3 Physics and Technology of Fusion

The activity on the physics of fusion plasmas was carried on along three main lines: theory and modelling of tokamaks, plasma-wall interaction and development of plasma diagnostics. Technology works were devoted to the development of material science and advanced materials for DEMO and to the technology developments related to techniques for controlling tritium inventory. Inertial fusion energy (IFE) "keep-in-touch" activity was focused on the analysis of emerging options of IFE on the basis of results of experiments and numerical modelling.

- **Theory and modelling of tokamaks**
  - Support to the advancement of the ITER Physics Basis
    Including:
    - Numerical analyses of impurity seeded plasma discharges in JET ILW configuration with the help of the COREDIV code
    - Numerical simulations with the TECXY code of different divertor concepts for the FAST tokamak. Analyses of the snow-flake divertor
    - Verification and validation of ETS. Physics application of the ETS and ITM tools
    - Nonlinear dynamics of fast ion driven plasma modes near instability threshold – theoretical basis for integrated tokamak modelling
    - Modeling of the spectrum structure for N-like (W67+) through Na-like (W63+) tungsten ions
  - Activities in support to the DEMO design
    Including:
    - Modelling of the DEMO reactor with the help of COREDIV code
    - Calculation of radiation profiles inside the separatrix
    - Novel Divertor Magnetic Configurations: Assessment of physics basis
    - Neutron heating at the inboard divertor rail
    - Monte Carlo Codes Comparision for neutronnic analysis
    - Assessment of ANSYS non-linear analysis capabilities
  - Produce models and perform analysis of candidate design
  - Support to the users of the ITM framework and for fusion modelling
    Including:
    - Core Programming Team
    - Participation in the work of the HLST
    - Support to the users of the ITM platform
- **Plasma wall interaction**
  - Extending knowledgebase on fuel release (and retention) of Be-containing mixed materials
  - Assessment of Fuel Removal Methods and Dust Generation
  - Assessment of Fuel Removal Methods and Dust Generation dust collection in aerogels
  - High power ICRF with high Z Wall
  - Improvement of understanding of (enhanced) gross and net erosion

- Providing input for dust sampled in present-day fusion devices
- Microscopic investigation of radiation damage in tungsten and its influence on deuterium retention

- **Fusion plasma diagnostics**
  - Applications of solid-state nuclear track detectors (SSNTDs) for fast ion and fusion reaction product measurements in tokamaks (TEXTOR, MAST, ASDEX)
  - Cherenkov detectors for fast electron measurements: new diagnostics for Tore-Supra and other MCF
  - CVD diamond detectors for plasma measurements
  - Detection of the delayed neutrons from activation of fissionable materials in the neutron field at fusion-plasma devices
  - Development of soft X-ray triple GEM gas detector for energy resolved soft X-ray plasma diagnostics
  - Construction and performances of prototype T-GEM Detector
  - Gateable MCP based Camera for VUV and Soft X-ray Imaging of Magnetically Confined Plasma
  - Multi-parameter gradient procedure for polarimetry data inversion in tokamak plasma
  - Prototype GEM neutron yield monitor as an indicator of fast particle confinement and fuel ratio determination in tokamaks
  - GEM KX1 detectors - construction and their performance
  - Study of LaBr3:Ce, CeBr3 and NaI(Tl) Scintillators for Gamma Camera for Plasma Monitoring in JET/ITER Tokamaks

- **Emerging technologies**
  - Techniques for controlling tritium inventory
    - Detection of the chemical components of ITER relevant (co)deposits by the LIBS investigation of calibrated samples in various irradiation conditions
  - Development of material science and advanced materials for DEMO
    - Development of W-Ta composites as long-term structural materials
    - Modelling of structure and properties of grain boundaries in iron
    - Optimisation of thermo-mechanical treatment of nano-structured ODS ferritic steel

    - Mössbauer spectroscopic study of the miscibility gap in Fe-Cr alloy system
    - Short-Range Order in Fe-Rich Fe-Cr Alloys with different thermal history
    - Formation energy of the σ-phase in the Fe-Mo alloy system
    - Effect of metallurgical state of samples on the kinetics of the sigma-phase formation in Fe-Cr alloy system

- **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 Theory and modelling

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Introduction

The activity of the IPPLM Euratom association in theory and modelling covers very broad list of subjects. The research work devoted to tokamak modelling is focused on edge plasma physics, plasma wall-interactions and core-edge coupling studies. This activity expresses the experience of the IPPLM theory group in the theoretical investigations of plasmas in toroidal devices and is aimed at the developing of validated models and numerical codes for present day tokamaks and for the ITER and DEMO reactors. It is based on extensive co-operation with European Fusion Laboratories (JET, TEXTOR, FTU, JET, Tore Supra) regarding the theoretical investigations of the edge plasma and interpretation of experimental measurements. Important part of our research program is devoted to the development of numerical models and codes for ITER and DEMO, in particular global models being able to describe self-consistently burning plasma in fusion reactors. In that respect we participate in the ITM TF and contribute to the development of the European Transport Solver (ETS) and provide support to the users of ITM tools.

The main research results obtained in 2012 are shortly summarized below and more detailed information can be found in corresponding reports.

Numerical analyses of plasma discharges in JET ILW configuration.

The code COREDIV describing self consistently the core and scrape off layer has been used to analyse a number of the L-mode and H-mode JET discharges with tungsten divertor and beryllium wall. The three well diagnosed L-mode discharges heated by ICRF at a power level of P_{ICRH} = 3 MW and with central line average density n_e = 1.65, 2.3 and 2.8 x 10^{19} m^{-3}, respectively, have been chosen (JET shots: 80896, 80889, 8089). Comparison of simulations with experimental data both of the core and of the SOL is generally quite satisfactory, with the exception of Z_{eff} for discharges at very low density, possibly due to radiofrequency-specific effects which are not accounted for in the model. For H-mode discharges, three JET H-mode (shots 82031-33) discharges with similar profiles for densities and temperatures and Z_{eff} but different radiation have been considered. The attempts have been made to adjust the parameters external to the code and not precisely determined by the diagnostics in order to obtain agreement between calculated and experimental data. The influence of the electron density at the separatrix and the radial diffusion coefficients in the SOL on the radiation has been studied. The results have shown that by modifying the above parameters the discrepancies in radiation can be reduced

Participation in ITM project (Integrated Tokamak Modelling.

A substantial part of the present ITM-TF activities is dedicated to the verification and validation of the developed tools and integrated workflows. The module for calculations of the impurity evolution in time has been verified by comparing the results of ETS with the results of JETTO/SANCO code. The very good agreement between two codes has been found. The module for neutrals transport in core has been verified using the comparison with ASTRA code. Despite the fact that in ETS diffusion model for neutrals and in ASTRA kinetic model are used the agreement between two codes is reasonable. The ETS was also tested for impurities by performing the simulation of JET discharge 81856. In this shot there are two phases, first with ICRH heating and the second with NBI heating. The power of the additional heating in both phases is the same but the two phases differ strongly in radiated power. In calculations, the following impurities are taken into account: Beryl, Nickel and Tungsten. The nickel concentration at separatrix in both phases is taken from experimental measurements. The calculated nickel radiation agrees well with experimental data. The experimental data show that the concentration of Nickel is three times bigger in ICRH phase than in NBI phase. The concentration of tungsten has been adjusted to get the agreement for the radiation. An agreement in total radiation can be achieved if also the similar tendency as for Nickel is present for Tungsten concentration. The sputtering of Tungsten by Nickel can be a possible mechanism explaining the increase of Tungsten concentration in ICRH phase.

Informatics supports necessary to accomplish final goal of ITM project.

The main goal of this activity was to provide informatics support for the fusion modelling. This activity was realized within following tasks:

- Core Programming Team - full-time support action for ISIP (Infrastructure Software Integration Project) of ITM TF

  Core Programming Team contributed to the three main ISIP missions: support to users, documentation and training, maintenance and upgrade of the existing tools, development of new tools / features for the ITM-TF platform.
- Participation to the work of the HLST (High Level Support Team)

  The main task of HLST "Deploying strategies for HPC and GRID execution of components and workflows" covered design, implementation and benchmarking of the advanced usage of whole ITM workflows in a parallel or distributed computing environment.
- Support the users of the ITM platform: provision of tutorials on ITM tools and Kepler during ITM general meeting and code camps

Analyses of nonlinear dynamics of fast ions driven plasma modes near instability threshold. Comparison of the result of the kinetic approach and modified Fermi model

The activity concerning the project is focused on the investigations of wave instabilities driven by energetic ions in fusion plasma. To perform the work, two classes of models have been used, namely: 1) the Fermi-like models which are numerical simulations modelling in simplified way the wave-particle interaction 2) the Berk-Breizman model, the class of analytical nonlinear models describing in kinetic approach the wave-particle interaction in systems close to linear instability threshold. In both models, an intrinsic damping in the system and relaxation processes ("collisions") in the presence of steady source have been included. The results of the Fermi-like model have been compared with the known solutions of one-mode Berk-Breizman model. Moreover, using analytical approach also some generalization of the one-mode Berk-Breizman model to the N-mode case was proposed. The 10-mode equations have been examined numerically.

Modelling of the spectrum structure for N-like (W^{67+}) through Na-like (W^{63+}) tungsten ions anticipated to be emitted in ITER plasma motivated by the high-resolution x-ray diagnostics.

The main objective of the work has been the computations of the plasma's L x-ray line structures for the tungsten ions. The results are presented for the ions, that are thought to be most important for the high-resolution x-ray plasma diagnostics to be developed at ITER, the N-like (W^{67+}) through Na-like (W^{63+}). The spectra were computed with the FAC code. As a sanity check, the energy of selected transitions has been recomputed: n=2 →n'=2, n=3→n'=3 and n=3→n'=2 (called as L x-ray lines) by means of the GRASP2K code. Both codes gave results that are close to each other and to the best available measured values.

Modelling of the DEMO reactor with the help of COREDIV code. Calculation of radiation profiles inside the separatrix.

Several DEMO design concepts, obtained by system code PROCESS, have been analysed with the help of COREDIV code, which describes self consistently tokamak plasma in the he core and the scrape off layer with the divertor regions (SOL).
The reduction of divertor target power load due to radiation of sputtered and externally seeded impurities in fusion reactor was investigated. Calculations were performed for inductive DEMO and steady-state scenarios with tungsten walls and Ar/Ne seeding. As the results of numerical calculation, the following conclusion can be derived:

- For all considered DEMO scenarios significant fusion power can be achieved. Increase of seeded impurity influx leads to the reduction of fusion power and Q-factor due to plasma dilution. Helium contributes predominantly to Zeff.
- Total radiation is almost independent on gas puff level and is dominated by core radiation (> 90%: W+Bremst.+Synch). W radiates predominantly inside separatrix. The radiation due to seeding impurity is small and the results are weakly affected by seeded impurity type.
- For pulsed DEMO concepts, accessible seeding level is limited. There is no steady state solution for stronger puffing. The solution terminates due to helium accumulation, if confirmed by more detailed investigations, might strongly affect DEMO design.
- **T**he differences between COREDIV and PROCESS results should be analysed and possibly leads to some modification of assumptions used in Process/COREDIV

Monte-Carlo analyses application to DEMO. Testing the Monte-Carlo methods. Calculation of neutron heating in inboard divertor rail for various rail concepts.

Distribution of the nuclear heating and the helium production in the area between the blanket and the divertor were calculated with the MCNP5 code for the reference case when the DEMO original geometry was unchanged. Next, a segment of the divertor and the lower part of the blanket were modified. Two new arrangements were investigated. The simulations show, that depending on the configuration, the helium production and the nuclear heating can be reduced roughly three or even four times in the examined area. In addition, the nuclear heating and the He production were estimated at the fastener (bolt head).

A comparison of simple calculations of neutron transport performed using FLUKA and MCNP codes has been done. The results allow concluding that FLUKA code gives good results and can be added to the shortlist of codes intended for benchmark analyses in the frame of DEMO project.

Evaluation of nonlinear analyses capability of ANSYS platform to investigate the material properties under the stress within the nonlinear material model

In the work, the evaluation of the non-linear analyses capabilities of ANSYS platform has been done. For the comparison purposes a non-linear material model has been considered, previously developed under ABAQUS code by KIT. It was assumed that only a combination of the already available options for material modelling in the ANSYS package would be used. The calculations performed have shown that up to 90% of the experimentally recorded material behaviour under specific loading conditions (strain-controlled low cycle fatigue (LCF) in elevated temperatures) can be accurately modelled with ANSYS using standard commands.

Numerical simulations with the TECXY code of different divertor concepts for the FAST tokamak. Analyses of the snow-flake divertor.

The comparison between the snowflake and the conventional divertor has been carried out with the 2D edge code TECXY in the case of the FAST project. The code takes into account all the plasma physics effects occurring in the scrape off layer but simplifies the overall neutral dynamics, considering a simple geometry for the divertor plates and an analytical model for the neutrals recycling.
The parameter space explored with the present study has allowed to identify the reason for strong extra mitigation of heat loads in snow-flake divertor configuration that adds on top of the topological effects. It is mostly the longer time spent by the travelling particles in the divertor because of the much longer magnetic lines. The consequent cooling and hence slowing down also triggers two positive feedbacks: more dwell time is available for interacting with the neutral and for diffusing in radial direction. This mechanism not only produces volume effects, but it is the fundament also of the very large peak load reduction, since it is particularly effective for the magnetic lines adjacent to the separatrix. Nevertheless, a minimum neutrals density is required to raise these effects to a significant level. Indeed, for the low density AT scenario, the mitigation is dictated mostly by the topological

effects. With the present investigation it has been also checked that one of the most weak point of the modelling, namely the neutral dynamics, is not so critical. Indeed varying the recycling coefficient to the point of changing the particle flux entering the SOL by a factor 10, no significant variation is obtained in the results. Nevertheless, these very appealing properties of the snow flake configuration need to be confirmed by a more accurate modelling of the plasma edge that takes into account the actual divertor geometry, including the very important private region, the divertor pumping and the real neutral dynamics.

Collaboration

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3.2 Plasma-Wall Interaction

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Introduction

The work conducted in the framework of the Plasma Wall Interaction included activities in the area of the following EFDA tasks:

- WP12-IPH-A01-3-06/IPPLM Extending knowledgebase on fuel release (and retention) of Be-containing mixed materials
- WP12-IPH-A03-2-04/IPPLM Investigation of surface effects and dust production in fiber-laser fuel removal treatment
- WP12-IPH-A03-2-08/IPPLM Characterization of laser ablated dust, including measurements of velocity and fuel content of single dust particle
- WP12-IPH-A11-3-03/IPPLM High power ICRF with high Z Wall
- WP12-IPH-A01-1-08/IPPLM Improvement of understanding of (enhanced) gross and net erosion
- WP12-IPH-A03-2-09/IPPLM Providing input for dust sampled in present-day fusion devices
- WP12-IPH-A03-1-08/IPPLM Microscopic investigation of radiation damage in tungsten and its influence on deuterium retention

All tasks are based on material research of samples from tokamak or samples treated by laser pulses as well as are based on dust analysis.

Results

The conducted research allows to state that the aluminium is the closest proxy for beryllium in terms of research aimed at the investigation of materials for PFC in fusion reactors, but the straightforward interpretation of the results obtained for Al as if they were obtained for Be cannot be recommended. On the other hand, the experiments on the aluminium may give a good view of general behaviour of beryllium subjected to the same experimental conditions.

The research showed that the application of the fibre laser can make the cleaning process more effective than it was in case of the Nd:YAG laser and reduces the risk of the damage of the substrate material as well as the dust generation. This advantage of the fibre laser was especially observed for 9.6×10^5 W/cm^2 and lower power densities in the case of investigation of W:Al:C layer of atomic ratio 1:1.6:2.4. Another valuable observation was that images taken by a CCD camera during the laser pulse interaction with the material showed that application of Yb:fiber laser does not create macroscopic dust like it was observed using high power density Nd:YAG laser.

The experiments with aerogels confirmed that CCD observation of the laser produced dust particles is a usable technique and allows for assessment of basic parameters of the dust. It has been also shown that aerogel dust collectors are a possible device for dust diagnostics as good collectors for post-mortem analysis.

The impurity release during Ion Cyclotron Resonance Heating (ICRF) operation was investigated in the full Tungsten (W) wall ASDEX Upgrade (AUG) tokamak. This contribution mainly focuses on documenting the W behaviour in the plasma. Long-term observation of W concentration in AUG plasma during ICRH showed reduction of the W content in the plasma with pulse number. Results of the experiments carried out on AUG aiming at the characterization of the effect of different gasses injection such as deuterium, neon and argon, on W release is presented. In all cases the increase of gas injection rate caused decrease in the W concentration. The experiments with the boron-coated ICRH antennas limiters confirmed the dominant role of the limiters as W sources and showed an improved operation with the W-wall. Additionally in ICRH discharges, the influence of the plasma shape was investigated. At higher plasma outermost position, when the plasma was closer to the antenna, the higher W concentration was observed.

The investigations of two samples from a bulk tungsten tile (from Bgr. 1) exposed at the outer strike point during the 2010/2011 campaign in ASDEX Upgrade, revealed the grinding/machining marks on the small sample. No evidence of surface damage or co-deposition was found. The surface of the large sample is distinctly smoother and the machining marks are hardly visible. It is covered by a deposit of stratified character. Two large cracks were found at the surface. The long transverse crack (to the longer tile side) crosses almost entire samples thickness. Additionally, the transverse "scratch-like" cracks and cracks with the deposit built up were found. At the surface thin, "veins-like" cracks were also present.

The part of the research in frame of the PWI was to characterize the dust collected in ASDEX Upgrade, with the special emphasis on size, morphology, structure and composition of the dust particles. The dust particles were collected after 2009 campaign using the filtered vacuum technique. The structure and composition of the particles were examined by HRSEM combined with EDS and FIB with special interest on the tungsten particles. The aim of the investigations was to obtain information on the origin of dust particles and to broaden the knowledge about relevant processes of dust formation.

TEM investigations of neutron-like damage in tungsten simulated by 20 MeV $W6^{+}$ implantation were performed. The influence of radiation dose on the microstructure development was observed. With increasing damage level the density of the irradiation defects increases up to the 0.1 dpa. A further implantation lead to rearrangement of the defects and defect density decrease is observed in the mid-zone of the damaged layer. The driving force of this observed defects rearrangement is believed to be solely related to the ion implantation process and can be attributed to the atomic jumps described in the thermal spike model.

Conclusions

Application of the fibre laser can make the cleaning process more effective than it was in case of the Nd:YAG laser and reduces the risk of the damage of the substrate material as well as the dust generation. Performed experiments showed that aerogels are a possible device for dust diagnostics as good collectors for post-mortem analysis.

Analyses of the ICRF antennas in ASDEX Upgrade with boron-coated limiter have shown an improved operation with the W-wall. Spectroscopic measurements indicated lower rise of W concentration in the plasma with ICRF power.

The dust collected in ASDEX Upgrade were examined by HRSEM combined with EDS and FIB with special interest on the tungsten particles. The following types of these particles were distinguished: spherical, flakes, irregular, multiphase ones, fine particles present at/inside the large ones and porous.

In the research, TEM investigations of neutron-like damage in tungsten simulated by 20 MeV $W6^{+}$ implantation were performed. The influence of radiation dose on the microstructure development was observed.

Collaboration

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References

[1] M. Kubkowska, P. Gąsior, E. Kowalska-Strzęciwilk et al. J. Nucl. Mat., 2013, *in press*
[2] M. Balden, V. Rohde et. al. PSI Conference 2012
[3] H. Bergsåker, B. Emmoth, P. Petersson et al., J. Nucl. Mat., 362, 215 (2007)

3.3 Emerging technologies

Techniques for controlling tritium inventory

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Introduction

The work conducted in the framework of the Emerging Technology included activities in the area of two EFDA tasks: WP11-DIA-02-02-01/IPPLM and WP11-ETS-DTM-01-05/IPPLM which were continued from 2011.

In frame of the first task, a fast Fourier Transform (FFT) based algorithm has been developed to interpret the speckle interferometry measurements of erosion under mechanical vibrations of few tenths of mm in amplitude and of hundreds of Hz to KHz frequency range. The task considered the possibility of the application of digital signal processing in speckle interferometry (a technique which in the previous year was proposed as a candidate method for erosion measurements in the ITER divertor).

The research in 2012 in frame of the second task was mainly focused on qualification of the LIBS applicability for characterization of samples with ITER relevant material mix. Research included investigation of calibrated samples in order to assess the possibility of conducting measurements of fuel inventory in in-vessel reactor components.

Results

Methods for measuring the fuel retention and characterization of the wall deposition in ITER and other future thermonuclear devices have high priority in EFDA programme. Several laser techniques, like LIBS (Laser Induced Breakdown Spectroscopy), LIDS (Laser Induced Desorption Spectroscopy) or LIAS (Laser Induced Ablation Spectroscopy) are considered as candidates for measurements of tritium as well as erosion and deposition of reactor wall materials. Moreover, the LIBS method which is under investigation at IPPLM is appropriate for characterization of chemical composition of ablated materials.

In 2012, a set of mixed W:Al:C and diamond-like carbon (DLC) layers with two different Deuterium content were prepared on W substrates by vacuum deposition. The LIBS signals obtained from the samples over a range of energy densities from 2-30 J/cm^2, showed consistent features as a function of the laser pulse number (pulses of few ns and spot sizes of 2-3 mm^2). The experiments showed a quite similar evolution of the Al, C and W signals up to the complete ablation of the layer. Fig. 1 shows a typical evolution of the normalized intensity of Carbon and Tungsten spectral lines with the number of laser pulses.

In part of experiments W:Al:C samples have been investigated in order to perform slope analysis []. All data have been subject to absolute calibration and then, based on the intensity of ionic lines, the depth profiles have been derived. The intensity of the tungsten line has been used for normalization of carbon and aluminium ionic lines. Analysis showed that after 10 shots which remove the most of the layer, Aluminium and Carbon lines drop quickly while the intensity of the Tungsten line increases.

Based on these results, the chemical contents of the sample was assessed as: 52% C, 41 % Al, 7% W. It is worth mentioning that the slopes of the components well correspond to the composition of the layer given by the manufacturer.

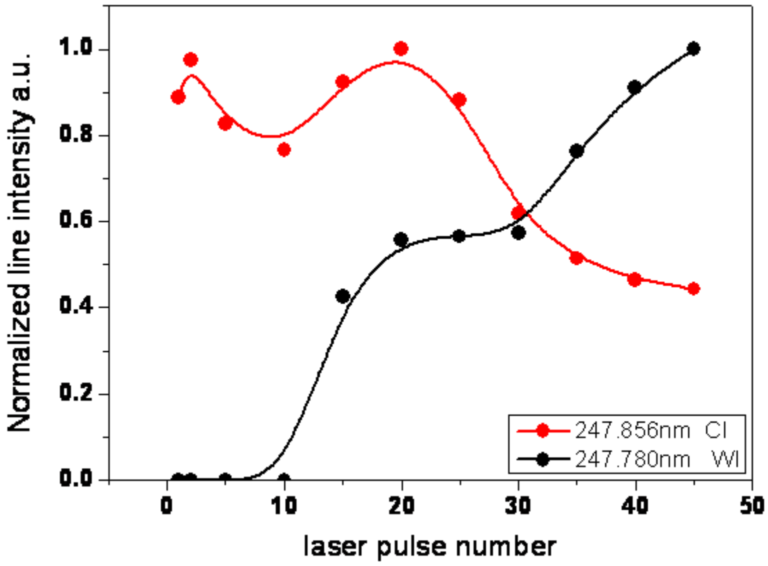

Fig.1. Evolution of the normalized intensity of CI and WI spectral lines with the number of laser pulses.

Concerning the analysis of deuterium line, it appears that it was present only in the first shot for the W:Al:C #D1 sample while small deuterium peaks were observed for first 3-4 shots at the W:Al:C #D3 sample. The measurements suggested that deuterium content was significantly lower than 10 % with rather poor accuracy. This estimation was based on poor amplitude of deuterium line in comparison to other lines and also to the amplitude of deuterium line which was previously measured in deuterium-rich deposits, e.g. from the TEXTOR limiter.

The task on identification of the signal processing method for speckle interferometry was not an experimental task and it was oriented on the literature study and implementation of a preliminary algorithms. In this case, the Least Mean Square filter has been taken into account and algorithm has been proposed.

Conclusions

The experiments performed at the IPPLM showed the relevance of the LIBS method for measuring chemical contents of mixes composed of Aluminium, Tungsten and Carbon as well as for detection of small amounts of deuterium in these mixes. It has been shown that the analysis gives consistent results in vacuum as well as in the ambient atmosphere.

The chemical content of W, Al and C in the W:Al:C sample was assessed with relatively good accuracy, however, it needs to be mentioned that for really reliable analysis more samples with more diverse composition should be investigated.

The trouble with the method originated from a difficulty of reliable analysis of deuterium contents – the provided samples contained too small amounts of deuterium and in too shallow layers to be precisely analysed. The measured deuterium lines had amplitudes incomparably lower than those which were recorded e.g. in the analysis of TEXTOR or AUG co-deposits in very similar experiments. The analysis which was performed with the use of low energy, well-focused laser pulses showed that such pulses are relevant for LIBS measurements and have an advantage of inflicting lower damage to the target with still reliable information of the chemical composition of the top layer.

In the field of the development of algorithms for signal processing for speckle interferometry in vibration conditions [2], a few interesting algorithms have been studied and proposed. Parts of the code for LMS have been developed.

Collaboration

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Association EURATOM – TEKES, Helsinki, Finland
Association EURATOM – DIFFER, FOM Rijnhuizen, Netherlands

References

[1] A. Malaquias, V. Philipps, A. Huber, A. Hakola, J. Likonen, J. Kolehmainen, S. Tervakangas, M. Aints, P. Paris, M. Laan, A. Lissovski, S. Almaviva, L.Caneve, F.Colao, G. Maddaluno, M. Kubkowska, P. Gąsior, H.J. van der Meiden, A.R. Lof, P.A. Zeijlmans van Emmichoven, P. Petersson and M. Rubel, Development of ITER relevant techniques for deposited layer removal and tritium inventory diagnostics under the EFDA Emerging Technologies programme, Journal of Nuclear Materials, 2013 *in press*
[2] P. Doré, E. Gautier, Journal of Nuclear Materials, **363–365**, 1414 (2007)

Development of material science and advanced materials for DEMO

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Introduction

The Association 2012 activities in the area of materials science and advanced materials for DEMO have been implemented via 7 tasks that can be grouped under three type of research, namely:

- Materials Modelling
  - Modelling of structure and properties of grain boundaries in iron (WP12-MAT-01-IREMEV-03-02/IPPLM)
  - Formation energy of the σ-phase in the Fe-Mo alloy system (WP12-MAT-01-IREMEV-01-01)
- Development of materials and materials technology
  - Development of W-Ta Composites as Long-term Structural Materials (WP12-MAT-01-HHFM-03-01)
  - Optimisation of thermo-mechanical treatment of nano-structured ODS ferritic steel (WP12-MAT-01-ODSFS-01-02)
- Materials Characterisation
  - Effect of metallurgical state of samples on the kinetics of the sigma-phase formation in Fe-Cr alloy system (WP12-MAT-01-IREMEV-03-01)
  - Mössbauer spectroscopic study of the miscibility gap in Fe-Cr alloy system (WP12-MAT-01-IREMEV-04-01)
  - Short-Range Order in Fe-rich Fe-Cr Alloys with different thermal history

These tasks have been carried out at AGH University of Science and Technology (AGH) and Materials Science and Engineering Faculty, Warsaw University of Technology (WUT). All the tasks have been performed in the scope of the EFDA Materials work programme under the topics of High Heat Flux Materials, Integrated Radiation Effects Modelling and Experimental Validation and Nano-structured ODS Ferritic Steel Development.

Results

The ***Modelling of structure and properties of grain boundaries in iron*** task was devoted to investigation of mechanical properties of grain boundaries in iron using molecular dynamics simulations. Based on the performed computations it was concluded that the grain boundary misorientation significantly influences its mechanical properties. While the shear modulus is similar for both type of GBs the maximum shear stress is much higher in the case of low-angle grain boundaries. Also strengthening effect is observed for low-angle grain boundaries and does not occur for high-angle ones. In order to analyse the ***Formation energy of the σ-phase in the Fe-Mo alloy system*** semi-ordered unit cells (samples) corresponding to the following two atomic configurations: σ-20812 σ-21824 were modelled. In other words, the first configuration represents an alloy $Fe_{13}Mo_{17}$, and the second one $Fe_{17}Mo_{13}$. Based on the results obtained it can be concluded that the formation energy of the σ-FeMo decreases with Mo content from ~0.46 eV/atom for $Fe_{17}Mo_{13}$ to ~ 0.36 eV/atom for $Fe_{13}Mo_{17}$. ΔE is characteristic of a given lattice site and it depends strongly on the number of Fe atoms, $N_{Fe,}$ in a unit cell for a given composition.

The Development of W-Ta composites as long-term structural materials aimed at the enhancement of fracture toughness of tungsten through the use of the concept of short fibre reinforced composites. The composites have been sintered using Pulse Plasma Sintering (PPS) and bulk tungsten – tantalum composites with relative densities exceeding 90% were produced. The performed experiments allowed to conclude that Pulse Plasma Sintering method can be successfully employed to fabricate high density W-Ta composites. The highest density has been achieved for W Ta (10%fiber) - 98.4% TD. The modification of tungsten powders both by mechanical alloying and admixing of Ta improves the sinterability. The milling process (MA) of tungsten powder leads to sinters grain size reduction and higher sinter density. This year activities in the area of the ***Optimisation of thermo-mechanical treatment of nano-structured ODS ferritic steel*** concerned the influence of HIP pressure on tensile properties (see fig. 1) of the 14Cr ODS ferritic steel. To this end oxide dispersion strengthened ferritic steel powders, with the nominal composition of Fe-14Cr-2W-0.3Ti-0.3Y2O3 (in weight %), were consolidated by hot isostatic pressing at 1150°C under various pressures of 185-300 MPa for 3 h.

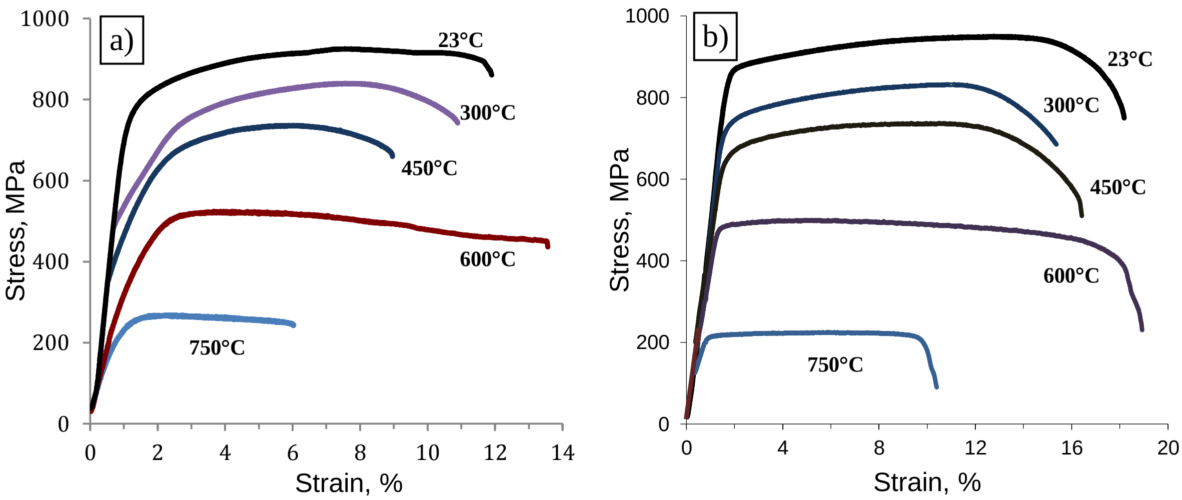

Fig.1. Tensile properties of the ODS ferritic steels as a function of testing temperature a) HIPped under pressure of 200 MPa, b) HIPped under pressure of 300 MPa.

The main results of the work indicated that by increasing the isostatic pressure during HIP process the density of the ODS steel can be improved, however a residual porosity was always observed. The HIPping pressure in the range between 185-300 MPa has negligible influence on the hardness and tensile strength of the ODS steel, however higher processing pressure significantly improves the ductility of the steel.

The Effect of metallurgical state of samples on the kinetics of the sigma-phase formation in Fe-Cr alloy system was studied for plastically deformed bulk samples (10 and 97% deformation caused by cold-rolling) and foils (77-97% deformation) of quasi-equiatomic Fe-Cr alloys ($Fe_{54}Cr_{46}$) using the Mössbauer spectroscopy. The transformation into the sigma-phase was done by isothermal annealing of the samples at 700 ^{o}C

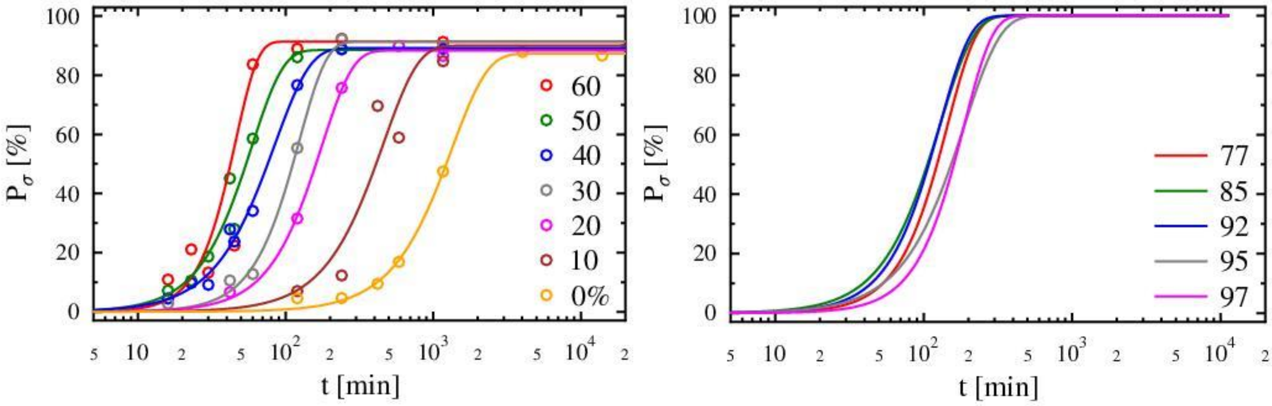

Fig. 2 Kinetics curves versus the annealing time as found from the *ex situ* (left) and *in situ* (right) measurements. The figures displayed on the right-hand side stay for the deformation degree in percentage.

The Mössbauer spectroscopy measurements allowed to prove that internal strain caused by plastic deformation (cold rolling) of the steel has a very significant influence on the kinetics of alpha-sigma phase transformation (see fig. 2). Concurrently, the mechanism responsible for the transformation does not expressively depend on the deformation degree, and its activation energy depends not only on the degree of deformation but also on the thermal history of the samples. Two issues relevant to the miscibility gap in the Fe-Cr alloy system viz. (a) short-range ordering (SRO) and (b) kinetics of the phase decomposition (PD) were studied in the ***Mössbauer spectroscopic study of the miscibility gap in Fe-Cr alloy system***. A redistribution of atoms, caused by an isothermal annealing at 415^{o}C, was traced within the first and the second neighbour shells and quantitatively expressed in terms of the SRO-parameters. It was concluded that annealing of the Fe-Cr14 alloy at 415^{o}C resulted in a clustering of Cr atoms. The time evolution of the SRO-parameters was shown to follow the Johnson-Mehl-Avrami-Kolgomorov (JMAK) equation. The kinetics of PD was studied by following a temperature dependence of the average hyperfine field, <B>, at 415 and 450^{o}C, which was successfully described with the JMAK equation. The activation energy was determined to be 122 kJ/mol. In the study of ***Short-Range Order in Fe-Rich Fe-Cr alloys with different thermal history***, ^{57}Fe Mössbauer spectra were recorded at 295 K in a transmission mode on a series of $Fe_{100-x}Cr_x$ alloys, including the model EFDA alloys. Three different heat treatments T1, T2, and T3 were applied:

- T1 – annealing at 800 ^{0}C for 3 h in argon, followed by quenching into liquid nitrogen.
- T2 – annealing at 800 ^{0}C for 20 h in argon, followed by 2h annealing at 520 ^{0}C, slow (20 h) cooling down to 430 ^{0}C and annealing for 12 h. Finally, the quartz tube was removed from the furnace and the samples moved on brass kept in the cool zone of the tube.
- T3 – vacuum annealing at 415 ^{0}C for different periods followed by a cooling in the tube removed from the furnace.

The results give clear-cut evidence that the actual distribution of Cr atoms in Fe matrix meaningfully depends on thermal history of the samples. In particular, the concentration at which the inversion of the SRO parameter occurs shows such dependence. A rather unexpected finding was that the most significant deviation from randomness was revealed in low-concentrated alloys that underwent a homogenization treatment.

Collaboration

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References

[1] Stadler J., Mikulla R., Trebin H.R. (1997) IMD: A software package for molecular dynamics studies on parallel computers, International Journal of Modern Physics C, Vol. 8, No. 5 (1997) 1131–1140
[2] E. D. Hall, and S. H. Algie, Metall. Rev., 11, 61 (1966)
[3] J.-M. Joubert, Progr. Mater. Sci., 53, 528 (2008)
[4] V. Philipps, J. Nucl. Mater. 415, no.1 (2011) S2
[5] S.H. Chang, S.C. Lee, S.H. Chang, T.P. Tang, H.H. Ho, H.Y. Bor, Effects of the temperature of hot isostatic treatment on Cr–Si targets, Ceramics International 35 (2009) 565–570.
[6] C. Li, Q. Huang, P. Zhang, FDS Team, Preliminary experimental study on Hot Isostatic Pressing diffusion bonding for CLAM/CLAM, Fusion Engineering and Design 82 (2007) 2627–2633.
[7] E. O. Hall, S. H. Algie, Metalurg. Rev., 11 (1966) 61
[8] A. Błachowski, J. Cieślak, S. M. Dubiel, J. Żukrowski, J. Alloys Comp., 308 (2000) 189
[9] A. Błachowski, J. Cieślak, S. M. Dubiel, B. Sepiol, Intermetallics, 8 (2000) 963
[10] G. Sauthoff, W. Speller, Z. Metallkde, 72 (1981) 462
[11] F. C. Pimenta Jr, A. F. Padilha, R. L. Plaut, Mater. Sci. Forum, 426-432 (2003) 1319
[12] I. Mirebeau, M. Hennion, G. Parette, Phys. Rev. Lett. 82, 104203 (2010)
[13] I. Mirebeau, G. Parette, Phys. Rev. B 82, 104203 (2010)
[14] N. P. Filippova, V. A. Shabashov, A. L. Nikolaev, Phys. Met. Metallogr. 90, 145 (2000)
[15] S. M. Dubiel, J. Cieślak, Phys. Rev. B 83, 180202 (R) (2011)
[16] R. Idczak, R. Konieczny, J. Chojcan, J. Phys. Chem. Solids 73, 1095 (2012)

3.4 Fusion plasma diagnostics

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Introduction

The work conducted in the framework of the Plasma Diagnostics in 2012 included activities in the area of multi-parameter gradient procedure for polarimetry data inversion in tokamak plasma; gateable MCP based camera for VUV and soft X-ray imaging of MCF; study of $LaBr_3$:Ce, $CeBr_3$ and NaI(Tl) scintillators for gamma camera for plasma monitoring in tokamaks, Cherenkov, CVD and solid-state nuclear track (SSNTDs) detectors for plasma measurements; detection of the delayed neutrons from activation of fissionable materials in the neutron field at fusion-plasma devices and development of soft X-ray triple GEM gas detector for energy resolved soft X-ray plasma diagnostics as well as a prototype GEM neutron yield monitor as an indicator of fast particle confinement and fuel ratio determination in tokamaks.

Results

Two multi-parameter gradient procedure is suggested which allows fitting tokamak plasma model to polarimetric data. One of the simplest version of gradient procedure deals with four parameters model: maximum values of electron density, maximum value of electric current density in plasma, common radius of electron density and electric current distributions and increment of the safety factor inside plasma. It is worth adding that numerical simulations have approved that gradient procedure provides acceptable accuracy of inversion already after several iterations.

Many scintillation materials were considered for gamma ray monitoring but presented work was focus on study the properties of NaI(Tl), CsI(Tl), $LaBr_3$:Ce and $CeBr_3$ and crystals (10x10x5 mm^3) as a one of the potential scintillators for the gamma ray camera for MHz counting rate measurements. The report summarized the results obtained on the light output, energy resolution, non-proportionality and decay time of the scintillator.

The scCVD diamond detectors of 500 μm thickness are destined for spectrometric measurements of 14 MeV neutrons. They are sensitive also to ions which leave tokamak plasma (in the case when the detector is placed inside the vessel). Therefore, response of the detectors for falling ions was investigated. A very good repeatability of various detector responses was stated. Therefore, a combination of thin and thick detectors is possible to be used in order to get demanded information when the detectors are used in mixed irradiation fields, which will be present at tokamaks.

At the NCBJ CR-39 track detectors and recently the PM-355 derivative of the CR-39 material (C12H18O7) have been used for a long time. Calibration studies of the aforementioned detectors have also been performed at NCBJ for several years. As a result of these studies an extensive collection of data was obtained on the shapes of tracks formed by different projectiles at various their energies. The problem of the track development geometry has been the subject of many studies in 2012.

In 2012, a new two-channel Cherenkov probe with diamond radiators was applied for electron measurements within the ISTTOK experiment. The preliminary measurements by means of the new single-channel measuring head were also performed within the COMPASS (IPP, Prague). The main assumptions of the design of a single-channel measuring head for electron measurements in the FTU tokamak (ENEA, Frascati) were agreed with our Italian partners.

Elaboration of a method of interpretation of the decaying delayed neutron flux from activated fissionable materials was continued in 2012. For this purpose, Monte Carlo simulations were performed to model irradiation of the fissionable samples with neutrons of various energies which can be present at fusion-plasma devices. Then the time decay of the delayed neutrons emitted from the samples was registered. Finally, transport of delayed neutrons from measuring position to detectors in the DET-12 device was simulated and the time distribution of counts was obtained.

For the purpose of detecting X-ray lines intensities from the energy resolved diagnostics two detectors based on Triple GEM amplification followed by the strip readout electrode were developed in order to measure intensities of soft X-ray radiation diffracted by the crystal suitable for the specific soft X-ray energy range. High-resolution X-ray diagnostics for MCF devices is expected to monitor the plasma radiation emitted by W46+ and Ni26+ ions at 7.8 keV and 2.4 keV photon energies, respectively.

To detect the fast neutrons the 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. The detector prototype and radiation source have been used for hardware verification and preliminary development of measurement algorithms implemented in FPGA.

Conclusions

Gradient procedure has approved its efficiency in condition of 4 parameters model it has demonstrated sufficiently fast convergence to “genuine” data and acceptable accuracy. Given the wide possibilities offered by multi-channel polarimetric measurements in combination with the gradient method it seems worth considering the possibility of incorporating the presented procedure into EFIT approach.

All the considered scintillators present high light output. At low energy (below 80 keV) the NaI(Tl) presents the best energy resolution. The best linearity of the gamma response shows $LaBr_3$:Ce. The fastest decay time (~17 ns) from the presented samples present both $LaBr_3$:Ce and $CeBr_3$.

In the case of investigation of CVD detectors, it appears that the manufacturer of the detectors, “Diamond Detectors, Ltd.” stopped the production. We have found another manufacturer, “CIVIDEC”, but this means that some research has to be repeated with use of new series of detectors.

Among several SSNTDs tested in the NCBJ laboratory, the PM-355 detector appeared to be the most suitable for the detection of primary ions and nuclear reaction products. The detector can be recommended as a relatively simple and reliable diagnostic tool for the detection and prompt analysis of many ion species emitted from high-temperature plasma experiments.

The performed measurements at ISTTOK proved that the Cherenkov probe with diamond radiators can successfully be applied for studies of fast electron beams inside medium-sized tokamaks. It was shown that outside the toroidal plasma column, there can be detected fast run-away electrons, and the Cherenkov radiators (separated by a 5-mm distance) can record well correlated electron-induced signals.

Response of the DET-12 device for the delayed neutrons emitted from samples of fissionable materials irradiated with primary neutrons from a fusion-plasma device was obtained with the Mote Carlo method. For each sample, the ratio of the count rate distribution in DET-12 to the emitted delayed neutron flux is constant in time. This allows relying on registered count rate time distributions to proceed with elaboration of the interpretation method.

For low at 2.4 keV (W^{46+}) and high-energy at 7.8 keV photon energy (Ni^{26+}) diagnostic channels two T-GEM detectors with 206x92 mm^2 detection area and 256 strip channels each have been constructed. Two materials are considered as final detector windows, namely Mylar 5 µm + Al 0.2 µm for W monitoring and Mylar 12 µm + Al 0.2 µm for Ni monitoring. The expected detector efficiencies are 45% at 2.4 keV (W monitoring channel) and 20% at 7.8 keV (Ni monitoring channel), respectively.

In case of the GEM neutron yield monitor the activation materials for 2.5 and 14 MeV neutrons have been selected. The calibration and computational procedure has been established. It has been tested for 2.5 MeV neutrons beryllium activation counter based on gas proportional detector. Test measurements of 2.5 MeV neutron yield from DD reaction have been performed on the PF-1000 device. The results are in agreement with standard neutron diagnostics. The prototype GEM detector for measurements of charged particles has been assembled. Suitable Monte Carlo calculations of charged particles transport have been done. Test measurements of β-radioactive source by constructed 3 GEM detector have been performed.

Collaboration

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3.5 Inertial fusion energy "keep-in-touch" activity

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Introduction

The Inertial Fusion Energy (IFE) "keep-in-touch" activity in 2012 involved the following tasks:

1. To analyse the prospects of emerging options of IFE on the basis of results of experiments and numerical modelling (Task 7.1 in the Work Programme 2012 of the Contract of Association).
2. To inform the wider fusion community of developments in IFE through publications, conference presentation, seminars, and workshops (Task 7.4 in the Work Programme 2012).

The first task involved research on the laser-driven acceleration of dense plasma projectiles, which is of interest from the point of view of the fast ignition of the inertial fusion targets [1,2]. Another line of research discussed within this task was the production of plasma jets via laser irradiation of solid foils [3,4].

Activities relevant for the second task involved publication of an extensive review article on the current state of the inertial confinement fusion research [5], and a lecture on current issues in the domain of ion fast ignition of inertial fusion targets, presented at the 2012 Kudowa Summer School [6].

Results

One of the outstanding issues in the domain of fast ignition of inertial fusion targets is the problem of efficient conversion of laser energy into the energy of igniting plasma bunch. It is usually assumed that in order to obtain a realistic ignition scheme the laser-to-ion energy conversion efficiency should be above 10%. Unfortunately, so far this proved difficult to achieve. An original method to increase this efficiency was proposed by the IPPLM laser plasma group. It is based on the observation that at high intensities a significant part of the incident laser energy is reflected from the target. It was therefore proposed to enclose the target in a cavity, so that the laser light reflected from the target would be redirected towards the target via reflection at the inner cavity wall. This method was dubbed laser induced cavity pressure acceleration (LICPA). The LICPA approach gave very good results in experiments on plasma acceleration at laser intensities of the order of 10^{16} W/cm^2 [1], relevant for the impact ignition, so it was tempting to test this approach at much higher intensities, of the order of 10^{20}-10^{21} W/cm^2, which are relevant for the ion fast ignition [1,2].

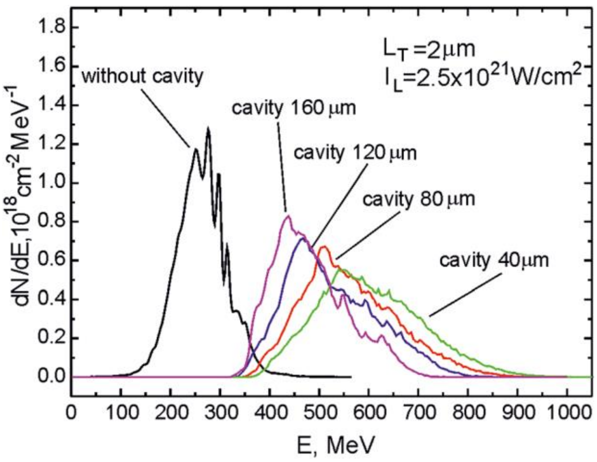

Fig. 1. Energy spectra of carbon ions accelerated according to the LICPA method with cavity depth varying from 160 µm to 40 µm, compared with the spectrum obtained in the absence cavity. The carbon foil was 2 µm thick, the laser intensity was 2.5×10^{21} W/cm^2 and the acceleration length was 150 µm.

To this end, a numeric simulation was performed of laser the interaction with a solid target enclosed in a cavity. At such high intensities and short durations of the laser pulse plasma is essentially collisionless. Dynamics of such plasma lends itself well to modelling using the Particle-in-Cell (PIC) method, in which the ion and electron distributions are discretized and approximated by the distribution of macroparticles interacting via electromagnetic fields. Because of high numerical complexity of the considered problem, it was assumed initially that all plasma parameters depend only on one spatial variable (although all three components of plasma velocities were retained). The PIC code created for this simulation takes fully into account the relativistic character of macroparticle dynamics and of the electromagnetic fields created by them. A thorough investigation was performed for the carbon target [2], since carbon ion beams are a very serious candidate for the fast ion ignition. It was found that the use of the LICPA mechanism results in a nearly doubling of the average ion energy in the beam, although the energy dispersion is also slightly bigger.

As for the creation of plasma jets [3,4], an attempt was made to use composite multi-layer targets consisting of a thin metal foil (Cu) and a plastic foil (Fig. 2). The expectation was that radial expansion of metallic plasma would be constrained by the influence of light plastic plasma (CH), which was shown in previous experiments to achieve higher pressure. For this scheme to succeed, the metal foil had to be thin enough so as to evaporate under the influence of the laser pulse, which implied thickness in the range of 1 µm for the Cu foil. The relation between pressures of the metal plasma and the plastic plasma could be controlled by varying the thickness of plastic (CH) layer: arrangements with 1, 2, 4 and 6 µm plastic layers were examined.

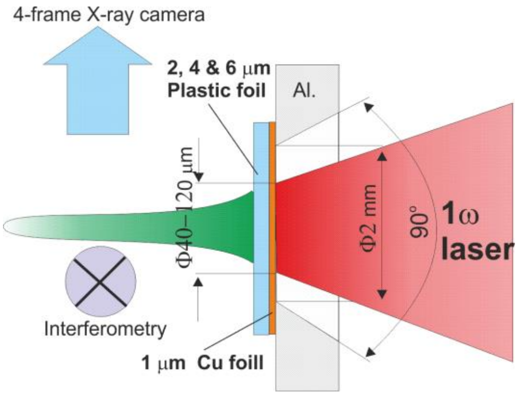

Fig. 2. A schematic illustration of generation of collimated plasma jets using composite targets consisting of a thin metal foil (Al or Cu) and a plastic foil.

The most interesting result was obtained for a combination of 1 µm Cu foil and 2 µm plastic foil. The sequence of electron density distributions obtained in this case at various times confirms the expectations concerning the influence of the higher pressure plastic plasma on the Cu plasma, which resulted in the formation of a collimated jet. The stream of metal plasma reaches the speed of 4×10^{7} cm/s, with the electron number density reaching values of the order of 10^{18}-10^{19} cm^{-3}.

Conclusions

Results of PIC simulations of the cavity-enhanced laser acceleration of ions (the LICPA mechanism) in one dimensional model are very encouraging. It would be of great interest to confront these results with the simulations carried out in two spatial dimensions, which are however much more demanding from the numerical point of view. It seems also that it would be very interesting to perform an experiment on cavity-enhanced ion acceleration using a laser delivering intensities in the range of 10^{20}-10^{21} W/cm^{2} and the pulse energy of tens of joules.

Concerning the formation of plasma jets, it seems that better results could be obtained if Cu foils of 0.1 µm thickness were used. Unfortunately, manufacturing of such ultra-thin foils is beyond present technical capabilities of IPPLM.

Collaboration

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References

[1] J. Badziak, S. Jabłoński, T. Pisarczyk, P. Rączka, E. Krousky, R. Liska, M. Kucharik, T. Chodukowski, Z. Kalinowska, P. Parys, M. Rosiński, S. Borodziuk, J. Ullschmied, *Highly efficient accelerator of dense matter using laser-induced cavity pressure acceleration,* Phys. Plasmas **19**, 053105 (2012).

[2] J. Badziak, S. Jabłoński, P. Rączka, *Highly efficient generation of ultraintense high-energy ion beams using laser-induced cavity pressure acceleration,* Appl. Phys. Lett. **101**, 084102 (2012).

[3] A. Kasperczuk, T. Pisarczyk, T. Chodukowski, Z. Kalinowska, P. Parys, O. Renner, S. Yu. Gus'Kov, N. N. Demchenko, J. Ullschmied, E. Krousky, M. Pfeifer and K. Rohlena: *Laser-produced aluminium plasma expansion inside a plastic plasma envelope,* Physics of Plasmas **19**, 092106 (2012).

[4] A. Kasperczuk, T. Pisarczyk, T. Chodukowski, Z. Kalinowska, S. Yu. Gus'Kov, N. N. Demchenko, D. Klir, J. Kravarik, P. Kubes, K. Rezac, J. Ullschmied, E. Krousky, M. Pfeifer, K. Rohlena, J. Skala, and P. Pisarczyk: *Plastic plasma as a compressor of aluminium plasma at the PALS experiment,* Laser and Particle Beams **30,** 1-7 (2012).

[5] J. Badziak, *Laser nuclear fusion: current status, challanges and prospect,* Bull. Pol. Acad. Sci. Tech. Sci. 60, 729 (2012).

[6] P. Rączka, *Current issues in ion fast ignition,* lecture at the Kudowa Summer School ''Towards Fusion Energy", 11-15.06.2012, Kudowa Zdrój, Poland.