Romanian Participation at EUROfusion

Scientifc Report

2015

Foreword

Realising fusion energy is a big, long term undertaking – fusion scientists tend to think in decades, rather than years. The experiments are large and expensive, and often require the collaboration of several laboratories. Europe's fusion laboratories manage their collaborative research and the joint use of facilities within the EUROfusion consortium.

All EUROfusion research activities are based on the Roadmap to the realisation of fusion energy*. The roadmap breaks the overall task into eight missions. EUROfusion funds the Research Units in accordance with their participation to the mission-oriented Work Packages outlined in the Consortium Work Plan.*

The Institute of Atomic Physics (IAP) is a member of the EUROfusion Consortium and ensures the management of 5 research institutes - National Institute of Laser, Plasma and Radiation Physics (NILPRP), National Institute of Cryogenic and Isotope Technology (NICIT), National Institute for Research and Development in Optoelectronics (INOE 2000), National Institute of Physics of Materials (NIPM), National Institute of Physics and Nuclear Engineering (NIPNE) and three universities - University of Craiova (UCv), University A. I. Cuza from Iassy (UAIC), Technical University Cluj-Napoca (UT-CN).

The Romanian participation in EUROfusion is focused on the Work Packages related to Integrated Tokamak Modelling Code (WPCD), Plasma-Facing Components (WPJET2), Preparation of efficient PFC operation for ITER and DEMO (WPPFC), materials (WPMAT), Magnets system (WPMAG) and Enabling Research (WPENR). It worth to be mentioned that Romania has leaded of two JET Enhancements (WPJET4). A significant participation at the experimental campaigns in JET (WPJET1), ASDEX and TCV (WPMST1) has been accomplished during the last two years. The participation in the Education Work Package (WPEDU) supported several MSc and PhD students enrolled in fusion research.

During this period of time Romanian Education and Research Ministry provided a significant support for the accomplishment of the scientific and technical tasks in the frame of the complementary research.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

The work carried out on complementary projects has been received funding from the Romanian National Education Minister / Institute of Atomic Physics under contract 1EU-6/2014.

Abstracts

CONFINEMENT DEGRADATION AND IMPROVEMENT IN FUSION PLASMAS

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WP-ENR

The transport induced by electrostatic turbulence and/or magnetic stochasticity in the extreme conditions of a reactor can be directly influenced by several factors that contribute to particle motion. They can lead both to the improvement and to the degradation of confinement. The dual nature of these basic processes is clarified for:

- The influence of the ionization and of the magnetic stochasticity on plasma rotation and confinement.
- The effects of the chaotic sheared magnetic field lines on fast particle transport and the evaluation of their energy at the maximum loss rate.
- The effects of the resonant magnetic perturbations and of the topology of ensemble of magnetic lines (described by the Gauss linking number) on turbulent transport.
- The effects of the quasi-coherent and random aspects of trajectories on turbulence evolution and on the generation of zonal flow modes (drift and ion temperature gradient driven turbulence in slab geometry).
- The multi-scale effects on electron heat transport.
- Effect of the gradient of the turbulence amplitude on impurity drift, and evolution of vorticity microstructures induced by plasma rotation as a possible mechanism for generation of plasma rotation.

Theoretical instruments were developed for these studies: the fast decorrelation trajectory method, the iterated self-consistent approach based on test particle and test modes on turbulent plasmas, a code for the evaluation of the rotation velocity induced by pellet injection, a code for the study of the fractionary anisotropic diffusion processes and several computer programs.

DEVELOP FULL 3D CODES TO DESCRIBE HALO CURRENT FORMATION AND ASYMMTETRIES

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WP-CD

The understanding of plasma disruptions in tokamaks and predictions of their effects require realistic simulations of electric currents excitation in 3-dimensional vessel structures by the plasma touching the walls. As it was discovered at JET in 1996, the Wall Touching Kink Modes (WTKM) are frequently excited during the Vertical Displacement Events (VDE) and cause big sideways forces on the vacuum vessel which are difficult to confront in large tokamaks. In disruptions, the sharing of electric current between the plasma and the wall plays an important role in plasma dynamics and determines the amplitude and localization of the sideways force. This work describes a flat triangle representation of electric circuits of a thin conducting wall of arbitrary 3D geometry [1]. Implemented into the Shell Simulation Code and the Source Sink Current code, this model is suitable for modelling the electric currents excited in the wall inductively and through the current sharing with the plasma. Another step consists in interfacing of the wall current codes SSC and SHL with the plasma core codes, such as JOREK or NIMROD.

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CODE DEVELOPMENT FOR ATOMIC DATA MODELLING AND REFERENCE DISTRIBUTION FUNCTIONS CALCULATION

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WP-CD

Abstract – The present project proposal aims to supply additional information on the atomic and ionic species into the plasma. We have performed several sets of calculations with three independent atomic structure codes, namely GRASP (general-purpose relativistic atomic structure package), FAC (flexible atomic code) and QRHF (quasi-relativistic Hartree-Fock), with increasing amount of configuration interaction (CI) for Cr-like ions. It is noted that CI is very important for Cr-like ions in spite of Co and Ni being moderately heavy. Our final results for all levels, obtained with the QRHF code, agree within 3% with NIST listings and there is no (significant) discrepancy in the level orderings. The level of CI included in the calculations was necessitated by the availability of measured energy levels, otherwise results obtained would have been highly inaccurate.

To our knowledge, no A-values are available in the literature for transitions in Co IV and Ni V. Therefore, we have calculated energies/wavelengths, radiative rates, oscillator strengths and transition line strengths for the electric dipole transitions of Co IV from the lowest 36 (which include all levels of the $3d^6$ ground configuration) to higher excited levels. Similar calculation has been performed for Ni V.

New class of numerical method for approximation of the stationary solution of the Fokker-Planck equation, associated to the microscopic dynamics of the tokamak plasma was studied. The knowledge of the drift, source terms and diffusion tensor are assumed. The approximation method use the new concept of generalized Rényi entropy as well as the extension of the previous maximal entropy principle to generalized Rényi entropy, that generate an extended class of reference distribution function for approximation of the true solution of the Fokker-Planck equation. The numerical stability properties of the generalized Rényi entropy, in comparison with the classical Shannon-Boltzmann entropy was studied. New deterministic numerical method and corresponding FORTRAN90 programme, for the determination of the free parameters in the new class reference distribution function was elaborated.

Also, a new class of stochastic optimization algorithm, for the determination of the free parameters in the reference distribution function, was elaborated. FORTRAN90 implementation of the algorithm was performed.

PORTAL AND WEB PAGE MAINTENANCE

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WPCD

Abstract

The Portal acts as an interface between users and the various tools available on the “Gateway” computing cluster. It is comprised of several applications and key infrastructure components, exposing Gateway functionality to users via a web browser.

All these tools require continuous maintenance in order to keep them working in the context of changes on the Gateway side (either new hardware or new operating system functionality). Furthermore, one of the key technologies used inside the Portal is the Single Sign On component, fully integrated with the Gateway authentication systems, requiring continuous supervision and testing in order to allow users to seamlessly interact with the system.

Periodically new components are developed and made available to users through the Portal system, either in this activity or by close cooperation with the software developers in other activities.

CODE DEVELOPMENT FOR MODELLING THE REFERENCE DISTRIBUTION FUNCTION

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WP-CD-C

New class of numerical method for approximation of the stationary solution of the Fokker-Planck equation, associated to the microscopic dynamics of the tokamak plasma was studied. The knowledge of the drift, source terms and diffusion tensor are assumed. The approximation method use family of reference distribution functions obtained from the maximal entropy principle with scale invariant restrictions, by using the classical Shannon-Boltzmann entropy[1-4] and its new generalizations, the generalized Rényi entropy [5]. The numerical stability and mathematical consistency aspects related to the Shannon-Boltzmann, Rényi and Generalized Rényi entropies were clarified: stabilizing conditions that guarantee the numerical stability of this class of entropies were established[6]. By using existing results on the Hyers-Ulam stability, the problem of best approximation of the solution of the stationary Fokker-Planck equation was reduced to the problem of nonlinear least square minimization with respect to the free parameters of the family of reference distribution functions. New deterministic and stochastic numerical methods that improve the classical Levenberg-Marquardt least square algorithm and the stochastic Kiefer-Wolfowitz method were elaborated and tested in FORTRAN90 test programme[7]. For the optimal approximation of the solution of the Fokker-Planck equation, FORTRAN90 modules were elaborated, tested on synthetic data and uploaded to the Gateway from Garching Computing Center:

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CODE DEVELOPMENT FOR ATOMIC DATA AND INTERFACE MODULES IN SUPPORT OF THE AMNS ACTIVITY

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WP-CD

The present project proposal aims to supply additional information on the atomic and ionic species into the plasma. INFLPR being member of the ADAS international consortium, the present project consolidates the link with ADAS as well as helps to improve the precision and completeness of the atomic database used for simulations with the suite of codes developed within WPCD which are aimed to be applied to the present fusion experiments, validated against plasma spectroscopy and furnish predictions for ITER. In addition this project aims to contribute to the development of new approach for designing an atomic data storage system based on graph algorithms and structures. This is aimed at huge databases, where a user usually wants to identify data based on its characteristics rather than based on data location.

We report calculation of fundamental and applied atomic data for light elements [1-4] and moderately heavy ions Co IV and Ni V [5]. To our knowledge, no A-values are available in the literature for transitions in Co IV and Ni V. Therefore, we have calculated energies/wavelengths, radiative rates, oscillator strengths and transition line strengths for the electric dipole transitions of Co IV from the lowest 36 (which include all levels of the $3d^6$ ground configuration) to higher excited levels. Similar calculation has been performed for Ni V .

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ROMANIAN PARTICIPATION IN THE EXPERIMENTAL JET CAMPAIGNS C33 AND C35-36

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WP-JET1

The participation of the Romanian group of experts to the experiments and analysis of JET experiments campaigns is related to the campaign C33 and to two programmatic goals: i) Fast ion confinement, its power scaling and effect on current drive and ii) prepare efficient PFC operation for ITER and DEMO. The main contributions are related to gamma-ray spectroscopy and tomographic analysis for plasma diagnostic and to the determination of emissivity for W coatings from the ILW.

The tomographic analysis has been performed in support of the experiments related to Fusion product studies - Diagnose confined and lost fast-ions and Runaway generation due to disruptions with an ITER-like wall. Extensive data processing of experimental data have been performed in order to retrieve the gamma-ray images of accelerated D-beam ions and the temporal evolution and spatial structure of RE electrons.

For the determination of emissivity for W coatings the previous experiments carried out at 1064 nm revealed a significant influence of the substrate structure on the emissivity of W coatings. Since the ILW contains about 1300 CFC tiles coated with 10 μm and 20 μm of tungsten, determination of emissivity at 4 μm is important for interpretation of the results associated with the surface temperature obtained during the JET campaigns. A concept for measuring this emissivity using an experimental setup out of JET has been developed.

In the framework of plasma diagnosis by image processing techniques, several approaches, based on the extraction of structural information from the visual scene, have been developed for the automatic detection of MARFE plasma instabilities. An original spot detection method for large surveys of videos in Joint European Torus (JET) and an image registration method based on SIFT descriptors and on the Coherent Point Drift points set registration technique, have been also developed.

The participation of the Romanian group of experts to the experiments and analysis of JET C35-36 experimental campaigns is related to four different experiments: M15-01: Baseline scenario for DT, M15-02: Hybrid scenario for DT, Experiment M15-24: Target discharge for TAEs in DTE2 and fast particle physics in all scenarios, Experiment M15-24: Target discharge for TAEs in DTE2 and fast particle physics in all scenarios.

For the preparation of these experiments an extensive work, related to of the study on the correlation between the D_alpha emission and the plasma rotation and to gamma-ray tomographic analysis for fast ion physics and runaway electrons characterisation, have been accomplished.

The connection between the increase of density (by gas-puff, pellet injection and impurity seeding) and the confinement will be an important subject of investigation. An original model has been proposed and the quantitative results are explored in analytic and numerical studies.

For the gamma emission and HXR tomographic analysis, related to fast ions experiments and to the characterisation of the runaway emission, several improvements of the methods and code have been obtained in order to ensure adequate time resolution for reconstructions obtained close to plasma disruption and to accommodate different upgrades of the hardware.

THERMAL EMISSIVITY AT 4 μm FOR W COATED CFC TILES DETERMINED WITH A SINGLE PIXEL SCANNING IR CAMERA

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WPJET1-C

In a previous project (JET Enhancements – ACIR) the emissivity of the W coatings deposited on CFC substrate was measured at 1064 nm. This was for the PIW (Protection of the ITER-like Wall) project. Since the ILW contains about 1300 CFC tiles coated with 10 μm and 20 μm of tungsten, and the scientific cameras work at 4 μm determination of emissivity at this wavelength is important for interpretation of the results associated with the surface temperature obtained during the JET campaigns. Because an IR camera was not available a new technique which could be called "Single Pixel Scanning IR Camera" was developed and applied. Instead of taking simultaneously the image of the entire W-coated CFC tube, a single pixel IR detector together with the IR optics is moved in X and Y directions scanning a surface of 20x20 mm.

W coatings of 10 μm and 20 μm were deposited on tubes (Φ16x85x0.8 mm) made of Dunlop CFC. Another tube of the same dimensions made of FGG (fine grain graphite) was coated with 10 μm of W. In the centre of the tube, perpendicular to its axis a hole with a diameter of 2 mm was drilled. This hole played the role of the black body. On the sides of the hole two pins of W and Be were mounted.

Using the IR signals from the surface of interest, black body and background the emissivity values were determined. The temperature dependence of the emissivity was investigated as well.

For 10 μm W coating deposited on CFC the emissivity increased from 0.18 to 0.27 when the temperature increased from 400 °C to 1200 °C. When the substrate was FGG the emissivity changed from 0.13 to 0.20 for the same variation of the temperature. No variation of the emissivity was detected when the thickness of the W coating was increased from 10 μm to 20 μm. For bulk W and bulk Be the emissivity increased from 0.09 to 0.12 and 024 to 0.30 respectively for a variation of the temperature from 400 to 900 °C.

MAGNETIC PERTURBATIONS EFFECT ON THE ONSET AND DYNAMICS OF THE NEOCLASSICAL TEARING MODES

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WP-MST1

Within the 2015 Medium-Size Tokamak 1 Campaign (WPMST1 2015) we have taken part to two experimental campaigns whose declared goals are to understand the neoclassical tearing modes (NTM) onset and dynamics scenarios on one hand and to describe the interaction between the NTM and the resonant magnetic perturbations on the other hand. The first campaign, “Advanced NTM physics”, having the ID TCV15-1.4-4, has been performed using the TCV tokamak installation by means of the 20 performed shots. The second experimental campaign, "Interaction between resonant magnetic perturbations and NTM stability", having the experimental campaign ID AUG15-1.4-3 of 7 performed shots, involved the ASDEX-Upgrade tokamak installation and is a continuation of the 2014 experimental campaign, "NTM dynamics and external magnetic perturbations", with the ID AUG14-1.4-4, where we have participated to 17 performed shots, in order to gain information concerning the integration of the MHD control into plasma scenarios.

The theoretical modelling of the NTM dynamics for low rotation rates (TCV campaign) and the description of the interaction of NTM with the resonant magnetic perturbations (AUG campaign) consisted our task to be achieved. The resonant perturbations assumed as tokamak B-coils error field perturbations have been considered and its destabilizing effect has been modelled. Our proposed model is a perturbed 3-dimensional model and, more important, is a dynamic one, i.e. the perturbations time dependence behavior is explicitly shown. Beyond the quasi-analytic solving of the system of ideal plasma (outside the NTM magnetic island) perturbed momentum equations, perturbed Laplace equation in vacuum, perturbed Ohm law integrated across the resistive wall (also considering the error field spectrum) and finally perturbed circuit equations for the active feedback coils surrounding the plasma column in order to obtain the so-called *outside* perturbed solution (that shows no information about the inner magnetic island physics), we have also solved the inner island dynamic equations. Based on the accurately derived *outside* perturbed solution (initially assumed to be an external test function), we have obtained an *inside* perturbed solution of the non-ideal magnetic island perturbed equations. Basically the magnetic island inner physics is modelled. Depending of the onset of the perturbation starting time, two time dependent solutions of the island equations have been obtained: an early solution covering the perturbation onset regime that measures the perturbation dynamics for a period of a few milliseconds and a second solution describing the dynamics within the Furth-Kileen-Rosenbluth and Rutherford regimes, transient to the saturation of the NTM. The derived solutions are powerful nonlinear solutions with respect to time. The second solution for instance depends of special functions such as the integral exponential function whose argument is a function of time. At the same time, the solutions present a quasi-analytic dependence of the perturbations initial values and of the resonant/non-resonant external magnetic perturbations of the magnetic error field type. Therefore we were able to provide more carefully calculated and realistic results. A quasi-analytic expression of the stability index Δ' for the NTM perturbation is also provided. Rarely a carefully calculated time dependent stability index is presented in literature. Usually there are

dependencies drawn from the experimental measurements. The Rutherford evolution equation of the island has been numerically solved. The NTM stability regimes are studied using the mathematical tool we have developed. The influence of the external resonant or non-resonant magnetic perturbations is included. The next step is to couple the island evolution equation with the already derived time dependent local toroidal plasma decreasing rotation rate in order to robustly achieve the evolution of the magnetic island covering all its stages of evolution, including saturation.

POST MORTEM ANALYSIS OF JET TILES

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WPJET2

In 2015 IAP was involved in the WPJET2 project with six deliverables. The main results obtained in the framework of this project are summarized below.

Be tiles received from CCFE were successfully cut in small pieces (9-10 mm and 2-3 mm thickness) in order to be sent to different laboratories for further analyses such as IBA, TDS, SIMS.

XRD and TDS analyses on selected samples cut from the2xR10 tile revealed re-deposition of materials and formation BeNi, Be, BeO compounds, as well as CrO_2, Fe_3O_4 oxides and Be_2Cr intermetallic compound. TDS measurements show that the release of deuterium atoms starts to at around 550 K. A shoulder at 600 K was associated to BeD_2 trapping state. All the samples present peaks at 700K, attributed to BeO.

The GDOES has been proved to be a reliable technique to investigate quantitatively the depth profiles of the constituents for surface layers deposited on metallic and carbon substrates before and after plasma exposure in a nuclear fusion device. It has been successfully applied for the first time to investigate the modifications occurring on the W coatings deposited on JET divertor tiles as a result to plasma exposure in 2011-2012. For porous materials such as CFC GDOES results have to be correlated with SEM analyses. Beryllium appears to be present on all divertor tiles, but the quantity is different. For the particular areas of the tiles where the GDOES analyses were performed very thin layers (< 1 μm) of Be were detected on Tiles 1, 4, 7 and 8, thicker layers 3-8 μm have been measured on tiles 3 and 6 and very thick layer (20-25 μm) was measured on HFGC tile. Erosion was not measured on any tile except tile 3 where the top Mo layer seems to be removed in certain areas.

X-ray micro-laminography was qualified and implemented as a complementary solution for the 3D microstructural analysis of tungsten coated carbon-fibre reinforced carbon (W/CFC) samples retrieved from JET ITER-Like Wall (exposed during 2011-2012). As expected, the W layers spatially correlate with the morphology of the CFC substrate that was visualized by X-ray microtomography.

LOST ALPHA PARTICLE MONITOR (LRM)

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WPJET4-LRM

The main objective of the Lost Alpha Gamma Rays Monitor (LRM) project is the development of a new diagnostics technique for the investigation of escaping fast particles (including alpha particles) in JET. The method is based on the detection of the gamma radiation induced by the escaping particles on a target external to the plasma. For a beryllium target this reaction is 9Be(α, nγ)12C. The implementation on JET of the Lost Alpha Monitor technique would make possible simultaneous measurement of both confined and lost alphas using the same nuclear reaction and possibly the same detectors.

The project objectives include calculations of alpha particle fluxes on the target, calculations of the target gamma-ray emission, radiation transport calculations, radiation system design, manufacture and installation, and the development of data processing to obtain plasma parameters.

In order to assess the operational features of the Lost Alpha Monitor (LAM/KA4) radiation system an evaluation of its collimation and shielding characteristics was required. The evaluation has been performed by means of Monte Carlo numerical simulations using the MCNP-6.1 code using point gamma-ray sources emitting within a defined narrow solid angle which ensures the coverage of the structures of interest. The point gamma-ray sources are placed at positions equivalent to KA4 target, the TAE antenna protection tile. The MCNP model takes into account both the existing KJ5 radiation shield and the newly designed LAM/KA4 radiation collimator and shield.

The MCNP numerical results show that the combination of the two radiation shields (KJ5 and KA4) provides adequate shielding and collimation for the KA4 detector, and that shielding factors of about 103 can be obtained. On the other hand, the designed KA4 configuration has to be improved in order to allow a larger area of the beryllium target to be seen by the KA4 detector.

The initial project proposal contained a simple low cost technical solution: insert a beryllium target into the Field-of-View of one of the JET gamma-ray camera (KN3) channels. Detect and analyse the gamma-ray emission using existing diagnostics devices or devices to be developed within another EUROfusion WPJET4 project.

Soon after the start of the LRM project it was realised that in order to implement on JET the simple physical principle of the Lost Alpha Monitor (LAM) one needs a rather complex technically challenging diagnostics device. The implementation on JET was further hindered by the existence of large quantities of carbon in the form of the divertor CFC tiles. Fast neutron interaction with this carbon leads to a high level of background gamma radiation of the same energy as that from the (α, Be) reaction.

The report on Feasibility Study and Conceptual Design, Phase I, contains detailed presentations of several technical solutions developed and evaluated for the LAM diagnostics. Two different locations on JET were considered: one on the horizontal KN3 gamma-ray camera in octant one and another on the KJ5 soft X-

ray camera in octant four. Two design options were investigated for the KN3 location and four design options for the KJ5 location.

One of the KJ5 design options was developed up to the level of conceptual design. Its evaluation showed that the design and construction of such a system would have needed financial resources several times larger than those allocated to the LRM project.

The LRM project included also a first phase of numerical work done in support of the diagnostics design. The results of the numerical work had a direct impact on the design of the LAM/KA4 diagnostics.

Together with the financial evaluation, the results of the numerical work have also been used to decide upon the continuation of the LRM project.

The WPJET4 Project Board decided on 03.07.2015 to close down the LRM project as no technical solution that could be designed and constructed with the available resources could be found.

JET gamma-ray spectrometer upgrade (GSU)

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WPJET4-LRM

As stated by the documents governing the European fusion research in the frame of Horizon 2020 ITER is the key facility. To ensure its success the preparation of operation on JET and JT-60SA will play the role of risk mitigation measures. JET served as a blueprint for the ITER construction and now JET experiments are devoted to validate the ITER design choices and prepare ITER operations. Special attention will be dedicated also to the characterization of the ITER regimes up to full performance of JET operation with the same combination of plasma facing material as ITER (the ITER Like-Wall in JET). In this context a DT campaign is intended, which provides the final demonstration of the compatibility of high performance inductive regimes of operation with the ITER wall materials.

Future deuterium-tritium experiments on JET are expected to produce a significant population of alpha-particles at plasma parameters approaching the ITER values as closely as possible. Therefore these shots will be a good opportunity for examining confined and lost fusion alphas. The confinement of fast particles produced in fusion reactions is of crucial importance for future fusion devices like ITER and DEMO. However a number of diagnostic upgrades are necessary for fusion α-particle measurements as stated in the Work Plan for the Implementation of the Fusion Roadmap in 2014 – 2018.

The GSU project addresses the upgrade of the KM6T spectrometric system in order to bring it at the desired level of compatibility with the future DT campaign. This project is running in the EUROfusion WPJET4 Work Package. IAP-INFLPR-INOE (Institute of Atomic Physics which is an EUROfusion member and its linked-third-parties the Institute for Laser, Plasma and Radiation Physics and the Institute for Optoelectronics) is leading the Project Consortium which includes the following partners: CCFE UK, ÖAW Austria, CNR Italy, IPPLM Poland, IST Portugal, SFA Slovenia.

The actitivity during 2015 comprises the development of the detailed design for a radiation field components assembly (RFCA) which will allow for the definition of the spectrometer Field-of–View (FoV) across the DT plasma and will provide adequate shielding of the gamma-ray detector from parasitic neutron and gamma-ray sources. For proper gamma-ray measurements, the necessary reduction of the neutron flux of 14 MeV neutrons reaching the detectors has been achieved by manufacturing set of LiH neutron attenuators. The procedures for storage, transport and handling have been also defined. The assessment of the shield and attenuators in what it concerns the radiation fields generated at the position of the detector has been performed by means of Monte Carlo numerical simulations using the MCNP.

EVALUATION OF RECONSTRUCTION ERRORS AND IDENTIFICATION OF ARTEFACTS FOR JET GAMMA AND NEUTRON TOMOGRAPHY

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§ See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia

WPJET4-C

Abstract

JET neutron profile monitor ensures 2D coverage of the gamma and neutron emissive region that enables tomographic reconstruction. Due to the availability of only two projection angles and to the coarse sampling, tomographic inversion is a limited data set problem. Several techniques have been developed for tomographic reconstruction of the 2-D gamma and neutron emissivity on JET, but the problem of evaluating the errors associated with the reconstructed emissivity profile is still open. The reconstruction technique based on the maximum likelihood principle, that proved already to be a powerful tool for JET tomography, has been used to develop a method for the numerical evaluation of the statistical properties of the uncertainties in gamma and neutron emissivity reconstructions. The image covariance calculation takes into account the additional techniques introduced in the reconstruction process for tackling with the limited data set (projection resampling, smoothness regularization depending on magnetic field). The method has been validated by numerically simulations and applied to JET data. Different sources of artefacts that may significantly influence the quality of reconstructions and the accuracy of variance calculation have been identified.

QUALITY CONTROL MONITORING OF DEMO MAGNETS (CONDUCTORS, JOINTS, STRANDS)

BY FULLY 3D X-RAY MICROTOMOGRAPHY

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WP-MAG

The task (WPMAG-IAP) is part of the main project – Power Plant Physics & Technology (PPPT) - Magnet System (WPMAG) and it comprises all the activities to be carried out by IAP (Institute of Atomic Physics) associated with the DEMO Magnet Conceptual Design and Advanced Magnet Technology. Two research groups of the Romanian Research Unit (RU) participate at the Magnet System Work Program (WPMAG): the X-ray Microtomography group of Institute of Laser, Plasma and Radiation Physics (INFLPR) and the Center of Superconductivity, Spintronics and Surface Science (C4S) of the Technical University of Cluj-Napoca (UTCN).

The X-ray Microtomography group is involved in the non-invasive examination of TF conductor structure by X-ray Computed Tomography (XCT). The C4S group contributes to the Advanced Magnet Technologies (AMT) work package. Their task is related to the program of the characterization of industrial fabricated High Temperature Superconductor (HTS) tapes.

Since the fabrication of the DEMO TF conductor prototypes takes longer than the initial plan the main deviation from the initial task has consisted in using an assembly of JT60-SA Cable-in-Conduit-Conductor sections for the XCT optimization studies.

In the reporting period following research activities were performed:

The mock up conductor samples that simulate the best the TF conductor that will be fabricated in the WPMAG context was defined and produced on the basis of CICC JT60-SA.

X-ray tomography feasibility tests on TF conductor mock ups were performed. These tests include X-ray tomography conducted on two high voltage X-ray systems with maximum energy of 300 and 450 kVp, respectively. The stack of reconstructed slices were used as input data for quantitative analysis consisting of i) determination of the local and global void fraction, ii) strands trajectories reconstruction.

In the frame of the project, commercially available HTS tapes from the following producers: Super Power Inc., American Superconductor Corporation, SuNAM Co., Ltd., Fujikura Ltd. and SuperOx were procured and examined. It is to be noted that all the investigated HTS tapes have been fabricated at the end of 2012.

The critical current, Ic, of the tapes was measured in a magnetic field up to 16 T at two reference temperatures: 77K and 65 K. The measurements were performed with the magnetic field perpendicular to the tape surface. For all the investigated tapes the ReBCO superconducting film is epitaxially grown with c-axis perpendicular to the metallic substrate. The AMSC tapes have the best in field superconducting transport properties. Thus, the Ic(B) curve for this tapes exhibit a large plateau up to 16 T at 65K, demonstrating the high efficiency of the BZO pinning centers. On the other hand, for SPI

tapes, which contain both BZO and Zr pinning centers, the Ic(B) rapidly decreases with magnetic at 77 K and exhibits a quasilinear decrease at 65K. The magnetic field dependece of the critical curent for SuperOx and SuNAM tapes is typical for the ReBCO epitaxial superconducting film in the absence of the artificial pinning centers.

Advanced X-ray imaging, magnetic and electrical characterisation techniques for fully 3D modeling of conventional and high temperature superconductor strands, cables and joints

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WP-MAG-C

X-ray micro-tomography (μXRT) non-invasive investigation method was applied for microstructural analysis of MgB_2 superconductor samples in form of bulk, tape, thin films and wires. The MgB_2 bulk material was produced by an unconventional technique, spark plasma sintering [1]. Although, at present, it is not possible to significantly advance the understanding of the milling-properties relationship, μXRT can reveal clear differences between samples milled in different conditions.

μXRT was applied for the first time to visualize the structure of an MgB_2 tape, of a precursor non-superconducting MgB_2 amorphous thin film on an Al_2O_3 substrate and of a reacted superconducting MgB_2 (Tc = 20.3 K) thin film. Tapes show a relatively uniform μXRT microstructure, when compared with the patterns taken on bulk, but one can easily observe regions with different densities. 3D images as well as selected sections can also give some information on the shape of the tape core or of the core–sheath composite, on the geometry of the metal–superconductor interface, and on the occurrence of large cracks or pores.

Commercial wires of MgB_2 with different architecture and two different heat treatments were visualized by 3D μXRT. For a particular architecture, heat treatment conditions of 625 °C/3 hrs or 700 °C/30 min produced relatively small differences.

Superconducting round wires of MgB_2 were produced by Hyper Tech Research Inc. by *in-situ* continuous tube forming and filling (CTFF) process [2]. The application of μXRT technique on MgB_2 wires checks the integrity, easily detecting in a non-invasive way 3D macro defects and shows their hidden extended shape. μXRT also allows a comparative geometry analysis between similar elements (e.g. filaments or filaments-matrix interfaces) from a particular wire or from wires with different architectures. Namely, μXRT shows that the geometrical perfection (defined as the degree of departure of the geometry from the designed one) of the inner MgB_2 filaments from the wires with 18 elements was lower than for the outermost ones from the same wires and was also lower than for the filaments from the wires with 7 elements. It is proposed that these results of geometrical perfection correlate with better overall superconducting quality of the wires with 7 filaments (except for the stronger presence of macro flux jumps in the wires with 7 filaments).

[1] Badica, P.; Aldica, G.; Craciunescu, T.; Tiseanu, I.; Ma, Y.; Togano, K. *Supercond. Sci Technol*. 2008 **21** 115017.

[2] Homepage of Hypertech Inc, USA: http://www.hypertechresearch.com/.

Scalable water-based precursors for the CSD deposition of ReBCO and ReBCO-APC nanocomposite films. ReBCO-x mol% BZO composite targets for laser ablation deposition

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WP-ENR

Water-based deposition has been used for the growth of YBCO films. The thermal analyses of the precursor powder have been performed in order to propose the optimal thermal treatment of the thin films. A pyrolysis time of about 60 min at 600°C is necessary to avoid the formation of the $BaCuO_2$ phase in the YBCO film due to the reaction between $BaCO_3$ and CuO. The as-obtained YBCO films are c-axis oriented with a FWHM of the ω-scan through the (005)YBCO peak of 0.11. The films have an orthorhombic crystalline structure with the lattice parameter along the c-axis of 11.685 Å, close to the theoretical value of 11.680 Å. The YBCO films are smooth and have a dense morphology. The film pyrolyzed at 600 °C for 60 min exhibits a critical current density of 0.8 MA/cm^2 and self—field (Jc0) slightly smaller than the values reported for CSD YBCO films (1–2 MA/cm^2) indicating that further optimization of the thermal treatment is necessary. Anyway, our investigations have demonstrated that the fluorine-free propionate precursors are very promising to obtain YBCO films with good superconducting properties in a single-step thermal treatment.

The YBCO-$BaZrO_3$ nanocomposite films have been obtained by ex-situ chemical solution deposition technique. The epitaxial growth and superconducting properties of nanocomposite films grown on (100)STO single-crystalline substrates by a propionate based low fluorine precursor solution. Epitaxial YBCO-BZO nanocomposite films, having a thickness of approximately 500 nm, were obtained. *ω*-scans performed around the (005) YBCO reflection confirm a low out-of-plane mosaicity, while also revealing the effect of the BZO inclusions on the YBCO matrix strain. Cross-sectional TEM observations have shown that isolated, ~30 nm in diameter, BZO pinning centers are uniformly distributed within the host film. A tendency for the twin boundaries, present in the YBCO film, to locate at the BZO sites has been observed. The effect of the BZO additions has been quantified by means of electrical transport measurements. These reveal an increase of the critical current density at 77 K in zero-field, from 1 MA/cm^2 in the un-doped film, to 3 MA/cm^2 in the YBCO-10 mol %BZO doped sample, due to an increase in the pinning force density.

The effect of the GFO pining center on the superconducting properties of the YBCO films have been studied. In order to find the optimum concentration, different volumetric percentages of GFO in the YBCO precursor solution have been used. The epitaxial nanocomposites films have been structural (XRD), morphological (AFM, TEM), electric and magnetic (SQUID) characterized. The addition of the GFO significantly reduce the critical current density (from 1.5 to 0.3 MA/cm^2), as compared with the pristine YBCO, due to the high reactivity between the yttrium and iron ions.

Different YBCO-BZO target compositions, in the range 2.5-10 mol % have been prepared by solid state reaction.

W laminates produced using a FAST based technology

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WP-MAT

FAST has been successfully used to create W-laminates with Cu, V, Ti, Pd and W. Multi-layered composites with different rectangular and disc shapes have been produced for mechanical tests and thermal properties investigations, respectively. The method was further tested to produce laminates with more complex shapes (corrugated or with angled profiles) and pipes (up to 6 cm length). The effect of long term (up to 1000 hours) exposure to high temperature (1000°C) has been assessed. W joined samples using Ti shows that the Ti-W inter-diffusion is large and makes Ti unsuited for W joining, while the use of Pd is not adequate due to high costs and the Pd retention of gases. To allow further use of Ti, W multi metal laminates (using W foils with Cu or Cr deposited layers) have been produced and the procedure allows to use also Ti interlayers without detrimental effect of 1000°C exposure of samples for 1000 hours. The structure of the samples with has been investigated by SEM/EBS. Thermal properties (thermal diffusivity, specific heat, thermal conductivity) have been measured using a LFA for W laminates samples with Cu and V (different foil thickness and number), for W from room temperature up to 1000°C.

High heat flux interface materials for DEMO fusion reactor

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WP-MAT-C

In Eurofusion work we are involved in the production an investigation of various interface materials for different cooling options in the DEMO fusion reactor. W-Cu FGMs have been created by powder metallurgy route. Different compositions layers and whole FGMs have been investigated by SEM/EBS and for their thermal properties. For 1 step produced thin FGMs (below 2 mm) the results show that although the thermal behaviour is consistent with theoretical predictions, the FGMs microstructure shows inhomogeneity on a 100-300 micron scale due to W agglomeration tendencies. This imposes a multi-step production approach. Testing various compositions we have shown that good homogeneity can be achieved around equal volumetric percent, as demonstrated by both SEM/EBS and X-ray microcomputer tomography. Also materials for thermal barriers have been produced as Cu composites with various dispersions (oxides, SiC, C) with different concentrations and grain sizes. Thermal properties and microstructure analyses have been used to select the best candidates for a given operation parameters window. While thermal transport properties are directly related to the dispersion concentration, thermal expansion coefficients strongly depend also on the microstructure and dispersions type. The most stable materials are realized using micrometric Cu powders and nanometric SiC dispersions. A complex table relating conductivities, microstructure and thermal expansion was defined using these materials, allowing the component design using FEM to simulate the thermal properties.

ITER related mixed reference coatings preparation and characterization

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WPPFC-C

Tungsten, beryllium and tungsten-beryllium mixed materials were deposited in Ar-D gas mixture by high power impulse magnetron sputtering (HiPIMS) and TVA within the framework of the EUROfusion Consortium as a Complementary project. The deposited films were characterized in terms of morphology and structure, by Atomic Force Microscopy (AFM), Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD).

The following activities were also performed: (a) Film characterization using 5 MeV Tandem Accelerator for RBS measurements and NRA for deuterium retention studies. Comparison of the films prepared by HiPIMS and TVA methods, (b) Development and study of hollow cathode discharges with tungsten electrodes generated in hydrogen, (c) Establishment of the plasma operating domains and preliminary tests of tungsten erosion in hollow cathode plasmas, (d) Deposition of thin composite films of C/W with different elemental ratios by PLD and RF-PLD, (e) Characterization of second stage thin films structure, composition, and morphology. Study of C/W thin when further exposed to hydrogen/deuterium plasma, (f) Analysis of W, C and Be based deposited films using AFM, XPS, SEM and XRD, (f) Characterisation of W sputtered material in the gas phase by Laser Absorption Spectroscopy and Laser Induced Fluorescence and study of W and C erosion under self-sputtering. The erosion process under self-sputtering was investigated for W and C layers, (g) Preparation of Fe based intermetallic films with Cr and/or Mo alloying elements and preliminary characterization, (h) Complex characterization of the systems (morpho-structural, local interactions and configurations).

PLASMA CHARACTERISATION AND W BASED COMPOSITE LAYER DEPOSITION

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WP-PFC

The high power impulse magnetron sputtering (HiPIMS) technique was used to obtain W coatings with nitrogen inclusions. The chemical composition and the corresponding structural changes in the obtained films were investigated by Ion Beam Analysis (IBA), X-ray diffraction (XRD) and Atomic Force Microscopy (AFM). All deposited films are polycrystalline and the phase composition depends on the nitrogen content in the sputtering atmosphere. By increasing the nitrogen flow in the HiPIMS discharge, the structure of the film changes from W dominant phases to WN_x phase. A deuterium plasma torch was used to investigate deuterium retention in the coatings with respect to nitrogen concentration in the films.

As support for the EIRENE database, an extensive description of Magnum-PSI plasma column was reported in terms of 2D cross-section distributions of the floating potential and ion saturation current, at target position. The results were provided for 5 values of the discharge current and 3 settings of the magnetic field strength and they were obtained by processing the data acquired in previous measurements performed in Magnum-PSI, using a multi-probe system. The distribution of the probe current (composed of electrons and ions) across the target surface was obtained as a function of the target bias, for one operating condition. When all the probes were biased at the floating potential of the target, it was observed that the probes collect electron dominated current in the central region of the target and ion dominated current in the outer part of the target. This means that a floating conductive surface that interacts with an inhomogeneous plasma collects non-zero local currents despite its total null current. This fact generates electron current flows within the conductive surface, from the zones which collect electron dominated currents to the zones collecting ion dominated currents. The current flowing through the floating target was calculated for different discharge currents. It is of the order of Ampére and it is larger at lower discharge currents. In order to perform the same type of measurements as in Magnum-PSI, a new multi-probe system was designed for PSI-2.

INTERACTION OF HIGH DENSITY TRANSIENT PLASMA WITH W, C AND BE TARGETS IN LABORATORY DEVICES

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WP-PFC

The aim of the project is to study the interaction of high density transient plasma with W, C and Be targets in laboratory devices. Two main aspects of this interaction are foreseen: the direct impact of the plasma on the target material and the behaviour of the sputtered material into the discharge. To achieve the goals of the project we have investigated: the erosion of the targets, the sputtered material fluxes and the thin films resulted from the deposition of the sputtered material.

Tungsten target was eroded in high power impulse magnetron sputtering device (HiPIMS) under argon and nitrogen ions bombardment. Target erosion profile as well as the re-deposition process were evidenced by profilometry measurements. The chemical composition of the sputtered target was obtained by Energy-Dispersive X-ray spectroscopy (EDX). The radial distribution of nitrogen incorporated in the W target is very well correlated with the erosion profile. Correlated with target erosion, the sputtering process of W atoms in HiPIMS was investigated in the gas phase by time resolved Laser Absorption Spectroscopy (LAS) and time averaged Laser Induced Fluorescence (LIF).

W, Be and W-Be mixed materials deposited in Ar-D gas mixture by HiPIMS technique, were characterized, in term of morphology and structure, by Atomic Force Microscopy (AFM), Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD). The study of the erosion of W and Be targets under Ar, Ar-D and Ar-N_2 ion bombardment was performed by monitoring the deposition rate of the sputtered materials using a Quartz Crystal Microbalance (QCM). The fluxes of particles sputtered from W and C targets were investigated by measuring the ions energy distribution function using a mass spectrometer (EQP 1000, Hiden Analytical).

Post mortem analysis of tiles retrieved from JET

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WP-PFC-C

W/Mo markers with thickness of 35 μm have been deposited and characterized. The characterization included *GDOES* measurements for chemical analysis, *SEM* investigations and adhesion assessment. The markers behavior to thermal load was evaluated by a *HHFT* (High Heat Flux Test) program. The results indicated a good behavior of W markers of 35 μm to thermal cyclic load. After 35 hours at testing temperature (1000^0 C) a percent of 0.073% of the coating surface was affected by minor defects. The markers preserved a very good adhesion after the *HHFT* program. This evaluation has been performed by scratch test where a value of 90N was determined for critical load.

W coatings containing deuterium and helium have been obtained and characterized. Their thicknesses were 6 μm for the W+D coating and 9.6 μm for the W+He coating. An initial evaluation of the gas content within the coatings has been performed by *TDS* (Thermal Desorbtion Spectrometry) analysis, then the samples were sent to research units across Europe for further analysis and *LIBS* measurements. A deuterium content up to 0.9 at. % have been measured by using nuclear analysis methods for W+D coating, whereas for W+He coating the helium content was 14 at.%.

The technology to coat *WEST* divertor *FGG* (Fine Grain Graphite) tiles with W coatings of 10-15 μm has been elaborated. The technology has been applied to coat a prototype tile tested in *GLADIS* facility at *IPP* Garching.

The emissivity of W coating of 10-15 μm deposited on *N11 CFC* and fine grain graphite cylinders has been determined. The measured values were 0.52 ± 0.04 for *N11 CFC* and 0.45 ± 0.02 for *FGG* at 1100 °C.

Assessment of W erosion at high temperature under exposure to H/He containing plasmas

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WP-PFC-C

Abstract – In the present study we focused on the assessment of W surface modification at high temperature under He or He/H_2 plasma exposure. Tungsten samples were heated by He or He/H_2 radiofrequency hollow cathode discharges. For these experiments commercially available tungsten samples having 30 x 15 mm dimensions and 0.1 mm thickness were used. Onto the as received tungsten samples optical microscopy, SEM, AFM and weighting investigations were performed.

The experimental setup consists in a vacuum chamber pumped by two pumps: a rotary pump and a turbo molecular pump. The pumps ensure an initial vacuum of $4*10^{-4}$ mbar. Plasma is generated in RF (13.56 MHz) using a parallel plate hollow cathode configuration. The parallel plate electrodes consist in two tungsten pieces positioned face to face at 3 mm distance. The pieces under study were mounted as one of the electrodes. The tungsten samples were heated in the He or He/H_2 discharge at temperatures in the range 950-1230^{o}C when power values in the range 200-300W were applied. The exposure time was varied in the range 30-90 minutes. The mass flow rates were set at 375 sccm.

From the SEM images we observed that the tungsten surfaces exposed in He/H_2 radiofrequency hollow cathode discharge transformed in porous surfaces, while the tungsten surfaces exposed to He plasma appear as covered with bubbles. From AFM investigations we observed that the surfaces roughness increased with the temperature increasing. The tungsten samples were weighted prior and after processing them. Some weight changes between 2 and 5 mg were noticed, corresponding to relative mass changes of 0.23 %, and 0.57 %.

Thin films of C/W and C/W/Mg prepared by Pulsed Laser Deposition

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WP-PFC-C

Abstract

In the frame of Eurofusion complementary research, the Photonic Processing of Advanced Materials Group from NILPRP investigates the preparation of thin films of W, C and Mg (replacing Be) and the influence H_2 and/or D_2 plasma has on these samples.

Sequential PLD and RF PLD were used to produce thin films containing C/W or C/W/Mg, starting from W and C targets or W, C, Mg targets respectively and working in argon or argon/hydrogen atmosphere (with or without RF discharge) at a pressure varying between 10^{-2} mbar and 10^{-1} mbar. Silicon has been used as substrate/collector. The distance between the target and collector was set at 4.3 cm. The deposition temperature varied from room temperature (RT=24°C) up to 400°C; the substrate was heated with 20°C/min and cooled with 10°C/min. In order to determine the influence of the ratios between the elements we have used several ablation sequences and we have finally chosen an ablation sequence made of 100:30:30 laser pulses on W, C and Mg respectively.

The samples have beed characterized by XRD, AFM, SIMS and SE. XRD spectra have shown that the thin films are amorphous. AFM analysis prove that the roughness of the thin films is under 10 nm. SIMS investigations show that the layers are uniform and have composite character. We have built a comparative study of the influence of hydrogen plasma exposure of the thin films during and after the depostion process.

Complex characterization of intermetallic ribbons with Cr/Mo/W alloying elements

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WP-PFC-C

The present report is focused on processing- and annealing-induced effects on the local configuration, phase composition and atomic intermixing in Fe-rich $Fe_{1-x}Mo_x$ and $Fe_{1-x}Cr_x$ ribbons (x=0.05, 0.1, 0.15), as well as $Fe_{1-x}Mo_x$ and $Fe_{1-x-y}Cr_xW_y$ films of interest for plasma facing components in nuclear devices. The Fe-based thin ribbons have been prepared by induction melting, followed by melt spinning, and further annealed in either Ar or He atmosphere at 850, 1100 and 1250°C. The $Fe_{1-x}Mo_x$ and $Fe_{1-x-y}Cr_xW_y$ films have been deposited on Si substrates by rf magnetron sputtering and thermo-ionic vacuum arc methods (in collaboration with Dr. C. Lungu's group), respectively. The ribbons were characterized from the structural, compositional, thermal and intermixing point of view by X-ray diffraction (XRD), differential thermal analysis (DTA), differential scanning calorimetry (DSC) and transmission Mössbauer spectroscopy. Thus, the XRD analysis indicates the formation of desired bcc structured solid solutions in the as-quenched state. Also, the Mössbauer spectroscopy results on the thermal threated samples reveal on the one hand the presence of magnetic phases assigned to bcc α-Fe with 0, one and two Mo / Cr neighbour and on the other hand magnetic oxide and paramagnetic FeMo/FeCr phases and considerable changes in the local Fe configurations. Increase in Mo concentration induces higher oxidation and, on the contrary, the Cr concentration increase induces strong reduction of the oxidation degree and a very strong modification of the local configuration, in the sense of an increased clusterization of the Cr atoms.

The films were characterized by Grazing Incidence XRD and Energy Dispersive X ray spectroscopy (EDS), as well as by Conversion Electron Mössbauer spectroscopy (CEMS). Grazing Incidence XRD measurements on $Fe_{1-x}Mo_x$ thin films show amorphous structure, while the relative concentration of their components is envisaged from energy dispersive X ray spectroscopy (EDS). CEMS spectra revealed paramagnetic characteristics for $Fe_{1-x}Mo_x$ and $Fe_{1-x-y}Cr_xW_y$ films of low Fe content, as well as prevailing magnetic behavior for high Fe content. The annealing threatment on the $Fe_{0.2}Mo_{0.8}$ film resulted in the formation of a Mo-reach FeMo phase, confirming the intermixing processes.

EUROfusion Consortium contribution to education in fusion research at the predoctoral and PhD level

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The main activities focused on educating, mentoring and monitoring of MSc and PhD students enrolled in the project, aiming to a successful development of their research themes. The activities developed according to the working plans, being sustained by experiments, interpretations and periodic meetings between the young researchers and their mentors. The PhD students matriculated in 2014 have passed their examinations according to the doctoral programme and each of them presented two reports with data from literature and from their own experiments performed in the institute laboratories. In the second part of 2015 they prepared and presented the PhD research projects, a milestone for their doctoral stage. The PhD students in the terminal year, matriculated in 2012, were supervised to focalize on results interpretation and thesis elaboration. Two thesis were finalized and defended. With respect to recruitment, one new PhD student was recruited and enrolled in the project with a subject in fusion technology. The research activity of all students was performed in groups working in fusion research projects. Further activities will focus on continuation of research according to the plans. Supplementary funding is necessary.

Papers

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