3 Physics and Technology of Fusion

Work in fusion plasma physics and technology includes 18 tasks. The tasks are grouped under the five following sub-headings corresponding to the EFDA Task Forces and Topical Groups:

- Integrated tokamak modelling
    - Tokamak modelling and preliminary analysis of baseline DEMO concepts
    - Nonlinear dynamics of fast ion driven plasma modes near instability threshold – theoretical basis for integrated tokamak modelling
    - Support of the workflow orchestration system for fusion modelling
- Plasma wall interaction
    - Spectroscopic and ion diagnostics for laser-induced removal of fuel and co-deposits from PFCs in tokamaks
      Including:
        - Removal of the deposited materials by laser ablation techniques. Investigation of carbon layers with varying concentrations of Al (Be analogue), W and W-Be
        - Investigation of film break-up processes during laser cleaning. Monitoring of the composition of gases and particles released from the target
        - Irradiation of TEXTOR and AUG samples containing material mix of carbon and tungsten by the Nd:YAG pulsed repetitive laser. Use of optical spectroscopy together with ion diagnostics to characterize chemical composition of samples
        - Photonic cleaning methods
        - Conversion of deposits to dust
    - Studies of material erosion and re-deposition on plasma facing components from the present day machines.
      Including:
        - Characterisation of dust collected during plasma operation
        - Characterization of W PFCs with various microscopic and analytical techniques: TEM, SEM, XPS, AES, XRD, FIB etc.
        - Analysis of W-C AUG deposits and comparison to laboratory experiments
        - Microscopic investigation of radiation damage in tungsten and its influence on deuterium retention
- Development of material science and advanced materials for DEMO
    - Ab-initio study of defects configurations and their interactions in W-Ta and W-V model alloys
    - W/steel joints fabrication route based on pulse plasma sintering (PPS) method and explosive bonding
      Including:
        - Fabrication of He cooled divertor finger modules via Pulse Plasma Sintering
        - Development of W-Ta Composites as Structural Materials
        - Development of W-to-steel joining process by explosive welding
    - Hydrostatic Extrusion (HE) processing of ODS ferritic steel: microstructure characterisation, mechanical properties and thermal stability
    - Application of Mössbauer spectroscopy to Fe alloys characterization
      Including:

  - Interatomic bonding and phase stability
  - Experimental validation of models

- Fusion plasma diagnostics
  - Diamond detectors to detect escaping fast alpha particles
  - Applications of solid-state nuclear track detectors (SSNTDs) for fast ion and fusion reaction product measurements in TEXTOR experiments
  - Determination of emission characteristics of fast electron streams within Tore-Supra and other MCF experiments High-temperature Hall sensor for future applications in measurements of magnetic field in fusion reactors
  - Identification of the physical factors limiting the accuracy of the polarimetric measurement and development of methods for minimizing their influence
- Inertial fusion energy "keep-in-touch" activity
  - Analysis of emerging options of IFE on the basis of results of experiments and numerical modelling

3.1 Integrated Tokamak Modelling

Corresponding author **Roman Stankiewicz**
roman.stankiewicz@ifpilm.pl

Introduction

The activity in the frame of Integrated Tokamak Modelling is organised within the following scopes:

1. **Tokamak modelling**: participation in the work of ITM-IMP3 task force

   The aims of ITM project is to developed the system of codes covering the all task. involved in full modelling of the tokamak. The particular codes are considered as the modules implemented as the actors in KEPLER system. The actors communicate between themselves by the predefined pieces of information so called CPO (Consistent Physical Object). The activity within ITM-IMP3 covers the physical model development, implementation it's into the codes, developing numerical method to solve the problem as well as implementing of modules on Kepler platform.

2. **Preliminary analysis of baseline DEMO Concepts**

   In the frame of the EFDA PPPT program the feasibility of future fusion power plant has been studied.

3. **Nonlinear dynamics of fast ions** driven plasma modes near instability threshold – theoretical basis for integrated tokamak modelling

4. **Support of the workflow** orchestration system for fusion modelling: participation in ITM-ISIP

Success in ITM activity required strong support from the ITM-ISIP group developing informatics tools helping to build the total system of codes and connect this system with libraries necessary to store the experimental data, various tokamak descriptions as well as the results of modelling.

Results

Tokamak modelling.
The ETS (European Transport Solver) solving the transport equations for ions densities, toroidal rotation, electron and ions temperatures and plasma current has been tested and the weaknesses of the used algorithms detected. The new algorithm satisfying the particle and energy conservation low has been develop, implemented and tested. The feasibility of solving the stiff transport problem using algorithm based on introducing additional diffusion has been studied.

The module ITS (Impurity Transport Solver) developed in IPPLM has been tested by comparing results of ETS/ITS with the results of Jetto/Sanco. The tests show very good agreement of the results of both codes.

The new module for neutrals in the core has been developed. The transport of neutrals is described by diffusion equations with diffusion coefficient defined by mean free path. Atomic processes like ionisation, recombination and charge exchange have been taken into account. The neutrals for main ions and for impurity ions have been considered and two energy groups for neutrals have been introduced.

Preliminary analysis of baseline DEMO Concepts

In the frame of the EFDA task WP11-SYS-01-ACT5-02, two scenarios, pulsed and steady state for Demo reactors have been analysed using code COREDIV[1,2]. The intensity of Argon seeding has been increased until the steady state solution does not exist due to excessive radiation or plasma dilution. It was shown that for steady scenario the power to target plate can be reduced with the increasing of Argon concentration to acceptable level. But it turns out the radiated power remains almost constant but dilution of plasma by impurities reduces the alpha power and in consequence the power load to the plate. Reduction of the power load to plate reduces the self-sputtering of Tungsten but the sputtering of Tungsten by Argon increases with the Argon concentration. As the results, the concentration of Tungsten remains constant. Since Tungsten radiates more than 90% of the whole radiation the radiated power become constant.

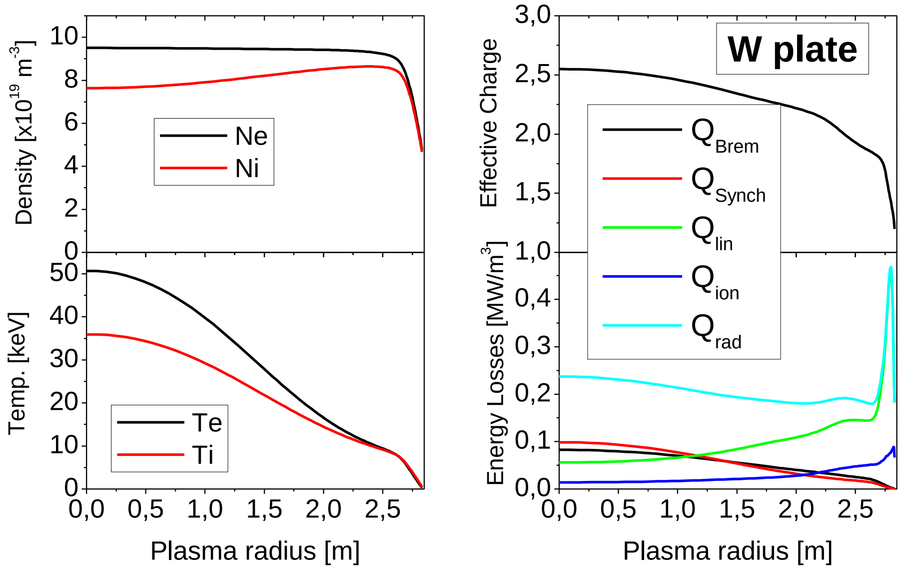

Fig. 2 Profiles of plasma density, temperature, effective charge and radiation losses fo the DEMo steady-state scenario.

Non-linear dynamics of fast ions driven modes.

Simplification of the two-mode Berk and Breizman model expressed in integral –differential equations to differential equations has been performed [3,4].

The physical contents of the new equations was compared with the integro-differential model. In spite of these simplifications the main features of the dynamics of the two plasma modes are retained. The numerical solutions to the model equations show competition between the two modes for survival, oscillations, chaotic regimes and ‘blow-up’ behaviour. Some physically unacceptable feature of the model is the explosive behaviour occurring in the regime of small values of the collision frequency parameter

Simulations for the Fermi-like model [5] in the case of bump on tail instability**.** The bump on tail instability can be easily described in the Fermi-like model by appropriate choice of the velocity distribution function. The numerical code describing the Fermi-like model has been developed. To prove the validity of the numerical code the results obtained in literature for collision less case were reproduce. To broaden the model and to test it some simplified dissipative processes were added.

Work in progress

Support of the workflow orchestration system for fusion modelling: participation in ITM-ISIP

1. The procedures and tools for monitoring and execution of actors on GRID and HPC as well as booking resources on GRID/HPC in advance before the actors are actually run have been prepared..
2. The training courses and on line tutorials has been provided. The training and tutorials cover the following topics:
   - Building simple workflows in Kepler

- Building complex workflows in Kepler (loops, composite actors, integration with Python, visualization using build-in actors)
- Integration of Kepler and ITM tools (FC2K, HPC2K, ISE)
- Execution of physical codes on Grid/HPC using Serpens extension for Kepler

Conclusions

The new module describing neutrals of main plasma and impurities in the core has been incorporated in Kepler system of the codes. New algorithm for solving transport equations has been proposed and implemented into ETS (European Transport Solver). ITS (Impurity Transport Solver) has been tested. The analyses of the numerical methods applicable to stiff transport equation has been studied. The two scenarios of Demo project has been analysed with the help of COREDIV code. It was shown that in case of steady state scenario the sufficient amount of energy can be radiated in order to reduce the power load to target plate to acceptable level. In case of pulsed scenario it turned out that the dilution of plasma by Helium might be a serious problem. The simplified approach to Berk-and Breizman model of fast particle driven instabilities has been developed and tested showing that the physical contains of the model is preserved. Also the Fermi like model of the instabilities has been analysed.

Collaboration

Association EURATOM-VR, Stockholm, Sweden

References

[1] R. Zagórski and R. Stankiewicz, J. Nucl. Mater. 313-316 (2003) 899

[2] R. Stankiewicz and R. Zagórski, J. Nucl. Mater. 337-339 (2005) 191

[3] G. Galant, J. Zaleśny, M. Lisak, P. Berczyński and S. Berczyński, Physica Scripta 83 (2011) 055502 (7pp)

[4] J. Zaleśny, G. Galant, M. Lisak, S. Marczyński, P. Berczyński, A. Gałkowski and S. Berczyński, Physics of Plasmas 18, 062109 (2011),

[5] R.M. Nyqvist, M. Lisak and J. Zaleśny, On wave–particle interaction in axisymmetric toroidal systems, Physica Scripta 84 (2011) 015503 (8pp)

3.2 Plasma-Wall Interaction

Corresponding author **Monika Kubkowska**
monika.kubkowska@ipplm.pl

Introduction

The work in 2011 related to Plasma-Wall Interaction (PWI) included the following EFDA tasks:

- WP11-PWI-02-03-01 Photonic cleaning methods
- WP11-PWI-02-06-01 Conversion of co-deposits to dust
- WP11-PWI-05-01-01 Characterization of W PFCs with various microscopic and analytical techniques: TEM, SEM, XPS, AES, XRD, FIB etc.
- WP11-PWI-02-07-01 Characterisation of dust collected during plasma operation
- WP11-PWI-05-01-02 Analysis of W-C AUG deposits and comparison to laboratory experiments
- WP11-PWI-01-02-01 Microscopic investigation of radiation damage in tungsten and its influence on deuterium retention
- WP11-DIA-02-02-01/02 Development of a FFT based model to interpret the measurements under vibrations by identifying the mechanical vibrations (of few tenth of mm amplitude and of hundreds of Hz to KHz range) from the erosion measurements
- WP11-ETS-DTM-01-05-01 Qualification of the LIBS operation on ITER relevant calibrated samples

The aim of these tasks was to optimize in laboratory experiments the removal process with the use of Yb:fiber and Nd:YAG lasers, investigate a dust formation and describe material mixing and plasma-induced damages of the analysed samples by different surface analysis methods.

Results

In laboratory experiments the Nd:YAG laser (EKSPLA, 0.5J@1.06 µm, 3.5 ns, up to 10 Hz) has been used to investigate a dust formation from the thick TEXTOR co-deposite sample. To get a better insight in the film break-up processes, the fast high resolution camera has been installed.

Registration of dust emission was starting approximately 40 µs after a laser pulse and lasted for a relatively long time reaching even more than a half of millisecond (up to 700 µs). Basing on the recorded traces, the velocities of dust particles were estimated in the range of 100 m/s in vacuum and it was decreasing with mass and pressure of the gas when it was applied. Moreover, after the image processing and zooming of the dust traces, the “comet” effect for the high pressure of active gases became apparent which suggested that dust particles were “burning” during their flight.

In 2011 an optimization of the removal processes with the use of Yb:fiber laser (IPG) has been performed Power density threshold for graphite substrate was found and it appeared to be significantly higher than the one assessed for the hydrogenized/deuterized carbonous or mixed material layers (which consisted of C, W and Al). It allowed for a successful removal of such layers from both graphite and aluminium substrates with laser scanning. Profilometry indicated that the whole deposited layer was removed and the roughness of the surface was approximately the same as the roughness of the original substrate. CCD camera observed no traces of dust. Moreover it was found that the temperature evolves during the removal process in such a way that it allows for development of pyrometric diagnostics.

In frame of PWI research in 2011 there were also post-mortem examinations of ASDEX Upgrade (AUG) samples to describe material mixing and plasma-induced damages. The present investigations were carried out on nine CFC samples from the inner divertor tile 4 from the carbon dominated operation phase of AUG.

The structure and composition of co-deposited layers were examined by the following methods: scanning electron microscopy (SEM) combined with energy dispersive X-ray spectroscopy (EDS), focused ion beam (FIB), X-ray photoelectron spectroscopy (XPS) and optical profilometry.

Three types of the deposits morphology were revealed at the examined samples:

- Cracked deposit resembling roof tiles, of stratified character and fibrous structure, 8 µm thick, with sublayers of 100 nm. Distinctly directional character. The EDS measurements showed tungsten, carbon and oxygen. Boron was very likely present.
- Multilayer structure with several sublayers of 1-2 µm. The porous and compact layers appear sequentially, total thickness about 13 µm. Main constituents: carbon, oxygen, silicon, tungsten and boron. Tungsten detected only in the top layers.
- Asparagus-like morphology, several tens of microns thick.
- XPS results show the main constituents of deposit are: boron (~39 at.%), carbon (~37at. %) and oxygen (~20at. %). The silicon, tungsten and nitrogen were detected at the level of one atomic percent. Residues of iron and sodium were also revealed.

In frame of PWI research in 2011 there were also examination of particles from the filter no 1 from sector 8 (above an ECRH mirror), collected after 2009 ASDEX Upgrade campaign. In that case the structure and composition of dust particles were examined by: high resolution scanning electron microscopy (HRSEM) combined with energy-dispersive X-ray spectroscopy (EDS), transmission electron microscopy (TEM), focused ion beam (FIB). The main results can be listed as follows:

- The investigations revealed the largest group of particles were small ones (composition: carbon-based, co-deposits containing: C+O+Si+Fe+Cr or C+O+Si and C+O+Ca particles). They comprise 70% of the analysed particles. The second group includes carbon-based rod-like particles (small fragments of CFCs). Additionally the iron-based, tungsten and bronze particles were identified.
- The tungsten particles were of special interest. The following types of these particles were distinguished:

  a) spherical (typical size: 1 to 3.5 µm, coated with materials of different chemical composition, three types of microstructure: (i) two phase particles, one phase is tungsten or tungsten rich, the other one contains boron and carbon, (ii) grained structure, (iii) the particles with two characteristic areas,

  b) irregular (1 to 8 µm), of columnar or multilayer structure, origin: a small fragments of co-deposited layers or small fragments of tungsten coating,

  c) fine present at/inside the large one,

  d) large flakes (20 to 70 µm),

  e) polyhedral (0.5 to 2 µm).
- The HRSEM observations revealed that the PTFE disc filter consisted of two layers. The size of the channels on one side of the filter is about 200nm. Additional layer attached to the filter is characterized by a very fine size of the order of 20-30 nm. At the disc edge (the region where the disc is mounted to the additional ring), filter is covered by a deposit. The HRSEM observations prove the deposit consists of nanoparticles.

In 2011 the ASDEX Upgrade tile nr. 4 (poloidal coordinate s ~ 510 mm) after 2007 campaign (with the highest previously identified re-deposition) has been also investigated by high resolution scanning transmission electron microscopy. Detailed microstructural investigation has been performed together with nano-diffraction phase analysis. Small – 3-6 nm size – carbides have been detected. Nano-diffraction phase analysis revealed dominant presence of WC1-x type carbide with additional W2C carbide type (no WC was detected).

Moreover, amorphous tungsten doped carbon films (a:C-W) with 9-22% tungsten concentration annealed at 1100K, 1450K, 1800K, 2200K, 2500K and 2800K have been investigated as a laboratory model of the re-deposit formation conditions. Various concentrations of WC, W_2C and WC1-x type carbides have been found depending on tungsten concentration and annealing temperature. Furthermore, different carbides sizes have been revealed depending on both annealing temperature and tungsten concentration.

Based on laboratory a:C-W layer model, re-deposit formation condition resulting in the best fit to the experimentally observed deposits were obtained for the 9% W doped carbon film annealed at 1450K for one hour.

The polycrystalline W samples after being damaged by 20 MeV W+ at IPP were investigated by FIB/TEM at WUT. The TEM images of cross sections perpendicular to the sample surface showed damaged zone of a depth of c.a. 2.5 microns. The damaged zone was not uniform but composed of 3 distinctive sub-regions:

1) near surface area with high density of dislocations up to 0.4 microns,
2) intermediate area with lower density of “long” dislocations and “sub-grain” regions free from dislocations from 0.5 microns up to 1.7 microns,
3) deep region with high density of “short” dislocations from 1.7 microns to 2.4 microns

The observed damaged depth well coincided with values calculated for 20 MeV W+ ion by colleagues from IPP.

Conclusions

In 2011 laboratory experimental set-up on removal and conversion of codeposits to dust has been enriched with the profilometry stage. Such profilometry measurements made it possible to assess power-density threshold for removal of the materials of interest which e.g. for Aluminium was estimated for ~6 MW/cm^2. Irradiation with slightly lower power density can be considered as capable for the removal of the deposited layers without substrate damage. It is also worthwhile to mention that no dust was observed in the interaction of the fiber laser beam with any of the target materials.

The structure and composition of dust particles from the filter no1 collected after 2009 AUG campaign were examined by several methods: HRSEM combined EDS, TEM and FIB.

There were also post-mortem examinations of AUG samples to describe material mixing and plasma-induced damages. Three types of the deposits morphology were revealed at the examined nine CFC samples from the inner divertor tile 4 from the carbon dominated operation phase of AUG.

The FIB/TEM observations of polycrystalline W samples damaged by 20 MeV W+ at IPP proved to be an effective technique allowing for characterisation of the damaged structure of tungsten. This shall allow for understanding the hydrogen trapping mechanisms in the defected zone.

In 2011 the task on experimental studies leading to the qualification of laser induced breakdown spectroscopy (LIBS) for deposited layer removal and in vessel fuel inventory measurements for ITER has been started but due to preparation time of calibrated samples the main part of the experiments was rescheduled for 2012.

Collaboration

Association EURATOM–IPP, Garching, Germany
Association EURATOM–FZJ, Juelich, Germany
Association EURATOM–ENEA, Frascati, Italy
Association EURATOM–DIFFER, FOM Rijnhuizen, The Nederlands
Association EURATOM–TEKES, Helsinki, Finland

3.3 Development of material science and advanced materials for DEMO

Corresponding author **Łukasz Ciupiński**
lukas@inmat.pw.edu.pl

Introduction

The Association 2011 activities in the area of materials science and advanced materials for DEMO have been implemented via nine EFDA tasks that can be grouped under three type of research, namely:

1. Materials Modelling
   - Grain boundary structure and statistical distribution of grain boundary types in iron (WP11-MAT-REMEV-01-06)
   - Ab-initio calculations of irradiation induced point defects in W-alloys (WP11-MAT-WWALLOY-05-01)
   - Formation energy of the σ-phase in the Fe-V alloy system (WP11-MAT-REMEV-01-04)
2. Development of materials and materials technology
   - Fabrication of He cooled divertor finger modules via Pulse Plasma Sintering (WP11-MAT-WWALLOY-01)
   - Development of W-to-steel joining process by explosive welding (WP11-MAT-WWALLOY-01-01)
   - Development of W-Ta Composites as Structural Materials (WP11-MAT-WWALLOY-02-01)
   - Optimisation of thermo-mechanical treatment via hydrostatic extrusion of nano-structured ODSFS (WP11-MAT-ODSFS-01-01)
3. Materials Characterisation
   - Fe-rich border and kinetics of phase decomposition in Fe-Cr alloys (WP11-MAT-REMEV-01-02)
   - Short-Range Order in irradiated Fe-Cr Alloys as Revealed by Mössbauer Spectroscopy (WP11-MAT-REMEV-05-01)

These tasks have been carried out at Materials Science and Engineering Faculty, Warsaw University of Technology (WUT) and AGH University of Science and Technology (AGH).

Results

Modelling of W-Ta and W-V alloys using ab-initio approach resulted in conclusions that formation energies of dumbbell show that V atoms in the dumbbell may change the structure of the defect from <111> to <110> orientation. Moreover, the formation, migration energies of mono-vacancy in W-Ta and W-V alloys is strongly dependent on the crystallographic lattice site. The Monte-Carlo cluster expansion simulations based on many-body interactions derived from our first-principles calculations show fairly low temperature of order-disorder phase transformation of the studied alloys. The performed calculations allowed for prediction of self-diffusion activation energies for both binaries as function of tungsten concentration.

A number of different types of grain boundaries were studied by molecular dynamics (MD) simulations. Prior to that both DFT and MD studies were performed on the same grain boundary in order to compare the accuracy of the values of grain boundary energy, free surface energy and grain boundary cohesion energy. The results obtained showed that both DFT and MD methods provide similar values of the parameters for Σ5 210 Fe twin grain boundary, the grain boundary energy increases continuously for the misorientation angles in the range from 0-20 degree and the average energy of high-angle grain boundaries drops with increase of the temperature. The grain boundary surface with higher density has lower grain boundary energy and the asymmetrical, low- angle grain boundaries have a high tendency to transform into symmetrical ones with the same misorientation angle.

Formation energy of the σ-phase in the Fe-V alloy system, ΔE, as well as magnetic, S_M, and configurational S_C, entropies were computed as a function of the occupation changes on each of the five possible lattice sites for three different atomic configurations corresponding to three different samples. The results show that formation energy of the σ-FeV exhibits a strong growing dependence on the Fe concentration, and for a given composition it is characteristic of a given lattice site depending strongly on the number of Fe atoms in a unit cell. Similar dependence on the composition has been observed for the magnetic entropy, but for a given composition it weakly depends on the site. The configurational entropy, in contrast, exhibits a weak dependence on the composition, but for a given composition it is dependent on a given site and for a given site it strongly depends on number of Fe atoms. Moreover, the occupancy of A and D sites hardly depends on T and composition, whereas occupancy of sites B, C and D is sensitive both to T and composition.

The attempts of producing the finger divertor module according to the current conceptual design of helium-cooled DEMO divertor have not been successful. The produced parts have buckled and presented voids at the joined sub-components fusion lines. For a successful fabrication of faultless modules precise parts machining and precise temperature control in the sintered parts is needed. Machining of tungsten and WL10 alloy was developed by other EFDA partners and the exchange of information or fabrication of parts by those partners may allow successful fabrication of the module by PPS. Otherwise, verification of the PPS method usability as a viable fabrication route may be problematic.

The clads of tungsten on steel were obtained using copper as technological interlayer. Although the bonding shear stress test have shown good bonding strength the clad tungsten layer presented numerous cracks. Plastic deformation of tungsten was observed at the clad / base material interface and a characteristic wavy joint has formed. The parameters used during explosive cladding have been high enough to cause boiling of the copper technological layer and induce recrystallization of the plastically deformed tungsten. Based on the results obtained the fabrication of large area clads of tungsten on steel seems hardly feasible.

The W/short Ta fibre composites developed by Pulse Plasma Sintering proved the high efficiency of this consolidation method. Composites with relative density of 92% and high thermal diffusivity have been produced. The obtained results show that PPS sintered composites are prospective materials for structural applications.

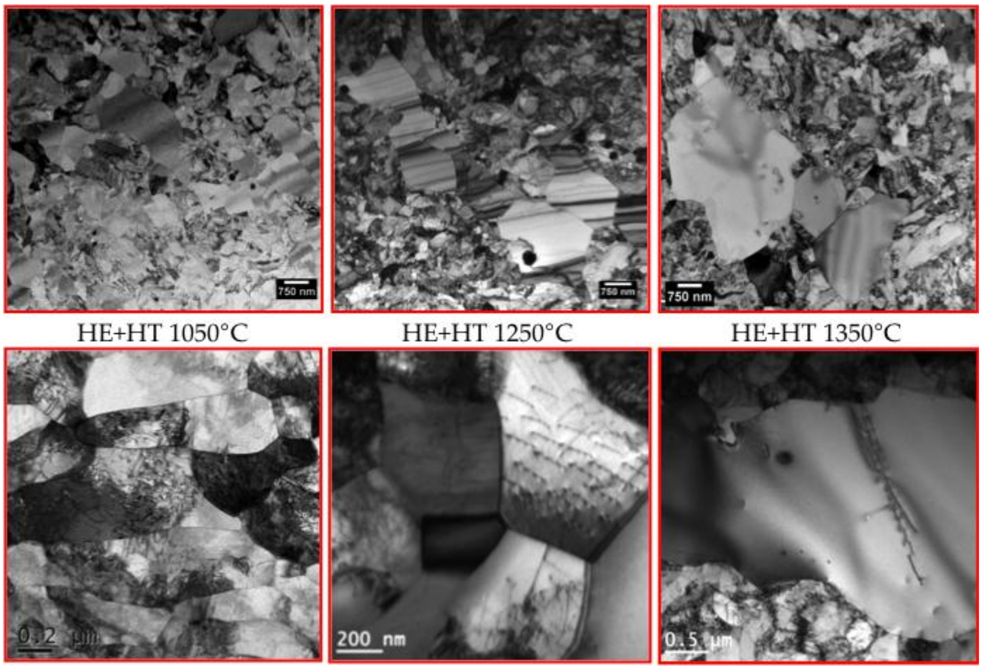

Fig. 3 Microstructural changes in ODS-FS hydroextruded steel with annealing temperature

The experiments on optimisation of nano-structured ODS FS have shown that the hydroextruded ODS RAF steel is thermally stable up to 1250 °C. At the same time annealing of these steels at 1050 °C after HE slightly decreases the strength however, significantly improves their ductility. Long-term ageing of the ODS RAF steel at 750 °C for 10000 hrs causes microstructure changes, increase in hardness and decrease in tensile properties, both strength and ductility. The evaluated activation energy in the ODS RAF gradually increases up to 600°C and then becomes stagnant (~3.5 eV) that suggests the dislocation climb as the rate controlling slip mechanism. The study shows that in order to improve mechanical properties of ODS steel it is necessary to homogenize the microstructure and reduce number density of larger Ti-Al-O particles which act as trigger sites for fracture initiation, weakening mechanical and thermal properties of the ODS steel.

Concentration of Cr in the Fe-rich α-phase, *x*, resulted from a phase decomposition caused by an isothermal annealing at T = 415 and 450 °C of a non-irradiated Fe-Cr15 EFDA sample and that of a He-ions irradiated one annealed at 415 °C was determined using the techniques of the conversion electron Mössbauer spectroscopy (CEMS). The *x*-value in the latter was by 2.7 at% higher i.e. the miscibility gap border significantly changed its position toward a higher Cr-content. The activation energy for the phase decomposition was found to be equal to 216 kJ/mol for un-irradiated materials whereas in the irradiated sample it was higher by ~3kJ/mol resulting in much higher decomposition rate of the alloy. As the phase decomposition into Fe-rich (α) and Cr-rich (α') phases is the main reason for the so-called 475°C embrittlement of steels the results show that irradiation of Fe-Cr based steels can be a serious problem if those are used at high temperatures.

Distribution of Cr atoms in $Fe_{100-x}Cr_x$ alloys with *x* = 5, 10, 15 within the first two coordination shells, 1NN-2NN, around probe ^{57}Fe atoms was studied by means of the conversion electron Mössbauer Spectroscopy (CEMS). Both non-irradiated and 25 keV He-ions irradiated samples with doses, D, up to 30 dpa were investigated. Clear evidence was found that the actual distribution of atoms in the irradiated samples depends both on the samples composition and on the irradiation dose. Among the three samples irradiated with the dose of 10 dpa, the most significant irradiation-induced redistribution of atoms was found for *x* = 15. The least affected was the $Fe_{90}Cr_{10}$ one. The distribution of atoms in the $Fe_{85}Cr_{15}$ sample strongly depends on the dose of 25 keV He-ions and at D ≈ 7 dpa there is an irradiation-dose caused inversion in <α12> SRO parameter from a weak ordering into a strong clustering.

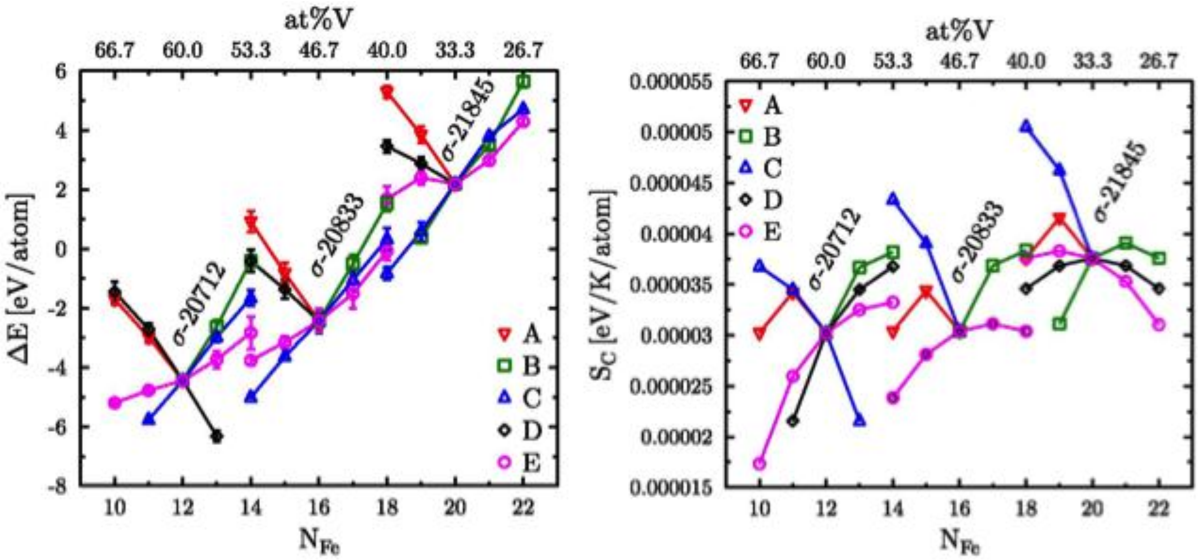

Fig. 4 Formation energy, ΔE, and configurational entropy, S_C, of the σ phase in Fe-V alloy system

Collaboration

Association EURATOM–CCFE, Culham, United Kingdom
Association EURATOM–KIT, Karlsruhe, Germany
Association EURATOM–IST, Lisbon, Portugal
Association EURATOM–CRPP, Lausanne, Switzerland

3.4 Fusion plasma diagnostics

Corresponding author **Marek Scholz**
marek.scholz@ipplm.pl

Introduction

Fusion plasma diagnostics programme concerns the realization of the following tasks:

- Development of soft X-ray triple GEM gas detector for energy resolved soft x-ray plasma diagnostics (WP11-DIA-03-01-02,IPPLM)

High-resolution x-ray diagnostics for MCF devices is expected to monitor the plasma radiation emitted by W^{46+} and Ni^{26+} ions at 7.8 keV and 2.4 keV photon energies, respectively. Both, X-ray lines will be monitored by new generation energy-resolved micropattern gas detectors with 1-D position reconstruction capability. The detection structure is based on triple GEM (T-GEM) amplification structure followed by the strip readout electrode.

- Feasibility Studies of MCP Based Detectors for the future VUV and SXR Imaging (WP11-DIA-03-02-01, IFPiLM)

An arrangement consists of open MCP-based detectors can be considered as a candidate for imaging of VUV&SXR radiation emitted by magnetically confined plasma. Analogue electrical signals taken from these detectors will enable us to estimate radiation level emitted in different spectral ranges and evaluate noises level induced by hard X-ray and neutron radiation. The obtained results should be a base to answer on fundamental question: whether and what kind (analogue – imaging oriented or digital – photon counting & positioning oriented) VUV & SXR imager could be applied to magnetically confined plasma study.

- Construction of a prototype of GEM gas detector, filled with Neon, for detection of 14 MeV neutrons by means of neon activation in the drift region (WP11-DIA-03-01-01, IPPLM)

The best solution to detect the fast neutrons without simultaneously measuring scattering ones is to use threshold reactions. Therefore, the main aim of described project is to assess the feasibility of construction the 2.5 and 14 MeV neutron monitors based on gas detectors utilizing threshold reactions. To detect 14 MeV neutrons the following nuclear reaction is considered: n(14 MeV) + ^{20}Ne → p(6.5 MeV) + ^{20}F($T_{1/2}$=11 sec) → ^{20}Ne + β(2.5 MeV). Due to low target (neon) density the high-efficient detector is needed to record the charged particles being reaction products, i.e. electrons and/or protons. Therefore, Gas Electron Multiplier (GEM) detector seems to be the most suitable device to perform such measurements. It is also able to distinguish protons and beta particles caused by the mentioned nuclear reaction.

- CVD diamond detectors for measurement of fusion plasma products (PS WP11-DIA-03-04-01, IFJ)

Experiments with monoenergetic ion beams (protons, deuterons and alphas) from a van de Graaff accelerator have been performed to precise the spectral response of the diamond detectors (CVD monocrystal) at lower energies (below 3.5 MeV). Some differences in the responses of the diamond detectors for the ions with lower energies have been observed. A study on the radiation hardness of diamond detectors has been initiated.

Results

Development of soft X-ray triple GEM gas detector for energy resolved soft x-ray plasma diagnostics

The two prototype detectors based on the T-GEM structure were constructed. In the prototype phase it was demonstrated that the T-GEM detector filled with Ar/CO2 (13%-30%) gas mixture at atmospheric pressure provides a good charge gain. The T-GEM structure with inter-GEM spacing of 2 mm and the induction gap width of 2.5 mm should match the operational requirements of the high-resolution X-ray diagnostics. Each detector consists of 128 10 cm-long-strips with strip pitch of 0.8 mm. In order to optimize the detector efficiency the studies of the gas mixture and detector window materials have been performed. The Ar70%+$CO_2$30% mixture with maximum considered layer thickness of 1.5 cm has been chosen. In order to minimize the absorption in the window the technology of the thin (12 μm and 5μm) aluminized Mylar detector window with the applied HV of the order of 5kV has been verified in test X-ray measurements.

The T-GEM x-ray prototype detector with 10x10 cm^2 detection area was tested to study energy and space resolution and the Ar/CO2 (30%) gain as a function of applied voltages (GEMs, induction, drift and transfer voltages). Tests were mainly performed by means of the ^{55}Fe x-ray source and 2.5 kV X-ray generator (100uA) with X-ray photon energy peak at about 2 keV.

Feasibility Studies of MCP Based Detectors for the future VUV and SXR Imaging

- A feasibility study to apply a gateable detector based on microchannel plate (so-called Open MCP-based Device) to magnetically confined plasma devices was performed. The microchannel plate (MCP) itself is sensitive to vacuum UV and soft x-ray radiation for photons energy range (8 eV ÷ 6 keV) and with quite high detection efficiency (5 ÷ 15%). Therefore, the proposed MCP-based imager can be considered as complementary system to the CMOS-imager.

- The gating of the open MCP-based device is foreseen to be in range from a few nanoseconds to a few milliseconds. Hence, it will enable to capture events with characteristic velocities of tens kilometres per second. Generally, proposed MCP-based imager is supposed to be able to record images related to the behaviour of the plasma itself and plasma wall interaction, as well as its evolution caused by externally-triggered processes (e.g. heating, pellet and plasma jet injection, etc.) with high spatial and temporal resolution.

The usefulness of gateable, MCP-based devices for VUV & SXR imaging purposes has been definitely proved during dense plasma investigations (laser-matter interaction, Z-pinch, etc.). However, the electron density of magnetically confined plasma is usually a few orders of magnitude lower than the dense plasmas. Hence, one should expect a very strong decrease in emitted radiation level, which could prevent application of MCP-based imager from working in analogue mode of operation (image recording) and simultaneously digital operation mode (photon counting & positioning) would be become much more feasible. To solve this fundamental problem and measure VUV&SXR radiation level before final MCP-based imager development, we propose to apply a simple arrangement being a first step toward final imaging system. It is based on open MCP detector (double stack – Chevron type equipped with50 matched anode) that are able to deliver analogue electrical signals linearly dependent on incoming radiation.

Construction of a prototype of GEM gas detector, filled with Neon, for detection of 14 MeV neutrons by means of neon activation in the drift region

To detect the fast neutrons the T-GEM gaseous detector with 1D strip readout is constructed. The prototype detector was constructed to measure the characteristics of the charge multiplication and charge transfer processes what allows the internal electrode structure and strip geometry optimization. A small chambers having entrance window area of 10x10 cm^2 were constructed. In this geometry the strip detector can be kept on ground potential. The high voltage of negative polarity increases gradually reaching maximal value of the potential applied to the window. Thus, seven individual channels of high voltage can be employed. To investigate operation of prototype detector especially for measurement of anode signal on individual strip aimed at distinguished proton and beta signals on individual strip, the following measurement setup was performed and tested :

- 16-channel analogue Front-end Board (AFE) containing an independent charge amplifier a. The bandwidth of amplifiers is above 150 MHz to precisely measure useful signal, noises, and possible interferences,
- 4 oscilloscopes MSO4104. Each oscilloscope provided 4 channels with bandwidth of 1GHz and sampling frequency of 1.25 GHz in each channel,
- Router Ethernet 100 TB providing network connection between 4 oscilloscopes and a PC computer,
- The FPGA available on FMC board is devoted to input signal processing and real time raw data acquisition for debugging purposes,
- PC computer with Matlab package used to control oscilloscopes, to record and analyse signals

The preliminary test of the experimental setup was performed using X-ray source for the energy measurement capability and position reconstruction precision (in one dimension). The signals from the AFE board of 16-channels were converted from analogue to digital signal, transferred to FPGA module and later on to PC. The data reconstruction and data analysis allowed the cluster charge measurement of individual events, the measurement of a cluster size in terms of the number of activated strips, the measurement of the shape of the cluster distribution and, thus, the position reconstruction in one dimension.

CVD diamond detectors for measurement of fusion plasma products

In the experiments with the diamond detectors at a van de Graff accelerator, the RBS geometry (Rutherford Backscattering Spectrometry) was used. The accelerated ions (protons, deuterons and alpha particles) bombarded thin foil of gold and were scattered. The backscattered ions under the 150° angle in respect to the ion beam had a well-defined energies. They were measured with the diamond detectors (different in each series) and a silicon detector (as the reference counter – the same all the time). The scattering foil and the detectors were placed in a vacuum chamber.

Three detectors (D01, D08, D09) manufactured by the Diamond Detector Ltd. of a high purity single crystal CVD diamonds were used. Each single crystal plate had a thickness 50 µm with contacts on the top and bottom planes of the diamond (a sandwich configuration). The diameter of the contact was 1.8 mm. The operating voltage was +50 V.

Conclusions

WP11-DIA-03-01-02: For both low (W^{46+} at 2.4 keV) and high (Ni^{26+} at 7.8 keV) photon energy diagnostic channels two T-GEM detectors with 100x100 mm2 detection area and 128 strip channels each. Two materials are proposed as final detector windows, namely Mylar 5 µm + Al 0.2 µm (M5Al) and Mylar 12 µm + Al 0.2 µm (M12Al). The final detector windows should be supported by two slabs (0.8 mm in diameter) installed on the outer side of the window. As a working gas the ArCO2 (70:30) gas mixture with 15 mm thickness of gas-mixture layer has been chosen. The expected detector efficiencies are 45% at 2.4 keV (W monitoring channel) and 20% at 7.8 keV (Ni monitoring channel), respectively

WP11-DIA-03-02-01: The usefulness of gateable, MCP-based devices for VUV & SXR imaging purposes has been definitely proved during dense plasma investigations

The electron density of magnetically confined plasma is usually a few orders of magnitude lower than the dense plasmas. Hence, one should expect a very strong decrease in emitted radiation level, which could prevent application of MCP-based imager from working in analog mode of operation (image recording) and simultaneously digital operation mode (photon counting & positioning) would be become much more feasible.

To solve this fundamental problem and measure VUV&SXR radiation level before final MCP-based imager development, we propose to carry out preparatory works, in which a simple arrangement being a first step toward final imaging system is proposed to be applied.

WP11-DIA-03-01-01: The prototype detector will be tested with beta source and proton accelerator. After the series of testing measurements the thin window will be replaced with the working window to perform the tests with 14 MeV neutron source.

WP11-DIA-03-04-01: Each detector was calibrated using the isotopic alpha source (AMR-33, three energy peaks: 5.16, 5.46, 5.80 MeV). Some visible differences in the responses of the diamond detectors for the ions with lower energies have been observed.

Collaboration

Association EURATOM–CCFE, Culham, United Kingdom
Association EURATOM–CRPP, Lausanne, Switzerland

3.5 Inertial fusion energy “keep-in-touch” activity

Corresponding author **Tadeusz Pisarczyk**
tadeusz.pisarczyk@ipplm.pl

Introduction

In experiment at PALS (Prague Asterix Laser System) the previous research activities were continued, with the aim to improve parameters of plasma stream (jet) produced by cumulative acceleration of a thin, conically shaped, foil. This method of plasma jet creation is so called the RAS method (Reversed Acceleration Scheme) [1].

Our past investigations concerned the direct [2] and indirect methods of plasma jet generation using for this reason the conically shaped foils [3]. The direct method is that the cone is irradiated directly by a laser beam. In the latter case the foil cone is irradiated by an ablative plasma produced from the massive target placed behind the cone. In both the cases, however, it is crucial to match the foil thickness to the laser energy so that melting and evaporation of the foil appears before its acceleration. It allows to avoid acceleration of the solid cone. This condition is very difficult to be fulfilled. Therefore, to get the plasma jet with a good quality it is necessary to examine several cones with different thicknesses at the same laser energy. Unfortunately, because of technical problems we can only use the thinnest foil with a 10 µm thickness. So, the results obtained by both the methods used are rather moderate. Even if the laser energy is enough for cone evaporation, its acceleration is not effective. This is why we have proposed a new method of plasma jet forming with the use of the foil cone, however modified by its connection with the pressure cavity. The ablative plasma pressure is here employed as an additional accelerator.

Experimental results

The target construction being combination of the Al foil cone and the pressure cavity is shown in Fig 1. To recognize this target potential, in this preliminary experiment dimensions of the pressure cavity were taken without deeper analysis. Investigations were carried out at the PALS (Prague Asterix Laser System) iodine laser system. The laser beam passes through a small hole in the pressure cavity and heats the cone. To irradiate the target the first harmonic of laser radiation (λ =1315 nm) with energy about 500 J in a pulse of 250 ps width was used. The main diagnostic tool used in the experiment was a 3-frame interferometric system, allowing to obtain a sequence of interferograms with a time interval of 3 ns between them. Additionally, 4-frame x-ray frame camera with an exposure time below 2 ns was used.

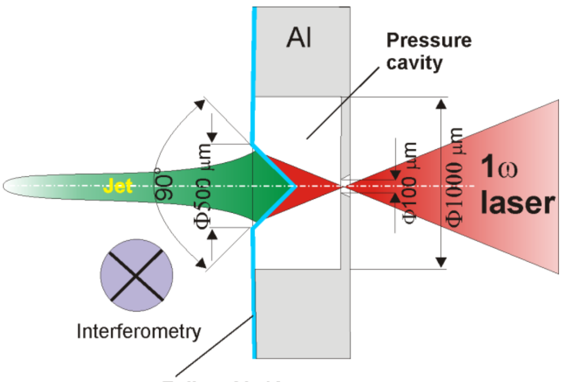

Fig. 5 Target construction constituting combination of classic and pressure methods.

The preliminary results are not satisfactory. Although we can observe the plasma stream generation, however its parameters (especially its velocity) are not yet acceptable. It seems that a failure reason is the incorrect target dimensions. First of all, the foil thickness should be smaller. May be, the pressure cavity volume is also too great and a distance between the hole and the cone, which is crucial for the target irradiation, is not proper too. So, to do such target with great accuracy, optimization simulations and advanced technology are necessary.

Conclusions

This preliminary experiment has shown that in order to obtain the good quality plasma stream by means of this new method, optimization research (numerical simulations) is necessary to determine parameters of proposed construction of the targets, e.g. thickness of foil, cone dimensions and angle, dimensions of pressure cavity with respect to laser energy and the like. Such numerical simulations, done with 2D magneto-hydrodynamical codes, are planned to be undertaken by theoretical teams from Lebedev Physical Institute in Moscow and Bordeaux University (Centre Lasers Intense et Applications-CELIA).

Collaboration

Association EURATOM–IPP/ASCR, Prague, Czech Republic
Czech Technical University in Prague, FEE, Prague, Czech Republic
P.N. Lebedev Physical Institute of RAS, 53 Leninsky Ave., 119 991 Moscow, Russia
Bordeaux University (Centre Lasers Intenses et Applications-CELIA).

References

[1] S. Borodziuk, A. Kasperczuk, T. Pisarczyk, J. Badziak, T. Chodukowski, J. Ullschmied. E. Krousky, K. Masek, M. Pfeifer, K. Rohlena, J. Skala, and P. Pisarczyk: Cavity pressure acceleration: An efficient laser-based method of production of high-velocity macroparticles. Applied Physics Letters 95, 231501/1-3 (2009).

[2] P. Velarde, F. Ogando, S. Eliezer, J. M. Martinez-Val, J. M. Perlado, and M. Murakami: Comparison between jet collision and shell impact concepts for fast ignition. Laser Part. Beams 23, 43-46 (2005).

[3] A. Kasperczuk, T. Pisarczyk, J. Badziak, S. Borodziuk, T. Chodukowski, N.N. Demchenko, S.Yu. Guskov, J. Ullschmied, E. Krousky, K. Masek, M. Pfeifer, K. Rohlena, J. Skala, and P. Pisarczyk: Testing of possibility of plasma jet creation by direct and indirect irradiations of conically shaped foils. 37th EPS Conference on Plasma Physics, Dublin, Ireland 2010.