Annual Report
2012

Association
EURATOM / IPP.CR

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

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PREFACE

This Annual Report summarizes the main activities and achievements of the Association EURATOM/IPP.CR in the year 2012 in the area of fusion research.

The Association was founded on December 22, 1999 through the Contract of Association (CoA) 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.
- Institute of Physics of Materials, v.v.i., Academy of Sciences of the Czech Republic
- Nuclear Physics Institute, v. v. i., Academy of Sciences of the Czech Republic
- Institute of Applied Mechanics, Brno, Ltd

In the past couple of years, the last two institutions mentioned were however not involved in the work programme under the CoA.

The overall expenditures toward the fusion programme have increased in 2012 to 2.35 M€ from 2.06 M€ in 2011. This reflects the increased national support through the project #LM2011021 "COMPASS-RI - Contribution to operation and baseline human resources of the COMPASS tokamak - a large research infrastructure of European impact" awarded in the frame of the program of Ministry of Educations, Youth and Sports "LM - Projects of major infrastructures for research, development and innovation".

Worth mentioning is another large project awarded in 2012 to our partner, Research Centre Rez, Ltd., namely, project #ED2.1.00/03.0108 "Sustainable Energy (SUSEN)", funded from the structural funds and covering also topics relevant for the development of fusion energy. In particular, the objectives include the construction of infrastructure to verify and develop remote handling procedures during erection and especially repairs and maintenance of the system with molten metal Pb-Li and to develop handling tools for hot cells in the ITER facility, as well as construction of an experimental facility for cyclic stress induced by high heat flow and high-energy neutrons applied to samples of the primary first wall.

On the ground of research, a milestone to be certainly mentioned here is the achievement of the H-mode on the COMPASS tokamak in November 2012 which opened the way to proceed with the "core" COMPASS physics programme – L/H transition, edge plasma and pedestal studies, SOL transport, etc.

Our activities in the area of technology within the EFDA programme "Power Plant Physics&Technology" have notably increased, too, and while they still represented less than 10% in 2012, we expect the share to raise in the coming years due to the evolution of the European fusion programme which is getting more focused on the ultimate target of fusion energy production, and also in view of the objectives of the SUSEN project.

The last point to be highlighted is the continuation and strengthening of our education activities, so important for continuity of fusion research and exploitation of the ITER experiment expected to start in ten years from now.

Pavol Pavlo
Head of Research Unit

I RESEARCH UNIT

1 Association EURATOM/IPP.CR

Composition of the Research Unit in 2012

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

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Vito Marchese, Unit K6
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Petr Křenek (Institute of Plasma Physics)
Pavel Chráska (Institute of Plasma Physics)

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Pavol Pavlo

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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

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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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Radomír Pánek	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
Jan Kysela	Research Center Řež, Ltd.

Part I – RESEARCH UNIT

The traditional Summer Training Course on experimental plasma physics (10th SUMTRAIC) took place on tokamak COMPASS and GOLEM on August 27th – September 7th 2012. This year we hosted and trained 15 participants from 8 countries.

On 29 November 2012 the COMPASS tokamak achieved the H-mode for the first time after its reinstallation in the Czech Republic. The photo shows the core of the team behind (and in front of) this success: from left to right, Filip Janky (tokamak control systems), RadomírPánek (head of the Tokamak department), Jan Stöckel (senior physicist), Vladimír Weinzettl (plasma diagnostics), Jozef Varju (neutral beam), and Josef Havlíček (shift operator).

II OVERVIEW

In accordance with the EFDA planning, the main areas of the research in the Association EURATOM/IPP.CR in 2012 were as follows:

1. Provision of Support to the Advancements of the ITER and 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 2012 Annual report of the Asociation EURATOM/IPP.CR the most important results, activities and achievements are briefly summarised. It also details that unfortunately, our last contribution to item 3 (in particular, EBW studies for the stellarators) was discontinued this year. 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 2012 are cited in this overview, the 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 and DEMO Physics Basis

1.1 Development of candidate operating scenarios

Edge plasma in JET at ITER advanced scenarios

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, taking into account local values of electron mean free path and parallel distributions of ne and Te deduced from fluid code simulations. We accommodated the code for simulation of electron distribution function near the JET divertor targets. The first results indicate the similar type of results than in case of TCV, i.e. predicted overestimation of Te by divertor Langmuir probes by a factor of 2 for the medium densities.
Ref.: [81]

ITER limiter power loads and SOL characterisation in the JET ILW.
Principal Investigator: J. Horáček
This project has direct impact on the design shape of the ITER inboard limiter, which is determined by the SOL decay length. The multi-tokamak database that we built, reveals a credible prediction of this value for ITER (~50mm for the 7.5MA scenario).
Ref.: [4, 43, 47]

1.2 Energy and particle confinement/ transport

L-H transition physics

Probe reciprocation into the COMPASS H-mode pedestal.
Principal Investigator: J. Horáček
Machining the tungsten was found too complicated. Therefore, we selected Copper as the bulk material, even though knowing the risk of the probe melting in too deep insertion.
Ref.: [41]

Investigation of the ion temperature during ELMs with fast swept BPP or triple BPPs on AUG and COMPASS.
Principal Investigator: J. Adámek
The fast swept ball-pen probe has been used in June 2012 on AUG to determine the ion temperature with high time resolution during ELMs. However, the measurements were partially successful because of high parasitic current on the cable. It is caused by the nature capacity of the cable and high frequency of the swept voltage. The data will be analyzed during the year 2013.

Modeling of edge turbulence on COMPASS.
Principal Investigator: J. Seidl
Since suitable experimental data from horizontal reciprocating probe on COMPASS were not available until the beginning of September, the work first focused on analysis of data measured with similar probe head on ASDEX Upgrade and their comparison with turbulence modelling by ESEL code. The analysis revealed strong coupling between plasma potential and electron temperature (measured at midplane). We interpret the coupling as a consequence of influence of sheath layer located at the field line ends. Modification of parallel dynamics in ESEL simulations according to this assumption gives reasonable agreement in radial potential profiles compared to experiment [40, 42]. Such agreement was not obtained in any of the earlier ESEL simulations. In the fourth quarter of the year, several ESEL simulations were made also for parameters of COMPASS plasmas. Their comparison with the experimental data is now in progress. We also participated on design of probe head that will allow measurements inside last closed flux surface [41]. This probe should in the future enhance comparision of turbulence behaviour inside so called blob-birth zone.
Three modifications of the ESEL code were made in 2012. First, we performed OpenMP parallelization of the code [108]. Second, a new alternative solver for equations of ESEL model was developed [28] using PETSc library. The new solver should avoid some stability issues of the original solver and presently it is undergoing performance benchmark and comparison against results of the original code. Third, coupling of ESEL with SOLF1D code that solves Branginskii equations for plasma transport along field lines was performed [108]. In the future, the coupled code should provide oportunity to compare turbulence modelling with simultaneous measurement of both reciprocating probes installed on COMPASS.
Finally, our previous results of fluid simulations of drift-waves were used for discussion of transport of particles with non-negligible Larmor radius [33] and under influence of resonant magnetic perturbations [32].
Ref.: [28, 32, 33, 40, 41, 42, 108]

The systematic measurements of the Ti and Te, Vpl during L-mode discharge in SOL on AUG, COMPASS, Tore-Supra or RFX by using BPP.
Principal Investigator: J. Adámek

We have performed the first systematic measurements of the ion temperature by using fast and slow swept ball-pen probe on AUG and COMPASS. The slow sweeping provided standard profile of the ion temperature during L-mode discharge on AUG with high errors. However, at the end of 2012 we have developed a new fitting routines, which are able to determine the ion temperature with lower errors. The first data analysis show that the resulting ion temperature values with high temporal resolution have non Gaussian PDF. On the contrary, the low temporal resolution provides the ion temperature values with almost Gaussian PDF. This could change the understanding of the behaviour of the ion temperature. The detailed analysis will be performed till summer 2013 and published in RSI.
The systematic measurements of edge plasma parameters (electron temperature, plasma potential, electric fields) have been performed on AUG and COMPASS by using ball-pen and Langmuir probe heads. The results show nice quantitative agreement of the SOL plasma of these two different fusion devices with divertor plasma (the shape of the radial profile of the electric field).
The unique comparative measurements of the plasma potential by ball-pen probe and self-emitting Langmuir probe were performed on AUG as well as COMPASS during deep reciprocation. The standard Langmuir tip on probe head became so hot that it becomes emissive probe. Both potentials, provided by BPP and self-emitting LP, agree quite well. The first results were presented on IAEA 2012 and will be published in NF. The detailed analysis will be presented in IWEP in 2013 and published in CPP.
The first results of the radial particle transport measurements on ISTTOK using BPP will be presented on EPS 2013.

L-H and H-L transition physics.
Principal Investigator: M. Hron
Since the H-mode was achieved in the last part of the year, no systematic studies of the L-H / H-L transitions could be performed.

Characterization of the pedestal parameters.
Principal Investigator: P. Bílková
In 2012, a comprehensive set of diagnostics was set up and tested for a purpose of measurements namely in the pedestal region. During the whole year, optimization of plasma discharges was a priority that succeed and by the end of 2012 year, H-mode was achieved followed by first H-mode experiments.
Ref.: [10, 11, 16, 24, 38, 41]

Construction and measurement with U-probe on COMPASS tokamak.
Principal Investigator: K Kovařík
Probehead with all structural parts has been manufactured at end of May. Several leaks have been detected at the complex vacuum port plug containing 4 vacuum feedtroughs and had to be welded by external company. 3D coil system was manufactured at the end of December. Installation of the coils into probehead is planned at the end of January.
The whole system will be prepared for vacuum (pump down, baking) till end of February. Installation will be performed in nearest shutdown.

Systematic measurements with COMPASS divertor probes and turbulence study with probe on vertical manipulator.
Principal Investigator: R. Dejarnac
Measurements in COMPASS divertor using the array of 39 Langmuir probes (LPs) are routinely operated using state-of-the-art electronics [9]. Spatial profiles during D-shape plasmas show the 2

strike points in the divertor region of COMPASS in ohmic mode [10] and even during H-mode (first ELM free/ELMy H-mode was achieved on COMPASS in December 2012). Plasma parameters like Isat, Te and Vf but also power flux and density have been measured and compared to old COMPASS data (back in Culham, UK). LPs are one of the basics and routine diagnostics used on COMPASS for years. Therefore we want to implement a second array of LPs in the divertor to study long range correlations. This second array was made by our Romanian colleagues from Iasi University. It was sent to IPP Prague in October 2012 and is ready to be installed in COMPASS. The cooling pipe system which was directly below the port where we want to insert it has been moved to have a free path for the manipulator. Unfortunately, to be inserted into the COMPASS divertor we need a system of double-valve + a manipulator which is not ready yet. The designed has been done with the collaboration of engineering students from Ecole National Superieure des Arts et Metiers (ENSAM) and it has been sent for construction. The manipulator should be ready for next spring shutdown (March-April 2013). Electronic boards for measurements are ready to use. This part of the task is delayed.
Measurements on COMPASS with the vertical reciprocating probe have been performed during several dedicated experiments, during our summer school and during the Joint Experiment organized by IAEA. Radial profiles of Te, ne, electron energy distribution function but also decay length of the power flux in the scrape-off layer have been measured and compared to profiles given by Thomson Scattering diagnostics. A draft of a paper have been written and will be soon submitted to a peer-review scientific journal. This part of the task is completed.
Ref.: [9, 10]

Control of ELM size and frequency using externally imposed changes of the plasma position in the COMPASS tokamak [GACR: P205/11/2470].
Principal Investigator: M. Hron
The progress in 2012 was significant and has prepared a good environment for next steps in studies of the Edge Localized Modes (ELMs) during the H-mode discharges on the COMPASS tokamak, and, in particular, for the ELM control experiments.
The main focus of the 2012 activities was to prepare the basis for the vertical kicks experiments to be performed in early 2013. Therefore, we concerned on

- plasma control and development of suitable discharge scenarios;
- construction, tests, and commissioning of the needed power supplies;
- development of the plasma equilibrium reconstruction EFIT;
- development of proper diagnostics control schemes to be able to gain maximum physics output from the experiments;
- adaptation of the data storage to accommodate the large amount of the experimental data;
- experiments to test the robustness of the plasma control with respect to the expected disturbance caused by the vertical kicks.

Ref.: [128, 129]

Resonant Magnetic perturbation experiment on COMPASS.
Principal Investigator: R. Pánek
The COMPASS tokamak is equipped with a complex system of saddle coils. The coils have been modified for the RMP experiment and the new power supplies are in final commissioning phase. The necessary diagnostics are available (divertor probe array, HRTS, reciprocating probes), however, work on more advanced arrays of divertor probes with higher spatial resolution as well as development of fast IR thermography system has been initiated. The necessary plasma performance

with H-mode regime have been achieved recently, therefore, the first RMP experiments are scheduled for Summer/Autumn 2013.
Ref.: [32, 84]

1.3 MHD stability and plasma control

Development of relevant codes

EFIT++ development [TF-ITM-IMP12].
Principal Investigator: J. Havlíček
During the year 2012 the contribution of IPP.CR to the EFIT++ development consisted mostly of finishing development and thorough benchmarking of the new induced currents module incorporated into the EFIT++.
The induced currents module implements a computational model to represent the induced currents that are generated in the passive structures of tokamaks - vacuum vessel, PF coils casings, eventually short-circuited turns used for plasma position stabilization. The currents in the passive structures are often difficult to measure. The used model is restricted to axisymmetric currents as the EFIT++ code is itself assuming axisymmetry.
The new induced currents module is written in C++ language and is fully integrated into EFIT++ object oriented structure. Therefore the module can be used for any tokamak as EFIT++ is machine independent and uses comprehensive xml based description of the tokamak and its passive structures.
The induced currents module was extensively tested against existing INDUCTION code which is used on MAST tokamak. The benchmarking revealed several minor errors in the INDUCTION code and in the end we were able to achieve perfect agreement between the independently developed two codes.
The new induced currents module is currently operational and included in the latest release of the EFIT++ project.
During the year 2012 COMPASS tokamak routinely achieved controlled plasma current flat-top phase and divertor configuration. The EFIT++ input files describing tokamak PF coils geometry and connections, limiter geometry, detection coils positions and angles were prepared and EFIT++ was used for equilibrium reconstruction in ohmic, L-mode and H-mode plasmas. EFIT++ runs automatically after each shot and equilibrium reconstruction is performed for the entire discharge with time slices separated by 1 ms. Results are used to automatically create movie which shows plasma shape evolution and basic parameters (q0, q95, betan, ...) on the front panels in the tokamak control room.
EFIT++ equilibrium reconstructed plasma centre position was compared with currently used real-time (RT) plasma position algorithm. The comprison showed that current RT algorithm has significant systematic error against the real plasma position and that this systematic error changes with changing plasma shape (especially limiter -> divertor transition). A new, more robust RT algorithm was designed and will be used in parallel with existing RT algorithm.

Modelling of ergodization by magnetic perturbations and plasma response to perturbations.
Principal Investigator: P. Cahyna
We used the results of plasma response modelling by the MARS-F code to simulate the divertor footprints. After the correction of a mistake in the initial approach we found that the inclusion of plasma response strongly reduces the divertor footprints, in a qualitative agreement with former results of our ad-hoc model of screening currents. MARS-F predicts some effects which are not obtained in the screening current model, namely the much larger footprints in MAST even-parity

magnetic perturbation, compared to the even parity perturbation. Initial simulation of resistive wall modes with MARS-F were also performed for COMPASS and it was found that the example equilibrium from the ACCOME code is stable to the current-driven RWM.

Useful results about divertor strike points were obtained from the analysis of data from the Langmuir probe arrays on MAST. Previously the only information about strike point splitting had been coming from the infrared camera, which is however looking only at one toroidal location, and this is not sufficient for detecting three-dimensional structures such as the divertor footprints. The Langmuir probes are installed at six locations, giving a more complete picture. Using them we were able to detect divertor footprints in both phases of even parity magnetic perturbation, where the camera was detecting them only in one of the parities. On the other hand, by using the probes and analyzing more experiments, we were able to confirm the absence of footprints with the odd parity perturbation. It is significant that the result can not be explained by vacuum modelling, but agrees with the results of the MARS-F model. We also used the probe and camera data to investigate the process of footprint appearance. We found that the appearance of footprints is suden, incompatible with vacuum modelling, but compatible with a nonlinear penetration event. Screening field for a particular DIII-D L-mode shot, which show similar experimental features to the MAST shots, was calculated. It will be used to calculate the impact on footprint and comparison with experimental data, this was postponed to 2013 due to the lack of needed information from DIII-D. Development of a virtual magnetic diagnostics for the plasma response model was started.

The ad-hoc screening current model was used to generate data for use on ITER, especially for the investigation of NBI-generated fast particle trajectories and their modification by the planned ELM control coils.

Improvements to the RMHD code were postponed because of higher priority tasks yielding promising results.

Ref.: [53, 54, 83, 84]

3D simulations of plasma response to magnetic perturbations for ITER with the code JOREK (F4E grant).

Principal Investigator: P. Cahyna

As the work has not been supported by an F4E grant, contrary to our plans, the scope was reduced and did not include work for ITER. The work focused on finding penetration of the externally applied perturbation in the location where the plasma (ExB) flow cancels the electron diamagnetic flow. A JET-like equilibrium was used, with flows adjusted so that the flows cancel near the plasma edge, at a q=2 rational surface. JOREK found no penetration of perturbation at this point, contrary to the results of the 4FC and RMHD codes for DIII-D-like parameters. The cause of this surprising result will be investigated further.

1.4 Power and particle exhaust, plasma-wall interaction

Interaction of hydrocarbon ions with the first wall elements

Modeling of the tile gaps by using 2D and 3D PIC codes.

Principal Investigator: M. Komm

The performance of Particle-In-Cell codes is vital element, which decides which plasma scenarios are we capable of simulating. Much of the work this year has been devoted to enhancement of SPICE2 and SPICE3 performance. SPICE3 has been updated to domain-decomposition with separated grids for each spatial slice, which greatly reduced the memory footprint (a limiting factor for a majority of large runs) and further optimization of code's internal algorithms increased the

speed of the code. Domain decomposition allowed effective parallelization on a larger number of processors so we can parallelize the code on up to 64 processors. At the same time we gained access to IFERC-CSC computational infrastructure, which allowed us to realize large runs.
The simulations performed this year focused on simulations of the lamella melting experiment in JET, where SPICE provided heat flux prediction on the misaligned lamella. A number of simulations was also performed to support experiment on TEXTOR with shaped gaps. A study of toroidal gap shaping was completed suggesting that it should reduce the peak heat flux received by the tiles close to gap entrance. A scan of gap orientation with respect to the magnetic field was performed in 3D [092], showing that electron transport into poloidal gaps is a robust feature, which is not sensitive to precise gap alignment.
Ref.: [92]

Measurement of plasma deposition inside gaps in TEXTOR (FZJ) and COMPASS (IPPCR) tokamaks + TOMAS toroidal machine (FZJ), comparison with numerical simulations.
Principal Investigator: R. Dejarnac
During this year 2012, the plasma deposition into gaps has been investigated experimentally with measurements in different machines in FZJ (Germany): the tokamak TEXTOR and the toroidal device TOMAS.
During a first mobility trip to FZJ (11 days) in April, with the help of our engineer, we have commissioned and installed the old CASTOR sandwich probe inside the toroidal device TOMAS and performed experiments. We have tested different working gases (Ar, O2, H) for each gap orientation, parallel and perpendicular to the (small) magnetic field. This experimental work is a part of the PhD thesis of Soeren Moeller from FZJ and the probe has remained there in order for him to continue measurements on his own. Particle-in cell simulation of plasma deposition in gap with TOMAS conditions have been performed for comparison.
During a second mobility trip to FZJ (10 days) in November, I have commissioned the new sandwich probe to TEXTOR, i.e., to finish assembling the probe, to make the electric connections, to install the probe in the tokamak and to condition it, with the help of local engineers. Then, experiments on TEXTOR tokamak have been performed during a dedicated full experimental day. 3D PIC simulations for comparison code/experiment are still under way.

1.5 Physics of plasma heating and current drive

Exploration of nonlinear effects near LH and ICRH antennas

Exploration of nonlinear ponderomotive effects near LH antennas.
Principal Investigator: V. Petržílka
A series of recent JET shots (#81890, 82217, 82218, 81299, 81301, 81302 and 81303) in the ILW (Iter-like-Wall) environment was successfully modeled by EDGE2D code, in which variations of the SOL (Scrape-off-Layer) due to parasitic absorption of the LH (lower hybrid) power were implemented. The density variations during LH were measured by Li-beam, and the results were compared with the EDGE2D computations. The power needed in the code for the fit of the observed enhancement of the SOL density to modeling results provides estimates of the heat flux into the hot spots from the grill mouth. A simple code for a more detailed description of the ponderomotive force effects just in front of the LH antenna – grill was also created, as planned. The boundary conditions were supposed to be supplied from the EDGE2D modeling. However, the SOL density increase due to direct ionization of the SOL by LH was rather strong in the modeled shots, and ponderomotive density depletion was found to be in these shots only a small perturbation. The

modeling results are prepared for publication in a journal paper, which describes the JET recent LH shots in the ILW environment.
Ref.: [3, 5, 25, 26, 27, 87]

Exploration of fast particle generation and direct SOL ionization near antennas.
Principal Investigator: V. Petržílka
As planned, we further analyzed data from RFA (Retarding Field Analyzer) and tunnel probe in Tore Supra shots. The results indicate one important effect, namely that the active ICRH Q5 antenna blocks the fast particle beam passing the antenna on its way from the LH antenna to the probe. Based on this finding, we plan to design (and to perform after the shutdown) further Tore Supra experiments, to elucidate in more detail the preliminary conclusions above. However, such shots can be performed not sooner than in year 2013. Further, we participated in analysis of the heat loads created by the older Fully-active modules (FAM) grill C3 and Passive-active modules C4 grill. This effect has been studied for the PAM and the FAM by using RFA, magnetically connected to either of the two launchers, in identical plasmac onditions. Infrared (IR) imaging of the hot spots on the launcher side protections, or on a magnetically connected limiter, was also used for the analysis. Both the RFA collector current and the IR hot spot temperature are consistently somewhat higher for the FAM than for the PAM, at same power (1.4MW) and same plasma-launcher distance (4cm). This is in agreement with test electron modeling of the electron power flux, based on the electric field pattern computed by the ALOHA coupling code. The simulations yield that the power flux is ~30% higher for the FAM than the PAM at 1.4MW and with density at the launcher mouth above 2×1017m-3. Furthermore, the power flux increases with increasing electron density in front of the launcher, a behavior which is well observed experimentally by the IR measurements. Rounding the waveguide septa reduces the electric field at the launcher mouth. Test electron simulations predict that the resulting power flux can decrease by almost a factor of eight, by rounding the waveguide septa on the PAM. Such modification may allow reducing significantly the localized power flux in the scrape-off layer. This will be tested experimentally in the forthcoming Tore Supra campaign.
Ref.: [3, 5, 25, 26, 27, 87]

Modeling of SOL during ICRH heating and gas injection.
Principal Investigator: V. Petržílka
The EDGE2D / NIMBUS code was adapted to model the presence of a wide SOL and a magnetic geometry with a 2nd X-point near to the top of the wall (as in JET pulses #68109-13). In contrast to the computational grid for the configurations considered previously, that have a SOL width of about 10 cm at the Outer Mid-Plane (OMP), EDGE2D simulations with the 2nd X point at the top are only carried out considering about 4 cm of SOL in the OMP. This is because the EDGE2D computational grid is restricted to a rather narrow OMP SOL layer in these ITER relevant configurations. One possibility is then to continue into the far SOL with "ad hoc" assumptions about transport with essentially 1D model. This then prohibits the modeling distant from the separatrix using EDGE2D. Following previous work, we have attempted to overcome this problem and to maintain the modeled SOL width at about 10 cm by introducing a limiter (particle sink) protruding radially down from the top. Then, the locations radially near the antenna front face are connected to the wall, similarly to the above mentioned ITER-like configuration with a 2nd X-point at the top. We computed OMP outward shift of the ICRF wave cut-off density for JET scenarios d as a function of the gas puff. It can be seen that the density shift depends on the additional power only marginally. The modeling results for OMP gas puff are for larger values of D in SOL near to the experimental results. To our opinion, the modeling and experiments do not indicate that a significant direct SOL ionization by ICRF wave takes place in analyzed JET experiments, in

contrast to the case of the lower hybrid (LH) heating . Observations from ASDEX-U by Li-beam and interferometry also exhibit similar neSOL increase and outward shifts of the cut-off density as that found in our JET simulations at similar gas puff rates. In agreement with some observations, the OMP gas puff is in the simulations more efficient for the OMP density enhancement than the TOP gas puff. Therefore, the OMP gas puff location should be preferred also in experiments for the purpose of OMP neSOL enhancement. The gas puff rate is needed a bit higher in simulations than it is in the experiments. The reason might be that it is not possible in the 2D model used to include effects of the distance between the gas puff location and the antenna on the density profile in front of the antenna.
Ref.: [3, 5, 25, 26, 27, 87]

1.6 Energetic particle physics

Development and tests of combined algorithms.
Principal Investigator: J. Mlynář
This task was postponed until 2013-2014 due to increased work load on JET SXR tomography analyses, as well as focused efforts into development of novel MFR tomographic algorithms for real-time applications at COMPASS and TORE SUPRA tokamaks, see task D.2. Limited efforts were invested in collaboration with ERM into conception studies and co-authoring of articles aimed at application of unfolding of energy spectra from data of activation probes. Two BSc students (K. Bauer from Charles University and O Ficker from Technical University) were accepted in IPP Prague to work on preparation of the response matrix for this task. K. Bauer works on activation contributions due to neutron irradiation, O Ficker on activation contributions due to proton irradiation.
Ref.: [13, 19]

2. Development of plasma auxiliary systems

2.1 Heating and current drive systems

Development of codes for existing and envisaged LH grill for COMPASS.
Principal Investigator: J. Preinhaelter
In collaboration with J. Hillairet from CEA Cadarache we collaborate on the development of efficient full wave code for the launching of lower hybrid waves in the tokamak plasma by waveguide structures so called grills. The ALOHA (J. Hillairet et al., Nucl. Fus. 50 (2010), 125010) code is frequently used as a standard to solve the coupling of lower hybrid grills to the plasma. To remove its limitations on the linear density profile, homogeneous magnetic field and the fully decoupled fast and slow waves in the determination of the plasma surface admittance, we exploit our recently developed efficient full wave code OLGA [023]. We modify OLGA code to adapt the conventions of ALOHA (different coordinate system, time dependence and the othonormal waveguide modes) and named it AOLGA. We substitute all IMSL routines by free access codes and compiled ALOGA under Linux so AOLGA code is now prepared for use in Cadarache.
Ref.: [23]

2.2 Plasma diagnostics

Edge plasma diagnostics

Measurements of fast radiating events in a tokamak plasma by the multi-channel visible light observation system on the COMPASS tokamak.

Principal Investigator: D. Naydenkova

Both unique wide angle objectives for the multichannel visible light observation system were successfully installed and tested. Few channels of the system are in routine used in combination with photomultipliers for absolute measurements of hydrogen and impurities spectral lines, spectrally integrated visible light and Bremsstrahlung radiation.

Minispectrometers were absolutely calibrated and are used routinely in every shots to study plasma composition in wide wavelength range (247-681 nm) with temporal resolution 7-20 ms or integrated in discharge duration. The minispectrometers allow also to study evolution of plasma composition during day and during experimental campaigns.

Ref.: [46, 61]

Detection of EC emission on COMPASS.

Principal Investigator: J. Preinhaelter

During last year we obtained the first results from EBW emission diagnostics on COMPASS ([11],[24]). COMPASS tokamak shots at low magnetic field feature overdense plasmas during the extended current flat-top phase. The first harmonic of the electron cyclotron emission is completely cutoff for O and X modes and so the emission caused by electron Bernstein waves (EBWs) propagating obliquely with respect to the magnetic field and undergoing so called EBW-X-O conversion process can be observed. We perform an angular scan of the EBW emission during a set of comparable shots in order to determine the optimum antenna direction. A weak dependence of the radiative temperature on the antenna angles indicates an influence of multiple reflections from the vessel wall. The low temperature at the mode conversion region is responsible for the collisional damping of EBW, which can explain several times lower measured radiative temperature than the electron temperature measured by the Thomson scattering system.

Ref.: [11, 24]

Development of Ka-band Doppler reflectometer.

Principal Investigator: J. Zajac

The testing of the microwave Doppler reflectometer was executed with the manually tuned Ka-band reflectometer. In the tests on Compass the oblique antenna in the low-profile port 10/11H was used. The Fourier analysis of reflected signals did not manifest any sign of the Doppler shift of the expected range of hundreds kHz. The probable reason is that the phase noise of the free-running oscillators overlaps the Doppler effect.

Establishment of routine operation of the first part of microwave reflectometry system (K and Ka bands).

Principal Investigator: J. Zajac

The first part of the microwave electronics (K and Ka bands) and the data aquisition, provided by IPFN/IST, was completed around the middle of 2012. The reflectometers were assembled and tested on the stand. The data acquisition system was integrated to the CODAC system. Because of persisting defects in the electronics, it was decided by the end of 2012 to send the reflectometer boxes back to Lisbon for the repair. New student Ondrej Bogar was admitted to PhD thesis on reflectometry.

Thomson scattering.
Principal Investigator: P. Bílková
During 2012, both core and edge Thomson scattering systems were put into operation. Main emphasis was focused on calibrations, alignment and data analysis. We started to operate both lasers, for that a need of triggering control unit arise. The unit was designed, manufactured and tested and is under operation now. It allows to choose a mode how lasers are operated (both at the same time - 30 Hz, independently but synchronized - (30 - 60 Hz)). While core TS system operates routinely and reliably, there are issues in the edge TS system alignment caused by non stable mechanic structure and port plug constraint. Therefore, a new design of both structures was done.
Since manufacture was not ready by the end of 2012, installation of upgraded structures was postponed to 2013.
Nevertheless, best effort was made to measure profiles of electron temperature and density in the edge region anyway. Thomson scattering was under routine operation. Electron temperature profiles are reliable for both core and edge systems while electron density profiles can be affected by possible misalignment especially at the plasma edge. During H-mode campaigns, pedestal was seen and fitted both in temperature and density profile.
Ref.: [11, 24, 38]

Commissioning of the BES system on the COMPASS tokamak and regular measurements.
Principal Investigator: P. Háček
The new Beam Emission Spectroscopy (BES) diagnostic for edge density measurements on the COMPASS tokamak is being commissioned in cooperation with the Association EURATOM – HAS. 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. During the year 2012, continuous comissioning of the Li-beam system was done. Several parts of the system have been improved (i.e. ion optics, interlock system, magnetic shielding) and the lithium beam current extraction and neutralization was succesfully tested. The CCD camera has been routinely operating during tokamak discharges. By the end of the year, first beam operations with plasma were performed and first plasma density profile reconstructions were calculated from CCD camera images. The installation of APD based system for fast BES measurements was delayed due to additional testing in Wigner RCP and was done in March 2013.

Atomic Beam Probe for the COMPASS Tokamak.
Principal Investigator: P. Háček
During the year 2012, continuous lithium beam commissioning was done and first succesful experiments with COMPASS tokamak plasmas were achieved in the last quarter of the year.The beam was operated with standard 30-40keV energies which are not sufficient for ABP measurement. The beam operation at high energies (100keV) needs several system improvements and was not possible until the end of the year. Therefore, the test measurements to confirm the ABP concept and determine the level of background noise as well as the development of the final design of the ABP detector could not be done yet. Several measurements during beam-in-plasma operation (with beam energies of 30-40keV) were performed which were able to detect a signal probably coming from beam ions. This is, however, uncertain and more measurements with lithium beam are necessary to be done in order to confirm these results. Moreover, the ABP detection system was tested and has shown its capability of detecting currents as small as 20nA with 1MHz bandwidth.
Ref.: [127]

Development of the ExB analyzer.
Principal Investigator: M. Komm
During this year the initial phase of the ExB analyzer construction was underway. An extensive series of Particle-In-Cell and Monte Carlo simulations was performed to optimize analyzer's components and evaluate instrumental effects [091]. The analyzer's design has been finalized and the construction has been contracted to HVM plasma. The analyzer has been manufactured and delivered to IPP. Some parts of the analyzer were either produced in IPP's workshop (16 channel current amplifier) or contracted elsewhere (the entrance slits, which were provided by IPP Garching).
A related experiment with Retarding Field Analyzer has been performed on COMPASS. The original ideal of the experiment (the RFA has been loaned from IPP Garching) was to perform calibration measurements of ion temperature profiles. During the experiment, a major issue with induced noise has been discovered, which hampered the measurements. However, the experiment was still valuable because it revealed a serious potential problem, which might also occured during ExB analyzer operation.
Ref.: [91]

Development of algorithms for fast Soft X-ray tomography.
Principal Investigator: J. Mlynář
In 2012, COMPASS experimental data achieved the required quality for the tomography inversion, in particular in the AXUV diagnostics. At the same time, JET interest in MFR analyses increased considerably due to significance of the SXR data linked to the new, all metal ITER-like wall. To facilitate the MFR applications in JET SXR tomography, a script was coded that writes all important MFR outputs to private ppf database (including the reconstructed 2D emissivity). Also for JET, based on the importance of combined data analyses from several diagnostics, the bolometric tomography was successfully implemented in the MFR in the framework of a student project.
The vision of real-time control via SXR diagnostics, possibly using the tomography reconstruction, has been fostered jointly by COMPASS and by TORE SUPRA tokamaks. Within the scope of this collaboration, the idea of replacing the iteration in MFR by direct step-by-step extrapolation - provided that data evolve slowly - was realised and tested on both phantom and real data first in the framework of a BSc thesis, and then implemented and tested for the WEST project at TORE SUPRA.
Ref.: [15, 16, 17, 18, 110]

Tunnel Probe design and calibration for COMPASS edge plasma.
Principal Investigator: R. Dejarnac
During the past 2 years, more than 2000 particle-in-cell (PIC) simulations of the plasma (ion current) distribution inside a tunnel probe (TP) have been made using our in-house 2D PIC code [49], for different aspect ratio (geometry) of the probe, scanning a wide range of possible tokamak plasma parameters (density & temperature, magnetic field, gas). During my stay in CEA Cadarache (from 19/11 to 21/12/2012) I dealt with this numerical database in order to find a calibration for the TP and an optimized geometry for COMPASS typical plasma parameters. Comparison of our PIC simulations have been compared with experimental results from tunnel probes installed in Tore Supra and Castor tokamaks. There is a good agreement between the numerical I-V characteristics and the experimental ones. The geometry of the 2 future tunnel probe heads for COMPASS has been settled.
Ref.: [49]

Probe measurements for fusion applications.
Principal Investigator: J. Mlynář
Experimental effort has been concentrated on improvement of the probe technique. Experiments have been performed in CW and pulsed plasma jet and in planar and cylindrical magnetron. Results have been published in Plasma Sources Science and Technology. The ball-pen probe has been used in low-temperature and low magnetic field conditions. Results have been accepted for publication in Contributions to Plasma Physics journal and published at the beginning of the year 2013. The ball-pen probe paper appeared in Nukleonika (International Journal of Nuclear Research, ISSN 0029-5922). The magnetron papers appeared in Surface and Coatings Technology, Journal of Applied Physics and in Applied Physics Letters. Diagnostics of the plasma plume of the Hall effect thruster by means of emissive and Langmuir probe was performed and the results published in Plasma Sources Science and Technology. The "modeling" group around Prof. Hrach (Z. Pekarek, T. Ibehej, J. Hromádka) pursued further the fluid/particle/hybrid codes for simulation of plasma-wall interaction. Z. Pekarek finalized the library for effective solution of Poisson equation in 3D and defended his PhD thesis. Further, it is developed the particle code package "concurrent" to SPICE3 code (R. Hrach, T. Ibehej). The hybrid code (much faster in comparison to purely particle codes) has been adapted to work in magnetic field. Results were published in Vacuum. In future the work will continue with new coauthor J. Hromadka (instead of Z. Pekárek).
Ref.: [55, 56, 57, 58, 62, 63, 64, 65, 66, 67, 68, 69, 115, 116, 117, 118, 119, 120, 121, 122, 123]

Conceptual design of a CXRS diagnostic system for COMPASS.
Principal Investigator: D. Naydenkova
Selection of a suitable experimental set-up for controlling of neutral beam parameters for CXRS diagnostic on COMPASS was the first task of this project which was successfully done, as it was planned, in year 2012.
Ref.: [46]

2.4 Real Time Measurement and Control

Developments of new techniques for improved data acquisition and analysis.
Principal Investigator: M. Hron
Due to the termination of PhD study of the key person responsible for development of data evaluation methods, the topic was cancelled at present.
Ref.: [14]

COMPASS CODAC system.
Principal Investigator: M. Hron
New database was prepared and tested. Two new ADC systems (12 MS/s, 500 kS/s) were put in operation and implemented in the central system (i.e. FireSignal and central database). Timing and triggering system was enhanced by implementation of start pulses for control of Thomson scattering, Li-beam and other systems, needing triggers before the start of toroidal magnetic field.
The operator interface, FireSignal GUI (Graphical User Interface) was adapted to better serve tokamak operators in a number of ways, the most important of them being the inclusion of checks that are made before the discharge is initiated – if any of them fails, it means that the discharge cannot proceed successfully, and the operator is given a choice whether to continue or not. The following conditions are checked: whether all nodes are present (particularly the MARTe one); whether all nodes are in the stand-by status; whether all waveforms were loaded;

and whether the energetics is operable. After these checks were introduced, the number of unsuccessful shots due to human error dramatically declined.

Real time feedback.
Principal Investigator: M. Hron
Recently, the COMPASS real-time control was upgraded to address several issues related to improvement of discharge parameters and plasma performance.
Two sources making the plasma unstable were found and their impact was significantly reduced: 1) Delays within the digital control loop were analysed and the key parts were improved, which shortened the reaction time and improved significantly the vertical stability.
2) During the discharge, there are periods controlled by pre-programmed waveforms and by real-time feedback. Smooth transition between these phases was implemented, which significantly reduced osculations of the controllers in the feedback phase.
Solving both these tasks broadened the operational space of COMPASS scenarios. Moreover, optimization of the start-up phase and of the plasma shaping was address, achieving thus a longer flat-top phase of the discharge.
In order to estimate the power dissipated in the central solenoid, a GAM that controls the I^2 was developed and included into the control loop to protect the COMPASS primary winding against overheating.

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

3.4 Theory and modelling

RF power deposition, current drive and emission in stellarators WEGA and W7-X.
Principal Investigator: J. Preinhaelter
During last year we do not visit IPP Greifswald. Unsuccessful attempt to explain extremely high radiative temperature observed at 28 GHz as EBW radiation on WEGA was cleared by Greifswald people by stating that emission is caused by different mechanism. Also they now do not continue in LH program for Wendelstein 7-X, so we have no new results connect4ed with this point.
Ref.: [12]

4. Emerging Technologies

4.1 Development of material science and advanced materials for DEMO

Irradiation and characterization of fusion-relevant materials.
Principal Investigator: J. Matějíček
A paper summarizing the irradiation effects on glass-ceramic materials was prepared and published [30].
No new results were obtained, due to lack of activity at RCR and FZJ.
Ref.: [30]

Development of W/Fe functional gradient materials.
Principal Investigator: J. Matějíček
Three alternative processing techniques were pursued: hot pressing, plasma spraying and spark plasma sintering.

In the hot-pressed W/Fe composites and FGMs, formation of Fe7W6 intermetallic phase was observed [29]. Therefore, ternary FGMs consisting of W/WC/Fe layers were explored. The W and Fe phases were effectively separated, however, a new phase - Fe3W3C - at the WC/Fe interface was found, as well as some cracking in the WC region. Mechanical and thermal characterization of all the composites and FGMs was completed.
A promising alternative is the SPS technique, which provides lower temperatures and pressing times, and thus may be the route to avoid the intermetallic phase formation. Single-material pellets from P91 steel and pure W were produced at several conditions. Structure and porosity were characterized to indentify optimal conditions for composite/FGM fabrication.
For the composites and FGMs plasma sprayed by the hybrid argon-water torch, characterization of the structure, Young's modulus and thermal conductivity was performed [88, 89, 90]. As expected, differences from the standard water-stabilized torch spraying were observed. Hot isostatic pressing was tested as a post-treatment method to increase the thermal conductivity.
Ref.: [29, 88, 89, 90]

Development and tests 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 for ITER ex-vessel steady-state magnetic diagnostic. The main open issue at present is achieving of sufficient thermal resistance in combination with already achieved radiation-resistance i.e. develop sensors with survival temperature around 300 degC. A number of on-line and off-line (with and without monitoring of sensors properties during irradiation respectively) neutron irradiation experiments was conducted on LVR-15 (NRI, Řež, Czech Republic), WWR-M (PNPI, Gatchina, Russia), and IBR-2 (JINR, Dubna, Russia). Optimum level of initial doping for InSb based Hall sensors to ensure constant sensitivity of the sensors along exposure to neutron radiation was identified. Stable performance of the Hall sensors based on InSb/i-GaAs heterostructures was demonstrated under high neutron fluences amounting up to $F=1.5x10^{18}$ cm^{-2}.
The applicability of various metal Hall sensors based e.g. on cooper was also investigated. A number of samples based on thin film copper layers with various thickness prepared by magneto-sputtering was prepared. Properties of these samples were characterized. The sensitivity of the samples showed good correspondence to theoretically expected values and the sensitivity remained constant in temperature range from 100 - 250 degC. Three samples were irradiated up to the total neutron fluence of $2x10^{18}$ cm^{-2} in LVR-15 reactor. Post irradiation characterization of the samples showed no effect of irradiation on sensor's sensitivity. Low level of output voltage, i.e. low signal to noise ratio, and certain technological issues related to manufacturing of the sensors, i.e. reliability of contacts between thin film and contact pads, technology of wire bonding to contact pads, encapsulation remain as the issues for further R&D.
Ref.: [75, 76, 77, 79, 80, 82]

Production and characterization of laboratory-scale batches of nano-structured ODSFS.
Principal Investigator: H. Hadraba, IPM
The aim of this work was to describe microstructural changes in Fe-14Cr-0.9Ti-0.3Mo-0.25Y2O3 ODS steel caused by long-term high-temperature exposure to liquid Pb and Pb-Bi metals environments. Tensile and impact bend tests were used to observe oxide scale development and microstructural changes. The surface oxide layer of the steel was depleted in Cr and Ti when exposed to liquid Pb and Pb-Bi. The embrittlement of ODS steel following exposure to liquid Pb and Pb-Bi was greater than embrittlement caused by isothermal aging. The degradation of

mechanical properties of the steel in liquid metals was caused by porosity development, precipitates coarsening and corrosion damage during long-term high-temperature exposure in liquid corrosive media.
Ref.: [124]

5. Training and career development

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

Training in laboratory experience, principles of data validation, analyses and interpretation, and presentation of results.
Principal Investigator: J. Stöckel
The traditional training course SUMTRAIC 2012 was organized on COMPASS for Czech/foreign master and PhD students in the period August 27 - September 7, 2012. The course was attended by 15 participants from 8 countries (Portugal, GB, Bulgaria, Slovakia, Hungary, Belgium, Pakistan and Czech Republic). The aim is to train participants in all practical aspects of experimental work on tokamak (measurements, data processing, discussion of results, ...). The SUMTRAIC was ended by a workshop, where achieved results of five experimental groups were presented in 8 lectures. Three best speakers were honoured. The course was managed by the COMPASS staff with help of two supervisors from Association EURATOM/HAS.
The SUMTRAIC was followed by another one week event - the Joint Experiment (JE), which was organized under the umbrella of the International Atomic Energy Agency. Several participants of the SUMTRAIC attended also the JE.
The similar training course (EMTRAIC 2012) was organized at COMPASS for the Erasmus Mundus programme in the period December 10 -19. The number of participants, as well as the training programme was similar to the SUMTRAIC.

Collaboration with french top classe engineering school, ENSAM.
Principal Investigator: R. Dejarnac
We had this year 2 students from ENSAM who arrived on the 25th of June 2012 for a 6 month internship at TOKamak Department in the frame of a bilateral ERASMUS agreement with Charles University in Prague. They were well integrated in our team and for the first time they worked on dedicated PCs connected to our network with new CATIA licences and not on their personal laptops like the previous students during previous years.
They worked on several topics as the design of COMPASS tokamak in 3D (which is a traditional, on-going task), the design of a system with a double-valve + a manipulator to implement samples in the tokamak divertor without breaking the vacuum, the design of 2 tunnel probe heads for the 2 reciprocating manipulators of COMPASS and the design of embedded ball-pen probes in the COMPASS divertor and Langmuir probes in the central column protective tiles. Both designs of the double-valve + manipulator, the tunnel and ball-pen probes have been finished. The double-valve + manipulator are under construction. The ball-pen probes are already implemented in the divertor tiles of COMPASS and ready for measurements. The students were happy with their stays and learned a lot at the contact of our engineers.
This task is completed and was successful this year again, what confirms that this collaboration with ENSAM is fruitfull for both parties.

Undergraduate and postgraduate studies in Fusion Science and Technology.
Principal Investigator: J. Mlynář
Project "The GOLEM tokamak" was supported in the frame of the FUSENET programme aiming to improve the DAS system, tokamak power circuits, vacuum operation, gas filling system, diagnostics enhancement and remote participation hardware. In February 2012 the FUMTRAIC 2012 (French fusion masters training course) took place - a whole week event in Cadarache. In June 2012, the science week 2012 took place aimed at high school students from Czech republic: 4 groups performed more than 70 discharges. Also in June 2012, the 5th International Workshop & Summer School on Plasma Physics in Kiten, Bulgaria had a remote experimental session, more then 80 discharges were performed by 21 students from 5 European countries. In August 2012, in the framework of SUMTRAIC 2012 Introductory session, more then 100 discharges were performed by 17 students from 7 European countries. The facility has been also used for the University of third age, in the Practicum for seniors. The GOLEM tokamak also run the traditional open competition "Hot Shots" and more than 20 excursions from high schools. However, the most significant event was the first run of the new GOMTRAIC school. GOMTRAIC stands for GOlem reMote TRAIning Course. GOMTRAIC aimed at Masters and PhD students with an interest in experimental tokamak physics. Within three months, they learned remotely (over the Internet) how to conduct tokamak experiments and how to operate the diagnostic systems that measure the plasma. In this first year, almost fifty participants registered from all over the world, altogether 17 countries from 3 continents. Besides, the facility was used also in three research topics:(i) High temperature superconductor magnets on tokamak (ii)Low Cost Alternative of High Speed Visible Camera for Tokamak Experiments and (iii)Evaluation of applicability of 2D iron core model for two-limb configuration of GOLEM tokamak. Tokamak GOLEM also participated in September 2012 IAEA Joint Experiment.
Ref.: [1, 7, 8,15, 21]

IPP collaboration with Czech universities, FUSENET, FUSION-EP and FUSION-DC.
Principal Investigator: J. Mlynář
Compared to rather technical topics in 2011, in 2012 our university students got more involved in scientific exploitation of tokamak COMPASS. Some students also worked in foreign laboratories, including in particular JET. Six new bachelor thesis were proposed at COMPASS, and half of them found students. Four new doctoral students were accepted for full training at COMPASS. The IPP staff were also involved in the teaching activities at the Czech Technical University Prague and at Charles University and published articles for University fusion teaching (see references). IPP also organised seminars for the students, including two major "colloquia" events at the Technical University (Dr P Holik from ITER, Prof G Bonhomme from University of Lorraine). IPP staff were in close contact with FUSION-EP and FUSION-DC programmes and proposes collaborative tasks for their students. Several foreign students visited COMPASS in 2012 both for working experience and for the SUMTRAIC summer training school. In December 2012, for the first time the winter training school EMTraic for the Erasmus Mundus MSc course was organised on COMPASS. The education and training tasks have been coordinated via participation of IPP in the FUSENET consortium, where J Mlynar (member of the Fusenet Board) successfully proposed M Tichy from Charles University to the new Academic Board.
Ref.: [14, 17, 20, 22, 28, 109]

6. Other activities in magnetic confinement fusion

6.1 Public information

Foster Public information in fusion.
Principal Investigator: M. Řípa
At the beginning of 2012 the third edition of the book "Controlled thermonuclear fusion for everybody" (in Czech) was officially presented at a press conference. The book has attracted attention of the ITER newsline and the Alpha Galileo Foundation. Another book "Nuclear Energy" (in Czech) was issued in spring 2012 in collaboration with the Czech University of Life Sciences. The book features several chapters on fusion basics, fusion history and current projects written by J. Mlynar. Public talks on Fusion were given also outside Prague, e.g. in Brno and in Kouty nad Desnou, Czech Republic. We have continued publication of papers in magazines, newspapers and online news, one radio interview was broadcast and in September 2012, the Czech public TV broadcast a spot on the COMPASS tokamak. Milan Ripa took part in the Public Information Network (PIN) Meeting in Culham on June 2012. The EU Education for competitivenes operational programme accepted the project "Materials for New Millennium (MAT 21)" for financial support. The coordinator of the project "Vítkovice – výzkum a vývoj – technické aplikace, a.s." invited the Institute of Plasma Physics ASCR to participate. This opened a new platform for fusion education at high schools.
Ref.: [22]

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

Ablation and acceleration processes in the plasma produced by a pulsed high-power laser
Principal Investigator: J. Ullschmied
The experimental studies of ablation and acceleration processes in laser–produced plasmas, conducted at the PALS Research Infrastructure were aimed at finding optimum conditions for energy transfer into the laser-produced plasma and at achieving maximum yield of the accelerated charged particles. They proved the possibility to compress and accelerate efficiently the expanding laser plasma generated on targets of special geometry and composition [34-37, 94-100] and brought record energies of accelerated protons, deuterons and carbon ions exceeding 4 MeV per electric charge unit [101-104]. The results achieved at PALS witness that due to non-linear processes of laser beam self-focusation and filamentation, evolving during the interaction of a „long“ (sub-nanosecond!) laser pulse with plasma, the laser radiation intensity in plasma increases periodically and locally by at least two orders of magnitude. A new class of IFE-relevant experiments aimed at validation of a new version of the Shell Impact concept started at PALS at the end of 2012, preliminary results having been presented at [105-107].
Ref.: [34, 35, 36, 37]

7.4 Maintain a watching brief on inertial confinement civil research activities

Report on the development in the area of inertial fusion energy.
Principal Investigator: J. Ullschmied
This task is to be probably cancelled, as no instructions concerning the "IFE Watching Brief 2012" preparation have been obtained from the chairperson of IFE Working Group yet.

III GENERATED INFORMATION AND INTELLECTUAL PROPERTY

1. Generated information

In this part, the list of 2012 research publications of the Association EURATOM / IPP.CR is presented. For the generated Public Information please refer to Part IV, section 7.

[1] **M. Gryaznevich V. Svoboda, J. Stockel et al:** First Results from Tests of High Temperature Superconductor Magnets on Tokamak. *Contribution to the 24th IAEA Fusion Energy Conference San Diego, USA.*

[2] **Havlíčková, E., Fundamentski, W., Naulin, V., Nielsen, A. H., Seidl, J., Horáček, J.:** The effect of plasma fluctuations on parallel transport parameters in the SOL. *Journal of Nuclear Materials* 415 (2012) S471

[3] **A. Ekedahl, V. Petrzilka, Y. Baranov, T.M. Biewer, M. Brix, M. Goniche, P. Jacquet, K.K. Kirov, C.C. Klepper, J. Mailloux, M.-L. Mayoral, M.F.F. Nave, J. Ongena, E. Rachlew and JET-EFDA contributors :** Influence of gas puff location on the coupling of lower hybrid waves in JET ELMy H-mode plasmas. *Plasma Physics Controlled Fusion* 54 (2012) 074004

[4] **C. Silva, G. Arnoux, M. Groth, J. Horacek, S. Marsen, G. Matthews, R. A. Pitts and JET-EFDA Contributors:** Comparison of scrape-off layer transport in inner and outer wall limited JET plasmas. *Conference Paper for PSI 2012 conference (Aachen, Germany)* submitted to J. Nucl. Materials

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2. Intellectual property

In collaboration with the Institute of Physics AS CR the industrial design for the tunnel probe was registered in 2012. Besides, IPP still pursues the possibility of getting a patent for the ball pen probe.

IV REPORTS

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

Modelling of edge turbulence on COMPASS

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In collaboration with:
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Comparison of reciprocating probe measurements in the scrape-off layer (SOL) with turbulence modelling provides opportunity to identify regimes of SOL plasma transport and to study impact of various assumptions made during derivation of the model. Our work was focused on development of ESEL code [1,2] and preparations for comparison of its simulations with experimental data from COMPASS.

Since data from reciprocating probe measurements suitable for comparison with turbulence modelling by the ESEL code were not available on COMPASS until September, in the first part of the year our effort focused on comparison of ESEL simulations with data from ASDEX Upgrade. The data were measured by reciprocating probe with similar type of probe head that is routinely used on COMPASS, which should allow reliable inter-machine comparison in the future. The probe heads are mounted with combination of several ball-pen and Langmuir probes in a configuration that allows simultaneous fast measurement of electron temperature T_e and plasma potential ϕ [3]. On long time scales (small frequencies) we found strong coupling between both quantities. This indicates presence of turbulence affected by sheath layers located at field line ends. This interpretation was supported by model-experiment comparison in the case when sheath-dissipation terms [4] were added into the ESEL model. The comparison showed good agreement in radial profile of plasma potential and improved agreement in radial density profile compared with previous efforts to model ASDEX Upgrade with ESEL [5]. We note that this was the first time when an agreement in potential profile was achieved with ESEL. Simulations with included sheath-dissipation term were made also for parameters of TCV edge plasma, which revealed favourable reduction of fluctuations of plasma and floating potentials compared to the case with sheath-dissipation mechanism neglected.

In the analysis of experimental data the relation between T_e and ϕ on short (fluctuation) time scales is not yet clear since the results are very sensitive to the assumptions made on the value of coefficient ϕ_{BPP} that determines influence of temperature fluctuations on the potential ϕ_{BPP} measured by ball-pen probe diagnostic, $\phi_{BPP} = \phi - \alpha_{BPP} T_e$. Turbulent structures in the experimental data have larger spatial extent when observed in plasma potential than in temperature [3]. When conditional average of ϕ_{BPP} is computed, triggered by large positive fluctuations of electron temperature, the $\phi_{BPP} T_e$ component of the ball-pen probe potential is responsible for a narrow drop observed at the position of temperature maximum (Fig. 1). Based on this observation we developed a method capable of determining the factor α_{BPP} from simultaneously measured fast signals of floating and ball-pen probe potential. First preliminary results based on ASDEX Upgrade data give $\alpha_{BPP} \approx 0.3$-0.6, which is in agreement with $\alpha_{BPP} = 0.6 \pm 0.3$ determined from probe's I-V characteristics [6]. More precise evaluation of α_{BPP} from COMPASS data is planned for 2013.

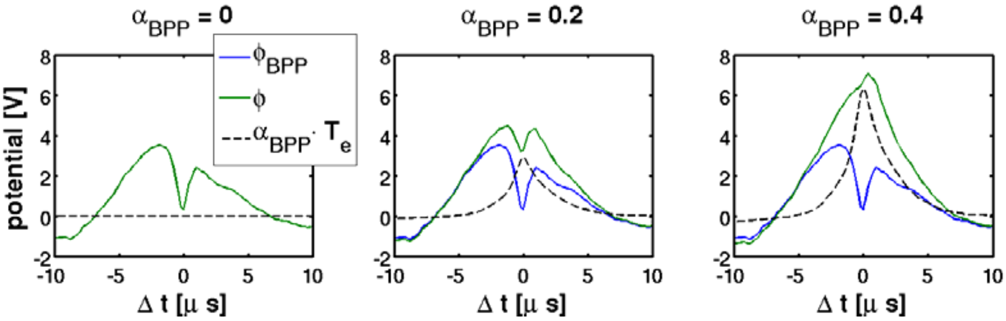

Fig. 1. Conditional average of ball-pen probe (blue) and plasma (green) potentials in SOL of COMPASS during discharge #3918, triggered by large fluctuations of T_e. The plasma potential ϕ was derived from simultaneous measurement of floating Langmuir probe and ball-pen probe, assuming three different values of α_{BPP} (left, middle, right). The drop in the middle of ϕ_{BPP} is caused by parasitic influence of electron temperature, $\alpha_{BPP} T_e$, and should not appear in ϕ. Therefore, disappearance of the drop from ϕ gives lower bound on estimation of α_{BPP}.

During the last quarter of 2012 there were several shots in which horizontal reciprocating probe on COMPASS penetrated the last closed flux surface (LCFS). These measurements show difference of turbulence characteristics inwards and outwards of the LCFS. Such data are extremely valuable for understanding of development of turbulent modes protruding into the SOL. Therefore, ESEL simulations were made for one of these cases and both simulations and processed experimental data are now ready for their mutual comparison.

Part of the work was focused on development of the ESEL code. Three modifications of the code were made in 2012:

– The code was paralellized using OpenMP library. Performance tests show 11× speed up for simulations with 1024×1536 spatial grid when 12 CPU cores are used, compared to non-paralellized ESEL version. This allows to significantly reduce running time of the simulations, which would otherwise pose a serious issue in modelling of low-collisional plasmas that requires large spatial resolutions.
– First version of a new solver of ESEL equations was developed using PETSc library. The new solver should avoid some stability issues of the original solver and presently it is undergoing performance benchmark and comparison against results of the original code. Preliminary results, however, show that some further modifications of the solver improving its performance will be needed.
– The ESEL code was coupled with SOLF1D code that replaced analytical approximations used in ESEL to describe plasma transport along field lines. After the coupling each spatial point in ESEL located outside LCFS has an associated instance of SOLF1D, that solves Braginskii equations for the associated field line. Cross-field transport is evaluated only in the ESEL drift plane and it is extrapolated to other positions along the field line, taking into account ballooning nature of the transport, i.e. localizing cross-field terms only in poloidally narrow 30° region around midplane. The coupled pseudo-3D code aims at explaining previously observed discrepancy of radial density profiles between ESEL and experimental data [2,5]. Moreover, it will allow comparison of ESEL with data from pair of reciprocating probes installed on COMPASS at two different poloidal positions.

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Characterization of pedestal parameters

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A comprehensive set of diagnostics was setup for pedestal study. Details on particular diagnostics are given below. H-mode was achieved and H mode experiments performed.

Both core and edge Thomson scattering diagnostics systems are in operation now (see Fig.1). Speed of data processing was increased by optimization of set of routines. Triggering of the diagnostic was improved by installation of a new triggering unit that was developed in our institute and allows control of operation of both lasers remotely while delay between them can be setup before operation. For routine operations we run the diagnostics at 60 Hz (30 Hz each laser).

Channels K band (18 – 26.5 GHz) and Ka band(26.5 - 40 GHz) of reflectometry were commissioned and first measurement performed.

Beam emission spectroscopy was tested to energies up to 40keV and reached high neutralization efficiencies (over 90%).

Vertical reciprocating probe is under routine operation. Additionally, upgrade for H-mode survival was designed and constructed aimed to measurement of the pedestal turbulent structures:

1. To minimize temperature, tungsten as a head material was used. Moreover, set of springs was installed such that the probe bounces on them at the end of the reciprocation in order to decrease the time spent in the pedestal
2. To minimize impurity contamination, the head was coated by sp^3 diamond-like layer.

First measurements by upgraded probe is planned for beginning of 2013.

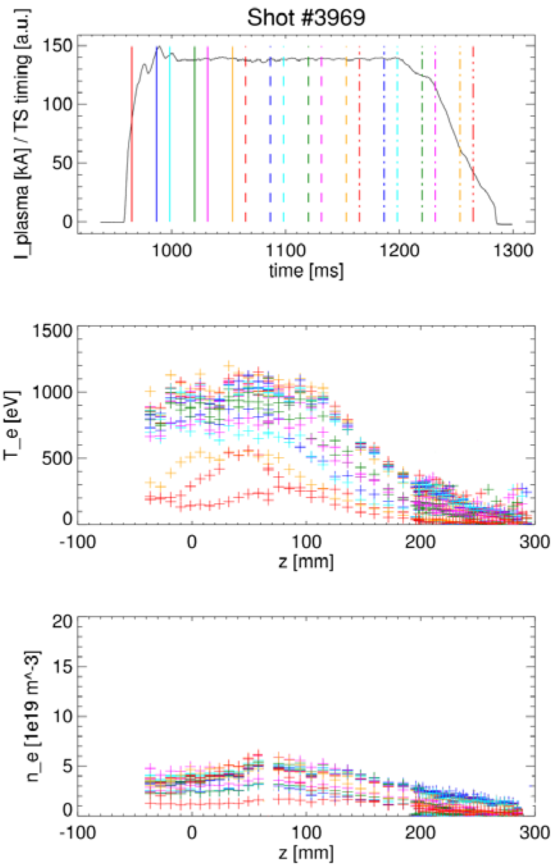

Fig. 1 Profiles of electron temperature and electron density along the vertical axis for #3969 shot

Horizontal Reciprocating probe - Langmuir and Ball-pen probe head for horizontal mid-plane manipulator are exchangeable with ASDEX-U. New probe head for COMPASS was built (smaller – less disturbs the plasma). Good agreement of electron temperature measured by Thomson scattering near separatrix during D-shaped plasma was seen.

The diagnostic systems of fast bolometers (6 arrays per 20 channels) and soft X-ray detectors (2 arrays per 35 channels) were adjusted to be able to diagnose a pedestal region of the diverted plasma on the COMPASS tokamak. The tomography code based on an algorithm of Minimum Fisher regularization was established and tested on measured data. Detection viewing angle for pedestal region optimized.

Reproducible plasma with a circular and D-shape ITER-like cross-section (200 kA, up to 1.8 T) is routinely achieved. Two NBIs are in operation. H-mode was achieved in December 2012 (Fig. 2). Campaigns on H-mode as well as pedestal analyses are planned since beginning of 2013.

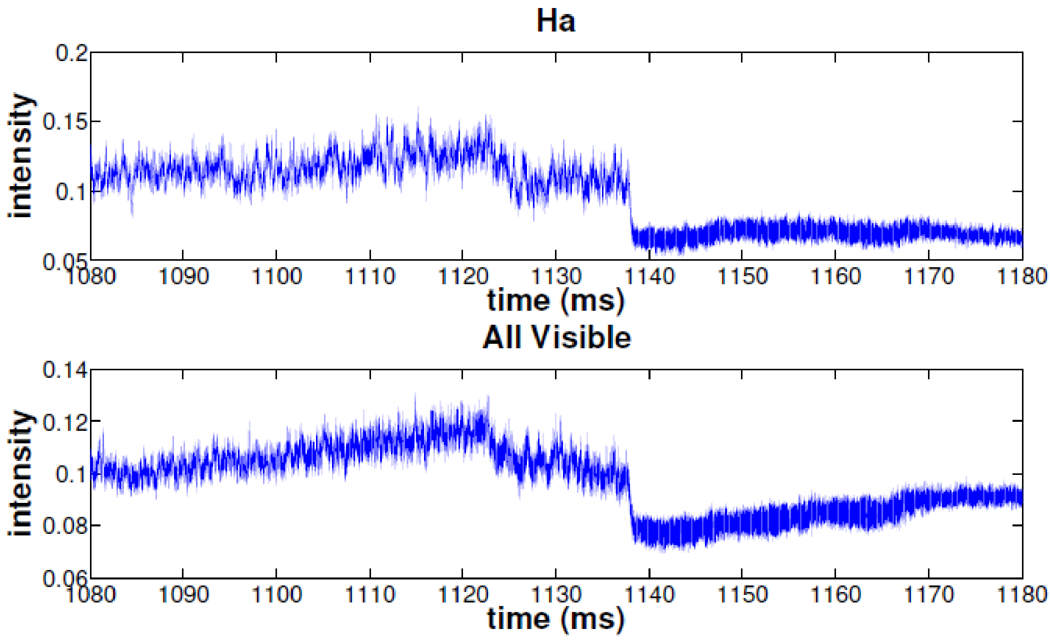

Fig. 2 L to H mode transition visible on H alpha and UV visible spectroscopy for a shot 4084

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Measurements with Langmuir probes in COMPASS

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Measurements in COMPASS divertor using the poloidal array of 39 Langmuir probes (LPs) are routinely operated using state-of-the-art electronics. Spatial profiles during D-shape plasmas show the 2 strike-points in the divertor region of COMPASS in ohmic mode (see Fig. 1) and even during H-mode (since first ELM free/ELMy H-modes were achieved on COMPASS in December 2012). Plasma parameters like ion saturation current (*Isat*), electron temperature (*Te*) and floating potential (*Vf*) but also power flux and density (*ne*) have been measured and compared to old COMPASS data (back in Culham, UK).

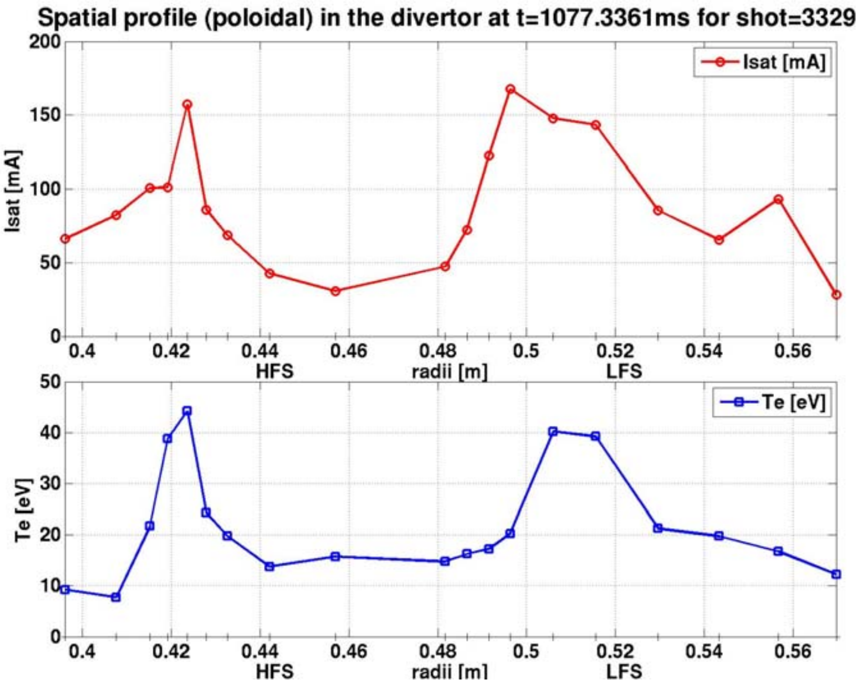

Fig.1: *Spatial profiles of ion saturation current (top) and electron temperature (bottom) in the COMPASS divertor*

LPs are one of the basics and routine diagnostics used on COMPASS for years. Therefore we wanted to implement a second array of LPs in a different sector of the divertor to study long range correlations. This second array was made by our Romanian colleagues from Iasi University. It was sent to IPP Prague in October 2012 and is ready to be installed in COMPASS (see Fig. 2).

Fig.2: *Photograph of the second LP array to be installed in COMPASS divertor*

The cooling pipe system which was directly below the port where we want to insert it has been moved to have a free path for the manipulator. Unfortunately, to be inserted into the COMPASS divertor we need a system of double-valve + manipulator which is not ready yet. The designed has been completed with the collaboration of engineering students from Ecole Nationale Superieure des Arts et Metiers (ENSAM) during the last quarter of 2012 and it has been sent for construction. The manipulator should be ready for next spring shutdown (March-April 2013). Electronic boards for measurements are ready to use.

Measurements on COMPASS with both vertical and horizontal reciprocating probes have been performed during several dedicated experiments, during our summer school and during the Joint Experiment organized by IAEA. Radial profiles of *Te*, *ne*, electron energy distribution function but also decay length of the power flux in the scrape-off layer have been measured and compared to profiles given by Thomson Scattering diagnostics. Moreover, data were processed using the new 1st derivative method to retrieve the electron energy distribution function. A comparison with classic Langmuir probe method was performed and can be seen on Fig. 3 for the vertical reciprocating probe during an ohmic discharge on COMPASS. While the classic method cannot give any information on the energy distribution of the electrons (star symbols on Fig. 3), the 1st derivative method shows that inside the last closed flux surface (LCFS), i.e., for $z < 207\ mm$, *Te* is bi-Maxwellian, with a bulk of low temperature electrons (triangle symbols) and a fraction of hot population (square symbols). The hot population temperature agrees well with the one retrieved by the classic Langmuir probe method which is, as we know, very sensitive to even a very small fraction of hot electrons. In the scrape-off layer ($z > 207\ mm$), both methods show a good agreement with Maxwellian distributions. Open symbols represent the profile during the insertion of the reciprocating probe and the full symbols represent the profile during the reciprocation way out. A draft of a paper have been written and will be soon submitted to a peer-review scientific journal.

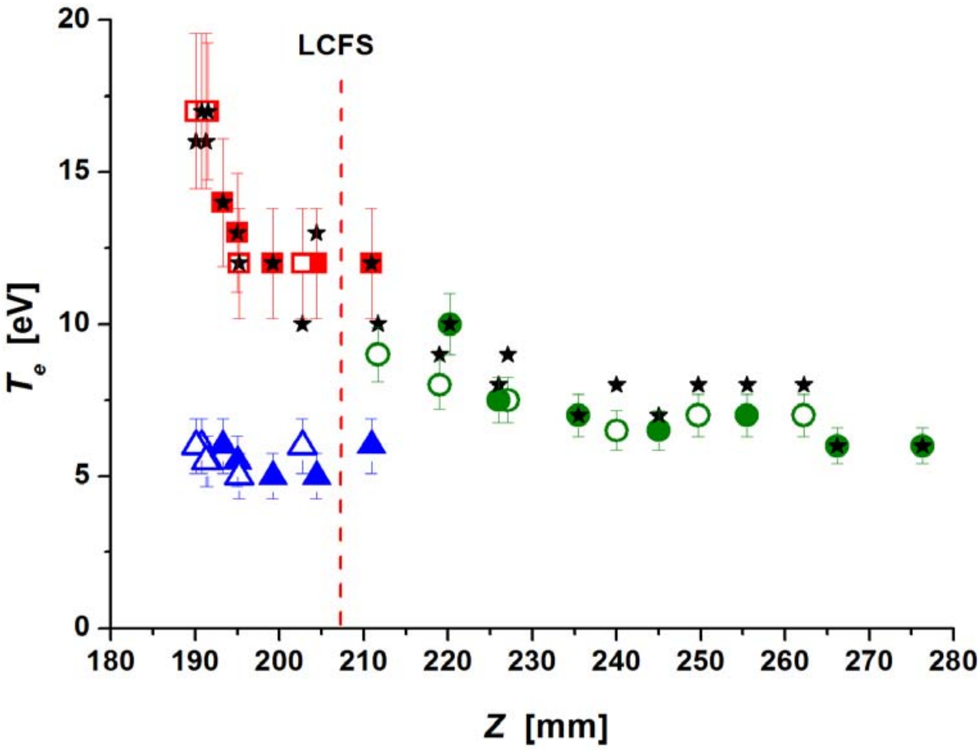

Fig.3: *Radial profile of electron temperature measured by the vertical reciprocating Langmuir probe of COMPASS tokamak. Temperature is retrieved using the classic Langmuir probe method (black stars) and using the 1st derivative method (other symbols). The temperature is bi-Maxwellian with a bulk population with low-temperature (triangles) and a small fraction of hot electrons (squares) in the confined plasma, while the electrons are Maxwellian in the scrape-off layer (circles) with good agreement of both methods. Open symbols represent the reciprocation in and closed symbols the reciprocation out of 1 plunge.*

Control of ELM size and frequency using externally imposed changes of the plasma position in the COMPASS tokamak [GACR: P205/11/2470]

M. Hron

To start with, it should be emphasised that the progress in 2012 was significant and has prepared a good environment for next steps in studies of the Edge Localized Modes (ELMs) during the H-mode discharges on the COMPASS tokamak, and, in particular, for the ELM control experiments.

Suitable discharge scenarios were developed, the HW equipment was built and the dedicated power supply for vertical kicks (VKPS) will be commissioned within a short period. The plasma diagnostics and the data storage were prepared for the expected exploitation. The plasma equilibrium is routinely reconstructed using the EFIT code, which was implemented for the COMPASS geometry. The plasma response and the robustness of the plasma control system were tested during artificial disturbances induced by the existing power supply for vertical position control (FABR).

This opens the possibilities to exploit fully the COMPASS tokamak for the planned experiments with the vertical disturbances – the vertical kicks induced by the new VKPS – to observe the ELM behaviour and the overall plasma reaction during induced position changes.

The key areas of the work are addressed in detail in the following sections.

1) Operation regimes of the COMPASS tokamak

Several important discharge scenarios, required for fulfilment of the project goals, were successfully developed in 2012.

- Vertically elongated (elliptical) plasma was created and the arising vertical instability was brought under control by the feedback system.
- D-shaped plasmas with standard and higher triangularity (so-called SND and SNT configurations) were obtained and stabilized after the improvements made in the plasma control loop.
- The first high (or improved) confinement mode, i.e. the H-mode, was achieved in a discharge heated by the Neutral Beam Injection (NBI) with a maximum plasma current approximately 200 kA. A 60 ms ramp-up of the plasma current with dI/dt = 800 kA/s was pre-programmed to support the L-H transition. During this period, the gas filling was switched-off, followed by a start of the NBI pulse with the maximum power slightly above 200 kW. The transition to an ELM free H-mode appeared shortly after and was well visible on the observed signals, namely on a rapid drop of the D-alpha line and spectrally integrated visible light radiation intensities. The observation by the fast camera showed that visible radiation from the scrape-off layer almost disappeared, which documents the reduced plasma-wall interaction. Consequently, the total radiated power presented a slow increase, caused by accumulation of impurities in the plasma core.
- The NBI assisted transition to the H-mode was repeated in several other discharges in the SNT configuration. Mostly, ELM free H-modes were achieved; in some of the shots there were also several ELMs observed shortly after the L-H transition.
- Finally, suitable conditions for transition to ohmic H-mode were found. The ELM free as well as ELMy H-modes were generated.

In conclusion, the NBI heated as well as ohmic H-mode discharges were successfully achieved. They are routinely generated at present and they belong to the standard COMPASS discharge portfolio now. Both the ELM free and ELMy H-mode scenarios are suitable to test the plasma response to the vertical kicks.

2) Power supplies for vertical kicks experiments
Fast feedback power supplies

The fast feedback power supplies (Fast Amplifiers, FAs) were commissioned, tested, and successfully put in routine operation. Currently they are used for control of both the radial and vertical position of the plasma column in the tokamak vessel. The so-called FABV creates the vertical magnetic field Bv, i.e. controls the radial position; the FABR is used for radial magnetic field Br and the vertical position control.

Each FA is a H-bridge built from eight MOSFET modules, each MOSFET module is a half-bridge, which can withstand 150 V and has nominal working voltage 100 V. Remaining 50 V are necessary for the MOSFET to withstand voltage spikes during the switching.

Each MOSFET module is created from three phases connected in parallel, each phase is capable of 300 Arms (with enough cooling) and up to 600 A in a pulse. There are 4 half-bridge modules in parallel, each of them has three phases, thus giving 4 × 3 × 300 A = 3600 Arms. The Fast Amplifier is overloaded to work with 5 kA for up to 1 second which is sufficient with respect to the COMPASS discharge length. The used switching frequency is 40 kHz and can be varied between 20 − 50 kHz. The energy for both FAs is supplied by a 6 kV grid from the flywheel generator, then transformed to 70 V and rectified.

Vertical Kicks Power Supply

A new power supply was needed to induce the fast movements of the plasma column in the vertical direction – the vertical kicks. Therefore, the Vertical Kicks Power Supply (VKPS), was designed and constructed.

The VKPS is to be connected in series with the FABR and it is also constructed as a H-bridge but based on IGBT modules. Each module consists of three transistors in parallel, it has the nominal current of 3.6 kA (providing sufficient cooling) and the maximal allowed voltage 1700 V. The VKPS is constructed from 8 such modules (i.e. there are two IGBTs connected in parallel in each leg of H-bridge) and it is expected to operate at maximum voltage 1.2 kV with switching frequency < 5 kHz.

There is not any transformer with sufficient power and voltage currently available to supply the VKPS continuously. Therefore, we decided to use a capacitor bank, which stores enough energy to feed the VKPS for several dozens of kicks (current pulses). Thus, the energy for VKPS is supplied by four large capacitors 2.53 kV, 4.14 mF each which should provide enough energy to change the current in the tokamak coils by up to 1 kA for approximately 1 ms and then recuperate the energy back from the coils into the capacitor. The capacitor will be charged from the grid by a 2 kW transformer and rectifier (using snubber capacitors) between the shots.

Each IGBT is controlled by its own commercially available driver, which among other things gives a reliable protection against over-current in all short circuit conditions and against over-voltage during turn-off. Mechanical design of the VKPS follows a sandwich scheme to minimize the inductance.

Recently, the VKPS was successfully tested at the voltage 500 V. Current > 1.6 kA was delivered to a test load of 100 microH, 10 mOhm. The tests identified possible modifications needed to be done on the transistor drivers and the areas for next tests to be performed before the system commissioning.

These power supplies, the FAs and the VKPS, are based on modern components with highest available ratings in their categories. Unique designs of the power supplies take advantage of the short duration of the COMPASS discharge by overloading the transistors above their maximal steady-state rating. The mechanical solutions are based on sandwich designs to minimize the inductances between transistors and capacitor bank in order to suppress the over-voltage peaks during switching of the transistors.

These features make the design unique and therefore the engineering designs and required output parameters of the both power supplies were described in a paper submitted for publication [J. Havlicek et al., Fusion Engineering and Design, submitted in 2012]. Since the FAs are regularly operated, we describe there their achieved performance parameters too. Finally, the common controller unit, communication, and error handling is also described in the paper. At present, the first revision taking into account the reviewers' comments is submitted to the journal.

The described serial connection of the FABR and VKPS is a key element in the scheme of the vertical position control circuit to be used for the vertical kicks. The grant team participated heavily in the the FABR and FABV tests and commissioning and in the VKPS design and its tests. Last but not least, the publication was prepared and submitted.

3) EFIT

A widely used magnetic equilibrium reconstruction code, the EFIT++ was adopted for the COMPASS geometry, tested, benchmarked, and put in use by members of the grant team. This code processes information from several key diagnostics (namely magnetic sensors) and delivers important discharge parameters related to the plasma shape, magnetic surfaces topology, and current profile. In particular, the safety factor on the axis and at the boundary - q_0 and q_95, normalized ratio of the plasma pressure to the magnetic pressure – beta_N, kinetic energy stored in the plasma, the plasma elongation, inner and outer clearance, i.e. distances from the wall, and positions of the strike points are provided. These data are further used as an input for many diagnostics.

In 2012, members of the grant team included new induced currents model into the EFIT++ code, they finished development and performed benchmarking of the module. The induced currents module implements a computational model to represent the induced currents that are generated in the passive structures of tokamaks – vacuum vessel, PF coils casings, eventually short-circuited turns used for plasma position stabilization coils. The currents in the passive structures are often difficult to measure. The used model is restricted to axisymmetric currents as the EFIT++ code itself is assuming axisymmetry. The induced currents module is written in C++ language and is fully integrated into EFIT++ object oriented structure. Therefore, the module can be used for any tokamak as EFIT++ is machine independent and uses comprehensive xml based description of the tokamak and its passive structures.

This model of induced currents is of particular importance for our team, as the currents in the vacuum chamber, induced by the vertical kicks, will have to be compensated during the analysis. Here, this model currents can be used to distinguish magnetic field generated by these currents flowing in the vacuum vessel and that one generated by currents in the plasma.

Therefore, also the EFIT++ input files describing COMPASS poloidal field coils geometry and connections, limiter geometry, detection coils' positions and angles were prepared and EFIT++ was used for equilibrium reconstruction. The results obtained from the EFIT++ for COMPASS are in a good agreement with other diagnostics, the plasma size and position and the plasma-wall touching points correspond very well to those seen on the fast camera observing the plasma radiation in visible spectra. Thus, the EFIT++ outputs can be used for monitoring of the bulk plasma reaction and observation of possible changes of the whole equilibrium of the plasma during the perturbations caused by the vertical kicks.

4) Plasma control

Another key element to fulfil the grant goals is a robust plasma control. Stabilized plasma in divertor configuration was achieved using the FAs. During the commissioning, it appeared that the digital fast feedback was not reacting quickly enough, which often caused loss of the plasma control. Therefore, delays in the real-time data processing and communication were optimized, the control loop was fastened by 40 microseconds so that the duration was reduced from 100-150 microseconds down to 60-110 microseconds. After this improvement, a stable diverted plasma was obtained.

Moreover, the feedback control of the plasma current was implemented to improve the quality of the steady-state phase of the discharges.

At present, the plasma position as well as the plasma current are well controlled by the real-time feedback. Key parts of the feedback optimization were performed by the members of the grant team. Selected issues related to the plasma position and shaping control are addressed in [V. Weinzettl et al., World Academy of Science, Engineering and Technology 2012, Vol. 71, 844-850].

5) Vertical kicks and robustness of the plasma control system

To test the robustness of the plasma control system, sudden request for a change of the vertical position was launched by the control system to test the robustness of the feedback control. The plasma position was changed by 4 cm with the maximum possible speed using the FABR power supply which is in full use at present. The control system was able to maintain the requested position very well. Therefore, we conclude that the feedback system is robust enough to keep control of the plasma also in case the plasma is shortly displaced by the VKPS pulse during the vertical kicks experiments.

6) Diagnostics

Suitable diagnostics are required to analyse properly the behaviour of the plasma between and during the ELMs and to address the difference between the natural and externally induced ELMs.
There are several diagnostics with high temporal resolution suitable for such observations (Langmuir probes in the divertor area and on the movable manipulators for edge density, temperature, and plasma potential monitoring; the bolometers and photo-multipliers for plasma radiation observation /see also [V. Weinzettl et al., World Academy of Science, Engineering and Technology 2012, Vol. 71, 844-850]/, microwave reflectometer, etc.).
However, key profiles of the density and temperature both in the plasma core and edge can be delivered only by the diagnostics based on Thomson scattering of laser light (TS diagnostics) which has a limited time resolution given by the repetition rate of the high-power lasers. COMPASS is equipped by two Nd-YAG lasers, each with energy of 1.5 J in a single pulse and 30 Hz repetition rate. In principle, the lasers can be used for simultaneous measurement (to double the power), for measurement at 60 Hz, or for measurement of two subsequent snapshots with variable delay – repeated with 30 Hz again.

The last case is obviously most advantageous for observation of the profiles evolution during and between the ELMs. However, this is not a built in feature of the system and a new synchronization and timing unit for the lasers had to be designed and constructed. The requirements for such unit are quite strict as for proper and safe operation of the laser system we have to manage a nanosecond precision of the timing, include special logics, checks, and protection. Such a unit was built, successfully tested and put in regular operation. Thus, the delay of the laser pulses can be chosen arbitrary within the technical possibilities given by the lasers at present. This significantly improves the possibility and quality of the measurements by obtaining the profiles with a pre-defined delay between the two laser pulses, which can be varied in the range from 1 microsecond to several ms. Moreover, the unit is ready for event driven triggering once the real-time event recognition is implemented.

The TS diagnostic synchronization and timing unit was designed, built and tested by the grant team. The design specification and commissioning was done in collaboration with the TS diagnostic team.

7) Data storage

The COMPASS operation currently generates 1-3 GB of experimental data per shot. Once all projected diagnostics are installed and used, this figure will increase up to 5 GB per shot, yielding 180 GB during a busy experimental day. The storage system with a limited capacity was expected to fill-up in a short time. Therefore, a new system able to host both live data coming from the running experiment as well as majority of already processed data was designed and built. The typical use scenario of the system is “write-once – append – read-many”, i.e. the experimental data are written by one or a few clients to the hierarchical data format (HDF5). A few clients then read the data, process them and append the results to the database or write new files. Many clients access the data in read-only mode.

The data storage was designed and set-up by a member of COMPASS IT team. As the physics studies related to our project require many signals connected, thus generating large amount of data, two members of the grant team participated in the design specifications, defined the particular requirements, and performed the tests of the storage. This helped us to avoid the database limits. Since we participated also in the description of the system, we refer also the publication [J. Pisacka et al., Fusion Engineering and Design 2012, Vol. 87, 2238– 2241].

Conclusion

The main focus of the 2012 activities was to prepare the basis for the vertical kicks experiments to be performed in early 2013. Therefore, we concerned on

- plasma control and development of suitable discharge scenarios;
- construction, tests, and commissioning of the needed power supplies;
- development of the plasma equilibrium reconstruction EFIT;
- development of proper diagnostics control schemes to be able to gain maximum physics output from the experiments;
- adaptation of the data storage to accommodate the large amount of the experimental data;
- experiments to test the robustness of the plasma control with respect to the expected disturbance caused by the vertical kicks.

EFIT++ development

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During the year 2012 the contribution of IPP.CR to the EFIT++ development consisted mostly of finishing development and thorough benchmarking of the new induced currents module incorporated into the EFIT++.

The induced currents module (ICM) is based on the model described in the article of G.J. McArdle and D. Taylor Adaptation of the MAST passive current simulation model for real-time plasma control [1].

The induced currents module is supposed to compute currents in passive structures, i.e. toroidal conductive structures, where current isn't measured. Passive structures can be vacuum vessel or short-circuited loops or casings of poloidal field (PF) coils. The model consists of solving induction equation:

$$(V=)0 = R_{ps} \cdot I_{ps} + L_{ps2ps} \cdot \dot{I}_{ps} + L_{ps2pf} \cdot \dot{I}_{pf} + L_{ps2g} \cdot \dot{I}_{pl} \tag{1}$$

where R_{ps} is matrix of passive structure resistances, I_{ps} is vector of passive structure currents, L_{ps2ps} is matrix of self and mutual inductances of passive structures, $\dot{I}_{ps}$ is vector of time derivatives of currents in passive structures, L_{ps2pf} is matrix of mutual inductances between passive structures and PF coils, $\dot{I}_{pf}$ is time derivative of currents in the PF coils, L_{ps2g} is three dimensional matrix of mutual inductances between passive structures and computational grid and $\dot{I}_{pl}$ is two dimensional matrix of time derivations of plasma currents in the grid.

The equation (1) differs in notation from induction equation in the article [1]. The notation used in this text is more compatible with EFIT++ internal structure. The article [1] describes principles of rewriting equation (1) to form:

$$dx_e / dt = \Lambda \cdot x_e + W^{-1} \cdot B \cdot u + W^{-1} \cdot C \cdot v \tag{2}$$

$$y = D \cdot W \cdot x_e + E \cdot u + F \cdot v \tag{3}$$

where Λ is diagonal matrix of eigenvalues of matrix $A = W \cdot \Lambda \cdot W^{-1} = -L_{ps2ps}^{-1} \cdot R_{ps}$, W is full matrix whose columns are eigenvectors of A, $x_e = W^{-1} \cdot x$ is state vector of eigenmodes, state vector is defined by equation $I_{ps} = x - L_{ps2ps}^{-1} \cdot (L_{ps2pf} \cdot I_{pf} + L_{ps2g} \cdot I_{pl})$, u is vector $u{=}I_{pf}$, $B = L_{ps2ps}^{-1} \cdot R_{ps} \cdot L_{ps2ps}^{-1} \cdot L_{ps2pf}$, v is vector $v{=}I_{pl}$, $C = L_{ps2ps}^{-1} \cdot R_{ps} \cdot L_{ps2ps}^{-1} \cdot L_{ps2g}$, $y{=}I_{ps}$, D is identity matrix, $E = -L_{ps2ps}^{-1} \cdot L_{ps2pf}$ and $F = -L_{ps2ps}^{-1} \cdot L_{ps2g}$.

The rewriting of equation (1) to equations (2) and (3) offers several advantages for computing of induced currents. The variable transformation from I_{ps} to state vector x allows to avoid numerical differentiation of the PF coils currents and plasma current. The used eigenvalue decomposition means that the matrix Λ is diagonal which allows solution of the set of equations (2) as set of independent equations. This feature allows truncation of the induced currents module.

The equations (2) and (3) in discrete representation are:

$$x_e(n+1) = A_d \cdot x_e(n) + B_d \cdot u(n) + C_d \cdot v(n) \quad (4)$$

$$y(n+1) = W \cdot x_e(n+1) + E_d \cdot u(n+1) + F_d \cdot v(n+1) \quad (5)$$

where matrices A_d, B_d, C_d, E_d and F_d have form depending on chosen method of solving of differential equations, i.e. the matrices differ for forward Euler method and Runge-Kutta method.

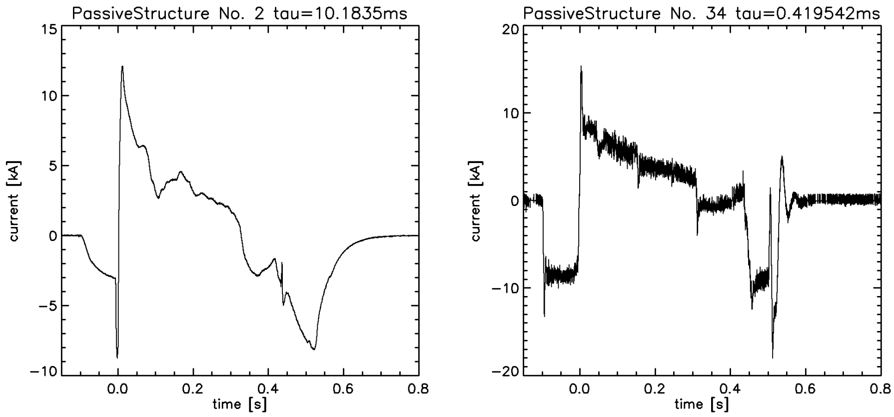

Fig. 1. Example of calculated currents in MAST tokamak, discharge #20790. Left panel: passive structure on the LFS with longer time constant (tau = L/R), right panel: passive structure on the HFS.

Induced currents module implementation imposes restrictions on the EFIT++ input files:

1. Both *pfcoils* and *pfpassive* instances in idam.xml file must be described by set of rectangles because ICM methods used to calculate mutual and self-inductances does not work with tilted shapes. The inductances are calculated by dividing the structures into series of infinitely thin toroidal wires with distance of the wires set by user.

2. It is not possible to use parallel connection of PF coils into PF circuits in the EFIT++ input.

3. All structures where current is provided to the EFIT++ must be listed as an active *pfcoils* instances. All structures listed as *pfpassive* instances must be without measured current.

4. All *pfpassive* instances must have only one resistance defined even when they are geometrically described by multiple rectangles. The current density distribution among the rectangles is assumed to be uniform.

The workflow of the ICM consists of calculating response matrices used in equations (4) and (5). Plasma and PF coils currents provided to EFIT++ are interpolated and smoothed to required calculation time step. Finally induced currents are calculated for the entire discharge using the artificial plasma current distribution and measured plasma current. Eigenvalue decomposition mentioned in the previous text is performed but truncation of the matrices is not implemented. Then the EFIT++ uses calculated induced currents when running equilibrium reconstruction.

The induced currents module was checked for speed optimization and the achieved runtime is in the order of seconds for 78 passive structures, dt = 1e-5 s and 1 second long discharge when compiled with -O2 flag of the GCC compiler.

Reference:

[1] G.J. McArdle and D. Taylor, Adaptation of the MAST passive current simulation model for real-time plasma control, *Fusion Engineering and Design*, 83, 188-192, 2008.

Modelling of plasma response to magnetic perturbations, divertor footprints and comparisons with MAST experimental data

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Experiments on MAST have shown that the effect of RMPs (divertor footprints, density pump-out) 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. We performed simulations with MARS-F to make predictions of strike point splitting in those conditions and compared them with experimental data from MAST.

For the first time on MAST we started using divertor Langmuir probes in addition to infrared cameras for strike point analysis. We developed a code which analyzes the Langmuir probe data and shows time traces and summary profiles of measured variables (j_{sat}, T_e, V_{float}, power flux estimate). We obtained clear traces of splitting especially in the power flux, and strong negative spikes of V_{float} during RMP application. We used the Langmuir probe data to investigate differences between odd and even RMP parity shots in L-mode, with scenario 4 plasma. The results confirm the earlier results obtained with an infrared camera, namely that only even parity shows traces of splitting. We consider the probe data more conclusive than the camera results however, as probes are measuring several toroidal locations and are available during most of the shots, while the camera in some shots was unavailable or zoomed to an inferior resolution.

In the area of theory and modelling, we developed a code which transforms the results from MARS-F to a coordinate system suitable for field line tracing and used it to model the divertor footprints. The results for MARS-F runs corresponding to the scenario 4 plasma show that splitting of the strike point is reduced and this reduction is much more significant for odd parity than for even parity perturbation. This explains for the first time the difference observed in experiments, vacuum field line tracing and the ad-hoc model of screening currents both being unable to account for the difference.

The lobes observed with visible camera in the poloidal plane when ELMs are mitigated by RMP are in qualitative agreement with vacuum field line tracing, but they are shorter than predicted. We calculated the plasma response field that would be produced by the assumed screening currents which would cancel the resonant components except at the edge. The lobes calculated with this field are in a good agreement with experiment, suggesting that such screening is indeed present. This is an important result for the understanding of the ELM mitigation process. We also provided the screening field for a DIII-D discharge to FZ Juelich with the purpose of transport simulations and for a reference ITER scenario to ITER for calculating losses of fast ions from NBI in the presence of screened RMP.

The homoclinic tangle structure which is supposed to be responsible for the divertor strike point splitting and the lobes observable by visible camera in poloidal plane can be conveniently modelled by the tools of nonlinear dynamics: the homoclinic coordinate and the Melnikov integral. We developed codes which provide the mapping to the homoclinic coordinate and calculate the Melnikov integral directly from the MAST database (IDAM).

Predictions of the lobes using this theory show qualitative agreement with the visible camera observations. The efficiency of this method allows making time-dependent predictions of splitting instead of just analyzing a single time instant. We produced a synthetic time trace which is supposed to mimic the divertor heat flux using this method and vacuum approximation. This time trace agrees well with the experimental time trace from an infrared camera, except for the time interval until the perturbation coil current reaches a flat-top phase. In the model the splitting increases continuously as the coil current is being increased, while in the experiment the splitting appears abruptly at one time instant. We consider this as a sign that the perturbation penetrates at this instant, where the vacuum approximation thus becomes approximately valid, while the field is screened before. This observation will be important for validation of plasma response codes. A similar observation on DIII-D prompted us to perform modelling of perturbation screening for the relevant DIII-D discharge. We have not yet done the modelling of strike points because of lacking data on the applied perturbation, this work will continue in 2013.

In addition to plasma response to footprints, MARS-F can also calculate resistive wall mode (RWM) stability. This is an important topic for COMPASS as COMPASS is well suited to the research of RWMs thanks to its extensive magnetic diagnostics and a rich set of perturbation coils. Initial simulation of resistive wall modes with MARS-F were performed for COMPASS and it was found that the example equilibrium from the ACCOME code is stable to the current-driven RWM.

The analysis of footprints using homoclinic coordinate and Melnikov integral shows that the footprints can be described by very few parameters: the amplitude, phase and toroidal mode number. We used this to produce a mock-up of footprints that would be generated by interaction of an applied RMP and the magnetic perturbation due to an ELM, which has a higher toroidal mode number. We have shown that the interference of the two leads to a combined footprint which resembles the footprint due to the external RMP and this may explain the heat load peaking observed in mitigated ELMs. This explanation is in qualitative agreement with many of the features of ELMs observed on MAST.

3D simulations of plasma response to magnetic perturbations with the code JOREK

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One important question of the ELM suppression by resonant magnetic perturbations (RMPs) is the question of island formation near the top of the pedestal. Island formation is normally prevented by low resistivity and fast rotation, but islands can form even in regions of fast rotation at the point where the plasma (ExB) rotation is compensated by electron diamagnetic rotation of the same speed and opposite direction, yielding a near-zero total velocity of electrons. This is thought to occur in particular in the DIII-D experiments. Such an island chain inside the plasma would significantly modify the local transport properties and in some proposed explanations for the ELM control mechanism this is the key point.

Using the nonlinear MHD code JOREK we attempted to determine if this effect can occur in JET and in particular if it is related to the multi-resonance effect on ELM frequency observed when the edge safety factor varies. Instead of a real equilibrium from a JET shot, which posed numerical difficulties, we decided to use an analytical "JET-like" equilibrium which had been already used by the CEA team. To investigate the issue we need a way to control the safety factor profile in the equilibrium, as the penetration is supposed to occur only in the special case when the resonant surface is at the point where the total electron velocity vanishes, and the resonant surface can be moved radially by changing the safety factor profile. We decided to change the safety factor by controlling the profile of the ff' function in the Grad-Shafranov equation – increasing ff' increases the toroidal plasma current and thus decreases the safety factor without changing the pressure profile. First of all, we had to produce a realistic safety factor profile. In the original analytical equilibrium the safety factor profile has a flat, almost reversed region at the edge. To correct this we changed the coefficient FF_coef(6) in the analytical expansion of ff'. We then changed the FF_0 coefficient, which is the multiplier in the expression for ff', to scale ff' linearly and thus change the safety factor. We could also have changed B_T (by changing the F_0 coefficient which is the multiplier in the expression for B_T) but this is less desirable: normalized perturbation coil field would be different. The next task was to localize the point of the zero crossing of the parallel electron velocity at the edge. For the initial profiles it is much inside the core ($\psi = 0.6$). With an increase of the toroidal rotation (by changing the coefficient V_0 from $-3.1\ 10^{-2}$ to $-6\ 10^{-2}$) the zero crossing moves. The resonant surface q=2 is among the values of the plasma current that we tried the closest to the zero crossing for FF_0 = 3.5 and FF_0 = 4 (see Fig. 1). For these values we ran the simulation with an n=2 external perturbation. The resulting poloidal modes of the n=2 mode of ψ are shown in references. Note that each mode is zero at its respective resonance, which means that it is completely screened at the resonance, presumably by an induced parallel current. The mode 4/2 shall be an exception – it should penetrate when the q=2 surface is at the zero crossing. We see that for FF_0 = 4 the mode at the resonance increases from zero (Fig. 2), meaning that the screening is not complete, but the value is still small so we can not say that the field penetrates. For FF_0 = 3.5 the field did not penetrate at all (the mode 4/2 was zero at its resonance).

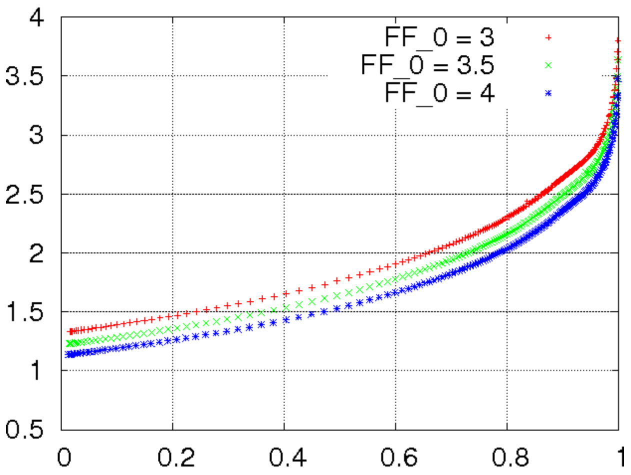

Fig. 1. Safety factor profiles with the q=2 rational surface close to the zero crossing of total electron velocity.

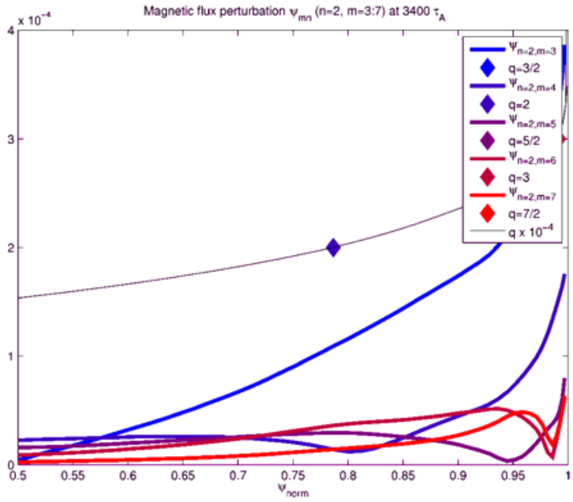

Fig. 2. Modes of the poloidal flux and the safety factor profile for FF_0=4.

Conclusion

Penetration of the perturbation near the zero crossing of the total electron velocity for a JET-like equilibrium was not demonstrated. The reason for that is not yet known, there are several possibilities:

- the resistivity may be too low, preventing the dissipation of screening currents,
- the zero crossing may be still too far from the resonance,
- the X-point geometry may be for some reason unfavorable to penetration (previous results showing penetration were obtained with the codes RMHD and 4FC in a simple cylindrical geometry).

Future work should focus at solving the question of island formation at the zero crossing, by examining a higher resistivity regime, doing a more detailed scan of the safety factor and comparing with the RMHD results (where penetration at the zero crossing was obtained for DIII-D).

Modeling of the tile gaps by using 2D and 3D PIC codes

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Particle-In-Cell simulations of plasma-facing components are an effective way of predicting the plasma interaction with objects of complex geometry, such as castellated tiles. The results help to predict heat loads impacting the tiles, which has crucial consequences on its lifetime. Optimization of tile geometry allows to distribute the heat loads and avoid hot-spots, which could damage the tiles. IPP Prague has quite a tradition in development of the PIC codes, a fruitful result of a long collaboration with CEA Cadarache. The family of SPICE codes allows 2D3V or 3D3V simulations of the tiles, so toroidal and poloidal gaps can be either studied separately or together including their intersections.

Much of the work in 2012 was devoted in optimization of the codes, especially the SPICE3 code. SPICE3 has been switched to domain decomposition scheme, which together with other optimization techniques allows effective parallelization on up to 64 processors. Each thread has now its on grid, which contains only its spatial slice of the whole simulated region. This approached radically reduced the memory footprint of the code and allowed large simulations to be performed on systems with restrictive memory limitations. The code was equipped with a timer, which allows to stop the simulation after an arbitrary number of hours – together with improved re-launch capability this was an important requirement for running the simulations in environments with tight time limits, such as HPC-FF in Juelich or IFERC-CSC in Rokkasho. All these improvements facilitated simulations of larger grids, in other words more realistic plasma parameters.

The simulations targeted the melting lamella experiment on JET, where SPICE2 was used to predict the heat loads impinging onto the lamella. Another series of simulations was used to optimize the shape of tiles for the experiment on TEXTOR, where hydrocarbon deposition inside the gaps was measured. Apart from poloidal gap shaping, which has been studied experimentally and theoretically in the previous years, the shaping of toroidal gaps has been identified as an important feature in order to optimize heat and particle fluxes on the system of tiles with gaps.

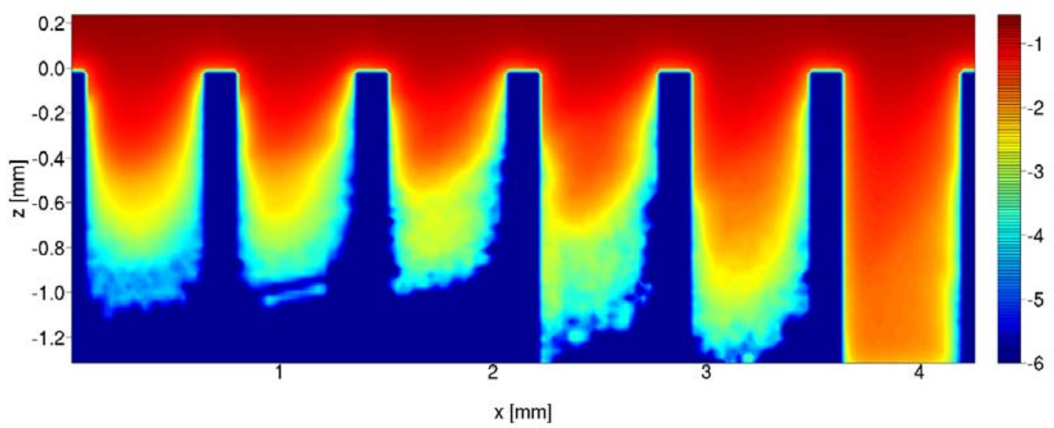

Fig. 1. Electron density inside a gap during its transition from poloidal (left) to toroidal (right) gap.

A study of the role of magnetic field orientation with respect to the gaps has been performed by using the SPICE3 code. The inclination with respect to the top surface has been constant but the gaps were gradually rotated in order to see the transition between toroidal and poloidal gaps. One objective of this study was to investigate electron leakage inside the poloidal gaps and its dependence on precise gap alignment. It has been found that electrons are present in the gaps for all studied orientations (see Fig. 1), hence this mechanism appears to be quite robust. The study did not confirm any preferred tile orientation, which would improve the heat flux distribution.

Attempts were made to perform 3D simulation of gap crossings for plasma conditions, which would be closer to the expected ITER parameters, meaning high density and low temperature plasma. Such a case is rather difficult due to small Debye length, which results in enormous spatial PIC grid. Although the simulation partially progressed, it has not been accomplished due to limited computational resources.

Measurements in gaps between tiles

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During this year 2012, the plasma deposition into gaps has been investigated experimentally with measurements in different machines in FZJ (Germany): the tokamak TEXTOR and the toroidal device TOMAS.

During a first mobility trip to FZJ (11 days) in April, with the help of our engineer, we have commissioned and installed the old CASTOR sandwich probe (SP) inside the toroidal device TOMAS and performed experiments. We have tested different working gases (Ar, O2, D) for each gap orientation, parallel (TG) and perpendicular (PG) to the (small) magnetic field. Typical values met in TOMAS are the following: $B = 0.067\ T$, $P_{ECRH} = 1500 – 1800\ W$, $Te = 10 – 15\ eV$. This experimental work is a part of the PhD thesis of Soeren Moeller from FZJ and the probe has

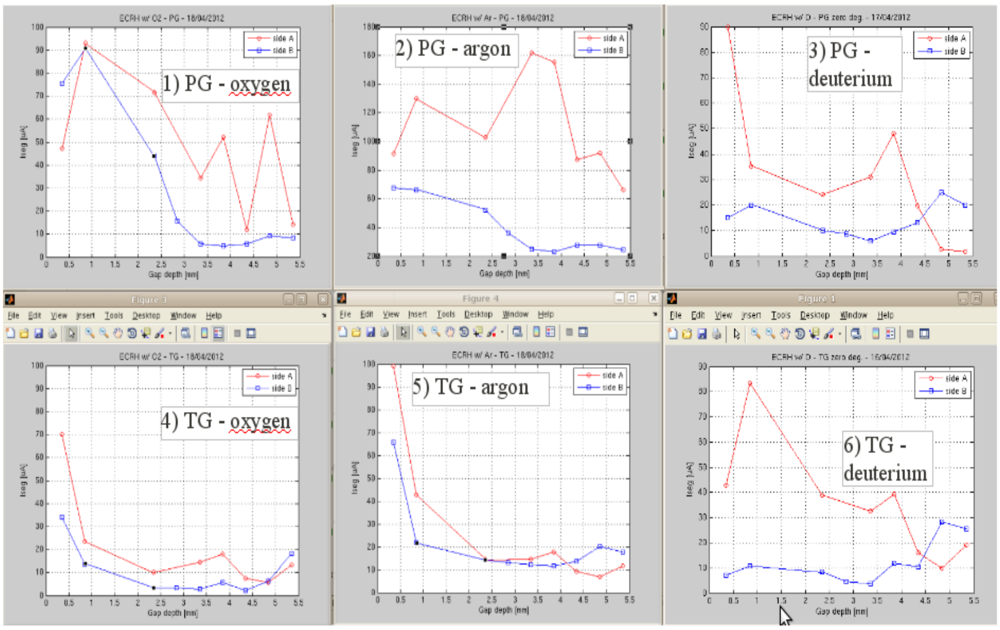

Fig.1: *Ion saturation current profiles [uA] for PG and TG orientations along the gap sides of a sandwich probe for different working gases in the toroidal device TOMAS*

remained there in order for him to continue measurements on his own. Particle-in cell simulation of plasma deposition in gap with TOMAS conditions have been performed for comparison. The CASTOR SP recreates a gap with 11 insulated segments on each side, A & B. We can thus measure the ion saturation profiles on both sides, which is proportional to ion flux and therefore cleaning. Results of the 4-day experiment with different working gases are summarized in Fig.1.

If we look first at the 1st quadrant (i.e., panels 1-2-4-5) we observe nice distributions with almost identical profiles for TGs on both sides and for both gases (4-5), the difference in absolute values is due to different gas pressures during separate experiments, and we observe an asymmetry *sideA/sideB* for PG profiles (1-2). This global result is what we secretly expected. Indeed, in strong magnetic field, particle-in-cell simulations show a strong asymmetry on profiles between the 2 sides of a PG, which is explained by geometric projection and a potential regime that is created in front of the gap and that favors one side more than the other. For TGs, PIC simulations show that the asymmetry is also present but much less pronounced and profiles could be similar in some plasma regimes. Looking at the panels 3 & 6 for deuterium gas, we see that PG profiles are quite coherent with PG profiles measured with the other working gases but for TG profiles, we observe a strong asymmetry that we do not understand and which is not present on the other graphs. Moreover, we can see that the deuterium profiles for both gap orientations are similar with an asymmetry along the gap and a reversed trend for the last 2 segments. Does it have a physical explanation or is it an artifact from bad measurements? This feature is not reproduced by PIC simulations. This work was part of the EFDA task WP12-IPH-A03-3-02 on baseline support.

During a second mobility trip to FZJ (10 days) in November, I have commissioned the new sandwich probe to TEXTOR, i.e., to finish assembling the probe, to make the electric connections, to install the probe in the tokamak and to condition it, with the help of local engineers (see Fig.2). The new sandwich probe is a complex probe especially developed for this dedicated experimental study. The design of the sandwich probe was based on several complicated techniques, which made its construction challenging. The design involved several complex steps such as cutting the molybdenum alloy block in a complex shape to make the body of the probe that face the plasma. This has been done in the FZJ workshop using the electro-erosion technique for a duration of six weeks. Another complicated technique was to make a metallic coating of a thin molybdenum layer on boron nitride (BN) by Combined Magnetron Sputtering and Ion Implantation. This technique was used to make the W coating of JET CFC tiles for the ITER-like wall project but never applied to boron nitride. The Mo layer is less than 5 microns thick and the hardness of the Mo coating is 800-900 HV 0.025. The layer can survive fluxes in the order of 10 MW/m2. This is the first time that Mo is coated on BN with such great properties. This metallic layer is to create the base of the conducting segments that measure the ion saturation currents along the gap sides. For this purpose, we made some parallel cuts in the coating till reaching the insulator below (BN) that have created the measuring segments with an electric insulation between them. The spatial resolution is limited by the size of the cutting tool and we achieved the high spatial resolution of about 0.2 mm. Then, experiments on TEXTOR tokamak have been performed during a dedicated full experimental day. 3D PIC simulations for comparison code/experiment are still underway.

Fig.2 *Photographs of the sandwich probe during its mounting. We can see the detail of the conductive segments (bottom right corner), the Langmuir probe (upper right corner) and the thermo-couple (bottom left corner).*

For this experiment, TEXTOR configuration was: H-mode plasmas with NBI, Bt = 2.25 T, Ip = 350 kA and a density of 3.5×10^{19} m^{-3}. The segments of the sandwich probe were biased with a constant voltage of Vbias = -100 V and the consequent ion saturation currents were measured as the drop voltage on independent resistors. During all the measurements, deposition profiles were measured unfortunately only on one side of the gap due to technical problems in the connections from the tokamak to the data acquisition system. The experimental plasma penetration is about 2.5mm whereas the estimated penetration by 2D PIC simulations (used for the design of the probe) is 2.0mm. New experiments will be performed this time in our tokamak COMPASS. Comparison with 3D PIC simulations will be then performed. This work was part of the EFDA task WP12-IPH-A01-1-11 on priority support.

Exploration of nonlinear ponderomotive effects near LH antennas

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Local density modifications and in particular the appearance of hump in front of the launcher have been observed and successfully modeled with the two dimensional code EDGE2D in the JET conditions. The code has been modified to take into account the presence of limiters in the SOL, ponderomotive forces and the heating in the SOL by a fraction of the LHCD power. The heating in the SOL is thought to contribute to the density increase, either because of the SOL heating by collisional dissipation of the LH wave or due to the fast electrons parasitically created by the LH wave in front of the grill mouth or both. On the other hand, ponderomotive forces of the LH wave expel plasma from the launcher and this leads to a density decrease.

Since EDGE-2D is a two-dimensional code (in radial and poloidal directions, it ignores the toroidal coordinate), it is assumed that the ionization by the LH wave is produced due to the local SOL electron heating by the LH waves in a radially narrow belt near the separatrix, with a poloidal width corresponding to the LH grill height. The absorbed power is introduced as a fixed source in the electron fluid equation. The ionization is computed in the code under the assumption that the electron velocity distribution is Maxwellian. Therefore, the ionization by the fast electron component is neglected in the modeling. We think that the error is not larger than several percent: Measurements reveal the presence of two electron components: the majority of "cold" background plus a several percent of minority of "hot" contribution corresponding to the fast electrons. The cold population seems to have typical temperatures usually from 10 to 30 eV, depending on radial location in the SOL.Therefore, a large fraction of the bulk electrons with approximately Maxwellian velocity distribution is in the region of the maximum ionization cross section, which is in the range of 30 eV.

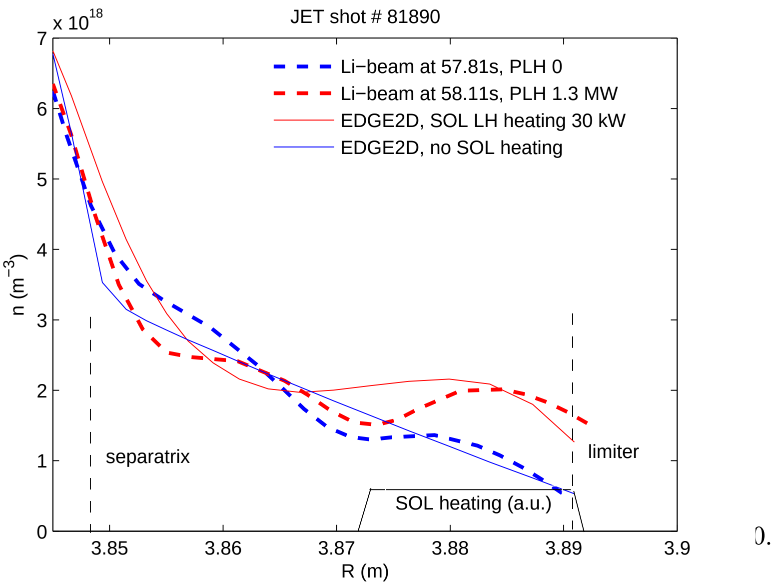

Fig. 1. SOL density modeling and Li-beam data for the shot #81890.

On the other hand, the remaining several percent of the fast electrons (with energy up to several keV) is in the region of decreasing ionization cross section. We therefore think that this small population of fast electrons will not contribute to the overall ionization rate by more than several percent. Results of the simulations are shown in the following figures.

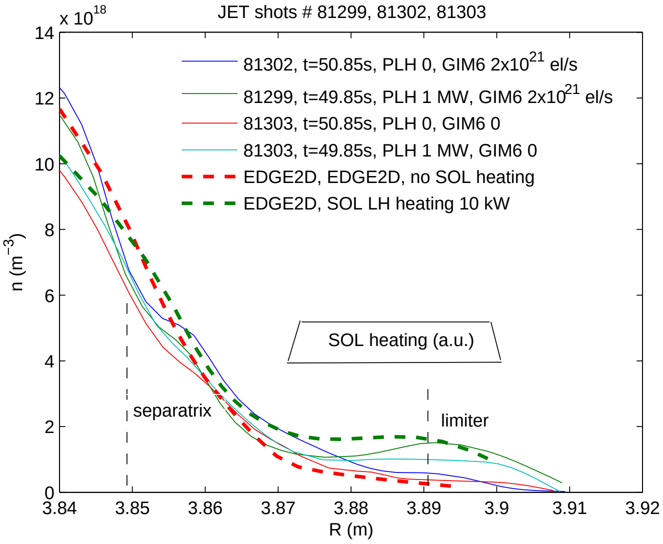

Fig. 2. SOL density modeling and Li-beam data for shots #81299, 81302 and 81303.

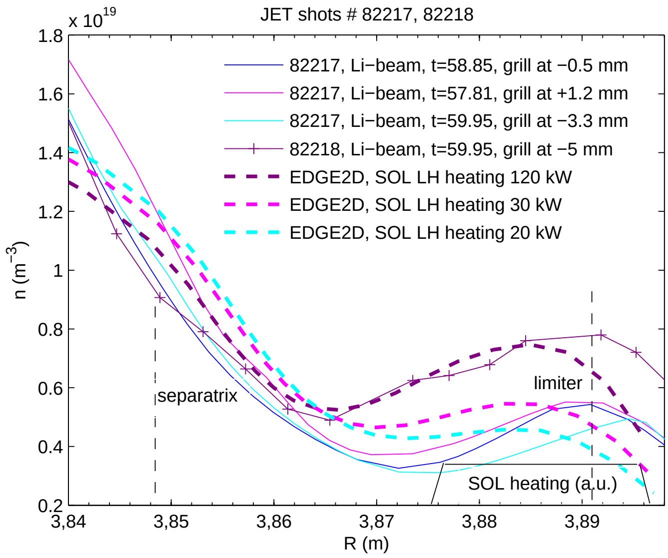

Fig. 3. SOL density modeling and Li-beam data for shots #82217 and n82218.

The model can predict reasonably well the changes in SOL density profiles with LH power, gas injection rate, and launcher position. In the latter case increase in dissipated power was needed in order to reproduce the density changes when launcher is retracted back in the shadow of the limiter. The density decrease due to ponderomotive forces was found to be negligible with respect to the density increase due to the local SOL ionization by the LH wave. The power dissipated in the SOL needed for the fit of the modeling to the Li-beam measurements is indicated in figures. From these simulations it can be concluded that only a few percent (maximum of about 5-6%) of the launched power is absorbed by the SOL plasma in the magnetic flux tubes in front of the LHCD grill.

Analysis of recent LH fast particle measurements with RFA and tunnel probe on Tore Supra antennas

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A Retarding Field Analyzer (RFA) and a tunnel probe ("probes" in what follows) were 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)[1] and of the C3 Fully-Active-Multijunction (FAM) [2] launchers.

The probes collect electrons that flow along field lines from the outboard side of the tokamak. The measurements were performed when wave-guide rows of the LH launchers were magnetically connected to the probes. The probes are mounted on vertically reciprocating probe drives, situated on top of the torus. Measurements of the full two dimensional spatial distribution of supra-thermal electron flux in the LH hot spots were performed up to the launched power of about 4 MW. The beam is several cm radially wide [2]. It was observed that protruding not-powered ICRF antenna, partially shadowing the space in front of LH launchers from the probes, cuts the beam radially: The part of the beam, which is not geometrically shadowed along the field lines by the antenna, is passing to the probes. However, when the ICRF antenna is powered, the beam does not penetrate to the probes even from the radially not shadowed locations in front of the LH launchers. Fig.1 shows that the fast beam can be fully blocked by the ICRH power, and the beam does not reach the probe.

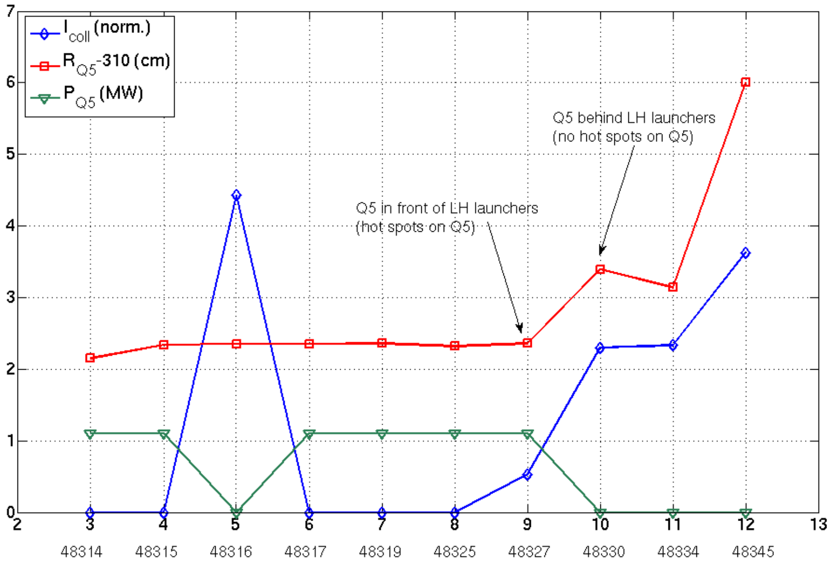

Fig. 1. The beam reaches the probe only in shot 48316, as indicated by the large value of I_{coll} .

Only when the ICRF power $P_{Q5}$was tripping in shot 48316, the beam reached the probe and the collector current I_{coll} caused by the fast electron beam was significant. We speculate that it could be because of the variations of the fast electron trajectory in electrostatic fields generated near the ICRF antenna. More detailed exploration of this effect is needed. Based on this finding, we plan to design (and to perform after the shutdown) further Tore Supra experiments, to elucidate in more detail the preliminary conclusions above. However, such shots can be performed not sooner than in year 2013.

Infrared (IR) imaging of the hot spots on the launcher side protections, or on a magnetically connected limiter, was also used for the analysis. Both the RFA collector current and the IR hot spot temperature are consistently somewhat higher for the FAM than for the PAM, at same power (1.4MW) and same plasma-launcher distance (4cm). For better understanding of the IR hot spots intensity measurements on the grill limiters, an independent estimate of the difference in power flow between C3 and C4 is obtained by a particle in cell (PIC) code that computes the electron dynamics in the electric field in front of the LH launchers. The code uses the electric field pattern from the ALOHA coupling code as input. The peak electric field reached 3.5kV/m, both on C3 and C4, for a density at the launcher mouth of $n_e = 2\times10^{17}m^{-3}$. In order to use an average electric field in the modelling, $|E_z|$ was multiplied by a factor $2/\pi$, to take into account the sinusoidal distribution of the field in the poloidal direction. The background electron temperature in the SOL was chosen as 10eV. Based on the average electric field values, a resulting parallel electron flow of $8.7MW/m^2$ and $15.3MW/m^2$ is obtained at the position of the side protections on C3, when the density in front of the launcher is $2\times10^{17}m^{-3}$ and $4\times10^{17}m^{-3}$, respectively (Fig. 2a).

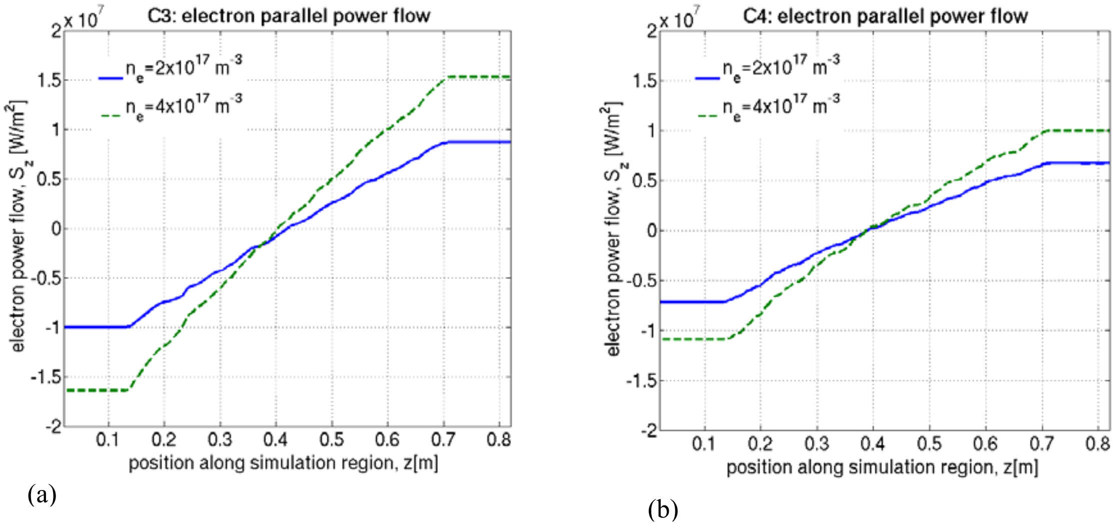

Fig. 2: simulated parallel power flow along the launcher mouth up to the side protections for C3 (a) and C4 (b).

The corresponding values for C4 are $6.7MW/m^2$ and $10.0MW/m^2$ (Fig.2b). The computed power flows are 30-50% higher for C3 (FAM) than C4 (PAM), which is consistent with the experimental data from both the RFA and the IR imaging. One can note that the power flow increases with increasing electron density in front of the launcher, a behavior which is also observed experimentally by the IR measurements.

References:

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SOL density variations during ICRF heating and gas injection

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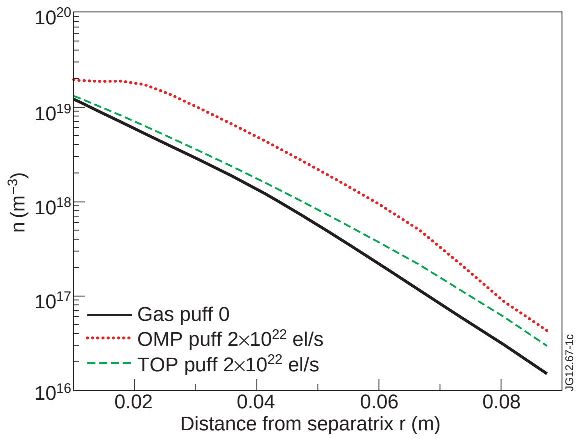
We present modeling results of the effect of gas injection on the SOL (Scrape-off-layer) density profiles (n_{eSOL}) during ICRF (Ion Cyclotron Resonance Frequency) heating. Gas injection during ICRF has been tested in several tokamaks with the goal of improving the coupling by modifying the density profile in front of the antenna, thus facilitating the fast wave propagation through the evanescent layer [1-4].

The EDGE2D / NIMBUS code was adapted to model the presence of a wide SOL and a magnetic geometry with a 2nd X-point near to the top of the wall (as in JET pulses #68109-13 [3,5]). In contrast to the computational grid for the configurations considered in [6] that have a SOL width of about 10 cm at the Outer Mid-Plane (OMP), EDGE2D simulations with the 2nd X point at the top are only carried out considering about 4 cm of SOL in the OMP. This is because the EDGE2D computational grid is restricted to a rather narrow OMP SOL layer in these ITER relevant configurations. One possibility is then to continue into the far SOL with "ad hoc" assumptions about transport with essentially 1D model. This then prohibits the modeling distant from the separatrix using EDGE2D. Following previous work [7], we have attempted to overcome this problem and to maintain the modeled SOL width at about 10 cm by introducing a limiter (particle sink) protruding radially down from the top. The power crossing the separatrix from the core to the SOL was set to 10 MW plus ICRF power from 0 to 3 MW. It is known that the SOL diffusion coefficient significantly varies with the SOL plasma temperature and density [8], themselves varying with the gas puff. Therefore, we considered several values of the diffusion coefficient D and heat diffusivities in the simulations, similarly as in [6]. The particle (and heat) diffusion coefficients were set to constant 0.1 m^2/s value from the core to the separatrix and to either the same value of 0.1 m^2/s also in the SOL (case a) or to various constant values up to 2 m^2/s in the SOL (case b). Fig. 1 compares n_{eSOL} for OMP and top gas injection for case a and shows well the lower efficiency of the top gas injection compared to the OMP one. This difference is similar for all values of D considered in the computations. The computed OMP outward shift of the FW cut-off density for JET scenarios described in [3] ($2x10^{18}$ m^{-3}), as a function of the gas puff, is shown in Fig. 2 for zero ICRF power (blue) and for 2MW of ICRF power (red). It can be seen that the density shift depends on the additional power only marginally, in agreement with [2].

We also compared simulated n_{eSOL} profiles with experimental ones from RCP (Reciprocating Probe) and Li-beam measurements for JET shots #68111-68113 that had various gas injection rates from different locations [3]: - #68111: no gas injected from the OMP (Gas Injection Module GIM 6), $1x10^{22}$ el/s injected from the divertor (GIM9 and GIM10); - #68112 : $4x10^{21}$ el/s gas injected from GIM6, $1x10^{22}$ el/s injected from GIM9 and GIM10; - JET pulse #68113: no additional gas injected. Fig. 3 shows comparison of the simulations for case b) profiles with D=1 m^2/s further out in the SOL.



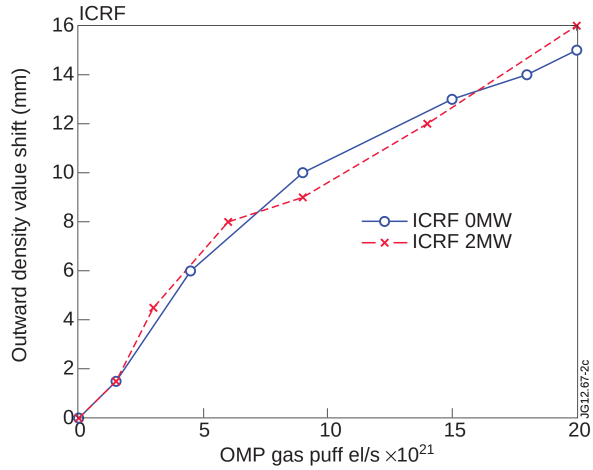


Fig. 1 (left). OMP n_{eSOL} profiles, TOP and OMP gas puff $2x10^{22}$ el/s and ICRF power level of 2 MW.
Fig. 2 (right). Outward OMP shift of the cut-off density value of $2x10^{18}$ m^{-3}.
(JET scenarios [3]) for different OMP gas injection levels.

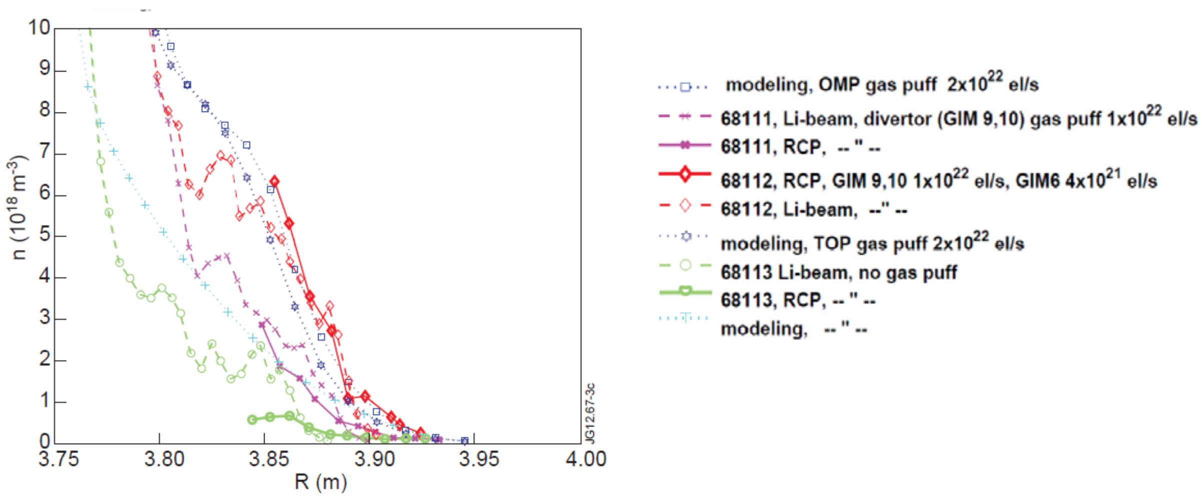


Fig. 3. Comparison of n_{eSOL} profiles simulations at the RCP and Li beam locations with the JET experimental profiles using D=1 m^2/s. The RCP and Li beam measurements were done at 8 s, at ROG 14 cm.

In agreement with some observations [2], the OMP gas puff is in the simulations more efficient for the OMP density enhancement (Figs. 1,2) than the TOP gas puff. Therefore, the OMP gas puff location should be preferred also in experiments for the purpose of OMP n_{eSOL} enhancement.

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2. Development of plasma auxiliary systems

Development of codes for existing and envisaged LH grill for COMPASS

J. Preinhaelter

In collaboration with J. Hillairet from CEA Cadarache we collaborate on the development of efficient full wave code for the launching of lower hybrid waves in the tokamak plasma. The waveguide structures so called grills are used for this purpose. The ALOHA (J. Hillairet et al., Nucl. Fus. ***50*** *(2010), 125010) code is frequently used as a standard to solve the coupling of lower hybrid grills to the plasma. To remove its limitations on the linear density profile, homogeneous magnetic field and the fully decoupled fast and slow waves in the determination of the plasma surface admittance, we exploit our recently developed efficient full wave code OLGA.*

To join these two codes we first must find the connection between the matrixes $\mathbf{R}$ of the amplitude reflection coefficients of waves from plasma in our code OLGA and $\mathbf{Y}^p$ of the plasma surface admittance in ALOHA. We found that $\mathbf{Y}^p$ is identical to $I_{\alpha\beta}^{plasma}\left(N_y, N_z\right)$ (see (A.27) in [023]) the "non-oscillating" part of integrand of the coupling element $K^{\alpha\beta}\left(m,n,p,k,j,q\right)$. We modify OLGA code to adapt the conventions of ALOHA (different coordinate system, $e^{j\omega t}$ time dependence and the othonormal waveguide modes) and named it AOLGA. To compare these quantities numerically we take in AOLGA linear density profile and the homogeneous magnetic field and consider standard 10 waveguide grill launching 3.7 GHz wave. We obtain good fit between $\mathbf{Y}^p$ computed from ALOHA and the same quantity from AOLGA for $N_{\|}$ out of inaccessibility region (for $N_{\|}$>1.4). This correspond well the limitation of ALOHA code, where fast and slow waves are completely decoupled (see fig. 1). ALOHA admittances differ from AOLGA results mainly for $N_{\|}$ in the inaccessible region.

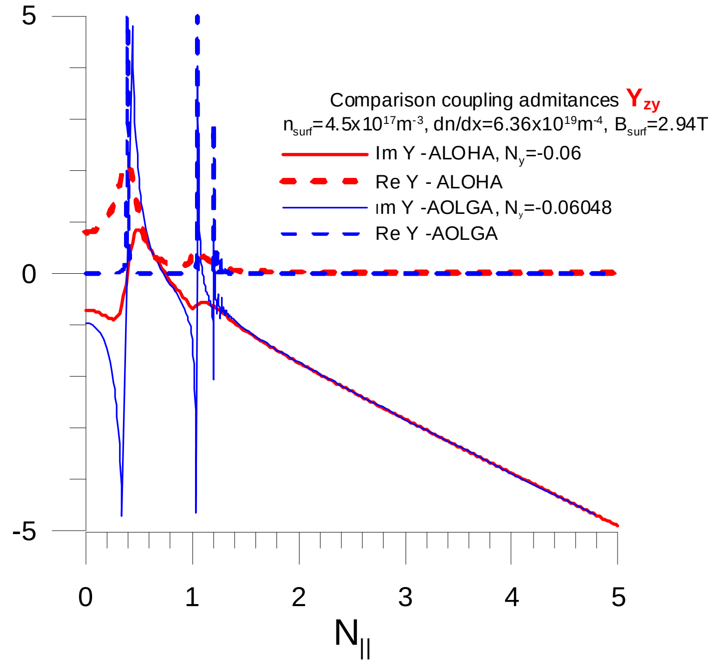

Fig. 1. Comparison of the plasma surface admittance computed by ALOHA and AOLGA.

As the next step we evaluated the coupling coefficients of ALOHA in AOLGA code. Coupling elements of waveguide modes are 2D integrals of product of the plasma surface admittance and the Fourier coefficients of waveguide modes. The same code also produce values of the plasma surface admittance on the mesh point in $(N_{pol}, N_{\|})$-space which are needed for determination of the power flux radiated from the grill to the plasma. The ALOHA coupling elements are linear combination of $K^{\alpha\beta}(m,n,p,k,j,q)$ so we can use the integration procedure from OLGA. In the next figure we compare ALOHA and AOLGA results. In the Fig. 2 we give the dependence of coupling elements between TE_{10} mode in first waveguide to TE_{10} mode in q waveguide ($q = 1,2,\ldots 10$). We see that ALOHA and AOLGA give similar results.

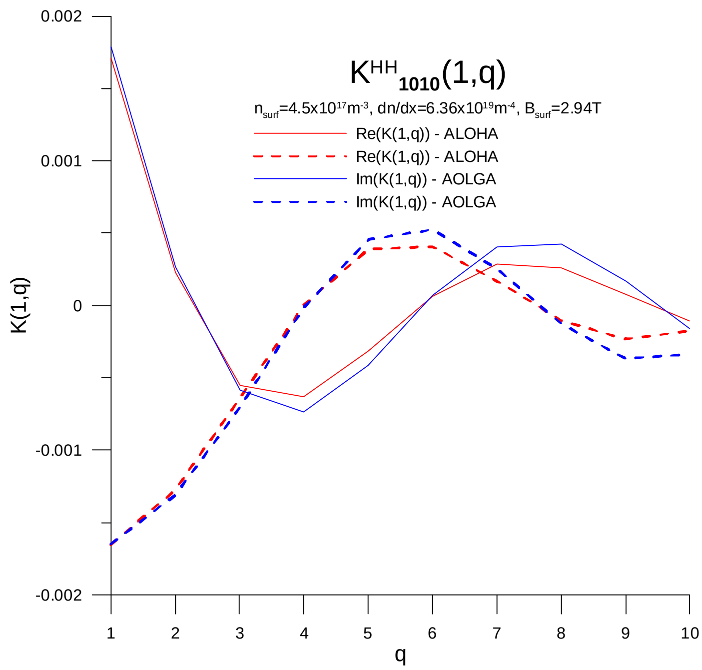

Fig. 2. Dependence of coupling elements of waveguide modes on the position of second waveguide q .

The solution of waveguide grill coupling to plasma is straightforward if we evaluated coupling elements and can be easily done in ALOHA.

We substitute all IMSL routines by free access codes and compiled ALOGA under Linux so AOLGA code is now prepared for use in Cadarache.

Measurements of fast radiating events in a tokamak plasma by the multi-channel visible light observation system on the COMPASS tokamak.

D. Naydenkova, V. Weinzettl

The COMPASS tokamak is being equipped with a multi-channel system for visible light observations of the core/edge plasma from two poloidal angles. Three minispectrometers are in routine use for studying of plasma composition and temporal evolution of observed spectral lines in wide spectral range. Four channels of the multi-channel system are in routine use to measure CIII and Hα spectral lines, spectrally integrated visible light and Bremsstrahlung radiation with high temporal resolution.

Both unique wide angle objectives for the multi-channel visible light observation system were successfully installed and tested and are in routine use in combination with photomultipliers for absolute measurements of CIII and Hα spectral lines, spectrally integrated visible light and Bremsstrahlung radiation, which is used for Zeff estimation. The system allows temporally resolved measurements of fast radiating events in plasmas of the COMPASS tokamak. Several important observations in COMPASS tokamak program were done using this system, namely spectroscopic measurements of L-H transitions and ELM's. These results will be published in year 2013. On the base of performed measurements the final amplification of signal for multi-channel system was chosen.

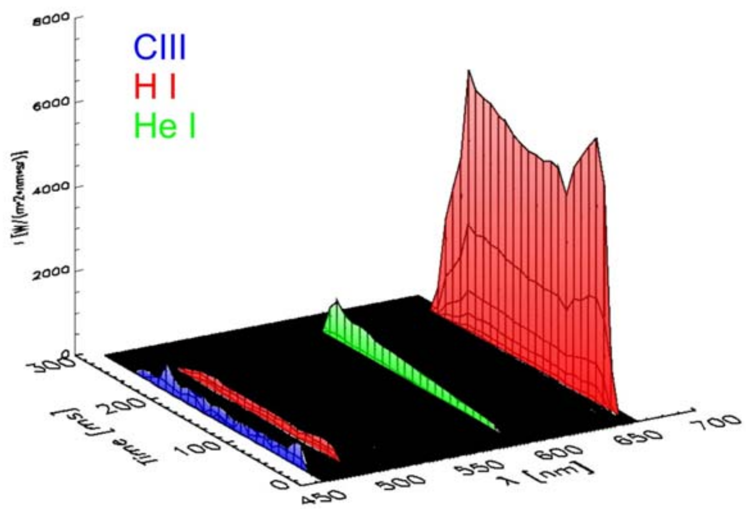

Fig. 1 Typical spectrum measured by minispectrometer in wavelength range 464-663 nm with temporal resolution 10 ms in circular plasma discharge with stable plasma position.

Three spectrometers with optical range 247-472 nm, 457-663 nm and 629-681 nm and optical resolution 0.15 nm, 0.17 nm and 0.04 nm respectively are the part of the system. Minispectrometers were absolutely calibrated and are used routinely in every shot with temporal resolution 7-20 ms dependent on experiment aims (Fig. 1). The measurements give possibility to study plasma composition and temporal evolution of plasma components during discharge and during experimental campaign. Among results of operation of the spectrometers are He and B observation, temporal evolution of Hα/Dα ratio in deuterium discharges (Fig. 2) etc.

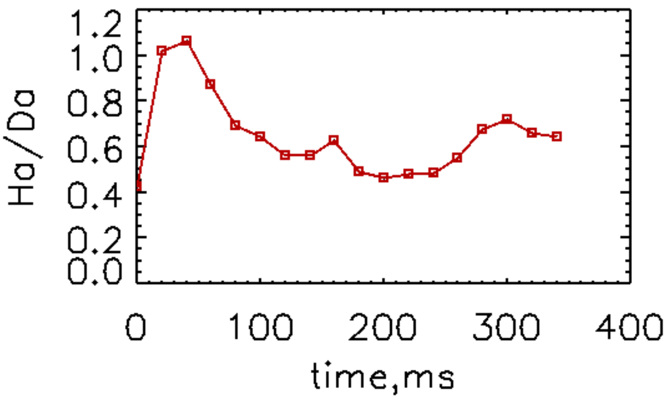

Fig.2 Temporal evolution of ratio Ha/Da was calculated from spectroscopic measurements during discharge with circular plasma and stable plasma position.

In the frame of absolute calibration the comparison of absolute values was received by different spectroscopic diagnostics. It shows perfect correspondence between the values measured by spectrometers and PMT. Hα temporal evolution received by means of minispectrometer and PMT can be seen in Fig 3 as an example of such a comparison.

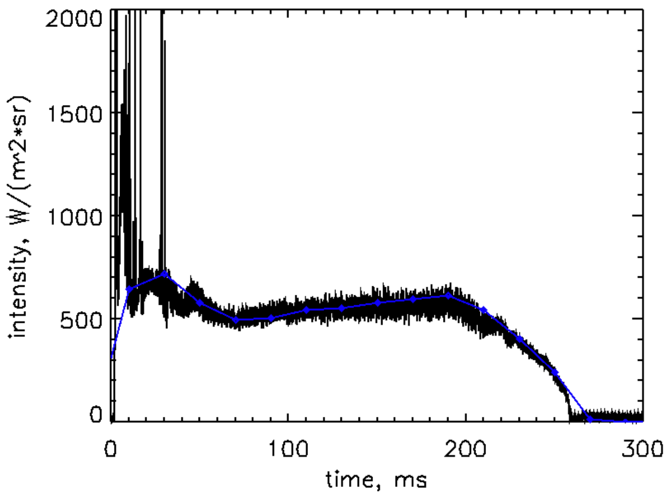

Fig.3 Comparison of the received by means of minispectrometer (blue) and PMT (black) detector spectral radiation for Ha during discharge with divertor and stable plasma position.

Detection of EC emission on COMPASS

J. Preinhaelter

In 2013 we published first results from a recently installed EBW emission diagnostic, which detects the first harmonic emission with the help of an angularly steered ellipsoidal mirror. The EBW-X-O process is involved and the EBW emission can be observed obliquely to the magnetic field.

In a dense plasma, the plasma cutoff exists near the boundary and the direct detection of O or X modes is impossible. In this case, the electron Bernstein waves (EBWs) excited at the electron cyclotron resonance and linearly converted to the X-mode in the upper hybrid resonance region can be emitted either directly as X-mode (EBWX tunneling) or, after the transmission through the plasma resonance region and the X-O conversion, as O-mode (EBW-XO conversion).

Our heterodyne radiometer assembly includes a quasioptical system, a Ka-band front-end and a 16-channel receiver. The new steerable mirror placed in the midplane inside the vacuum vessel provides a quasioptical beam shape focused on the plasma surface at the desired oblique angles. The ellipsoidal mirror re-focuses the beam at the plasma edge area.

Presently, only circular discharges are reliably reproducible on COMPASS with a plasma current flat top Ip = 130 kA. If the line averaged density is higher then 2×10^{19} m^{-3}, such discharges are overdense and practically free of runaway electrons and EBW signals with constant intensity lasting for more than 100 ms can be detected. A typical radiometer signal spectrum is presented in Fig. 1.

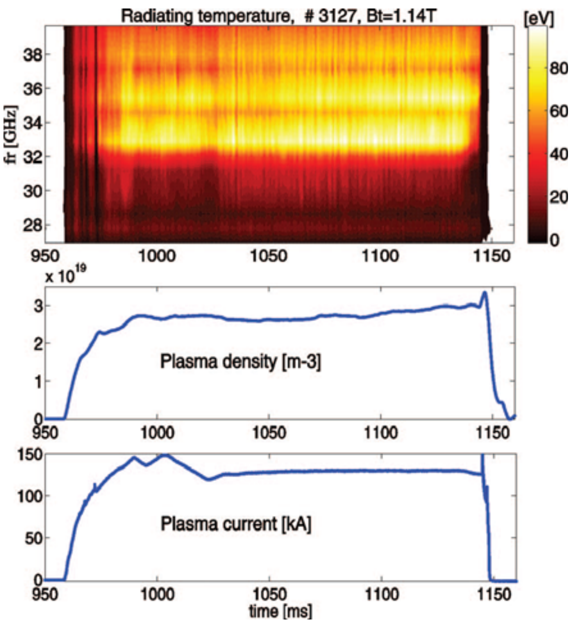

Fig. 1. Shot 3127: top-radiometer spectrum at the optimum angles α_{tor}= 28.5° and α_{pol} = 0°, absolutely calibrated signal, center-plasma density, bottom – plasma current.

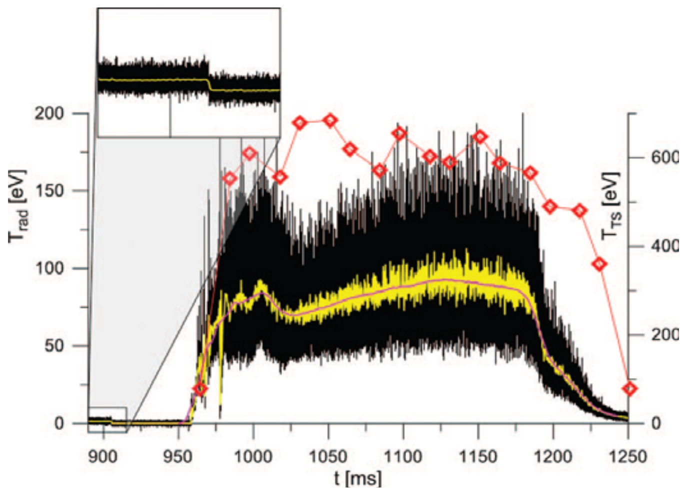

Fig. 2. Time development of the EBW emission from the plasma center (f = 32.875 GHz, shot 3117, α_{tor} = 33° and α_{pol} = −5°). Dark line – raw highly fluctuating signal, light colored line – once averaged signal, full smooth line – doubly averaged signal. Diamonds – T_{TS} at the position where $f = f_{ce}$ (right axis).

In Fig. 2 we present a detailed picture of the time development of the signal f = 32.875 GHz EBW emission from the plasma center. We see that a plateau of constant emission is develo-ped and lasts for about 200 ms. This corresponds to the current flat top and the more or less constant temperature T_{TS} measured by the Thomson scattering.

We mainly investigated the angular dependence of the emitted signal with the aim to determine the optimum antenna angle. The X-O conversion is strongly dependent on the angle between the incident wave-vector and the total magnetic field.

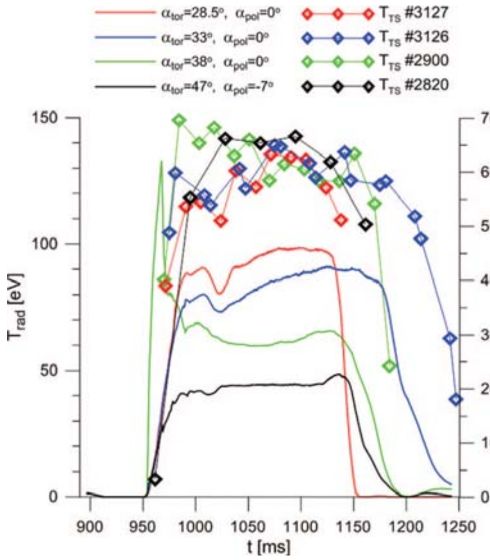

Fig. 3. Dependence of the time traces of the 32.875 GHz signals (full lines) on the incident angles. For comparison we add the time traces of the Thomson scattering central temperature (TTS – diamonds) for the corresponding shots.

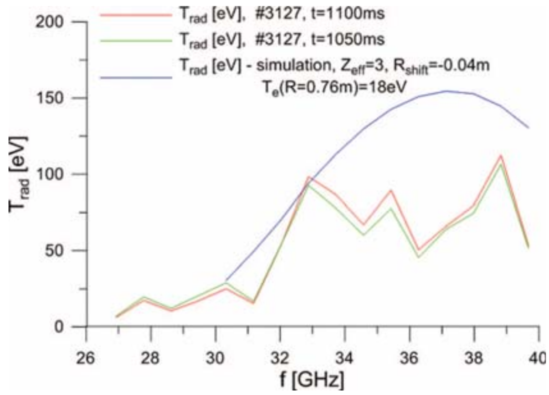

Fig. 4. EBW emission spectrum detected on COMPASS, shot 3127, $B_{tor} = 28^\circ$, $B_{pol} = 0^\circ$. Comparison with simulation.

In Fig. 3 we present some of the results for representative shots (the angels can be changed only between shots). The experimental optimum αtor is about 30° and αpol is about -2°.
To obtain a deeper insight into the EBW emission from COMPASS, we perform simulations with our AMR (Antenna, Mode-conversion, Ray-tracing) code.

The simulations predict much stronger decrease of T_{rad} with B_{tor} There is almost no dependence of T_{rad} on the incident poloidal angle B_{pol} in the measured interval $(-7^\circ, 5^\circ)$, which is also not predicted by the simulations. We therefore conclude that the tokamak vessel is filled with a diffracted radiation which smears the angular dependence of EBW emission substantially.

The EBW radiation temperature is relatively low in comparison with T_{TS} – see Fig. 3. The fact that we detect linearly polarized waves is responsible only for the half drop. The usual cause of the low EBW emission is a collisional damping of the EBW at the upper hybrid resonance region, which is situated outside the last close flux surface for most of our channels. The electron temperature at the scrapeoff layer, as follows from the threshold shift measurements, is sometimes lower then 10 eV. This, together with the estimated $Z_{eff} \sim 3$, causes a 54% decrease of T_{rad} for the 32.875 GHz signal. The simulation, on the other hand, predicts a conversion efficiency of the beam of the linearly polarized O-waves equal to 27%. Multiplying the product of these numbers with the central temperature produces $T_{rad} \sim 100$ eV, which more or less coincides with the measured value, as can be seen in Fig. 4. At the same time, simulations predict much weaker collisional damping at higher frequencies, resulting in about a factor 2 disagreement with the experiment. The measured frequency profile of T_{rad} has a drop around 36 GHz, which remains to be understood. One possible explanation may be in deformed magnetic surfaces on high field side so the higher emission around 39 GHz is from the free first harmonic and it has no connection to the EBW emission.

Establishment of routine operation of the first part of microwave reflectometry system (K and Ka bands)

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The first part of the microwave electronics (K and Ka bands) and the data aquisition, provided by IPFN/IST, was completed around the middle of 2012. The reflectometers were assembled and tested on the stand. The data acquisition system was integrated to the CODAC system. Because of persisting defects in the electronics, it was decided by the end of 2012 to send the reflectometer boxes back to Lisbon for the repair.

The reflectometry system for Compass is mainly designed to perform the relevant plasma density profile measurements in the pedestal region. The additional requirement is using of the reflectometers as an experimental diagnostics for studies of the plasma turbulence. The whole frequency range is 18-90 GHz, which is divided to four frequency bands called K, Ka, U and E bands. Five individual reflectometers were supposed originally to measure the edge plasma density profile. In the Ka-band the two reflectometers of two orthogonal polarizations were assumed, but the progress in the density profile evaluation allows us to use only O-mode polarization for the profile reconstruction, so four reflectometers will be enough for the whole system. Due to the costingness the project was divided to two parts and only reflectometers for the K and Ka-bands are realized currently.

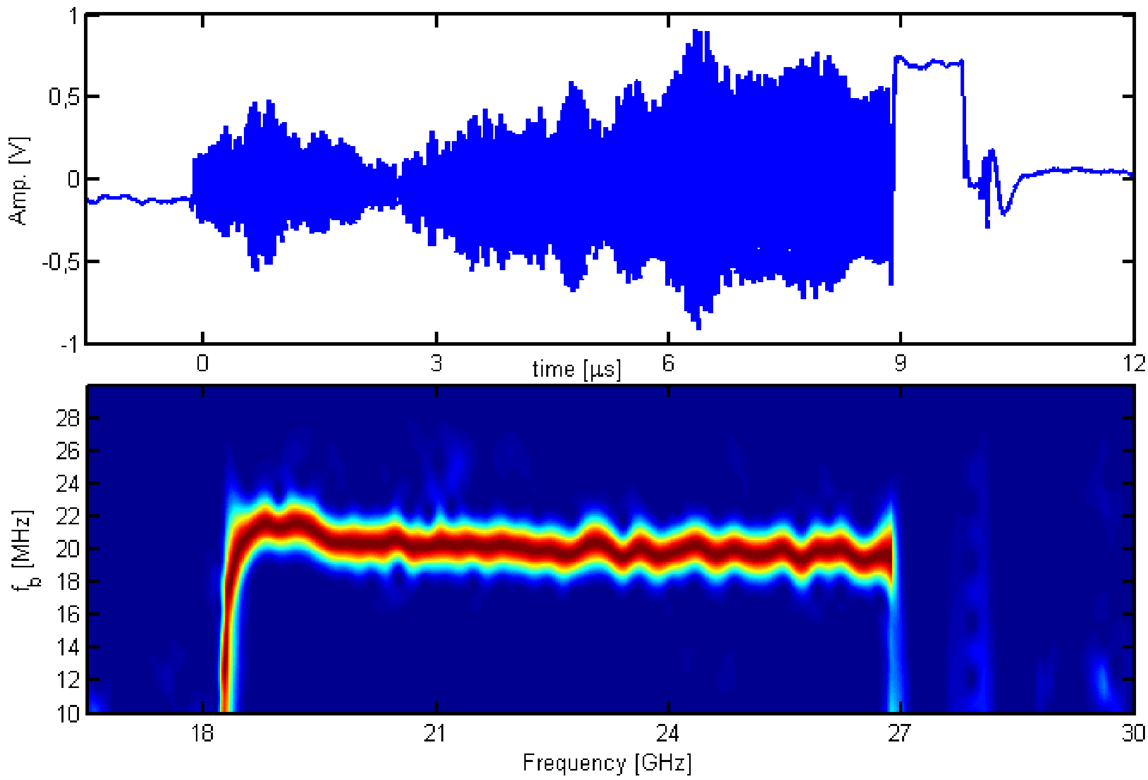

Fig. 1. Testing of the K-band reflectometer on the mirror at the distance of 496 mm from the antenna. Upper- reflected signal of one frequency sweep, lower – dependance of the beat frequency f_p on the signal frequency.

The originally planned term of the K and Ka bands installation on Compass was the end of 2010, but the development of the microwave electronics in IPFN/IST was pretty delayed. The new term of the intallation of reflectometers for both the K and Ka bands was the first half of 2012. Reflectometers were assembled with the band combiners. The system was tested and calibrated on the stand. At the same time the custom data acquisition system for the reflectometers, consisting 8 channels of 250 MSa, was integrated to the CODAC system. During tests both the reflectometers and data acquisition had to be repaired several times. The problems with the electronics persisted so, by the end of 2012, it was decided to send the reflectometer boxes back to Lisbon for the thorough repair. The new assembling of the system is supposed around the middle of 2013.

New student Ondrej Bogar was admitted to PhD thesis on reflectometry.

Thomson scattering

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In collaboration with:
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Thomson scattering (TS) diagnostic collection/detection system consists of two parts: one observing core plasma, one observing edge plasma. It covers 56 spatial points with spatial resolution of 10 – 12 mm in the core and 3 – 5 mm in the edge plasma region. Two independent lasers can fire at 30 Hz each or at 30 – 60 Hz both in combination. In the latter case, a 30 Hz option allows to use a small delay (in microsecond range) between lasers.

The core TS was put into operation in 2011 [1] and was operated all over the year 2012, with satisfactory reliability. The edge system was installed in beginning of 2012. The edge lens has been tested, profile of full TS range (core+edge) were obtained. The profiles from core and edge TS connect at the overlapping points (Fig. 1), proving cross-calibration of the two systems. However, alignment of the edge TS was not very stable so far, leading to low edge profiles reliability. Therefore, revision of the mounting structure is scheduled for the beginning of 2013 (ongoing at the time of writing of this report).

Small reconstructions (replacing some mirror mounts etc.) in the laser beam path improved convenience of operation and laser beam pointing stability and thus the alignment in respect to the TS collection optics.

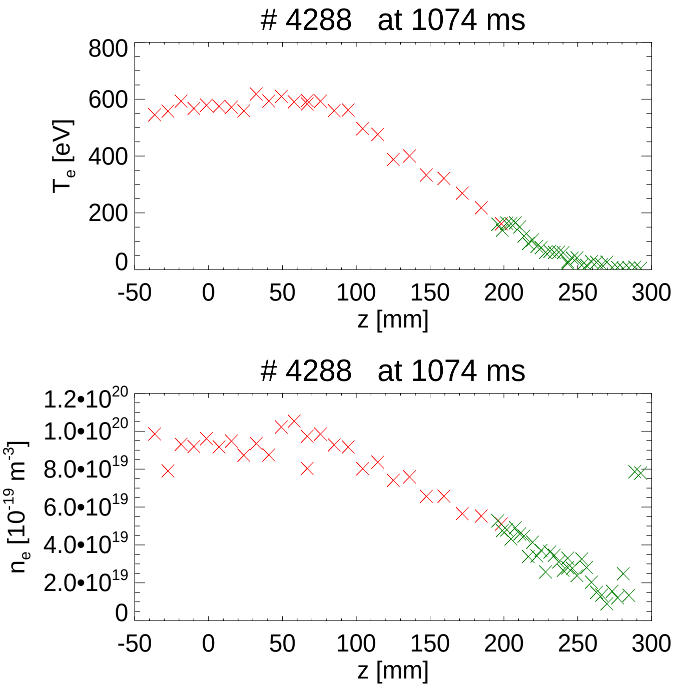

Fig. 1. Profiles of electron temperature and density for shot No 4288 at 1074 ms

Standalone triggering unit, controlling and synchronising two TS lasers, was tested and installed. The triggering unit simplified control of TS diagnostic, allowing semi-automated control of the TS operation. Based on the experience with the triggering unit, second generation of the triggering unit was designed, implementation is planned for spring 2013. Shutters in the laser beam path are newly equipped qith pneumatic drives and remote control. The above mentioned second generation of laser triggering unit will complete their full integration into automatic control and laser safety interlock.

Data processing routines are being continuously improved and optimised. Speed and reliability of data processing was increased although there are some remaining issues with diverging fitting routine occasionally. Work on elimination of this effect continues, for example, analysis of statistical and systematic errors. In order to run the diagnostic automatically without a necessity of human control we started routine modification to be run as service and client for communication with CODAC.

Data from TS were used for some basic plasma parameters calculation and estimation, like stored plasma energy, energy confinement time, effective nuclear charge (Z effective) [2], for comparison for other diagnostics or as their input [3]. Software used on JET for fitting of pedestal region was adopted for COMPASS needs by L. Frassinetti and first tests performed.

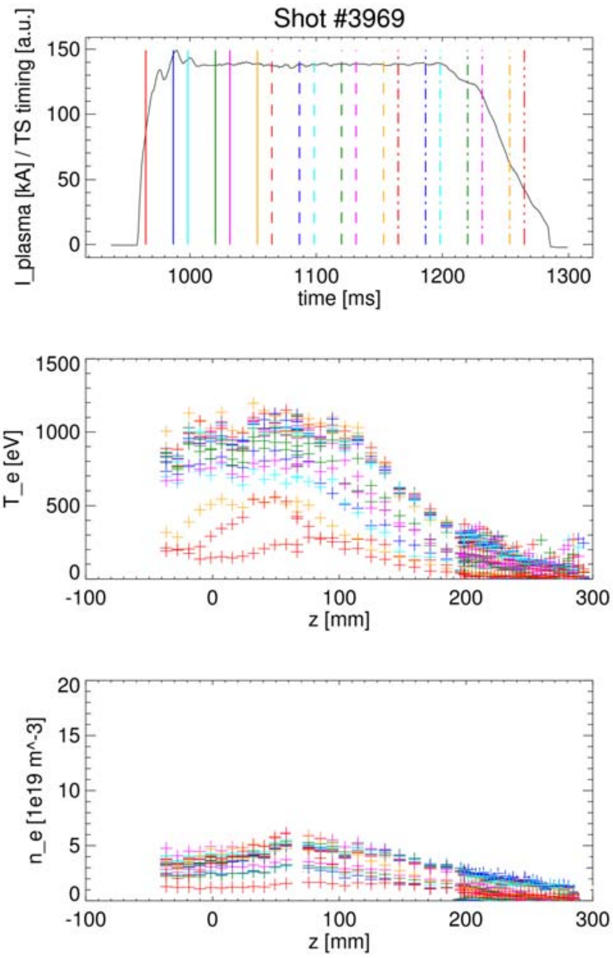

Fig. 2. Profiles of electron temperature and density for shot No 3969 at during whole plasma shot

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[1] M. Aftanas, *Journal of Instrumentation* 7 1 (2012) C01074-C01074.

[2] M. Aftanas, *Review of Scientific Instruments* 83 10 (2012) 10E350-10E350

[3] J. Zajac, *Review of Scientific Instruments* 83 10 (2012) 10E327-10E327

Beam Emission Spectroscopy system for COMPASS

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

The new Beam Emission Spectroscopy (BES) diagnostic for edge density measurements on the COMPASS tokamak is being commissioned in cooperation with the Association EURATOM – HAS in a framework of the bilateral agreement between IPP Prague and Wigner RCP. 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.

Recently installed diagnostic of the lithium beam on the COMPASS tokamak is one of the newly built tools aiming to measure important plasma parameters in the pedestal region with sufficient spatial and temporal resolution. The idea of diagnostic is that accelerated neutral lithium beam is injected radially into the vacuum vessel and interacts with plasma. The beam atoms are collisionally excited and ionized - the excited neutral atoms return to the ground state by emitting radiation with characteristic wavelength. In the case of certain beam species, e.g. Li, Na, sensitivity on the electron temperature is small, thus the electron density profile primarily determines the beam light emission. Measured intensity of the emitted light (670.8 nm for 2p–2s transition) therefore allows reconstruction of the electron density profile. Fast beam deflection (with frequency up to 400 kHz) to several vertical positions and correlation of the signals allows observation of turbulent structures in the plasma edge.

During the year 2012, continuous comissioning of the Li-beam system was done. Cabling and grounding of the system was remade and a new electrical control box was installed. An interlock system for the emitter water cooling circuit was installed in order to protect the emitter from overheating and mechanical failure. The ion optics design for the beam extraction had to be changed in order to improve the focusing of the beam. The beam was tested several times up to 40keV, with extracted currents reaching up to 2mA. The efficiency of neutralization was measured with very good results, as it is well over 90% for nominal beam energy of 30keV. The CCD camera for slow beam light detection (BES) has been routinely operated during tokamak discharges and was used also for important divertor region observations. The first successful experiments of the lithium beam with plasma were performed in the last quarter of 2012 (see Fig.1). During these shots, the first plasma density reconstructions based on the CCD camera images were calculated (see Fig.2) using a newly developed reconstruction code written in MATLAB. In the end of the year, a new flange with embedded vacuum window for improvement of the CCD camera view was ordered and magnetic shielding of a part of the system was improved. The fast detection system installation was done in March 2013.

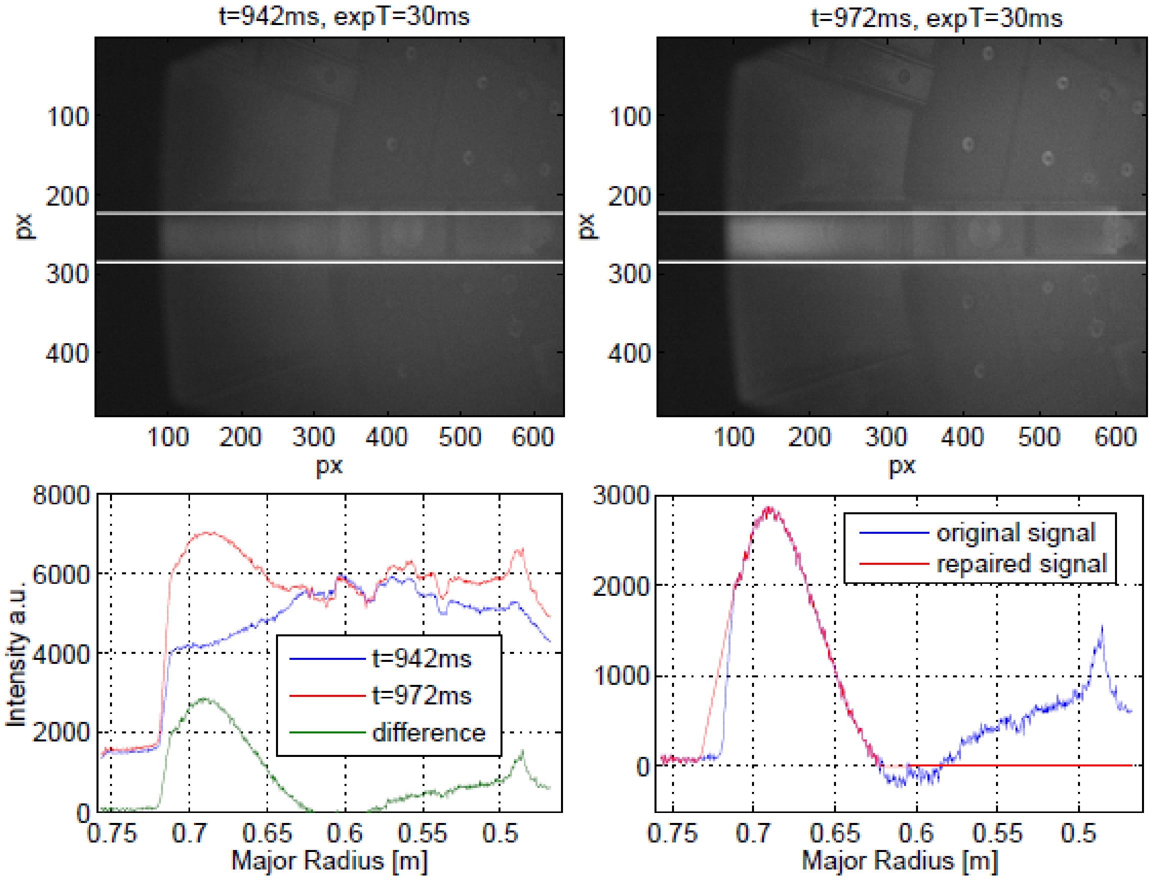


Fig.1: CCD camera image processing of a shot #4163. The intensity of the beam light is calculated and shown on the pictures below.

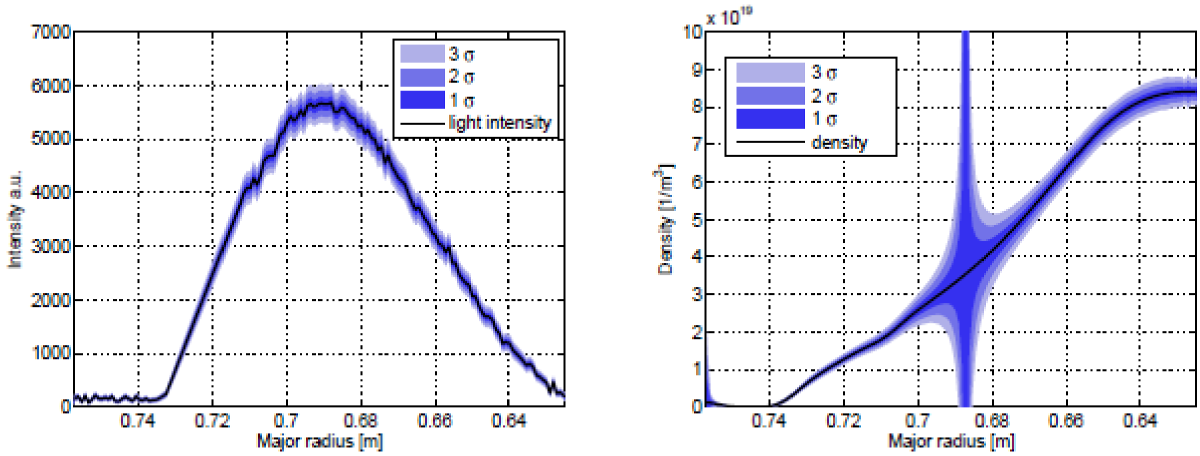


Fig.2: Left: Measured light profile of a shot #4163. Right: Reconstructed plasma electron density with shown error.

Development of the ExB analyzer

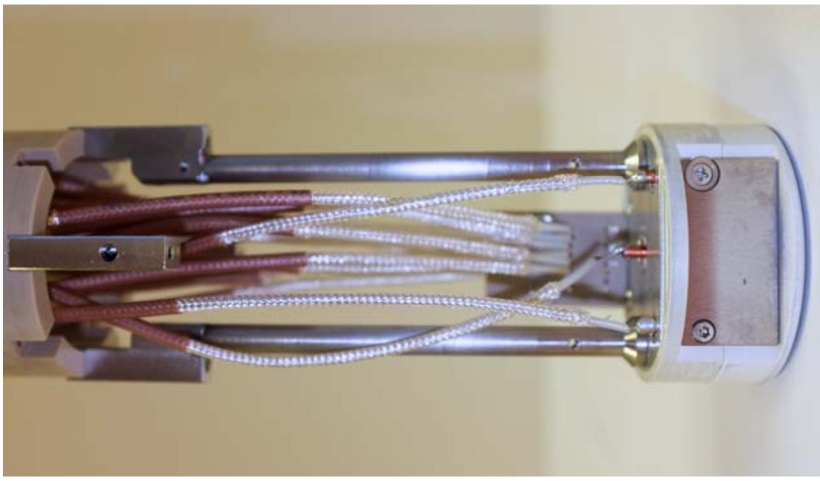
M. Komm

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

The ExB analyzer is a novel diagnostics, which should allow fast measurements of ion temperature in the SOL. Unlike other probe techniques (such as Katsumata probe or RFA), the analyzer does not require voltage sweeping, which usually limits the time resolution. The objective of the measurements is to study ion temperature fluctuations and its evolution during intermittent events, such as ELMs.

The design of the ExB analyzer is similar to the RFA - the ions are passing through an entrance slit, which is negatively biased to repel electrons, into a cavity. In the RFA the ion flux is then controlled by a series of grids, in case of the ExB analyzer, the cavity contains two planar electrodes, which are biased to different potentials in order to create an electric field. This field combines with the tokamak magnetic field and creates an **ExB** drift, which affects the ions. The drift velocity only depends on the applied E and B fields, so within the guiding-center approach, the ions with low parallel velocity which spend more time inside the cavity, will be more affected by the drift, than fast ions. This creates a mapping of the parallel velocity distribution function onto the array of collectors at the back of the cavity.

In 2012, the design of the analyzer has been finalized and its production contracted. The new design is substantially different from the original one used on DITE tokamak in the 80's. Instead of 4 collectors, there will be 12 of them, each 1.25 mm thick. The array of collectors is constructed on a PCB, which gives great flexibility and precision in spacing and positioning of the collectors - ie. collectors can have varying thickness depending on the expected ion current. The shape of the entrance slit has been optimized by means of PIC and MC simulations. This should allow higher ion flux passing through the slits and subsequently higher collector currents. However, the newly designed slit caused a significant delay in fabrication of the analyzer, as its production is much more difficult then a production of an ordinary rectangular slit.



Apart from the entrance slits, most of the parts of the analyzer arrived in fall 2012 (see Fig. 1). A custom-built 16 channel current amplifier has been developed and tested for frequency response.

In order to perform reference ion temperature measurements, the RFA probe head has been loaned from IPP Garching. A series of experiments has been performed in october. The quality of the signals has been seriously degraded by a high-frequency noise, which often drove the signals into saturation. Moreover, the large probe head probably acted as a limiter and as such affected the plasma. These obstacles did not allow successful measurements, however, they helped to identify problems, which will be most probably present also during the ExB analyzer operation. The design of the analyzer has been presented a the 20^{th} PSI conference in Aachen.

Minimum Fisher Regularisation in fast tomography

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In collaboration with:
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B. Alper, C. Giroud, Association EURATOM – CCFE, UK

In 2012, an article detailing performance of the optimized Minimum Fisher Regularisation was published [1]. As expected, COMPASS experimental data achieved the required quality for the tomography inversion, in particular in the AXUV diagnostics [2]. At the same time, JET interest in MFR analyses increased considerably due to significance of the SXR data linked to the new, all metal ITER-like wall. The analyses of the JET SXR data were focused in particular on impurity transport and runaway electron studies [3]. Prospectives of real-time control via SXR diagnostics, possibly using the tomography reconstruction, have been studied jointly by COMPASS and by TORE SUPRA tokamaks, where MFR had been implemented, further developed and tested [4].

The Nucl.Instrum. Methods article [1] details optimisation of the MFR algorithm for tomographic analyses using modern numerical libraries in order to achieve faster and more flexible performance, and its enhancement to Soft X-ray (SXR) data studies from the JET detectors known as KJ5 and KJ34. As foreseen, the recent JET campaigns with the new ITER-like first wall triggered considerably increased interest in the SXR tomography analyses by different JET groups, due to SXR relevance to the plasma-surface interactions and impurity transport. Some analyses also included comparisons with older (CFC first wall) data. The MFR tomography was applied in particular to SXR profile studies in plasma core with sawtooth activity, to preliminary studies of impurity dynamics, to analyses of SXR emission of runaway electrons after disruptions [3] and to preliminary identification of SXR emission properties during ELM crashes. Besides we initiated our own studies to compare magnetic position and SXR centre of mass, as presented at the HTPD conference [2].

In order to facilitate further exploitation of the MFR analyses, a script was edited that can write all important tomography results (including the evolution of two-dimensional SXR emissivity cross-section) to a private database (ppf). In preparation of future tomography applications at JET, geometry of the bolometric diagnostics (known as KB4 and KB5) was implemented into the MFR. Preliminary tests were run successfully.

Thanks to the experience with tomography at JET the MFR algorithm could have been successfully applied on data from the Czech COMPASS tokamak [2]. The analyses proved, among others, that plasma position can be determined reliably via the tomographic diagnostics. The edge cooling due to increased interaction of the wall was clearly observed, see figure 1. In collaboration with the French TORE SUPRA tokamak in the SXR tomography, which has been documented in [4],performance of MFR due to limited DTOMOX data in the designed WEST configuration were studied, see figure 2, and a new, streamlined, real-time relevant MFR version was developed and tested. Following the successful tests it was agreed that the COMPASS tokamak shall also participate via a feasibility study on the plasma position and real-time control based on the SXR tomography analyses in 2013.

In the MFR code development and benchmarking our department also co-operates with the Czech Technical University where the algorithm was implemented for the analyses of tomography based on low-cost cameras at the student facility tokamak GOLEM [5]. Furthermore, the expertise with inverse, ill-conditioned problems has been successfully extended in 2012 to development of advanced machine learning tools for plasma disruption prediction at JET [6]. This work is of primary importance due to the required plasma disruption prediction performance at ITER, however it also demonstrated the challenges caused by sparse data in critical regions of plasma parameters and by low portability of predictions from one machine to another.

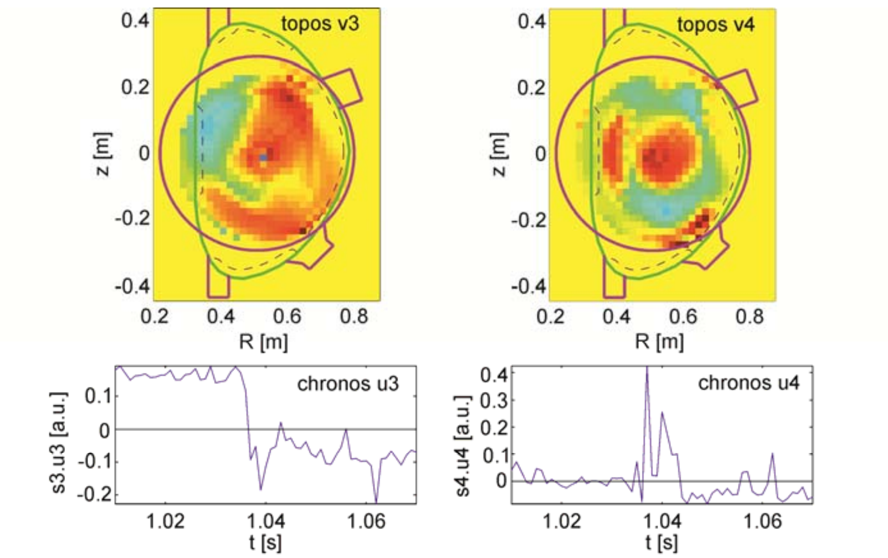

Figure 1: Singular value decomposition of tomographic analyses of the AXUV emissivity evolution in the COMPASS discharge #2648, showing the effect of inward plasma radial position shift at t = 1.04 s. Notice that the third eigenvector remains steady in its temporal evolution („chronos“) after the position change. The fourth eigenvector clearly features a temporary (perturbation) nature and demonstrates plasma edge cooling (in blue) due to the plasma-wall interaction (in red).

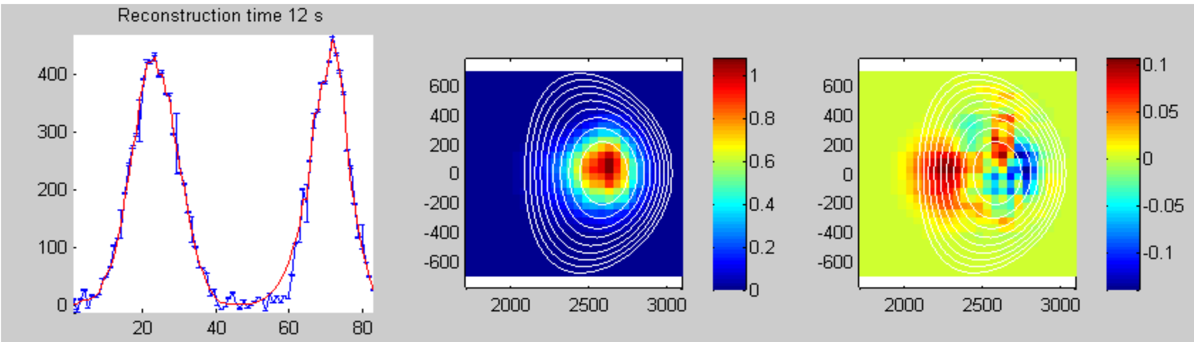

Figure 2: Tomography reconstruction of synthetic data at TORE SUPRA with the foreseen WEST geometry and the vertical channels 1-18 switched off. The magnetic contours correspond to Solovjev solution of the Grad-Shafranov equation, and the phantom function (source of the synthetic data) is a Gaussian peak on the flux surfaces with a banana-shape perturbation on the low field side. The perturbation as well as the random noise are time-dependent. From left to right: Synthetic data with simulated random errors s (blue, including the 18 channels that were not used for the reconstruction, ie. channels 37-50) and the fit corresponding to the reconstruction (red), the reconstruction (colour density plot, colorbar scaling is normalised to maximum of the radiation density) and the difference between the phantom function and the reconstruction (the same normalised scaling). Notice the systematic error on the high-field side which is due to the missing channels 37-50 but probably can be further minimised by suitable a-priori constraints.

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Calibration of the Tunnel Probe

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

During the past 2 years, more than 2000 particle-in-cell (PIC) simulations of the plasma (ion current) distribution inside a tunnel probe (TP) have been made using our in-house 2D PIC code, for different aspect ratio (geometry) of the probe, scanning a wide range of possible tokamak plasma parameters (density & temperature, magnetic field, gas). This numerical database is being used to find a calibration for the TP and an optimized geometry for COMPASS typical plasma parameters.

Each case of the database corresponds to 1 physical case for a given biasing voltage of the TP (Pot^{TUN}), a given aspect ratio ρ (one defines the aspect ratio as: $\rho = L^{TUN}/r^{TUN}$, where L^{TUN} and r^{TUN} are the length and the radius of the tunnel, respectively) and a given parameters ξ, which characterizes the width of the magnetic sheath inside the tunnel, therefore the physics that rules the plasma deposition there. ξ is proportional to the ratio r_L/λ_D, i.e., Larmor radius over Debye length. One should reorganize this database in order to find some physical trends for fixed parameters. The principle of the TP is to give the electron temperature (T_e) using the ratio R of the tunnel over back-plate currents ($R = I^{TUN}/I^{BP}$). R is a key element as it describes the distribution of the plasma inside the tunnel probe via the role of the sheath, which is proportional to incoming plasma parameters and therefore T_e. A program has thus been developed to scan the PIC database to give I-V characteristics for a given aspect ratio of the TP. One has to note that the outputs of the PIC simulations are normalized, so that a numerical case can correspond to several physical cases. As an example, Fig.1 shows the part of the database with a fixed aspect ratio as a chart with the tunnel radius [in λ_D] on one side and the ξ parameter on the other side. Each cross corresponds to an I-V characteristics for a given T_e and a given ion saturation current density (J_{sat}), pink dashed lines indicate a constant T_e and red dashed lines indicate a constant J_{sat}. A second program has been written to denormalize the data for a given magnetic field strength [T], tunnel radius [mm] and the gas species used (mass).

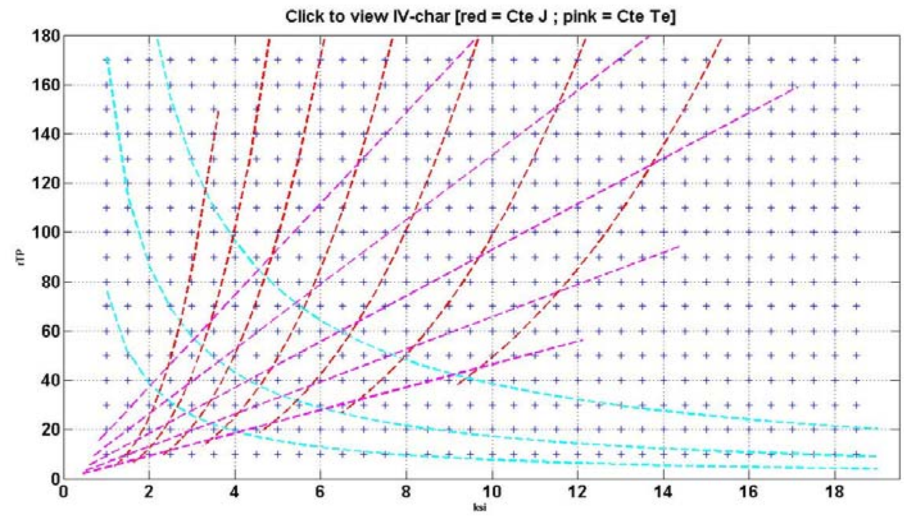

Fig.1: *Part of the PIC database for a given aspect ratio for fixed tunnel radius [in λ_D] and ξ parameter. Each cross corresponds to an I-V characteristics for a given T_e and a given J_{sat}, pink dashed lines indicate regions with a constant T_e and red dashed lines a constant J_{sat}.*

By clicking on the chart shown in Fig.1, one tunnel probe I-V characteristic is constructed for a given temperature and density, magnetic field and gas. Usually one I-V characteristic is made out of few Pot^{TUN} ranging from -250 V to +50 V, typical values used in Langmuir probe techniques. Fig.2 shows the values of the ratio R from tunnel and back-plate I-V characteristics as a function of different aspect ratio for different diameters of the TP (d_{tun}) for a deuterium plasma and $B = 2T$ (which are the gas and the magnetic field met in COMPASS tokamak).

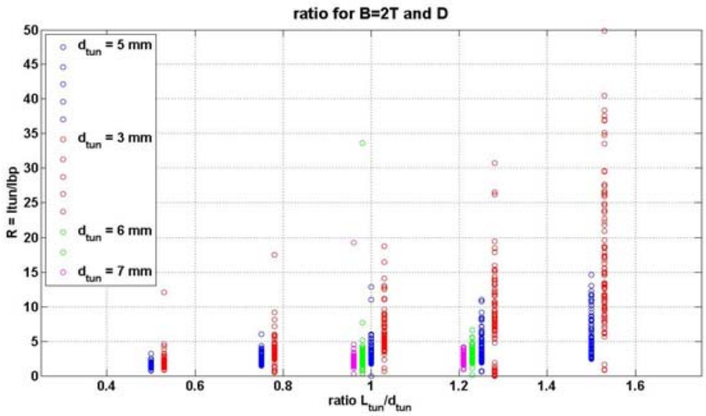

Fig.2: *Ratio R as a function of different aspect ratio for different radii of the TP for deuterium and B = 2T*

In order to have a good resolution in terms of T_e values, the ratio R should not be greater than 10. From results shown in Fig.2, one can therefore discard the couples (aspect ratio, d_{tun}) which do not fulfill this condition and focus on the others for designing the TP for COMPASS. Now that we have restricted our database, one can study the dependence of the ratio R with the main plasma parameters T_e and J_{sat} for a given couple *(ratio,* d_{tun}*)*. In order to validate our PIC simulation results, we have compared the numerical I-V characteristics with experimental ones measured with TPs in TORE SUPRA and CASTOR tokamaks. A TP current-voltage characteristic can be divided into 2 sub-characteristics, the one from the tunnel and the one from the back-plate. Fig. 3 shows a comparison PIC vs. experimental I-V characteristics for a CASTOR case [J. P. Gunn et al., Czech. J. of Phys., vol **55** (2005) no.3]. One can see a good agreement with the experiment for biasing voltages below the floating potential, where the (saturation) current is purely ionic. Indeed, the PIC code does not give accurate results for the electronic currents and there are 2 reasons for that. The first one is that the simulations assume a perfectly aligned tunnel with respect to the magnetic field lines. In reality this is not the case. If this effect does not have a strong influence on the ion currents, it strongly affect the electronic current since the gyration of the electrons is much smaller than the ions and they mainly remain magnetized, i.e., following the field lines. The second reason is that the code does not take into account the secondary electron emission. These results validate our simulations and allow a good calibration of the TP.

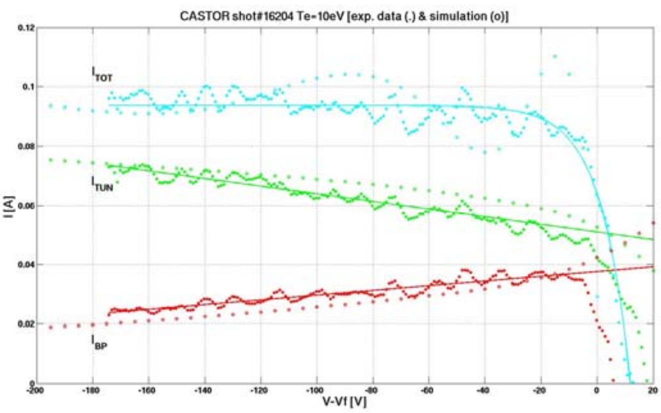

Fig.3: *Comparison of experimental I-V characteristics (full symbols) with ones calculated by our 2D PIC code (empty symbols) for the CASTOR case*

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

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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

In 2012 the experiments in cylindrical magnetron and pulsed plasma jet continued. The ball-pen probe was tested in low magnetic field conditions. The emissive as well as Langmuir probe was applied in stationary plasma thruster in collaboration with Dr. Stéphane Mazouffre and Käthe Dannenmayer, CNRS Orleans, France.

Operation of the plasma jet in the pulse regime enables a simple use of a classical Langmuir probe for the plasma flow velocity measurement. In this method we assumed that the plasma is generated solely inside the nozzle during the power impulse and we measured the time of flight of the ions along the known distance between the nozzle end and the probe. As the second method the well known Pitot tube was used for measurement of the neutral gas velocity. By comparison of both methods we have experimentally proved that the neutral gas flow velocity is almost not affected by the presence of plasma, i.e. it does not substantially depend on the fact whether the discharge is on or off. Results of both methods were in a good correspondence; detected differences were qualitatively explained, see Fig. 1. Results were prepared for publication in Plasma Sources Science and Technology scientific journal [1].

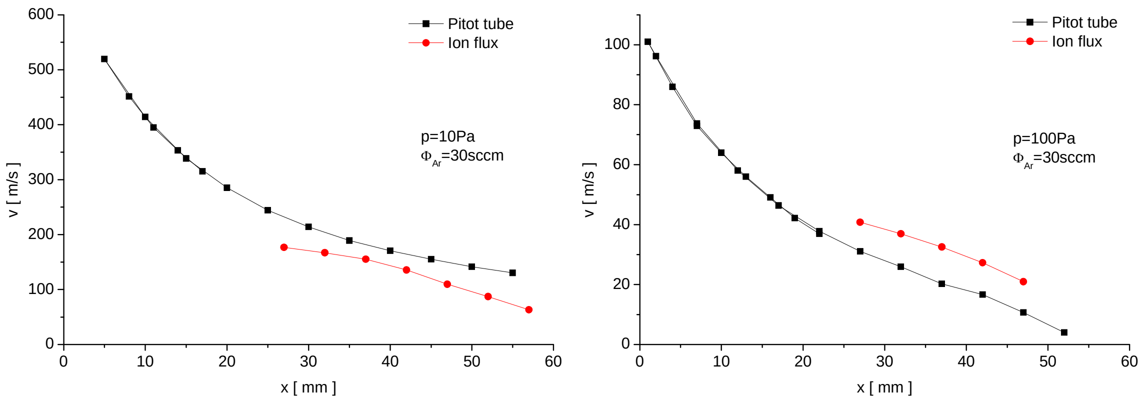

Fig. 1. The dependences of the plasma/gas flow velocity in the plasma jet axis on the distance from the nozzle outlet for different pressures in the reactor chamber. Points are connected in the sequence as the corresponding measurements were performed. Top left: plasma flow velocity measured by the ion flux. Top right: gas flow velocity measured by Pitot tube. Bottom panels: comparison of results from both methods at the argon pressures 10Pa and 100Pa.

The basic idea of ball-pen probe is to reduce the electron saturation current to the same magnitude as that of the ion saturation current, which is achieved by positioning the probe perpendicularly to the magnetic field lines so that the electrons are shielded due to their gyromotion. In this case, the floating potential of the probe becomes equal to the desired plasma potential. In 2012 we performed the first systematic measurements with the ball-pen probe in a low-temperature and weakly

magnetized plasma. Results were published in [2,3]. The corresponding poster received the EPS Best Poster Award.
In collaboration with the ICARE laboratory in Orleans, France the time-resolved measurements using electrostatic probes were performed in the far-field plume of a low-power permanent magnet Hall effect thruster. The plasma potential was measured by means of a cylindrical Langmuir and a sufficiently heated emissive probe, the electron temperature and density were measured with a cylindrical Langmuir probe. The thruster was maintained in a periodic quasi-harmonic oscillation regime by applying a sinusoidal modulation to a floating electrode in the vicinity of the cathode in order to guarantee repeatable conditions for all measurements. In order to achieve synchronism, the frequency of the modulation had to be close to the natural frequency of the observed phenomena. The measurements showed that the fluctuations of the electron density follow the discharge current fluctuations. The time-averaged properties of the discharge remained almost uninfluenced by the modulation. Measurements of the plasma potential with the two different probes were in good agreement. The observed phenomena were similar for Xe and Kr used as propellant gases [4].

The computational modeling group led by Prof. R. Hrach attempted to describe computational simulations of the propagation of a magnetized plasma to inner parts of porous solids or cavities. The geometry of such a problem requires generally three-dimensional simulations due to lack of symmetry. We proposed a hybrid method to overcome limitations of commonly used particle and fluid models. The hybrid method combines particle and fluid parts in an iterative manner to obtain results in a short time preserving information about individual particles. The hybrid model was applied to a study of ion propagation to a cylindrical hole in a conductive solid. The geometry of the problem is indicated in Fig. 2. The influence of a magnetic field and its orientation was discussed. The presence of the magnetic field enhanced the flux of ions to the hole; the influence of voltage bias on the substrate was highly important. The voltage bias may increase the total ion flux, however the distribution of the ion flux with respect to the z-coordinate is changed. The angular distribution is additionally influenced by **E**×**B** and ∇n×**B** drifts.

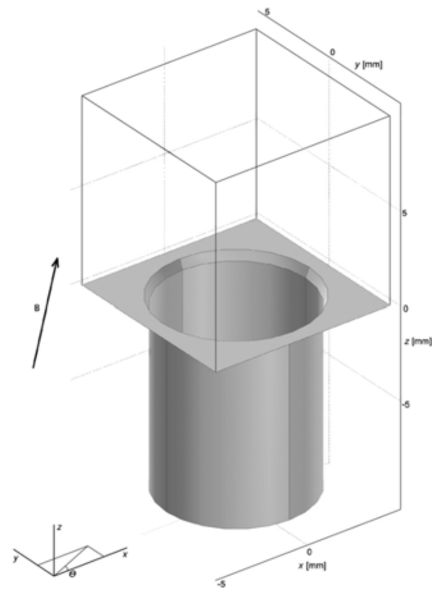

Fig. 2. The geometry of the problem. At the top of the computational domain, undisturbed plasma is expected. The conductive substrate is marked with grey colour.

The hybrid model represents a competitive alternative to PIC models. A typical time consumption of the hybrid model is 12 h (Intel Core i7 940 at 2.93 GHz), the PIC model for three dimensions would require weeks. However, the hybrid model is limited to steady-state problems due to the iterative coupling and is suitable only for collisional conditions because the drift-diffusion approximation is used. The results were published in [5,6].

References :

[1] J. Kluson, P. Kudrna, M. Tichy, *Plasma Sources Sci. Technol.*, in print.
[2] J. Adámek, M. Peterka, T. Gyergyek, et al., Nukleonika 57 (2) (2012) 297-300.
[3] J. Adámek, T. Gyergyek, M. Peterka, et al., 25th Symposium on Plasma Physics and Technology (SPPT), 18-21 June 2012, Prague, book of abstracts, p.44, poster.
[4] K Dannenmayer, P Kudrna, M Tichý et al., *Plasma Sources Sci. Technol.*, 21 (2012) 055020.
[5] V. Hrubý, R. Hrach, Z. Pekárek, *Vacuum* 90 (2013) 109-113.
[6] T. Ibehej, R. Hrach, 11th International symposium on Reactive Sputter Deposition, , Ghent, Belgium, 13-14 December 2012, abstract.

Development of CXRS diagnostic for the COMPASS tokamak

D. Naydenkova

Selection of a suitable experimental set-up for controlling of neutral beam parameters for CXRS diagnostic on COMPASS was the first task of this project which was successfully done, as it was planned, in year 2012.

The neutral beam, which will be used for CXRS diagnostics on COMPASS, contains three fractions with different energies: E, E/2 and E/3, as well as a fraction of impurity atoms. Knowledge of the percentage of these fractions in the total neutral beam intensity is essential for correct interpretation of the CXRS diagnostics. The energy spectrum of the beam can be derived from the Doppler shift of the Ha line.

As a first step, the optical system for measurements of visible radiation in the spectral range of 629-681 nm with the resolution 0.04 nm (Fig. 1) was designed and developed. It consists from fiber optics and high-resolution spectrometer, which allow measurement of spectral line intensities. Absolute calibration of the system together with measurements of temporal evolution of selected spectral lines will give information about impurities content in a beam.

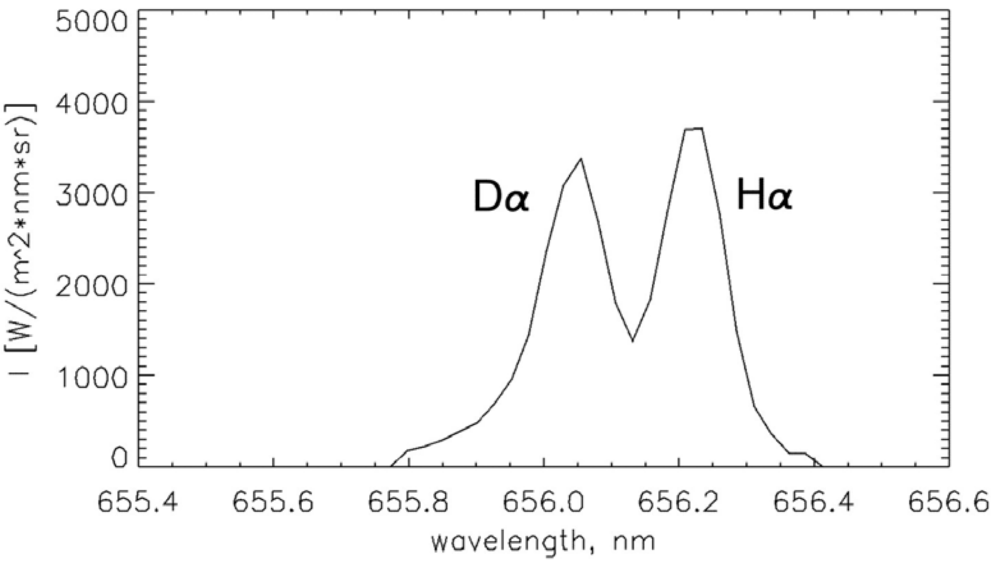

Fig. 1 Hydrogen and deuterium spectral lines at the beginning of discharge #3961, distance between lines in only ~0.17 nm.

The developed system was successfully tested by observations of COMPASS plasma. Typical spectrum, recorded in a COMPASS plasma discharge is shown in figure 2.

The designed system is now routinely used on COMPASS for measurements of selected spectral lines in the range of interest with temporal resolution ~10 ms. It will be moved in near future to another position to observe the neutral beam.

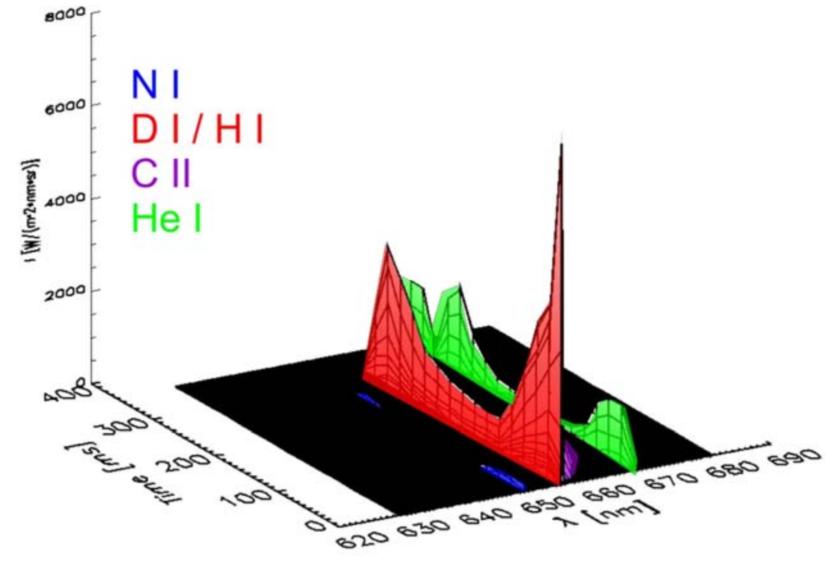

Fig. 2 Temporal evolution of plasma spectrum measured by the system during plasma discharge #3961 at COMPASS tokamak.

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

4. Emerging Technologies

Development of tungsten-based functional gradient materials

J. Matějíček, M. Vilémová, B. Nevrlá, V. Brožek, Z. Pala

In collaboration with:
P. Sachr, Czech Technical University in Prague (ČVUT), Prague, Czech Republic
K. Iždinský, Slovak Academy of Sciences, Bratislava, Slovakia

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.

Three alternative processing techniques were pursued: plasma spraying, hot pressing and spark plasma sintering.
In plasma spraying, previous experiments with the hybrid argon-water torch, aimed at process optimization [1,2], suppression of oxidation by inert gas shrouding [3], and fabrication of tungsten-steel composites and FGMs were evaluated (Fig. 1). The latter were characterized for their structure, composition, thermal and mechanical properties [4]. In interesting finding, already observed in plasma sprayed W+Cu composites, was the highest thermal conductivity in the middle of the composition range, suggesting a better bonding of dissimilar, rather than similar splats. As part of the processing study, detailed analysis of the in-flight evaporation and oxidation phenomena with respect to process conditions, was conducted [2]. Hot isostatic pressing was tested as a means to improve the W+Fe composite coatings' thermal conductivity by reducing the porosity and eliminating some of the poorly bonded interfaces. The samples are awaiting characterization.

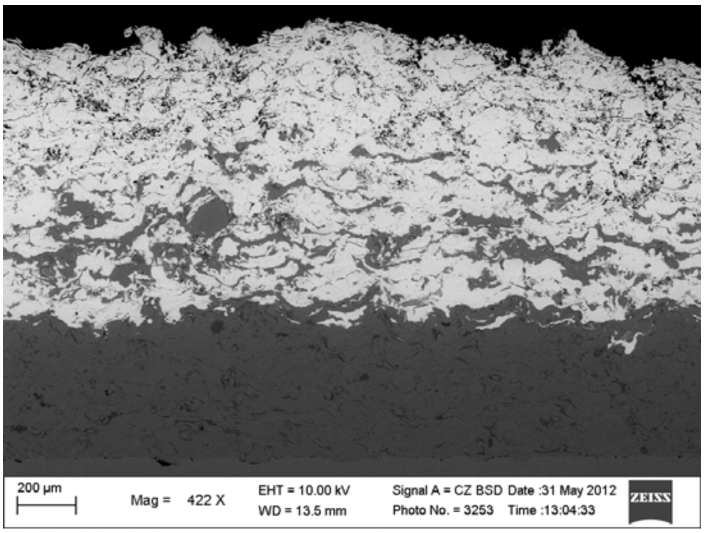

Fig. 1. Overview of a W+Fe FGM produced by plasma spraying with the hybrid torch (dark phase – steel, light phase – tungsten).

Previous results on hot pressed composites from tungsten and steel powders indicated that dense and conductive layers were formed, however, a brittle intermetallic phase Fe7W6 was formed at the interface [5,6]. To avoid its formation, a WC powder interlayer was introduced and five-layer FGMs (consisting of steel, steel+WC, WC, WC+W and W layers) were produced. While the tungsten and steel were effectively isolated from each other, cracking in the WC layer was observed, and moreover, thin Fe3W3C layer was formed at the steel/WC interfaces (Fig. 2).

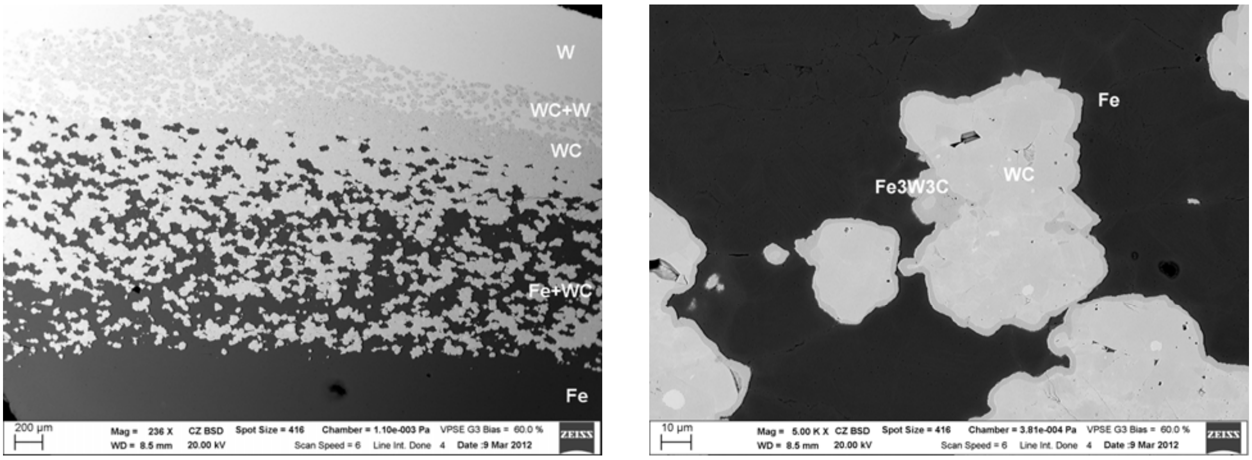

Fig. 2.a) overview of a hot-pressed W+WC+Fe FGM, b) detail of the Fe+WC region.

To explore the formation of dense composites at lower temperatures (with the perspective of suppressing the intermetallic phase formation), spark plasma sintering was introduced. In this technique, the sintering process is enhanced by a pulsed current passing through the powder sample, with local ohmic heating at the contact points. This allows to achieve similar results at generally lower temperatures and pressures. Using this technique, pure W and steel powders were sintered at a variety of temperatures. Their porosity was measured and based on this, optimal conditions for composite and FGM formation were chosen. Several composites of uniform composition were produced.

An agreement was made with Research Center Rez to conduct thermal cycling tests of various FGMs and multilayers in 2013, to provide a quantitative comparison of their performance.

References:

[1] T. Kavka et al., *J. Thermal Spray Technol.* 21 (2012) 695
[2] J. Matějíček et al., *J. Thermal Spray Technol.* 22 (2013) in press
[3] K. Neufuss et al., *CZ patent 303411* (2012)
[4] M. Vilémová et al., *11th Conf. on Coatings and Layers* (2012) 135
[5] J. Matějíček et al., *21st Intl. Conf. on Metallurgy and Materials* (2012) 177
[6] M. Rieth et al., *J. Nucl. Mat.* 432 (2013) 482

5. Training and career development

Collaboration with French engineering school ENSAM

R. Dejarnac, D. Sestak

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

We welcomed this year 2 students from the French engineering school Ecole Nationale Superieure des Arts et Metiers (ENSAM) who arrived on the 25th of June 2012 for a 6 month internship at TOKamak Department in the frame of a bilateral ERASMUS agreement with Charles University in Prague. They were well integrated in our team and for the first time they worked on dedicated PCs connected to our network with new CATIA licences and not on their personal laptops like the previous students during previous years.

They worked on several topics as the design of COMPASS tokamak in 3D (which is a traditional, on-going task), the design of a system with a double-valve + a manipulator to implement samples in the tokamak divertor without breaking the vacuum, the design of 2 tunnel probe heads for the 2 reciprocating manipulators of COMPASS and the design of embedded ball-pen probes in the COMPASS divertor and Langmuir probes on the central column protective tiles (see Fig. 1).

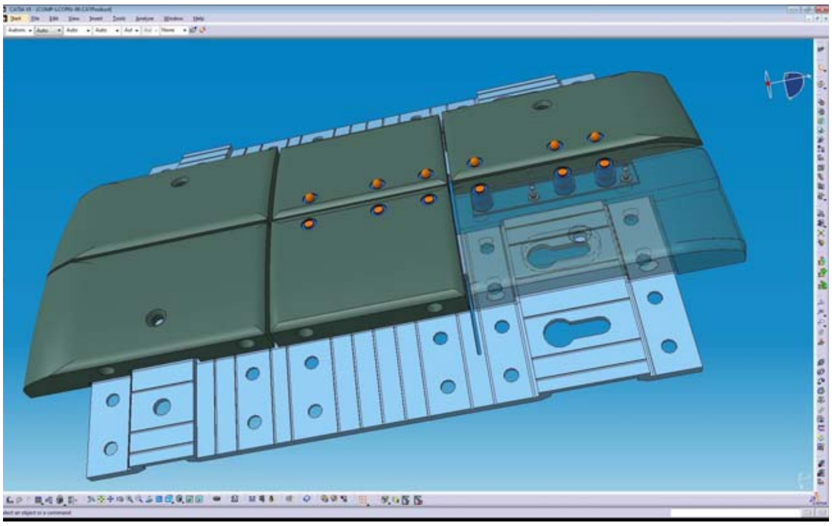

Fig.1: *CATIA(c) drawing of the Langmuir probe design embedded in the protective tiles of the COMPASS central column*

Both designs of the double-valve + manipulator, the tunnel (see Fig. 2) and ball-pen probes have been finished. The double-valve + manipulator (see Fig. 3) are under construction. The ball-pen probes are already implemented in the divertor tiles of COMPASS and ready for measurements. The students were happy with their stays and learned a lot at the contact of our engineers.

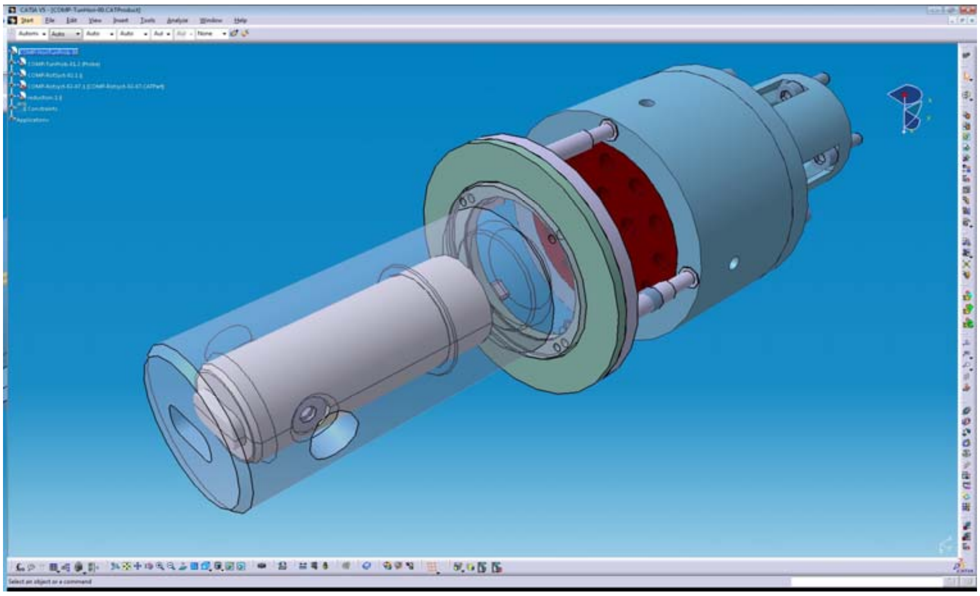

Fig.2: *CATIA(c) drawing of the tunnel probe design for COMPASS reciprocating manipulators*

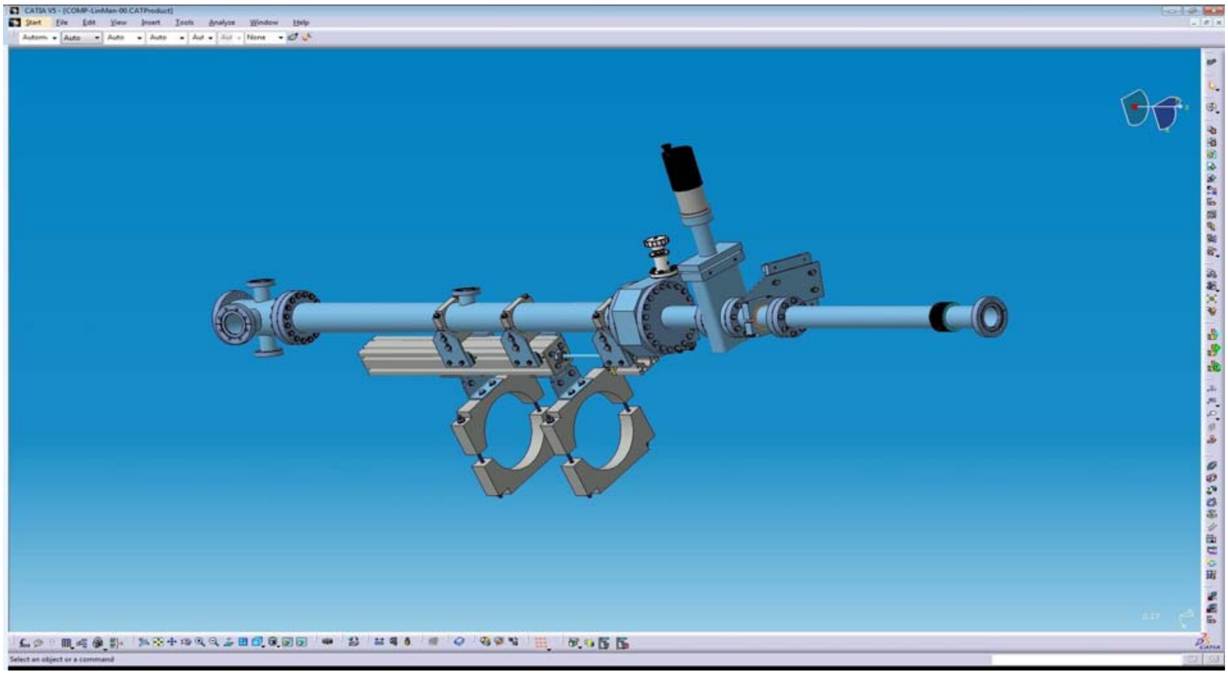

Fig.3: *CATIA(c) drawing of the double-valve+manipulator design for COMPASS. This system will allow insertion of objects like probes, samples, etc... in the COMPASS divertor without breaking the vacuum*

This task is completed and was successful this year again, what confirms that this collaboration with ENSAM is fruitful for both parties.

Tokamak GOLEM for fusion education and research

V. Svoboda, et al.
Faculty of Nuclear Sciences and Physical Engineering,
Czech Technical University in Prague

In 2012 the curricullum "Physics and Technology of Thermonuclear Fusion" (FTTF) at the Czech Technical University in Prague continued in education of bachelor and master students. In January 2012, the traditional winter seminar for all undergraduate students place in Marianska. Significant efforts were invested into publicity of the FTTF programme to increase number of students and in particular to eliminate the rumours that there are little job opportunities for the graduates in this programme. According to very recent enrollement of new students it seems the publicity campaign was successful. An important role in the publicity was played by the GOLEM tokamak.

Both the FTTF curriculum and the GOLEM tokamak worked in close cooperation with the FUSENET consortium, where we also manage the Work Package 9 (Multimedia). Important milestones were achieved in this work package - all the computer models were completed as well as their internal revision. A final report on this work package was edited and accepted by the FUSENET board.

Also the GOLEM tokamak was supported in the frame of a FUSENET grant, aiming to improve the DAS system, tokamak power circuits, vacuum operation, gas filling system, diagnostics enhancement and remote participation hardware.

In February 2012 the FUMTRAIC 2012 (French fusion masters training course) took place in collaboration of CEA Cadarache and the GOLEM tokamak. In June 2012, the science week 2012 was organized for high school students from Czech republic: 4 groups performed more than 70 discharges on GOLEM. Also in June 2012 the 5th International Workshop & Summer School on Plasma Physics in Kiten, Bulgaria included remote experimental session, where more than 80 discharges were performed by 21 students from 5 European countries. In August 2012, in the framework of SUMTRAIC 2012 Introductory session, more than 100 discharges were performed by 17 students from 7 European countries. The facility was also used for the University of third age, in the Practicum for seniors. The GOLEM tokamak also run the traditional open competition "Hot Shots" and more than 20 excursions from high schools.

However, the most significant event was the first run of the new GOMTRAIC school. GOMTRAIC stands for GOlem reMote TRAIning Course. GOMTRAIC aimed at Masters and PhD students with an interest in experimental tokamak physics. Within three months, they learned remotely (over the internet) how to conduct tokamak experiments and how to operate the diagnostic systems that measure the plasma. In this first year, almost fifty participants registered from all overthe world, altogether 17 countries from 3 continents.

In the same period, the GOLEM tokamak also pursued three reisearch topics: (i) High temperature superconductor magnets on tokamak [2,3] (ii) Low Cost Alternative of High Speed Visible Camera for Tokamak Experiments [1] (iii) Evaluation of applicability of 2D iron core model for two-limb configuration of GOLEM tokamak [4]. Tokamak GOLEM also participated in September 2012 IAEA Joint Experiment. Let us briefly review the main R&D results.

Evaluation of applicability of 2D iron core model for two-limb configuration of GOLEM tokamak [4]

This paper presents evaluation of applicability of 2D iron core model for highly non-axisymmetric two limb configuration of GOLEM tokamak (former CASTOR). Presented results explain the long-term discrepancy between measured magnitudes of external poloidal field and those calculated by air-core approach on this tokamak. The model has been applied to two poloidal planes at different toroidal angles in the vacuum vessel region and has shown that close to central column of the transformer, it is possible to correct for 3D effects by variation of chosen dimensions of axisymmetric iron core model. Satisfactory agreement of the 2D model results with the measured distribution of BR field component was achieved.

Progress in application of high temperature superconductor in tokamak magnets [2,3]

It has long been known that high temperature superconductors (HTS) could have an important role to play in the future of tokamak fusion research. Here we report on first results of the use of HTS in a tokamak magnet and on the progress in design and construction of the first fully-HTS tokamak. It has been shown that superconductivity has been achieved at 91 K with liquid Nitrogen cooling, current in 12 mm SuperPower YBCO tape used can exceed 1 kA in pulses and current ramp speed can exceed 100 kA/s and quenches do not cause degradation in the coil performance if controlled

Low cost alternative of high speed visible light camera for tokamak experiments [1]

We present design, analysis, and performance evaluation of a new, low cost and high speed visible-light camera diagnostic system for tokamak experiments. The system is based on the camera Casio EX-F1, with the overall price of approximately a thousand USD. The achieved temporal resolution is up to 40 kHz. This new diagnostic was successfully implemented and tested at the university tokamak GOLEM (R = 0.4 m, a = 0.085 m, BT < 0.5 T, Ip < 4 kA). One possible application of this new diagnostic at GOLEM is discussed in detail. This application is tomographic reconstruction for estimation of plasma position and emissivity.

References:

[1] T. Odstrcil, M. Odstrcil, at al. Low Cost Alternative of High Speed Visible Camera for Tokamak Experiments. Rev. Sci. Instrum. 83, 10E505 (2012)

[2] M. Gryaznevich et.al . First Results from Tests of High Temperature Superconductor Magnets on Tokamak. Contribution to the 24th IAEA Fusion Energy Conference San Diego, USA.

[3] M. Gryaznevich et.al. Progress in application of high temperature superconductor in tokamak magnets. Contribution to the 27th Symposium on Fusion Technology (SOFT) Liege, Belgium.

[4] T. Markovič, M. Gryaznevich, I. Ďuran et.al. Evaluation of applicability of 2D iron core model for two-limb configuration of Golem tokamak. Contribution to the 27th Symposium on Fusion Technology (SOFT) Liege, Belgium.

Role of IPP in fusion education

J. Mlynar, F. Zacek, J. Stöckel, R. Panek and I. Duran

In collaboration with FUSENET, FUSION-EP and FUSION-DC

In 2012, 14 pre-graduate and 17 post-graduate students worked on their fusion oriented theses in the Institute of Plasma Physics. Compared to previous years with rather technical tasks, doctoral, master level and bachelor students at COMPASS got more involved in the physics research exploitation. Their training included diagnostics maintenance, tokamak operation, CODAC development and data analyses. Some students also participated in fusion research in collaboration with foreign laboratories, including in particular JET. Besides, five members of our staff contributed to teaching at all levels of University education.

New and updated subjects for thesis were proposed, e.g. 6 new bachelor thesis were proposed at COMPASS, and two of them found interested students. More importantly, six new doctoral students from three different Faculties were accepted for full training at COMPASS. In this respect, it has been very encouraging that the COMPASS tokamak has received funding for increased amount of students in the framework of the support for large infrastructures by Czech Ministry of Education.

Similarly to the previous years, the IPP staff were involved in teaching activities, in particular in the courses of the Master's level curriculum “Physics and technology of thermonuclear fusion” that is accredited at the Faculty of Nuclear Sciences and Physical Engineering of the Czech Technical University Prague. Besides, IPP also participates in teaching the plasma physics at Charles University and several IPP experts serve as permanent members of thesis juries at several universities. IPP also organised seminars for university students: prof. P. Kulhanek on cosmic plasma, Dr. M. Svanda on helioseismology, and two former students of the fusion curricullum, O. Kudlacek and M. Kazda, on their current projects. In 2012 we also succeeded in invitation of Pavel Holik, the Czech speaking electrical engineer employed by the ITER Organization, to colloquia of the Czech Technical University on 2nd May, and of Prof. Gerard Bonhomme from University of Lorraine, France to the same colloquia on 12th December.

As another tradition, IPP organised a joint winter seminar for IPP University teachers and students of the MSc fusion curriculum in its training centre in the Ore Mountains. This year this joint seminar took place from 16th January.

IPP staff were also in close contact with FUSION-EP and FUSION-DC programmes and proposed collaborative tasks for their students. Several foreign students visited COMPASS in 2012 both for working experience and for the SUMTRAIC summer training school. In December 2012, for the first time the winter training school EMTRAIC for the Erasmus Mundus MSc course was organised on COMPASS.

The education and training tasks have been coordinated via participation of IPP in the FUSENET consortium, where J Mlynar (member of the Fusenet Board) successfully proposed Prof. Milan Tichy from Charles University to the new FUSENET Academic Board.

6. Other activities contributing to the EURATOM fusion programme

Boosting Public awareness of fusion

M. Řípa, J. Mlynář, V. Svoboda

In collaboration with EFDA Public Information Network

As the main highlight of 2012 Public Information work in IPP.CR the startup of the project Materials for the new millennium (MAT21) can be singled out. The project, supported by EU, aims at improving physical education and science understanding, and the Institute of plasma physics AS CR is a partner to the project, which is managed by industrial research company Vitkovice s.r.o. Since the project has been launched in 2012, the number of visitors on COMPASS site as well as the range of other "routine" Public Information works (publications, lectures, media contacts etc.) considerably increased.

At the beginning of 2012 the ceremony of launching the third edition of the book „The control thermonuclear fusion for everybody", published at the end of 2011, took place in the headquarters of Academy of Sciences of the Czech Republic. A successful press conference was attended by both the former and the current president of the Academy of Sciences prof.Václav Pačes and prof. JiříDrahoš, respectively. In the role of the book's godmother, the Vice-Chairperson of the Senate of Czech Republic Mrs AlenaGajdůšková spoke. The book attracted attention of the ITER newsline and the Alpha Galileo Foundation.

As planned, the book "Nuclear Energy" (in Czech) was issued in spring 2012 in collaboration with the Czech University of Life Sciences. The book features several chapters on fusion basics, fusion history and current projects written by J. Mlynar.

On May 14th, Jan Mlynar gave an invited talk on fusion „Energy production after 2050: cautious optimism" to the meeting of the Czech learned society dedicated to the UN year of Sustainable energy for all. Milan Ripa took part in the Public Information Network (PIN) Meeting in Culham on June 2012. Public talks were given in the framework of workshop The Nuclear Energy and the Universe in Brno as well as in the international conference The Renewable Sources of the Energy in KoutynadDesnou, Czech Republic. We have continued publication of papers in magazines and newspapers, one radio interview was broadcast. On8thSeptember 2012, the Czech public TV broadcast an influetial spot on the COMPASS tokamak including an interview with the COMPASS Head dr. Radomir Panek.

The EU Education for competitivenes operational programme accepted the project „Materials for the New Millennium (MAT 21)" for financial support. The coordinator of the project „Vítkovice – výzkum a vývoj – technickéaplikace, a.s." invited the Institute of Plasma Physics ASCR to participate. This gave us a new platform for fusion education at high schools, for organising visits, excursions, public lectures etc.. In this framework, we have been also working on updating the successful book „Controlled thermonuclear fusion for everybody". We have also started a project on a simple construction set of a tokamak for pupils and students.

Institute of Plasma Physics AS CR purchased an ITER model produced byHabich& Martin GmbH. In short time, the model became popular with visitors and media. The model is exhibited in the entrance hall tokamak COMPASS building.

350 high school students from twelve schools visited the COMPASS tokamak during November Open Days, wher, among others, the new ITER leaflet (Czech version) was distributed. Open Days are a traditional part of national Science and Technology Week (STW). In the week, IPP also organised the Energy Future round tablein collaboration with Czech physical society. In the frame of MAT21 project we have also started publishing articles in a new, dedicated MAT21 magazine.

Public information papers:

Milan Řípa: Theguardsof ITER plasma vertical stability, Technický týdeník, 60(2012), No 5, p.16
Milan Řípa: NuclearEnergy and Universe , Akademický bulletin, No 4, 2012, p.25
Milan Řípa: Do FusionReactorsreplacetodayPowerPlants?, ; Alternativní energie, No.3 (2102), pp. 28 – 30
Milan Řípa:TheFriendship and ReciprocalFavorableCollaborationTreatybetweenUniverse and Tokamak Plasma., Třetí pól, ČEZ, září 2012
Milan Řípa: On theRoad to ThermonuclearFusion, Alternativní energie, No 6, 2012, pp. 18 až 19
Milan Řípa: ThePhysicstLavrentev Story – the Man, whoStayed his Idea Loyal,Alternativní energie, No 6, 2012, pp. 22 až 25
Jan Mlynář: Interview forthe Atom Info 2012, http://atominfo.cz/2012/10/jan-mlynar-z-ustavu-fyziky-plazmatu-kdyby-o-fuzi-mela-zajem-armada-uz-bychom-ji-asi-meli-ale-nebyla-by-spolehliva/
Milan Řípa: Institute ofPlasmaPhysics AS CR, V.v.i., MAT21, No 1, 2012, p. 7
Milan Řípa: FlyingthroughFusionWorld, part I, MAT21, No 1, 2012, pp. 8 až 9

Public Lectures (MAT 21 = Materialsfor New Millenium)

Milan Řípa: From Sun to Tokamak, worshopNuclearEnergy and, Hvězdárna a planetárium Brno, February 23rd, 2012, Brno: http://www.youtube.com/watch?v=AliAqZRjHfs
Milan Řípa: BetweenTokamaks, International ConferenceofRenewableEnergyRecources OZE 2012, Kouty nad Desnou,April25th to 27th, 2012
Milan Řípa: ITER Yesterday and Today, seminary IPS, Mariánská nad Jáchymovem, September6th, 2012
Milan Řípa: ThermonuclearFusionforEverybody, MAT21, seminaryfortheachers Pardubice,October5th, 2012
Milan Řípa: FusionStories, MAT21, seminaryfortheachers Pardubice, October 5th, 2012
Milan Řípa: Fusion – theEnergyfortheFuture, MAT21, vocationalschool Škoda Auto, Mladá Boleslav, October12th, 2012
Milan Řípa: HighSchool Student firestheControlledThermonuclearFusionResearch, MAT21, November8th, 2012, AS CR Building, Prague, Národní 3,

Milan Řípa: HighSchool Student firestheControlledThermonuclearFusionResearch, MAT21, November9th, 2012, South Czech Museum, Pardubice
Milan Řípa: HighSchool Student firestheControlledThermonuclearFusionResearch, MAT21, November 16th, 2012, SOU Kutná Hora, 9:00 hours
Milan Řípa: HighSchool Student firestheControlledThermonuclearFusionResearch, MAT21, November 16th, 2012, Jiřího Orten Gymnasium, Kutná Hora, 11:00 hours

RadioBroadcast:
Milan Řípa, Jan Mlynář: TheEnergywiththeFuture – Třetí dimenze, Czech Radio Leonardo, March16th, 2012, 14:00hours

Rollup:
ITER – nearer to Sun, MAT21

Leaflet:
ITER – translationof ITER organization

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

Ablation and acceleration processes in the plasma produced by a pulsed high-power laser

J. Ullschmied, K. Boháček, D. Klír, E. Krouský, M. Pfeifer,K. Řezáč, J. Skála, R. Dudžák,

In collaboration with:
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The inertial fusion-relevant experimental studies of ablation and acceleration processes in laser–produced plasmas conducted at the PALS Research Infrastructure are aimed at finding optimum conditions for energy transfer into the laser-produced plasma and at achieving maximum yield of the accelerated charged particles. Our experiments proved the possibility to compress and accelerate efficiently the expanding laser plasma generated on targets of special geometry and composition and brought record energies of accelerated protons, deuterons and carbon ions, exceeding 4 MeV per electric charge unit.

The investigated plasmas were created by means of the kJ-class iodine terawatt sub-nanosecond laser PALS at the mean target irradiation intensities of up to 10^{16} W/cm^2. The laser beam was focused on massive or foil targets made of various materials. Many unique diagnostic tools developed at PALS and at its partner laboratories were used to diagnose the laser-produced plasma, such as a three-frame laser interferometer/polarimeter, gated 4-frame pinhole x-ray camera, XUV spectrometers, Thomson and electrostatic time-of-flight ion analysers, and fast radiation, charged particle and neutron detectors. The efficiency of laser energy transfer into plasma was studied in dependence on the target material and structure, the target irradiation geometry, laser energy and wavelength. Comparative experiments were conducted also by using the auxiliary high-repetition rate Ti:Sapphire femtosecond in-house laser PILS of a pulsed power of up to 20 TW, launched at the PALS Research Infrastructutre last year.

Our extensive experiments on laser ablation proved the possibility to compress and accelerate efficiently the expanding laser plasma generated on targets of various geometry and composition [1-5]. The experiments on ion acceleration by using the PALS iodine laser and both massive and foil targets brought record energies of accelerated protons, deuterons and carbon ions exceeding 4 MeV per electric charge unit [6-9] - see Fig.1. Theoretically, such a strong ion acceleration should be expected only at the laser energy densities by at least 2 orders of magnitude higher than the mean intensity of the focused PALS laser beam on the target. The ion energies achieved at PALS are comparable with those reported at PW-class fs lasers, as during the interaction of a „long“ (sub-nanosecond!) laser pulse with plasma the radiation intensity increases periodically and locally due to non-linear processes, such as laser beam self-focusation and filamentation.

A new class of IFE-relevant experiments aimed at validation of a new version of the Shell Impact concept started at PALS at the end of 2011 [10,11]. Systematic studies of the effect of large scale preformed plasma on parameters of the laser-driven shock wave produced in a planar target at the physical conditions relevant to Shock Ignition continued at PALS in autumn 2012 in the frame of LASERLAB-EUROPE III project. Two delayed high-power laser pulses were used, the first one producing the pre-plasma and the second initiating the shock. The diagnostics used permitted to evaluate the shock breakout time, the quantity of fast electrons, the thickness and the temperature of the pre-plasma and the emissions (at 3/2 ω, ω and ω/2) of the backscattered energy. Preliminary analysis indicates that the maximum shock pressure achieved in these experiments was as high as 140 Mbar, the conversion efficiency into hot electrons with an average energy of 50 keV having been estimated to 0.1%. Final results are being prepared for presentations at the IFSA 2013, PLASMA 2013 and EPS 2013 conferences.

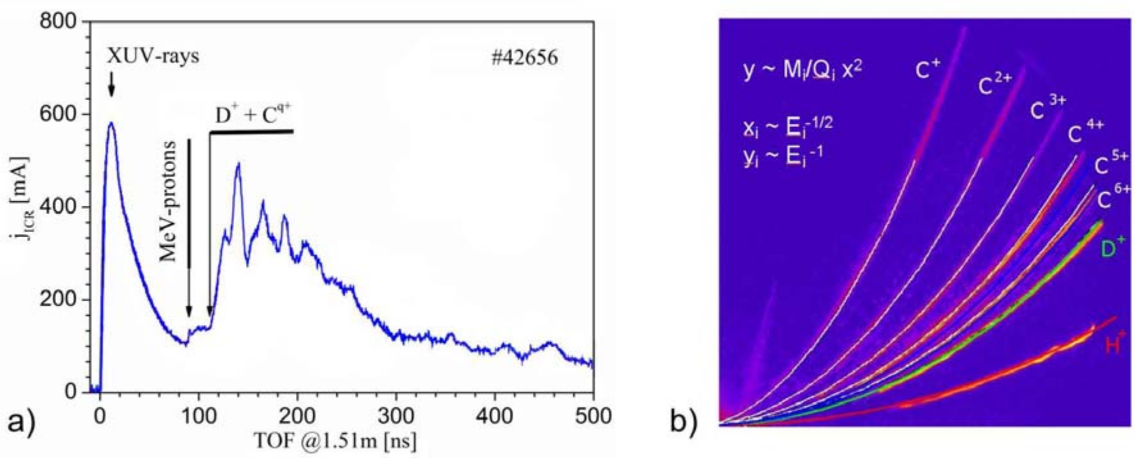

Fig. 1 *Analysis of the ions accelerated in the plasma produced by PALS laser on a deuterized polyethylene target.* ***a)*** *Total ion current measured by a distant ion collector. Well-marked maximums correspond to ions with different energies.* ***b)*** *Ion charge spectrum obtained by using Thomson parabola spectrometer.*

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V ADDITIONAL INFORMATION

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

Annual report on activities for EFDA in Centrum výzkumu Řež s.r.o.

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Introduction: During the year 2012 the experimental work and review activities of Centrum výzkumu Řež s.r.o. (CVR) were performed. The review work consists of three topics: Oxide Dispersion Strengthened Steels for Fusion Reactors Application (Annex 1, contribution to the task PPPT-WP12-MAT-01_ODSFS), Application of Tungsten and its Alloys in Fusion Reactors (Annex 2, contribution to the task WP12-MAT-01-HHFM-03-01 Long-term Structural Materials), Report on EUROFER investigation in ÚJV/CVŘ and Report on Be-CuCrZr joint's performance (Annex 3 and Annex 4, both contribution to the task WP12-MAT-02-M03-01 Review R&D on materials). The review work is not further reported, the documents are attached as annexes.

The experimental work is for year 2012 divided in two topics: In-pile Thermal Fatigue Test of Be Coated Primary First Wall Mock-ups .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 CVR, UJV subsidiary, 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.
Second experimental activity is Degradation Properties Assessment of Steels P91 and 316 SS after Exposure in Helium Atmosphere. The work summarizes experimental work done in 2012 on the above mentioned steels in experimental facilities in CVR.

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

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 Fig. 1.

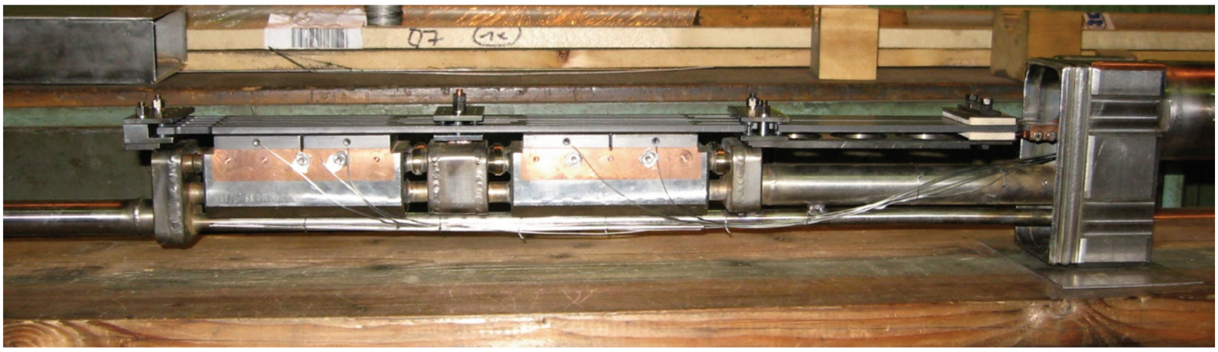


Figure 1: Rig final assembling before inserting in LVR-15 core (side-view without metal sheath)

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 Fig. 1: the mock-ups are connected by middle mixing block; the cooling water enters the upper mock-up first (shown on right on Fig.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 on Fig. 3.

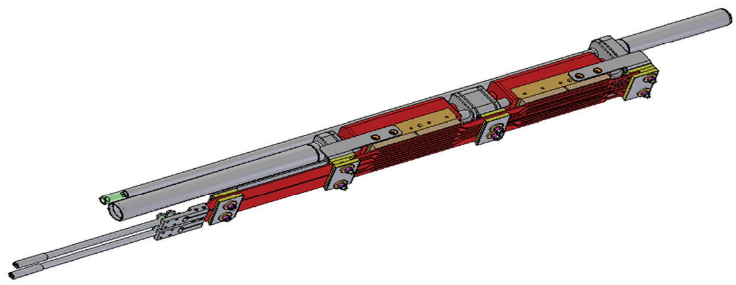


Figure 2: 3D model of TW3 rig without metal sheath

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 Fig. 1 and Fig. 2. As indicated on Fig. 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 Fig. 3, see [3].

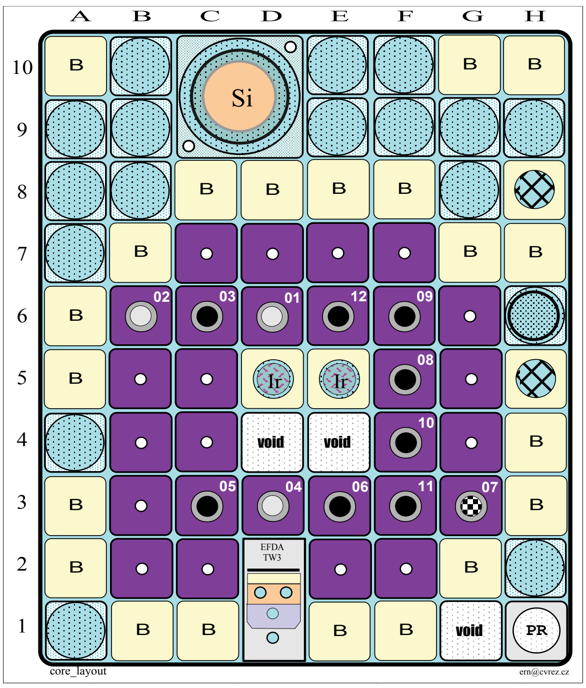


Figure 3: K136 core with TW3 on position D1/D2.

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 Fig. 4, 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 Fig. 4.

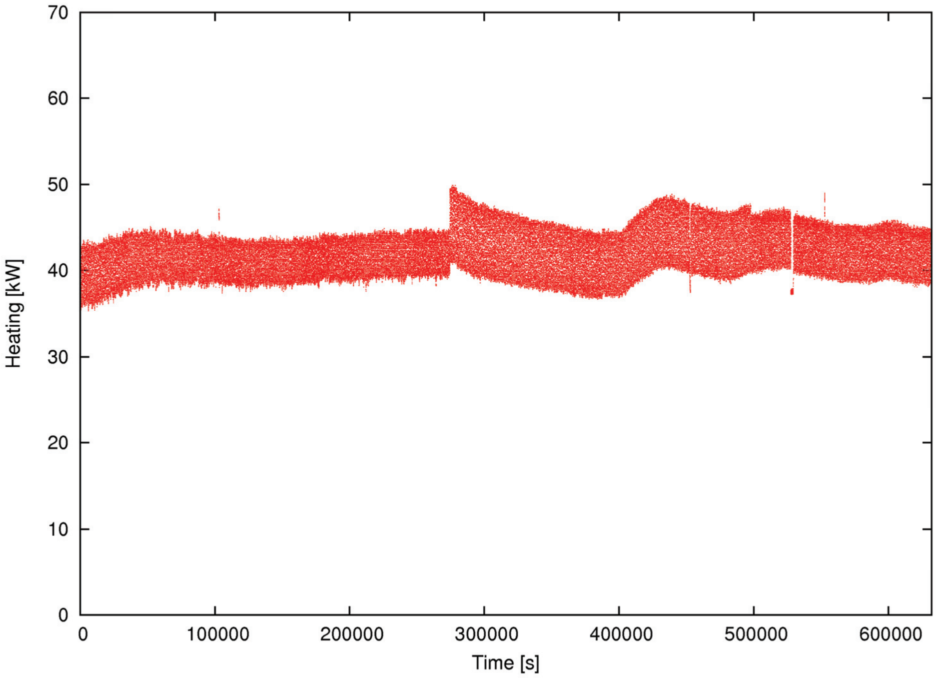


Figure 4: Record of cyclic heating from TW3 rig (including nuclear heating)

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 Fig. 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.

Degradation Properties Assessment of Steels P91 and 316 SS in very high temperature helium environment

1 Experimental

The experimental testing was carried out on samples of steels P91 a 316 SS. The chemical composition of tested steels is shown in table 1 and 2.

Table 1: Chemical composition of steel 316 SS (wt. %)

	C	Si	Mn	P	S	Cr	Mo	Ni	Co	N	Fe
Min						16.50	2.00	10.00			Bal.
Max.	0.021	0.34	1.73	0.027	0.025	16.50	2.03	10.03	0.120	0.0320	Bal.

Table 2: Chemical composition of steel P91 (wt. %)

C	S	Mn	Si	P	Cu	Ni	Cr	Mo	V
0.12	0.002	0.36	0.39	0.011	0.041	0.034	10.06	0.88	0.22
Ti	W	Co	Nb	As	Sb	Sn	Al_{celk}	N	Fe
0.007	<0.005	<0.003	0.052	0.003	0.001	0.002	0.005	0.065	Bal.

Tested specimens were manufactured from the rod with a diameter of 91 mm, in case of P91 steel and with a diameter of 30 mm in case of 316 steel, respectively. The notched specimens type sub-size 3PB SEN with dimensions of 5 x 2 x 40 mm and 4 x 3 x 27 mm were carried out according to pre-cutting plan parallel to the axis of the rod (most components are also produced by machining rods parallel to the axis). Specimens with dimensions 5 x 2 x 40 mm were manufactured with two types of surfaces: milled (coarse) and ground (finer).

For metallographical analysis and evaluation of corrosion attack, coupons (tapes) with dimensions 5 x 40 x 2 mm were used. For the fracture toughness tests, the specimens with dimensions 4 x 3 x 27 mm (size of the sub-3PB SEN) with notch, pre-cracked and lateral notches were used. In some cases, the specimens with dimensions of 15 x 40 x 2 mm and 28 x 49 x 2 mm were tested for the evaluation of corrosion attack of metal surfaces by means of GD-OES techniques, because the application of this method on specimens with dimensions 5 x 40 x 2 mm is not possible on some devices. For the hardness test, specimens with dimensions 11 x 11 x 5 mm were used.

Then the specimens were exposed at 750°C for 1,000 hours in the gaseous atmosphere. The retort gas flow was about 0.1 l/min or lower. The following chemical composition of gaseous atmosphere listed in the table below (see table 3) was chosen for the mentioned experiments. The gaseous mixture was prepared by Linde gas Inc. The moisture was dosed into the gas in most cases. For comparison, the exposure of some types of specimens was performed also in the air (with relative humidity: 50-90%).

After the exposure, testing of mechanical properties was carried out. The fracture toughness at 25 °C, the hardness and microhardness was measured. The obtained values were compared with the values of specimens in as-received state (i.e., the specimens without exposure).

The evaluation of corrosion attack of tested specimens followed. For this purpose, optical and electron microscopy, X-ray photoelectron microscopy (XPS) and GD-OES (Glow Discharge Optical Emission Spectroscopy) were used. The metallographic analysis and evaluation of changes in the microstructure of both steels after exposure were performed. Then weight changes of specimens after exposure were observed.

Table 3: Chemical composition of gaseous atmosphere during the testing of steels

Chemical composition	Concentration [ppm_v]
CO_2	1
O_2	2
CH_4	35
CO	250
H_2	400
Helium	Bal.

The summary of all tested specimens from both mentioned steels and testing conditions is shown in table 4.

Table 4: The outline of all tested specimens from the steels P91 and 316 and testing conditions

Exposure time	Medium	Tempe-rature	Specimens (quantity)	Tests carried out after exposure
As-received state (without exposition)			3PB SEN (2 x 8), Spec. for tensile tests (2 x 2 +2), 5 x 2 x 40 mm, 15 x 2 x 40 mm, 28 x 49 x 2 mm, 11 x 11 x 5 mm	Fracture toughness, metallographic analysis, hardness and microhardness, GD-OES,
0,53 hr	air	750°C	11 x 11 x 5 mm (2 x 1)	Hardness and microhardness
1 hr	air	750°C	11 x 11 x 5 mm (2 x 1)	Hardness and microhardness
2,02 hrs	air	750°C	11 x 11 x 5 mm (2 x 1)	Hardness and microhardness
2,2 hrs	air	750°C	11 x 11 x 5 mm (2 x 2)	Hardness and microhardness
23,65 hrs	air	750°C	11 x 11 x 5 mm (2 x 1)	Hardness and microhardness
24 hrs	He + impurities	750°C	5 x 2 x 40 mm (2 x 1) grinding surface, 15 x 2 x 40 mm (2 x 1), 28 x 49 x 2 mm (2 x 1),	GD-OES, metallographic analysis
24 hrs	air	750°C	5 x 2 x 40 mm (2 x 1) grinding surface, 15 x 2 x 40 mm (2 x 1), 28 x 49 x 2 mm (2 x 1),	GD-OES, metallographic analysis
48,4 hrs	air	750°C	11 x 11 x 5 mm (2 x 1)	Hardness and microhardness
74 hrs	air	750°C	11 x 11 x 5 mm (2 x 1)	Hardness and microhardness
75,33 hrs	air	750°C	11 x 11 x 5 mm (2 x 1)	Hardness and microhardness
75,4 hrs	air	750°C	11 x 11 x 5 mm (2 x 1)	Hardness and microhardness
77 hrs	air	750°C	11 x 11 x 5 mm (2 x 1)	Hardness and microhardness
120 hrs	He + impurities	750°C	5 x 2 x 40 mm (2 x 1) grinding surface, 15 x 2 x 40 mm (2 x 1), 28 x 49 x 2 mm (2 x 1),	GD-OES, metallographic analysis
120 hrs	air	750°C	5 x 2 x 40 mm (2 x 1) grinding surface, 15 x 2 x 40 mm (2 x 1), 28 x 49 x 2 mm (2 x 1),	GD-OES, metallographic analysis
151,6 hrs	air	750°C	11 x 11 x 5 mm (2 x 1)	Hardness and microhardness
312 hrs	air	750°C	11 x 11 x 5 mm (2 x 1)	Hardness and microhardness
500 hrs	He + impurities	750°C	5 x 2 x 40 mm (2 x 1) grinding surface,	Metallographic analysis, XPS SEM/EDX
1000 hrs	He + impurities	750°C	5 x 2 x 40 mm (2 x 1) grinding surface, 5 x 2 x 40 mm (2 x 1) milled surface, 3PB SEN (2 x 9), spec. for tensile tests (2 x 2 + 2)	Metallographic analysis, fracture toughness, XPS SEM/EDX
1000 hrs	air	750°C	Spec. for tensile tests (2 x 2 + 2), 5 x 2 x 40 mm (2 x 1) grinding surface	Tensile tests, GD-OES, microhardness

2 Summary and results

2.1 Mechanical properties of steels 316 and P91

The fractographic analysis of failed test specimens of **316 steel** clearly showed that the crack propagated during the fracture toughness test by transgranular mechanism. In case of specimens of 316 steel after exposure, fractographic analysis proved that the crack propagated also by transgranular micromechanism with typical ductile dimples even after exposure 1,000 hrs./750 °C in a gas mixture of helium and impurities during the fracture toughness test. The results of the specimens of steel 316 without exposure also showed significantly higher resistance against crack propagation, i.e. values of fracture toughness $J_{0,2}$ ($KJ_{0,2}$, respectively) were higher than those measured on specimens exposed at 1,000 hrs./750 °C in helium with impurities.

By the specimens of P91 steel, the exposure 1,000 hrs./750 °C in helium with impurities did not lead to a significant change in the values of fracture toughness $J_{0,2}$ ($KJ_{0,2}$, respectively). By fractographic analysis, it was found out that cracks propagated by the transgranular mechanisms in failed test bodies of steel P91 in as-received state. A different situation was observed by the test specimens after exposure 1,000 hrs./750 °C in helium with impurities. In some cases, the crack jumped (so-called pop-in) during the testing of exposed specimens, which lead to a sharp decrease in force on the force-displacement curve. On the fracture surface, the area failed by transcrystalline cleavage were visible that corresponded with the crack jumps. It can be assumed that a change in micromechanisms of failure of P91 steel was due to an increase in the transition temperature between brittle and ductile fracture.

The results from fracture toughness test at 25 °C for the steel 316 and P91 is possible to see in table 5 and 6.

Table 5: The results of fracture toughness test

Number of tested specimens	8 (As-received state)		9 (After exposure, 750 °C, 1,000 hrs.)		
	$J_{0.2}$ [J.cm^{-2}]	$K_{J0.2}$ [MPa.m$^{1/2}$]	$J_{0.2}$ [J.cm^{-2}]	$K_{J0.2}$ [MPa.m$^{1/2}$]	Variance $J_{0.2}$ [%]
Mean	62	320	20,6	212,7	67
Scatter	10,9	32,2	1,8	9	-

Table 6: The results of fracture toughness test at 25 °C for the steel P91

Number of tested specimens	8 (as-received state)		9 (After exposure, 750 °C, 1,000 hrs.)		
	$J_{0.2}$ [J.cm^{-2}]	$K_{J0.2}$ [MPa.m$^{1/2}$]	$J_{0.2}$ [J.cm^{-2}]	$K_{J0.2}$ [MPa.m$^{1/2}$]	Variance $J_{0.2}$ [%]
Mean	27,3	247,6	27,3	244,9	0
Scatter	3,5	16,5	3,2	14	-

The exposure of specimens from both steels for the determination of micro- and macro- hardness was carried out at 750 ° C in air. The dependencies of micro- and macro- hardness on exposure time are shown in the graphs below (figs. 1 and 2). It is clear that in the case of P91 steel, hardness values with exposure time at 750 ° C decreases, the first significant decline caused after about 132 and 1400 minutes. For steel 316L, the measured hardness values did not show any significant trend depending on the time of exposure at 750 ° C. Fluctuations in the measured hardness values were comparable to the scattering of measurements. For a clear explanation of the variation in hardness values, it would need to carry out extensive experiments.

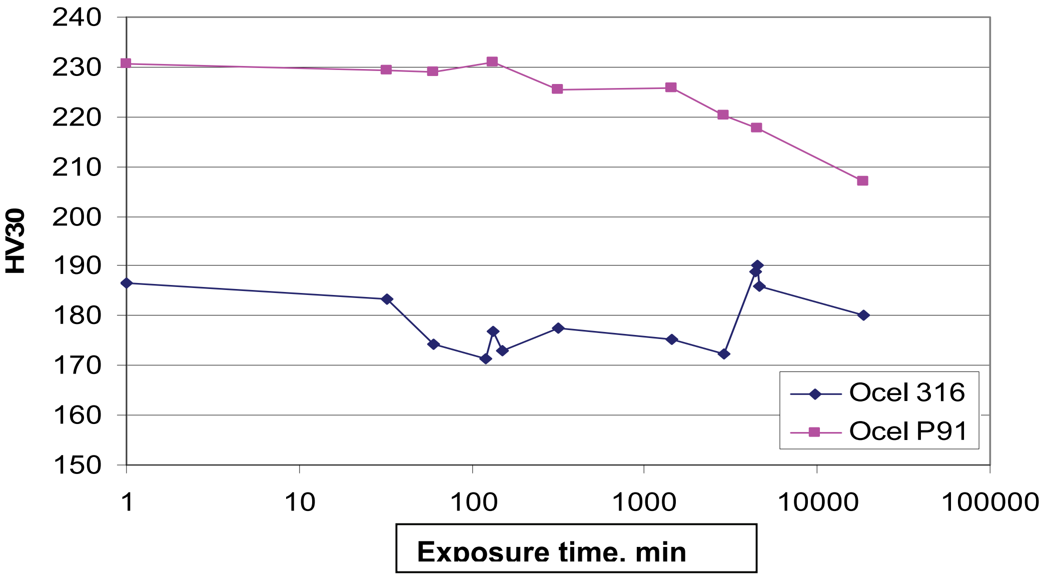


Figure 5 The dependence of HV30 values on the time of exposure at 750 ° C

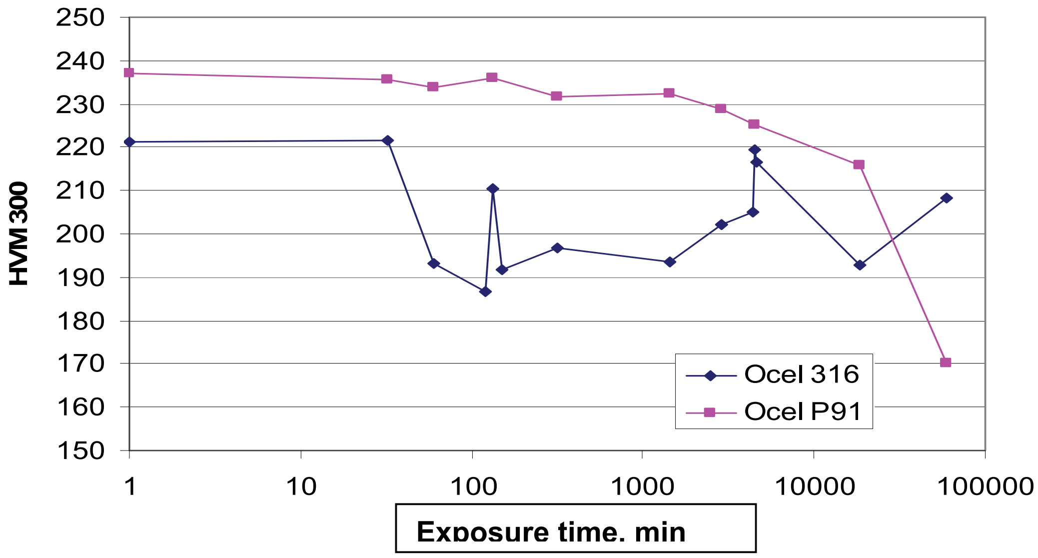


Figure 6: The dependence of HVM300 values on the time of exposure at 750 °C

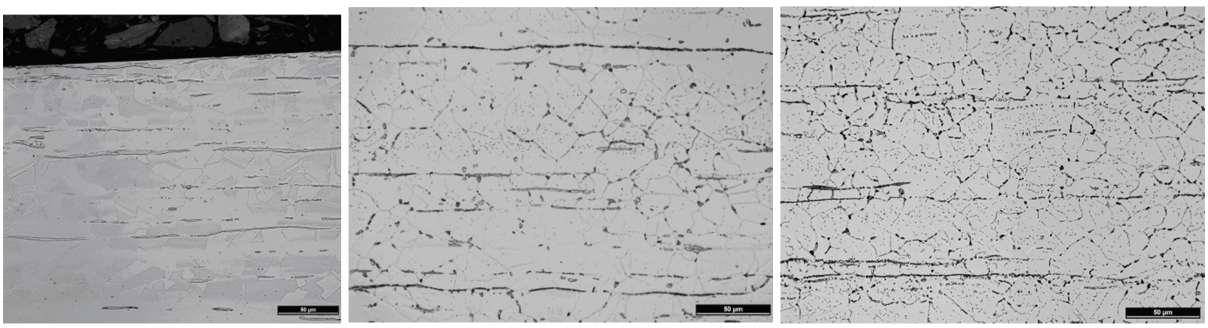
2.2 The metallographic analysis and corrosion resistance of both tested steels

The influence of exposure time in a mixture of helium and impurities at high temperature to the microstructure changes of steels 316 and P91 was investigated. The evaluation of the formation of subsurface layers and the interface between surface and oxide layers on the exposed specimens was performed.

The microstructure of steel 316L in as-received state consisted almost by equiaxed austenitic grains with numerous twins and a high amount of δ-ferrite, elongated in the direction of forming. The oval or elongated inclusions are rarely represented in the structure. After the exposure at 750 ° C for 500 hrs., there was a significant collapse of the δ-ferrite and secondary austenite and to exclude coarse particles, especially along the grain boundaries. The particle coarsening occurred as well as in strips of segregation. After the exposure at 1000 hrs., further disintegration of δ-ferrite and especially significant exclusion of particles along the boundaries and within the matrix were observed. Segregation bands were not visible. The excluded particles have different grey level and a mixture of several types of carbides ($M_{23}C_6$, M_6C) and intermetallic phases (δ, η, χ) was possible to expect. Changes in microstructure of steel 316 are shown in figures below.

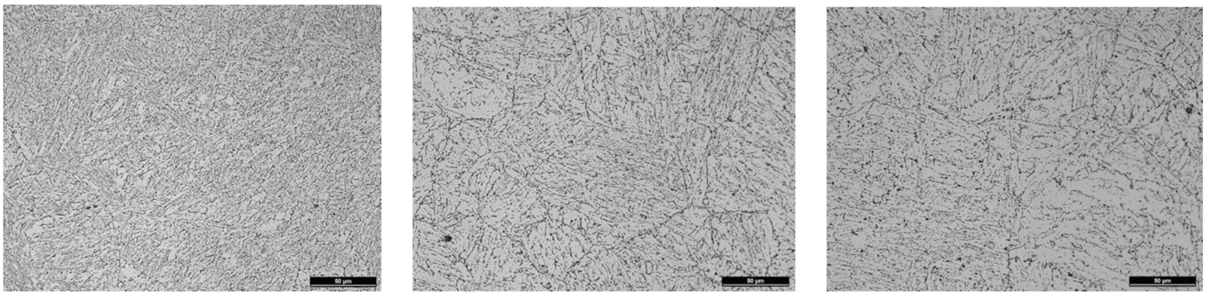
The microstructure of P91 steel in as-received state was typical for tempered martensitic-ferritic steels. The structure was consisted of a ferritic-carbidic mixture, and carbides ($M_{23}C_6$ probably) are excluded mainly along the borders of martensitic laths, the proeutectoic ferrite was represented in a small amount. The primary boundaries of austenite grains were not visible. The infrequent inclusions in this section were oval. After the exposure at 750 °C for 500 h, there was a highlight of primary austenitic boundaries due to the exclusion of particles (carbides), the coarsening of particles along the border and a lathy structure; proeutectoic ferrite was not observed. After the exposure for 1,000 h, especially the further coarsening of laths was significant.

The microstructures of both steel in as-received state and after the exposure are shown in figs. 3 and 4.



a/ b/ c/

Figure 7 Microstructure of the 316 steel: a/ as-received state, b/ after the exposure in He 750°C/500 h, c/ after the exposure in He 750°C/1,000 h



a/ b/ c/

Figure 8 Microstructure of the P91 steel: a/ as-received state, b/ after the exposure in He 750°C/500 h, c/ after the exposure in He 750°C/1,000 h

The thickness of corrosion (oxide) layer on the surface of specimens was measured after the exposure. The layer thickness was measured on both cut cross section of the specimen and also it can be estimated by means of SEM/EDX or GD-OES analysis of the chemical composition of the material in the cross section of the specimen. The thickness of oxide layer is generally equal to the distance the intersection of the concentration depth profile of Fe and Cr from the surface of the specimen. The thickness can be estimated from the peak width of the O_2 content on the specimen´s surface. Measurement of oxide layers was carried out in some specimens (exposure up to 120 hours) at ICT Prague and other samples (exposure for 500 and 1000 hours) in NRI Rez. The ascertained thicknesses by direct measurement in NRI Rez and estimated thicknesses from GD-OES and SEM/EDX are different.

Corrosion layer after exposure was not uniform and in fact, it was created by two layers. The outer layer was composed primarily of iron oxides (on basis of Fe_3O_4), the inner layer is rich in Cr (Cr_2O_3). The depleted layer of Cr was observed beneath a layer of corrosion. In the case of P91 steel, corrosion under the coating layer was observed without carbides. The values of the corrosion layer thicknesses, layer with depletion of chromium and layer without carbides are summarized in the table 7. The dependence of the thickness of the corrosion layer on the exposure time at 750 ° C in helium and air is shown in the graphs below (see fig. 5 and 6). Corrosion layer thickness determined by direct measurement from metallographic analysis performed in NRI Rez (after exposure for 500 and 1,000 hours at 750 °C) is significantly different from the thickness determined from GD-OES and SEM / EDX analysis. These values are not shown in the graphs.

Table 7: The thicknesses of corrosion layer, the layer depleted of Cr and without carbide after exposure at 750°C)

Material/ surface of specimen	**Exposure time [hrs.]**	**Atmosphere**	**Corrosion layer (from metalographic analysis) [µm]**	**Corrosion layer (from GD-OES or SEM/EDX) [µm]**	**The area without carbide (from metalographic analysis) [µm]**	**Depleted area of Cr (GD-OES, SEM/EDX) [µm]**	**Depletion of Cr [wt. %]**
316/ grounded	24	He + impurities	3.00	3.00	Not observed	4	10
	120		6.00	6.00		4	9
	500		0.64	6.00		16	23
	1000		1.96	9.00		12	19
316/ Milled	1000		1.43	-		18	8
P91/ grounded	24		-	4.00	6	7	15
	120		-	7.00	11	9	10
	500		2.67	10.00	16	23	15
	1000		1.86	13.00	17	4	25
P91/ Milled	1000		1.88	-	22	33	11
316/b grounded	24	Air	1.50	1.50	Not observed	6	28
	120		6.00	6.00		4	8
	1000		15.00	13.00		-	-
P91/ grounded	24		-	-	6	-	-
	120		-	7.00	10	10	19
	1000		-	27.00	29	-	-

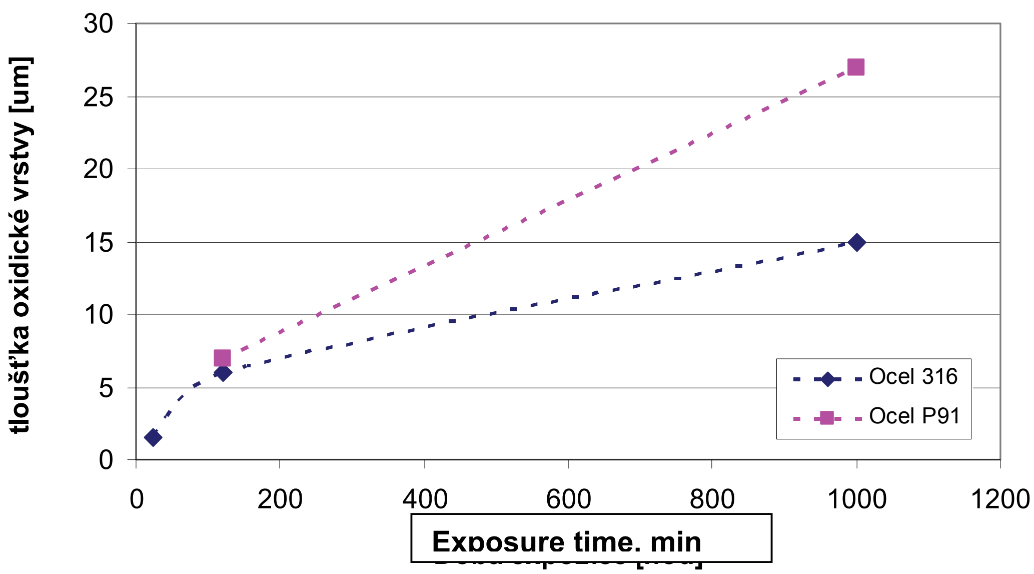


Figure 9 The corrosion layer thickness after exposure in air at 750°

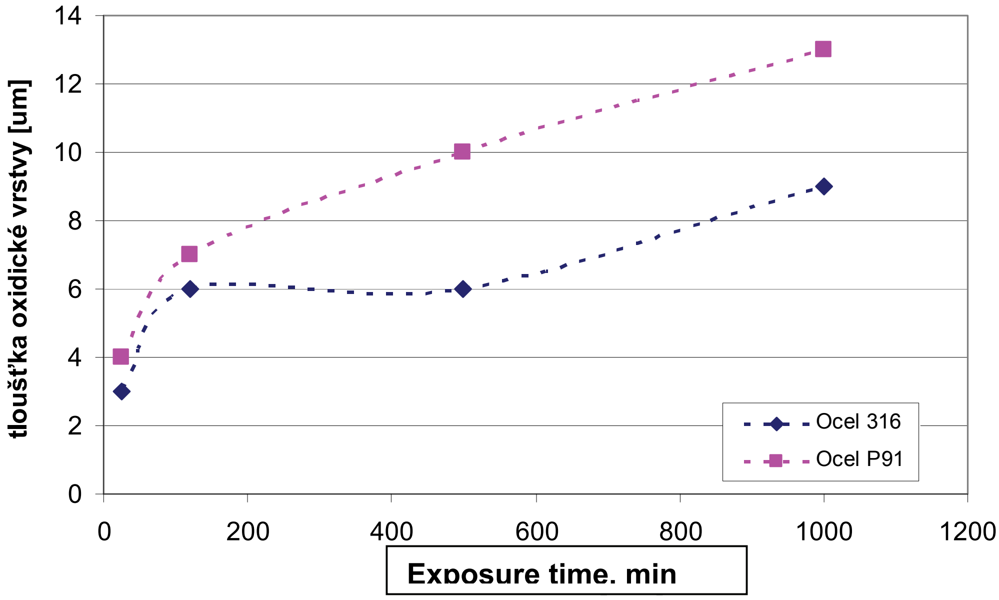


Figure 10 The corrosion layer thickness after exposure in He at 750°

After the exposure at 750°C/1,000 hrs. in air, the penetration of oxidation into the matrix along the grain boundaries of the metal was recorded by the 316 steel.

The weight increments of specimens depending on the exposure time are shown in the graph in Fig. 7. It is evident that higher weight increments were observed in the case of P91 steel in comparison with 316 steel. Thicker corrosion layer were observed for P91 steel.

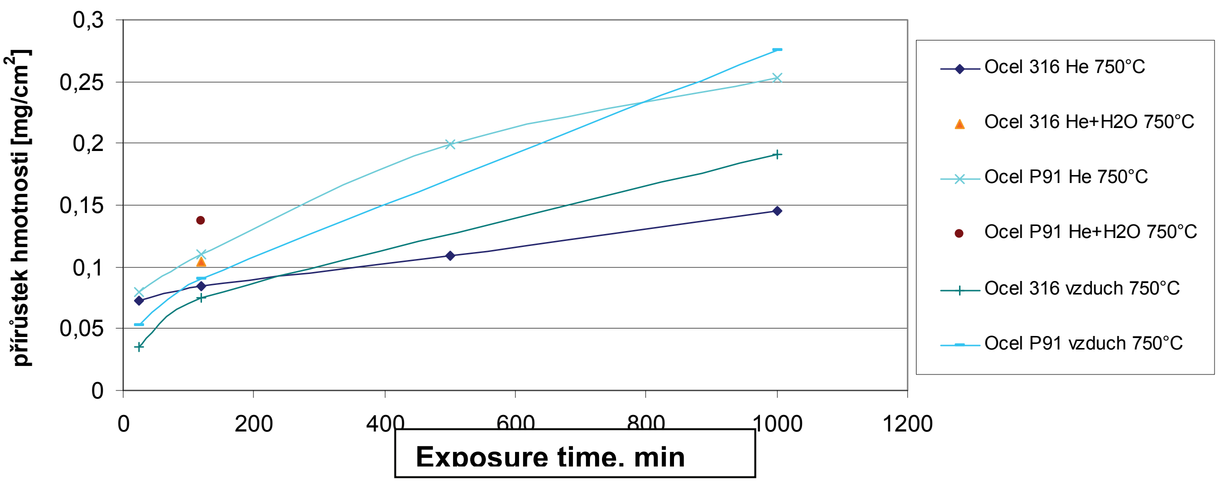


Figure 11 The weight increments of specimens depending on the exposure time

By means of XPS spectroscopy, it was found out that in a depth of 20 to 30 nm the corrosion layer contained about 1.79 at. % of carbon in the carbides after 500 hours exposure in He 750 °C and 2.35 at. % after 1,000 hours exposure in the same gaseous atmosphere. Apparently, these were chromium carbides.

3 Conclusion

The data about the changing of properties and corrosion resistance of high temperature steels P91 and 316 in helium atmosphere with impurities and in air at 750 °C and exposure for up to 1,000 hours were obtained. The data in He are necessary for the development of V/HTR systems. In above mentioned conditions, it was also found out that it caused to minor changes in the mechanical properties of P91 steel after exposure at 750 °C for 1,000 hours in comparison with changes in the mechanical properties of steel 316. On the other hand, thicker corrosion layer on the surface of specimens were found for P91 steel.

There might be some possible interferences that could influence the results of mentioned experiment. For example, the furnace in which exposure was carried out is not equipped with a closed circuit of corrosive media and it also works at a pressure close to atmospheric. Under these conditions, it is possible intrusion of air into the retort of furnace during the experiments. In future experiments, it can be reduced the oxygen content in helium in the furnace, e.g. by inserting the graphite into hot parts, thus the conversion to CO and CO_2 takes place. By this arrangement, the composition of the corrosive medium will be also closer to the real coolant in HTR. Another possibility is the production of retort that allows the exposure at higher pressures.

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