-Planck modelling

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In collaboration with:
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G. Taylor Princeton Plasma Physics Laboratory, NJ, USA

Our AMR (Antenna, Mode-conversion, Ray-tracing) code is specifically suited for electron Bernstein wave (EBW) simulations. It has been recently coupled with the LUKE Fokker-Planck solver to enable quasilinear damping and current drive calculation. The coupling is two-way, i.e., AMR can use LUKE and vice versa, providing all plasma parameters are consistent. Batch processing of different cases is easily possible using the AMR driver script.
The AMR-LUKE suite is presently used for predictive modelling of EBW heating and current drive on spherical tokamaks, particularly NSTX, MAST and their envisaged upgrades. Promising results have been found that show efficient EBW current drive over the whole tokamak radius.

A two-way interface between our AMR (Antenna, Mode Conversion, Ray-tracing) and LUKE (3D Fokker-Planck) codes has been implemented. Overall, the AMR driver script (written in Python) is now able to launch LUKE (written in Matlab) in a batch process—all particular cases simulated in AMR can be processes by LUKE, which generates Matlab (.mat) output data files. These outputs can be read by either AMR or LUKE (or Python or Matlab themselves) and processed by users or scripts. AMR can include several LUKE results (particularly the power deposition and current drive profiles) into the figures it generates. It is also possible to start from the LUKE interface and launch AMR. This integrated interface gives the user a great flexibility in running the AMR-LUKE simulation suite, capable of antenna, mode conversion, ray-tracing and Fokker-Planck calculations for electron Bernstein waves. Both codes are maintained by versioning systems (Subversion and CVS) and benchmarking is performed for every new release of either code.

A relativistic correction to the imaginary part of the electrostatic dispersion relation, which is used for EBW damping calculation, has been introduced in AMR. The model of Decker and Ram [1], which takes into account the relativistic shift and possibly the relativistic curvature of the resonance for sufficiently large parallel wave number, was chosen for its simplicity (and hence its speed). The speed is very important for AMR as it often simulates large problems (e.g., temporal evolution of EBW emission spectra). This relativistic correction is essential for calculations with T_e>1 keV or suprathermal electron populations such as in WEGA and enabled reliable functionality of the AMR-LUKE suite for such cases. However, it does not work correctly for low parallel wave numbers (typical for mid-plane launched rays) and some deviations from fully-relativistic models implemented in LUKE exist in many cases. This motivates us to implement a more appropriate (yet probably slower) relativistic damping.

AMR is now technically capable of adding arbitrary current drive (CD) models that are appropriate for ray-tracing. Several possibilities have been implemented so far. The very basic model of Hansen et al. [2] enables EBW current drive calculations in tokamaks and stellarators; however; it neglects trapped electrons which restricts its usage for configurations with negligible electron trapping. We have begun implementing two more advanced linear CD models—Cohen's model [3] and the model of Lin-Liu/McGregor et al. [4, 5] (for axi-symmetric plasma only). These models seem to be very sensitive to the damping model and hence the relativistic damping must be implemented before the linear CD calculation can be validated. The quasi-linear current drive calculation by LUKE works well and is, at the moment, used for EBW CD modelling for large spherical tokamaks.

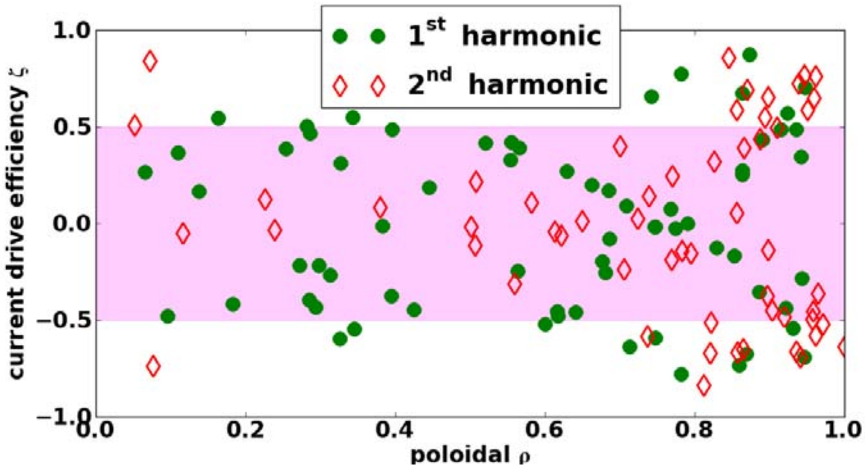

Fig. 1. Normalized EBW current drive efficiency ζ versus poloidal ρ (normalized radius) for various launch parameters (vertical antenna position and frequency) in a typical NSTX H-mode plasma (B_0=0.5 T, $n_{e0}=4\times10^{19}$ m^{-3}, T_{e0}=5 keV, I_p=1 MA).

The electrostatic EBW is a promising candidate for localized heating and current drive in high-ß plasmas, where the standard electron cyclotron O- and X-waves are cutoff. EBW heating and current drive was simulated in spherical tokamak conditions, particularly in typical NSTX equilibria and also in equilibria predicted by transport modelling for the NHTX spherical tokamak [6]. The EBW injection parameters were varied in order to find optimized scenarios and a possible way to control the deposition location and the driven current. For the NSTX L- and H-mode parameters, it has been found that EBWs can be deposited and drive current at any radius, depending on the launching vertical position, the frequency and the launching toroidal angle sign. Normalized current drive efficiency ζ [7] of ~0.5 (see figure 1) can be found across the whole plasma. For NHTX, the normalized efficiency is similar; however, the total current is much lower due to higher collisionality and the accessibility is worse. Calculations for MAST and its possible upgrade are currently in progress.

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Detection of EBW emission on COMPASS

J. Preinhaelter, J. Urban, J. Zajac, F. Žáček

Our 16-channel radiometer was completed and we absolutely calibrated. Two antenna systems for oblique electron Bernstein waves (EBW) detection, both with steering mirror, are prepared for two ports of COMPASS. Preliminary testing shots with underdense, highly non-thermal plasma with large portion of runaway electrons do not allowed to study EBW emission so we measured only direct perpendicular emission of O-mode from fundamental harmonic.

During year 2009 we tested our radiometer and some new parts was purchased. First, two collaborators of Elva company tuned the electronic parts of delivered device namely 16 channel receiver. Then, we absolutely calibrated the radiometer in laboratory conditions using two normals of black body radiation on two temperatures, at liquid nitrogen and at room temperature.

We use two ports of COMPASS tokamak for the detection of the electron cyclotron emission. First, it is triple port (8/9 H), which can be used both for detection of the signal propagating obliquely with respect to the magnetic field (detection of the mode converted EBW) and also for detection of signal propagation perpendicularly to the magnetic field (the electron cyclotron emission of X-mode from the second harmonic in Ka band). The oblique port is rather narrow ($\varnothing = 50\text{mm}$) so we cannot use the Gaussian beam antenna (26-40GHz band) purchased with radiometer and we constructed special antenna system consisting with a horn, a lense and remotely steered mirror (see Fig 1,2). The first results of measurement were presented on the 18th RF Power in Plasma Conference in Gent (2009).

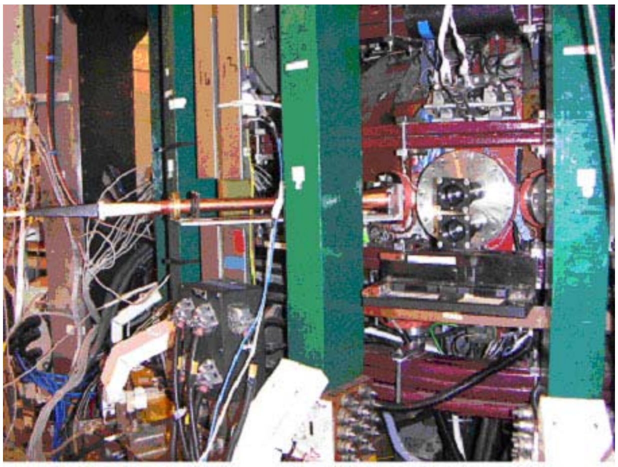

Fig. 1. Antenna for 26.5-40 GHz band in front of the vacuum window. The 8/9 H triple port.

Fig. 2. Steerable mirror placed in the COMPASS chamber (model).

The Gaussian beam antenna ($\varnothing = 140\text{mm}$, 26.5-40 GHz band) will be installed in the broad ($\varnothing = 200\text{mm}$) 1/2 H port. Revised proposal of steerable mirror for oblique detection of EBW emission was finished and the realization of this device was started. The microwave mirror is steerable in two planes and it will be placed in COMPASS vessel (see Fig 4).

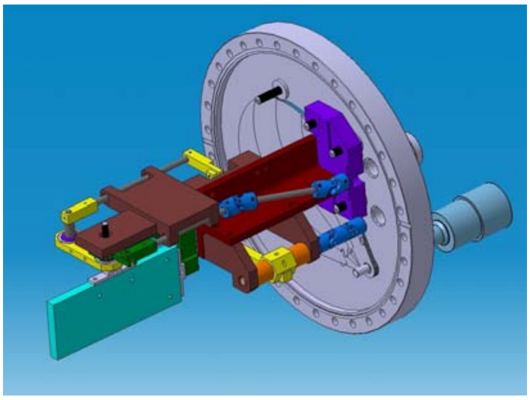

Fig. 3. 3D proposal of steerable microwave mirror.

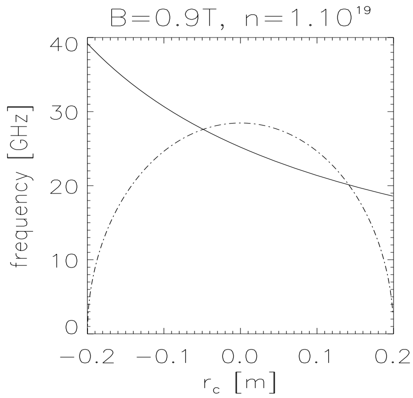

Fig. 4. Radial profiles of plasma (dotted line) and cyclotron (full line) frequencies for shot 852.

The underdense, highly thermal non-equilibrium plasma of testing shots do not allowed the detection of EBW. From Fig. 4 it follows that the first harmonic oh high field side is open (where $f_{ce} > f_p$) for emission of O-mode in the 26.5-40GHz band. Time development of measured radiative temperature of plasma from three selected chanels is given in Fig 5. The detected signal are highly fluctuating so we added the running average (red line). It is seen that the radiative temperature decreases from the plasma interior to the plasma boundary. Non-equlibrium state of plasma do not allowed to convert the radiative temperature to the electron plasma temperature. The last signal shows that both the plasma density and the plasma current are unstable during the test discharge

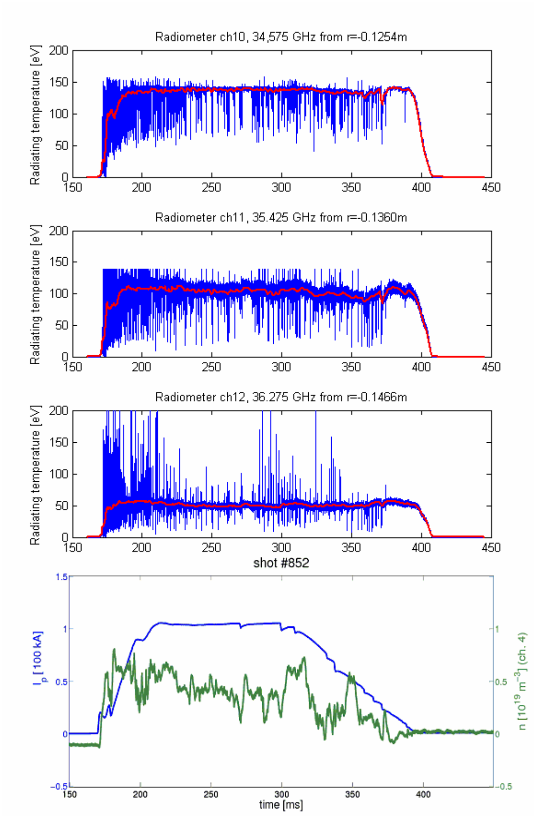

Fig 5. Time development of radiative temperature in COMPASS, #852

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4. Emerging Technologies

Investigation of Impact of Neutron Irradiation on Properties of InSb-based Hall Plates

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Hall sensors based on InSb thin film layers are presently being evaluated as one of the options for ITER ex-vessel steady state magnetic sensors. The compatibility with vacuum vessel baking temperature of 220℃ and with the maximum life time neutron fluence of 10^{18} cm^{-2} has to be demonstrated. Recently, the InSb Hall sensors with operational temperature up to 350℃ were developed. We investigated stability of these sensors type when exposed to neutron irradiation on experimental fission reactor LVR-15, and during short term post-irradiation temperature cycling. Parameters of the samples were measured before and after irradiation up to the total neutron fluence of 10^{17} cm^{-2}. Stability of parameters, within a few percents, of the InSb sensors highly doped by Sn was observed. Novel approach to further stabilization of sensors properties based on shielding thermal neutrons and curing the damage caused by fast neutrons by proper annealing was proposed and tested.

Six samples of Hall sensors, compatible with elevated temperature up to 350 °C, based on 0.9 µm thick InSb layer doped by Sn, deposited on crystal of Al_2O_3 (corundum) and AlN were prepared in Poznan University of Technology. Three of the samples were shielded by 1 mm thick CdTe/InSb plates (sintered mixture of fine powders of InSb and CdTe) to assess effect of reduced transmutation (see Fig. 1 - middle panel). All the Hall sensors together with samples of the InSb layers, array of activation detectors, and aluminum cylindrical filling were inserted in aluminum container, and irradiated in the reactor LVR-15. Inner atmosphere of the irradiation container was air with atmospheric pressure. The outer walls of the container with samples were cooled by water with temperature of 45 °C. Samples were irradiated for 30 minutes at average neutron fluence rate of $\varphi=62.5\times10^{12}$ $cm^{-2}s^{-1}$, reaching the total neutron fluence of 1.12×10^{17} cm^{-2}. The ratio of number of neutrons with energy higher than 1 MeV and lower than 0.1 MeV was about 0.048 during this experiment. This value is comparable to that for ITER steady state magnetic sensors ex-vessel locations where the ratio of neutron fluence rate with energy higher than 12 MeV and lower than 0.1

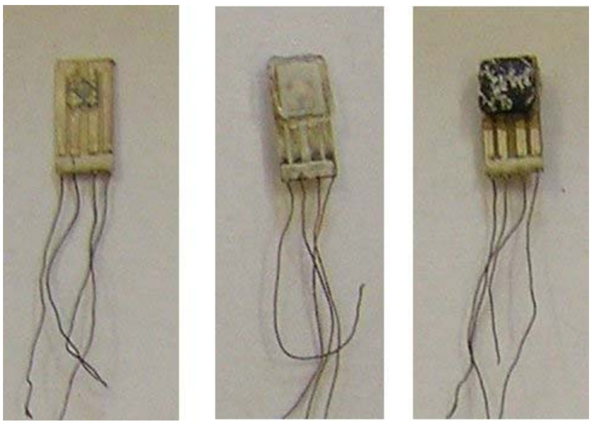


Fig.1. Left panel – bare Hall sensor before irradiation; middle panel – Hall sensor with sensing layer protected by InSb/CdTe glass shield before irradiation; right panel – shielded Hall sensor after irradiation.

MeV is expected to be 0.03 – 0.1 depending on exact location. Parameters of the Hall sensors (input/output resistance and sensitivity) were measured before and after irradiation.

Visual inspection of sensors after irradiation revealed significant radiation induced changes on InSb/CdTe shields, see Fig.1. The shields completely darkened showing signs of local melting of the surface layer. On average, we observe more significant changes of input and output resistances of the sensors which rise by 4% – 10% compared to the sensitivities which drop by less than 3% only. The changes of sensor's input resistances are screened by comparable drop of their free charge carrier mobility. Similarly, small drops of sensor's sensitivities (Hall voltages) are translated into small increase of their free charge carrier densities. The observed changes of parameters of the sensors are comparable for shielded and unshielded sensors, so no apparent effect of the CdTe/InSb shielding was found. Further, effect of irradiation is possibly overridden by thermal effects. As a result, our main conclusion is that we did not observe any significant radiation induced effects on InSb sensing layer properties exposing this material to the total neutron fluence of 1.12×10^{17} cm^{-2} with fission like neutron spectrum.

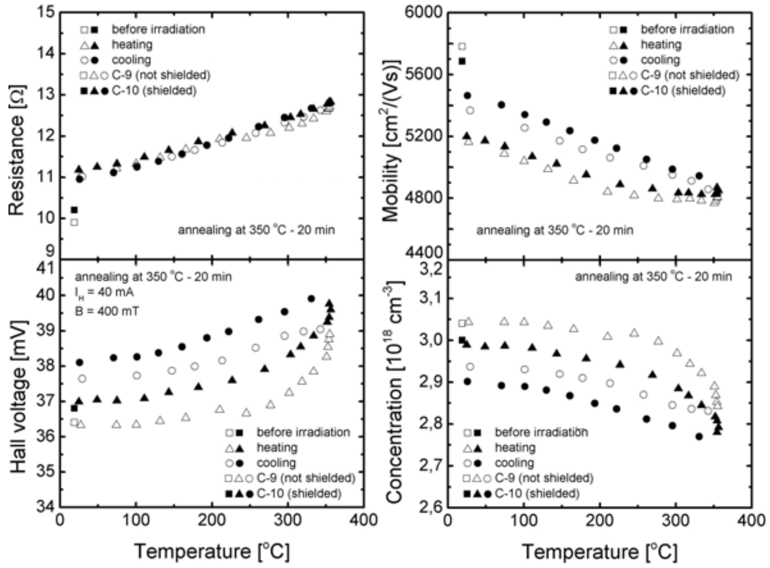


Fig.2. Impact of post irradiation annealing on sensor #9 (unprotected during irradiation – open symbols) and sensor #10 (shielded during irradiation by InSb/CdTe – full symbols) properties. Heating phase of the annealing is always denoted by triangles while cooling down phase is denoted by circles. Original pre-irradiation values are shown by squares. Left top panel – Input resistance; left bottom panel – Hall voltage measured for I_H=40 mA and B=400 mT; right top panel – free charge carrier mobility; right bottom panel – free charge carrier concentration.

Post-irradiation annealing of the sensors at temperature of 350 °C with duration of about 20 minutes was tested as a possibility to reduce neutron radiation induced damage of inner structure of the sensing layer. Figure 2 shows evolution of the basic parameters of the two Hall sensors, #9 (open symbols) which was irradiated without InSb/CdTe shields and #10 (full symbols) which was shielded, during one heating/cooling cycle from room temperature to 350 °C and back. We see that annealing process leads to permanent increase of mobility and decrease of free charge carrier density as expected similarly for sensor #10 and for unprotected sensor #9. This experiment confirms the potential of annealing to permanently 'heal' in certain extent the structural defects within the InSb sensing material. However, low total neutron fluence accumulated during these experiments, and consequently, not well pronounced radiation induced changes of InSb semiconductor material properties, does not allow quantitative evaluation. Additional irradiation experiments with higher target neutron fluence are recently under preparation to complement these qualitative findings by more quantitative analysis.

Influence of neutron irradiation on the properties of candidate fusion materials

J. Matějíček

In collaboration with:
L. Viererbl, Nuclear Research Institute, Rez, Czech Republic

IPP participates in a broader project "Materials and Components for Nuclear Reactors", led by the Nuclear Research Institute, Řež.
The goal is to investigate the changes in candidate fusion materials properties after neutron irradiation. Particular focus is placed on plasma sprayed coatings (tungsten, copper, stainless steel, alumina) and other bulk materials with potential application in ITER, DEMO or other fusion devices. The material features studied include structural changes, thermal and electrical properties and behavior under heat flux.

Irradiation campaign

The irradiation campaign, started in May 2008, was concluded in July 2009. The targeted fluences ranged from 0.05 dpa to 1 dpa. Majority of the samples were extracted from the irradiation capsules. Some of them still remain enclosed due to complications with the extraction; alternative approaches are considered. Activity of the extracted samples was measured. Transport of samples for thermal conductivity and heat flux characterization at Forschungszentrum Juelich was organized and is planned for February 2010. As for the remaining samples, transport to Ciemat and Politecnico Torino, as well as characterization of some of them at NRI are under negotiation.

Development of tungsten-based functional gradient materials prepared using powder laser deposition.

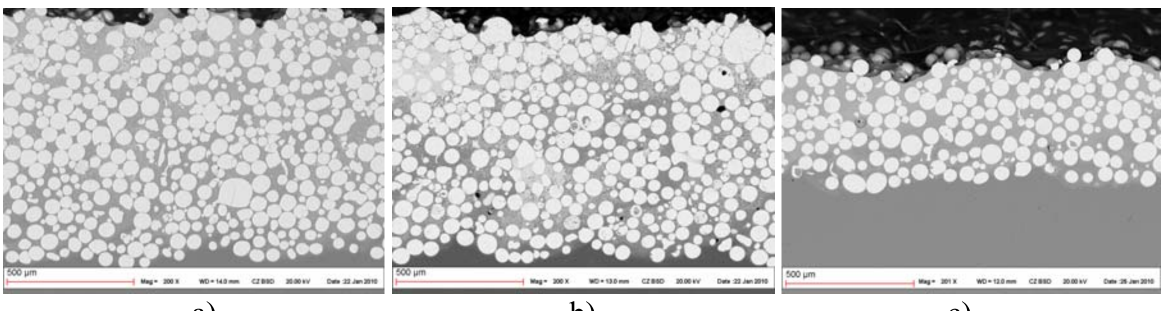
H. Boldyryeva, J. Matějíček

In collaboration with:
P. Ambrož, Czech Technical University in Prague (ČVUT), Prague, Czech Republic

Tungsten-based functional gradient materials have potential application as a heat-protection armor, e.g. in fusion reactor components. This study is focused on processing of tungsten-steel functionally graded materials (FGMs) by laser deposition and their characterization. Various processing conditions are also employed.

Laser deposition experiments, started in the previous year, continued in collaboration with Czech Technical University in Prague. Scanning speed (200 mm/min), feed rate of tungsten powder and supplying Ar gas pressure (1 Bar) were kept stable. Two different regimes of scanning were employed: a) double-scanning of one laser spraying line in an *x*-coordinate direction and then 0.5 mm shift in an *y*-coordinate direction to the next scan line; and b) single scanning of one line with a following shift of 0.5 mm to the next scanline. Experiments with a different scanning speed were done previously. With applying lower scanning speed, increasing thickness of single sprayed layer was observed.

Cross-sectional SEM image of samples prepared with a different regimes of scanning are in Figure 2. Fig. 2(a) shows laser sprayed layer prepared using double-scanning regime; it consists of slightly melted tungsten microgranules immersed and uniformly distributed in a melted steel substrate to the depth of over 1 mm. Fig. 2(b) represents the sample prepared by the same conditions but with applying laser after-treatment, which means treatment by the laser beam solely, without powder feeding. It increases tungsten concentration toward the surface through additional partial melting of tungsten and possible evaporation of steel matrix simultaneously. Figure 2(c) shows cross-section of a sample prepared with applying single line scanning regime. One of the issues of laser spraying technique employed for preparation of tungsten-based FGMs is the control of sample thickness. By applying different scanning regimes as well as scanning speed and powder feedrate, the thickness of a single layer could be varied. In our experiments the thickness of homogeneous continuous non-porous single layer reached up to over 1 mm.



a) b) c)

Fig. 2. Cross-sectional SEM image of FGM layer prepared by powder laser spraying. White indicates tungsten, gray – steel. a) double-scanning regime; b) double-scanning regime with laser after-treatment; c) single-scanning regime.

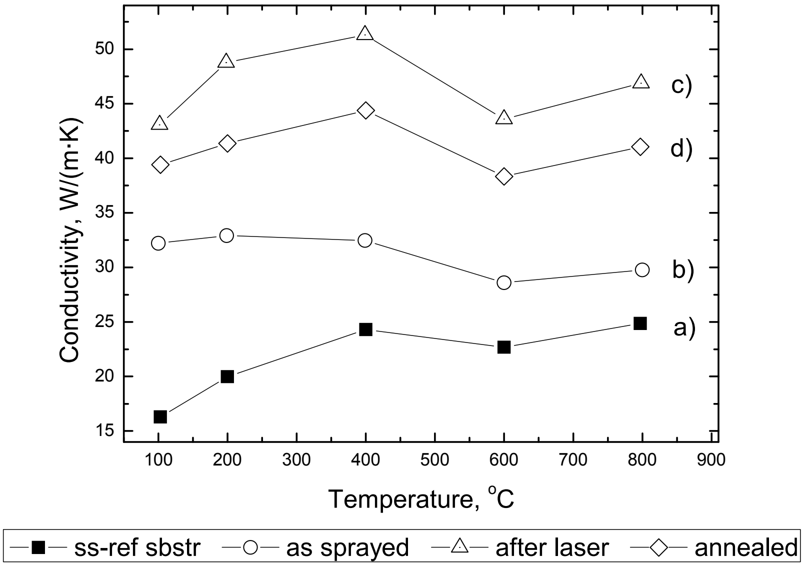


Fig. 3. Temperature dependence of thermal conductivity for the samples prepared with (c) and without (b) applying laser beam treatment after the deposition; (d) – sample annealed at 1000°C for 5 h.; (a) – stainless steel substrate.

With the aim to improve thermal properties, two methods were chosen for after-treatment: laser scanning with no powder feeding and annealing at 1000ºC for 5 hours. Fig 3 shows thermal conductivity measured on a double-scan regime sample. For comparison, data of thermal conductivity taken from literature for a several materials are listed below: stainless steel SS316 - 16 $W \cdot m^{-1} \cdot K^{-1}$, Eurofer97 - 28 $W \cdot m^{-1} \cdot K^{-1}$, tungsten - 170 $W \cdot m^{-1} \cdot K^{-1}$.

Thermal properties improve after applying different after-treatment methods. Further processing options/modifications are planned to be investigated in future research. These include hot isostatic pressing (HIP); solely laser beam treatment; use of different tungsten powder with various grain diameter and combinations of tungsten and steel powder. Comparison of properties with plasma sprayed FGMs [1] will also be made.

References

[1] Jiří Matějíček, Hanna Boldyryeva: Processing and temperature-dependent properties of plasma-sprayed tungsten–stainless steel composites; Physica Scripta, T138 (2009) 014041

Study of the micro-mechanisms of cleavage fracture of 14% Cr and 18% Cr ODS ferritic steels

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In collaboration with:
B. Fournier, CEA Saclay, France

The distinctive degradation of fracture properties of ODS variant of the Cr-W steels had been observed. In these materials reinforced with phases of a few nanometers, larger Y_2O_3 oxides are also present. They might act as carbides in 9%Cr ODS steels, and lead to a degradation of impact properties. The influence of the production way (powder metallurgy and hot extrusion) is also of major interest regarding impact properties. In contrast to the carbide containing steels, there is no comprehensive idea of the role of nanometric oxide particles in cleavage fracture micromechanism. Possible microstructural changes connected with operation temperatures (considered in range of about 550 - 650°C) such as precipitation, grain coarsening and grain boundary embrittlement could also occur. Synergy of the effects of the oxide particles with the influence of long term thermal ageing on cleavage fracture remains unexplained as well. Detailed understanding of failure mechanism of these steels in thermally unaffected and affected state is critical for their proposed future applications.

A 14wt.%Cr and 18wt.%Cr ferritic alloy containing 1wt.%W and 0.3wt.% or 0.56wt.% Y_20_3 was produced by mechanical alloying of the atomised alloy by Y_20_3 powder. An one bar and one plate of 14wt.%Cr (circular section with a diameter of 12mm and rectangular section with thickness 3mm and width 32mm) and two plates of 18wt.%Cr (containing 0.2wt.% and 0.56wt.% of Y203).
The powders were produced by atomisation of the prealloyed powder (Aubert & Duval) and subsequent mechanical alloying of the powder by Y_20_3 (Plansee). Mini-Charpy (KLST) specimens of 3 × 4 mm cross section and length of 27 mm were then machined from the semifinished bars. The “V” notch of 1 mm depth was machined in tensile side of the specimens. The KLST specimens prepared were oriented along the length of the bar or plate, which means that the crack propagated perpendicularly to the extrusion direction. For the 18%Cr steel three types of mini-Charpy specimens orientation were tested: longitudinal, transversal and askew directions. An impact testing of specimen prepared was conducted by means of instrumented pendulum impact tester.

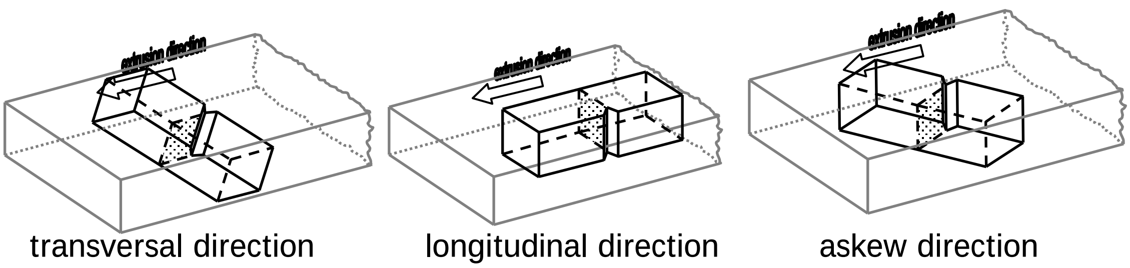

Fig. 1. Orientation of specimens inside the 18%Cr steel steel bar.
The arrows indicate the direction of material flow during extrusion.

The macrostructure of both steels presented grains elongated parallel to the extrusion direction of the bars (14%Cr steel) and also perpendicularly along the width of the plate

(18%Cr steel). The EBSD examination revealed grains (or agglomerates of grains) elongated in the extrusion direction with aspect ratio about 10:1.
The observation of fracture surfaces for both 14%Cr and 18%Cr ODS steel highlighted the strong influence of morphological texture (elongated grains) on the brittle fracture process. Numerous secondary cracks were observed. Elongated grains along the extrusion direction (with an aspect ratio around 10) were observed by optical microscopy. This suggests that the secondary cracks observed on fracture surfaces might correspond to intergranular cracking along this elongated direction.
The two processes contributed to the energy consumption during fracture process were described: the physical mechanism of the fracture process and the delamination according the grain boundaries. The impact energy of the steel depends on the orientation of the crack plane with regard to the extrusion direction (see Fig. 2).

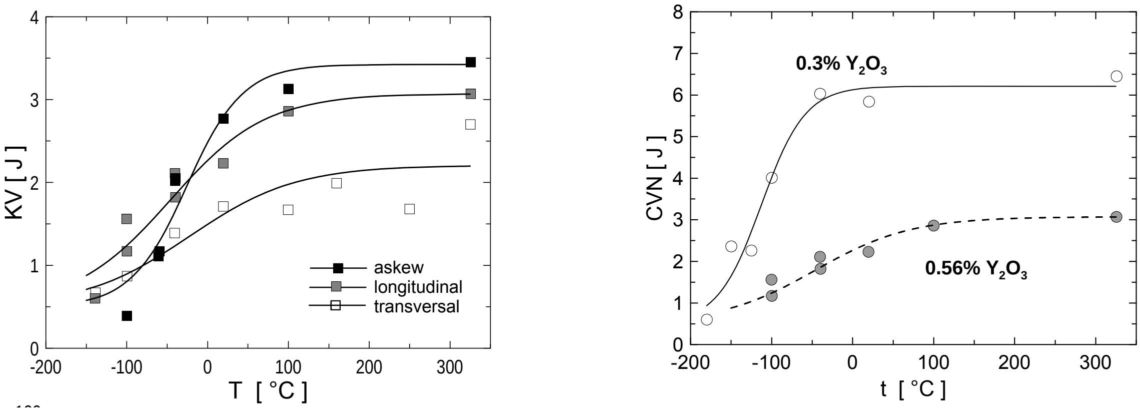

Fig. 2. Temperature dependence of the impact energy of the steel 18Cr-1W-Y_2O_3 for three orientation of the sample tested (left) and for the same steel containing 0.3wt% (F70) and 0.56wt% (F20) of Y_2O_3.

The content of yttria particles is necessary to achieve the high temperature properties of the ODS steels. It was found that the high amount of yttria particles led to the downgrade of the impact fracture behaviour of the steel (see Fig. 3).

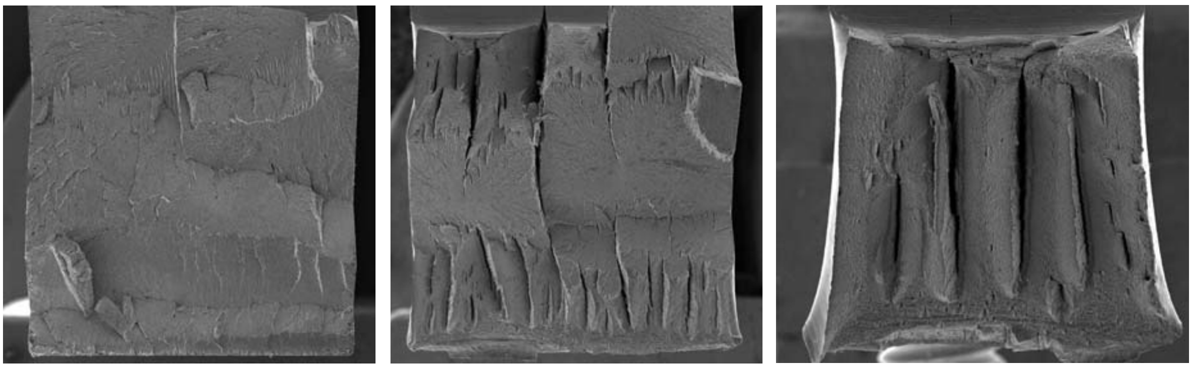

Fig. 3. Fracture surfaces of 18Cr-1W-0.19Ti-0.3Y_2O_3 steel fractured near LSE, T_{DBTT} and USE, overviews.

Erosion, Transport and Deposition of Wall Materials SEWG Chemical Erosion and Material Transport (WP09-PWI-04) Ion-Surface Scattering Experiments: Derivation of general rules determining ion survival factors. Low energy beams on Be, W or C. PWI-04-04

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In collaboration with:
T. D. Märk and his research group (Institute for Ion and Applied Physics, University of Innsbruck, Innsbruck), Association EURATOM-ÖAW, Austria

The research aims on studies of ion-surface scattering using low-energy beams of hydrocarbon and other ions colliding with fusion-relevant surfaces of carbon, tungsten, and beryllium at room or elevated (600^0 C) temperature to determine energy transfer, surface processes and ion survival probability as a function of impact energy using special ion-surface beam machines.

1. General correlations between survival probabilities of slow ions colliding with room-temperature and heated surfaces of C, W, and Be and their ionization energies.

Absolute survival probability, S_a(%), the ratio of the sum of intensities of all product ions scattered from the surface to the intensity of the projectile ions incident on the surface, was determined for hydrocarbon ions C1, C2, and C3 and several non-hydrocarbon ions (Ar^+, N_2^+, CO_2^+) on room-temperature (hydrocarbon-covered) and heated (600^0C) surfaces of carbon (HOPG), tungsten, and preliminary data were obtained for room-temperature beryllium. The S_a values were determined using the ion-surface scattering method for several incident energies from a few eV up to about 50 eV and for the incident angle of 30^0 (with respect to the surface). Earlier published data were complemented by new measurements of the survival probabilities.

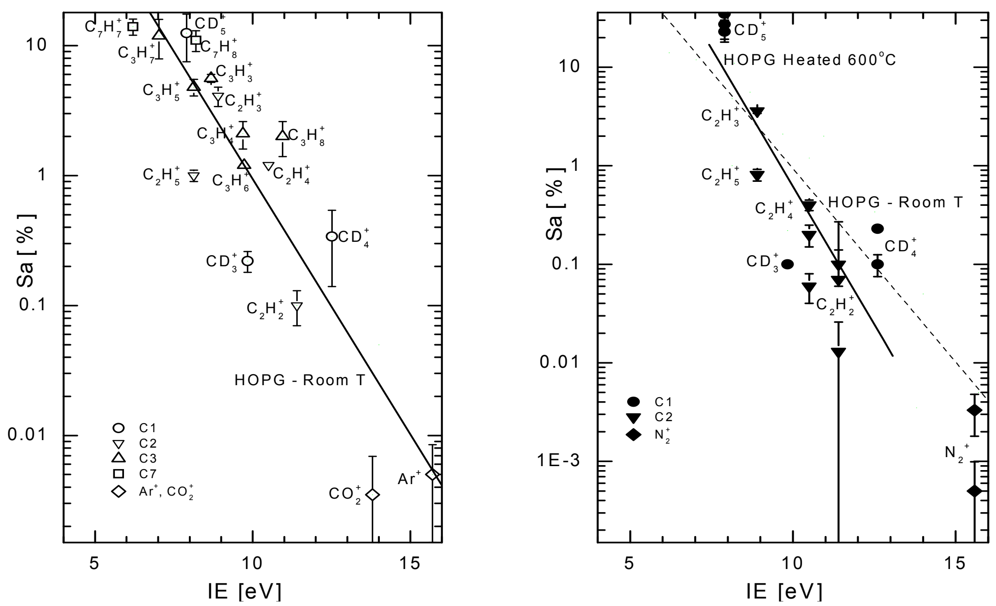

Fig. 1: Dependence of survival probabilities of ions (S_a) on their ionization energies (IE) for collisions with room-temperature (left) and heated to 600^0C (right) carbon (HOPG) surfaces

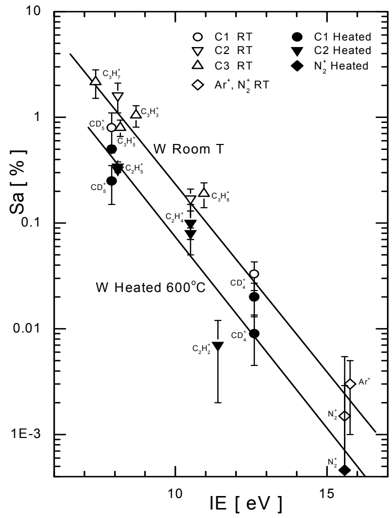

Fig. 2: Dependence of survival probabilities of ions (S_a) on their ionization energies (IE) for collisions with room-temperature and heated to 600^0C surfaces of tungsten.

A simple correlation between S_a and the ionization energy (IE) of the incident ions was found in the semi-logarithmic plot of S_a vs. IE. The plots of the data at 31 eV (Fig. 1 and Fig. 2) were linear for all studied surfaces and could be fitted by an empirical equation

$$\log S_a = a - b(\text{IE}).$$

The values of the parameters a and b were determined for all investigated room-temperature surfaces (carbon, tungsten, beryllium) and for heated surfaces of carbon and tungsten Table 1).

Table 1. Values of parameters *a* and *b* in the plots $\log S_a = a - b$(IE) for different surfaces

surface	*a*	*b*
carbon(HOPG),RT	3.9 ± 0.5	0.39 ± 0.04
carbon (HOPG), H	5.4 ±1.1	0.5 ± 0.1
tungsten, RT	2.9 ± 0.2	0.35 ± 0.02
tungsten, H	2.5 ± 0.4	0.35 ± 0.04

Note: RT – room-temperature, H- heated to 600^0 C

The data for room-temperature surfaces showed very similar slopes both for carbon, tungsten, and beryllium. This was presumably due to a hydrocarbon layer covering all these surfaces at room temperature. The correlation $S_a = a - b$(IE). can be used to estimate unknown survival probabilities of ions on these surfaces from their ionization energies.

2. Survival probabilities of ions on room-temperature and heated surfaces of beryllium

The measurements sub (1) were complemented by new measurements and extended to heated (600^0C) surfaces of beryllium. The data on both surfaces (room temperature and heated) fit the general equation (see above) S_a = (0.29±0.6) – (0.31 ±0.06)IE. Preparation of a publication is under way.

Reference:

1. Z. Herman, J. Žabka, A. Pysanenko, *J. Phys. Chem. A* 113 (2009) 14838-44
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3. L. Feketeová, J. Žabka, F. Zappa, V. Grill, P. Scheier, T.D. Mark, Z. Herman, *J. Am. Soc. Mass Spectrom.* 20 (2009) 927-938.

5. Training and career development

Collaboration of IPP Prague with Universities in fusion training

J. Mlynář, I. Ďuran, J. Stöckel

The start of operation of COMPASS proved to set a major incentive for students in 2009. We have witnessed both good activity and iniciative of current students and an increased number of new students interested in COMPASS research. For example, 6 new students decided to do their bachelor thesis in our tokamak department in autumn 2009. In total, 19 undergraduate and 15 doctoral students participated in fusion research at COMPASS. Besides, our experts organised 8 regular courses at Czech Technical University in Prague and in Charles University, including practica and a seminar.

Doctoral students played a key role in COMPASS commissioning and several foreign students visited COMPASS, in particular from Belgium and France. Dr. Jana Brotánková successfully finished her Ph.D. at Faculty of Mathematics and Physics, Charles University with thesis “Study of high temperature plasma in tokamak-like experimental devices” and Dr Eva Havlíčková at the same faculty with doctoral thesis “Computer modelling of plasma processes and transport for selected applications”. Two students of the FNSPE (Martin Imríšek and Ondřej Kudláček) obtained their BSc diploma with the research work based at IPP. Another student from the same faculty (Pavel Háček) obtained the MSc degree based on his diploma thesis on COMPASS.

Research scientists from the institute also participated in teaching at several universities in the framework of both regular and irregular courses. The major teaching load was linked to the collaboration with the Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague (FNSPE) which runs from 2006 a masters curricullum “Physics and Technology of Thermonuclear Fusion”. In the summer term, our staff was responsible for 2 courses: Introduction to thermonuclear fusion and Technology of thermonuclear facilities. One course of plasma physics was also taught at the Faculty of Mathematics and Physics. We also participated with several lectures in the course Plasma diagnostics and organised practica in which several labs from Prague participate. In the winter term, our staff was responsible for the course Tokamak physics and for organising joint FNSPE – IPP seminars. In total, fusion researchers from IPP Prague taught more than 200 hours at universities in 2009.

For the first time, a joint IPP-FNSPE winter school for students was run in January 2008 in IPP premises in Marianska (west Bohemia). Besides we participate in the EURATOM CSA in education (FUSENET) and although this is a marginal activity, the regular SUMTRAIC course (see separate report) clearly benefited from this coordinated action. Last, but not least our staff read nine lectures at the summer school “Plasma Physics in Science and Technology”, organised by University Greifswald in Prague.

Situation in the University education in fusion related fields with respect to the role of IPP Prague was detailed in the special issue of the Czechoslovak Journal of Physics to commemorate 50th Anniversary of IPP Prague [1].

Reference:

[1] Svoboda V., Mlynář J., Stöckel J., Jex I.: Vzdělávání v oblasti termojaderné fúze v ČR. Čs.čas.fyz. 59 (2009) 233

Undergraduate training in Fusion at Faculty of Mathematics and Physics (FMP), Charles University and at Faculty of Nuclear Sciences and Physical Engineering (FNSPE), Czech Technical University in Prague

V. Svoboda, D. Břeň, M. Tichý , R. Hrach

In 2009, the Faculty of Nuclear Sciences and Physical Engineering, Technical University in Prague (FNSPE) successfully continued the MSc curricullum "Physics and Technology of Thermonuclear Fusion". In February, in collaboration with IPP, FNSPE organised the joint workshop (one week winter school) for all students of the curricullum. In the summer term, all courses were run and many seminars took place. In June, two students (Pavel Háček and Martin Kubič) passed final exams and have received their MSc degree - for the first time in this field. In September, four students received their BSc degree. FNSPE also takes part in the FUSENET consortium - it works in several Work Packages and leads WP9 (multimedia).

However, the main achievement of FNSPE since last Report was the successful reinstallation of the GOLEM tokamak at the faculty (former CASTOR) which is foreseen as the main practica tool for the MSc students. The GOLEM facility operates currently at modest range of parameters, $B_t < 0.5$ T, $I_p < 8$ kA, pulse length < 10 ms, and with a limited set of diagnostics . First plasma was achieved on 8th July 2009 and tokamak immediately took part in the SUMTRAIC summer school. Consequently advanced control operation technology was implemented making possible remote handling operation through the internet access. The setup of the experiment, outlined in Figure 1, describes the remote control of the toroidal magnetic field and plasma current generation, vacuum system and gas handling operation and the DAS system via TCP/IP and USB controlled A/D, D/A converters and bank of relays, which is PC controlled and connected via web server to the internet. Remote control is possible either in the online mode via WWW or SSH interface or in the offline mode with the batch proccesing code.

The remote control from several foreign universities in Hungary, Belgium and Costa Rica and a summer school in Poland has been successfully performed.

At present, two students of the fusion curriculum makes their BSc thesis at the tokamak GOLEM, in particular on dynamic plasma position stabilization and on magnetic field measurements. In parallel, a 3D (vrml) virtual model of the tokamak is generated with the 3D modelling group of the Faculty of Electrical Engineering.

The Faculty of Mathematics and Physics, Charles University (FMP) is, in mutual agreement with FNSPE, focused on post-graduate (doctoral) level in the fusion education. In this respect, FMP participates in FUSENET and also took part in the consortium (lead by University of Ghent) that applied for the Erasmus Mundus support for European Doctoral course in fusion. In collaboration with the IPP Prague, FMP prepares extension of the doctoral curriculum in plasma physics by one week of lectures focussed on fusion. The FMP also hosted and took part in the 2009 summer school “Plasma Physics in Science and Technology”, organised by the University Greifswald in Prague.

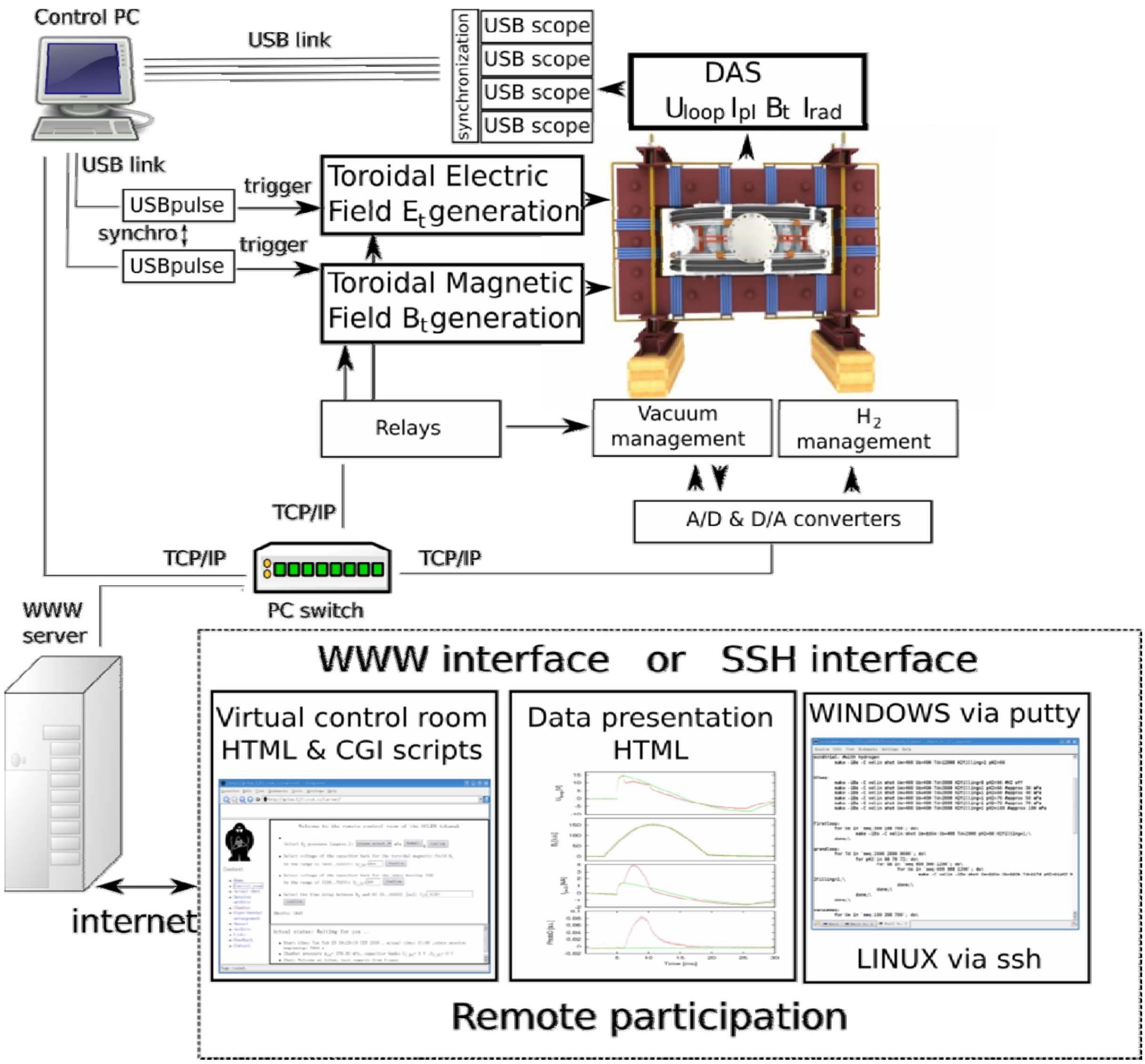

Fig. 1 Tokamak GOLEM experimental setup with the remote access

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Pratical Training on tokamak operation

J Stockel, J Brotánková, R Dejarnac, J Havlíček, J Horáček, M Hron, J Mlynář. D Naydenková, R Pánek, V Weinzettl, J Zajac

In collaboration with:
G. Veres, M. Berta, Association EURATOM-HAS, Hungary

The 7th Summer Training Course (SUMTRAIC 2009) was organized for the first time on the COMPASS tokamak in collaboration with the Association EURATOM/HAS in the period 26.8.08 - 4.9.2009. Before practical training, several introductory lectures have been presented. The Course was attended by 13 students from five countries. Students were divided to five experimental groups supervised by local and Hungarian supervisors. Four days were devoted to experiments on the COMPASS tokamak, the remaining time was spent by data processing and preparation of presentation at the closing workshop.

The 7th Summer Training Course (SUMTRAIC 2009) was organized on the COMPASS tokamak in the period 26.8.08 - 4.9.2009 in a close collaboration with the Association EURATOM/HAS. Before practical training, several lectures have been presented to participants:

- Principle of tokamak operation (J Mlynar)
- Introduction of COMPASS (R Panek)
- Status of COMPASS diagnostics (V Weinzettl)
- Data acquisition system of COMPASS (M Hron)
- IDL for COMPASS data processing (J Brotankova)
- Matlab/Octave for COMPASS data processing (J Horacek)

The Course was attended by 13 students from 5 countries: Hungary (4 participants), Bulgaria (2), Belgium (1), France (1), Czech republic (5). Students were divided to five groups – measurements with diveror probes, the optical diagnostics, the microwave diagnostics, fast visible camera and the magnetic diagnostics. Each group was supervised by at least one supervisor (J Horacek, J Havlicek, J Brotankova, R. Dejarnac, J Zajac, V Weinzettl, D Naydenkova, M Berta, G Veres). Four days was devoted to experiments on COMPASS, the remaining time was spent by data processing and preparation of presentation at the closing workshop. Students have also spent half a day by performing experiments on the GOLEM tokamak at the Czech Technical University supervised by V Svoboda. The SUMTRAIC was closed by the workshop, where majority of participants presented achieved results.

The next SUMTRAIC 10 will be organized at IPP Prague on the COMPASS tokamak in the period 26 August – 4 September 2010 again in a close collaboration with Association EURATOM/HAS. Provisionally, 16 participants will be trained.

6. Other activities contributing to the EURATOM fusion programme

Outreach And Public Information Activities

Milan Řípa, Jan Mlynář

Official start of tokamak COMPASS operation in Prague on 19th February 2009

The 2009 year was extremely motivating and busy for the Public Information collaborators in our Association IPP.CR. The official start of COMPASS operation on February 19th was the major public information event. Tokamak operation was demonstrated "live" to media including the Czech state TV. The event was witnessed by the president of Czech Academy of Sciences, Euratom delegates and, in a videoconference also by former COMPASS-D staff in Culham Science Centre. On this occassion, Mr Hugues Desmedt from EC took video footage at COMPASS. However, the official start of the COMPASS operation was by far not an isolated Public Information event in the year. The facility was in focus of many VIP and media visitors in early 2009 as a showcase of science development in the Czech Republic who held EU presidency. For example, a group of Members of European Parliament (ITRE committee) led by Mr. V. Remek (Czech MEP and the first European astronaut) visited COMPASS and other IPP laboratories on February 26. Association EURATOM/IPP.CR was also deeply involved with the Research Connection Conference in Prague, May 7-8. In this conference our Association took responsibility for Fusion Expo stall and a panel discussion on Fusion and Industry, besides we also organised a press conference on the COMPASS tokamak and a media visit to COMPASS. This resulted in very important articles, e.g. in a feature article in the Belgian newspaper "Le Soir" on June 5. Thanks to this event, new brochures were printed in English and in Czech, e.g. "Fusion and Industry together for the future", with two success stories from our Association – on COMPASS re-installation and on the support blanket tests organised by the Czech Technical University.

Mr V Remek MEP visits tokamak COMPASS on 26th February 2009

Another important incentive for broad public information has been the 50th anniversary of IPP Prague. A dedicated press conference was organised and a special issue of the Czechoslovak Journal of Physics (in Czech) allowed us to target audience educated in physics (including physics teachers) with detailed information on our research [18,20,81,82].

In this busy period we also continued the regular PI work. Besides the events mentioned, there was one TV broadcast, two radio broadcasts, 22 public talks and about 40 articles in different Czech journals. From 2009 we also started to accompany some of the lectures by interactive demonstration of simple fusion-relevant experiments. We have also welcomed more than 40 groups visiting

COMPASS, in particular high schools, Universities and foreign visitors. In the frame of the Open Day in the Institute of Plasma Physics, 320 students from 11 high schools and several tens of individuals visited tokamak COMPASS.

IPP Prague also continues to coordinate its PI within the EFDA PIG and participated in the meeting in Slovenia. Thanks to the PIG netowork we could have quick and reliable feedback on different questions from public concerning fusion research abroad, and of course we informed our collaborators on the progress of COMPASS re-installation. In particular we were in touch with Örs Benedekfi (EFDA Garching, PIG chairman), Aline Dürmaier (EFDA Garching), and Sabina Griffith (ITER).

Next, we took part in the national conference "Methods of Science popularisation" with talk "Methods and Experiences from Fusion Popularisation". Our lecture had positive feedback from participants from different scientific and educational fields. New contacts with fission community were established. We also seized another important opportunity for a PI lecture at a fission conference "The nuclei against crisis" and as a result an important fusion paper appeared in the magazine "All for Power".

Our Association collaborates with the large public Science Park in Czech Republic, the iQPARK located in Liberec town is 100 km from Prague.

A semestral course "The Socio-economical Aspects of Fusion" was hold for students of the Faculty of Nuclear Sciences and Physical Engineering.

On its meeting on popularisation, the Czech Physical Society explicitly appreciated our contribution to public information activities.

Due to considerable load on PI and also important modification in the task agreement, IPP Prague with regrets withdrew from the SERF studies.

List of published PI articles:

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Milan Řípa: But yet it is rotating or it is concerned science curiosity and big money, Technický týdeník, 57 (2009), No 2, p. 23

Milan Řípa: The diamond windows for ITER tokamak, Technický týdeník, 57 (2009), 4, p. 4

Milan Řípa: Does nuclear sludge find a disposal site?, Lidové noviny, March 20, 2009, 14,

Matouš Lázňovský, Milan Řípa: The star on the needle tip, Lidové noviny, Apríl 2, 2009, 14

Milan Řípa: Obama's atom men, Lidové noviny, Apríl 2, 2009

Milan Řípa: COMPASS in the Institute of Plasma Physics Academy of Science of the Czech Republic, Technický týdeník, 57 (2009), No 7, p. 6

Milan Řípa: Will be Obama's power-supply men energetic fairly?, Technický týdeník, 57 (2009), No 7, p. 28

Milan Řípa: 50 years of tokamak, 3pol, 2 (2009), March, p. 12

Milan Řípa: 50 successful years of Institute of Plasma Physics Academy of Science of the Czech Republic, v. v. i., Energetika, 59 (2009), No 4, pp. 146-151

Milan Řípa: Members of European Parlament before COMPASS tokamak, Technický týdeník, 57 (2009), No 8, p. 16

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Milan Řípa: What is common between the largest tokamak and Airbus?, Technický týdeník, 57(2009), No 26, p. 25
Milan Řípa: Coconuts on...tokamak, Technický týdeník, 57(2009), No 26, p. 25
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J. Mlynář, R. Pánek: Tokamak COMPASS back in operation, Le Scienze Web News, ISSN 1827-8922, http://www.lswn.it/en/energy/news/tokamak_compass_back_in_operation, 2009-09-15 (in English)
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V. Svoboda, J. Mlynář, J. Stöckel, I. Jex, Education in the field of thermonuclear fusion in the Czech republic, Čs.čas.fyz. 59 (2009) 233
I. Jex, V. Svoboda, J. Mlynář, Physics and technology of thermonuclear fusion – a loving touch from Sun Pražská technika 4 (2009) 16-17

List of PI Lectures:
Milan Řípa: Energetic Safety of the Czech Republic, Secondary School Čáslav, Čáslav, March 5, 2009,.
Milan Řípa: Energetic Safety of the Czech Republic, Secondary School Beroun, Beroun, March 12, 2009
Milan Řípa: ITER is a way, Secondary School Beroun, Beroun, March 12, 2009,
Milan Řípa: Plasma helps to people, J.Seifert Secondary School, Praha 9, Apríl 23, 2009,
Milan Řípa: Energetic Safety of the Czech Republic, Secondary Turnov and IPP AS CR, Turnov, May 6, 2009 (2x)
Milan Řípa: Plasma helps to people, Enviromental Secondary School Praha, May 26, 2009
Milan Řípa: ITER is a way, Enviromental Secondary School Praha, May 26, 2009,
Milan Řípa: Plasma helps to people, University for Seniors, Faculty of Nuclear Sciences and Physical Engineering, May 28, 2009,
Milan Řípa, Jan Mlynář: Public Information Activities in the Association EURATOM-IPP.CR, 9th Public Information Meeting, Ljublajana, May 14 –15, 2009 (in English)
Milan Řípa: Methods and Experiences of Controlled Fusion Popularization in Czech Republic, „Methods of science popularizaion“ national conference, Olomouc, September 10 – 11, 2009
Milan Řípa: „Way Fusion?“, semestral course: Physics and Technology of Nuclear Fusion, IPP ASCR, v.v.i., Praha, September 22, 2009
Milan Řípa: „The best of fusion or ITER is a way...“, training centre Škoda Auto, Mladá Boleslav, October 16, 2009
Milan Řípa: „The best of fusion or ITER is a way...“, Secondary School Lovosice, Lovosice, October 23, 2009
Milan Řípa: Plasma – From the energy of the stars to new materials, Secondary School Modřany, IPP ASCR, v.v.i., November 4, 2009

7. Coordination, in the context of a keep-in-touch activity, of the Member State's civil research activities on Inertial Fusion Energy

Laser radiation coupling to laser-accelerated foil targets.

Jiří Ullschmied, Eduard Krouský, Karel Mašek, Miroslav Pfeifer, Jiří Skála

In collaboration with:
A. Kasperczuk, T. Pisarczyk, S. Borodziuk, J. Badziak, T. Chodukowski, Association EURATOM-IPPLM, Warsaw, Poland
J. Limpouch – FNSPE CTU Prague, *K. Rohlena* – Institute of Physics, ASCR, v. v. i.

The experiments on laser interaction with double and flyer targets performed in Prague in collaboration with the PALS team by Polish physicists from IPPLM, Warsaw, resulted in proposing a novel method of acceleration of macroparticles to high velocities, based on exploiting the pressure and radiation of the hot plasma produced by laser on a massive auxiliary target. This reversed scheme acceleration (RAS), the advantages of which were demonstrated in [1-4], was further improved by providing the auxiliary target with a cavity. The new concept called the Cavity Pressure Acceleration (CPA) makes it possible to accelerate both light and heavy macroparticles in arbitrary direction, with the acceleration efficiency far exceeding that achieved up to now by using the classic ablative acceleration scheme. High velocities of the accelerated foil fragments and possibility of accelerating even rather heavy macroparticles are promising from the point of view of impact fusion studies, of the impact fast ignition in particular.

The CPA scheme was tested first during the Laserlab-Europe-supported cooperative experimental campaign at the PALS facility supported by in the period February-March 2009 and then during the EURATOM-supported mission in the period November–December 2009. The "cavity" type targets used consisted of a massive Al slab with a cylindrical hole of 600 μm in diameter and 100 μm in depth, covered by Al foil 10, 300 or 500 μm thick, which created a closed cavity configuration. To ensure a free laser beam pass, the laser radiation was let in the cavity through a pinhole drilled in the foil. The target was irradiated by the 1st harmonic PALS laser beam (λ=1.315 μm) of energy in the range of 120-500 J and pulse duration of 250 ps (FWHM). The focal spot diameter at the target surface was set to 100 – 200 μm. The schematic of the experimental arrangement is shown in Fig. 1.

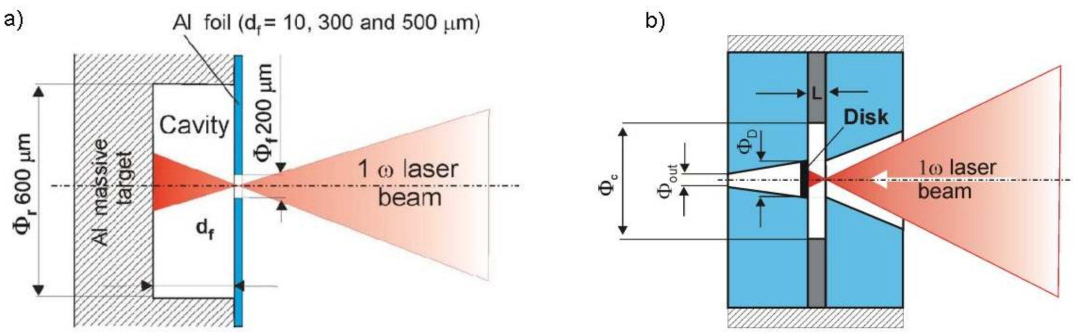

Fig. 1. a) Schematic of the "cavity" type targets used in the experiment. b) Modified cavity target for laser fusion experiments (by J. Badziak, IPPLM)

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The dynamics of the flying foil and its deformation by plasma action was visualized by a three-frame shadographic/interferometric system, which was designed and built for the joint experiments at PALS by T. Pisarczyk and his colleagues from IPPLM, Warsaw. A sequence of three shadowgrams showing movement of a 10-μm Al foil at three selected times (5, 8 and 11 ns after the laser pulse) is presented in Fig 2. The laser beam (E_l = 500 J) is incident from the right. The foil velocity averaged over the time range of 1-5 ns, evaluated from the interferometric measurements, amounts to ~ $3x10^7$ cm/s. By taking into account that in the beginning the foil was at rest and then it was accelerated to its maximum velocity v_{max}, we can estimate that v_{max} should reach a value of up to $(5±1)x10^7$ cm/s.

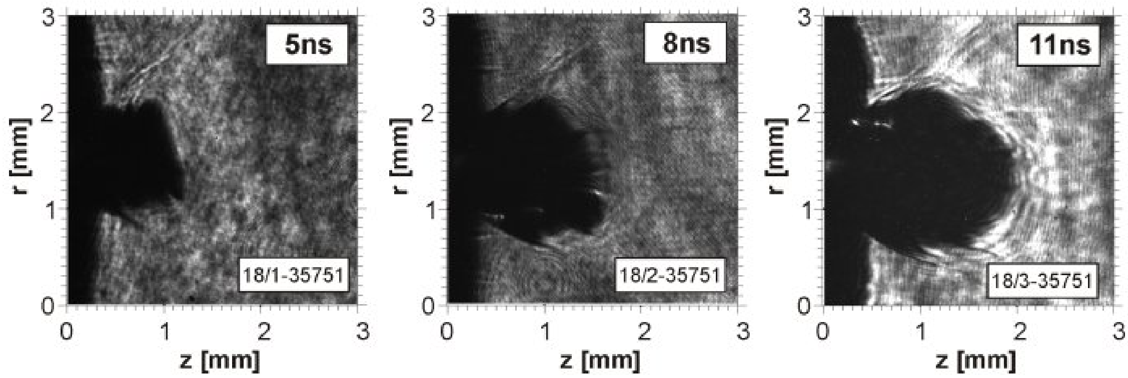

Fig. 2. Shadowgrams of a 10 μm thick Al foil accelerated by 1-ω iodine laser pulse of energy 500 J. (S. Borodziuk et al., Appl. Phys. Letters 95, 231501, 2009)

The reported experiments affirm that the CPA method leads to velocities of flyer foils significantly higher than those achieved in similar experimental conditions, but by using a traditional ablative acceleration scheme. CPA enables acceleration of very heavy macroparticles ($\rho d_f \sim 10^{-1}$ g/cm^2) to velocities as high as ~ $1x10^7$ cm/s, whereas the attempts aimed at conventional ablative acceleration of flyers of the same mass were completely unsuccessful

Very high hydrodynamic efficiency of the CPA scheme offers a chance to construct an impact ignitor for laser fusion experiments (cf. Fig 1b). Another advantage of the CPA method is that there is no need (contrary to the case of ablative acceleration) to apply short-wave lasers or to convert laser radiation to higher harmonics. Generally, for moderate laser light intensities ($I_l \sim 10^{15}$ W/cm^2) the resulting velocity and hydrodynamic efficiency obtained with the first harmonic frequency of iodine laser are at least as good as those with the third one used in our previous experiments.

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Formation of supersonic laser-driven plasma jets in a cylindrical channel

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In collaboration with:
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Supersonic laser-driven plasma jets are subject of growing interest due to their recently recognized importance in inertial confinement fusion research, as well as in laboratory astrophysics. The collaborative experiments performed at the PALS laboratory by Polish and Czech physicists since 2006 have provided numerous experimental data on the backward-propagating (i.e. against the laser beam direction) plasma jets launched on solid laser targets of different shapes (planes, cones, reversed cones), made of materials of different atomic numbers [1,2]. They gave base for numerical simulations of the jet formation carried out by the PALS EURATOM partners in France and Spain. In 2009 we proposed and tested a new method of generation of supersonic plasma jet, which exploits a cylindrical or conical channel for guiding and collimating the plasma created of a laser-irradiated thin foil [3-5]. It makes it possible to produce high-Mach-number forward-emitted CH plasma jets even at low laser energies of the order of ~1°J. Energetic efficiency of the jet formation in the channel is high, so that the collimated jets produced by high-energy lasers may find use in ICF research.

The arrangement of the reported PALS experiments is shown in Fig. 1a. The focused iodine laser beam generated plasma on PET foil 10 μm thick, which covered the entrance aperture of a cylindrical channel of diameter 0,3-0,5 mm, drilled in a target made of a massive solid material (Al or Au). The plasma was accelerated and transported through the channel up to a distance of several mm. The back part of the target (the stopper) was removable.

When removing the stopper, the plasma exits the channel in the form of a narrow supersonic jet, the density profile of which can be measured by a laser interferometer. Examples of the interferogram and of the corresponding reconstructed electron density longitudinal profile of the plasma jet at the output of the cylindrical channel of diameter 0.3 mm are presented in Fig. 1b. The maximum electron density on the jet axis amounts to 2×10^{20} cm^{-3}.

The volume of the crater produced in the stopper can be used as a measure of the energy transmitted through the channel. In Fig. 1c) a microphotograph of the crater in Al stopper is shown together with transverse cross-sections of the crater wax replicas (right).

For irradiating the target foil the first

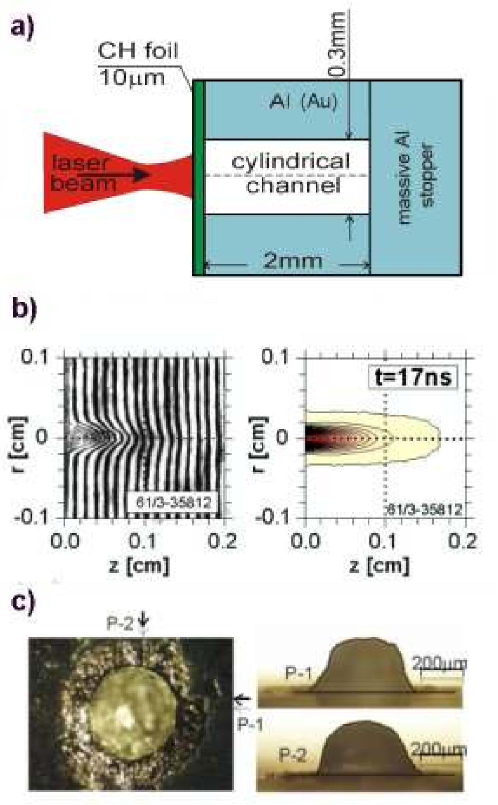

Fig. 1. a) Schematic of the experiment with a cylindrical transport channel.
b) Interferogram and density profile of the plasma jet at the channel output.
c) The crater produced in the Al stopper and transverse cross-sections of its wax replicas.

harmonic of the iodine laser (wavelength 1 315 nm) of energy 120 J and pulse duration ~0.3 ns was used. The maximum focused laser beam intensity at the target amounted to $4x10^{15}$ W/cm^2. The ion flux at the channel output was analyzed by ion charge collectors and a Thomson-parabola spectrometer. The influence of the laser focal spot diameter (L =100, 200, and 400 μm), of the foil thickness (10 or 20 μm) and the channel length on the plasma flux parameters were studied. For the target foil 10-μm thick the best parameters of the plasma jet at the output of the 2-mm channel were found to be the following: plasma temperature of up to 12 eV, jet velocity $(1.5\text{-}4)x10^7$ cm/s, Mach number 8-22. The experiments have shown that plasma transported in the channel becomes effectively compressed and its energy density is much higher in comparison with the free expansion case.

The experimental arrangement has been further improved by replacing the cylindrical channel by a conical one and by providing the channel input with a small cavity located in front of the foil target. Then the foil plasma in the channel behaves as a bullet being accelerated by the pressure induced inside the cavity, in a similar way as macroparticles are accelerated in the Laser Induced Cavity Pressure Acceleration (LICPA) scheme. Energetic efficiency of the LIPCA accelerator (Fig. 2) is high, up to 30-times higher in comparison with purely ablative acceleration. Besides the high hydrodynamic efficiency, it is also due to that a part of the radiation and fast particles confined in the cavity is absorbed in the plasma, increasing thus its ablative pressure. The results of the related experiment performed at PALS at the end of the year will be published in 2010.

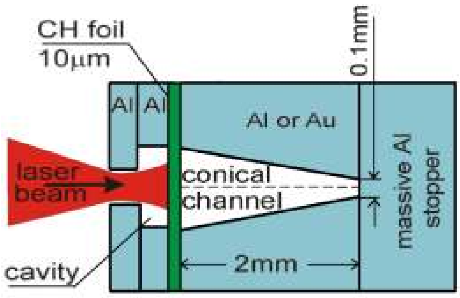

Fig. 2. Schematic of the LICPA plasma accelerator (by J. Badziak, IPPLM Warsaw)

One of the advantages of the new method of plasma jet generation and compression consists in its unique capability to create supersonic plasma jets consisting of light elements. The method is flexible enough to be exploited for generating plasma jets of various compositions and various cooling parameters by means of both high-energy (kJ) and low-energy (J) subnanosend and nanosecond lasers. It may find its use, therefore, not only in laboratory astrophysics, HED physics, and material processing, but also in fusion-related applications.

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V ADDITIONAL INFORMATION

Work for European Joint Undertaking for ITER and develpment of Fusion for Energy (F4E)

In-pile Thermal Fatigue Test of Be Coated Primary First Wall Mock-ups

O. Zlamal, T. Klabik, V. Masarik, NRI Rez

In collaboration with:
F. Zacchia, P. Lorenzetto, S. Wikman, Fusion for Energy

In the frame of ITER project's R&D, the request for thermal fatigue testing of Primary First Wall(PFW) mock-ups was raised. The PFW mock-up consists of beryllium tiles jointed to CuCrZr alloy heat sink; the diffusion joint between beryllium and basis metal alloy is object of thermal fatigue testing, which needs to prove it is able to withstand significant cyclic thermal loads. NRI Řež plc is involved in such research, where previous experiences from contactless graphite panel heating of similar PFW samples is employed. The activity described in this paper is developed for using in-pile, i.e. inside LVR-15 research reactor, where additional heating is provided by gamma and neutrons from the reactor core.

The objective of this task is to perform in-pile thermal fatigue testing of actively cooled Primary First Wall (PFW) mock-ups to check the effects of neutron irradiation on the Be/CuCrZr heterogeneous joints under representative PFW operation conditions. Two PFW mock-ups are prepared to be irradiated at 0.6 dpa level, with parallel thermal fatigue testing at 0.5 MW/m^2 for 20,000 cycles. Investigation is aimed on the design, manufacturing and verifications of thermal fatigue equipments and qualification testing prior and after irradiation.

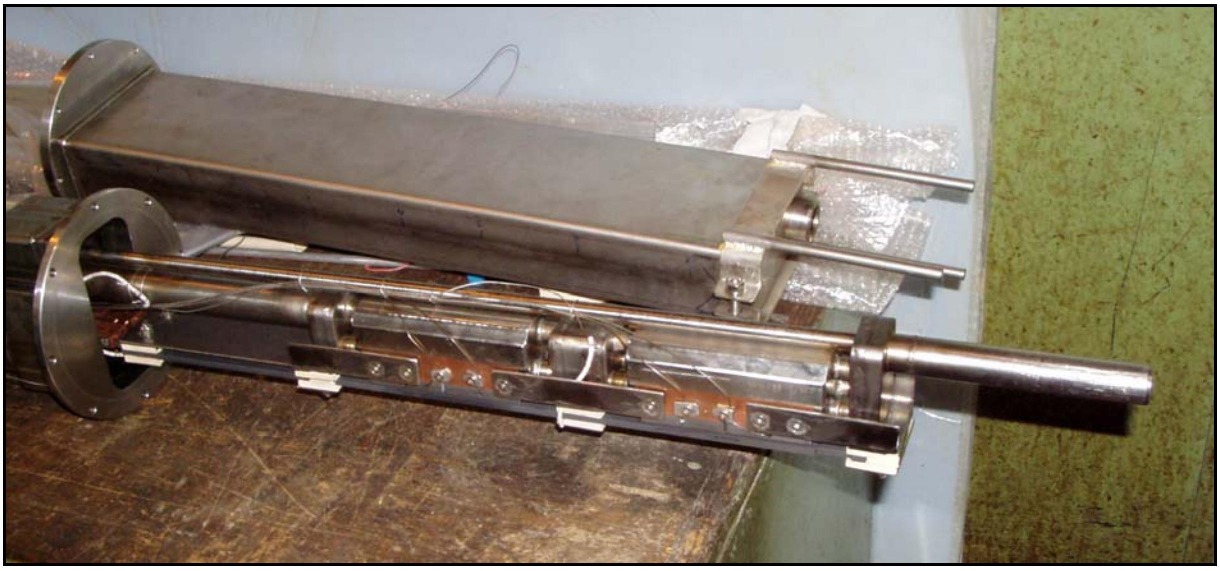

Fig. 1: Disassembled body of the testing rig with two PFW mock-ups

In-pile testing device, testing rig, was constructed to determine and evaluate soundness and life-time of tested joint between CuCrZr alloy and beryllium tiles on PFW mock-ups under more demanding conditions than out-of-pile testing. Aside of long-term cyclic heat load, each mock-up will be facing neutron flux provided by LVR-15 research reactor in NRI Řež plc. Significant efforts and funds were invested into the selection and verification of the best heat source, capable to provide long-term cyclic heat load and transfer requested heat flux on beryllium surface without direct contact. The most efficient heat source was found in planar meander-shaped graphite panel, which is able to withstand cyclic high heat flux generation in conditions of super-clear gas surroundings.

Testing rig for two PFW mock-ups will be placed in E1 and E2 positions in LVR-15 core, where both mock-ups are jointed together by stainless steel cooling water pipe. Heating of PFW mock-ups is supplied by graphite resistance-heating panel and gamma heating from the reactor core. According to ITER Organization's documentations 50 W/cm^2 heat flux is requested on beryllium surface and each of 20,000 cycles shall take 7 minutes. The programmable logic controller HC 900, supplied by Honeywell company, is used for regulation and control of proposed testing rig. Control applications are developed under Hybrid Control Designer, communication and visualisation of PLC output is directed on PC with SpecView32 user interface.

Fig. 2: Setting of out-of-pile testing of the rig

Recent status of project progress is that testing rig body is manufactured and computations are carried out to asses heat load on internal rig components due to small inner volume. Selection of construction material in central rig part and their cooling is verified by computation codes.

Computations also verified feasibility of proposed solution with graphite heating panel. Out-of-pile testing must be carried out to validate all computations with heat transfer, regulation, control and other design features before starting tests in-pile, i.e. in the reactor core. Results from non-active tests shall be also used as a basis for documentation submitted to State Office for Nuclear Safety. To obtain applicable results from out-of-pile testing, NRI staff will come up with test as similar as in-pile test, only without presence of neutron flux. Same testing rig, same control system and same heating panel will be employed in order to get best estimate results for further evaluation.

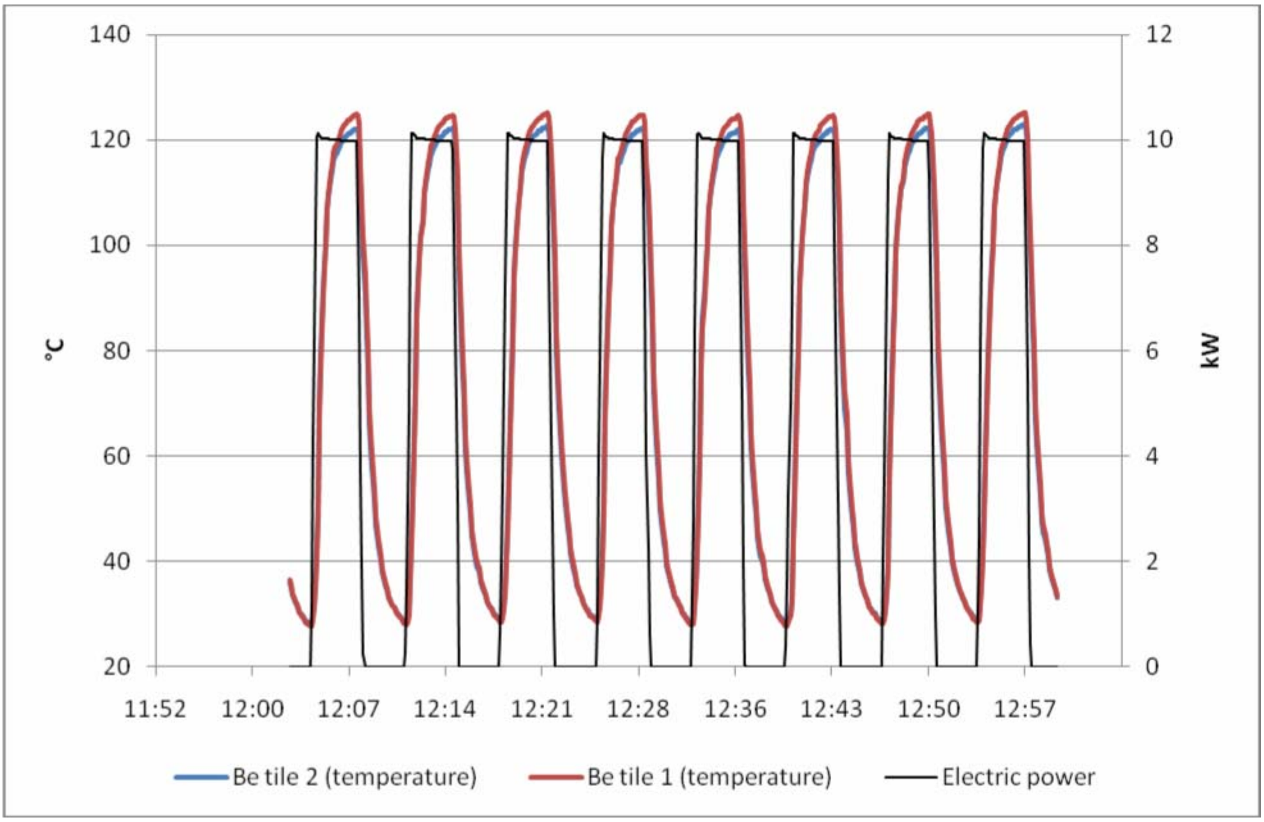

Fig. 3:Thermal fatigue cycles

Complex out-of-pile rig test is recently ongoing in vicinity of LVR-15 research reactor; the experience will be used to improve rig performance and necessary rig design modifications.

References:

[1] J. Zmítková, V. Olišarová: Termohydraulické výpočty sondy TW-3, ÚJV-13077

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Thermal Fatigue Testing of Be Coated Primary First Wall Mock-ups

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Report describes using of earlier developed experimental BESTH device in NRI Rez, Czech Republic, for cyclic thermal fatigue testing of Primary First Wall mock-up and First Wall Qualification mock-ups – material samples from the ITER Blanket section. The mock-ups for BESTH device were supplied in frame of NRI Rez involvement in ITER from various cooperators all over the world. The mock-ups were tested for quality of beryllium tiles bonds to CuCrZr heat-sink. Required testing procedure simulated cyclic thermal load from planar heat source in the BESTH device in NRI Rez and then mock-ups underwent similar thermal fatigue testing on the JUDITH-2 device in Forschungszentrum Julich, where the heat source was provided by electron beam. The soundness and quality of joint between the beryllium and CuCrZr alloy was verified by the ultrasound non-destructive inspection before, in between and after the tests. The BESTH device was used to test six different mock-ups from five different manufacturers: EU, US, South Korea, Russia and China.

The BESTH device tests mock-ups in pairs under protecting helium atmosphere. In between mock-ups, the planar heat source, the graphite panel, is positioned with emphasis of no direct contact to one or other mock-ups. Beryllium tiles are only few millimeters from the graphite panel, thus very small heat losses are accompanying each testing. The thermal fatigue tests of beryllium coated primary first wall mock-ups of dimensions 250 mm x 110 mm x 70 mm were used to compare the fatigue performance of different beryllium/CuCrZr alloy joints. The tests were performed at 0.625 MW/m^2 surface heat flux for a total number of 12,000 cycles of 235 s duration. The inlet water temperature was 100 °C with a water velocity of about 2 m/s. Ultrasonic testing was performed on each mock-up to check the integrity of the Be/CuCrZr joints before start of the thermal fatigue testing and after the end of test campaign of 12,000 cycles.

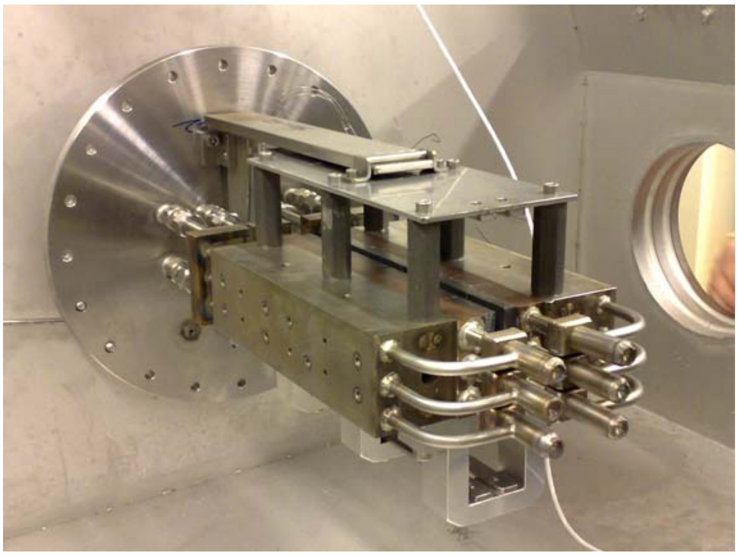

Fig.1. Inner parts of the test equipment with two mock-ups

Heat flux on the mock-up surface consists of heat radiation, helium gap convection and conductivity. Inductive method is used to heat-up the heating panels. The mock-ups are connected in parallel (Fig. 1) and the heat is removed by circulating using coolant water. Flow rate of the cooling water is controlled to specified Be/CuCrZr joint temperature range and is adjusted during a mock-up test using a special regulation valves and flow rate measurement. The device is instrumented as follows: one thermocouple located in each Be tile of each mock-up, one thermocouple in Cu-alloy, inlet and outlet cooling water temperature, electric power of each heating panel. Measured data are collected by a PC. Perfect the detachment of one Be tile from a mock-up during thermal cycling is detected by control system to minimize the spread of contamination and to exclude contact between the Be tile and any hot surfaces. Ultrasonic testing was performed on each mock-up to check the homogeneity of the Be/CuCrZr joints before start of testing and at the its end.

Pre - test thermal fatigue experiments were performed with Be specimen and cooper specimen and 12 000 cycles was achieved. Homogeneity and output thermal on Be tile surface were evaluated and results correspond to required testing parameters and required lifetime conditions.

The mechanized ultrasonic examination of the mock-ups have been aimed to detection of potential macroscopic defects (detachments) between beryllium tiles and CuCrZr plate before, after the first and after the second Qualification Thermal Fatigue Testing of mock-ups at the BESTH and JUDITH-2 facilities The mechanized UT examinations were performed using SUMIAD UT system with the PET-2 scanner and assessed by certified NRI staff.

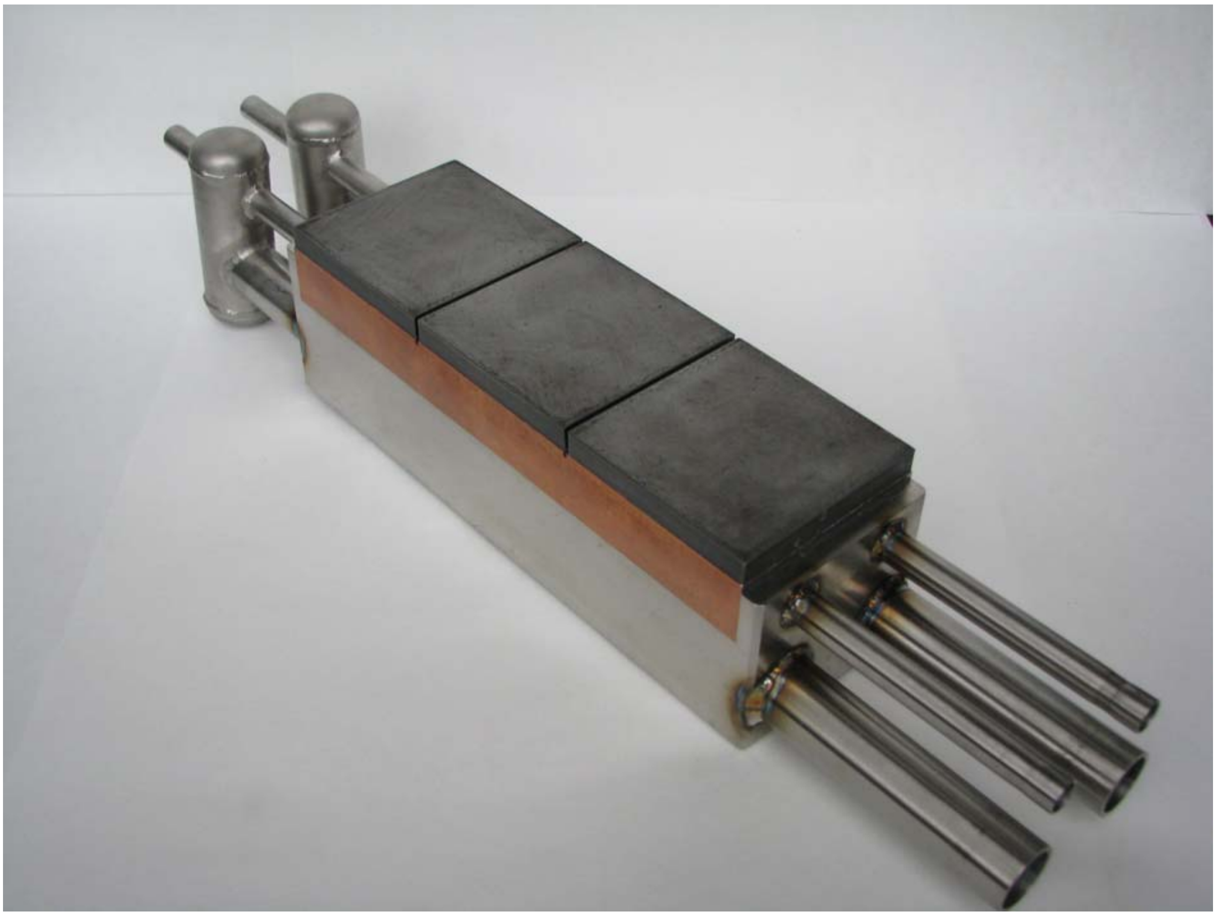

Fig.2. Berylium mock-up

The SUMIAD automatic UT equipment (producer TECNATOM S.A., Spain) was used for described mechanized UT examination. The most important parts of used ultrasonic testing device are:

- SIROCO PC system with power supply unit
- Scanner PET-2 with ultrasonic probe
- SUMIAD UT data acquisition and storing data system

- Double crystal UT probe RTD 0° TRL5 (longitudinal waves, frequency 5 MHz, crystal dimensions 2x(½Ø 8 mm), RA = 3°)
- Cables and connectors
- MASERA-NT SW for UT data evaluation

As a result of mechanized UT examination of the interface between beryllium tiles and CuCrZr plate is required the decision whether in this interface are present macroscopic discontinuities or not. This decision could be based on two primary presumptions. In such a case that in interface are not present macroscopic discontinuities could be supposed that:

- The amplitude of the reflected ultrasonic signal from the interface will be without substantial variations in whole inspected areas of beryllium tiles.
- The echoes from both pipes located in CuCrZr material will be visible (after filtering the interface echoes) without substantial variations of amplitude and in whole inspected areas.

No macroscopic discontinuities in the interface between beryllium tiles and CuCrZr plate were found in the all tested mock-ups with exception to the US and Russian mock-ups: the US mock-up exhibit significant aggravation of UT signal on one of Be tiles, most likely caused be Be tile detachment; the Russian mock-up showed minor difference in Be/CuCrZr soundness on the edge of one of Be tiles.

References:
[1] T. Klabik, O. Zlamal, Vl. Masarik: Description of Thermal Fatique Testing Equipment for Be Coated Primary First Wall Mock-ups, final report, ÚJV-13213
[2] T. Klabik, O. Zlamal, Vl. Masarik: Test report for mock-up FWQM-1NM-US2
[3] T. Klabik, O. Zlamal, Vl. Masarik: Test report for mock-up PH/S-75QB

Numerical Simulations of Welding for the EU HCPB TBM Project

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The aim of this work is to demonstrate the ability and effectiveness of using numerical simulations of welding processes. Submitted work should be taken as based work, which will be used as a starting point for the next proposed numerical analyses of welding in the frame of HCPB - TBM (Helium Cooled Pebble Bed - Test Blanket Module) project.

The report [1] covers numerical analyses of three different welding joints and two welding technologies. The first model is EB (Electron Beam) butt joint of two plates 5 mm thick. The second model is represented by EB T-joint 22 mm thick. The third model is a local connection of ribs cross section 11 mm thick plates welded by laser. These welding joints represent so called local models, which will be used in the future for TBM assembling. Created numerical local models have to be validated on the base of comparison between numerical results and experimental measurements.

In the frame of the report [1] the material database of EUROFER 97 for numerical simulations of welding was prepared and the ability to simulate of two different technologies by numerical method was confirmed. Moreover heat sources were adjusted and additional necessary aspects for numerical simulations were clarified (namely the size of finite elements near the fusion line and in the heat affected area, the level of plastic deformation near the fusion line).

The main aim of the future works will be to predict the distortion during welding assembly process of TBM box in order to compare these calculated distortions with the prescribed manufacturing tolerances. When larger computed distortions in comparison with prescribed manufacturing tolerances appear it is possible to suggest some optimisation changes in welding technology. On the base of numerical calculations it will be possible to make several variants in order to obtain satisfactory results.

References:

[1] V. Divis, M. Jary, L. Vlcek, *Task 22.1 del. 1: Starting Seam Assembly Program for Local Model Simulations,* July 2009