Annual Report
2011

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 our Association EURATOM/IPP.CR in 2011.

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). In the course of time, several other institutions have been included in the Research Unit to contribute to the work programme in physics and technology research. These are

- 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
- Research Centre Řež, Ltd.
- Nuclear Physics Institute, v. v. i., Academy of Sciences of the Czech Republic
- Institute of Applied Mechanics, Brno, Ltd
- Institute of Physics of Materials, v.v.i., Academy of Sciences of the Czech Republic

The Research Centre Řež, Ltd. is a non-profit research organization established and 100% owned by the former member of our association, Nuclear Research Institute Řež, plc. (now ÚJV Řež). RC Řež is now operating the two research fission reactors in Řež and took over all research activities of NRI including fusion R&D.

Compared to the previous year, the overall 2011 expenditures toward the fusion programme significantly decreased (from 2.6 to 2.06 M€). This is however due to the fact that the preferentially supported project “Enabling a programme of ITER relevant plasma studies by transferring and installing COMPASS-D to the Institute of Plasma Physics AS CR, Association EURATOM-IPP.CR” was financially closed in 2010. The manpower slightly increased, and is expected to increase more in the next year when the COMPASS machine will enter into the scientific “production” stage. To make this possible, a huge effort has been spent by the COMPASS staff to commission the most important systems and a wide range of diagnostics. Notably, the Thomson scattering system was put in routine operation in November, and one of the two NBI injectors has been attached and successfully tested in a plasma discharge in December. At this time, it is proper to thank all the COMPASS team, but also many collaborators from other European Associations (HAS, IST, CCFE, INRNE, IPPLM, CEA, and others) for their enormous effort.

While setting up new diagnostics and improving performance of systems is a never ending story in most experimental facilities, the current status already allows a real planning of experiments in line with the “core” COMPASS physics programme – edge plasma and pedestal studies, SOL transport, L/H transition…

With the gradually changing structure of the European fusion programme toward a more focused one, and establishment of the Power Plant Physics&Technology programme within EFDA in particular, we also expect, in future years, a growth of “technological” activities which now represent less than 10%.

The last point to be highlighted is that despite of (or maybe because of?) the intensive work on all the COMPASS systems, we were able to continue in a broad range of education and training activities, and we hope to keep, and even strengthen them, in the future.

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

I RESEARCH UNIT

1 Association EURATOM/IPP.CR

Composition of the Research Unit in 2011

IPP **Institute of Plasma Physics, v.v.i., Academy of Sciences of the CR**
Address: Za Slovankou 3,
182 00 Praha 8, Czech Republic
Tel: +420 286 890 450
Fax: +420 286 586 389
Contact Person: Radomír Pánek
e-mail: panek@ipp.cas.cz

FMP **Faculty of Mathematics and Physics, Charles University**
Address: V Holešovičkách 2,
182 00 Praha 8, Czech Republic
Tel: +420 221 912 305
Fax: +420 221 912 332
Contact person: Milan Tichý
tichy@mbox.troja.mff.cuni.cz

JHIPC **J Heyrovský Institute of Physical Chemistry, v.v.i., Academy of Sciences of the CR**
Address: Dolejškova 3,
182 23 Praha 8, Czech Republic
Tel: +420 266 053 514
Fax: +420 286 582 307
Contact person: Zdeněk Herman
zdenek.herman@jh-inst.cas.cz

FNSPE **Faculty of Nuclear Science and Physical Engineering, Czech Technical University**
Address: Břehová 7,
115 19 Praha 1, Czech Republic
Tel: +420 224 358 296
Fax: +420 222 320 862
Contact person: Vojtěch Svoboda
svoboda@br.fjfi.cvut.cz

NPI **Institute of Nuclear Physics, v.v.i., Academy of Sciences of the CR**
Address: 250 68 Řež, Czech Republic
Tel: +420 266 172 105 (3506)
Fax: +420 220 941 130
Contact person: Pavel Bém
e-mail: bem@ujf.cas.cz

RCR **Research Centre Řež, Ltd.*)**
Address: 250 68 Řež, Czech Republic
Tel: +420 266 172 453
Fax: +420 266 172 045
Contact person: Ondřej Zlámal
e-mail: zla@cvrez.cz

**) Non-profit 100% daughter company of ÚJV Řež, Plc. which overtook all research activities of ÚJV*

IAM **Institute of Applied Mechanics Brno, Ltd.**
Address: Veveří 85,
611 00 Brno, CR
Phone: +420 541 321 291
Fax: +420 541 211 189
Contact person: Lubomír Junek
e-mail: junekl@uam.cz

IPM **Institute of Physics of Materials, v.v.i., Academy of Sciences of the CR**
Address: Zizkova 22, 616 62 Brno,
Czech Republic
Tel: +420 5 322 90 379
Fax: +420 5 412 18 657
Contact person: Tomáš Kruml
e-mail: kruml@ipm.cz

Steering Committee

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Vito Marchese, Unit K6
Marc Cosyns, Unit K7
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IPP.CR

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Petr Křenek (Institute of Plasma Physics)
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Head of Research Unit

Pavol Pavlo

Secretary of the SC

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The Board was established in 1999 to help with the formulation of the scientific program, and to assess the scientific achievements of the Association EURATOM-IPP.CR.

Representatives of the Association IPP.CR in Committees and Bodies

STC - Science and Technolgy Committee EURATOM

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

Milan Tichý	Faculty of Mathematics and Physics, Charles University, Prague
Pavol Pavlo	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	Research Center Řež, Ltd.

2 Manpower and Budget

Manpower Analysis of the Association EURATOM/IPP.CR in 2011

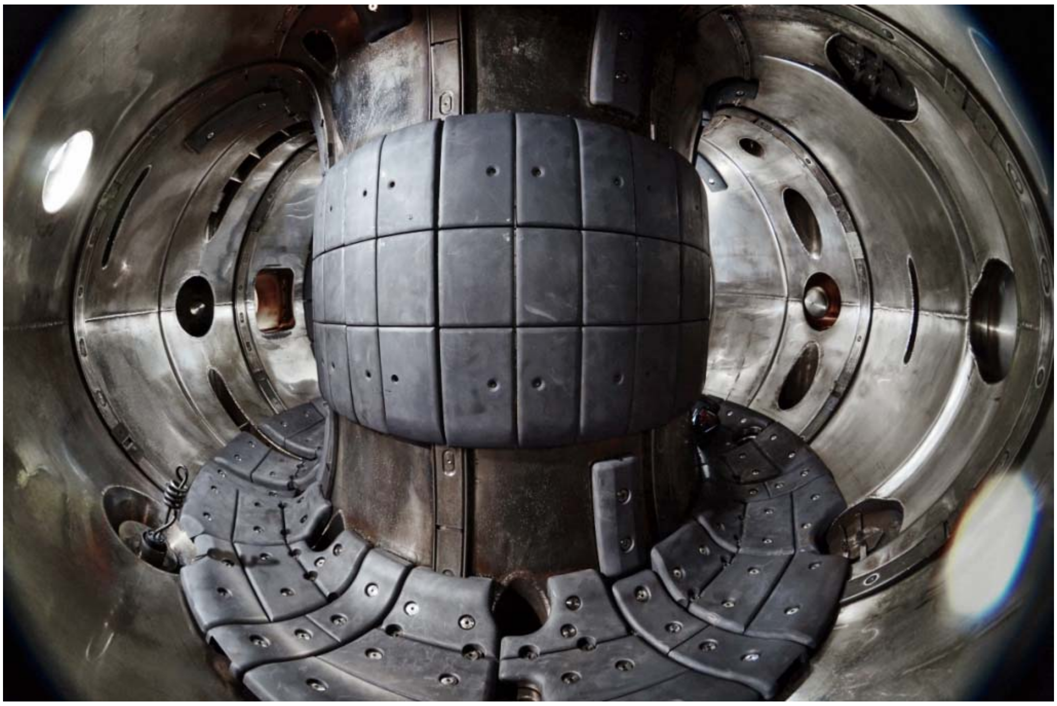
*)

Institution	STAFF, PY		STAFF, Persons				
	PY	%	Female	Male	Prof.	Non-Prof.	TOTAL
IPP	38.24	90.9	7	53	45	15	60
FMP	0.60	1.4	0	6	5	1	6
JHIPC	1.00	2.4	0	1	1	0	1
FNSPE	0.35	0.8	0	3	2	1	3
IPM	1.88	4.5	2	16	18	0	18
RCR*)	0.00	0.0	0	0	0	0	0
NPI*)	0.00	0.0	0	0	0	0	0
IAM*)	0.00	0.0	0	0	0	0	0
TOTAL	**42.07**	100	**9**	**79**	**71**	**17**	**88**
		Total, %	**10.2**	**89.8**	**80.7**	**19.3**	**100.0**

*) These institutions are involved in the European fusion programme directly through Fusion for Energy (not under the Contract of Association).

Expenditures in 2011

	Euro
Physics	1 424 309
JET Notifications	19 915
Operational cost of major facilities	593 363
Coordination, in the context of a keep-in-touch activity, of the Member State's civil research activities on Inertial Fusion Energy	4 575
Sub-total	**2 042 162**
Large Devices	**0**
Specific Co-operative actions 8.2a	(23 789)
Specific Co-operative actions 8.2b	1 661
JET S/T Task (EFDA Art. 6.3)	7 202
Fellowship contracts	10 510
Sub-total	**19 374**
TOTAL	**2 061 535**
Mobility Actions	**50 367**



Inner view of the COMPASS tokamak vacuum vessel after its thorough mechanical cleaning (March 2011).

*On 23rd June 2011, UK Prime Minister David Cameron visited the COMPASS tokamak.
From left to right: Head of Tokamak research at IPP Prague Radomír Pánek,
UK Prime Minister David Cameron and the Prime Minister of the Czech Republic Petr Nečas
on a viewing platform above COMPASS.*

II OVERVIEW

In accordance with the EFDA planning, the main areas of the research in the Association EURATOM/IPP.CR in 2011 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

In this part of the 2011 Annual report of the Asociation EURATOM/IPP.CR the most important results, activities and achievements are briefly summarised. The principal investigators of the tasks are from the Institute of Plasma Physics AS CR, v.v.i., if not stated otherwise. Papers and other works published in 2011 are cited in this overview, the d references can be found in Part IV. Notice that the decisive 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

Edge plasma in JET at ITER advanced scenarios

Interaction of plasma particles with RMP ergodic layer and the edge electrostatic potential.
Principal Investigator: L. Krlín
In our prepared work, we found, according of our meaning, two important effects in the contemporary acting ergodic layer and electrostatic turbulent potential. We found that for ions and for usual expected parameters, the ergodic layer looses its influence and the effects od ¨diffusion in the electrostatic turbulent potential predominates. For electrons, the usual accepted model od diffusion of electrons along the net of stochastic magnetic field lines is valid, with an exception of electrons with low energy. There, the traping of electrons in the potential tubulence appears, and, consequently, the anomalous diffusion of electrons can be lower. The model was based on the assumption of the egg-crate potential and of the ergodic layer created in two overlaping rows of magnetic islands. We entend to replace the egg-crate potential with the Hasegawa-Wakatani potential in a frozen (time independent) form.

Modeling of electron distribution function at divertor target plates and comparison with JET experimental data from Langmuir probes.
Principal Investigator: I. Ďuran
Unrealistically high electron temperatures are systematically measured by JET and other tokamak divertor Langmuir probes at high recycling and detached regimes. Previous results from TCV tokamak suggests that this problem can be caused by penetration of fast electrons to the divertor targets due to significant parallel gradients along the SOL. For this purpose a relatively simple kinetic model has been developed at TCV several years ago. Due to unavailability of the code itself, we recreated it again according to the existing publications

with a few minor enhancements and benchmarked the new code to the previously published results from TCV reaching a good agreement. In the end of 2012, we started accommodation of the code to make it suitable to model penetration of fast electrons toward divertor targets in JET SOL plasmas.

1.2 Energy and particle confinement/ transport

L-H transition physics

Hron - 1.2-A1: Hysteresis L-H versus H-L transition [WP10-TRA-01-05].
Principal Investigator: M. Hron
Due to the delay in the construction of the power supply for the fast plasma position feedback, the plasma performance did not allow to proceed towards the H-mode and to study the L-H transition. However, the new power supplies for the vertical and horizontal plasma stabilization were successfully commissioned. The optimization of the plasma position feedback control performance has started in the late 2011. Therefore, the project WP10-TRA-01-05 had to be cancelled and the study of the hysteresis L-H versus H-L transition will be re-open when the necessary plasma performance is available.

Pedestal physics

Long-range correlations on COMPASS.
Principle investigator: J. Horáček
Study of Long-range correlations is a long-term project. It requires two probes reciprocating inside LCFS in both L and H-mode. Even though both reciprocating probes have been completely installed in 2011, the COMPASS plasma position became stable only at the Autumn 2011. In addition, the existing probe heads cannot survive inside LCFS. Therefore, we concentrated on design of probe capable of withstanding high heat flux in the H-mode pedestal. Temperature simulations verified the previous assumption that the probe surface temperature determines the maximum depth of penetration into plasma. The results clearly demonstrate that a classical Langmuir probe pin (even made out of the best suitable material - tungsten) cannot survive longer than 4ms in the H-mode pedestal and thus have to be excluded. Therefore, we studied a concept of a rotating Langmuir probe disc. We found experimentally, however, that this concept is not feasible because of too high friction. The design therefore continues with just ball-pen probes. Since probing the pedestal has a potential of exploring unknown physics responsible for the H-mode transport barrier, development of such probe has been granted by the Czech Science Foundation. Gaining experience with 3D heat conduction simulations, a Bachelor thesis [93] has been written on simulating ITER divertor target heating during ELM events. The simulation input was taken from D. Tshakhaya kinetic simulation of parallel energy propagation in SOL during ELM crash and its spatial distribution on the divertor targets taken from M. Komm PIC simulations. Our results showed surprisingly very little divertor target erosion and no tungsten melting due to ELMs.
Ref.: [39, 93]

Pedestal width physics [WP10-TRA-01-03].
Principal Investigator: R. Pánek
The core multi-point Thomson scattering system has been commissioned and related calibration performed (electric setup and optimization, white light calibration and spectral calibration, absolute calibration by means of Raman scattering). The edge Thomson scattering

diagnostics commissioning was delayed due to delay in edge collection optics delivery and is expected in March 2012. The core Thomson scattering diagnostics using both Nd:YAG lasers is in a routine operation. Edge reflectometry: First part of microwave reflectometry system (K band) has been successfully commissioned. Delivery and commissioning of the second part (Ka band) is expected during the first half of 2012. Preliminary laboratory test of Doppler reflectometry system have been successfully performed in 2011. The final commissioning and tests with plasma are planned by end of 2012. It was not possible to determine pedestal plasma parameters, because the H-mode has not been achieved yet. It is scheduled for June/July 2012.
Ref.: [26, 46, 75]

ELM physics & ELM's mitigation

Commissioning and optimization of the RMP system in COMPASS [WP10-TRA-01-04].
Principal Investigator: R. Pánek
COMPASS is equipped with a system of coils enabling Resonant Magnetic Perturbation studies. Simulations have been done to identify the two most important odd and even configurations. The RMP coils had to be modified partly due to enlargement of the tangential ports for NBI injection. The new characteristics of the RMP coil have been measured and the inter-connection have been installed. Due to optimization of the coil connections, only two power supplies will be used. Their design has been originally provided by IST Lisbon, however, the prototype did not meet the specifications. Therefore, a new design has been prepared within IPP Prague and external experts based on MOSFET transistor module technology. The components have been procured and assembly and commissioning will done within the first half of 2012. Afterwards, the power supply will be installed into sub-basement of the experimental hall and will be connected to the RMP coils. The first experiments will start in summer 2012 depending on status of the COMPASS plasma parameters.
Ref.: [16]

Edge Turbulence

The complex measurements of the edge plasma parameters on COMPASS, ASDEX Upgrade or other facilities by using BPPs and LPs.
Principal Investigator: J. Adámek
We have used a novel probe method for ion temperature measurements by using a swept ball-pen probe during the systematic measurements in L-mode on ASDEX Upgrade. The time resolution is given by the sweeping frequency. The special fitting routines and error analysis were used. The results of the first measurements with fast (f~50kHz) swept BPPs fixed on the midplane manipulator show time evolution of the ion temperature and also radial profile of the ratio of ion and electron temperature. The electron temperature is routinely obtained by using BPP and LP in floating regime. The novel technique of the swept BPP provides the ion temperature in a simple way. The improved measurements on ASDEX Upgrade with time resolution less then 5 μs is planned for year 2012. We did not measure yet the radial particle flux by two BPPs(floating regime) and one LP(ion saturation current). This is planned for the next year as well. However, the new optimized ball-pen probe head (smaller dimensions) has been manufactured for COMPASS and ASDEX Upgrade as well.
Ref.: [30]

ESEL Development.
Principal Investigator: J. Seidl
Since ESEL code does not include drift-wave closure of parallel terms in the edge region, separate code solving Hasegawa-Wakatani model of drift waves was developed in order to compare turbulence behavior inside last closed flux surface with ESEL and to asses the influence of adding drift-wave terms into ESEL. Further, we perform examination of boundary conditions in ESEL and their influence on turbulence statistics in SOL to improve the control over free parameters of the model during comparison with experimental data. Comparison of different closures of parallel current is in progress, showing change of blob properties (size, tilt, velocity) and consequently properties of turbulence statistics under different regimes. The blobs are detected using newly developed routine that analyses density field in the ESEL code and computes spatial and temporal characteristics of detected structures. Previously investigated properties of parallel transport of temperature and density modeled by SOLF1D code under forcing given by ESEL were published [27], together with investigation of effect of turbulent fluctuations on averaging of transport coefficients [28]. For planned comparison of simulation with experimental data from COMPASS tokamak, reciprocating data from sufficiently long period of saturated state of turbulence are necessary. However, such reciprocating probe measurements on COMPASS were not available before the last quarter of the year and therefore comparison of ESEL model with reciprocating probe data from JET was started instead. The developed drift-wave model was used also for analysis of transport of particles with non-negligible Larmor radius by the turbulent field. Effects of compressibility of polarization drift are being compared with simulation tracing the full particle orbits. Our results show that compressibility of velocity field of non-ideal plasma impurities results in their increased radial transport [55,77].
Ref.: [14, 27, 28, 55, 77]

Investigation of magnetic turbulence on TJ-II.
Principal Investigator: I. Ďuran
The activity was canceled due to insufficient manpower resources. We decided to concentrate the effort in this research area rather to development of so called U-probe for COMPASS tokamak and its exploitation for investigation of electrostatic and magnetic turbulence in COMPASS SOL plasmas.

Construction and measurement with U-probe on COMPASS tokamak.
Principal Investigator: K. Kovařík
Improved understanding of properties of the current filamentary structures in edge plasma region is believed to allow better insight into development and possible control of the Edge localised modes (ELMs) and consequently mitigation of their impact on plasma performance and first wall structures. Several advanced probe diagnostics for characterisation of the filamentary structures at the plasma edge were recently developed. We have focused on measurements of electric and magnetic properties of the filaments and electromagnetic features of edge turbulence using combination of 3D coil systems and Langmuir tips in one complex probe.
Ref.: [92]

1.3 MHD stability and plasma control

Development of relevant codes

EFIT++ development [TF-ITM-IMP12].
Principal Investigator: J. Havlíček
We started integrating EFIT++ into the ITM infrastructure. The standalone version of EFIT++ is now running on the ITM gateway. This step necessitated installing and configuring several libraries and solving some incompatibilities because of their different versions. An interface function with ITM CPO inputs is now being prepared; however, it has not been fully implemented yet. The next step will be to create a Kepler actor, similarly to other equilibrium codes in ITM (e.g. EQUAL) and put EFIT++ on G-forge. EFIT++ has also been installed on IPP Prague computers, with difficulties similar to the gateway installation. No tests with actual COMPASS experimental data had been performed in the year 2011 for two important reasons. First, the plasma performance and diagnostics were not well suited for equilibrium reconstruction - positionally stabilized circular plasma was produces at the very end of the year 2011. Second, a new experimental database (CDB) is to be released soon for COMPASS. It is reasonable that EFIT++ uses directly this database instead of starting with the present (temporary) system. Development of the Induced Currents Module for EFIT++ was delayed (working version was produced in early 2012)

Modelling of ergodization

Generation of radial electric field in the ergodic layer of RMP
Principal Investigator: L. Krlín
Recently, a paper on the generation of radial electric field in RMP system, using gyrokinetic code appeared by R.G. Kleva et al.: Phys.Plasmas 17 112303 (2010). Since our approach intended to use less sophisticated (and, therefore, less exact) code, we leave the idea of study of electric field generation inside of the ergodic layer, and we limit ourselves to use our approach to study of radial elctric field in a combination of electrostatic turbulent potential and ergodic layer. Here we intend to compare both effects, and for this, a simplier approach will be sufficient. Electrostatic turbulent potential brings two important effects. namely, the contribution of heavier ions for the generation of electric field, and the effect of traping of low energy electrons in the turbulent potential.

Study of plasma response to the resonant magnetic perturbation field and the associated transport.
Principal Investigator: P. Cahyna
The impact of RMP screening on divertor footprints in DIII-D was quantified using field line tracing (done in IPP Prague using codes originally provided by Eric Nardon) and using EMC3-EIRENE transport modelling done in FZJ by Heinke Frerichs, for which we supplied the screened magnetic field. Results show significant changes, which in the EMC3-EIRENE case improve agreement with the DIII-D experiments (the disagreement is not resolved completely however). Experiments for the ongoing MAST campaign were suggested and have been carried out by the MAST team. We then searched all available MAST shots in L-mode, scenario 4 for the presence of strike point splitting. We also developed a code which allows to trace divertor footprints in the perturbed field calculated by MARS-F, and used it on MAST cases.
Ref.: [15, 16, 17, 78, 79]

Runaway electrons

Simulations of the technique of runaway electron mitigation by magnetic perturbations.
Principal Investigator: P. Cahyna
During the work on the JET data the main issue identified was the uncertainty of the background magnetic field. EFIT provides several very different equilibria and the results are sensitive to the choice of the background magnetic field. We thus focused on coupling with the global MHD code JOREK which should be able to predict self-consistent magnetic field during the ITER disruption, including intrinsic 3D effects (MHD modes). Development of runaway electron test particle tracking code in time-dependent magnetic potential taken from JOREK was started. The code should be able to predict average radial displacement of REs under different mitigation scenarios (MGI, Pellets, RMP..). We made computations of time development of safety factor profile and Poincare sections in different times of reconstructed magnetic field to check the correctness of algorithm computing magnetic field from JOREK code. We found some discrepancy so there is further need to benchmark correctness of reconstruction of magnetic field. Correctness testing of trajectory integrator was performed by energy-conservation in “frozen” magnetic field and by comparing of banana orbit width with theoretical prediction. The work on the proposed JET coils was postponed due to funding reasons.
Ref.: [80]

Fokker-Planck study of electron runaway in COMPASS.
Principal investigator: V. Fuchs
The CQL3D code was applied for the study of runaway electrons in the COMPASS tokamak. CQL3D is general facility for calculation of particle distributions in a tokamak: it is a multi-species, 2D in velocity space, 1D in non-circular plasma radial co-oordinate, fully relativistic, bounce-averaged, collisional/quasilinear Fokker-Planck equation solver. 2D in velocity space means parallel and perpendicular velocity or a scalar energy and the pitch angle. 3D in space can be reduced because of axisymmetry and symmetry around the cross section center. The particle distributions were taken to be toroidally symmetric and independent of azimuthal angle about the ambient magnetic field. Radial drifts are neglected but the radial transport is included. The radial transport includes diffusion and pinch terms. With the bounce-average, account is taken of variations as a function of (non-circular) radial coordinate, poloidal angle, and two momentum-space directions. A kinetic bootstrap current calculation is included. Distribution functions are calculated on each flux surface and are plotted on 10 selected surfaces. Thus we could follow how the distribution function deviates from a Maxwellian at various distances from the tokamak core. The main result is that at typical ohmic operating conditions in COMPASS, considerable electron runaway is expected. The runaway rate peaks at the plasma core, wherefrom the runaway electrons will diffuse to the edge.

1.4 Power and particle exhaust, plasma-wall interaction

Interaction of hydrocarbon ions with the first wall elements

Exploration of fuel removal methods compatible with retention inmixed materials and metals, including beryllium and dust generation and characterization
[WP11-PWI-02]
Principal Investigator: Z. Herman, J Heyrovsky Institute of Physical Chemistry AS CR

Data on correlation of survival probabilities of ions on several ITER-relevant surfaces of carbon, tungsten, and beryllium, both room-temperature and heated to 1000 K, were complemented. The expressions obtained make it possible to estimate the unknown survival probability of an ion on these surfaces from the ionization energy of the ion.
Ref.: [83, 84]

Modelling of heat loads of divertor plates on ITER

Combined 3D Particle-In-Cell & neutral transport modelling of the gap crossings.
Principal Investigator: M. Komm
Particle-In-Cell (PIC) simulations of the gaps between divertor tiles can serve to understand plasma interaction with the divertor and predict heat and particle fluxes impacting onto the tiles. This has a critical importance for ITER, as the heat fluxes must not exceed material limits of the divertor. The problem of the heat fluxes falling on the tile edges has been previously addressed by means of 2D PIC simulation by using the code SPICE2 [19]. This approach required separate simulations for poloidal (PG) and toroidal gaps (TG) and assumed the gaps to be of infinite length. In order to simulate more realistic geometry with crossings between PG and TG, a full 3D PIC code is required. Such code (SPICE3) has been developed and benchmarked with SPICE2 [20].
Ref.: [19, 20]

PIC simulations of power loads in ITER divertor tiles and simulations of dedicated experiments for benchmarking of the code
Principal Investigator: R. Dejarnac
Simulations are nowadays important tools for physicists, especially for predicting results, for ITER for example, or to understand the physics by comparison with experiments. However, one needs reliable and powerful codes. This task concentrate of both aspect by optimizing the cpu-time of our in-house particle-in-cell codes and to compare results with experimental data from dedicated probe to validate our model. Predictive calculations have also been made for ITER and a new collaboration with our neighbours from Comenius University in Bratislava, Slovakia, was created.

1.5 Physics of plasma heating and current drive

Exploration of nonlinear effects near LH and ICRH antennas

Understanding of gas puff ionization effects in the SOL during LH heating, including ponderomotive force effects, in ITER like discharges with 2nd X-point near to the top of the machine.
Principal Investigator: V. Petržílka
In the JET tokamak, it was demonstrated that injecting gas in the outer mid-plane (OMP) can result in a peripheral plasma density increase, which improves the Lower Hybrid (LH) wave coupling. Gas puffing proved to be useful in JET particularly in cases with a relatively large distance of about 10 cm between the LH grill mouth and the plasma. It was shown by EDGE2D modelling that the increase in the Scrape-off-Layer (SOL) density and the consequent LH wave coupling improvement can be explained by ionization of the SOL neutral due to heating by the LH wave. In contrast to the computational grid for configurations considered before that have a SOL width of about 10 cm at the OMP, ITER relevant magnetic configurations, with the 2nd X point at the top, have only a several cm wide

computational grid in the SOL in the OMP. The EDGE2D computational grid is restricted to a rather narrow OMP SOL layer in these ITER relevant configurations, which excludes the study of processes more distant from the separatrix using EDGE2D. In the modelling, we have attempted to overcome this problem by introducing a limiter (particle sink) protruding radially down from the top. Then, the locations radially near to the grill mouth are connected to the wall (particle sink), similarly to the above mentioned ITER-like configuration with a 2nd X-point at the top. The modeling then shows that the configuration with the top limiter (i.e. ITER-like configuration) has lower gas puff efficiency than the configuration with no top limiter, and the top puff is very inefficient in ITER-like configurations. The top puff enhances at the top the far SOL density a bit more than the OMP puff, both in the configurations with and also without the top limiter. This is consistent with the density enhancement measured at the top by the Li-beam, while the LH coupling remained bad, i.e., the OMP density was not enhanced sufficiently for the coupling amendment, even if the top far SOL density increased. In conclusion, the modeling shows that much higher gas puff rates for the top gas puff are needed for an appropriate LH coupling improvement in ITER relevant configurations. Therefore we believe that the milestones were reached.
Ref.: [5, 6, 7, 8, 9, 10, 14, 55, 71, 74]

Exploration of fast particle generation in a radially wide layer.
Principal Investigator: V. Petržílka
A Retarding Field Analyzer (RFA) was used during lower hybrid (LH) current drive experiments in the Tore Supra tokamak to characterize the supra-thermal particles emanating from the region in front of the C4 Lower Hybrid (LH) Passive-Active-Multijunction (PAM) grill. This work is continuation of our previous measurements on Fully-Active-Multijunction (FAM) launchers C2 and C3. The RFA collects electrons that flow along field lines from the outboard side of the tokamak. The measurements were performed when wave-guide rows of the C4 launcher were magnetically connected to the RFA. The RFA is mounted on a vertically reciprocating probe drive, situated on top of the torus. The analyzer is biased to collect only supra-thermal electrons with energy greater than 200 eV. The maximum power reached in the C3 and C4 comparison experiments was 1.4 MW. The energy distribution measurement shows that, also for the RFA electron repelling grid voltage -600V, there is still enough electrons with energy larger than 600 eV producing collector current. The main conclusion is that the parasitic LH wave dissipation in front of PAM (C4) grill is lower than in front of the FAM (C4) grill antenna, and therefore the C4 grill generates lower averaged supra-thermal electron fluxes than the C3 grill for identical SOL plasma conditions. We think that the milestones were reached.
Ref.: [5, 6, 7, 8, 9, 10, 14, 55, 71, 74]

1.6 Energetic particle physics

Implementation of new algorithms for data analyses for neutron diagnostics.
Principal Investigator: J. Mlynář
In 2011, the development of optimised version of the Minimum Fisher Regularisation (MFR) in Python was concluded and commissioned, which allowed to stop using the phased out MatLab at JET. The Python MFR package was tested and a fully satisfactory performance was demonstrated [11],[13]. However, for a full numerically optimised version, local computer (laptop) is required as the Fedora operating system of JAC features an obsolete version of Python. Due to the shutdown and low power C28 campaign, no neutron data analyses were performed, however, the MFR code was broadly used in Soft X-ray analyses

(see a separate contribution). We also contributed to the introductory article on potential application of unfolding in data from the activation probe [12].
Ref.: [11, 12, 14]

2. Development of plasma auxiliary systems

2.1 Heating and current drive systems

NBI heating for COMPASS
Principal Investigator: J. Stöckel
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 were manufactured at the Budker Institute of Nucler Physics (BINP), Novosibirsk, Russian Federation. The full energy (40 keV), the expected ion current (12 kA) and an efficiency of neutralization (~70%) were achieved in the pulse length 300 ms by firing the beam to a special calorimeter, which was provided by BINP. These experiments were performed at the beginning of the year 2011. The first injector was connected to the tokamak vessel via a special beam duct and several shots with a moderate power were executed. To achieve full performace, the beam dump, located at the opposite side of the injection port was designed.

Development of codes for existing and envisaged LH grill for COMPASS
Principal investigator: J. Preinhaelter
We develop a code which solves, in the 3D geometry of the grill structure, the problem of efficient coupling: the power density spectrum of the emitted waves, the power reflection coefficient, the power lost by the waves launched in the inaccessible region and the directivity of the waves transmitted into the accessible region. The code is also able to determine the 3D electric field in front of the grill.We also send the paper describing the LH grill code and the corresponding theory to the Nuclear Fusion.
Ref.: [3, 68]

LHCD for COMPASS
Principal Investigator: V. Fuchs
Simulations were carried out of Lower Hybrid (LH) slow wave antenna – plasma coupling, and of lower hybrid current drive (LHCD) for the IPP Prague COMPASS tokamak, in support of a choice between a 1.3 GHz or 3.7 GHz LH power system. The presented evidence favours a 3.7 GHz system for a number of reasons. First, at the LH power launching stage, a prospective 3.7 GHz multi-junction antenna proves superior to the existing 1.3 GHz grill in terms of reflectivity while the directivites are comparable. An obvious advantage of the projected 3.7 GHz LH rf system is a much larger available operating power, as it can easily supply the maximum allowable 0.5 MW (corresponding to the empirical antenna power density limit of 25 MW/m2) to the plasma, as compared to the maximum possible 0.2 MW with the 1.3 GHz system. The 3.7 GHz LH system also offers the possibility of comparison with other existing LH experiments in Europe (Tore Supra, JET, ASDEX). In addition, operation at 3.7 GHz appears more robust than at 1.3 GHz, in the sense that it is less likely to be effected by slight changes in plasma and configuration conditions. Finally, the most important factor favouring 3.7 GHz for COMPASS is the density limit caused by parametric decay instability. At 1.3 GHz, the density limit lies barely above a line average of 1019 m-3, whereas for 3.7 GHz the density limit goes well beyond 1020 m-3. LHCD simulations with

the C3PO/LUKE and GENRAY/CQL3D codes give estimates of LHCD efficiencies of the order of (0.5-1) A/W, depending on COMPASS operation scenario conditions.

2.2 Plasma diagnostics

Edge plasma diagnostics

Development of the ExB analyzer.
Principal Investigator: M. Komm
The ExB analyzer is an unique diagnostics for fast ion temperature measurements in tokamak SOL. The time resolution of the measurements should be sufficient to resolve fast transient events, such as ELM filaments. The analyzer will be mounted on a reciprocating probe manipulator, which has the same interface on COMPASS and AUG tokamaks. In order to optimize the design of the diagnostics, the analyzer chamber had to be simulated by means of Monte-Carlo (MC) and Particle-In-Cell simulations (PIC).

Atomic Beam Probe for the COMPASS Tokamak.
Principal Investigator: V. Weinzettl
The Li beam system was installed on the COMPASS tokamak in summer 2011. The beam energy is gradually increased to allow ABP measurements in near future. At the same time, the new electronics for the ABP test detector was installed on the COMPASS tokamak. Noise tests were performed in the experimental campaigns in 2011 but necessary circumstances for real measurements with ABP (Li beam operation at 100 keV, H – mode plasma) have not been achieved on COMPASS yet.
Ref.: [46, 75]

Electrostatic probes for COMPASS.
Principal Investigator: R. Dejarnac
For diagnosticians, probes are and always will be important to measure quantities in situ and to have fixed points for other diagnostics comparison. IPP Prague has a long experience with probes and COMPASS benefits it. This task concerns probes from the 3 steps leading to results: design and fabrication, calibration, measurements. In order to measure plasma parameter using the novel technique of first derivative in tokamak plasma, a probe has been designed and built by our colleagues from Sofia University, Bulgaria, and measurements have been performed in COMPASS. To record the data with the less parasitic noise, special electronics was designed, based on previous test-measurements in COMPASS, was built and commissioned to Prague by our Bulgarian colleagues from Sofia University and Bulgarian Academy of Sciences for a total of 60 channels (=probes) including for routine measurements with the 39 COMPASS divertor Langmuir probes. Finally using 2D kinetic simulations, a calibration was found for a new type of probe, the so-called Tunnel Probe, to measure plasma parameters and its fluctuations for any type of plasma and probe dimensions. This work has been done in close collaboration with our colleague from CEA Cadarache, France. This task is completed now.

Probe measurements on COMPASS.
Principal Investigator: M. Tichý, Charles University
Experimental effort has been concentrated on improvement of the probe technique. Experiments have been performed in CW and pulsed plasma jet. Results have been accepted for publication in Contributions to Plasma Physics journal in frame of the IWEP Workshop in

Iasi, Romania in September 2011 and for publication in Nukleonika (International Journal of Nuclear Research, ISSN 0029-5922) in frame of the PLASMA 2011 conference in Warsaw, Poland in September 2011. Diagnostics of the plasma plume of the SPT by means of emissive and Langmuir probe was performed and the results published. The “modeling” group around Prof. Hrach (M. Komm, Z. Pekarek) pursued further the fluid/ particle code for simulation of plasma inside the ball-pen probe. Z. Pekarek finalized the library for effective solution of Poisson equation in 3D; it was used in M. Komm’s publications already. Further, it is developed particle code package “concurrent” to SPICE3 code (J. Lachnitt, R. Hrach, T. Ibehej). The hybrid code (much faster in comparison to purely particle codes) has been adapted to work in magnetic field. Unfortunately further development of this code is unlikely since the main author V. Hruby passed away in 2011.
Ref.: [19, 20, 21, 22, 30, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65]

Microwave reflectometry

Establishment of routine operation of the first part of microwave reflectometry system (K and Ka bands).
Principal Investigator: J. Zajac
The reflectometry system for Compass was mainly designed to perform the relevant plasma density profile measurements in the pedestal region. The additional requirement was using of the reflectometers as an experimental diagnostics for studies of the plasma turbulence. The first part of the microwave electronics and data aquisition, provided by IPFN/IST, was delivered and tested on the stand in Nov/Dec 2011.

Beam emission spectroscopy

Installation of the BES system on the COMPASS tokamak and first measurements.
Principal Investigator: V. Weinzettl
New diaphragms were added to the fly-tube with the aim to improve a separation between the neutralizer of the beam and the tokamak vessel. Consequently, a new turbo-pump and a vacuum gauge were installed close to the tokamak vessel to ensure a sufficient pumping of the fly-tube part. Then, the vacuum subsystem was carefully checked for the leaks confirming a full vacuum compatibility with the tokamak operation. The first measurements with the slow detection were performed with the tokamak vessel filled by hydrogen gas as well as in both vacuum and plasma shots showing a necessity of better beam alignment and technical improvements in the emitter part of the beam. Namely, an increase of the beam portion reaching the tokamak vessel and a better beam symmetry are planned to be achieved. The new flange equipped with specially designed viewpoints has been installed to the bottom oval diagnostic port allowing mounting of the fast APD system, which is still under development in Budapest.
Ref.: [46, 75]

Fast tomography

Development of fast tomography systems based on fast bolometric and SXR arrays for COMPASS.
Principal Investigator: V. Weinzettl
The new fast tomographic system composed from four independent port plugs containing bolometers, soft X-ray detectors and objectives for the visible light detection equipped with the improved slit holders, new cabling well protected against an electromagnetic interference

and new amplifiers allowing for switching amplification was installed on the COMPASS tokamak. The first measured profiles indicate a possibility to use both the bolometric and SXR signals for tomographic reconstructions and also for fast (real-time) vertical and radial plasma column position estimation.
Ref.: [75]

Development and application of fast inverse methods.
Principal Investigator: J. Mlynář
In 2011, the efforts on developing a fast tomographic method for Soft X-ray reconstruction were first focused on JET data, with contribution at the EPS conference [11]. Next, the optimised and enhanced Minimum Fisher Regularisation (MFR) code was applied on TORE SUPRA, including a new phantom function. In CEA we also learned details of planned direct SXR analyses, avoiding the inverse problem. New ideas on possible implementation of iteration cycle in real-time emerged then and since autumn have been implemented by a student of the Czech technical university in Prague. The MFR code was also applied on COMPASS data from its tomographic diagnostics system [75], in particular towards the end of 2011 when the diagnostics started working properly. A contribution to the HTPD conference is planned in 2012. A journal article overviewing novel numerical methods applied in the optimised MFR tomography was edited in the end of 2011, to be submitted to Nucl. Instrum. Methods in the early 2012.
Ref.: [011, 075]

Calibration of fast tomography system for visible plasma radiation measurements for COMPASS tokamak. First measurements.
Principal Investigator: D. Naydenkova
New multichannel diagnostics for visible light radiation measurement have been installed on the COMPASS tokamak as a part of the tomographic system for transport studies. The diagnostic has a time resolution in few microseconds range and a spatial resolution better than 1 cm in the pedestal region. It allows observations of the core/edge plasma from two poloidal angles. In 2011, alignment of the system and troughput measurements were performed resulting in the first test measurements.
Ref.: [23, 25, 75]

Thomson scattering

Data acquisition of the Thomson scattering system.
Principal Investigator: M. Aftanas
Thomson Scattering (TS) diagnostic system started its operation in the year 2011. The data acquisition (DAQ) system worked well during tests. At the end of the year 2011 the TS diagnostic start to work in routine operation. The triggering of DAQ system by the Q-switches of the lasers has been implemented and the newly HDF5 data format has been adapted for the measured signal.
Ref.: [26, 75]

Laser part of the Thomson scattering system.
Principal Investigator: P. Böhm
Thomson scattering (TS) diagnostic was put in operation in the year 2011. The laser system, as an integral part of the TS diagnostic, performed well during diagnostic tests, calibrations and first measurements. In the end of the year, TS measurements with one laser were performed routinely. To improve the TS diagnostic capabilities, external triggering unit was

designed and initial tests of the unit were performed. Control of data acquisition by an internal laser trigger was implemented. Laser safety system was tested and slightly re-designed according to working experience; some errors were occurring from time to time, the remedy is in progress.
Ref.: [26, 75]

Detection line of the Thomson scattering system
Principal Investigator: P. Bílková
Detection of the core TS system has been commissioned and tested. In particular, 29 spectrometers have been completed and set-up and first spectral calibration performed. Based on the results of calibration, some problems have been identified and solves (replacement of bad mirror, improvement of electronic setup). Final spectral calibration has been performed after all as an input for the data processing. Optical fibers have been placed into the area and tested. Raman (absolute) calibration of the system using nitrogen at different pressures inside the tokamak has been successfully performed and thus the very first signals from the diagnostics have been obtained after adjustment of the core collection objective. During this adjustment, a major role had a split fiber that allowed to find an optimal position of objective with respect to a laser beam. Results from Raman calibration have been processed and as a result, so called Raman products for each of 13 spectrometers belonging to the core TS system has been calculated. Knowing of these coefficients enabled calculation of electron density once the first TS signals have been obtained in September 2011. The electron temperature and electron density profiles have been measured with a spatial resolution of around 1 cm and temporal resolution of 33.3 ms have been obtained since than. More effort after obtaining first profiles has been paid to the processing data optimization, aimed to a fast delivery of profiles after each shot.
Ref.: [26, 75]

2.4 Real Time Measurement and Control

COMPASS CODAC system and real time feedback.
Principal Investigator: M. Hron
In 2011, new database using SQL database for metadata and hdf5 files with the experimental data has been developed in IPP and put in standard use in the order to allow easier, faster, and more efficient access to the experimental data, including attaching of processed data and modelling results. Extension of the data acquisition system a) fast data acquisition at sampling rate of few MS/sec for fast (turbulence) measurements, b) sampling rate around 1 MS/sec for integrated magnetic signals digitalization and c) slow data acquisition at several tens of kS/sec was detailed, and real-time control hardware extension for feedback control of density, plasma current, and NBI heating power designed.
Ref.: [34, 36]

Real time feedback.
Principal Investigator: M. Hron
The fast feedback power supplies (FFPS) had to be designed newly at the end 2010 - beginning 2011, after unsuccessful tests of the original fast amplifier designed in the IST Lisbon. The power supply was designed and built newly within the IPP Prague with subcontractors from the industrial sphere. The new power supply was successfully tested in August 2011 and after that the whole feedback system commissioning was started. The

stabilized circular plasma was achieved. The vertical hydraulic system was commissioned for use up to B_tor = 1.6 T.
Ref.: [34, 36, 37, 38]

COMPASS interlock system.
Principal Investigator: M. Hron
In 2011, both the time non-critical and the time-critical sections of the machine protection system were under further development. This included fine tuning of the interlock conditions, tests and maintenance of the existing systems.

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

3.4 Theory and modelling

Detection of EC emission on COMPASS.
Principal Investigator: J. Preinhaelter
Fabrication of the ellipsoidal mirror was finished. This mirror quasioptically focuses our antenna Gaussian beam on the plasma surface. The mirror is steerable in two planes so it can be adjusted the optimum angel for penetration of the electron Bernstein (EBW) waves through the plasma resonance region. In the collaboration with the Max-Planck Institute in Greifswald, we have performed, with our radiometer, a measurement of EC emission from WEGA stelarator. We published extensive paper devoted to the possibilities of the plasma heating a current generation with the electron Bernstein waves in spherical tokamaks. Previously developed codes were successfully used for the study of plasma heating and the current generation in the hybrid reactors.
Ref.: [1, 2, 18, 70, 76]

RF power deposition, current drive and emission in stellarotor WEGA.
Principal Investigator: J. Preinhaelter
To solve bad coupling of WEGA cylindrical 5 waveguide grill we run extensive simulation with our OLGA code. Simulations predicted good coupling for a broad range of surfaces densities and density gradients and also for studied antenna radial positions. So probably problem is somewhere in the grill construction. Some results of our EBW heating simulation was presented on the 38th EPS and on International Conference on Research and Applications of Plasmas, Warsaw.
Ref.: [4, 69]

Ray tracing and Fokker-Planck modelling.
Principal Investigator: J. Urban
Our ray-tracing code (AMR) and the LUKE Fokker-Plack code can now be routinely utilized in a fully coupled mode. Using these codes, we have been able to perform an extensive numerical study of electron Bernstein wave (EBW) heating and current drive (H&CD) performance in four typical ST plasmas (NSTX L- and H-mode, MAST Upgrade, NHTX). We have simulated EBWs of varying frequencies and launch conditions, which are the fundamental EBW parameters that can be chosen and controlled. Our results indicate that an efficient and universal EBW H&CD system is indeed viable. In particular, power can be deposited and current reasonably efficiently driven across the whole plasma radius. Such a

system could be controlled by a suitably chosen launching antenna vertical position and would also be sufficiently robust.
Ref.: [1, 2, 18, 70]

4. Emerging Technologies

4.1 Development of material science and advanced materials for DEMO

Irradiation and thermal resistance of Hall probes and plasma facing materials

Development of Hall sensors for use within magnetic diagnostic of fusion reactors.
Principal Investigator: I. Ďuran
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. Results from installation of six 3D Hall probes on JET tokamak was analyzed and presented at ANIMMA conference and the journal publication of these results has been submitted to Trans. Nucl. Sci. Irradiation experiment was conducted on LVR-15 experimental fission reactor where several samples of InAs, InSb and InAsxSb1-x Hall sensors with various level of initial doping were irradiated up to the total neutron fluence of 10^{16} cm^{-2}. It was demonstrated that for each sensing material and optimum initial doping level exists that ensures stable performance of the sensor under neutron irradiation. In parallel, R&D on metallic Hall sensors was conducted leading to the first prototypes of copper Hall sensors with the design compatible with general requirements for use of these sensors at future fusion devices. The operational parameters of these samples were characterized in the wide range of calibration magnetic fields, biasing currents and temperatures. Neutron irradiation tests are under preparation.
Ref.: [33, 72]

Development and testing of advanced materials (metals and ceramics)
for future reactor systems

Irradiation and characterisation of fusion-relevant materials.
Principal Investigator: J. Matějíček
Following the 2010 irradiation campaigns, the remaining samples were extracted from the irradiation capsules. Measurement of electrical properties of the plasma sprayed metallic materials was performed on the modified rig. An order-of-magnitude decrease in conductivity was observed. Complex metallographic examination (including porosity, hardness and phase and composition) of both un-irradiated and irradiated glass-ceramic samples from Politecnico Torino was performed. No significant changes in properties or composition was observed, except for slight discoloration, which might be a result of irradiation-induced defects. A paper including these results was submitted to J. Nucl. Mat. Transport of the steel samples to Ciemat is planned for April 2012, for TEM studies of structural changes. Due to ongoing reconstruction of the hot cell labs in Juelich, results from the thermal conductivity and high heat flux tests are still pending.

Development of W/Fe functional gradient materials using laser deposition.
Principal Investigator: J. Matějíček
Two alternative processing techniques were pursued: hot pressing and plasma spraying with hybrid argon-water torch. Hot pressing from powders was used to form homogeneous

stainless steel/tungsten composites as well as FGMs. Essentially full density composites with homogeneous distribution of the phases and good bonding were produced. Formation of Fe7W6 phase at the interface was found. Complex characterization of the structure, thermal and mechanical properties was performed. Extensive plasma spraying with hybrid torch and inert gas shrouding was performed, with separate optimization of spraying parameters for tungsten and steel. W/steel composites were produced at conditions chosen as optimal from the previous experiments.

Mechanical properties of advanced materials (metals and ceramics) for future reactor systems

Nano-structured ODS Ferritic Steel Development [WP2010- MAT-ODSFS]
Principal Investigator: H. Hadraba, Institute of Physics of Materials AS CR
Manifestation of the operational embrittlement of 14%Cr ODS steel in the cooling media was analysed. The detailed microstructural evaluation done in this year shown growth of temperature unstable constituents. Also increase in tensile strength and decrease in tensile extension after high-temperature annealing in air and in Pb was found. The embrittlement of the steel was explained by the porosity development and precipitates coarsening in the bulk of the steel and intercrystalline corrosion of the surface of the steel during long-time high-temperature exposition in liquid metals.

5. Training and career development

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

International Summer Training Course (SUMTRAIC)
Responsible officer: J. Stöckel
The 9th summer school SUMTRAIC in 2011 was focused to teach participants all important aspects of experimental work on tokamaks, i.e. planning of experiment, performing experiment, processing of experimental data, discussion of achieved results within a experimental group, preparing of the presentation and present results at the closing workshop. SUMTRAIC 2011 was attended by 10 participants from six European contries, two parcicipants were Czech students.

Collaboration with the top level French engineering school "Ecole Nationale Superieure d'Arts et Metiers" (ENSAM).
Responsible officer: R. Dejarnac, D. Sestak, J. Stockel, M. Tichy, M. Chichina
The collaboration with the French engineering school ENSAM was always fruitful, for us and for the students doing their internships in our laboratory. This year was not an exception. We hosted 3 students for 3 long-period internships (6 months) and it gave excellent outputs. The students were all working on modeling of the full COMPASS tokamak in 3D using the CATIA (c) software and on designing diagnostics for COMPASS as such as electromagnetic probes (U-probe, Sandwich probe, Ball-pen probe) or part of diagnostics like an articulated manipulator, holders, valve and beam dump. Probes will be used on COMPASS in very near future during experimental campaigns to investigate edge plasma physics. Support of the Charles university allowing to use the Erasmus Mundus mobility is acknowleded. Subjects for new internship proposals in 2012 will be prepared, the collaboration will continue next year.

IPP collaboration with Czech Universities
Responsible officer: J. Mlynář
In 2011 both academic terms were quite busy with students at COMPASS tokamak in due to high number of students who decided to participate regular fusion courses of IPP experts and/or to start their thesis on COMPASS. Besides, several seminars for students were organised at IPP. At the same time, IPP participated in co-operation with FUSENET and became an associated member of the Erasmus Mundus Fusion Doctoral College.
Ref.: [35, 39, 40]

Undergraduate and postgraduate studies in Fusion Science and Technology.
Responsible officer: V. Svoboda
The MSc programme Physics and Technology of Thermonuclear Fusion continued at the Faculty of Nuclear Sciences and Physical Engineering of the Czech Technical University in Prague. Most of the doctoral students follow the Plasma physics curriculum at Faculty of Mathematics and physics of Charles University in Prague. Mobility of students increased considerably - most of them could participate in summer schools in particular due to the FUSENET support. Besides, FUSENET awarded a grant for upgrade of the flagship of the MSc fusion students' practica, the GOLEM tokamak. In 2011, the GOLEM tokamak continued to work regularly and in particular, in collaboration with CCFE allowed for the historical testing of plasma discharges with vertical field produced by high temperature superconductors.
Ref.: [13, 24, 35, 37, 38, 39, 40, 46, 53, 54, 56, 58, 64]

6. Other activities in magnetic confinement fusion

6.1 Public information

Foster public information in fusion.
Responsible officer: M. Řípa
Besides the regular activities, the 2011 year marked in Public Information above all the visit of UK an Czech Prime Ministers at tokamak COMPASS on 23rd June 2012. We also completed the third edition of the book The Controlled Thermonuclear Fusion for Everybody. IPP also decided to participate in preparation of the educational project „Materials for the third Millennium“ which in 2012 won the EU support. IPP participated in two exhibition fairs and in the regular Week of Science. The association published approximately 30 newspaper articles and read 10 lectures for high school students.

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

Improve laser radiation coupling to ICF targets..
Principal Investigator: J. Ullschmied
The experiments with jet-like structures created by laser interaction with planar targets, conducted at the PALS Research Centre with with participation of IPPLM-Warsaw teams helped to elucidate the role of several competing mechanisms of the jet formation and to optimize the jet parameters from the point of view of their applications in science and

technology. They demonstrated also the possibility of efficient jet guiding and collimation in cylindrical or conical channels. The next experiments were aimed at exploiting mutual interaction of plasma jets of different composition for their efficient steering, shaping and compression. In the year 2011 these activities gave rise to 9 new publications [47-52] and [88-90].
Ref.: [47, 48, 49, 50, 51, 52, 88, 89, 90]

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
The "Watching brief report on the development in the area of inertial fusion energy in the period 2007-2011" elaborated on the base of contributions by 9 participants of the IFE-KiT activites, including the IPP-CZ contribution, was presented by the IFE-WG chaiperson Sylvia Jacqemot at the 53rd meeting of the Consultative Committee for the EURATOM specific research and training programme in the field of Nuclear Energy (CCE-FU) on October 5, 2011.
Ref.: [91]

III GENERATED INFORMATION AND INTELLECTUAL PROPERTY

1. Generated information

In this part, the list of 2011 research publications of the Association EURATOM / IPP.CR is presented. For the generated Public Information please refer to Part IV, section 7.

[1] **Urban J., Decker J., Peysson Y., Preinhaelter J., Shevchenko V., Taylor G., Vahala L., Vahala G.:** A survey of electron Bernstein wave heating and current drive potential for spherical tokamaks. *Nuclear Fusion* 51 (2011) 083050

[2] **Urban J., Decker J., Peysson Y., Preinhaelter J., Shevchenko V., Taylor G., Vahala L., Vahala G.:** EBW H&CD Potential for Spherical Tokamaks. *19th Topical Conference on Radio Frequency Power in Plasmas*, Newport, RI, USA (2011)

[3] **Preinhaelter J., Urban J., Vahala L., Vahala G., Záruba M.:** Full Wave 2D Theory of LH Grills Suitable for Large Structures. *19th Topical Conference on Radio Frequency Power in Plasmas*, Newport, RI, USA (2011)

[4] **Laqua H.P., Chlechowitz E., Chouli B., Marsen S., Stange T., Otte M., Preinhaelter J., Urban J.:** Multi-Frequency Microwave Heating and Current Drive in over-dense Plasmas at the WEGA Stellarator. *38th EPS Conference on Plasma Physics*, Strasbourg, France (2011) 03.114

[5] **V. Petrzilka, J.P. Gunn, A. Ekedahl, L. Delpech, V. Fuchs, M. Goniche, M. Kubic, J.–Y. Pascal:** Comparison of fast electron fluxes generated in front of Passive-Active and Fully-Active Multijunction LH antennas in Tore Supra. *38th EPS Conference on Plasma Physics*, Strasbourg, (2011) P4.100

[6] **V. Petrzilka, G. Corrigan, V. Fuchs, A. Ekedahl, M. Goniche, P. Jacquet, J. Mailloux, M.-L. Mayoral, J. Ongena, V. Parail and JET EFDA contributors:** Modelling of the density modifications in front of the LH launcher during gas injection in ITER. *38th EPS Conference on Plasma Physics* (2011), Strasbourg P4.099

[7] **C.C. Klepper, R.C. Isler, L. Colas, M. Goniche, D. Guilhem, J. Hillairet, P.M. Ryan, Ph. Lotte, G. Colledani, Y. Marandet, A. Ekedahl, J.P. Gunn, V. Petrzilka, V. Martin, T.M. Biewer, D.L. Hillis, J.H. Harris, and B. Saoutic:** Spectroscopic Characterization of the Plasma in the Near-Field of RF Antennas in Tore Supra. *38th EPS Conference on Plasma Physics* (2011), Strasbourg P2.070

[8] **A. Ekedahl, L. Delpech, M. Goniche, D. Guilhem, J. Hillairet, M. Preynas, P.K. Sharma, J. Achard, Y.S. Bae, X. Bai, C. Balorin, Y. Baranov, V. Basiuk, A. Bécoulet, J. Belo, G. Berger-By, S. Brémond, C. Castaldo, S. Ceccuzzi, R. Cesario, E. Corbel, X. Courtois, J. Decker, E. Delmas, B.J. Ding, X. Ding, D. Douai, R. Dumont, C. Goletto, J.P. Gunn, P. Hertout, G.T. Hoang, F. Imbeaux, K. Kirov, X. Litaudon, P. Lotte, P. Maget, R. Magne, J. Mailloux, D. Mazon, F. Mirizzi, P. Mollard, P. Moreau, T. Oosako, V. Petrzilka, Y. Peysson, S. Poli, M. Prou, F. Saint-Laurent, F. Samaille, B. Saoutic:** Long Pulse operation with the ITER-Relevant LHCD Antenna in Tore Supra. *19th topical conference on RF power in plasmas*, Newport, RI, (2011), invited paper I01

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[93] **Alexander Wolff (supervised by Jan Horacek):** Heat conduction in the divertor target plate of the ITER tokamak . *Bachelor thesis,* FNSPE Czech Technical University in Prague, 2011

2. Intellectual property

No intellectual property was reported to be generated in the Association EURATOM/IPP.CR in 2011.

Regarding he intention 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, as detailed in the past Annual Reports, the proposal was still under investigation of the Patent office at the end of 2011.

IV REPORTS

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

Fast measurements of the ion temperature using ball-pen probes in the SOL of ASDEX Upgrade during L-mode

J. Adamek, J. Horacek, M. Tichy

In collaboration with:
H.W. Muller, Max-Planck-Institute for Plasma Physics, EURATOM Association
R. Schrittwieser, Association EURATOM/ÖAW
A.H. Nielsen, Association EURATOM - Risø DTU

We describe a novel probe method for ion temperature measurements by using a swept ball-pen probe. Originally ball-pen probes (BPPs) were developed to directly measure the plasma potential in DC regime. We report results of the first measurements with fast swept BPPs fixed on the midplane manipulator of ASDEX Upgrade (AUG) during L-mode to determine the ion temperature with a time resolution of 10 µs.

The ion temperature, T_i, is one of the most important but also most elusive parameters of toroidal fusion plasmas. In the scrape-off layer (SOL) of tokamaks, retarding field analyzers are routinely used to provide T_i with low time resolution. Ion sensitive probes, especially Katsumata probes, can also be used to determine the ion temperature with higher time resolution. This technique requires simultaneous sweeping of collector and metal shielding to measure only ion current. Thus, it is difficult to identify the pure exponential part of the *I-V* characteristics.

We have developed a novel method to measure T_i, using a swept ball-pen probe (BPP) [1,2]. The electron branch of the *I-V* characteristic contains the exponential decay of the ion current magnitude with the coefficient T_i, starting at the plasma potential which here is equal to the collector's floating potential. The electron current is mainly saturated or linearly increasing with the probe voltage. The fitting procedure starts at an exact value where the probe current is zero and the probe potential is close to the plasma potential, i.e. $I = 0$ A and $V \approx \Phi$. Note that in case of a Katsumata probe or BPP the ions are partially transported across the magnetic field into the shielding tube by Larmor motion. The ions and electrons are also transported inside the shielding tube by $\boldsymbol{E}\times\boldsymbol{B}$ drifts, as was recently found by 3D PIC simulations [3]. Therefore T_i can be deduced from the exponential part of the *I-V* characteristics of the BPP if the collector is retracted by a value equal to about two times the ion Larmor radius.

The BPP head is mounted on the mid-plane manipulator of ASDEX Upgrade (AUG) and inserted several times during L-mode discharges into the SOL with $B_T = -2.5$ T, $I_P = 0.8$ MA, $n = 4{\cdot}10^{19}$ m^{-3}, $P_{ECRH} = 0.8$ MW. The single BPP was swept from 0 to +200 V with a frequency of 50 kHz. It provides about 20 data points per each characteristic since the sampling frequency is 2 MHz, as seen in the example of an *I-V* characteristic in Fig. 1a.

Radial profiles of ion and electron temperatures are plotted in Fig. 1b. The electron temperature T_e is provided by the difference of the second BPP and neighbouring Langmuir probe potentials divided by 2.2. Both profiles provide averaged values with corresponding error bars. We see an increase of the ion temperature towards the separatrix from 30 eV to 80 eV. The ratio T_i/T_e is exponentially decreasing down to approximately 5 at a normalized radius of 1.015 (≅ 10 mm from the separatrix). Similarly different values of the ratio T_i/T_e are also reported in [4]. The ratio varies from 2 to 3.5 on the separatrix on AUG during L-mode discharges.

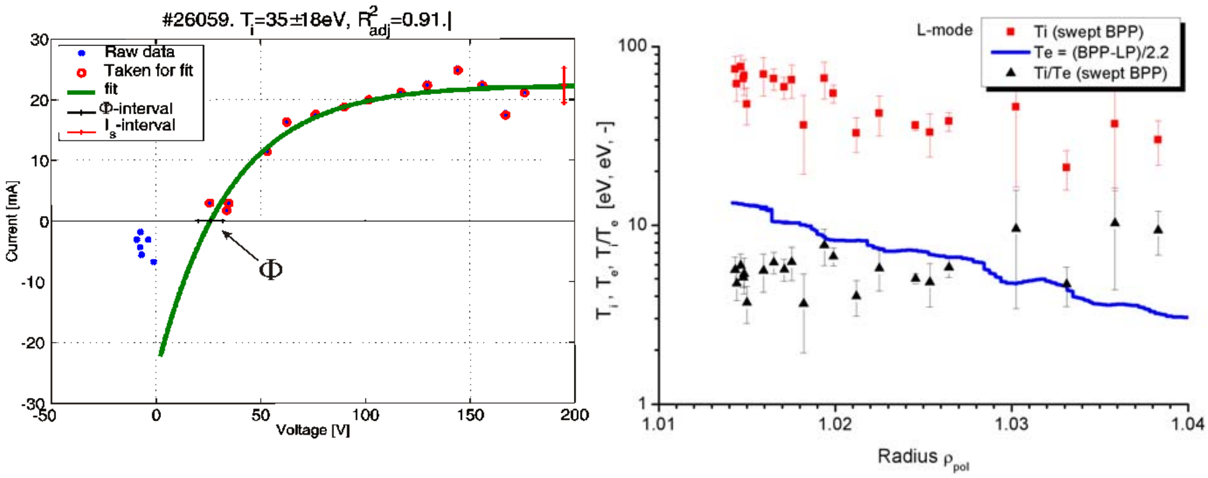

Fig. 1. a) Example of I-V characteristic of swept BPP0 with exponential fit. The red points are used for the fit procedure, the green line shows the resulting fit of the electron branch. b) The averaged radial profiles of the ion and electron temperature and its ratio.

The fast swept BPP delivers the ion temperature with a time resolution of 10μs. However, the sweeping frequency must be higher to capture also fluctuations. The ratio *Ti/Te* decays exponentially towards the separatrix from 10 to 5. The BPP has simple and compact design.

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ESEL development

J. Seidl, J. Horáček

In collaboration with:
A. H. Nielsen, Association EURATOM-Risø
E. Havlíčková, Association EURATOM-CCFE

Our work was focused on development of an algorithm for identification of blobs inside two-dimensional edge turbulent code ESEL [1,2]. For the identified blobs, their movement is tracked along the scrape-off layer (SOL) region and statistics of their properties such as speed, size, tilting angle or amplitude of pressure fluctuations are computed and can be compared with the overalls fluctuation statistics. This allows to determine influence of various blob properties on the plasma transport in SOL.

ESEL model was previously compared with experimental measurements on TCV [1,2,3] and JET [2], showing reasonable agreement for regime with high parallel collisionality on TCV, however revealing some discrepancies for low-collisional plasma on JET. Especially e-folding length of radial density profile λ_n is observed as too high in the ESEL simulations of JET plasmas compared to the experiment. This is confirmed also by comparison of ESEL results with reciprocating probe measurements on ASDEX Upgrade [4], which is currently in progress.

ESEL is two-dimensional model solving fluid equations in the plane perpendicular to the magnetic field, with parallel transport reduced to simple analytical expressions. In our work [5] we have shown that level of plasma outflow from the simulation region along magnetic field-lines is underestimated in ESEL compared to the predictions of 1D fluid code SOLF1D. This is one of possible candidates for explanation of the discrepancy in λ_n. This should be verified by numerical model coupling ESEL and SOLF1D codes which is under development, expected to bring first results in 2012.

In general, local (one-point) fluctuation statistics in SOL (including mean density and its radial profile) is significantly influenced by properties of turbulent structures such as their birth-rate, velocity, size and amplitude of the density and temperature perturbation. In order to evaluate these quantities, we have developed algorithm for routine detection of blobs in the density field of ESEL simulation and tracking of their time evolution. The blobs are detected in each time-step based on conditional averaging approach as areas with relative density perturbation larger then some multiple of standard deviation of local density fluctuations. The factor is typically chosen in range *1-2.5*. Matching of structures detected in the consequent times then provides blob trajectory and information on its speed. Structures detected in two different times together with their trajectory and estimation of blob dimensions and tilt made by fitting of a rotated ellipse are illustrated in Fig. 1.

As a result of scaling of blob velocity with its spatial scale and amplitude of perturbation (see [6] and references therein) we observe in the model scaling of radial velocity of plasma at given radius as a power function of local density, temperature or pressure fluctuation. For the case of temperature it is shown in Fig. 2. Results of the blob-tracking algorithm are expected to provide detailed explanation of dependence of the scaling on blob properties and reproducing of the dependency in experimental data and comparison with the model is planned.

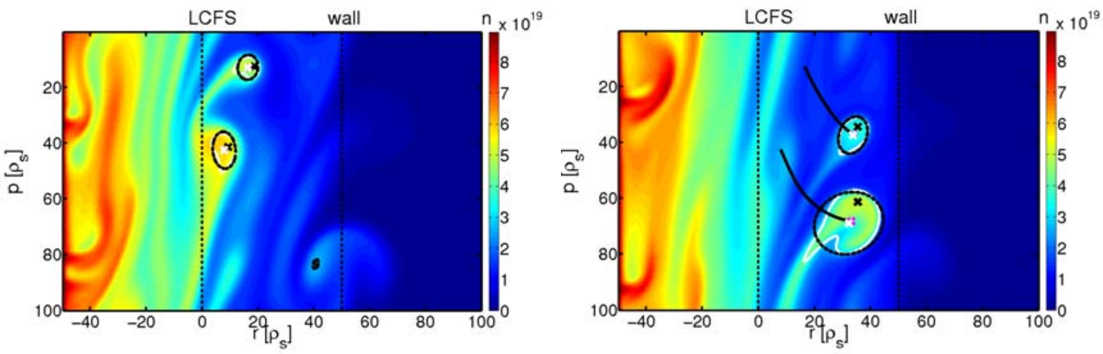

Fig. 1. Example of structure detection in density field of ESEL simulation made for parameters of TCV plasma [1]. Time difference between the two snapshots is 15 μs. Contours of areas with relative density fluctuation n/<n>-1 > 1.5σ_n are marked by white line and approximated by black dashed ellipses. Black lines mark trajectory of blobs' center of mass (white cross) between the snapshots. Black crosses are located at positions of local density maximum.

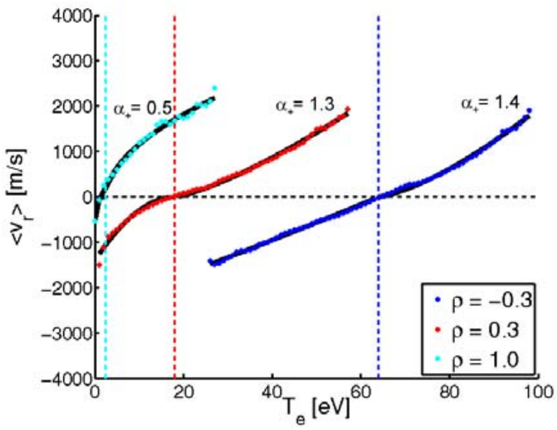

Fig. 2. Dependence of radial plasma velocity on local temperature, $\langle v_r \rangle(T_e)$, for three different radial positions in ESEL simulation (dots). Fit of the form $\langle v_r \rangle \sim (T_e - \langle T_e \rangle)^{\alpha}$ is made separately for positive and negative fluctuations (marked by solid black lines) and coefficients α_+ for the positive branches are stated.

Standard closure of parallel currents in ESEL assumes that turbulent structures are electrically disconnected from material surface at the ends of magnetic field-lines and takes into account only convective losses of plasma vorticity. This closure allows reasonably strong velocity shear to develop in the vicinity of last closed flux surface, but at the same time results in fluctuations of plasma potential being too large compared to experimental observations. Especially for plasmas with lower values of parallel collisionality, closure describing sheath-connected regime of blobs should become relevant. So far, there were problems with implementation of this term in the ESEL model, resulting in weakened transport barrier and very flat density profiles in the SOL. By changing potential boundary conditions in the simulation domain we have managed to stabilize simulations with sheath-connected terms even for low electron temperatures, that appeared most problematic in the past. This introduces new free parameter to the model, but on the other hand brings positive effects like suppressing potential fluctuations to the level of fluctuations of temperature or decreasing maximum poloidal velocities in the simulations.

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Study of plasma response to the resonant magnetic perturbation field and the associated transport

P. Cahyna

In collaboration with:
A. Kirk, YQ. Liu, A. Thornton, J. Harrison Association EURATOM-CCFE
M. Becoulet, F. Orain, E. Nardon, Association EURATOM-CEA
O. Schmitz, H. Frerichs, Association EURATOM-FZJ

Plasma response to resonant magnetic perturbations (RMPs) may affect their application as an ELM control mechanism. One of the effects of RMPs are the divertor footprints - splitting of the divertor strike points into spiralling patterns. Those footprints may serve as a useful diagnostic tool, revealing the structure of the magnetic field inside the plasma. Some disagreement of transport simulations of footprints with experiments had been found before, so we calculated the plasma response field and repeated the transport simulations using it to check if it explains the results. The transport modelling has been also applied to ITER because the divertor footprints are a potential threat to the divertor plasma-facing components.

Recent experiments on MAST have shown that the effect of RMPs is very different between even and odd field configurations, even if models using only resonant mechanisms predict the same behavior. This suggests that non-resonant effects are important. One of them is the global plasma response which can be calculated using the MARS-F code, so we continued the experimental investigations on MAST and perform simulations of footprints with MARS-F to see if they can provide an explanation.

The magnetic perturbations used as an ELM control mechanism are expected according to MHD simulations to be in some cases strongly screened by fluxes, especially in the pedestal. We previously investigated the influence which a complete screening would have on the divertor footprints which are formed as a consequence of applying magnetic perturbations to a divertor tokamak configuration. The results, reported in [1,2], show that the footprints are significantly reduced. We now continued this study, focusing on the following topics:

- Inclusion of realistic screening factor in the screening model, instead of the simple assumption of complete screening.
- Transport simulations in the perturbed field with inclusion of screening in order to explain the observations on DIII-D and predict the fluxes to the divertor of ITER.

Concerning the first subject, we used screening coefficients (ratio of expected perturbation field relative to the vacuum perturbation field) obtained by M. Becoulet using a cylindrical reduced MHD code for the case of ITER. It turned out that the screening is predicted to be strong and the screening coefficients are small, so the results are not very different from an assumption of complete screening and the footprints are significantly reduced. We also included a phase shift of perturbations due to the screening, represented as the complex phase of the screening coefficient. The screening coefficients are usually so small that their phase does not play a role and the results are virtually unchanged in comparison with a case where we disregard the phase. Nevertheless we include the phase in our calculations as it is more realistic and does not incur any penalty.

Concerning the second subject, it had been known [3] that transport simulations using EMC3-EIRENE codes in a vacuum perturbation field for DIII-D yield fluxes on divertor which are not in agreement with the low collisionality experiments, especially with heat flux which is measured to be much lower than predicted by the simulation, and less asymmetric. We thus designed a method of coupling between the screening model and EMC3-EIRENE and H. Frerichs repeated the transport simulations with the screening field included, using the assumption of complete screening on a range of resonant surfaces near the edge. The inclusion of screening brings the results in closer agreement with observation – the flattening of temperature profile, which is not observed in experiment, disappears in the screened region and the asymmetries of heat flux to divertor are reduced.

In a similar way the screened field was calculated for ITER, using screening coefficients from reduced MHD simulations, and provided to H. Frerichs for transport simulations. The case of ITER was more complicated than the one of DIII-D as the toroidal spectrum of the proposed ELM control coils is less pure and has a significant n=6 component in addition to the dominant n=3 one, so we needed to include screening of the n=6 component as well.

The ITER parts of this task were funded by the Fusion for Energy grant F4E-GRT-055 (PMS-PE).

The experiments on MAST provide an interesting opportunity of testing the plasma response models. The so-called Scenario 4 (DND with 750 kA plasma current) is the most interesting as neither odd nor even parities are fully resonant with edge field line pitch angle and both have actually a similar edge resonant field component. This scenario is thus suited to investigate field parity effects. For this reasons comparisons experiments of even and odd parities were performed during the previous years and the results were reported in [4]. As described in this reference, only the even parity had an effect on the L-mode plasma, which manifested as density pump-out after the coils had been switched on. The hypothesis presented in the paper was that the density pump-out is correlated with the displacement of the X-point, as calculated with the MARS-F MHD code. An interesting question is if the postulated differences in plasma response are revealed in the divertor footprints. We thus analyzed the footprint data for all the available L-mode shots in Scenario 4, and we developed a method of coupling the MARS-F results with the footprint calculation.

The camera data for scenario 4 show significant footprints in one of the even perturbation field phases, and no or small footprints in the other. A tentative explanation is that the footprints are the same, but rotating the perturbation moves then out of the view of the infrared camera. Interference with the error field can also play some role. For odd parity no footprints were observed, but there are only few shots available for this parity. Another interesting result is that the footprints sometimes appear suddenly during a transient event, which may indicate the penetration of the perturbation field.

Results show that the plasma response does not lead to a significant modification of the footprint shape and length, compared to the vacuum case. This is especially surprising in the ideal case, as using an ad-hoc model of screening currents, we universally obtain a significant reduction of footprints when the resonant perturbation components are fully screened by the plasma, and ideal plasma response also screens the resonant perturbation components completely, so we expected the results to be similar. The reason for this difference is not yet known and will be a subject of a future study.

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Simulations of the technique of runaway electron mitigation by magnetic perturbations

R. Paprok, P. Cahyna

In collaboration with:
C. Reux, Association EURATOM-CCFE
E. Nardon, Association EURATOM-CEA

Runaway electrons generated during the current quench phase of disruptions pose a real threat to plasma-facing components. It is therefore needed to find some mechanism to suppress them before ITER starts to operate. Our research effort should led to a better understanding of time development of coordinate space part of runaway electron probability distribution function which is necessary for estimates of effectiveness of particular runaway electron suppression mechanisms.

In past we made simulations of runaway electron trajectories in the “vacuum” field of JET EFCCs superposed with EFIT reconstruction and we found that there is no diffusion expected what was in consent with JET experimental results. Achieved results were presented in [1].

During the work on the JET data the main identified issue was the uncertainty of the background magnetic field mainly during disruption. Equilibrium code EFIT provides several very different equilibria and the results are sensitive to the choice of the background magnetic field as described in references above. Also the fact that EFIT can generate only a topology with magnetic surfaces poses a problem to get realistic predictions or runaway electron radial “diffusion” during disruption.

We have thus focused since second half of 2012 on coupling of the particle trajectory solver with the global MHD code JOREK which predicts magnetic field self-consistently during a disruption including intrinsic 3D effects - MHD modes, ergodization of magnetic field. Development of the runaway electron test particle tracking code in time-dependent magnetic potential taken from JOREK was started and now the first version of parallel particle tracking code coupled to JOREK time-dependent field is completed. We have used “PSPLINE” libraries [2] to interpolate 3D magnetic filed grid taken from JOREK code, as guiding center equation of motion we have used set of equation from [3] and as the integrator we used Runge-Kutta-78 with adaptive time step.

We made computations of time development of safety factor profile and Poincare sections in different times of reconstructed magnetic field to check the correctness of algorithm computing magnetic field from JOREK code. We found some discrepancy so there is further need to benchmark correctness of reconstruction of magnetic field. Correctness testing of trajectory integrator was performed by energy-conservation in “frozen” magnetic field and by comparing of banana orbit width with theoretical prediction. Then the code will be used to predict average radial displacement of runaway electrons under different mitigation scenarios (MGI, Pellets, RMP *etc.*).

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Study of electron runaway production in COMPASS

L. Kocmanova, V. Fuchs

The CQL3D code [1] was applied for the study of runaway electrons in the COMPASS tokamak [2]. CQL3D is general facility for calculation of particle distributions in a tokamak: it is a multi-species, 2D in velocity space, 1D in non-circular plasma radial co-ordinate, fully relativistic, bounce-averaged, collisional/quasilinear Fokker-Planck equation solver. 2D in velocity space means parallel and perpendicular velocity or a scalar energy and the pitch angle. 3D in space can be reduced because of axisymmetry and symmetry around the cross section center.

The particle distributions are taken to be toroidally symmetric and independent of azimuthal angle about the ambient magnetic field. Radial drifts are neglected but the radial transport is included. The radial transport includes diffusion and pinch terms. With the bounce-average, account is taken of variations as a function of (non-circular) radial coordinate, poloidal angle, and two momentum-space directions. A kinetic bootstrap current calculation is included. Distribution functions are calculated on each flux surface and are plotted on 10 selected surfaces. Thus we can follow how the distribution function deviates from a Maxwellian at various distances from the tokamak core.

A typical steady state ohmic electric field is E≈1 V/m. Table 1 shows the normalized runaway rate γ and runaway rate Γ for the typical steady state ohmic electric field at the 10 selected flux surfaces. The distance from the core along the minor radius is in the first column. The corresponding electron temperature and density are plotted in Fig.1. The sharp increase of runaway rate at the plasma edge owes to the corresponding drop in density. The dependence on Z_{eff} is shown in Table 2, where comparisons from various calculations of the normalized runaway rate γ are shown. The critical electric field E_c increases with the distance from the core and falls with Z_{eff}.

The results will be verified in 2012 using an HXR camera (on loan from CEA Cadarache) to be installed on the COMPASS tokamak.

Tab. 1. Electron runaway characteristics at 10 selected positions ρ=r/a along the COMPASS minor radius. A typical steady state ohmic electric field is $E \simeq 1$ V/m, ν_0 is the electron collision frequency.

ρ=r/a	Te [keV]	10^{-19} n_e [m^{-3}]	10^{-5} ν_0 [1/s]	10^{-9} v_e [m/s]	10 E/E_c	v_c/v_e	γ	$\Gamma=n_e\nu_0\gamma$
0.025	1.1	2.00	0.94	1.39	1.04	3.1	$7.3\text{x}10^{-4}$	$2.83\text{x}10^{21}$
0.15	1.05	1.93	1.0	1.34	1.05	3.08	$4.9\text{x}10^{-4}$	$9.46\text{x}10^{20}$
0.25	0.91	1.85	1.15	1.26	1.02	3.13	$2.8\text{x}10^{-4}$	$5.96\text{x}10^{20}$
0.35	0.75	1.76	1.44	1.14	0.94	3.26	$1.2\text{x}10^{-4}$	$3.04\text{x}10^{20}$
0.45	0.57	1.66	2.03	1.00	0.80	3.53	$3.1\text{x}10^{-5}$	$1.04\text{x}10^{20}$
0.55	0.39	1.53	3.26	0.84	0.63	4.0	$4.0\text{x}10^{-6}$	$2.00\text{x}10^{19}$
0.65	0.23	1.39	6.25	0.64	0.44	4.8	$1.1\text{x}10^{-7}$	$1.00\text{x}10^{18}$
0.75	0.12	1.22	15.3	0.45	0.26	6.2	$1.22\text{x}10^{-10}$	$2.28\text{x}10^{15}$
0.85	0.045	0.79	37.5	0.28	0.16	7.9	$5.18\text{x}10^{-14}$	$1.53\text{x}10^{12}$
0.95	0.022	0.20	27.5	0.20	0.32	5.6	$6.45\text{x}10^{-9}$	$3.55\text{x}10^{16}$

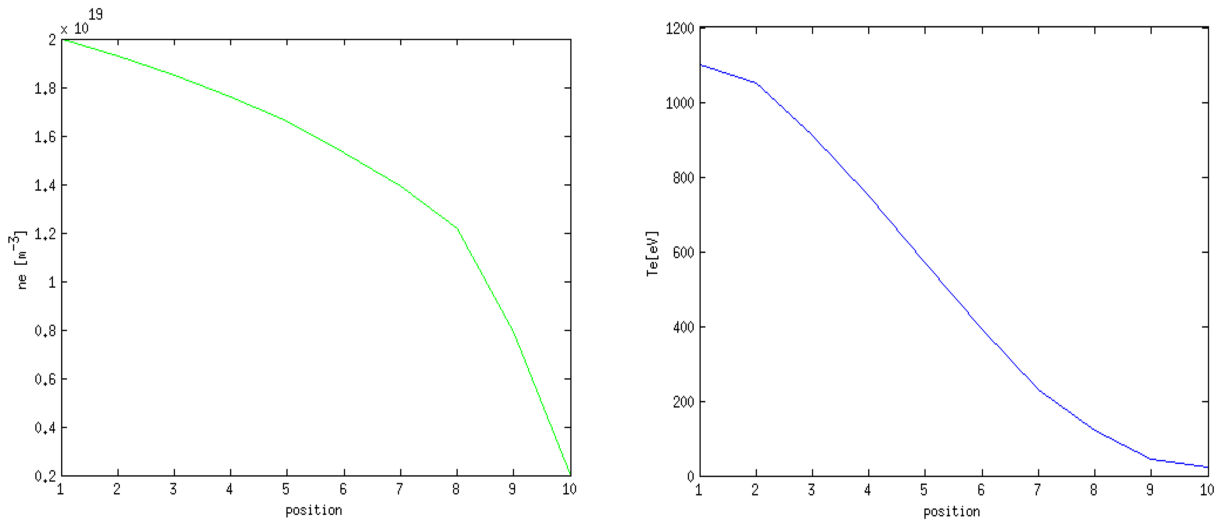

Fig.1 Shown is the electron density and temperature at radial positions corresponding to Table 1.

Tab. 2 Dependence of runaway rate γ on Z_{eff}, and on the critical field E_c, from theories of Kruskal-Bernstein [3], Lebedev [4], and from the CQL3D code [1].

	Z_{eff}=1				Z_{eff}=2				Z_{eff}=3		
E_c	γ_{KB}	γ_L	CQL3D	E_c	γ_{KB}	γ_L	CQL3D	E_c	γ_{KB}	γ_L	CQL3D
7.5	1.9e-3	1.3e-3	1.5e-3	7.1	9.6e-4	1.6e-3	1.0e-3	7.0	5.3e-4	1.8e-3	7.3e-4
7.5	1.9e-3	1.3e-3	1.1e-3	7.2	9.3e-4	1.6e-3	7.3e-4	7.0	5.1e-4	1.7e-3	4.9e-4
8.3	1.3e-3	8.5e-4	7.4e-4	7.9	6.4e-4	1.0e-3	4.4e-4	7.7	3.4e-4	1.2e-3	2.8e-4
9.5	8.0e-4	4.5e-4	3.6e-4	9.0	3.6e-4	5.6e-4	1.9e-4	8.8	1.8e-4	6.4e-4	1.1e-4
11.5	3.0e-4	1.5e-4	1.2e-4	11.0	1.3e-4	2.0e-4	5.7e-5	10.7	6.5e-5	2.3e-4	3.0e-5
15.2	6.4e-5	2.6e-5	2.4e-5	14.5	2.6e-5	3.6e-5	9.0e-6	14.1	1.1e-5	4.4e-5	3.9e-6
22.7	3.3e-6	9.8e-7	1.3e-6	21.6	1.1e-6	1.6e-6	3.5e-7	20.9	4.4e-7	2.1e-6	1.1e-7
36.5	1.8e-8	3.9e-9	4.4e-9	34.7	5.5e-9	7.9e-9	6.5e-10	33.6	1.8e-9	1.2e-8	1.3e-10
59.6	6.1e-12	9.0e-13	5.6e-12	56.4	1.7e-12	2.7e-12	5.2e-13	54.5	4.5e-13	5.3e-12	7.1e-14
30.8	1.5e-7	3.6e-8	9.9e-8	29.1	5.0e-8	6.9e-8	2.5e-8	28.2	1.8e-8	1.0e-7	7.6e-9

In conclusion, at typical ohmic operating conditions in COMPASS, considerable electron runaway is predicted. The runaway rate peaks at the plasma core, wherefrom the runaway electrons are expected to diffuse to the edge.

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Exploration of fuel removal methods compatible with retention in mixed materials and metals, including beryllium and dust generation and characterization (WP11-PWI-02) Chemical Cleaning Methods

(WP11-PWI-02-02)

Z. Herman
J. Heyrovsky Institute of Physical Chemistry AS CR

In collaboration with:
Prof. P. Scheier, Prof. T. D. Märk et al., Institute for Ion and Applied Physics, University of Innsbruck, Innsbruck, Association EURATOM-ÖAW, Austria

Ion-surface interactions were studied between nitrogen-containing ions and hydrocarbon ions of different incident energies colliding with beryllium kept at different temperatures.

Survival probabilities of slow ions colliding with room-temperature and heated surfaces of beryllium.

Earlier data on survival probabilities of ions interacting with surfaces of carbon and tungsten and preliminary data on collisions with beryllium surfaces were complemented by measurements of the survival probability of selected C1, C2, and C3 hydrocarbon ions and some non-hydrocarbon ions (CO_2^+, N_2^+) on surfaces of beryllium. For the incident angle of 30° (with respect to the surface) and incident energy of 31 eV, the dependence of the absolute survival probability (S_a) on the ionization energy of the ion in question (IE) showed a linear dependence in semi-log coordinates (Fig. 1) and could be correlated using the emprirical relation log S_a = (2.9±0.6) – (0.31±0.06)IE for both room-temperature (hydrocarbon-covered) and heated (600°C) surfaces. The similar dependence for both non-heated and heated surfaces may be presumably due to a similar work function of heated samples containing substantial amounts of beryllium oxide and carbides on the surface and hydrocarbon-covered non-heated surfaces.

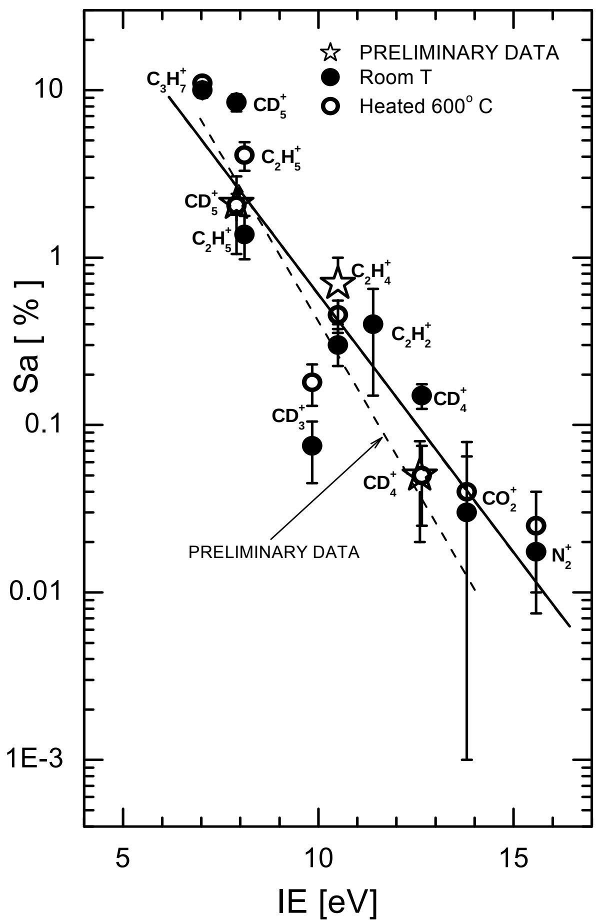

Fig. 1. Survival probability as a function of the ion energy

By these measurements, the data on correlation of survival probabilities of ions on several ITER-relevant surfaces of carbon, tungsten, and beryllium, both room-temperature and heated to 1000 K, were complemented. The expressions obtained make it possible to estimate the unknown survival probability of an ion on these surfaces from the ionization energy of the ion. The results are summarized in Table 1.

Tab 1. Values of parameters a and b in the plots log $S_a = a - b$ (IE) for different surface (incident angle $\Phi_s = 30^0$, incident energy E_{inc} = 31 eV).

Surface	*a*	*b*
Carbon (HOPG), RT[a]	3.9±0.5	0.39±0.04
Carbon (HOPG), H[b]	5.4±1.1	0.5±0.1
Tungsten, RT[a]	2.9±0.2	0.35±0.02
Tunsten, H[b]	2.5±0.4	0.35±0.04
Beryllium, RT[a]	2.9±0.6	0.31±0.6
Beryllium, H[b]	2.9±0.5	0.31±0.5

[a]Room-temperature surfaces
[b]Surfaces heated to 600^0C

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Combined 3D Particle-In-Cell & neutral transport modelling of the gap crossings

Michael Komm, R. Dejarnac

In collaboration with:
D. Matveev, Association EURATOM-FZJ

Particle-In-Cell (PIC) simulations of the gaps between divertor tiles can serve to understand plasma interaction with the divertor and predict heat and particle fluxes impacting onto the tiles. This has a critical importance for ITER, as the heat fluxes must not exceed material limits of the divertor. The problem of the heat fluxes falling on the tile edges has been previously addressed by means of 2D PIC simulation by using the code SPICE2. This approach required separate simulations for poloidal (PG) and toroidal gaps (TG) and assumed the gaps to be of infinite length. In order to simulate more realistic geometry with crossings between PG and TG, a full 3D PIC code is required. Such code (SPICE3) has been developed and benchmarked with SPICE2.

The first simulations have revealed a new mechanism of electron transport inside PG, which modifies the potential distribution inside the gap and subsequently the deposition of ions on gap sides. Since both PG and TG have preferred side for particle and heat deposition, one of the tile corner at the crossing receives higher heat flux then predicted by 2D simulations (up to 1.7x). Note that since the full 3D simulations are extremely demanding on computational power, the simulation had to be performed for plasma conditions, which are relevant for existing tokamaks, however far from conditions expected in ITER divertor. The point of this preliminary simulation was not to predict heat fluxes for ITER divertor but to demonstrate mechanisms which take place in the gap crossings. In order to achieve realistic ITER conditions, the code will have to be substantially accelerated and its parallelization improved. First part of this process was already performed and SPICE3 now calculates approx. 2x faster than at the beginning of 2011, with lower memory footprint.

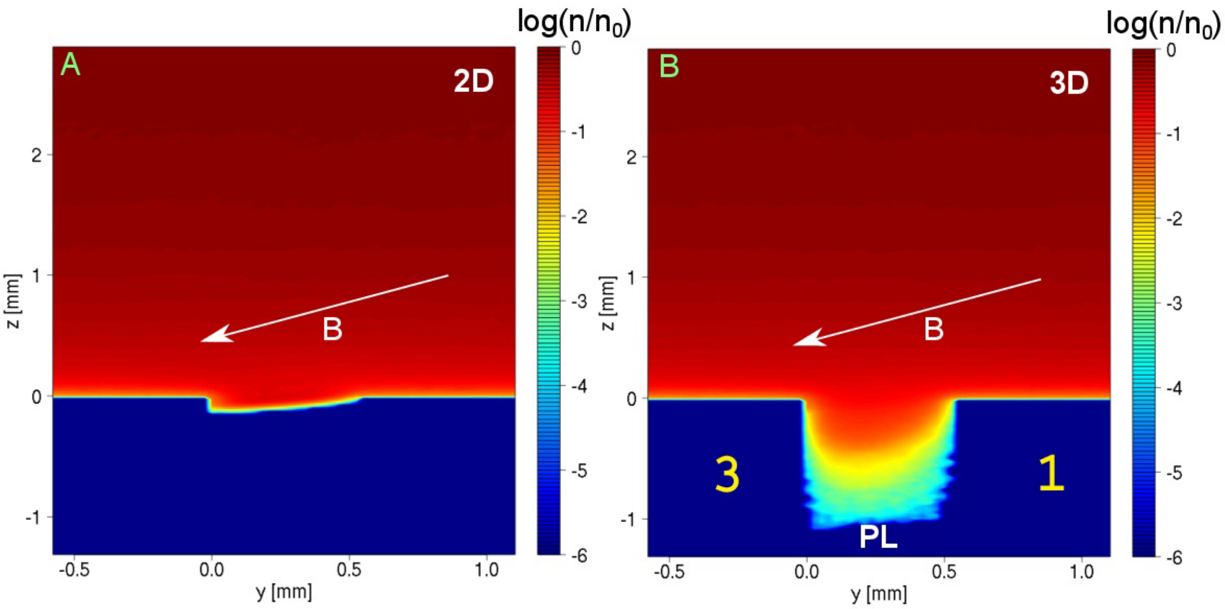

Fig. 1. Electron density inside PG simulated by SPICE2 (left) and SPICE3 (right)

Second part of the study addressed the influence of magnetic field orientation onto the particle and heat fluxes falling on tile edges. Contemporary tokamaks have gaps aligned strictly in poloidal or toroidal sense, however a transition between these two orientations is in principle possible. A series of simulations have been performed, where the total angle between magnetic field and the top tile surface has been kept constant but the orientation has been gradually changed from 0 degrees (TG) to 90 degrees (PG).

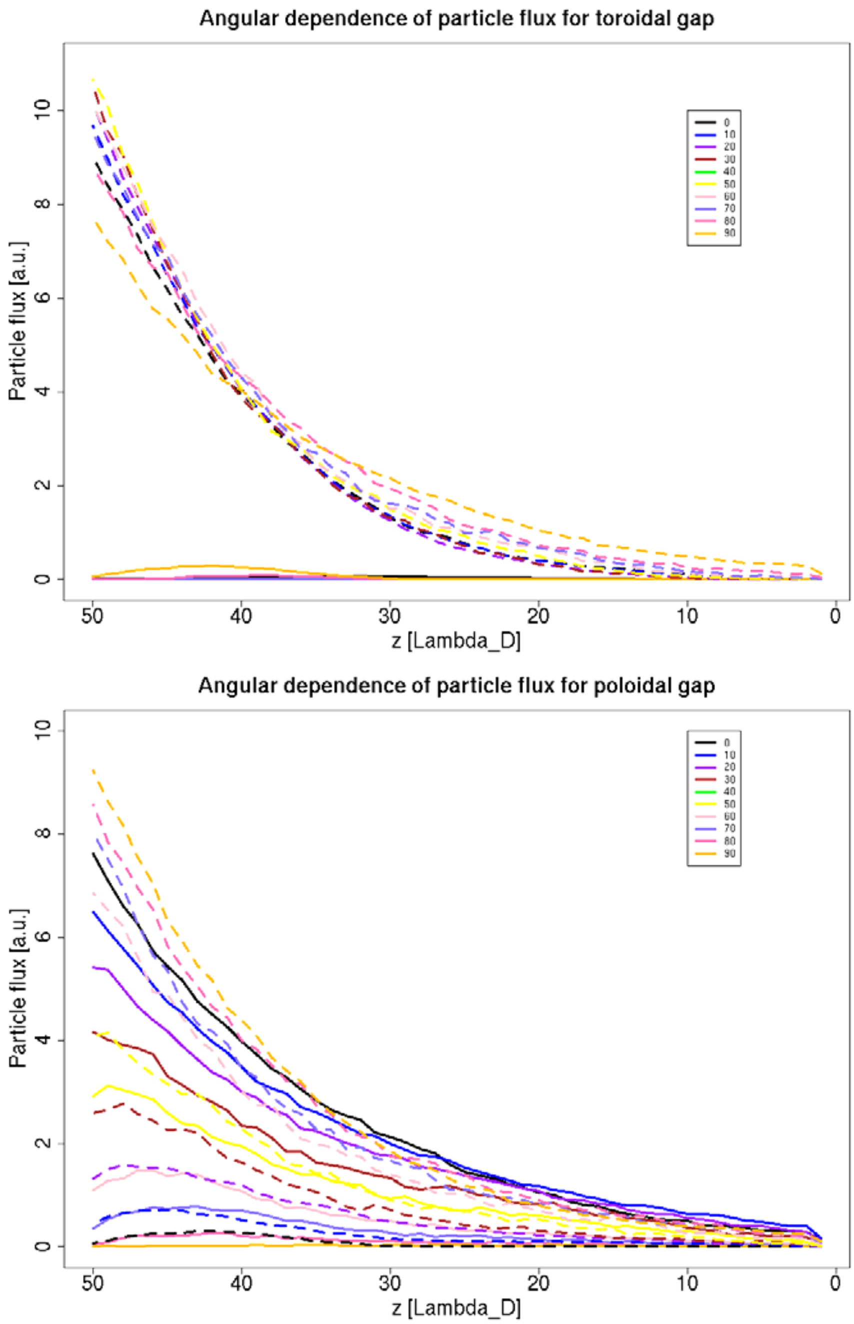

Fig. 2. Particle flux dependence on magnetic field orientation in TG (top) and PG (bottom)

The simulations have revealed that the peak flux in the PG can be substantially decreased, when the orientation is approaching 45 degrees, however the maximal flux in TG shows little variation with the angle. This is due to different mechanisms leading to the flux asymmetry. In PG the asymmetry is due to one side of the gap being opened to direct plasma flux (and therefore depends on the total angle between the magnetic field and the gap side), while the other side is in the plasma shadow. In TG the asymmetry is due to the sense of ion gyration. Since the ion trajectories in the vicinity of TG are heavily distorted by the sheath electric fields, the dependence on the orientation is reduced. In total the simulations have shown that the divertor tiles are not very sensitive to the orientation of the magnetic field.

PIC Simulations for ITER and Diagnostics

R. Dejarnac, M. Komm, D. Sestak

In collaboration with:
R. Pitts, ITER Organization, Cadarache, France
M. Matejka, Comenius University in Bratislava, Slovakia
A. Huber, A. Kreter, B. Schweer, Forschungszentrum Juelich, Germany
J. P. Gunn, IRFM, Association EURATOM-CEA, Cadarache, France
D. Tshakahaya, Innsbruck University, Association EURATOM-OAW, Austria

Simulations are nowadays important tools for physicists, especially for predicting results, for ITER for example, or to understand the physics by comparison with experiments. However, one needs reliable and powerful codes. This task concentrate of both aspect by optimizing the cpu-time of our in-house particle-in-cell codes and to compare results with experimental data from dedicated probe to validate our model. Predictive calculations have also been made for ITER and a new collaboration with our neighbours from Comenius University in Bratislava, Slovakia, was created.

The first and important point of this more general task about particle-in-cell (PIC) simulations deals firstly with the optimization of our codes SPICE2 and SPICE3, 2D and 3D PIC codes respectively, for a better use of CPU-time. PIC codes are extremely useful to describe the physics of charged particles in complex geometry but are extremely slow since they calculate all particle trajectories. Effort in optimizing the CPU-time is highly relevant and needs a lot of effort. For example, ITER simulations can run for several months! So, in this respect, we have undergone a reorganization of the code lines to enhance the code performances. When running in our PC server at IPP Prague, simulations can be enhanced by the use of graphic cards. Those have been implemented and they optimize the speed of operations by a better coordination between the cores of our multi-core PC. Finally, we modified the initial scheme used for the parallelization of the code. This new parallelization allows us to gain 10% in speed of operations. This point is completed but the optimization of our code is constantly running since everyday brings new improving techniques.

The second point of this task consisted in using our in-house PIC codes to simulate the plasma (particle and heat fluxes) deposition in ITER plasma facing components during non-ELMy discharges, especially in gaps between tiles of the divertor plates. Our previous study, last year, was to study the same consequences but during ELMs [1]. The main point is to predict whether the power flux falling on the edge of misaligned tiles will be strong enough to melt the tungsten (W) tiles or not. This work was done in direct collaboration with Dr. R. Pitts from ITER Organization who is in charge of the ITER divertor and first wall design. The main result can be seen on Fig. 1 that shows the power flux profiles in a poloidal gap between 2 ITER divertor tiles. It shows that in steady-state without ELMs, the power is not deposited deep in the gap (~0.05 mm) and that the edge gets in absolute value a low flux that should not be a problem for the W tiles. This point is fulfilled.

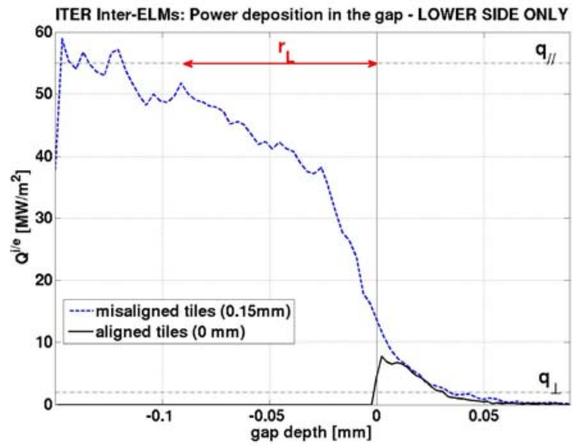

Fig. 1. Power deposition calculated for ITER by SPICE in a poloidal gap between aligned (black) and misaligned (dots-blue) tiles.

The point 3) of this task concerns simulations but also the construction of a dedicated probe, the sandwich probe. The main aim is to build a probe that recreates a gap between tiles and to measure the plasma deposition (= ion saturation current) along the gap and to compare it with our 2D and 3D simulations to validate our codes. Experiments will be done in the TEXTOR tokamak, Germany, and later on in COMPASS. The design of the probe (gap width, inclination angle with magnetic field, number of measuring segments, etc..) was made using our PIC codes. Fig. 2 shows the plasma deposition predicted by SPICE2 in a poloidal gap for typical TEXTOR edge plasma parameters. Conductive segments (green) with a thickness of 0.3 mm and insulation layers (black), 0.2 mm, have been added on the graph. With this design, we have 4 segments, which should be enough to have good spatial resolution. In the last quarter of 2011, the material for building the sandwich probe cap, block of TZM (Mo alloy), was purchased and was delivered in IPP Prague at the end of December 2011. This block of metal will be used for the probe cap that will face the plasma. It's a strong material and special technique should be used for machining it. In this respect and to finalize/validate the whole sandwich probe design, R. Dejarnac and D. Sestak, the chief-engineer at IPP Prague/TOKAMAK, went to FZ Juelich, Germany, to discuss with TEXTOR engineers. We agreed on one design and that their workshop will machine the TZM and manufacture the different parts from this material. Unfortunately, some delays occurred in the designing of this complex probe and we were not able to build the probe in 2011 as we thought, and therefore to perform experiments. However, the design is ready and the material received, so the probe will be built in 2012 and so will be the experiments. This part of the task is in progress.

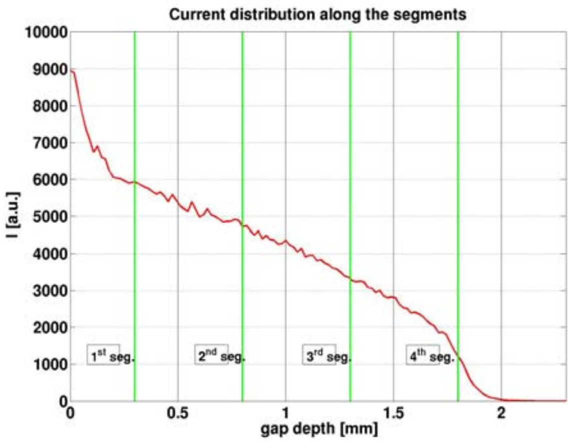

Fig. 2. Ion current profile calculated by SPICE in the sandwich probe with TEXTOR parameters. Vertical lines show segments (green) and insulation layers (black).

Last point of this task is the collaboration will Comenius University, Slovakia. Originally planned was also a collaboration with CIEMAT, Spain but this task was cancelled from their side, so we had to change topic. The new main goal is now to simulate a new kind of electrostatic probe which should be used to measure the ion temperature, the so-called cylindric probe. Our in-house 2D cylindrical particle-in-cell code has been successfully (after some bugs fixing!) installed in servers in Comenius University and has been modified for the geometry of the cylindrical probe (originally the code was used to model a concave probe, the tunnel probe, and minor modifications have been done to model the convex geometry of the cylindrical probe). After being assure that the code works correctly, a set of simulations has been performed for the exact geometry of the existing probe and typical edge plasma parameters. The ultimate goal is to compare those results with experimental ones from the unique prototype of cylindrical probe which is now mounted in GOLEM tokamak in Prague and find some calibration. This collaboration will continue in 2012.

As a conclusion, I can say that this task is completed, except for the last 2 points which are still in progress. One, because of delay and the second, because of long term collaboration with Comenius University in Bratislava, Slovakia.

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Modelling of the density modifications in front of the LH launcher during gas injection in ITER

V. Petržílka, V. Fuchs, P. Pavlo

In collaboration with:

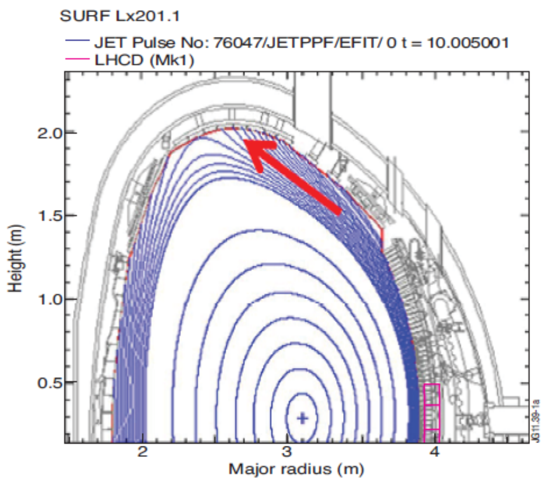
G. Corrigan, P. Jacquet, J. Mailloux, M.-L. Mayoral, V. Parail, Assoc. EURATOM-UKAEA, Culham Science Centre, Abingdon

M. Goniche, A. Ekedahl, Association EURATOM-CEA, IRFM, France

J. Ongena, Plasma Physics Laboratory, Association EURATOM-Etat Belge, RMA, Brussels

It was shown by EDGE2D modeling that the growth of the SOL (scrape-off-layer) density and the consequent LH (Lower Hybrid) wave coupling improvement can be explained by LH SOL neutral gas ionization due to heating of the SOL by the LH wave. ITER relevant magnetic configurations with the 2nd X point near to the top of the wall were considered.

In the JET tokamak, it was demonstrated that injecting gas in the outer mid-plane (OMP) can result in a peripheral plasma density increase, which improves the LHwave coupling. Gas puffing proved to be useful in JET particularly in cases with a relatively large distance of about 10 cm between the LH grill mouth and the plasma. It was shown by EDGE2D modelling that the increase in the SOL density and the consequent LH wave coupling improvement can be explained by ionization of the SOL neutral due to heating by the LH wave. In contrast to the computational grid for configurations considered before that have a SOL width of about 10 cm (Fig. 1, right) at the OMP, ITER relevant magnetic configurations, with the 2nd X point at the top, have only a several cm wide computational grid in the SOL in the OMP (Fig. 1, right).



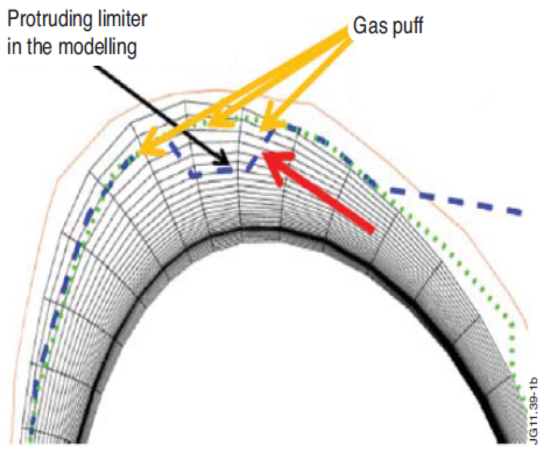


Fig. 1. Left: Iter-like geometry with the 2nd X point near to the top. Right: Wide OMP SOL grid of the shot #66972 with the top limiter. Top gas puff location in the modeling is indicated by yellow arrows. Red arrows indicate flows to the wall (left)/top limiter (right).

The EDGE2D computational grid is restricted to a rather narrow OMP SOL layer in these ITER relevant configurations, which excludes the study of processes more distant from the separatrix using EDGE2D. In the modelling, we have attempted to overcome this problem by introducing a limiter (particle sink) protruding radially down from the top, cf. the dashed blue line in Fig. 1. Then, the locations radially near to the grill mouth are connected to the wall (particle sink), similarly to the above mentioned ITER-like configuration with a 2nd X-point at the top. A comparison of the computed plasma density for a top gas puff of 1.e22 el/s (black solid line), the same puff rate injected from the OMP, similar to GIM6 (green dashed line), and no puff (red dotted line) is shown on Fig. 2.

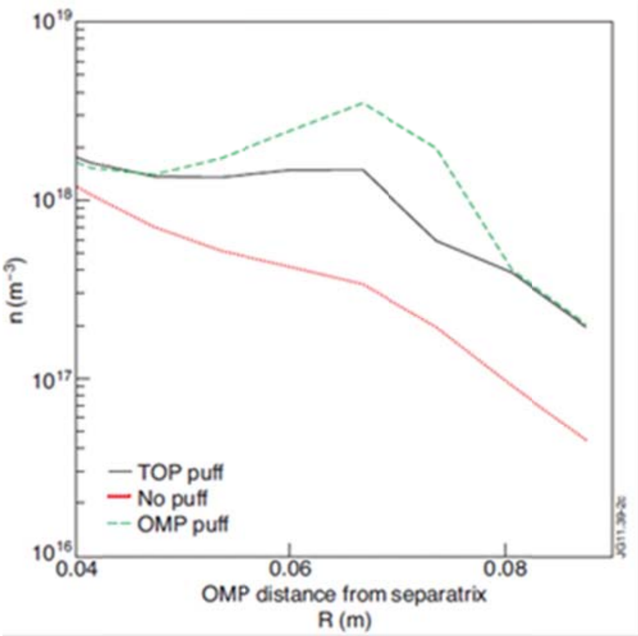


Fig. 2. Comparison of the top and OMP gas puff efficiency for the configuration with the top limiter as shown in Fig.1.

The modeling also shows that the configuration with the top limiter (i.e. ITER-like configuration) has lower gas puff efficiency than the configuration with no top limiter, and the top puff is very inefficient in ITER-like configurations. The top puff enhances at the top the far SOL density a bit more than the OMP puff, both in the configurations with and also without the top limiter. This is consistent with the density enhancement measured at the top by the Li-beam, while the LH coupling remained bad, i.e., the OMP density was not enhanced sufficiently for the coupling amendment, even if the top far SOL density increased.

In conclusion, the modeling shows that much higher gas puff rates for the top gas puff are needed for an appropriate LH coupling improvement in ITER relevant configurations.

Comparison of parasitic dissipation in front of PAM C4 and FAM C4 LH antennas in Tore Supra and fast beam energy measurements

V. Petržílka, V. Fuchs

In collaboration with:
J.P. Gunn, A. Ekedahl, L. Delpech, M. Goniche, M. Kubic, J.–Y. Pascal, Association EURATOM-CEA, IRFM, 13108 Saint Paul-lez-Durance, France

A Retarding Field Analyzer (RFA) was used during lower hybrid (LH) current drive experiments in the Tore Supra tokamak to characterize the supra-thermal particles emanating from the region in front of the C4 Lower Hybrid (LH) Passive-Active-Multijunction (PAM) grill. This work is continuation of our previous measurements on Fully-Active-Multijunction (FAM) launchers C2 and C3. The RFA collects electrons that flow along field lines from the outboard side of the tokamak. The measurements were performed when wave-guide rows of the C4 launcher were magnetically connected to the RFA. The RFA is mounted on a vertically reciprocating probe drive, situated on top of the torus. The analyzer is biased to collect only supra-thermal electrons with energy greater than 200 eV.

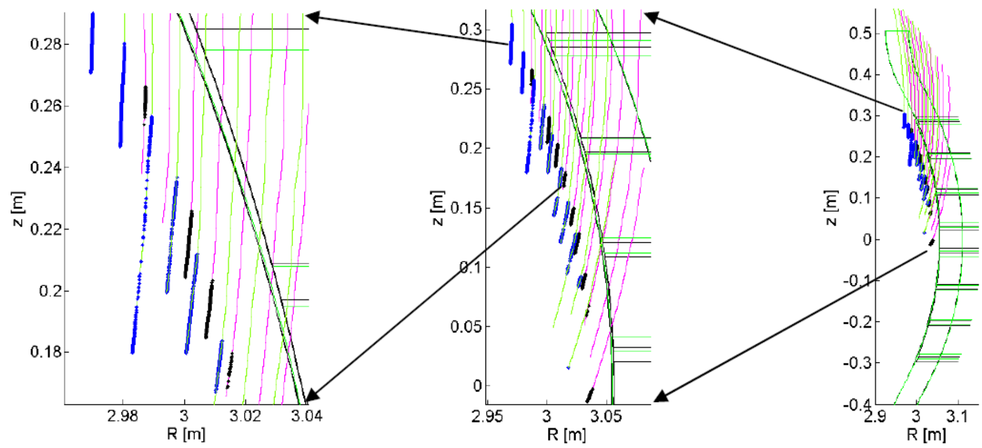


Fig. 1. Scheme of individual RFA plunges mapped to in front of the grill (magenta lines) for C3 in shot #46465 (blue dots denote measured collector current I_{co} <10 μA , green C3 grill drawing) and C4 in shot #46463 (black dots I_{co} <10 μA, black C4 drawing). The LH power is 1.5 MW.

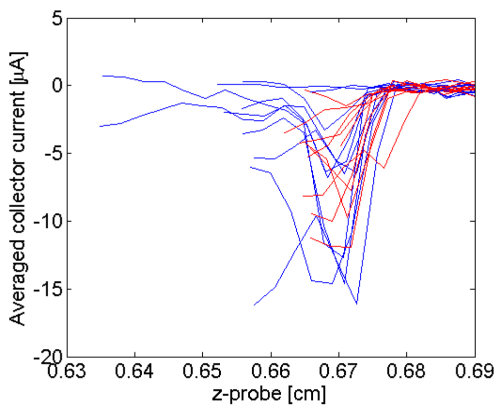


Fig. 2. Averaged collector current, C3 blue, C4 red, for individual plunges of Figure 1.

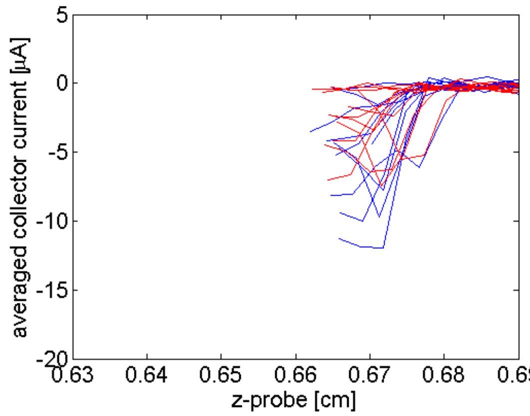


Fig. 3 Averaged collector current, 46462 blue, 46463 red, for individual plunges similarly as in Figure 1; the scale is the same as in Figure 2.

Comparison of the fast electron beam from C3 and C4 on the same plasma
The maximum power reached in the C3 and C4 comparison experiments was 1.4 MW.
We compared three similar shots: shot #46462, 63 and 65, with C4, C4 and C3 active, power 1.4, 1.4 and 1.3 MW, line averaged density 5.1, 4.0 and 4.9x $10^{19}m^{-2}$, limiter position 3.044, 3.045 and 3.044 m, respectively, and the same antenna position 3.055 m.

Energy distribution in the C4 fast beam
Fig. 4 shows measured collector currents I_{co} less then 10 μA in all RFA plunges mapped in front of the C4 grill in shots #44168,69,70, in which the voltage of the RFA electron repulsing grid Ug2 was varied from shot to shot, Ug2 = -200 V (blue, #44168), -400V (red, #44169),-600V (green, #44170).

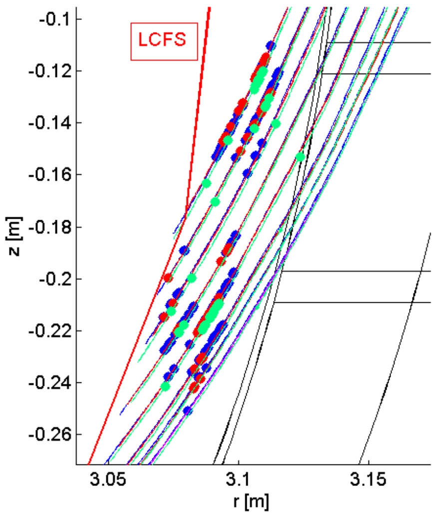


Fig. 4. Show measured values of I_{co} less than 10 μA in all plunges of shots #44168,69,70, Ug2 = -200 V (blue), -400V (red),-600V (green).

The energy distribution measurement shows that, also for the RFA electron repelling grid voltage -600V, there is still enough electrons with energy larger then 600 eV producing collector current. As it is also obvious from Figures, the main conclusion of our contribution is that the PAM (C4) grill generates lower averaged supra-thermal electron fluxes than the FAM (C3) grill for identical SOL plasma conditions.

Data analyses for neutron diagnostics at JET using Minimum Fisher Regularisation

J. Mlynář, T. Odstrčil

In collaboration with:
G. Bonheure, Association EURATOM-Etat Belge, ERM/KMS, Brussels, Belgium
A. Murari, Association EURATOM-ENEA, Consorizio RFX, Padova, Italy
S. Popovichev, Association EURATOM-CCFE, Culham Science Centre, Abingdon, UK
and JET EFDA contributors

In the second half of 2011 JET restarted experiments after the major shutdown when the first wall was completely refurbished to become the ITER-like wall. However, as expected, the C28 and C29 campaigns brought along little opportunities for neutron diagnostics, as the applied heating power and densities were kept rather low. Therefore according to the plan the work on the code package was concentrated on completion of the Python version of the Minimum Fisher Regularisation (MFR) code, which replaces the unsupported MatLab code. Secondly, data from the JET Soft X-ray diagnostics were analysed using the MFR code as will be reported in a separate contribution. Recovered interest in the neutron data analyse is expected in 2012-2013.

The transfer from MatLab to Python for neutron tomography and unfolding analyses via Minimum Fisher Regularisation (MFR) was successfully concluded in the beginning of 2011. All the routines are now available and working in the Python environment, including a user friendly GUI (see the figure) and dedicated data access, and new features including e.g. the Wavelet analyses, or rapid calculation of pre-form functions.

At the same time, the MFR implementation was extended also to analyses of JET SXR data, which is more relevant with respect to the planned JET ILW campaigns in 2011. The mobility visit to JET in August was fully devoted to development (in particular the data storage to the ppf files was coded) and analyses of past Soft X-ray data, and the secondment stay in the autumn was partly dedicated to applications of the code to the new data from the C28 campaign.

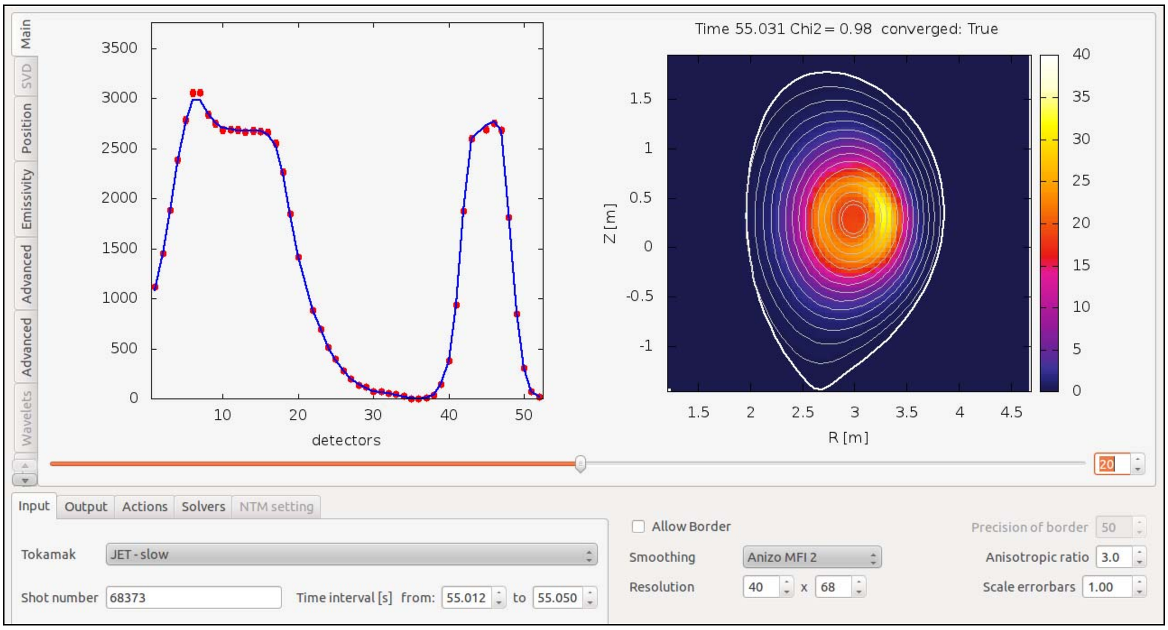


Figure 1: Graphical user interface of the new Python version of the MFR algorithm

The Python MFR code package was tested and benchmarked against MatLab version, where fully satisfactory performance was demonstrated. However, it must be noted that Python is more demanding on development and due to obsolete version of libraries for the JET Fedora operating system, the full version of tomography must be run locally (on a laptop). A simplified JET Fedora version of MFR is under development and should be implemented in the early 2012.

Basic features of the optimised code were presented at the EPS 2011 Plasma physics conference in Strasbourg, France [1] and in the Conference of Slovak and Czech physicists in Zilina, Slovakia [2]. A diploma thesis by M. Imrisek on JET tomography was also successfully completed [3], to be presented to the state committee in early 2012. A detailed article on the optimised version of MFR and some recent results from JET A is in a final stage of preparation for Nucl. Instrum. Methods, and a manual for internal use was produced [4].

The article on activated probes as a novel reactor-relevant diagnostics was finalised and published by Dr G Bonheure from ERM Brussels [5], with our cooperation in the applications of the MFR unfolding method. Increased interest in the activation technique is again foreseen in the coming years.

Last, but not least, our collaborating student Mr M Odstrcil, who considerably contributed to the MFR shift from MatLab to Python was introduced to the JET data environment. At spring, he worked on the final implementation of MFR in Python at the JET site. Partly due to this experience he won FUSENET support and spent autumn at JET, preparing data analyses of JET disruptions for his diploma thesis on learning machines.

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2. Development of plasma auxiliary systems

Development of codes for existing and envisaged LH grill for COMPASS

J. Preinhaelter, J. Urban, M. Zaruba

In collaboration with:
H. P. Laqua, Max-Planck Institut für Plasmaphysik, Association EURATOM-IPP Garching

Lower hybrid (LH) waves are very important for heating and current drive in tokamaks. Phased arrays of rectangular waveguides, generally called grills, are typically used as launchers. We develop a code which solves, in the 3D geometry of the grill structure, the problem of efficient coupling: the power density spectrum of the emitted waves, the power reflection coefficient, the power lost by the waves launched in the inaccessible region and the directivity of the waves transmitted into the accessible region. The code is also able to determine the 3D electric field in front of the grill.

An efficient adaptive full wave solver is used to determine the wave propagation in a 1D plasma slab geometry. To evaluate the very large number of 2D k-space infinite integrals for the coupling elements, we have developed a method based on high order Gaussian quadratures combined with 2D B-splines in the accessible region for the plasma related part of the integrands. This method is well suited to handle large structures and many modes because the computational time is only weakly dependent on the size of the problem. An iterative evaluation of the integrands in the inaccessible region is adopted to handle the presently overlooked near singular behaviour of the integrands as well as the spectral power density associated with the eigenmodes. The role of collisions is clarified in this context.

The code is applied to several COMPASS grills operating either at 1.3 GHz or at 3.7 GHz. First we thoroughly analyze the original 1.3 GHz, 8-waveguide conventional grill at various waveguide phasing. Then, the coupling of two grill designs for 3.7 GHz is solved. The suitability of all the grills is discussed, showing compatible grill and plasma parameter ranges. The results were presented at 19th Topical Conference on Radio Frequency Power in Plasmas and at 14th European Fusion Theory Conference, Frascati, Roma, September 26 - 29, 2011. We have also submitted a paper describing the LH grill code and the corresponding theory to the Nuclear Fusion journal in 2011.

Assessment of Lower Hybrid Current Drive System for COMPASS

V. Fuchs, J. Preinhaelter, J. Urban, F. Žáček

In collaboration with:
R. W. Harvey, CompxCo, San Diego, California, USA
R. A. Cairns, University of St Andrews, Scotland, United Kingdom
Y. Peysson, J. Decker, J. Hillairet, M. Preynas, M. Goniche, Association EURATOM-CEA

COMPASS is a compact size tokamak [1] with major radius R_p =0.576 m, minor radius r_a=0.21 m, operating at a toroidal magnetic field between 1.2 Tesla and 2.1 Tesla, and a plasma current between 0.1 MA and 0.25 MA.

Scenario	Triangularity, δ	Elongation, κ	Magnetic field, B_T [T}	Plasma current, I [kA]
SND-01	0.4	1.55	1.2	175
SND-02	0.4	1.55	2.1	250
SNT-01	0.5	1.75	1.2	175
SNT-02	0.5	1.75	2.1	250

Tab. 1: COMPASS operation scenarios foreseen for neutral beam and lower hybrid auxiliary heating and current drive

The principal operation scenarios of COMPASS were discussed in [2] and are specified in the above Tab. 1.

The IPP Prague installation of the COMPASS tokamak, originally at UKAEA Culham, came with a system capable of launching about 200 kW of lower hybrid (LH) power into the plasma at 1.3 GHz. The associated LH slow wave launcher is a Brambilla-type 8-waveguide antenna (grill), but lacking power supplies and other necessary hardware. A substantial investment is therefore necessary to render the system operational. As an alternative, IRFM, CEA Cadarache, has offered IPP Prague 3 of their older 3.7 GHz, 500 kW pulsed klystrons TED TH2103 (now replaced by a series of CW 750 kW TH2103C klystrons) to power a prospective multi-junction antenna for COMPASS. Two klystrons would be necessary to power two modules of a proposed multi-junction antenna, one additional klystron serving as reserve. Such a new LH system for COMPASS would likewise require a substantial investment into antenna construction and auxiliary hardware. We note that a prospective new LH antenna has to fit the existing machine port designated for this purpose. The port dimensions are 14 cm toroidally and 17 cm poloidally, perfectly accommodating the 8-waveguide 1.3 GHz grill, but conveniently allows two rows of waveguides at 3.7 GHz.

With LH power, COMPASS expects to achieve plasma heating and non-inductive current drive at densities which are too low for neutral beam injection (the NBI shine- through limit from FAFNER code simulations [2] is about $\bar{n} \approx 3\mathrm{x}10^{19}\,\mathrm{m}^{-3}$). We immediately mention a few reasons why in COMPASS LH power at 3.7 GHz is preferable to 1.3 GHz:

- A 3.7GHz multi-junction LH antenna has a much smaller reflectivity than the Culham 1.3 GHz standard 8-waveguide grill.
- Compared with the Culham 1.3 GHz klystrons, the 3.7 GHz TED TH2103 klystrons can deliver much more LH power. Moreover, the power density transmitted through the antenna increases with frequency.

- The 3.7 GHz LH system provides the possibility of direct comparison with other experiments in Europe which use the same frequency (Tore-Supra, JET, and is closer to the 5 GHz ITER frequency).
- Most importantly, the LHCD density limit increases with the LH source frequency [3].

The density limit is caused by parametric decay of the incident LH slow wave (the "pump") into a LH sideband and a low-frequency ion sound or ion cyclotron wave, which draws power from the pump and is thereby driven unstable [3]. The low-frequency ion wave is subsequently damped on the ions thus diverting the LH power away from the electrons. The density at which LH power absorption on the ions takes over is given by the experimentally verified condition

$$\omega_0 \geq 2\omega_{LH}; \quad \omega_{LH}^2 \equiv \frac{\omega_{pi}^2}{1+\omega_{pi}^2 / \Omega_{ce}\Omega_{ci}} \propto n_{e0}$$

where ω_0 is the source frequency and the other symbols have their usual meaning. For COMPASS, the above condition leads to the result of the following Figure, which indicates that at 1.3 GHz operation with LH is limited to below a line-average density of about $\bar{n} \approx 1.5\text{x}10^{19}\,\text{m}^{-3}$, whereas at 3.7 GHz LH operation is possible well beyond a density of 10^{20}m^{-3}.

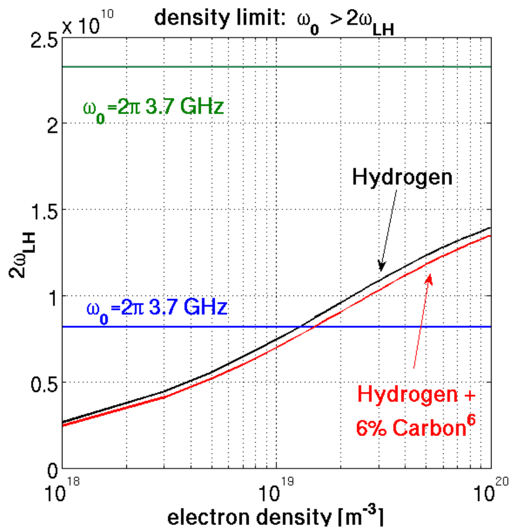

Fig. 1. LHCD density limit. Lower hybrid frequency ω_{LH} vs electron density in typical COMPASS plasma. The region of LH slow wave interaction with electrons lies below the source frequency (ω_0) lines.

We verified independently with the LUKE [4] and CQL3D [5] LHCD simulation codes that COMPASS should at 3.7 GHz easily achieve full non-inductive current drive.

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Development of the ExB analyzer

Michael Komm

In collaboration with:
M. Kocan, Association EURATOM-IPP

The ExB analyzer is a unique diagnostics for fast ion temperature measurements in tokamak SOL. The time resolution of the measurements should be sufficient to resolve fast transient events, such as ELM filaments. The analyzer will be mounted on a reciprocating probe manipulator, which has the same interface on COMPASS and AUG tokamaks. In order to optimize the design of the diagnostics, the analyzer chamber had to be simulated by means of Monte-Carlo (MC) and Particle-In-Cell simulations (PIC).

The ExB analyzer consists of several components, which geometry can critically influence the performance of the diagnostics. In order to achieve optimal measurements with high resolution, such parts have to be modeled and optimized.

One such component is the entrance slit, which serves to prevent electrons from entering the cavity of the analyzer. At the same time the slit should allow sufficient ion flux to reach the collectors. The slit can be characterized by transmission factor for ions, which ideally should be close to unity and insensitive to parallel velocities of incoming ions. The geometry of the slit has a crucial impact on the transmission factor. The slit geometry has to be also compatible with heat loads coming from the plasma and should not allow spatial charge to be built inside the cavity. In order to optimize the geometry a series of PIC simulations has been carried out by using the SPICE2 code for a conical slit with varying angle between 0 and 25 degrees. The results show satisfactory transmission for slit already at 20 degrees with low dependence on parallel velocity for v_x > 4kTe (note that the slit will be biased to a negative potential in order to repel electrons).

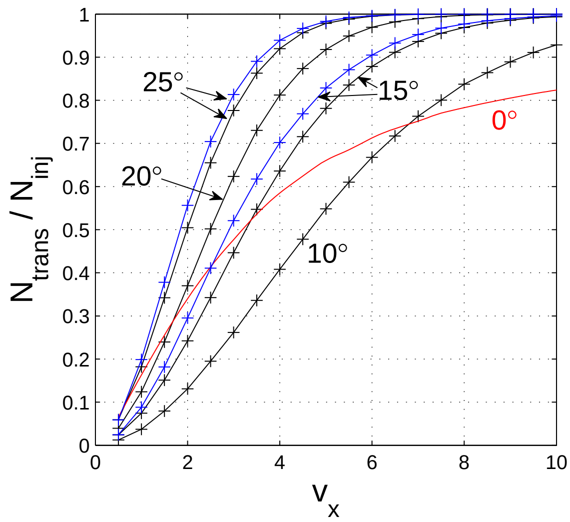

Fig. 1. Transmission factor of the slit as a function of parallel velocity for slits with different angles

Using a dedicated MC code, we were able to simulate motion of ions inside the ExB analyzer in static electric and magnetic fields. The simulated collector currents were fitted using the same procedure as will be used on experimental data and the resulting ion temperature was compared with the temperature of injected ions. It was found that there is a systematical difference between the two values:

$$Ti_{real} = k\, Ti_{simulated}$$

where the coefficient *k* is in general a function of *Ey* (electric field applied between the electrodes), *B* (tokamak magnetic field), bias voltage, *Ti* and τ (ratio of ion and electron temperature). By making a series of simulations for varying parameters, we were able to find combinations of *Ey* and bias voltage, where the coefficient k has only week dependence on *Ti* and τ .

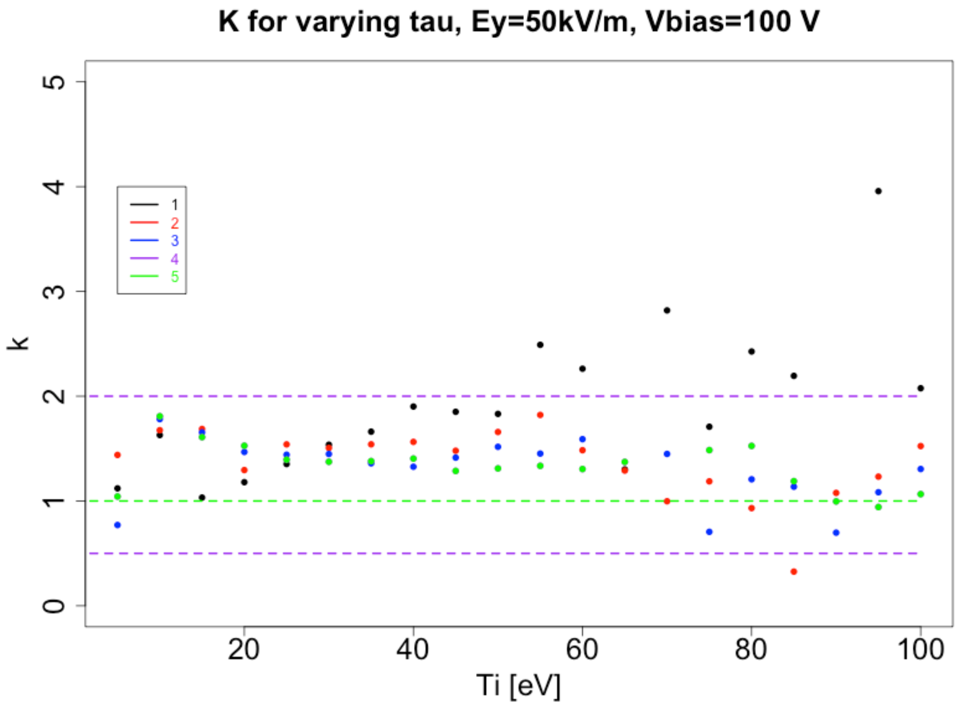

Fig. 2. Factor k as a function of ion temperature for optimal value of the applied electric field and biasing.

Atomic Beam Probe system for COMPASS

V. Weinzettl, P. Hacek, J. Krbec

In collaboration with:
M. Berta, G. Veres, G. Anda, S. Tulipan, T. Ilkei, D. Dunai, D. Nagy, A. Bencze, S. Zoletnik, Association EURATOM – HAS

The new Atomic Beam Probe diagnostic for edge current measurements by collecting the ions stemming from diagnostic beam ionization on the COMPASS tokamak is under development in collaboration with the Association EURATOM – HAS. The diagnostic system consists of the Li beam injector and the detection part based on a two dimensional array of ion collectors.

Atomic beam probe *(ABP)* is an innovatory diagnostic for measurement of poloidal magnetic field changes, and thus plasma current fluctuations in the plasma edge. It is an extension of the beam emission spectroscopy (BES) system, in which lithium ions stemming from beam ionisation are collected. For this purpose, a two-dimensional segmented multichannel system is used providing a direct measurement of the ion current. In front of the detector, there will be placed a biased entrance slit to reduce a background noise. For ABP measurements, the neutral lithium beam with standard diameter of about 1–2 cm for BES measurement will pass through a diaphragm causing reduction of its diameter to few millimeters. Also the energy of the beam will be increased to about 100 keV with respect to BES measurements with usual beam energies around 40 keV. The size of one detector segment in toroidal direction is planned to be about 0.5 mm. However, the exact dimensions and capabilities of the final detector will strongly depend on the level of noise coming from plasma (i.e. charged particles and secondary electrons generated by UV and X-ray radiation and energetic neutrals). Therefore, a test ABP detector was installed on COMPASS in order to measure a background signal and other effects disturbing ABP measurements. The test detector has 25 channels (20 detector segments, 4 Langmuir probes and one channel for grounding) and a possibility to move in a vertical direction. In the deepest position, the detector plate's front surface is 30 mm far from the wall tangent.

The Li beam system was installed on the COMPASS tokamak in summer 2011. The beam energy is gradually increased to allow ABP measurements in near future. At the same time, the new electronics for the ABP test detector was installed on the COMPASS tokamak. Noise tests were performed in the experimental campaigns in 2011 but necessary circumstances for real measurements with ABP (Li beam operation at 100 keV, H – mode plasma) have not been achieved on COMPASS yet.

References:

[1] V. Weinzettl, et al.: Overview of the COMPASS diagnostics. *Fusion Engineering and Design 86 (2011) 1227–1231*

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Electrostatic Probes for COMPASS

R. Dejarnac, J. Stockel, J. Horacek

In collaboration with:
Tsv. Popov, M. Mitov, Sofia University, Association EURATOM-INRNE, Bulgaria
M. Dimitrova, Bulgarian Academy of Sciences, Association EURATOM-INRNE, Bulgaria
J. P. Gunn, IRFM, CEA Cadarache, France

For diagnosticians, probes are and always will be important to measure quantities in situ and to have fixed points for other diagnostics comparison. IPP Prague has a long experience with probes and COMPASS benefits it. This task concerns probes from the 3 steps leading to results: design and fabrication, calibration, measurements. In order to measure plasma parameter using the novel technique of first derivative in tokamak plasma, a probe has been designed and built by our colleagues from Sofia University, Bulgaria, and measurements have been performed in COMPASS. To record the data with the less parasitic noise, special electronics was designed, based on previous test-measurements in COMPASS, was built and commissioned to Prague by our Bulgarian colleagues from Sofia University and Bulgarian Academy of Sciences for a total of 60 channels (=probes) including routine measurements with the 39 COMPASS divertor Langmuir probes. Finally using 2D kinetic simulations, a calibration was found for a new type of probe, the so-called Tunnel Probe, to measure plasma parameters and its fluctuations for any type of plasma and probe dimensions. This work has been done in collaboration with our colleague from CEA Cadarache, France.

Our long lasting collaboration with University of Sofia and Bulgarian Academy of Sciences led to a new and concrete achievement for COMPASS: 60 electronic boards for measurements of Langmuir probe data with minimum parasitic noise and good amplification. The boards were commissioned in Prague on December 2011 and a photograph of 1 box out of 3 with 20 channels can be seen in Fig. 1. This electronics will be used for the routine measurements with the array of 39 Langmuir probes in the divertor of COMPASS and for other probe measurements (21 channels) like with the new divertor array of 15 probes or for dedicated probes like ion sensitive probe, tunnel probe etc... that we plan to insert in the edge plasma of COMPASS via several manipulators. All the channels are operational and this part of the task is completed.

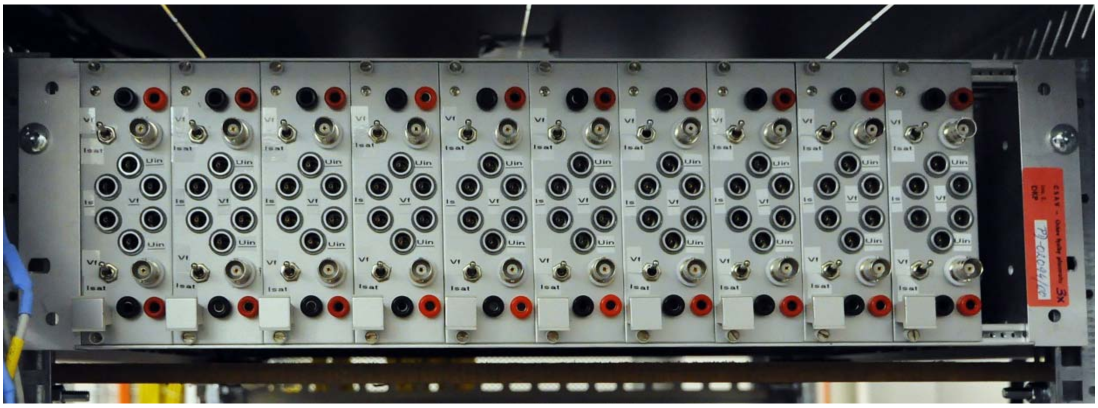

Fig. 1. Photograph of 1 of the 3 twenty-channel electronic boards built by our Bulgarian colleagues and commissioned in Prague on December 2011.

The contribution of our Bulgarian colleagues continues with the construction of a probe head, built in Bulgaria, which was mounted on the vertical reciprocating manipulator of COMPASS for measurements of heat flux decay length, λ_q, in the scrape-off layer. This is a hot topic this year in the fusion community in view of the design of ITER first wall. Several shots were used to calculate the λ_q from raw data and to add points in the ITER scaling law with data from other tokamaks like JET and TCV by Dr. Horacek (see Fig. 2). Moreover those data were processed using the (Bulgarian) first derivative method to find electron energy distribution function. Processing is still running and will most probably lead to a publication in 2012. This part of the task is also successfully completed.

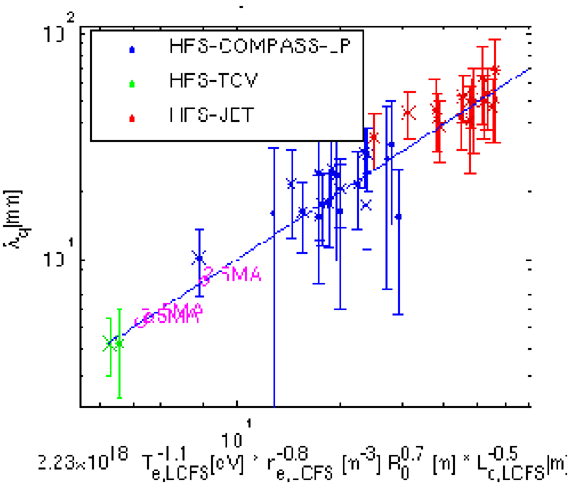

Fig. 2. Heat flux decay length in the plasma edged during the start-up phase calculated using data from COMPASS, TCV and JET tokamaks for the ITER scaling law.

Finally, the last point of this task was to calibrate the tunnel probe, a novel type of electrostatic, concave Langmuir probe [1]. We have generated tunnel probe I-V characteristics for any probe geometry, ion current, electron temperature, and magnetic field based on the 2D kinetic code [2] results from a numerical database that consists of 2500 runs. The results agree quite nicely with measurements made in Tore Supra tokamak, France (see Fig. 3). Plotted with dots are experimental I-V characteristics on the different parts of the tunnel probe and the curves represent the code prediction of ion current for each collector. It's worth noting that Tore Supra is equipped with 3 geometries of tunnel probes (different radii and depths) and the code predicts the curves quite well for all of them. Tunnel probes have already been shown to measure Jsat with very high precision [3], but now we can claim that we can use tunnel probes in DC mode to measure Te fluctuations with reasonable confidence.

As a general conclusion, we can state that the whole task was completed.

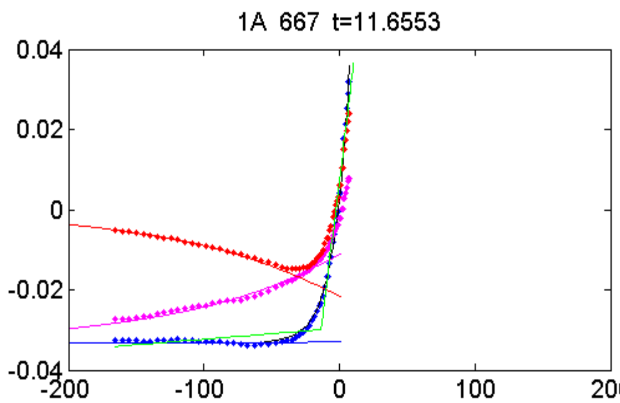

Fig. 3. I-V characteristics of the different collectors of the Tore Supra's tunnel probe (current in A and voltage in V). Dots are experimental points and lines are results from the 2D simulations. Blue is total current, red is current on the back plate and pink the current collected by the tunnel.

References:

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Application of the ball-pen probe in low-temperature magnetized plasma development of particle and hybrid computer codes

J. Adámek, J. Havlíček, M. Komm, M. Peterka, P. Kudrna, M. Tichý, R. Hrach, T. Ibehej, V. Hrubý, Z. Pekárek

In collaboration with:
R. Schrittwieser, Petru Balan, Association EURATOM-OAW, Innsbruck
T. Gyergyek, Association EURATOM MHEST-Jožef Stefan Institute, Ljubljana, Slovenia
Mirko Ramisch, Ulrich Stroth, Universität Stuttgart, Germany
Jordan Cavalier, Institut Jean Lamour, Vandoeuvre Les Nancy, France
S. Mazouffre, K. Dannenmayer, CNRS Orleans, France

Experiments in cylindrical magnetron and pulsed plasma jet continued in 2011. The ball-pen probe was tested in conditions of low magnetic field in low temperature plasma. The emissive probe as well as the Langmuir probe was applied for diagnostics of the stationary plasma thruster in collaboration with Dr. Stephane Mazouffre, and Käthe Dannenmayer, CNRS Orleans, France. The computer code library for effective solution of the Poisson equation in 2D and in 3D was finalized. The 2D particle code as well as 3D hybrid code pursued in the FMP CU was brought to functional state. In this short survey we briefly comment only the results from the experiments with ball-pen probe and the software development activities.

The ball-pen probe is an innovative electric probe for direct measurements of the plasma potential in magnetized hot plasma. The ball-pen probe can adjust the ratio $R = I^-_{sat}/I^+_{sat}$ of the electron and ion saturation currents to be close to one. If this is achieved, the floating potential of the ball-pen probe is equal to the plasma potential. The ball-pen probe consists of a metallic collector, which is shielded by an insulating tube; the probe head itself must be oriented perpendicular to magnetic field lines. Figure, detailed description and experiments performed so far can be found in our previous works, see e.g. [1]. In 2011 we tested the ball-pen probe in three experimental systems: in cylindrical magnetron in Prague, in linear magnetized plasma device in Ljubljana and in torsatron TJ-K in Stuttgart. We have used ball-pen probe with movable collector accommodated within ceramic shielding tube. Therefore, we were able to reduce the electron current by retracting collector into the shielding ceramic tube. The results of all three experiments indicate that the ball-pen probe might be applicable also for diagnostic of weakly magnetized plasma.

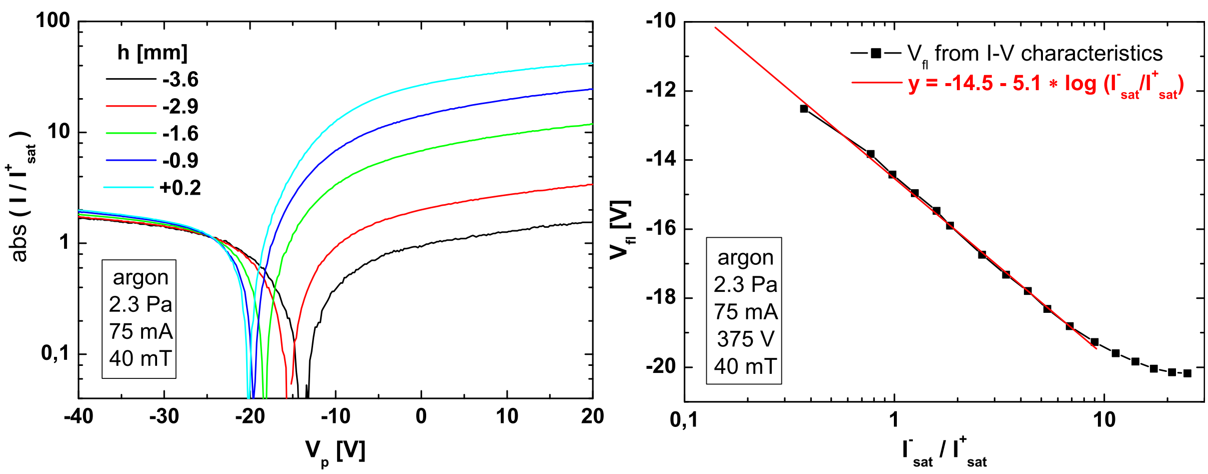

Fig.1. Left panel (a): Normalized I-V characteristics at different depths of retraction (negative h) and protrusion (positive h) of the ball-pen probe collector. Right panel (b): Dependence of the ball-pen probe floating potential on the ratio I^-_{sat}/I^+_{sat}.

Sample of the results from the magnetron system in Prague is depicted in Fig. 1. The plasma potential determined by conventional way from the ball-pen probe operating as a Langmuir probe, i.e. for positive h, was approximately −10 V while V_{fl} amounted to around −20 V. That data well agree with the data published in [2] that were taken in the same system at similar conditions. Looking at Fig. 1(b) we infer that extrapolation of the red line down to R = 0.1 gives approximately −10 V, however, at R = 1 we arrive in Fig. 1(b) on the ordinate axis at around −14.5 V. At the same time follows from the simple theory assuming the Maxwellian electron energy distribution function and the saturated currents I^-_{sat} and I^+_{sat} independent of the probe potential the following relation between the floating potential V_{fl} and plasma potential Φ:

$$V_{\mathrm{fl}} = \Phi - \left(\frac{kT_{\mathrm{e}}}{e}\right)\ln(R)$$

Here the symbols k, T_e and e have their usual meaning. In other words the floating potential of the ball-pen probe should reach the plasma potential for R=1.

We attempted in [3] to explain this discrepancy by the existence of a non-Maxwellian EEDF in the system under study, see e.g. [4]. Similar problem arose when interpreting ball-pen probe data taken in the linear magnetized plasma device in Ljubljana. Also in this system the EEDF was not Maxwellian. However, even in such conditions the simple extrapolation of the plot V_{fl} vs depth of retraction h yielded for reasonably large h values of V_{fl} of the ball-pen probe very close to the plasma potential determined from Langmuir probe data.

We can conclude that in 2011 we employed the ball-pen probe for measurements of the plasma potential at different experimental conditions: in the system in Prague at magnetic field 40 mT and argon pressure around 3 Pa, in the system in Ljubljana at low magnetic field 7 mT and low argon pressure 0.12 Pa and in torsatron TJ-K in Stuttgart at magnetic field 72 mT and very low hydrogen pressure 2.5 mPa. We experienced that for sufficiently deep collector retraction the floating potential of the ball-pen probe approached in all three systems within reasonable error limits the plasma potential determined from Langmuir probe measurements. It can hence be concluded that the performed experiments indicate that the ball-pen probe can be successfully applied for direct display of the plasma potential also in low-temperature slightly magnetized low-pressure plasma.

In 2011 Z. Pekárek finalized his code library for effective solution of the Poisson equation in 2D and especially in 3D. This library was implemented into SPICE 3 code created in IPP AS CR by M. Komm and co-workers. This library is also utilized in 2D and 3D codes that are in development in the Faculty of Mathematics and Physics, Charles University Prague. This library will not be further developed since it presents part of Z. Pekarek's PhD thesis that he submitted in the middle of March 2012. The particle code prepared in 2D in the Faculty of Mathematics and Physics, Charles University Prague was utilized in publication [5].

The hybrid 3D code has been elaborated functional and was utilized in [6]and in a conference presentation entitled V. Hruby, R. Hrach: Computational simulation of metal ion propagation from plasma to substrates with uneven surfaces. Further development of this code is, however, unlikely since the main author V. Hruby died unexpectedly in December 2011.

References:

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[4] J.F. Behnke, E. Passoth, C. Csambal, et al., *Czech.J.Phys*. 49 (1999) 483.

[5] T. Ibehej, R. Hrach, *Vacuum* 86 (9)(2011) 1220.

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

J.Zajac, F.Zacek, J. Vlcek

In collaboration with:
M. Manso, A. Silva, P. Varela, L. Meneses, L. Cupido, Association EURATOM - Instituto Superior Technico / Instituto de Plasmas e 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 was using of the reflectometers as an experimental diagnostics for studies of the plasma turbulence. The first part of the microwave electronics and data aquisition, provided by IPFN/IST, was delivered and tested on the stand in Nov/Dec 2011.

Five individual reflectometers are supposed to measure the edge plasma density profile. The whole frequency range is 18-90 GHz, which is divided to four frequency bands called K, Ka, U and E bands. In the Ka-band the two reflectometers are supposed for the two polarizations. Due to the costingness the project was divided to two parts and only reflectometers for the K and Ka-bands are realized currently. The originally planned term of the K and Ka-bands installation on Compass was the end of 2010, but the part of the microwave electronics provided by IPFN/IST has been still delayed. The intallation of reflectometers for Ka-band is expected in the first half of 2012.

In 2011 the K-band reflectometer (18 – 26.5 GHz) was delivered to Prague. This part of the system was succesfully tested by specialists from IPFN/IST. The test bed included the data acquisition system, the band combiner and the mock-up of the Compass vacuum chamber including the vacuum window. The picture of the test arrangement is in Fig. 1. The reflectometer in the sweeping regime, which will be used for the measurement of the plasma density profile, was calibrated. The reflecting plasma surface was supplemented by the metal mirror. The system will be put in operation on Compass tokamak after the delivery of the Ka-band reflectometers.

Fig. 1. Testing of the K-band reflectometer on the vacuum chamber mock-up

Beam Emission Spectroscopy system for COMPASS

V. Weinzettl, P. Hacek, J. Krbec

In collaboration with:
G. Veres, M. Berta, G. Anda, S. Tulipan, T. Ilkei, D. Dunai, D. Nagy, A. Bencze, S. Zoletnik,
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 consists of the Li beam injector and the detection part based on an array of avalanche photo diodes and a fast camera allowing both density profile and density fluctuation measurements.

The newly constructed Li beam injector (5-10 mA, up to 100 keV) for COMPASS was successfully assembled and tested in the laboratory in the first half of 2011, and consequently attached to the tokamak vessel. In the injector, lithium ions are emitted constantly during the tokamak discharge by a resistively heated solid ion emitter, then accelerated and focused by ion optics. Deflection plates are used to deflect the beam trajectory in the plasma vertically or horizontally (<5 cm) or to target the beam outside into a Faraday cup, which allows a background noise measurement. Lithium ions are neutralized via charge exchange by passing through a chamber with sodium vapour. Then, the accelerated Li atoms continue to the tokamak vessel, where they are excited and ionized, mainly in collisions with electrons. Two optical systems are mounted in vertical ports looking to the beam in perpendicular direction, as can be seen on Figure 1, and equipped with interference filters for a detection of lithium spectral line at 670.8 nm. The top vertical port is used by the CCD camera for slow measurements, the bottom vertical port is used by avalanche photodiodes for fast measurements. The CCD camera with optics has been already installed on COMPASS; it has 640x480 pixel resolution at frame rate of 100–200 Hz, and digital temperature compensation.

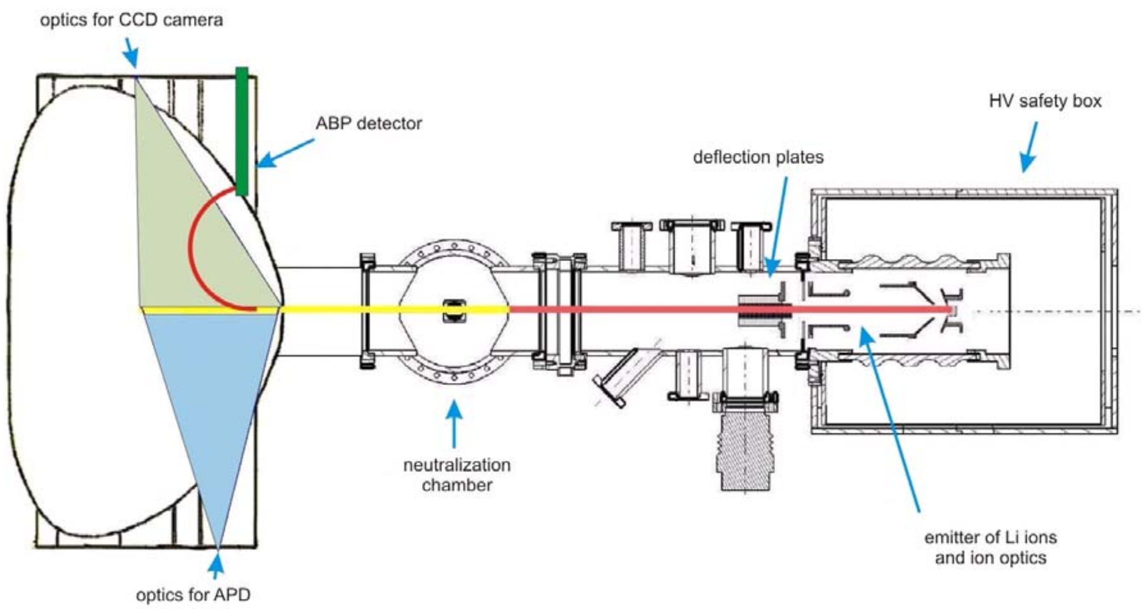
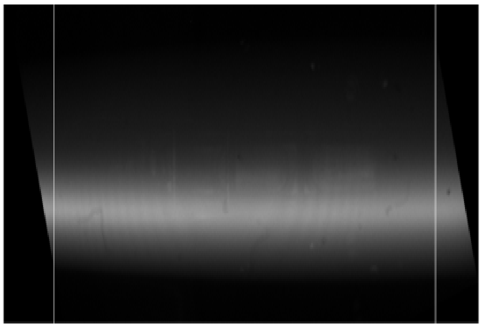
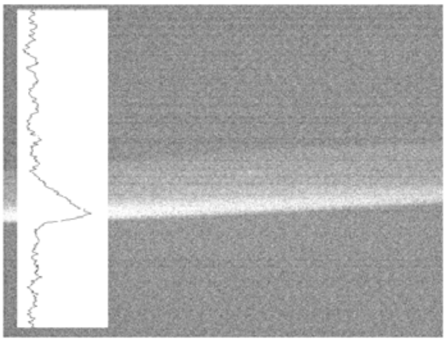


Fig.1: BES and APD diagnostics based on the Li beam .

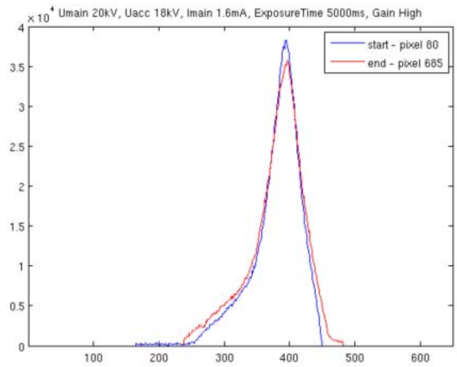
Also, the new flange equipped with specially designed viewpoints has been installed to the bottom oval diagnostic port allowing mounting of the fast APD system, which is currently under development. It will have about twenty channels of silicon-based APDs of the S8664-55 type with the effective area of 25 mm^2, quantum efficiency of 85 % (at 650 nm) and gain about 50 at 360 V. The unit will feature special low noise operation amplifier developed in RMKI, Hungary, internal ADC with optical interface and will operate with 1 MHz bandwidth. The whole unit will be encapsulated in a temperature-stabilized housing.

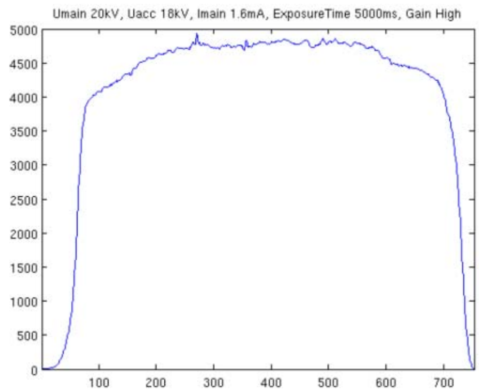


a)



b)





c)

Fig.2: The first CCD camera pictures of the Li ion (upper left)and neutralized (upper right) beam. Bottom figures show both cross sections of the Li ion beam.

The first measurements with the camera visualizing the ion beam in the tokamak vessel were performed in the chamber filled by hydrogen gas (without presence of magnetic field), see Fig. 2 a) and c). At that time, currents measured close to the tokamak using a Faraday cup reached only about 20% of the ion current at the ion optic. Therefore, the alignment procedure will follow causing a symmetrization of the observed beam shape and an increase of the beam portion reaching the tokamak vessel. Similarly, the neutralized beam was observed in the chamber filled by hydrogen gas, see Fig. 2 b).

Currently, parameters of the diagnostic Li beam are being optimized with the aim to prepare the whole system for routine density profile measurements.

References:

[1] V. Weinzettl, et al.: Overview of the COMPASS diagnostics. *Fusion Engineering and Design 86 (2011) 1227–1231*

[2] P. Hacek, V. Weinzettl, J. Stockel, G. Anda, G. Veres, S. Zoletnik, M. Berta: Diagnostic Lithium Beam System for COMPASS Tokamak. *WDS'11 Proceedings of Contributed Papers, Part II, XXX, 2011, MATFYZPRESS, Prague, ISBN 978-80-7378-185-9*

Development of fast tomography systems based on fast bolometric and SXR arrays for COMPASS

V. Weinzettl

In collaboration with:
V. Igochine, Association EURATOM-IPP, IPP Garching, Germany
D. Sarychev, ITP RRC "Kurchatov Institute", Moscow, Russia

The new fast tomographic system composed from four independent port plugs containing bolometers, soft X-ray detectors and objectives for the visible light detection has been installed on the COMPASS tokamak in 2011. The first measured profiles indicate a possibility to use both the bolometric and SXR signals for tomographic reconstructions and also for fast (real-time) vertical and radial plasma column position estimation.

After successful testing of the first two diagnostic port plugs containing fast bolometers, soft X-ray detectors and objectives for the visible light detection in 2010, minor improvements of the plug design were realized in spring 2011. There were installed better adjustable slit holders, new cabling well protected against an electromagnetic interference and improved modular amplifiers allowing for switching amplification. In the same manner, additional two port plugs equipped with the same detectors were installed into the mirror diagnostic ports of the same poloidal cut of the tokamak vessel in autumn 2011. The whole multi-spectral range diagnostic system was connected to the ATCA-based data acquisition system of 2 MHz sampling rate.

To protect detectors and the objectives against an impurity layer deposition during a vessel cleaning procedure (glow discharge), a control of the corresponding shutters is implemented into the java-based environment integrating all vacuum and gas-handling systems of the COMPASS tokamak. T\At the same time, temperature stabilization during a vessel cleaning procedure (vessel baking) is ensured by thermorezistors of the PT-100 type inserted in all plug bodies monitored by simple electronics, which is able to switch-off a local port baking.

Currently, the diagnostic system contains six 20-channel AXUV-based bolometers and two 35-channel silicon-based soft X-ray detectors but all bolometers are replaceable with 20-channel soft X-ray detectors. The first measured profiles indicate a possibility to use both bolometric and SXR signals for tomographic reconstructions. A basis of the reconstruction is an algorithm of Minimum Fisher Regularisation (MFR), i.e. a code based on Tikhonov regularization with the edge condition in the form of minimum of Fisher information. Such method brings sufficiently fast and precise solutions, which can be also used in real-time applications for fast vertical and radial plasma column position estimation.

References:

[1] V. Weinzettl, et al.: Overview of the COMPASS diagnostics. *Fusion Engineering and Design 86 (2011) 1227–1231*

Minimum Fisher Regularisation in fast tomography

J. Mlynář, T. Odstrčil, V. Weinzettl

In collaboration with:
D. Mazon, D. Vezinet, Association EURATOM – CEA Cadarache, France¨
B. Alper, C. Giroud, Association EURATOM – CCFE, UK

After its optimisation in the preceding year, the Minimum Fisher Regularisation (MFR) code was widely applied in Soft X-ray (SXR) data analyses in 2011. Novel results were achieved and published with MFR application on SXR data at JET. In collaboration with CEA, the code was tested on TORE SUPRA. The system was also further developed for the COMPASS SXR and bolometry diagnostics environment, where considerable progress is expected in the early 2012.

At the beginning of 2011, the efforts in this task were focused on tomography analyses of the JET SXR data. These analyses were successful although the diagnostics setup at JET is far from ideal: (i) the cameras are at different toroidal locations, (ii) their spectral sensitivity is not identical (they have different Be foil thickness). The consequences have been studied in detail (in particular in the framework of diploma thesis [1]). Considerable efforts were also invested into studies of the properties of the anisotropic smoothing along magnetic flux surfaces, in particular into finding its optimised amplitude. Results of the studies as well as of first real SXR data analyses were presented in a poster and 4 page proceedings contribution to the EPS Plasma physics conference in Strasbourg [2], see figure 1 and 2. Notably, a method for phase shifting of the high temporal resolution data to compensate for the toroidal shift was published in this conference contribution, which allowed for emissivity studies with high temporal evolution.

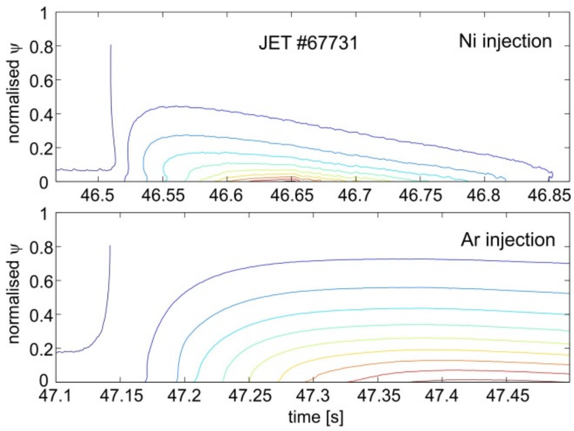


Figure 1: Evolution of the MFR reconstructed JET SXR profile perturbation after Ni and Ar injection.

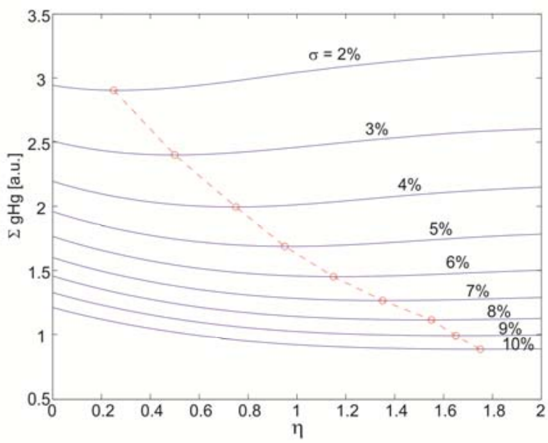


Figure 2: The emissivity smoothness as a function of the anisotropy factor and the expected data error

The MFR was also used for studies of slow processes on wider selection of JET discharges, in particular those with impurity injection (shots 67729-67732, 67678-67680 with Nickel and Argon injection, and 68373 with W ablation). The analyses led us to several improvements in the code, in particular with respect to data upload from the database (switching to mdsplus) and the magnetic flux surfaces (formerly loaded from a separate MatLab code, now fully implemented into the Python environment).

Apart from the work at JET, in collaboration with CEA the Minimum Fisher Regularisation for plasma tomography was successfully used for data analyses on TORE SUPRA. Valuable results were obtained for example in studies of the sawteeth and MHD activities in discharge #41870 with high temporal resolution in the SXR diagnostics (1 MHz). Modes m=1 eg. at 6.013 s and m=2 at 8.509 s were visualized using Singular Value Decomposition on the evolution of the 2D SXR emissivity reconstructed by MFR. The algorithm was compared in detail with algorithm developed in CEA. This triggered productive discussions that resulted in proposal of a new routine for real-time iteration of chi2 and possibly also the nested Minimum Fisher iteration. The idea is currently being implemented by an undergraduate student of the Technical university in Prague. The results achieved will be proposed for a publication at CEA.

Second, the methods used at TORE SUPRA for SXR real-time applications, in particular the direct analyses that do not require applications inversion algorithms were discussed and tested jointly with the aim at their prospective testing at COMPASS in Prague.

In autumn, software interface with the new data acquisition system for the SXR diagnostics was prepared, with expert advice provided by Dr. Antoine Sirinelli from JET. Future collaboration on data analyses is foreseen with Dr Carine Giroud from JET; based on her recommendation, data from the SXR tomography analyses are now stored into a private JET database. The work also allowed to re-establish collaboration with Dr Vlad Plyushnin from IST Portugal, who is interested in experimental studies of JET disruptions and who had asked in past for a possibility of spatial SXR analyses during disruptions in order to trace the runaway electrons [3]. JET disrupted discharges 79414-79426 were analysed, with interesting although very noisy preliminary results. Last, but not least brand new SXR data from the current campaigns were analysed, however, due to hardware noise in the preamplifiers the results have not been satisfactory as yet.

The MFR fast tomography was occasionally applied also on data from the COMPASS tomography diagnostic system [4] where the progress relied in particular in hardware development and data conditioning in 2011. Due to substantial improvement of the data and the plasma stabilisation at the end of the year it was proposed to present the COMPASS tomography results in the 2012 HTPD conference.

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[3] Plyusnin V.V., Riccardo V., Jaspers R., Alper B., Kiptily V.G., Mlynář J., Popovichev S., de La Luna E., Andersson F.: Study of runaway electron generation during major disruptions in JET. Nuclear Fusion **46** [2] (2006) 277

[4] Odstrčil M. (supervised by J. Mlynář): Tomografie plazmatu na tokamaku COMPASS (Plasma tomography on the COMPASS tokamak). *Bachelor thesis* FJFI ČVUT (FNSPE, Czech Technical University in Prague, 2010)

Calibration of the fast tomography system for visible plasma radiation measurements for the COMPASS tokamak

D. Naydenkova, V. Weinzettl, R. Melich, D.Jares

New multichannel diagnostics for visible light radiation measurement have been installed on the COMPASS tokamak as a part of the tomographic system for transport studies. The diagnostic has a time resolution in few microseconds range and a spatial resolution better than 1 cm in the pedestal region. It allows observations of the core/edge plasma from two poloidal angles. In 2011, alignment of the system and throughput measurements were performed resulting in the first test measurements.

The tomography system for visible plasma radiation measurements for the COMPASS tokamak consists of two identical parts, which have been installed in different diagnostic ports of the same poloidal cross-section in autumn 2011.Each part of the system includes three principle sections: collection optics (see Fig.1), 20 m long optical fibres for transferring light to diagnostic room, and detection part.

The alignment of the total system was done to receive maximal troughput for each channel. The difference in transmittance between channels looks like connected with non-precision of production of each element of the system, as a result of losses of light at connection of the parts. The spatial separation of channels was measured too. The overlapping of signal for total system is less then 6 percent, and takes place between fiber optics and detector surface. It is better than overlapping of channels for the system, which we expected.

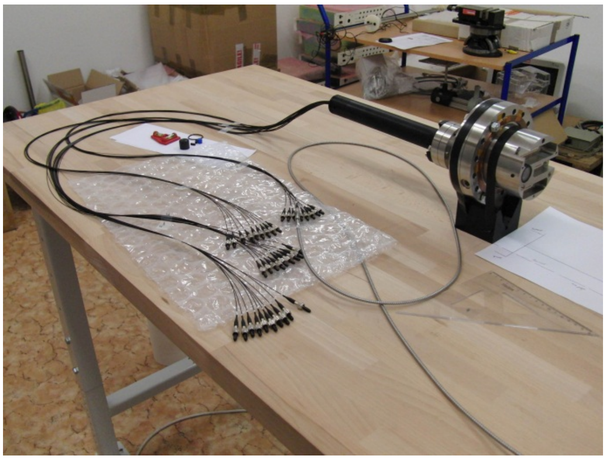

Fig.1. Assembly view of the collection optics of the upper part of the multichannel system. The linear fiber bundle is attached to the wide-angle objective integrated into the port plug.

After the alignment, the test measurements with plasma discharge were done to check if amplification of registrated signal was enough. The received signal was too weak and additional amplification of 2-4 times was applied to part of channels to estimate roughly a value of correction in amplification. On the base of received signals new design of amplifier was done. The new design is 3-stage amplifier, which allows some required basic amplification with possibility to correct the amplification of each channel.

References:

[1] Naydenkova D., Weinzettl V., Stockel J., Sestak D., Janky F.: The optical system for visible plasma radiation measurements in the COMPASS tokamak - design and testing. *Acta Technica, Supplement to Topical Issue.* Vol. 56 (2011), pp. T93-T100, ISSN 0001-7043.

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Data acquisition of the Thomson scattering system

Milan Aftanas, Petr Böhm, Petra Bílková

In collaboration with:
M.J.Walsh, ITER IO, St. Paul-lez-Durance, France
R Scannell, G Naylor, M Dunstan, Association EURATOM-CCFE, Culham Science Centre, Abingdon, Oxfordshire, OX14 3DB, United Kingdom

Thomson Scattering (TS) diagnostic system started its operation in the year 2011. The data acquisition (DAQ) system worked well during tests. At the end of the year 2011 the TS diagnostic start to work in routine operation. The triggering of DAQ system by the Q-switches of the lasers has been implemented and the newly HDF5 data format has been adapted for the measured signal.

The DAQ system has been commissioned and has performed well. The shift from the proprietary TDMS to the open HDF5 data format has been performed. The triggering of the DAQ was set to be controlled by the internal laser triggers. This solution helped us to automatize the data acquisition process but has one drawback – the delay between laser shot and Q-switch trigger could vary in the range of tens of ns and thus we measure the signal in the different positions for each laser shot. As a next step the DAQ system will be controlled by the external triggering (based on micro-processor dsPIC) unit together with the lasers and automatic beam shutters, as a part of the laser safety system. This unit has been designed and tested and will be installed in the next year.

Data processing has been improved with the fitting of the time evolution of the signals (the Gaussian profiles has been found to be good approximation) and the routines for determination the electron temperature and density has been implemented (in IDL). The evaluation of the electron temperature and density errors will be implemented in the year 2012. To the increase the robustness and decrease the computation time of the data processing code the pulse shape monitor will be installed in the next year. It will reduce the number of the fitted parameters (pulse width and pulse position.

References:

[1] Aftanas M, Böhm P, Scannell R, Tripsky M, Weinzettl V, Hron M, Panek R, Stöckel J, Walsh M and Bilkova P: Thomson scattering on COMPASS – commissioning and first data, *Journal of Instrumentation* **7**, C01074 (2012), doi: 10.1088/1748-0221/7/01/C01074

Laser part of the Thomson scattering system

P. Böhm, P. Bílková, M. Aftanas, D. Šesták

In collaboration with:
R. Scannell, G. Naylor, M. Dunstan, Association EURATOM-CCFE, UK
M. Walsh, ITER IO, France

Thomson scattering (TS) diagnostic was put in operation in the year 2011. The laser system, as an integral part of the TS diagnostic, performed well during diagnostic tests, calibrations and first measurements. In the end of the year, TS measurements with one laser were performed routinely. To improve the TS diagnostic capabilities, external triggering unit was designed and initial tests of the unit were performed. Control of data acquisition by an internal laser trigger was implemented. Laser safety system was tested and slightly re-designed according to experience from praxis; some errors were occurring from time to time, the remedy is in progress.

The lasers were aligned into the tokamak and then aligned together with TS collection optics. Raman scattering tests were performed and also first TS measurements. Lasers performed well, minor problem with alignment laser pointing stability was observed. In the end of the year, TS measurements with one laser were performed routinely.

Automatic, air-operated beam shutters, part of a laser safety system, were designed, components were delivered, the rest parts will be manufactured in the local workshop in the beginning of 2012. The laser safety system was tested and slightly re-designed according to experience from praxis, unfortunately several errors in the program were discovered, the remedy is in progress.

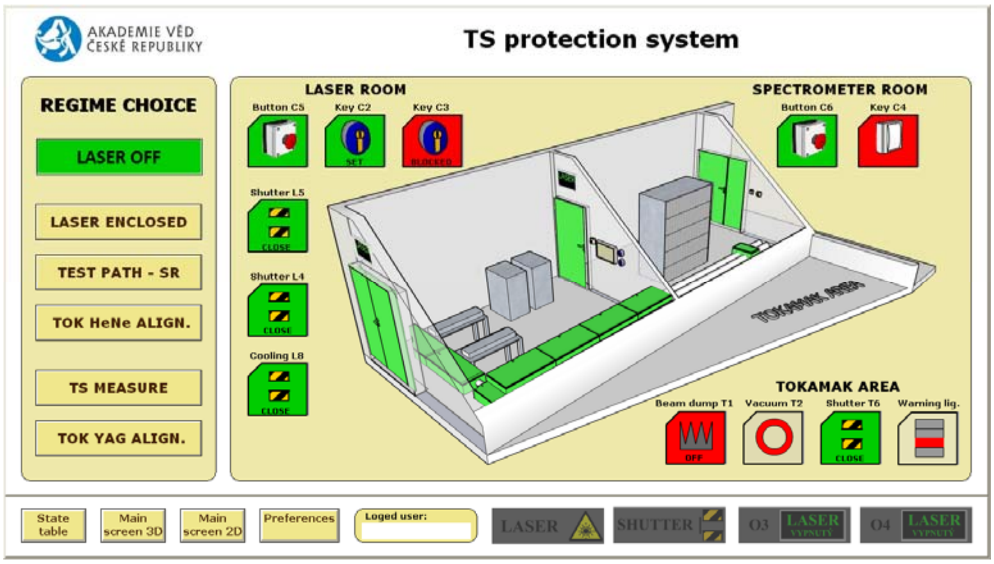

Fig. 1: Laser safety system – interface.

Triggering unit for laser synchronisation, based on micro-processor dsPIC, was programmed; basic tests of the unit alone were performed. Interface circuits between the triggering unit and the lasers were developed. Another part of the triggering system, unit for triggering data acquisition by the lasers, was tested and optimised and is fully functional now.

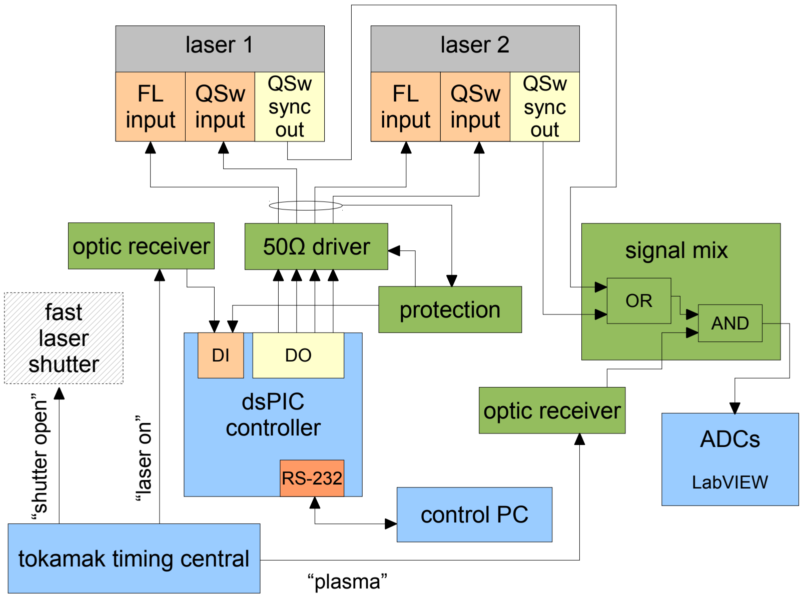

Fig. 2: TS triggering layout.

Laser pulse energy monitoring and remote control of laser operation via RS232 were postponed to the next year.

The whole TS laser system optimisation continued. The alignment laser power reduction was optimised for convenient work without necessitating goggles. The vacuum part of the laser beam path was finalised, baking of the vacuum components was implemented. Based on experience from TS operation, remote control of two hardly accessible mirrors is being designed. Camera for the remote control was tested. Standardised laser operation procedure was written down to enable anyone from the TS team to operate the system.

References:

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[2] Aftanas M, Böhm P, Scannell R, Tripsky M, Weinzettl V, Hron M, Panek R, Stöckel J, Walsh M and Bilkova P: Thomson scattering on COMPASS – commissioning and first data, *Journal of Instrumentation* **7**, C01074 (2012), doi: 10.1088/1748-0221/7/01/C01074

Thomson scattering diagnostic – detection part of the system

P.Bilkova, M. Aftanas, P.Bohm, D.Sestak, Tadros Momtaz, R.Melich, D.Jares

In collaboration with:
R.Scannell, Association EURATOM-CCFE, United Kingdom
M.J.Walsh, ITER IO, France

In the 2011 year, the full commissioning of the core Thomson scattering diagnostics has been realized. Besides the first measurements of profiles of electron temperature and density, the performance of the particular parts of the system was checked and data analyzed. Due to still delayed delivery of the edge collection optics, the edge Thomson scattering diagnostic has not been used for routine measurement so far. On the other hand, all the equipment related to the edge Thomson scattering system including spectrometers, data acquisition system and optical fibres was made ready for first measurement once the edge objective is installed.

Following tasks have been fulfilled during 2011 year :

- Setup of electronics inside polychromators
- Spectral calibration of polychromators and calibration of white light
- Identification of two problematic spectrometers and its correction (replacement of bad mirror, improvement of electronic setup)
- Alignment of the collection optics
- Testing and final check of optical fibres placed into the area
- Checking of the laser beam position using a specially designed fibre bundle enabled and tested
- Absolute calibration of the core TS diagnostic based on Raman scattering in nitrogen at pressures of 50 mbar – 200 mbar as an input for electron density calculation
- Upgrade of nitrogen technology for Raman scattering for the B.I.P. (bottle inside purifier) technique and its tests
- First Thomson scattering signals have been detected from 13 spectrometers (1 pectrometers is checking position of a laser and is used during alignment, 12 spectrometers give signals form 24 spatial points - june 2011)
- After optimization of the alignment and plasma performance, the first electron temperature profile has been succesfully measured (september 2011)
- First tests with edge objective lead to a request to do corrections so that required parameters of the optical system is met
- Optimization of codes for the data analysis

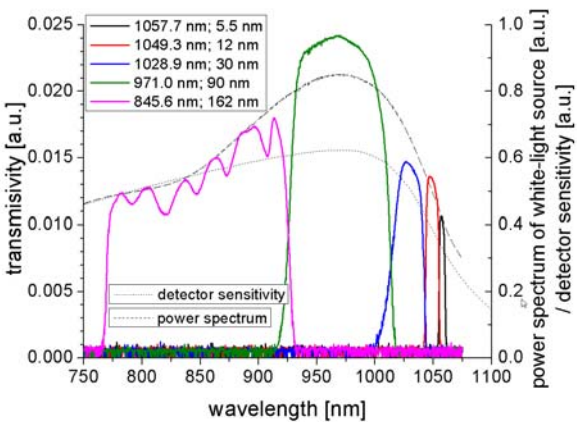

Fig. 1: Raw data of spectral calibration: channel (specified by filter parameters – center wavelength and bandwidth) sensitivity (left y-axis); sensitivity of calibrated detector (right y-axis), power spectrum of white-light source (right y-axis). Published in: [1]

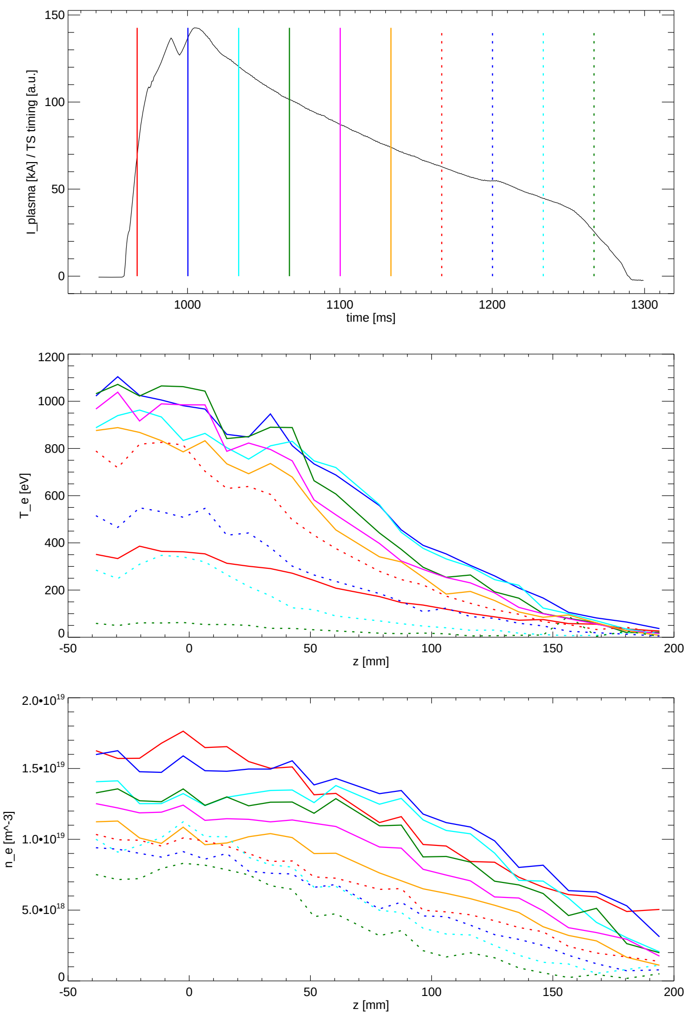

Fig. 2: Full core profile of electron temperature and electron density, shot 2512

References:

[1] Aftanas et al. at LAPD conference 2011, accepted in JINST 123P-111

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

Detection of EC emission on COMPASS

J. Preinhaelter

In the experimental part of our program we tested our radiometer during the international summer school SUMTRAIC in August 2011. We measured X-mode emission from the second harmonics in 60 – 73.5 GHz band. Plasma parameters do not allowed determining the radiative temperature of electrons. We observed typical fast oscillations of radiative temperature connected with unstable short discharges in COMPASS. This measurement had only educational significance.

In the collaboration with the Max-Planck Institute in Greifswald, we have performed a measurement with our radiometer on WEGA stelarator, First we measured in the Ka band (26.5 – 40 GHz) emission from the first harmonics. This measurement has been used for the study of conversion of electron Bernstein waves (EBW-X-O process). Then, in the E band (60 – 90 GHz), we measured EC emission, We also calibrated radiometer in the both bands. The measurement will be evaluated and the results will be published.

We also finished fabrication ellipsoidal mirror, which will be placed into tokamak vacuum chamber. This mirror quasioptically focuses our antenna Gaussian beam on the plasma surface. The mirror is steerable in two planes so it can be adjusted the optimum angel for penetration of the electron Bernstein (EBW) waves through the plasma resonance region.

In the theoretical part of program we paid attention to the finishing extensive paper devoted to the possibilities of the plasma heating a current generation with the electron Bernstein waves in spherical tokamaks. Mutual interconnection of AMR code (conversion of the ordinary and the extraordinary waves to the electron Bernstein waves and the monitoring of electron Bernstein rays) with Fokker-Planck code LUKE makes possible to simulate the EBW heating and current drive in the dependence on the wave frequency and the conditions of wave launch. It is shown that the effective way to generate current with the help of EBW really exists. Specially, it is shown that power can be deposited a current generated at the arbitrary radial position. We published extensive paper devoted to the theme in Nuclear Fusion at the end of year 2011 and survey of results was presented on 19th Topical Conference on Radio Frequency Power in Plasmas v USA.

Large survey paper about physical results of investigation on facility NSTX (Princeton Plasma Physics Laboratory), published in Nuclear Fusion, included our contribution connected with simulation of the electron cyclotron emission caused by the conversion of the electron Bernstein waves.

Previously developed codes were successfully used for the study of plasma heating and the current generation in the hybrid reactors. This combination of the spherical tokamak - source of neutrons - and the fission reactor provides not only power but also enable to burn accumulated radioactive waste. In the contribution on the 53rd Annual Meeting of the APS Division of Plasma Physics, November 14-18 , 2011, Salt Lake City, Utah, we presented our results about role of EBW heating in hybrid reactors.

For the references, see the list of 2011 IPP generated information in Part III.

RF power deposition, current drive and emission in stellarator WEGA

J. Preinhaelter

In 2011, cylindrical 5 waveguide grill was developed for lower hybrid heating in WEGA stellarator. The phase shift between waveguides $\Delta\varphi = \pi$ suits well for plasma heating because the main peak of the power spectrum is situated at $N_{\|} = 3.3$ well above a rather high accessibility limit 2.35. To coupe with the simulation of the coupling of this rather unusual structure we investigated a more simple 5 rectangular waveguide grill with similar size of waveguides. We investigated influence of two main parameters, i.e. the surface density and the density gradient, on the coupling of our grill for WEGA relevant equilibrium.

We found that the power reflection coefficient is acceptable low in a broad range of surfaces densities and that the more than 50% of launched power is converted to the slow waves, which can heat the central plasma. Similar results was obtained for the effect of the density gradient on the grill coupling. We found that both these important parameters, i.e. the power reflection coefficient and the power transmission coefficient to eigenmodes depend only weakly on the density gradient.

The LH grill on WEGA can be radially shifted inward to reach the higher density plasma. The next simulations solved this situation. We see that coupling improves substantially in the antenna mouth is placed dipper into the plasma.

These results were in contradiction with the experiment where the coupling was pure independently on the plasma parameters and the antenna position. One possible explanation offers the possible discrepancy between the shape of grill mouth and the plasma surface. In this case the grill serves as limiter and the gap between grill mouth and the plasma prevents the good coupling.

We also investigated coupling of the simple one open circular waveguide antenna radiating LH waves at 2.45GHz. We simulated this structure as 2 rectangular waveguide with zero phase shift between the incident waves. We confirmed rather good coupling observed experimentally (the power reflection coefficient is 40%) but the transmitted waves consist predominantly from plasma eigenmodes (standing coupled slow to fast waves). These eigenmodes are probably responsible for the intensive acceleration of runaway electrons to MeV energies.

We also continued in the EBW heating simulation for 28GHz launched wave. The results were presented at the 38th EPS Conference on Plasma Physics, Strasbourg, France (2011) and at International Conference on Research and Applications of Plasmas, Warsaw, 12-16 September 2011, Poland (to be published in NUKLEONIKA journal). The extremely high radiative temperature the determined from the measured EBW emission was not explained.

Ray tracing and Fokker-Planck modelling of electron Bernstein wave heating and current drive

J. Urban, J. Preinhaelter

In collaboration with:
J. Decker, Y. Peysson, Association EURATOM-CEA Cadarache, France
V. Shevchenko, Association EURATOM-CCFE, Culham, UK
G. Taylor, Princeton Plasma Physics Laboratory, NJ, USA
L. Vahala, Old Dominion University, Norfolk, VA, USA
G. Vahala, College of William & Mary, Williamsburg, VA, USA

By means of coupled ray-tracing and Fokker-Planck simulations, we have thoroughly investigated electron Bernstein wave heating and current drive prospects for spherical tokamaks, particularly for four typical present and prospect plasmas: NSTX L- and H-mode, MAST Upgrade and NHTX [1]. For the first time, a simple analytic formula for the O-X conversion efficiency of a Gaussian beam is derived from 1D plane wave theory. This formula supports our choice of the Rayleigh range as the antenna beam principal parameter that is fixed for all simulated cases.

Figures 1 and 2 show current drive efficiency results for NSTX L-mode and for MAST Upgrade. In general, on an extensive set of EBW launch scenarios with varying frequency, vertical antenna position and toroidal injection angle, we show that EBWs can be absorbed at almost arbitrary radius and that EBWs can drive current with efficiencies comparable to electron cyclotron O- or X-modes. Moreover, the efficiency does not change with radius, while typically X- and O-modes' efficiency decrease with radius. Best results in terms of efficiency and flexibility are achieved in NSTX plasmas, where the electron cyclotron frequency radial profiles are monotonous. In general, normalized current drive efficiencies $|\zeta|$ on the order of 0.3 – 0.4 are feasible for all target plasmas, absolute efficiencies then depend on the plasma parameters as $\eta \equiv I_{\mathrm{RF}} / P_0 \cong 0.31 \zeta T_{\mathrm{e}} / R_0 n_{\mathrm{e}}$, where the units are A/W for η, keV for T_{e}, m for R_0 and $10^{19}\,\mathrm{m}^{-3}$ for n_{e}.

For EBWs, only initial $N_{\|}$ sign can be chosen at will, while further evolution is determined by the wave frequency, the vertical launch position and by the plasma parameters. We have shown how different vertical launch position influences the $N_{\|}$ spectrum and consequently the current drive efficiency. However, there seems to be no general correlation between the current drive efficiency and the $N_{\|}$ spectrum and its width. This result is rather surprising.

Input power scans have been performed to investigate the quasilinear effects. Increasing power generally leads to either lower or similar current drive efficiency, although contrary results exist. Higher power also causes the wave absorption to occur further in the propagation direction, which can either be towards the axis if the absorption occurs on the outboard side or away from the axis in the opposite case. An important factor is the effective ion charge, which determines the electron-ion collisionality and significantly affects the current drive efficiency. Minor effect of Z_{eff} on the driven current location can be observed, which is caused by changing the plasma quasilinear response.

The sensitivity of EBW heating and current drive to changes in plasma parameters has been investigated. It has been shown that the EBW performance is rather robust. Neither the current drive efficiency nor the radial location changes significantly when the electron temperature or density changes moderately. Larger sensitivity is observed for magnetic field changes, especially the (dominant) toroidal field.

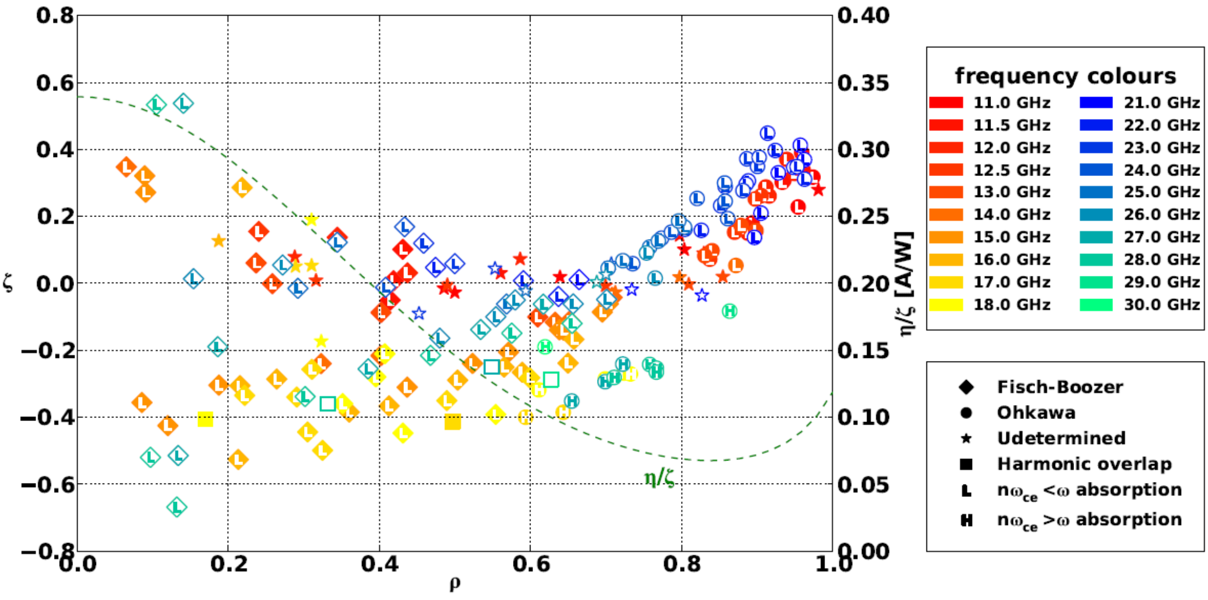

Fig. 1. Normalized current drive efficiency ζ (symbols) and η / ζ conversion factor (dashed line) versus ρ, NSTX L-mode first (full symbols) and second (open symbols) harmonics, different frequencies and vertical launch positions, 1 MW incident power.

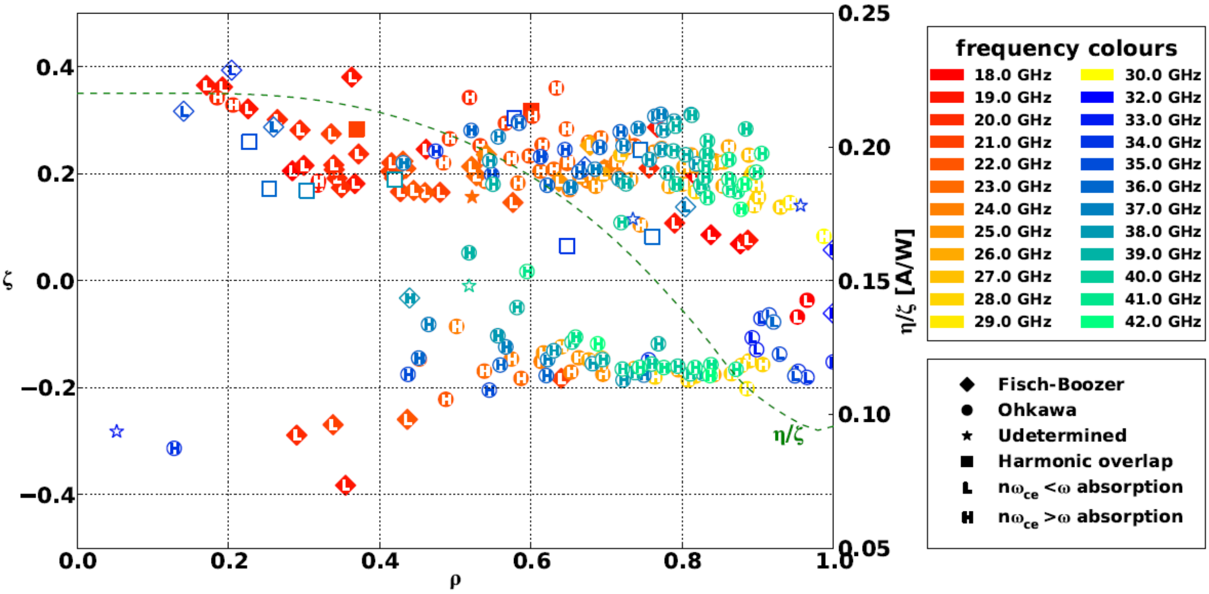

Fig. 2. Same as Fig. 1 but for the spherical tokamak MAST Upgrade.

References:

[1] J. Urban et al., *Nucl. Fusion* 51 (2011) 083050

4. Emerging Technologies

Influence of neutron irradiation on the properties of candidate fusion materials

J. Matějíček

In collaboration with:
J. Sedláček, Czech Technical University, Prague, Czech Republic
L. Viererbl, Z. Skoumalova, J. Burda, Nuclear Research Institute, Rez, Czech Republic
M. Roedig, Forschungszentrum Juelich, Germany

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.

Post-irradiation experiments

The remaining samples were extracted from the irradiation capsules.

Measurement of electrical properties of the plasma sprayed metallic materials was performed on the modified rig. An order-of-magnitude decrease in conductivity was observed.

Complex metallographic examination (including porosity, hardness and phase and composition) of both un-irradiated and irradiated glass-ceramic samples from Politecnico Torino was performed. No significant changes in properties or composition was observed, except for slight discoloration, which might be a result of irradiation-induced defects. A paper including these results was submitted to J. Nucl. Mat. [1]

Transport of the steel samples to Ciemat is planned for April 2012, for TEM studies of structural changes.

Due to ongoing reconstruction of hot cell labs in Juelich, results from the thermal conductivity and high heat flux tests are still pending.

References:

[1] Ferraris, M. et al.: Irradiation behavior of glass ceramics as pressure-less joining materials for nuclear application, submitted to J. Nucl. Mat.

Development of tungsten-based functional gradient materials

J. Matějíček, H. Boldyryeva, V. Brožek, Z. Pala, P. Ctibor, T. Kavka

In collaboration with:
E. Čižmárová, 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 various techniques and their characterization.

Two alternative processing techniques were pursued: hot pressing and plasma spraying with hybrid argon-water torch.

Hot pressing from powders was used to form homogeneous stainless steel/tungsten composites as well as FGMs. Essentially full density composites with homogeneous distribution of the phases and good bonding were produced. An example of five-layer FGM is shown in Fig. 1a. Thermal conductivity of the homogeneous composites varied with composition, increasing from steel to tungsten, the terminal composition being close to bulk materials. In composites with higher W content, formation of Fe7W6 phase was observed at the tungsten/steel interface (identified by x-ray diffraction). On the steel side, a microcomposite with ultrafine lamellar grains (likely consisting of the Fe and Fe7W6 phases) was observed in some cases (Fig. 1b). Instrumented indentation was performed to assess the mechanical properties of these phases. The Fe7W6 phase exhibited the highest hardness and the lowest ability for plastic deformation. In addition, a ternary FGMS consisting of steel, WC and W were formed, the purpose of the WC interlayer being to inhibit the brittle intermetallic phase formation. Their detailed characterization is underway.

Plasma spraying is a technology that offers large area coverage capability. Extensive spraying experiments with a hybrid (water-argon) plasma torch, with and without argon shrouding, were performed. Pure steel and tungsten coatings were produced at a variety of conditions and characterized [1]. It was found that for tungsten, the highest torch power, highest argon flow rate and short injection distance were optimal. For steel, moderate-to-high torch power, lower argon flow rate and long injection distance were optimal. In both cases, the application of argon shrouding was found beneficial in reducing the oxide content in the coatings. The best conditions were selected for the production of composites and FGMs, whose characterization is underway.

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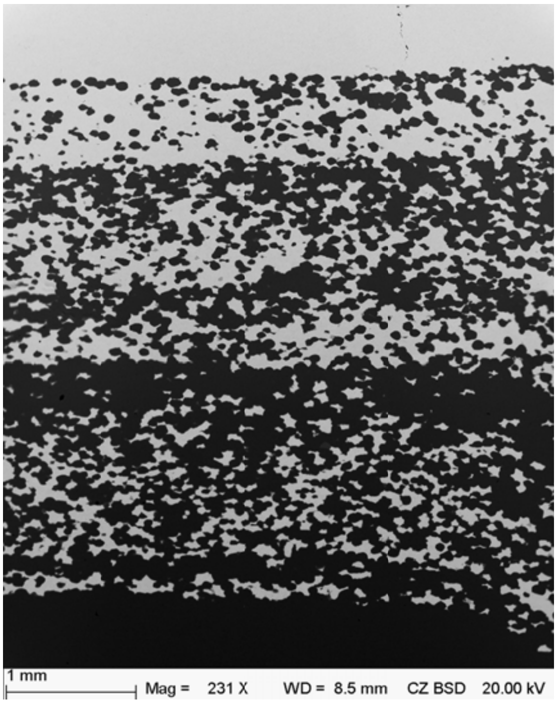
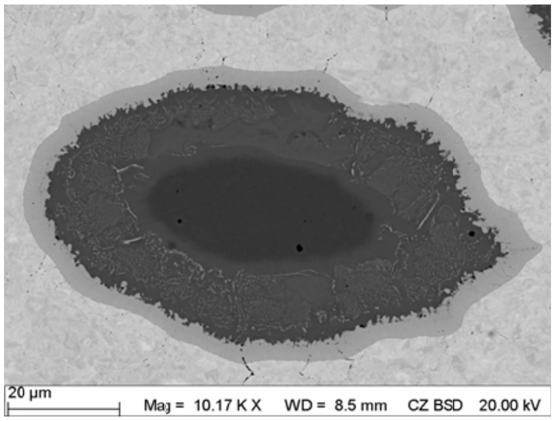

1 mm
Mag = 231 X
WD = 8.5 mm
CZ BSD
20.00 kV


20 μm
Mag = 10.17 K X
WD = 8.5 mm
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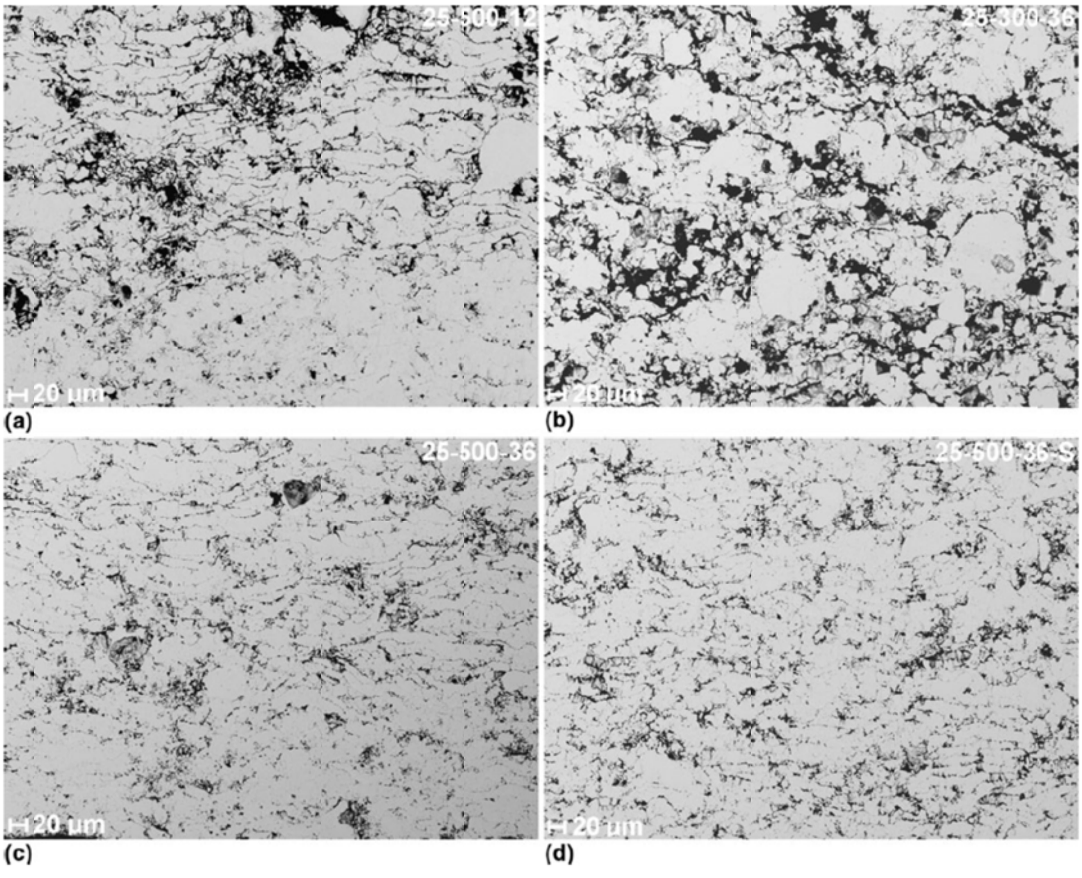
, steel).


25-500-12
25-300-36
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20 μm
20 μm
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(a)
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(c)
(d)

Ferritic 12-14Cr ODS steels embrittlement at high temperatures

H. Hadraba
Institute of physics of materials AS CR

In collaboration with:
B. Fournier, Association EURATOM-CEA, Saclay, France

The oxide dispersion strengthened steels (ODS) are consider as a structural material of the major future nuclear energy production systems developed: i) the generation IV fission reactors, ii) fusion reactors and iii) spallation neutron sources. The aim of this work was to describe microstructural changes caused by the long-time high-temperature exposition of the ODS steel ODM401 to the liquid Pb and Pb-Bi metals environments. The influence of the oxide scale development and microstructural changes was described by the tensile and impact bend tests. The surface region of the steel was during the exposition in the liquid Pb and Pb-Bi depleted from Cr and Ti formed the oxide scales. The outstanding embrittlement of the ODS steel was found after exposition to the liquid Pb and Pb-Bi compared with the steel isothermally aged. The embrittlement of the steel was explained by the porosity development and precipitates coarsening during long-time high-temperature exposition.

The ferritic high-chromium steel ODM401 of nominal composition (wt.%) Fe-14Cr-0.9Ti-0.3Mo-0.25Y_2O_3 was produced by mechanical alloying process. Commercially available atomized powders were mixed in exact proportions and order and own processed in high energy ball mills for 24 hours in air atmosphere. The degassed powder was cold pressed to compact pellet and a rod of diameter 30 mm was hot-extruded at 1150°C from the pellet. The high-temperature long-time exposition of the steel for 1.000 h was done in the air atmosphere at 650°C, in the liquid lead environment at 600°C and in the liquid lead-bismuth environment at 550°C. The exposition in the liquid metals environments has been done in the convection loop at liquid metal flow rate 1-2cm$\cdot$s^{-1} with an oxygen content of about 10-6wt.%. Mini-Charpy KLST specimens of 3 × 4 mm cross section and length of 27 mm and tensile specimens of diameter 2 mm were machined from the ODS s steel.

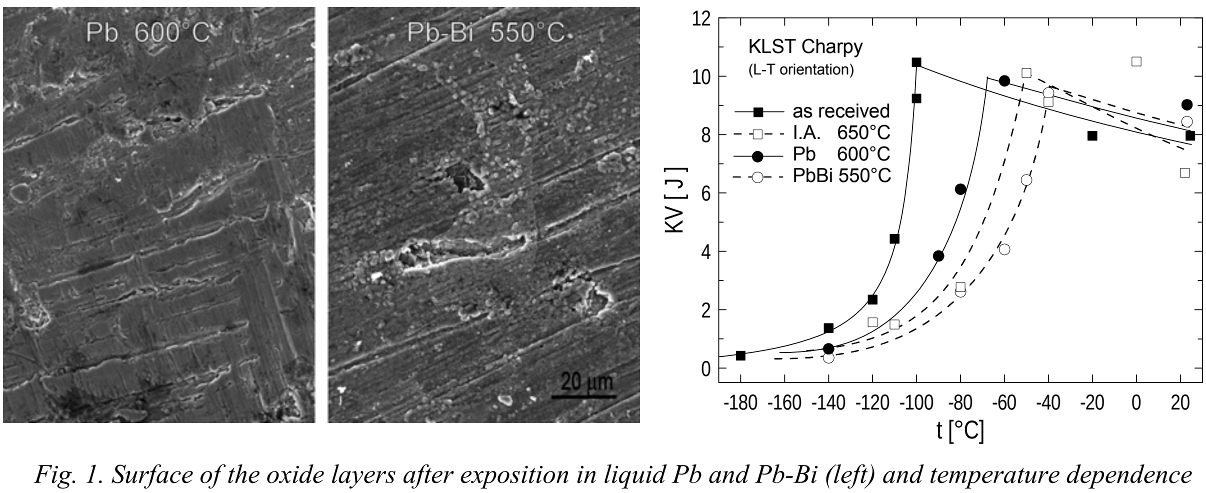

Fig. 1. Surface of the oxide layers after exposition in liquid Pb and Pb-Bi (left) and temperature dependence of impact energy of ODM401 steel before and after expositions (right).

During exposition of the steel in liquid metals environments the oxide scale developed at the surface of the steel (see Fig. 1) contained chemical elements both from the bulk (Cr,Ti,Fe) of the steel and the liquid media (O,Pb and/or Bi). The oxide layers covered not-uniformly the original surface of the steel and the marks of the intercrystalline corrosion of the surface have been found. The thickness of the oxide layer after exposition in liquid Pb-Bi was about 100 nm while after exposition in Pb about 300 nm. It is in accordance with higher temperature of the Pb bath (600°C) comparing with Pb-Bi bath (550°C) and thus higher velocity of oxidation in the Pb liquid metal. The temperature dependence of impact energy of ODM401 steel measured in the temperature region from -180°C to +24.5°C before and after expositions is given in the Fig. 1. The lower shelf energy (LSE) region of the impact energy was about 0.5 J and upper shelf energy (USE) region was about 10.5 J. The ductile to brittle transition temperature (DBTT) of the steel in as-received state evaluated as a midway between LSE and USE was about -110°C. After isothermal ageing the shift of the DBTT by about 40°C to the -70°C was found. The shift of the DBTT of the samples subjected to the liquid Pb was very close: the -80°C. The shift of the DBTT of the samples exposed to the liquid Pb-Bi was substantially higher and was about 55°C to the -55°C. It is in good agreement with observed change in the fracture mechanism of the tensile samples.

By EDS analysis of the oxide layer and subsurface region of the steel cross section the redistribution of the Cr and Ti was studied (see Fig. 2). The Cr- and Ti-depleted subsurface region was found in the samples exposed to the liquid metals. The thickness of depleted region was comparable for both the liquid media used and was about 5 μm. The level of chromium in the subsurface region was still sufficient to provide heat resistance of the steel. But the reduction of the titanium content in the steel can cause destabilization of the main strengthening phase of the steel, the Y-Ti nano clusters. Microstructural changes in the bulk of the steel were connected mainly to the precipitates coarsening and porosity development.

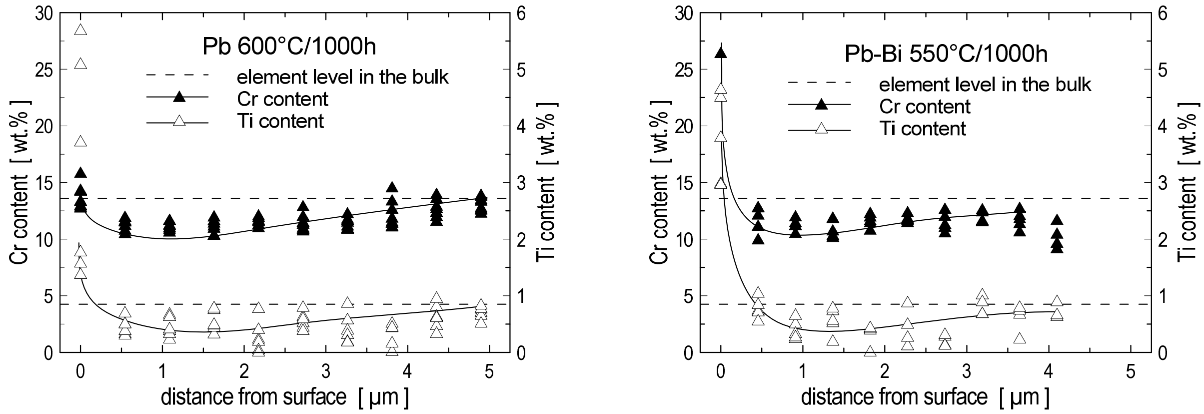

Fig. 2. Redistribution of the Cr and Ti in the steel near the oxide after exposition in liquid Pb and Pb-Bi.

Microstructural changes in the bulk of the steel were connected mainly to the precipitates coarsening and porosity development. No noticeable change in the porosity content was found after exposition in the liquid Pb and Pb-Bi comparing with the steel in as-received state. The increasing of the porosity after isothermal ageing at 650°C was connected to the specific embrittlement mechanism of ODS steels recently described – the void formation in grain interior. The stringers of pores oriented along particle stringers, elongated due to compaction of ODM401 steels by extrusion, are formed during high-temperature ageing by diffusional relaxation of stressed matrix. The migration of dislocation introduced to the structure during compaction process and trapped by nano-sized precipitaes starts generally around temperature about 475°C.

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[1] H. Hadraba, I. Dlouhy, *Journal of Nuclear Materials* 386-388 (2009) 564.

[2] H. Hadraba et al., *Journal of Nuclear Materials* 411 (2011) 112.

[3] H. Hadraba et al., *Journal of Nuclear Materials* 417 (2011) 241-244.

5. Training and career development

Collaboration with French engineering school ENSAM

R. Dejarmac, D. Sestak, J. Stockel, M Tichy, M. Chichina

In collaboration with:
A. Barbedette-Green, Ecole Nationale Superieure des Arts et Metiers.

The collaboration with the French engineering school ENSAM was always fruitful, for us and for the students doing their internships in our laboratory. This year was not an exception. We hosted 3 students for 3 long-period internships (6 months) and it gave excellent outputs. Students were all working on modeling of the full COMPASS tokamak in 3D using the CATIA (c) software and on designing diagnostics for COMPASS as such as electromagnetic probes (U-probe, Sandwich probe, Ball-pen probe) or part of diagnostics like articulated manipulator, holders, valve and beam dump. Probes will be used on COMPASS in very near future during experimental campaigns to investigate edge plasma physics. The task is completed. Subjects for new internship proposals in 2012 will be prepared and the collaboration will continue next year.

The 3 ENSAM students, Matthieu Arneodo, Gontran Boizante and Alexis Guerin, started their internship at IPP Prague on the 1st of July 2011 and finished on the 20th of December 2011. They all worked using the CATIA (c) software to create pieces in 3D and provide technical drawings for manufacturing. Each of them worked on the global modeling of COMPASS tokamak. For several years, we are working on this complex and long topic in order to have a full description of COMPASS in 3D. Our aim is to have a general 3D 'picture' of the tokamak and its associated diagnostics (and especially the available space) before designing a new diagnostic and see if it fits in. Then each student had a special task related to a diagnostics or part of diagnostics.

Gontran Boizante worked on the design of a prototype probe, so-called sandwich probe, to measure plasma deposition in gaps between tiles. This probe will be used in several tokamaks, including COMPASS, to make several measurements with different edge plasma paramenters and to benchmark the kinetic simulations done in our department on this precise topic. The probe design was completed (see Fig.1). Then Gontran work on the design of a double valve and a manipulator to insert some samples to be exposed to plasma in the tokamak COMPASS. The design has been finished but modifications on the tokamak itself (cutting some pipes) have to be done in order to install the whole module.

Matthieu Arneodo worked on the electro-magnetic probe, so-called U-probe, design. This complex probe is a prototype for COMPASS based on an already existing probe used in Italian machines to measure and investigate the transport of matter+energy in tokamaks during transient events. The first draft of the complete designed has been made. The probe is so complex that it will need some further developments. Then Matthieu designed a lens holder for COMPASS diagnostic related to plasma rotation measurements.

The last student, Alexis Guerin, worked the most of the COMPASS 3D model and made electronic drawings for segments of the vacuum chamber and limiters, vacuum vessel assembly, central column limiters and X-point limiters. He also participated to brain-storming with physicists for the diamond-coated probe which was abandoned and replaced by a tungsten probe. Finally he designed the neutral beam dump which is used now in COMPASS when using the neutral beam injector.

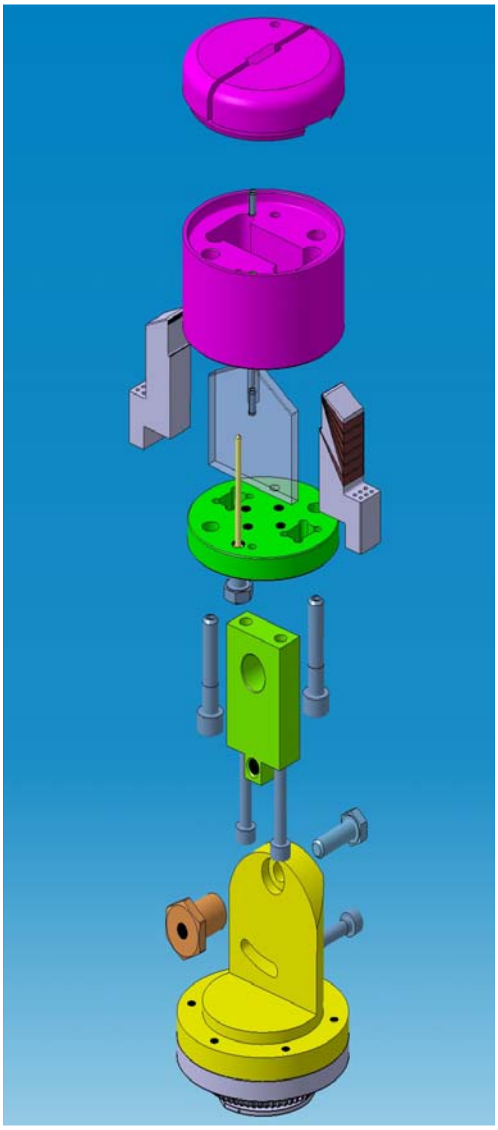


Fig. 1. 3D final design of the sandwich probe, ready for manufacturing in IPP Prague workshop and Forschungszentrum Juelich's workshop, Germany, for the machining the hardest part of the probe. (Molybdenum in pink).

As a conclusion, we can say that this year collaboration was fruitful for us but also for the students. They learned a lot by working daily with our chief-engineer David Sestak. The output we got from them are precise and ready for manufacturing. New subjects for future internships will be thought about and the collaboration will continue in 2012.

The students visited the Czech republic in the framework of the Erasmus Mundus mobility programme and in this respect the administrative and personal help of the Faculty of Mathematics and Physics was highly appreciated.

The task is completed.

IPP collaboration with Czech Universities and SUMTRAIC

J. Mlynář, J. Stöckel

In 2011 about ten undergraduate students decided to participate in regular fusion courses by IPP experts and/or to start their thesis on COMPASS, which presented an unusualy high, although a welcome workload on the COMPASS team. Besides, several seminars for students were organised at IPP. At the same time, IPP participated in co-operation with FUSENET and became an associated member of the Erasmus Mundus Fusion Doctoral College.

Scientists and engineers from the COMPASS tokamak read lectures for the MSc fusion programme run by the Technical University in the following undergraduate courses: Introduction to Thermonuclear fusion, Technology of Thermonuclear fusion, Plasma Diagnostics, ITER, Topics from MCF (which gave unique opportunity to practice teaching also to our junior staff), Practica and Seminars. Also in support of the MSc fusion programme the IPP Prague provided for free for one week its training centre in Marianska (Ore Mountains, Czech republic) for the joint winter school in January.

Many interesting seminars were based on invited talks by external experts. These included a seminar on space plasmas by Prof Kulhanek from the Czech Technical University, on research for F4E by O Zlamal from the Centre of Research Rez, and by ATEKO, Hradec Kralove who supply ITER with He pumps. Prof Marco de Baar from FOM accepted our invitation and had a talk at Technical University colloquium on 4th May on “Track-and-kill system for tearing instabilities in tokamaks“. on 19th October, Dr Michael Gryaznevich from CCFE accepted the invitation to read a colloquium talk on “Fusion for Neutrons”.

In 2011, two bachelors’ theses and one master’s thesis supervised by IPP were successfully finished. Several students’ projects were also concluded. Six new subjects for theses were proposed in detail and four of them found a candidate student willing to pursue the topic.

Collaboration is also established with the Faculty of Mathematics and Physics, Charles University, in particular IPP runs the Plasma Physics courses for students of the mathematical physics and supervises several doctoral students of Plasma physics. In 2011, M. Komm finished the PhD degree with dissertation on “Studies of tokamak edge plasma and its interaction with the first wall”, and continues in a postdoc position on COMPASS tokamak. IPP also participated in the FUSENET consortium and became an associated member of the Erasmus Mundus Fusion Doctoral College.

Participants of the 9th SUMTRAIC in front of the IPP tokamak department entrance

A special mention also deserves the 9th summer school SUMTRAIC in 2011 which was traditionally organized in order to train participants in all important aspects of experimental work on tokamaks, i.e. planning of experiment, performing experiment, processing of experimental data, discussion of achieved results within an experimental group, preparing of the presentation and present results at the closing workshop. SUMTRAIC 2011 was attended by 10 participants from six different European contries, two participants were Czech students.

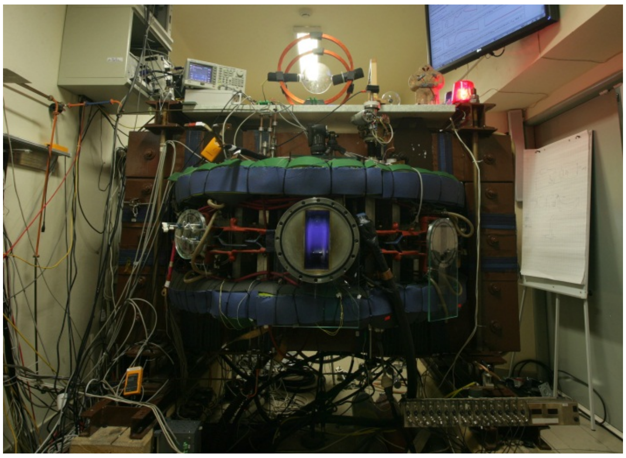
Undergraduate and postgraduate studies in Fusion Science and Technology

V. Svoboda, J. Mlynář, M. Tichý, R. Hrach

In collaboration with:
FUSENET consortium coordinated by TU/e

In the undergraduate level of studies, the main contributor to fusion education is the Faculty of Nuclear Sciences and Physical Engineering of the Czech Technical University in Prague (FNSPE) with its MSc dedicated programme "Physics and Technology of Thermonuclear Fusion". With direct collaboration of other faculties (in particular the Faculty of Electrical Engineering), the Charles University (Faculty of Mathematics and Physics) and in particular the Institute of Plasma Physics, the programme is now responsible for approx. 20 students working on either Bachelor or Masterslevels of fusion education. In the postgraduate (doctoral) level of studies the majority of fusion related students (11 out of 16) follow the Plasma physics programme of the Faculty of Mathematics and Physics, Charles University.

In 2011, mobility of students increased considerably in particular thanks to the FUSENET support - most of them could participate in summer schools, two students from the MSc curricullum were selected by the Erasmus Mundus Fusion-EP to continue their MSc studies abroad, and one student was granted FUSENET support to prepare his MSc thesis at JET. The FNSPE fusion curricullum was slightly amended so that it fulfils new legal requirements (BSc and MSc levels had to be separated completely). FNSPE also contributed to the FUSENET coordination by management of Work Package 9 – multimedia.



The flagship of the MSc fusion students' practica, the GOLEM tokamak at FNSPE (see the photo), received a grant for upgrade from the FUSENET consortium. In particular, the grant allowed modernising the DAS system, tokamak power circuits, vacuum operation, gas filling system, diagnostics and remote participation hardware. New GOLEM facilities in particular improved its flexibility in remote operations that continued to provide very popular fusion practica not only to our own students, but also on international level. In 2011, the GOLEM tokamak continued to work regularly and operated e.g. during the science week for high school students, in the introductory session of the summer school SUMTRAIC 2011, in the framework of practicum for seniors participating in the University of third age programme and in the "Hot Shots" competition. More than 20 excursions visited the GOLEM tokamak. Besides, on 29th August GOLEM in collaboration with CCFE ran the first experiments ever with high temperature superconductors generating a part of the vertical field (their heat insulation is clearly visible in the figure).

Faculty of Mathematics and Physics continued in both their teaching and research programme in fusion (see above) in close collaboration with the Institute of Plasma Physics AS CR. The regular Week of Doctoral Students again provided a unique opportunity to students of the faculty to present their research work in a conference-like environment, either in a form of poster or in an oral contribution.

6. Other activities contributing to the EURATOM fusion programme

Fostering Public Information in Fusion

M. Řípa, J. Mlynář, J. Ullschmied

In collaboration with:
Public Information Network (PIN), EFDA

On 23rd June, UK PM D Cameron visited the COMPASS tokamak. Besides this highlight, the third edition of the Czech book „The Controlled Thermonuclear Fusion for Everybody" was finalised. The project „The Materials for the third Millennium" was submitted for the EU operational programme support "Education for Competitiveness". Two exhibitions welcomed fusion: International Fair Ampere 2011 and traveling photo exhibition The Sciences on Backstage. The association wrote approximately 30 articles for public media and gave 10 lectures for high school students.

In 2011, work in public information concentrated on keeping and improving the routine duties, including visits of schools and general public at COMPASS tokamak (on average 2 groups every month), public talks and PI articles in newsletters and journals (about 20) including an article in the ITER Newsline on 11th February, an interview in the CCFE InFusion journal, a major English article in the Energetika journal, an invited lecture on ITER at the ENYGF conference in Prague, and a major article in the daily newspaper Mlada Fronta on 25th March. Extraordinary events included visit of MEP J Brezina (31st March) and in particular visit of British Prime Minister D Cameron and Czech PM P Necas on 23rd June 2011, see picture in Part I, and CCFE web news item "view from the top":
http://www.ccfe.ac.uk/news_detail.aspx?id=120

The Laser Plasma department realized 12 excursions accompanied with films, besides the traditional Open days. The open days were organized as a part of the Week of Science and Technology in November. As a part of the week, 2 public talks on tokamaks were read (by J. Mlynar and M. Ripa).

Considerable efforts were also dedicated to preparation of the updated edition of the booklet "The Controlled Thermonuclear Fusion for Everybody", see figure. The third edition of this book features new chapters on plasma diagnostics and on COMPASS tokamaks and large amount of updates, including figures and photographs. The book was printed in December 2011.

The project for the EU structural funding "The Energy Around Us" as prepared in 2011 was awarded 62 points from 80. Unfortunately this did not suffice to obtain financial support. However, some experts and institutions (including IPP Prague) continued to collaborate. As a result, a new project called „Materials for the third millenium“ was submitted, with an important pillar dedicated to fusion popularization.

The Institute also succesfully participated in the international trade fair AMPER 2011. Our exhibition was focused on thermonuclear fusion. Three “fusion” articles in technology magazines was distributed during trade fair and the Czech Academic Bulletin and EFDA Fusion in Europe mentioned this event, too. An interview on fusion was broadcasted by the internet radio Electrica TV.

Fusion themes dominated in our participation to the travelling photographic exposiotion “Science backstage” at Science Centre IQ-Park at Liberec. Fusion topics were on the programme of three conferences. The Energy of the Future (photovoltaics), Brno March 31, The Renewable Sources, Kouty nad Desnou, April 13 – 15, and Seminar of the Department of Impulse Plasma Systems, Mariánská, September 2. A part of the semester course The historical and socio-economical aspects of fusion for five class of Faculty of Nuclear Sciences and Physical Engineering was dedicated to fusion popularisation.

The 11th Public Information Network Meeting was held in Greifswald from May 11 to 13. Besides its new name – PIN changed PIG – the need of new methods of communication was underlined - in particular, 3D video, images and social networks. The article describing experineces related to trip on Wendelstein stellarator was published in technology newspaper Technický týdeník No 5/2011. Three students of Martin high shool, Slovakia participated in all Slovakia student competition CASCADE. Their fusion thema won the second place. The reward was excursion on COMPASS tokamak in Prague. Our Association delegated the advisor. The story was published in Fusion in Europe magazine.

List of generated Public Information in Czech or English (en)
Papers

Křenek P., Mlynář J.: Focus on nuclear fusion research. *Energetika* **61** [-] (2011) 62-63. (en)
M Řípa: What has the same mass as Eiffel Tower? Technický týdeník, 59(2011), No 1, p. 22
M Řípa: Golem’s ways, Technický týdeník, 59(2011), No 2, p. 10
M Řípa: What will express the main ITER building?, Technický týdeník, 59(2011), No 2, p. 28
M Řípa: The Science and Technology in Chechoslovakia from the years 1945 to 1960, rewiev, Technický týdeník, 59(2011), No 4, p. 27
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M Řípa, Petr Křenek: Tokamak COMPASS, Inovační podnikání a transfer technologií, 2011, No 1, pp. 32–34
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M Řípa: The international fair AMPER 2011, Akademický bulletin, May 2011, p. 23
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M Řípa: Thermonuclear energy aims uncomprisingly to future energy mixture (editorial), All for Power, 5 (2011) , No. 2, p. 2
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M Řípa: Thermonuclear fusion as entrepreneurial busness, 3pól, July 12, 2011, http://3pol.cz/1091-termojaderna-fuze-jako-podnikatelsky-zamer
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M Řípa: Stellarator in Greifswald, Technický týdeník, 59(2011), No 15, p. 9
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M Řípa: Popularization of Fusion in Europe, Department Pulse Plasma Systems Seminary, Mariánská 2011, September 2, 2011, Mariánská / Jáchymov
M Řípa, Jan Mlynář, Vladimír Weinzettl: Tokamak Compass updating, Inovační podnikání a transfer technologií, 2011, No 3, pp. 36-37
M Řípa: JET with us once again, Technický týdeník, 59(2011), No 18, p. 45
M Řípa: Thermonuclear fusion celebrates two anniversary this year, All for Power, 5 (2011) , No 3, p. 58
M Řípa: Science backstage, Technický týdeník, 59(2011), No 22, p. 2
M Řípa: ITER thinks on back wheels, Technický týdeník, 59(2011), No 22, p. 4
M Řípa: Two anniversary of Ronald Richtr –Sokolov native, Technický týdeník, 59(2011), No 23, p. 28
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M Řípa: Science backstage, Akademický bulletin, 2011, No 12, p.40
M Řípa: Home-made neutrons, Fusion in Europe, 2011, No 3, p. 21
M Řípa: Predators and thein preys (in plasma), Technický týdeník, **59**(2011), No. 26, p. 4

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M Řípa: The best of fusion or ITER is a way...", Pelhřimov gymnasium, April 7.2011, Pelhřimov,
M Řípa: Thermonuclear Fusion or Sun on Earth, Ronov nad Doubravou basic school , 12.5.2011, Ronov nad Doubravou
J. Mlynář: The mission of ITER. Invited talk at European Nuclear Young Generation Forum (ENYGF), 17-22 May 2011, Prague, Czech Republic (en)
P Švihra, B Nabová, M Račko: „Termonulear fusion" – the second place of All Slovakia High School Competition (Milan Řípa – advisor)
M Řípa: Plasma seriously – unseriously.... Škoda Auto trade school, Mladá Boleslav, October 21, 2011,
M Řípa**:** Who lights us thermonuclear fusion here?, Science and technology week, Akademické konferenční centrum, November 2, 2011
J Mlynář: News in the fusion research, Science and technology week, Police museum, November 2011
J Ullschmied: Pals, for international students in the frame „Athens" course ; 2x (en)

Interviews
J Mlynář for the InFusion CCFE journal "COMPASS points in a new direction", see the Winter 2011 issue, http://www.ccfe.ac.uk/assets/Documents/infusion2.pdf, page 8-9 (en)
M Řípa, Thermonuclear fusion, interview for internet broadcast Elektrika TV, April 29, 2012, Brno, International Fair AMPÉR 2011

Expo
M Řípa: International Fair AMPER 2011, April 28. to May 5.2011, ÚFP AV ČR (directed to fusion
M Řípa: Traveling Photographic expozition „Science Backstage" started in the Liberec IQ Science Park

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

Acceleration, compression and shaping of dense plasmas

Jiří Ullschmied, Daniel Klír, Eduard Krouský, Miroslav Pfeifer, Jiří Skála, Roman Dudžák

In collaboration with:
J. Badziak, S. Borodziuk, A. Kasperczuk, T. Pisarczyk, T. Chodukowski
Association EURATOM-IPPLM, Warsaw, Poland

The fast ICF ignition could be achieved by impact of an accelerated high-velocity macro-particle or plasma projectile onto a highly compressed DT target. As the required impact velocities above 10^8 cm/s are difficult to achieve by using the ablative laser acceleration (standard rocket effect) only, more sophisticated techniques are needed. Several advanced cavity pressure acceleration (CPA) schemes proposed by IPPLM, Warsaw, were validated at PALS in Prague: the Laser-Induced Cavity Pressure Acceleration (LICPA [1]), and the Reversed Acceleration Scheme (RAS, [2,3]). They both proved to efficiently accelerate plasma projectiles to highly supersonic velocities at moderate incident laser energies of the order of hundreds of joules. Moreover, the experiments conducted at PALS have demonstrated, that using laser targets made of combination of light and heavy materials makes it possible to efficiently steer, shape and compress the accelerated dense plasma streams.

Highly supersonic plasma jets generated at interaction of high-power laser beams with solid targets represent a prospective tool for validating an alternative impact ignition concept – the jet impact ignition. Generation and dynamics of laser-produced plasma jets as well as their mutual interaction and transport through ambient media were systematically investigated at the PALS facility. The experiments have proved that annular target irradiation plays a decisive role at the initial stage of the plasma jet formation. However, well-formed plasma jets have been observed at laser interaction with high-Z targets only. Further experiments on mutual interaction of coaxial plasma jets launched on targets made of two different materials (high-Z targets with low-Z cylindrical inserts and vice versa) resulted in an idea to use the observed difference in high-Z and low-Z plasma pressures for compressing the central plasma jet [4].

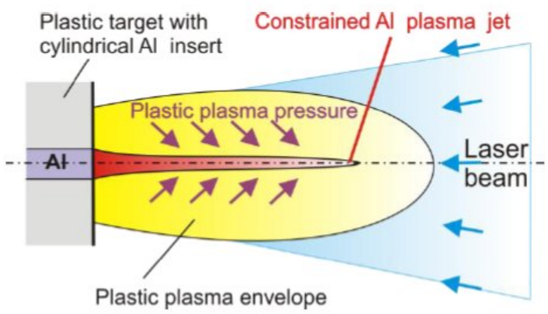

Fig. 1 *Plastic plasma as a compressor of aluminium plasma - schematic of the experiment [5]*

In the experiment carried out at PALS the plasma was generated by the third harmonic of the laser frequency used (λ=0.438 μm), with laser energy 130 J, pulse duration ≈ 250 ps (FWHM), and focal spot diameters 800, 1000, and 1200 μm. The laser irradiated a plastic target with an Al cylindrical insert of 400 μm in diameter (Fig. 1). A three-frame laser interferometer and a four-frame x-ray pinhole camera registering soft x-ray plasma radiation in the range of 10-1000 eV were used to image the jet formation. An imaging soft x-ray spectrometer equipped with a mica (004) crystal spherically bent to a radius of 150 mm measured the electron temperature distribution in the Al plasma jet.

The upper and lower sequences of X-ray frames in Fig. 2 illustrate the development the Al plasma jet launched on the plain aluminium target and on the plastic target with a cylindrical Al insert. In the latter a narrow bright aluminium streak can be clearly distinguished against the plastic plasma background. The Al plasma jet of diameter around 100 µm starts very early close to the target surface. It propagates with an average velocity of 7×10^7 cm/s, which is considerably higher than the axial velocity of the pure Al plasma (the upper sequence of frames). Thus, mutual interaction of the aluminium plasma with the surrounding plastic plasma envelope results in not only in creating but also in accelerating the axial Al-plasma jet.

The experiment demonstrating the possibility of the Al plasma jet creation and acceleration by using plastic plasma as a compressor is described in detail in [5]. The same principle was applied at shaping and compressing a copper plasma jet [6]. The use of more complex target compositions, either axially symmetrical or asymmetrical, consisting of materials with low and high atomic numbers makes it possible to create various plasma stream configurations, such as very narrow needle jets, pipes or tubes [7], or even to steer the jets and tailor them for different application in science and technology.

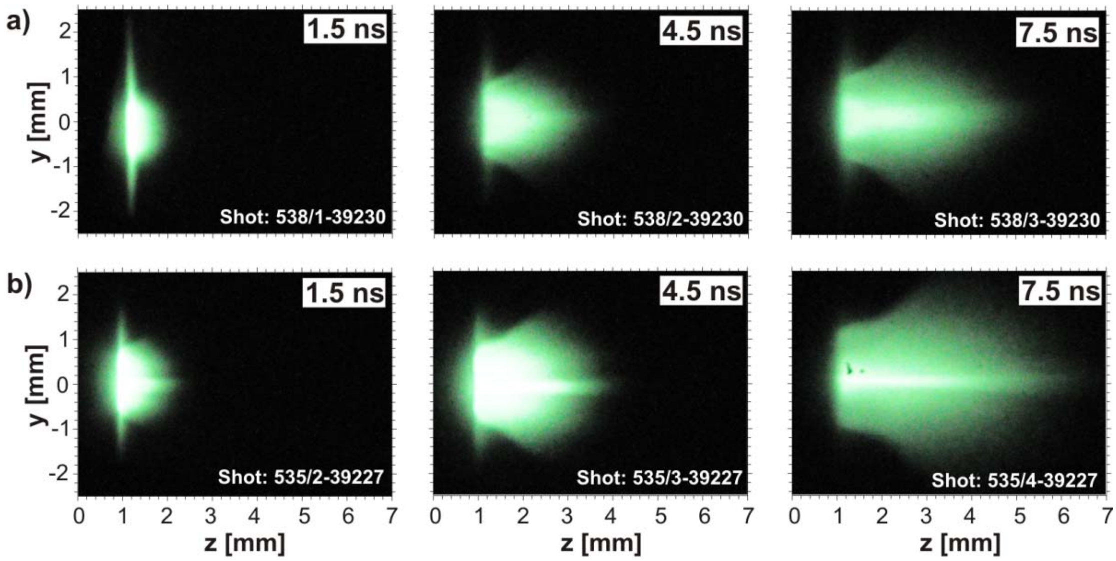

Fig. 2 X-ray images of development of the jet launched on the Al target (a) and on the plastic target with a cylindrical Al insert (b) [5].

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V ADDITIONAL INFORMATION

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

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

O. Zlamal, T. Klabik, R. Vsolak, Centrum Vyzkumu Rez s.r.o.

In collaboration with:
F. Zacchia, B. Bellin, Fusion for Energy, Spain

The ITER requirements for testing of Blanket's materials led to cooperation between EFDA and EURATOM-IPP.CR Association member, NRI Rez, plc, which operates LVR-15 research reactor for material irradiation and testing. In frame of EFDA task TW3-TVB-INPILE irradiation campaign for two small Primary First Wall mock-ups was proposed to be performed on LVR-15 reactor's special designed rig, called simply "TW3". On the break of 2011 LVR-15 reactor with all technology and staff was transferred under the Centrum Vyzkumu Rez, s.r.o., NRI Rez's daughter company, similar to transfer of TW3-TVB-INPILE task from EFDA under the F4E year before. During the 2011 TW3 rig finished out-of-pile testing and received approval for in-pile operation from both F4E and SUJB, Czech nuclear regulator. As a result TW3 started its in-pile operation on January 2012.

ITER operation is expected to produce significant heat and neutron fluxes on the First Wall (FW) of the Blanket, the in-vessel component closest to confined plasma. In average, FW is expected to receive about 0.5 MW/m^2 and divertor about 5-10 MW/m^2, depending on position. This results in need to have materials and technologies capable of withstanding such fluxes, especially with focus on joint between Beryllium (used as the plasma armor) and CuCrZr alloy, serving as the heat sink. The diffusion joint between beryllium and basis metal alloy will be object of severe thermal fatigue loading, taking in account ITER is slated for pulse operation, with average pulse duration about 400 seconds. In order to examine performance of above mentioned Be/CuCrZr joint, several EFDA task were carried out in CV Rez, first out-of-pile, now in-pile. Previous experience from contactless graphite panel heating of similar PFW samples from TW4-TVB-TFTEST2 task is employed on the TW3 rig. The technology 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 the examined 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 diffusion joint under representative PFW operation conditions; the joint is made by HIP technology, which stands for Hot Isostatic Pressing: materials for connecting are pressed under the pressure of tens of MPa and hundreds of Celsius degrees for several hours. In the frame of performed task, two PFW mock-ups are prepared to be irradiated at 0.6 dpa dose, with parallel thermal cyclic fatigue testing at 0.5 MW/m^2 for 20,000 cycles; with each cycle being 7 minutes long, approximately 100 full-power days are expected for the irradiation of the rig. Each reactor campaign takes in average 21 days, so at least 5 campaigns shall be employed. Similarly, 5-6 campaigns are necessary to gather 0.6 dpa dose on Beryllium.

In the first years of TW3-TVB-INPILE task, the various designs of heating panel and used graphite grades and insulating ceramics were investigated, resulting in selection of meander-shaped R 8710 isostatic graphite grade panel with Si_3N_4 low Yttrium doped ceramics as given in [1, 2]. Such selection was supported by results from TW6-TVM-TFTEST and TW4-TVB-TFTEST2 tasks performed on BESTH device and also by experience gained during out-of-pile testing of TW3 rig, when several types of ceramics and graphite grades were tested. The final setting of the rig (without metal sheath) is shown on ***Figure 1***.

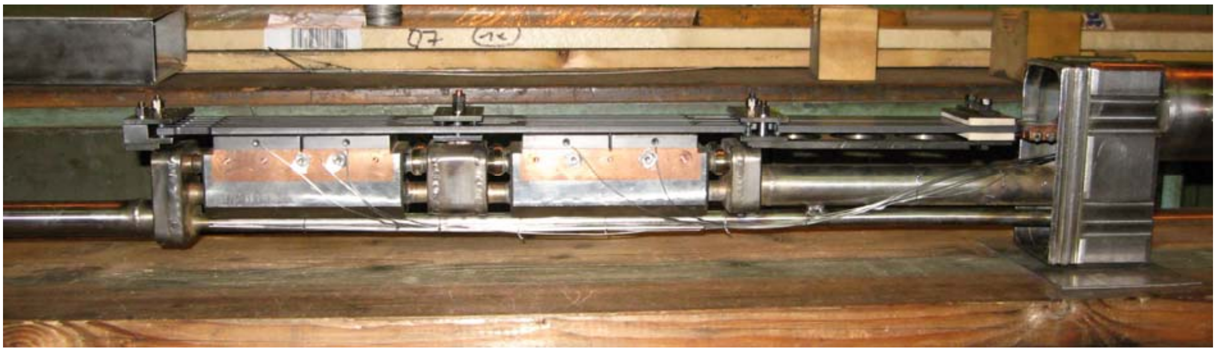

Figure 1: Rig final assembling before inserting in LVR-15 core (side-view without metal sheath)

Due to limited space in LVR-15 core and dimension of irradiated mock-ups, the serial setting of both mock-ups was used as given on ***Figure 1***: the mock-ups are connected by middle mixing block; the cooling water enters the upper mock-up first (shown on right on ***Figure 1***) and then passes through the lower mock-up to the reactor pool (shown on left). It should be mentioned that reactor pool water is used for cooling instead of the separated cooling circuit as used on other experimental devices. Due to mock-up dimensions and requirements on low heat losses, TW3 rig occupies two cells in the reactor core as depicted in ***Figure 3***.

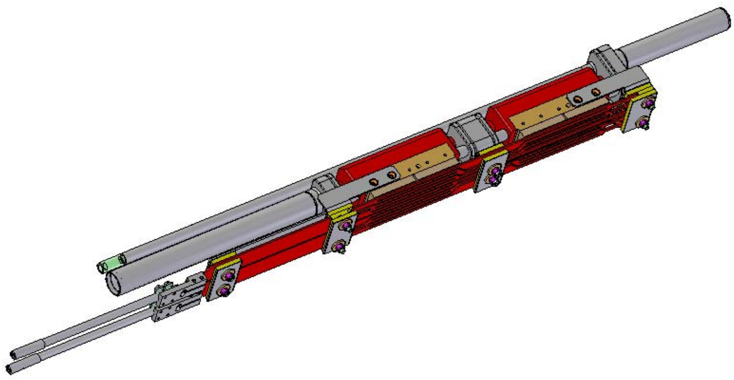

Figure 2: 3D model of TW3 rig without metal sheath

Serial connection of both mock-ups led to development of plane and thin heating panel, which is placed on top of Beryllium tiles as shown on ***Figure 1*** and ***Figure 2***. As indicated on

Figure 1, the 1-2 mm gap between Beryllium and heating panel ensures no short electric circuits leak into the mock-up bodies but heat losses are still kept as low as possible.

In frame of TW3-TVB-INPILE, the TW3 rig was tested out-of-pile in two shorter screening tests, totalling about 6 000 cycles. Screening tests were performed after consultation with F4E's responsible officers in order to verify TW3 rig's design, power conditions and gather data for in-pile operation. Such data were later used for application to the Czech nuclear regulator, State Office for Nuclear Safety (SUJB), which is the governing body over the nuclear safety on all nuclear installations in Czech Republic, including LVR-15 research reactor. TW3 rig is experimental installation with significant impact on nuclear safety hence the approval from SUJB was required for its in-pile operation. Such approval was obtained on the eve of 2011 and since January 2012 the TW3 rig is in full operation. TW3 rig was operated in-pile for the first time in K136 reactor campaign, in position D1/D2 as shown on ***Figure 3***, see [3].

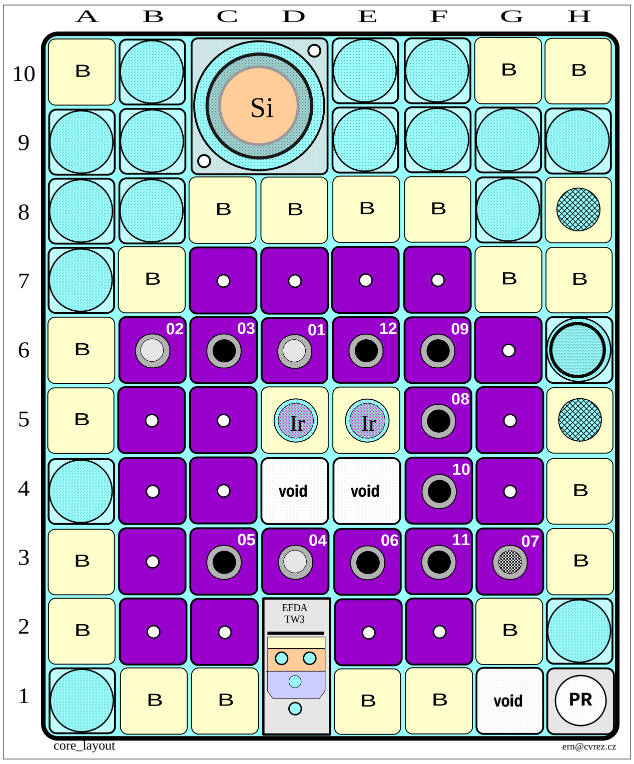

Figure 3: K136 core with TW3 on position D1/D2.

Same as during out-of-pile operation, TW3 rig generates 7 minutes long cycles during the in-pile operation. The DC powered heating graphite panel needs 30 seconds to heat to full power (9.2 kW), 180 seconds to keep full power, 30 second to cool down to zero power and 180 seconds to keep on zero power. The full power is computed to generate 0.5 MW/m^2 over the whole Beryllium surface, which was also read on calorimetric measurement of cooling water during the out-of-pile screening tests.

The TW3 rig is operated only with LVR-15 reactor on full power; as a result, significant radiation heat is generated in all rig materials. Metal sheath, which is in direct contact with reactor pool's water, is cooled independently and almost no heat is transferred from it to the mock-up due to helium atmosphere around the mock-ups. Similarly almost all radiation heating generated in mock-ups is removed by its cooling circuit where flow-rate, inlet and outlet temperatures are measured for calorimetric evaluation.

Although the radiation heating strongly depends on fuel burn-up, fuel loading pattern and mostly also on the position of reactor control rods which are in close vicinity of the rig, as indicated on ***Figure 3***, approximately 37 kW of radiation heating power is generated in the rig, excluding metal sheath which is cooled independently; see [1, 3] for further details. The recorded calorimetric heat from K136 campaign, including both radiation and electric cycling, is shown on ***Figure 4***.

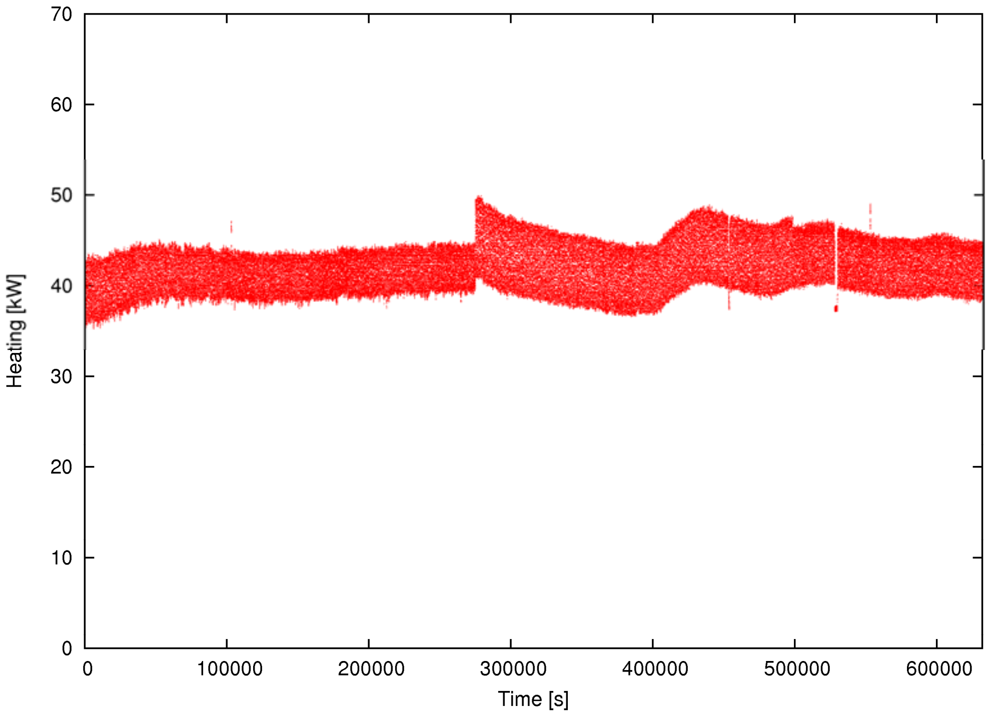

Figure 4: Record of cyclic heating from TW3 rig (including nuclear heating)

In order to generate 20 000 cycles as required by TW3-TVB-INPILE task objectives, TW3 rig is expected to be operated in 6 campaigns, starting with K136 campaign on January 2012 and ending with K141 campaign on June 2012. According to dose calculations performed in MCNPX code with ENDEF-VII library (MT444 cross section in particular) and methodology from SPECTER program (see [4]) on TW3 rig model given on ***Figure 2***, it is expected close to 0.6 dpa will be accumulated in Beryllium by the end of the irradiation. Such value is in concurrence with requirements from task objectives.

After finishing of irradiation, TW3 rig is slated to be kept several months under the water shielding in LVR-15 reactor's wet depository. During this period, residual heating will be removed and certain radioactivity decrease is expected. Rig will be then cut open, first in LVR-15 reactor's hot cells, where mock-ups will be retrieved from metal shielding. Second, more precise cutting shall take place in close semi-hot cells, where smooth ending of each cooling water pipes will be finished. Clean cuts with no metal chips are required as mock-ups are planned for further testing in Forschungszentrum Juelich (FZJ) in Germany on JUDITH device equipped with electron beam. JUDITH device is world-wide unique device (see [5]), which is able to generate heat fluxes up to 20 MW/m^2; JUDITH will continue with testing of irradiated mock-ups and will load them with heat fatigue up to several MW/m^2.

As mentioned in [6], similar in-pile test with FW mock-ups was performed in RIAR Dimitrovgrad, in cooperation with NIIEFA Eframov, but only 3700 cycles were reached before the testing rig experienced heating panel's failure. With several times higher number of generated cycles under the similar irradiation conditions, TW3 rig appears to be world-wide unique device.

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