Workshop on fusion plasma physics

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Joint meeting with “Association Days” of the Association EURATOM – MEdC Romania for fusion

And including

Memorial Session dedicated to Radu Balescu

Book of Abstracts

Nonlinear excitations of zonal structures by Toroidal Alfvén Eigenmodes

Fulvio Zonca

Zonal flows and, more generally, zonal structures are known to play important self-regulatory roles in the dynamics of microscopic drift-wave type turbulences. Since Toroidal Alfvén Eigenmode (TAE) plays crucial roles in the Alfvén wave instabilities in burning fusion plasmas, it is, thus, important to understand and assess the possible roles of zonal flow/structures on the nonlinear dynamics of TAE.

It is shown that zonal flow/structure spontaneous excitation is more easily induced by finite amplitude TAEs including the proper trapped ion responses, causing the zonal structure to be dominated by the zonal current instead of the usual zonal flow.

This work shows that proper accounting for plasma equilibrium geometry as well as including kinetic thermal ion treatment in the nonlinear simulations of Alfvénic modes are important ingredients for realistic comparisons with experimental measurements, where the existence of zonal field has been clearly observed.

Stochastic trapping effects on drift turbulence evolution and transport

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The paper deals with the fundamental problem of strongly nonlinear stage in the evolution of drift type turbulence. We show that trajectory trapping or eddying in the structure of the turbulence potential is the main physical reasons for the strong nonlinear effects.

This conclusion is drawn from a study of test modes on turbulent plasmas, which is based on a new Lagrangian approach that accounts for ion stochastic trapping in the turbulence. We have shown that trapped trajectories form quasi-coherent structures, which determine non-Gaussian distribution of the displacements $P(\mathbf{x},t)$. Trapping combined with the motion of the potential with the diamagnetic velocity V_* determines ion flows when the amplitude of the E×B velocity is larger than V_*. The trapped ions move with the potential while the other ions drift in the opposite direction leading to opposite (zonal) flows. They compensate such that the average velocity is zero but determine the splitting of $P(\mathbf{x},t)$. The test mode propagator is strongly modified due to trapping through the non-Gaussian $P(\mathbf{x},t)$.

The first effect of trapping in turbulence evolution appears when the fraction of trapped ions is small and the ion flows are negligible. The trapped ions determine the evolution of the turbulence toward large wave lengths (the inverse cascade).

The influence of the ion flows produced by the moving potential appears later in the evolution of the turbulence when the fraction of trapped ions is comparable with that of free ions. The ion flows determine first the damping of the small wave numbers drift modes and eventually the damping of the all drift modes. In the same time, trapping in connection with the compressibility produced by the polarization drift in the background turbulence determine transitory zonal flow modes. This are modes with completely different characteristics, which are considered to limit the increase of drift turbulence amplitude following a predator-prey paradigm. Our first principle study leads to the conclusion that there is no causality connection between the damping of the drift turbulence and the zonal flow modes and thus the predator-prey model is not confirmed. These two processes, which are produced by ion trapping in the moving potential, are just temporally correlated. They determine oscillatory evolution of the turbulence and of the transport.

New methods in the investigation of the general properties of the magnetically confined plasma

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The magnetically confined plasma has an extremely complex evolution, involving many spatial and temporal scales and exhibiting turbulent as well as coherent flow dynamics. However there are few general constraints that allow to get a general perspective on the dynamics of the plasma immersed in a strong magnetic field. We show that developing particular models and using adequate mathematical description, general properties become accessible. We exemplify by the methods of field theory applied to a two-dimensional approximation of the confined plasma. The transition from low confinement to high confinement regime and the density pinch appear as necessary consequences of the vorticity evolution. The limit regime of the pedestal can be associated with the infinite value of the effective Larmor radius and the Edge Localised Modes are initiated by particular solutions of the equation for the streamfunction in this limit.

The presentation will make frequent reference to works of Radu Balescu, from whom I still have to learn a lot.

Particle and heat transport in turbulent plasma: a unified approach to deterministic, stochastic, and fractional transport

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We present a simple, but general conservation law in state space that is formulated in terms of probabilities, and that actually expresses a mathematical identity in probability theory. The conservation law is an integral equation, it hence allows for non-local effects in space, velocity and time, and it can naturally be interpreted as describing a general random walk process. It is then shown how from the conservation law the classical diffusion equation, as well as the standard Fokker-Planck equation, can be derived, basically by excluding non-local effects. These equations are models of classical, stochastic transport. In a second step, it will be shown how from the state-space conservation law also deterministic transport equations can be derived, namely the Boltzmann equation and, more specific for the case of plasma, the Vlasov equation. In a third step, non-localities will explicitly be allowed by making use of Levy distributions in the state-space conservation law, which, in the random walk picture, corresponds to Levy walks in state space. The fluid limit will then be applied to the conservation law, which leads to the fractional Fokker-Planck equation. It will be discussed how the deterministic, stochastic, and fractional transport equations, due to their common derivation from the same conservation law, can be combined into a realistic transport model for plasma turbulence that includes static background magnetic fields, turbulent magnetic and electric fields, and collisions. Also, first results from a numerical application will be shown.

SIMULATIONS OF MHD TURBULENCE. STUDY OF ANOMALOUS TRANSPORT

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In the last decade, we mostly studied the diffusion processes for various configurations of stochastic fields (magnetic and/or electrostatic) that are typical for fusion plasma. In particular, we have studied the diffusion of stochastic magnetic field lines, the diffusion of an electron in a combined structure of stochastic magnetic and electrostatic fields and the zonal flow generation (the quasi-particles diffusion) in the drift electrostatic turbulence. In all these models were solved numerically the differential stochastic Langevin equations associated to the system. The final goal for each individual study was the estimation of the diffusion tensor components.

In the most recent studies we start to evaluate, by means of HPC simulations, the particle transport of charged particle in “frozen” or even full MHD turbulence. Plasma is generally composed of several species of charged particles as well as neutrals. Its complete description may thus require the use of several coupled kinetic equations. In the fluid limit, the large scale features of the plasma can be described using the MHD equations. Depending on the level of description, single fluid or multi-fluid MHD approaches can be developed. The simplest fluid description of the plasma will has been considered and its evolution has been assumed to be driven by the incompressible MHD equations. Ensembles of test particles interacting with the plasma and the electromagnetic fields have been considered.

The presence of persistent large-scale structures, the reminiscent of zonal flow structures, has been observed in various fusion plasma situations, also in our simulations. The particle transport in Navier Stokes Kolmogorov flow displays anomalous transport properties.

SIMULATIONS OF MHD TURBULENCE. STUDY OF ANOMALOUS TRANSPORT

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The purpose of the first topic of our work has been the description of particle transport in turbulent plasmas. Plasma is generally composed of several species of charged particles as well as neutrals. Its complete description may thus require the use of several coupled kinetic equations. In the fluid limit, the large scale features of the plasma can be described using the magneto-hydrodynamic equations. Depending on the level of description, single fluid or multi-fluid MHD approaches can be developed. The simplest fluid description of the plasma will has been considered and its evolution has been assumed to be driven by the incompressible MHD equations. Ensembles of test particles interacting with the plasma and the electromagnetic fields have been considered.

The presence of persistent large-scale structures, the reminiscent of zonal flow structures, has been observed in various fusion plasma situations, also in our simulations. The particle transport in Navier Stokes Kolmogorov flow displays anomalous transport properties.

Other topic of the work was the study of a low-dimensional model for the description of periodic nonlinear perturbations of the plasma (sawteeth, fishbones, ELMs, NTMs) including the pellet injection effects. The model is based on two equations (MHD force balance and energy conservation) and additional Gaussian periodic perturbations were considered in order to include the pellet injection effects. The temporal dependence of the pressure gradient and of the magnetic perturbation before, during and after pellet injection was studied for various values of the parameters. It was observed that pellet injection increases the ELM frequency almost by a factor two. After pellet injection stops, the number of ELMs is almost the same as before of injection. It is interesting to note that not all pellets trigger an ELM. We also studied the relation between the natural ELM frequency and the maximally achievable ELM frequency with pellet in different regimes described by experimental data accumulated in ASDEX Upgrade and other machines. It was observed that pellets are able to increase the ELM frequency if their frequency is larger than the frequency of natural ELMs. The reduction of ELM frequency is not possible. Increase of the ELM frequency is accompanied by reduction of the ELM amplitude, but the total power outflow remains the same. This is true both for natural ELMs and pellet triggered ELMs. The results are in agreement with experimental observations, proving that the model we propose is consistent and can be used with confidence in the study of quasiperiodic phenomena.

ETG instabilities driven by parametric perturbations and the electron heat transport.

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In the framework of the shearles slab geometry, we elaborated a model based on drift kinetic equations for electrons, coupled with Poisson equation. The coupled nonlinear set of equations was linearized, by using a background solution that includes also stochastic components for density and temperature fields. Random field with spatial correlation invariant under translations and having temporal white noise structure modelled the stochastic effects of the multiplicative noise generated by temperature and density fluctuations. The resulted set of stochastic linear partial integro-differential equation converted in a set of deterministic linear partial integro-differential equation for the equal time, two-point correlation functions. This approach is a realization of the programme of stochastic linear stability analysis, whose mathematical background was previously elaborated beginning with the works G. Steinbrecher, B.Weyssow, PRL 92, 125003 (2004) and G. Steinbrecher, X. Garbet, B. Weyssow: arXiv: 1007.0952v1 [math.PR], (2010). In this framework, the stochastic stability is characterized by a spectrum of Liapunov exponents for the moments of the linear combination of the potential and phase-space probability density perturbations. In real physical systems the calculation of these Liapunov exponents for moments of arbitrary order *n* encounters difficulties like the solution of the quantum mechanical *n*-body problem, where the role of the interaction potential formally is played by the two-point correlation function of the parametric noise. As a result we are restricted to perturbative results, in the limit of the small noise intensity to the solution of the corresponding equations of second order moments. Perturbative results were obtained for the leading Liapunov exponent, that describe the large-time evolution of the correlation functions. Implications on the electron heat transport are studied.

RESPONSE OF A 3D THIN WALL TO AN EXTERNAL KINK MODE OF ROTATING PLASMA

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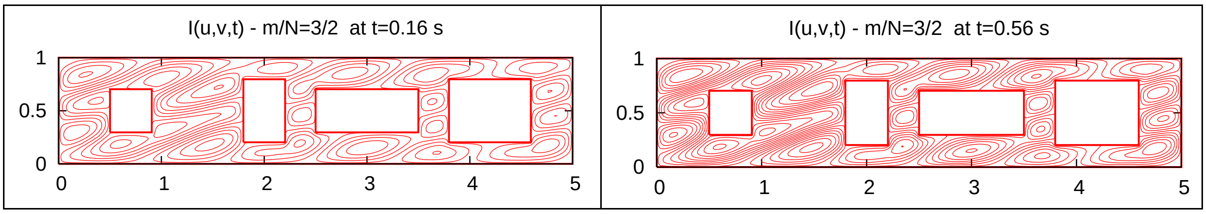
In this contribution we present our calculation of the response of 3D thin multiple connected walls to an external kink mode (a RWM mode) in diverted axisymmetrical tokamak configurations.

To calculate the contribution of the plasma perturbed magnetic field in the vacuum region in toroidally symmetric tokamak discharges, we have made use of the concept of a surface current [1]. In order to simplify the description and calculation of the stability of modes and the plasma response, we limited ourself to the reduced MHD approximation. The expression of the normal component of the magnetic field produced by the perturbation of the flux function has been calculated using the methodology developed in Ref. [2]. In a vacuum gap separating the toroidal plasma from the wall and other current-currying current elements, the perturbed magnetic field can be expressed as $\tilde{\mathbf{B}} = \tilde{\mathbf{B}}^{pl} + \tilde{\mathbf{B}}^{w} + \tilde{\mathbf{B}}^{ext}$, where each term corresponds to the plasma contribution, to the wall contributions and to the electrical currents flowing outside the wall, respectively. For a general wall structure, we have considered a surface curvilinear coordinate system (*u, v*), where two of the covariant basis vectors are tangent to the wall, $\mathbf{r}_u$⍰$\partial\mathbf{r}/\partial u$, $\mathbf{r}_v$⍰$\partial\mathbf{r}/\partial v$, $\mathbf{r}_w$⍰$d(\mathbf{r}_u \times \mathbf{r}_v)/|\mathbf{r}_u \times \mathbf{r}_v|$ and the diffusion equation describing the eddy current density distribution $\mathbf{J}=\mathrm{grad}\, I \times \mathbf{r}^w$ in the thin wall is

$$d\,\frac{\partial(\mathbf{r}^{w}\cdot\mathbf{B})}{\partial t} = -\frac{1}{D}\left\{\frac{\partial}{\partial u}\left[\frac{1}{\sigma d}\left(\frac{g_{uv}}{D}\frac{\partial I}{\partial v} - \frac{g_{vv}}{D}\frac{\partial I}{\partial u}\right)\right] - \frac{\partial}{\partial v}\left[\frac{1}{\sigma d}\left(\frac{g_{uu}}{D}\frac{\partial I}{\partial v} - \frac{g_{uv}}{D}\frac{\partial I}{\partial u}\right)\right]\right\}. \quad (1)$$

where *I* is the stream function of the eddy currents, *d* is the wall thickness and σ the electrical wall conductivity. g_{jk} are the metric coefficients and *D* is the Jacobian. For the determination of the stream function *I*, appropriate boundary conditions have been fixed on all contours. To solve Eq. (1), two approaches have been considered. One, where B^{pl} has been considered only as l.h.s of Eq. (1), while B^{w} was taken iteratively as a source term. The second approach considers B^{w} as a part of the l.h.s of the equation, expressed in terms of the unknown *I* via a mutual inductances matrix. A fast numerical algorithm has been developed [3]. In the next figure, constant *I* lines in a toroidal wall with elliptical cross-section and holes, at two different times are presented.



This task has been carried out in close collaboration with the Tokamak Physics Department of the Max-Planck-Institut für Plasmaphysik, Garching.

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THE INFLUENCE OF THE KINETIC EFFECTS ON THE RESISTIVE WALL MODES STABILIZATION

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In recent years, it has been found that the resonance of the resistive wall modes (RWM) frequency with the toroidal precession frequency of the trapped energetic particles banana orbits stabilizes the former at low toroidal rotation levels of the tokamak plasmas. Being almost locked to the resistive surrounding wall, the RWM frequency is much smaller compared with the trapped or circulating energetic particle bounce motion frequency but comparable to the particle orbits drift motion frequency (diamagnetic or precessional). For a plasma rotation frequency higher than the diamagnetic frequency, the bounce motion prevails if any non-zero harmonic perturbation number in the bounce orbit expansion is considered. We concentrate on the zero bounce harmonic number contribution to the resonance, in a slow plasma rotation regime. The bounce-averaged toroidal precession motion of the trapped energetic particles prevails and the resonance with the RWM frequency is possible. The latter physical mechanism has been proposed as the main energy dissipation channel in order to stabilize the RWM.

A semianalytic theoretical model that describes the RWM stabilization as a result of the above mentioned resonance effect is to be derived. We start from the perturbed MHD equations with the kinetically derived pressure tensor term instead of using the kinetic magnetohydrodynamic (MHD) energy principle. In a two-dimensional, axisymmetric equilibrium magnetic field geometry (toroidicity, Shafranov shift, ellipticity and triangularity parameters are considered), we use a three-dimensional description of the magnetic perturbations. Firstly, the kinetically derived perturbed pressure tensor terms (that contain the RWM/bounce-averaged particle toroidal precession resonance information) to be inserted into the linearized perturbed MHD equations have been explicitly derived. The obtained expressions of the perturbed pressure tensor components are polynomials in the RWM growth rate. Therefore, inserted into the derived 3-dimensional perturbed MHD momentum equation, an exact polynomial RWM dispersion relation is expected to the obtained. The calculated RWM growth rate shows the effect of the above mentioned kinetic resonance on the RWM stability. This is the second task to be fulfilled.

Mean sojourn time of the charged particles in frozen turbulence

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Abstract

General methodology for the study of the long time behaviour of the random Hamiltonian systems is elaborated in the framework of the ergodic theory. In this framework the confinement of particles in a given domain are quantified by the mean sojourn time, that in turn is related to the matrix elements of projection operator on the subspace of invariant functions, from the von Neumann mean ergodic theorem. The case of turbulence with symmetries is studied, in particular the case of the Hamilton function modelled by random field with homogenous, isotropic increments.

We study the limiting case of the projection operator, when the random field is also self-similar, so the Hamilton function is not differentiable and we prove that the limit of the projection operator is still well defined. The formalism is applied to the study of transverse charged particle transport in constant magnetic field in drift approximation, under the effect frozen electrostatic turbulence.

Under the hypothesis of homogeneity, isotropy and self-similarity, we prove that, with probability one, all of the trajectories are either unbounded (that corresponds to sub, normal or super diffusion) either are degenerated to a single points. It follows that in the physical model, when the self-similar random field is regularized at short distances, the diameter of the closed trajectories is of the order of magnitude of the regularising spatial scale.

Development of non-linear MHD models of ELM cycle, including the effect of magnetic or pellet perturbations

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A low-dimensional model for the description of periodic nonlinear perturbations of the plasma (sawteeth, fishbones, ELMs, NTMs) including the pellet injection effects has been studied. The model is based on two equations (MHD force balance and energy conservation) and additional Gaussian periodic perturbations were considered in order to include the pellet injection effects. The temporal dependence of the pressure gradient and of the magnetic perturbation before, during and after pellet injection was studied for various values of the parameters. It was observed that pellet injection increases the ELM frequency almost by a factor two. After pellet injection stops, the number of ELMs is almost the same as before of injection. It is interesting to note that not all pellets trigger an ELM. We also studied the relation between the natural ELM frequency and the maximally achievable ELM frequency with pellet in different regimes described by experimental data accumulated in ASDEX Upgrade and other machines. It was observed that pellets are able to increase the ELM frequency if their frequency is larger than the frequency of natural ELMs. The reduction of ELM frequency is not possible. Increase of the ELM frequency is accompanied by reduction of the ELM amplitude, but the total power outflow remains the same. This is true both for natural ELMs and pellet triggered ELMs. The results are in agreement with experimental observations, proving that the model we propose is consistent and can be used with confidence in the study of quasiperiodic phenomena.

Complex characterization of Beryllium containg films of interest for plasma facing components

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Deuterium and nitrogen doped and undoped Be and Be-W samples with different thickness were produced using Thermionic Vacuum Arc (TVA) method. Surface chemical analyses were performed by X-Ray Photoelectron Spectroscopy (XPS) in order to determine the chemical bonding of the elements and relative concentration. The undoped samples were also implanted with deuterium and were analyzed for their deuterium content and composition using Nuclear Reaction Analysis (NRA), Secondary Ion Mass Spectroscopy (SIMS), Laser Induced Breakdown Spectroscopy (LIBS) and Accelerator Mass Spectrometry (AMS). The Rutherford Backscattering Spectroscopy (RBS) and Thermal Desorption Spectroscopy (TDS) analyses were performed at IPP Garching in order to determine the nitrogen and the oxygen content in the “as prepared” and thermal treated samples. Some Eurofer membranes of 40 mm in diameter 0.5 mm thickness, coated with 5-6 micrometer thick Be-W films were characterized as point of view of hydrogen permeation, in cooperation with Slovenian specialists. In comparison to uncoated membranes, the corresponding permeation reduction factor was of 100-420, an order of magnitude higher than that of pure beryllium films tested in the past. It manifests both high reactivity of the Be film with all active gases and the Be-W film ability for hydrogen trapping.

We greatly acknowledge the contribution of collaborators of other EURATOM Associations: Jari Likonen and Anti Hakola, TEKES Association, Finland, Wolfgang Jacob and Kazuyoshi Sugyiama, IPP Graching, Germany, Vincenc Nemanic, Slovenian Association, as weel as to our colleagues Victor Kuncser (NIFM), Catalin Sion (IFIN-HH), Victor Andrei (ICN-Pitesti)

Plasma torch cleaning: study of conversion/redeposition of removed layers

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The removal of co-deposited carbon layers by a plasma jet source operating at atmospheric pressure was proposed previously and its successful operation was demonstrated. The cleaning experiments were successful on flat surfaces and also inside gaps (0.5-1.5 mm wide). By optimization of working conditions (injected power, gas nature, substrate temperature) removal rates of 10^{-2} g/min were attained. An open issue was whether the removed material is transported and redeposited in another place, or not. The present contribution focuses on investigation of conversion products arising from the etched material, specifically on the redeposition of a solid phase from the exhaust during cleaning with the plasma torch. Carbon materials were exposed as targets to the plasma jet. The targets were eroded. Silicon wafer collectors were placed downstream plasma-target interaction zone and the collected material was analyzed. We show that the collected material can be classified in three categories: particulates of irregular forms, spherical particles, and film zones. The particles of irregular forms looks like broken parts from the target, transported to collector by the plasma flow, or foam like material synthesised on the collector. The spherical particles seems to be synthesised locally on collectors; the film-like material centred on and surrounding the spherical particles, suggests a condensation process, supported by gaseous precursors formed via plasma species reaction with the carbon target. The chemical composition (EDX) of the redeposited materials indicates the presence of carbon, and possible the formation of a carbon oxy-nitride compound. We conclude that some redeposition exists, but the amount of the eroded material found on the collectors, is much less than the eroded one.

In addition, we will report results regarding the obtaining of deuterated samples by magnetron sputtering of W in Ar/D_2 atmosphere and by exposure of W samples to deuterium plasmas.

ADVANCED X-RAY IMAGING OF METAL COATED/IMPREGNATED PLASMA-FACING COMPOSITE MATERIALS

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Carbon Fiber Composites (CFCs) are one of the candidate armor materials for ITER's plasma facing components. The heat flux received by these components is intense and requires active water cooling. This is achieved through a welding between the metallic water loop and the CFC material. An all tungsten divertor is the favored solution for ITER. A realistic simulation of this situation is carried out in the JET tokamak by completely replacing the existing JET CFC tiles with tungsten-coated tiles within the JET ITER-like wall project. In the thermal screening tests the tungsten coatings were exposed to a power density of more than 23 MW/m^2. The thermal expansion mis-match between the CFC substrate and the metallic coating could lead to tensile cracks, delamination and buckling in the coatings.

A combination of X-ray imaging techniques is employed for the characterization of coated/impregnated carbon based composite materials to be used as Plasma Facing Components (PFC) in fusion devices. X-ray micro-tomography (µXCT) is applied for the visualization of Carbon Fiber Composites (CFC) – Cu joined samples and also for the CFC and SiC material porosity network characterization. The quantitative determination of the tungsten coating thickness on carbon materials is performed using a combined absorption/fluorescence X-ray technique (µXRFT). In parallel with the qualification and cross-validation of the thickness measurements the µXRFT method was applied at the analysis of different coatings (W and stainless steel from ASDEX Upgrade tokamak, W/Mo and W/Re from JET) on fine grain graphite (FGG) and CFC tiles. Also µXCT have been used to analyze the SiC-W composites realized by SPS sintering. The present results can be used as a start point in defining a relatively simple route to produce improved W-SiC composites.

Producing and characterization of thin films of ternary and quaternary systems: W/C/Mg/O/N

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Studies regarding the properties of ternary and quaternary systems based on Beryllium, Tungsten and Carbon that include oxygen as unavoidable intrinsic impurity represent an important aim for ITER. The producing of such layers is challanging and the scientific literature in the field is very poor. Moreover, experiments are difficult because Be toxicity. For this reason it is replaced by Mg , which has similar properties. It is then of big interest to deposit and characterize thin films containing C, W and Mg in chemical compounds including oxygen .

Laser based methods have become widely used for obtaining thin films on different supports. Among these, Pulsed Laser Deposition (PLD) emerged as an attractive solution. A new approach concerning Pulsed Laser Deposition (the main technique used) was developed: Radiofrequency Assisted Pulsed Laser Deposition (RF-PLD). This new technique allows the increase of the reactivity on the substrate area, where species from laser plume and from the RF beam simultaneously arrive.

Thin films with different composition containing C, W and Mg and including oxygen were obtained by alternative ablation of graphite, W and MgO targets in oxygen reactive atmosphere. For the first stage, definition of a fabrication route (PLD and/or RF-PLD) and producing of thin films of ternary (W/C/Mg) was checked. The three targets o (W, C and MgO) were alternatively ablated in the presence of oxygen and of a discharge in oxygen to produce layers with different chemical composition. The W/C/Mg ratios were tuned by number of subsequent laser pulses sent on the same target. Investigation techniques like Atomic Force Microscopy, Secondary Ion Mass Spectrometry and Spectro-ellipsometry were used for layers characterization

PARTICULAR ASPECTS OF ELECTRICAL PROBES IN MAGNETIZED PLASMAS

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Electrical probes are among the first and most commonly used plasma diagnostic techniques. For decades probes have been studied both theoretically and experimentally for a better understanding of their behaviour and for an accurate interpretation of their current-voltage characteristic. In the case of magnetized plasmas, the experimental results obtained with probes are still not completely understood. The anizotropy induced by the magnetic field makes the probe characteristic strongly dependent on the probe orientation with respect to the magnetic field lines, both for plane and cylindrical probes. Moreover, probe characteristics with negative slope in the electron saturation region have been reported in the literature. This last aspect has been investigated using cylindrical probes in a linear magnetized plasma device. The plasma source is a hot cathode DC discharge operated at constant current (1 A) and the plasma confinement is achieved using four magnetic coils. Probe current-voltage characteristics were recorded using the following control parameters: probe's length (0 ÷ 7 mm), probe's diameter (0.2, 0.5 and 1.6 mm), the magnetic field strength (up to 0.42 T) and the working gas pressure ($10^{-3} \div 10^{-4}$ mbar). Additionally, numerical simulations have been of great help in understanding particular aspects of probe characteristics.

The behavior of W coated CFC tiles at cyclic high thermal fluxes

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The failure mechanism of the plasma facing components (*PFC*) that appears under normal operation of a tokamak, plays a major role in expected lifetime of the *PFC* themselves and on the amount of the erosion products resulted in the form of dust and particles. On the other hand this failure affects the operation parameters of the fusion equipment. Consequently, plasma wall interaction is a crucial issue not only for the largest operational fusion reactor (*JET*) currently in use but also for the future generation of tokamaks (*ITER* and *DEMO*) that should demonstrate the technical feasibility of the nuclear fusion.

After the successful deposition of W coatings of 10µm and 20µm on *CFC* (Carbon Fibre Composite) tiles by using the *CMSII* (Combined Magnetron Sputtering and Ion Implantation) method, we focused our attention on the assessment of coatings limits. This assessment can supply essential information for a possible prediction concerning the lifetime under a normal operation of the fusion reactor and the limit of W coatings (the ultimate thermal load acceptable for a safe operation of the *JET* wall). At the same time a realistic evaluation of the main factors (thermal fatigue phenomena and coating carbidization) that contributes to coating failure will be presented. This realistic character of the coatings behavior under high thermal load is based on the relative large number of heating cycles employed. Up to 3500 pulses have been applied on W coated *CFC* samples. The heating was performed by an electron gun with the following operating parameters: the accelerating voltage 15 keV, the beam current 100 mA and the beam diameter ~16 mm. The equipment can operate in pulsed regime with pulse duration between 1-999s and a interpulse duration of 1-999 s. The power density can be varied between 4 and 15MW/m^2 allowing the testing of the coatings up to a temperature of 2000^{0}C. The current experiments were conducted in order to test the coatings up to a peak temperature of the surface of 1250^{0}C and 1450^{0}C respectively. The optical inspection of the samples surface after the thermal loading experiments indicated the occurrence of some delaminated area with size in the range 50-500µm. The ratio between delaminated regions and beam-surface interaction area increases with pulse number and testing temperature. It has been also noticed that the delaminated area for samples coated with W of 10µm is lower that the delaminated area for the samples coated with W coatings of 20µm.

Automatic Real-Time Disruption Prediction by Fast Visible Camera Video Image Processing

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See the Appendix of F. Romanelli et al., Proceedings of the 23rd IAEA Fusion Energy Conference 2010, Daejeon, Korea

Video cameras have recently become diagnostic tools widely used on Joint European Torus (JET) for fusion plasma diagnostic and control. Camera based instruments provide essential information for both the control of the experiments and the physical interpretation of the results. These cameras can produce up to hundreds of kiloframes per second and their information content can be very different, depending on the experimental conditions. However, the relevant information about the underlying processes is generally of much reduced dimensionality compared to the recorded data. The extraction of the relevant information, which allows the full exploitation of these diagnostics, is a challenging task. In the last few years, new tools and methods were developed in order to manipulate this huge amount of data and to retrieve the desired information.

Three different approaches, based on the extraction of structural information from the visual scene, were developed for the automatic detection of MARFE (Multifaceted Asymmetric Radiation From the Edge) plasma instabilities. MARFE instabilities may reduce confinement leading to harmful disruptions. They cause a significant increase in impurity radiation and therefore they leave a clear signature in the video data. This information can be exploited for automatic identification and tracking. Experimental tests, optimization and validation wwere performed using the JET database. Good rates of correct classifications together with low rates of false alarms were obtained. Further work will be dedicated to implementation compatible with online MARFE identification.

JET GAMMA-RAY DIAGNOSTICS UPGRADE

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The JET gamma-ray diagnostics provide information on the evolution of fast particles within the tokamak configuration. Information on the spatial distribution of the interacting fast particles is obtained from the gamma-ray cameras, while energy distribution information is provided by gamma-ray spectrometers. These techniques have been very successfully applied so far in fast particle simulation experiments (RF accelerated particles) at JET. The extension of these diagnostics to high power (high neutron yield) discharges is not straightforward. One necessary condition is to have a proper definition of the radiation (neutron and gamma) fields along the diagnostics line-of-sight.

Two gamma-ray diagnostics upgrade projects at JET addressed this issue by developing neutron/gamma radiation filters ("neutron attenuators") and collimators. Neutron attenuators have been designed and constructed for the JET neutron/gamma-ray cameras. A pair of neutron/gamma collimators working in a tandem configuration have been designed and constructed for the JET tangential gamma-ray spectrometer. All the devices have been installed on the machine, and the first experimental results are expected to be obtained during the following months.

The upgraded diagnostics are going to be applied to JET high power deuterium discharges during the next years. The full potential of these new and original techniques will be tested in a deuterium-tritium campaign at JET proposed to take place by 2015

TRITIUM RETENTION IN JET DIVERTOR TILES MEASURED BY AMS AND FCM+SD ANALYZING METHODS

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The Full Combustion Method followed by Scintillation detection (FCM+SD) and the Accelerator Mass Spectrometry have already proven to be the experimental methods able to measure tritium in an efficient and accurate way in plasma facing materials. Many other ion beam techniques like PIXE, ERDA, RBS, SIMS, etc. have failed in different reasons to measure this heavy hydrogen isotope. On one hand, these other methods lack of sensitivity because they use very low energy -decay and on the other hand due to the molecular interferences that can't be avoided or rejected from the registered data.

This paper will present results of our study of tritium retention in W-coated protection tiles compared with the retention in uncoated (ordinary) CFC tiles. An AMS measured complete poloidal distribution of the tritium retention in the new divertor geometry, used in the discharge campaign from 2007-2009, will also be presented.

W-steel joining using powder metallurgy routes

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Different routes for joining W with steel are investigated and optimized to match the requirements of the current DEMO design. The limitation and possible improvements for W-steel FGMs are presented and compared with that ones obtained by plasma sintering/hot press direct joining and plasma sintering/hot press brazing using V based alloys. SEM/EDX and thermal properties investigations are used to asses the joints quality between W and steel. The present results have been obtained in the frame of WP12-MAT-HHFM-01-01 and WP12-MAT-HHFM-04-01 projects.

SiC-W complex composites

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SiC matrix composites with nm and μm sized W dispersions have been sintered by FAST technique and investigated by SEM, BSD, XRD and XRT. Also W plates have been joined using a direct SPS route to a SiC matrix with various W and W-V insertions. These samples have been investigated by SEM, BSD and thermal properties measurements at high temperatures. The results show a considerable increase of thermal conductivity and also improved mechanical strength. A filamentary dispersion of nm W was observed in a particular case which suggests the possibility of a new route for further development of such composites. The present results have been obtained in the frame of WP12-MAT-HHFM-03-01 project.

Spark Plasma Sintering of Fe9Cr-0.3Y2O3 and Fe14Cr-0.3Y2O3 ODS

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The development of the DEMO fusion reactor is established as a priority in EU. Production of Eurofer steels - a former candidate to be used as a structural material on which the armour material is placed- was halted. A replacement is necessary and oxide dispersed steels (ODS) and their synthesis routes are explored in this regard. In our work we focus on using unconventional technique of Spark Plasma Sintering (SPS). The main objective is to evaluate the potential of SPS for fabrication of ODS.

Mixtures of powders with model-like compositions (Fe9Cr-0.3Y2O3 and Fe14Cr-0.3Y2O3) were mechanically alloyed for 20h in Ar by planetary ball milling. Raw powders, non-alloyed and alloyed powder mixtures were characterized by thermal analysis (DSC), X-ray diffraction (XRD), scanning electron microscopy (SEM) and Mossbauer spectroscopy. Differences between powders were revealed. Non alloyed (containing Fe and Cr phases) and alloyed (milled) powders (containing FeCr α-bcc phase) were SPSed at two temperatures of 850 and 1050°C selected based on thermal analysis data. SPSed samples were characterized by XRD, SEM/EDS and Vickers hardness (HV). A higher temperature of SPS of 1050 °C applied on the alloyed powders leads to ODSFS samples with density above 95% showing a HV of about 450 HV units. SPS at 850°C results in densities below 90%, and a lower HV of about 250 HV. Our results are comparable with the HV values presented in literature for ODS with the same composition and prepared by other methods.

Effect of residual process control agent on the microstructure and mechanical properties of ODSFS prepared by mechanical alloying

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Fe-14Cr-0.4Ti ODS ferritic steels have been produced from mechanical alloyed powders consolidated by SPS. The amount of presintering residual PCA was varied by different drying methods applied on the as-milled powder consisted of ~10 nm-sized crystallites. Irrespective of the quantity of residual PCA, the crystallite size has increased by only ~40 nm after SPS consolidation. The Vickers microhardness of the steels increases between 362.5 - 604 VH as the amount of residual PCA in presintered powders decrease. The measured density varies between 5.57-7.60 g/cm^3. Although the SEM micrographs reveal better densification in the steels derived from the powders with lower amount of residual PCA, the measured Archimedes density does not show the similar tendency. Density and porosity was shown to be determined, particularly, by the amount of gases release at the preconsolidation stage (25-450° C, applied pressure of 2 kN). The microhardness was demonstrated to be affected mainly by the porosity. The mechanism of densification of preconsolidated products was inferred from the recorded SPS date at the final consolidation stage (450-900° C, 2 kN -17 kN; 5 min at 900° C).