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523	P5a.120	Analysis of Ion Temperature in High Intense Gas Puffing Experiment on Heliotron J	Magnetic Confinement Fusion	Chenyu	Wang
550	P5a.121	High accuracy Landau collision operator and transport coefficients for gyrokinetic and fluid turbulence simulations	Magnetic Confinement Fusion	Klaus	Hallatschek
351	P5a.122	Application of FIDA as a charge exchange loss measurement for NB-produced fast ions in small or medium-size devices	Magnetic Confinement Fusion	Shin	Nishimura
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19	P5a.201	PIC simulations of strongly magnetized parallel collisionless shocks in pair plasmas	Beam Plasmas and Inertial Fusion	Antoine	Bret
262	P5a.203	Injection tolerances for a quasilinear wakefield accelerator	Beam Plasmas and Inertial Fusion	John	Farmer
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482	P5a.301	Plasma potential control in a weakly magnetized plasma column using negatively-biased emissive electrode	Low Temperature and Dusty Plasmas	Francis	Pagaud
494	P5a.302	Dust Ion Acoustic Modified Korteweg-de Vries Solitons in Dusty Plasmas with Boltzmann Electrons	Low Temperature and Dusty Plasmas	SAMIRAN	DAS
231	P5a.401	Plasma characterisation for nonlinear wave-plasma interaction experiments	Basic, Space and Astrophysical Plasmas	Liam	Selman
369	P5a.402	Investigation of tin plasma driven by high-energy 2-µm-wavelength light	Basic, Space and Astrophysical Plasmas	Lars	Behnke
490	P5a.404	Numerical investigation of non-homogeneous ECR plasma opacities assuming an external black-body radiation	Basic, Space and Astrophysical Plasmas	Matteo	Bezmalinovich
491	P5a.405	High-resolution Optical Emission Spectroscopy characterization of hydrogen and argon laboratory magneto-plasmas of astrophysical interest	Basic, Space and Astrophysical Plasmas	Giulia	Emma

Numerical modelling of fast electron transport on neoclassical tearing mode stabilization by electron cyclotron current drive

Xiaojing Wang[1], Yang Zhang[1], Xiaodong Zhang[1], Q. Yu[2], Liqun Hu[1], Haiqing Liu[1]

[1] *Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, People's Republic of China*

[2] *Max-Planck-Institut für Plasmaphysik, D-85748, Garching, Germany*

Recent studies had shown the beam broadening of electron cyclotron wave due to plasma density fluctuations, which would affect the stabilization of neoclassical tearing modes (NTMs) by electron cyclotron current drive (ECCD) in ITER. The electric and magnetic field perturbation due to plasma turbulence can lead to the anomalous perpendicular transport of fast electrons generated by electron cyclotron wave. Together with the parallel transport, this will broaden the fast electron density profile or the driven current density profile. NTM stabilization by ECCD based on reduced MHD equations has been numerically investigated with a wide wave deposition as predicted for ITER. It is found that the mode stabilization by the modulated current drive is greatly degraded by the perpendicular diffusivity of fast electrons. The necessary modulated driven current for mode stabilization is proportional to the square root of the perpendicular diffusivity of fast electrons. When the perpendicular diffusivity of fast electrons approaches to the anomalous transport level due to plasma turbulence, the necessary modulated driven current for mode stabilization is increased by 2-4 times.

Plasma Parameters of Compact Fusion Reactors using Similarity Scaling Laws of Spherical Tokamak Fusion Plasmas

Francesco Paolo Orsitto and Michele Romanelli

Tokamak Energy Ltd., 173 Brook Drive, Milton Park, Oxfordshire, OX14 4SD, United Kingdom

E-mail: Francesco.Orsitto@tokamakenergy.co.uk

Abstract

Spherical tokamaks (ST) represent an attractive alternative to large aspect ratio tokamaks as they may provide a faster, more economical and compact solution on the path to a fusion reactor. Plasma studies carried out so far on compact, low aspect ratio tokamaks have been limited to small, low/ medium magnetic field and low plasma current therefore the information available for extrapolating to large scale ST plasmas are limited. The scaling law recently obtained [1] links the major radius (R_{ST}) to the fusion gain factor (Q_0) , the magnetic field on axis (B) , the aspect ratio (A), the isotopic mass (M) and the cylindrical safety factor (q) (where C_{ST} is a dimensional constant and H_{ST} is the confinement improvement factor with reference to the ST confinement scaling law): $R_{ST} = C_{ST}\ H_{ST}^{-1/2.23}\ Q_0^{0.464}\ B^{-1.13}\ A^{1.59}\ M^{0.22}\ q^{0.4}$, and allows for the plasma design of compact spherical neutron sources with higher magnetic field compatible with the use of high temperature superconductors. In fact, a feature of the scaling for fusion-reactor plasmas is a stronger dependence on the magnetic field and aspect ratio than the one for ordinary sub-ignited plasmas. The parameters of a spherical tokamak producing the same fusion gain Q (=10) of ITER under different confinement assumptions and for different aspect ratios are presented and discussed. An example of parameters of a ST device deduced using the previous scaling and the ITER confinement time scaling is : R=1.58m, A=1.8, B=3.7T, plasma current Ip=7.8MA, fusion power P_{fus}=118MW, auxiliary heating power P_{AUX}=11.8MW, confinement improvement factor with respect to the ITER IPBy2 confinement time scaling H_{IPBy2} =3.5, q=1.99. In addition, scaling laws for spherical tokamaks related to TFTR supershots and JET hot-ion scenarios are derived and discussed in the context of the operation of compact neutron fusion sources.

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Systematic dissection of the guiding center phase space based on orbital spectrum analysis

Y. Antonenas, G. Anastassiou, Y. Kominis

School of Applied Mathematical and Physical Sciences,

National Technical University of Athens, Athens, Greece

The Guiding Center (GC) description of plasma particles motion plays a crucial role in the study of particle, energy and momentum transport in fusion plasmas. For an axisymmetric toroidal magnetic field configuration, the particles' motion is integrable and can be fully described in terms of the three Constants Of the Motion (COM), uniquely labelling each orbit. In addition to their topological character as trapped, co-passing or counter-passing and their shapes (thin/fat banana, potato and stagnated orbits), GC orbits are characterized by a set of frequencies, namely bounce/transit, orbit-averaged toroidal precession and gyration frequency. These frequencies crucially determine the particle transport due to resonances with characteristic frequencies of various non-axisymmetric perturbations such as MHD instability or plasma wave modes. Due to its resonance character, strong transport takes place in localized regions of the GC phase space.

In a recent work [1], the full Orbital Spectrum of the GC motion has been obtained analytically for a large aspect ratio equilibrium magnetic field, demonstrating a remarkable agreement to numerical calculations. In this work, the analytical results are utilized to construct the full skeleton of the resonance structure in the space of the COM, known as Arnold web, along which significant particle energy and momentum transport takes place under the presence of non-axisymmetric perturbations. Moreover, we pinpoint the location and the extent of various resonances in the GC phase space [2] and systematically dissect the phase space with appropriate Poincare surfaces of section to confirm our analytical predictions and further study single and collective particle dynamics.

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PFPO plasma scenarios for exploration of long pulse operation in ITER

A.R. Polevoi[1], A. Loarte[1], N.N. Gorelenkov[2], Y. Gribov[1], A.Yu. Kuyanov[3], S.Yu. Medvedev[4], S.H. Kim[1], M. Schneider[1].

[1] *ITER Organization, Route de Vinon-sur-Verdon, CS90046, 13067 St Paul-lez-Durance, France*

[2] *PPPL, PO Box 451, Princeton, NJ 08543, United States of America*

[3] *NRC 'Kurchatov Institute', Kurchatov sq. 1, 123098, Moscow, Russian Federation*

[4] *Keldysh Inst. of Applied Mathematics, Miusskaya 4, 125047, Moscow, Russian Federation*

Long Pulse Scenarios (LPS) in ITER at Pre-Fusion Power Operation (PFPO), foreseen in the ITER Research Plan (IRP) [1], are assessed using 1.5D transport simulations within the ASTRA framework [2]. Such assessment is required to predict the operational space for LPS operation in PFPO, as well as to estimate which physics processes for LPS operation at Fusion Power Operation (FPO) could be validated at PFPO. An important issue is to minimize lifetime consumption of the Central Solenoid (CS). Therefore, the maximum pulse length achievable in PFPO with no consumption of CS lifetime ($I_{CS} \leq 30$ kA) has been assessed showing that H-mode operation at 5 MA and 7.5 MA could provide LPS with a duration in excess of 1000 s. The operational space of such H-modes has been explored through density and power scans to determine the operational space with H&CD mix suggested for steady state phase of ITER operation [3] with acceptable NBI and ECH shine through loss (with the ECH calculated by OGRAY code [4]). For 7.5 MA/2.65 T plasmas weak reversed shear configuration with a high fraction of suprathermal ions, as expected in DT steady state ITER scenarios [3], can be obtained at PFPO between the sawteeth. The MHD stability was assessed with KINX [5] and TAE stability with NOVA-K [6] codes for half-field, B/Ip=2.65/7.5 T/MA, and third field, B/Ip= 1.8/5 T/MA, PFPO scenarios in L-mode and H-mode operations and compared with those at steady- state operation in DT [3].

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Available energy and its relation to turbulent transport

R.J.J. Mackenbach[1], J.H.E. Proll[1], P. Helander[2]

[1]Eindhoven University of Technology, 5612 AZ Eindhoven, The Netherlands
[2]Max Planck Institute for Plasma Physics, 17491 Greifswald, Germany

r.j.j.mackenbach@tue.nl

Any collisionless plasma possesses some "available energy" (AE), which is that part of the thermal energy that can be converted into instabilities and turbulence. Here, I present an investigation into the available energy carried by trapped electrons in a slender non-omnigenous flux tube of plasma. We compare this AE with gyrokinetic simulations of the non-linear saturated radial energy flux resulting from turbulence driven by collisionless trapped-electron modes in various stellarators and a tokamak. The numerical calculation of AE is extremely fast and shows a strong correlation with the turbulent energy fluxes found in the gyrokinetic simulations, resulting in a power law. Finally, we implement AE as a proxy for turbulence optimisation and investigate the resulting optimized devices.

A free-boundary MHD code for axisymmetric equilibrium configurations with flow.

G. F. Torija-Daza[1], J. M. Reynolds-Barredo[1], R. Sánchez[1]

[1] *Universidad Carlos III de Madrid (UC3M), Madrid, Spain*

The calculation of MHD equilibria is routinely required in many contexts in fusion plasmas, starting at the initial phases of the design of the confining magnetic configuration and extending into the interpretation of multiple diagnostic systems during their operation. In many situations, however, significant plasma flows exist that can affect the geometry and properties of the equilibrium in a non-trivial way. The fusion community has developed various codes that calculate their effects in the magnetohydrodinamics equilibria. Most of them, however, consider a fix-boundary at the plasma edge. This is a reasonable assumption when measurements from the discharge to be analyzed can provide with information about the plasma shape. However, it is not so convenient when trying, for instance, to assess in advance the modifications to the plasma shape, the position of the X point or the magnetic flux expansion at the divertor associated to the presence of these flows. This work aims at showing how to build a free-plasma-boundary code from a previously existing fixed-boundary code. It is done by modifying the computational volume and integrating the information about the external coils using scheme previously used successfully in the stellarator equilibrium code SIESTA.

The fixed-boundary code uses pseudo-spectral methods and finite differences in an eulerian frame. As an example, an ITER equilibrium has been studied by using a set of different flow profiles with different intensities with which the capabilities of the free-boundary code could be showcased.

References

Physically based modelling of EC pre-ionization and assisted breakdown under ITER-like constaints

P. Ch. Papagiannis[1], G. E. Anastasiou [1], K. Hizanidis[1], Abhay K. Ram[2]

[1] *School of Electrical and Computer Engineering, National Technical University of Athens, Athens 15780, Greece*

[2] *Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

In order to reduce demand on the central solenoid for startup in ITER, radio frequency power in the electron cyclotron (EC) frequency range will be used for ionizing the neutral gas [1].

Features of EC power, confined to a nearly-Gaussian beam, cannot be incorporated in the usual framework of Townsend theory for the breakdown phase [2]. The approach taken in our studies on the breakdown phase by EC beams, consists of modelling the interaction of an ensemble of seed electrons, confined by a magnetic field, with a spatially localized Gaussian beam in the presence of a background electrostatic potential. The canonical Hamilton-Jacobi dynamical equations of motion are solved numerically to study the energization of seed electrons by the wave fields. In the spatial region away from the beam, the electron motion is affected only by the toroidal electric field. We consider multiple interactions with the EC beams and characterize the electron energization in terms of the width of the beam, the frequency and polarization of the waves, the beam power, the direction of propagation of the beam (launching inclination), and the initial energy of the electrons. We incorporate cross-section evaluations for electron impact ionization of the neutral gas as well as elastic collisions [3], so as to determine the rate at which the electron population increases as a function of beam parameters.

The aim of our studies is to determine the threshold needed for the generation of an electron avalanche and reduce the time to reach this threshold. The projection of our preliminary results for ITER-like parameters [4] predicts that prionization with EC increases the energization rate about 4 times, leading to an ionization ratio 1.5 times greater at the breakdown time. Furthermore we can reduce the power at about two thirds and achieve the same energization rate and ionization ratio as long as we adjust accordingly the beam inclination and width.

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Effects of alpha particles on the transport of helium ash driven by collisionless trapped electron mode turbulence

Guangting Zhu[1], Weixin Guo [1], Lu Wang[1]

[1] *Huazhong University of Science and Technology, Wuhan, China*

The effects of alpha (α) particles on the removal of helium ash driven by collisionless trapped electron mode (CTEM) turbulence are analytically studied by means of quasi-linear theory. Under the parameters used in this work, the removal of helium ash is mainly determined by diffusivity due to much weaker impurity convective velocity. Through analyzing the parametric dependence of the ratio between helium ash diffusivity and the effective electron thermal conductivity (i.e., D_{He}/χ_{eff}), it is found that although $D_{He}/\chi_{eff} < 1$, which is less efficient for the removal of helium ash as compared with ion temperature gradient (ITG) mode [1], D_{He}/χ_{eff} can be increased 50% by the presence of 3% α particles with their density gradient being twice that of electrons. This is mainly because the destabilizing effect of α particles [2] on helium ash diffusivity is stronger than that on electron thermal conductivity. Moreover, the higher concentration as well as the steeper profile of α particles, the stronger enhancement of D_{He}/χ_{eff} . Meanwhile, α particles do not qualitatively change the parametric dependence of D_{He}/χ_{eff} on the electron temperature and the fraction of tritium (T) ions. Finally, it is also found that both the diffusivities of deuterium (D) and T ions are still smaller than that of helium ash even with α particles, which is similar to the case without α particles [3]. These results might be favourable for more accurate prediction of helium ash profile and efficient removal of helium ash in the fusion reactor burning plasmas.

Key words: alpha particles, removal of helium ash, CTEM, D_{He}/χ_{eff}

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3D MHD simulations of unmitigated Vertical Displacements Events in ITER

F.J. Artola[1], A. Loarte[1], M. Lehnen[1], M. Hoelzl[2] and the JOREK team[3]

[1] *ITER Organization, Route de Vinon sur Verdon, 13067 St Paul Lez Durance Cedex, France*

[2] *Max Planck Institute for Plasmaphysics, Boltzmannstr. 2, 85748 Garching, Germany*

[3] *please refer to [M Hoelzl et al, Nuclear Fusion 61, 065001 (2021)]*

One of the high priority research needs for the ITER project is the development of a solid physics basis of plasma disruptions and their mitigation. Present predictions for the thermal and electromagnetic loads caused by unmitigated Vertical Displacement Events (VDEs) rely on experimental observations and axisymmetric simulations [1,2]. 3D effects, such as the sideways vessel force produced by toroidally asymmetric VDEs, must be understood to provide the basis for load validation in support of the ITER Research Plan and make predictions for full current operation. In this work, 3D simulations of such events are performed for an ITER 15MA/5.3T plasma with the MHD code JOREK coupled to the STARWALL wall code. The main goal of these simulations is to study different asymmetric features occurring during unmitigated VDEs that remain unclear for ITER. Among those features, the evolution of the distribution of the plasma and wall current density, the triggering time of the thermal quench, the distribution of the heat-fluxes onto the first wall, the minimum edge safety factor and the maximum sideway force and its toroidal rotation will be studied.

In these simulations, a VDE is triggered in an L-mode plasma by applying a current perturbation in the ITER in-vessel coils. Since the expected time scales for unmitigated VDEs in ITER are of the order of ~500 ms due to the long decay time of the ITER vessel currents, the main plasma and wall parameters are re-scaled by a given factor in order to reduce the computational cost to present computing capabilities (~million cpu.h). The influence of the re-scaling factor on the results will be studied together with convergence tests (e.g. for the toroidal resolution). In addition, the effect of the VDE direction (upwards or downwards), the parallel transport in the open field line region and the plasma viscosity will be studied. One of the main results obtained from this study is the confirmation that despite different assumptions, the thermal quench is triggered once the edge safety factor decreases to a value of 2 due to the reduction of the plasma volume during the VDE.

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First Simulations of Pellet Injections into Heliotron J using HPI2

N. Panadero[1], G. Motojima[2], K. Nagasaki[3], KJ. McCarthy[1], F. Koechl[4] and Heliotron J team

[1]Laboratorio Nacional de Fusión, CIEMAT, *Madrid, Spain*

[2]*National Institute for Fusion Science, Toki, Gifu, Japan*

[3]*Institute of Advanced Energy, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan*

[4]*Culham Centre for Fusion Energy, Abingdon, United* Kingdom

Efficient plasma core fuelling is a key challenge for the development of steady-state operation in large magnetically confined plasma fusion devices. At present, cryogenic Pellet Injection (PI) is the most advanced technique for solving this problem. Core fuelling is particularly important for helical machines due to the predicted core particle depletion [1]. However, most studies have been carried out to date in tokamaks [2]. This, compounded by the fact that PI experiments in non-axisymmetric devices are more difficult to interpret due to the complexity of the magnetic fields, has positioned stellarators at a disadvantage with respect to tokamaks. However, this situation has been reverted recently as the main helical devices, Wendelstein 7-X, LHD, TJ-II and Heliotron J, are now equipped with PIs and several studies have been carried out [3–6]. These reveal that plasmoid drift, usually well understood in tokamaks (*i.e.,* directed along the $\nabla\mathbf{B}$ direction), is more complex than expected and not fully understood. For instance, in W7-X, High-Field Side injections were predicted to be advantageous [7]. However, experiments show no, or near negligible, improvement in fuel penetration and efficiency when compared to Low-Field Side injections [3]. Now, new pellet studies performed in the Heliotron J are presented with the aim of obtaining further insights into plasmoid drift in non-axisymmetric devices. In this work, the stellarator version of the HPI2 code [8–10], redeveloped for W7-X and initially benchmarked on TJ-II [7], has been implemented for the Heliotron J geometry. In this version, the fully 3D magnetic configuration is taken into account when calculating plasmoid drifts by averaging the magnetic gradient along the plasmoid parallel length [7]. HPI2 results are compared with experimental observations from Heliotron-J and discussed.

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Energetic particle transport: diffusion vs convection and phase-space barriers

N. Carlevaro[1], G. Montani[1,2], M.V. Falessi[1], Ph. Lauber[3]

[1] *ENEA, FNS Department, C.R. Frascati, Via E. Fermi 45, 00044 Frascati (Roma), Italy*

[2] *Physics Department, "Sapienza" University of Rome, P.le Aldo Moro 5, 00185 Roma, Italy*

[3] *Max-Planck-Institut fuer Plasmaphysik, Boltzmannstrasse 2, D-85748 Garching, Germany*

Energetic particle (EP) redistribution due to the interaction with electromagnetic fluctuations is a key issue for magnetic confinement fusion. When multiple Alfvén eigenmodes with overlapping resonances are considered, the commonly used reduced description is based on diffusive quasi-linear (QL) models [1, 2]. In Ref.[3], from the analysis of the ITER 15MA baseline scenario, it is instead pointed out how realistic non-linear simulations are not properly characterized by QL predictions because typical avalanche phenomena are not reproduced. This specific transport feature is instead retained by the 1D reduced description introduced in Ref.[4] illuminating the relevance of the stable part of the fluctuation spectrum.

In this work, using this simplified 1D Hamiltonian method, we investigate the transport character of domino EP redistribution. The relaxation of tracers that interact mostly with the initially linear stable part of the spectrum is shown to have, in the non-linear phase, a temporal quadratic dependency of the mean square path, highlighting the convective nature of transport towards the plasma edge. Meanwhile, tracers dominated by interaction with overlapping unstable modes in the plasma core exhibit a linear dependence, characteristic of pure diffusion. Moreover, the formation of transport barriers in the phase space and their connection with the diffusive/convective transport regimes is studied by means of the Lagrangian Coherent structures technique [5].

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Slow thermal quench in ITER disruptions

H. Strauss[1]

[1] *HRS Fusion, West Orange, USA*

Fast disruptions occur in JET and other present experiments. The thermal quench (TQ) occurs [1] in about $1ms$. Slow disruptions are predicted to occur in ITER. The thermal quench is predicted [2] to have a much longer time scale of order $50ms$.

Most disruptions in JET are of the locked mode type. The plasma toroidal rotation slows and locks. Tearing modes produce stochastic parallel thermal transport in the edge region, which along with impurity influx, cools the edge. This precursor stage might last $100ms$. It is followed by an MHD instability, which has recently been identified as a resistive wall tearing mode (RWTM) [1], by comparing theory and simulations with experimental data. The TQ time is the inverse of the RWTM growth rate. The RWTM in ITER grows much more slowly than in JET, because the resistive wall time τ_{wall} is two orders longer. This was confirmed by simulations [2] of an ITER baseline scenario 2 equilibrium.

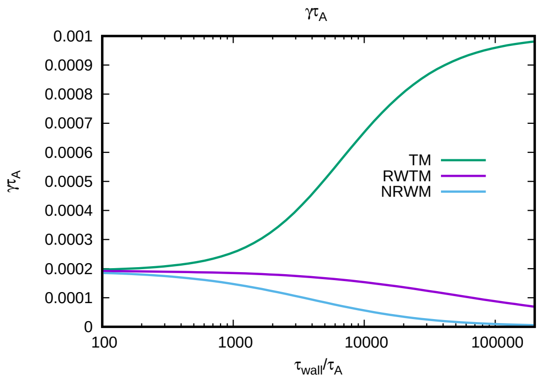

Figure 1: *Growth rates γ of TM, RWTM, and NRWM as functions of the resistive wall time τ_{wall}, where τ_A is the Alfvén time.*

The dispersion relation of the RWTM [1] also includes tearing modes (TM), and a new (neo) resistive wall mode (NRWM). These modes branch from the TM no wall limit at the left of Fig. 1, $\tau_{wall} \to 0$. The usual RWM branches from the ideal no wall limit. The growth rate γ depends on τ_{wall}, S, Δ_0, and Δ_1, where S is the Lundquist number, $\Delta_0 > 0$ depends on the no wall free energy, and $\Delta_1 = \Delta'$ with an ideal wall. The curves in Fig. 1 are with $S = 10^5$, $\Delta_0 = 0.125$, and $\Delta_1 = 1, 0, -1$.

The fastest growing mode is the TM, with $\Delta_1 > 0$. When the TM is marginally stable, $\Delta_1 = 0$, the RWTM occurs, with $\gamma \propto \tau_{wall}^{-4/9}$. If $\Delta_1 < 0$, the NRWM can occur with $\gamma \propto \tau_{wall}^{-1}$. The TM and RWTM are the precursor and TQ stages of the disruption, respectively. The NRWM might be unstable before the TMs are destabilized, a subject requiring further investigation.

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Plasma magnetic control scenarios for the ITER PFPO-1 phase

M. Dubrov[1], Y. Gribov[1], A. Kavin[2], P. de Vries[1], V. Lukash[3], R. Khayrutdinov[3], R. A. Pitts[1]

[1]ITER Organization, Route de Vinon-sur-Verdon, CS 90 046, 13067 St. Paul Lez Durance Cedex, France

[2] Efremov Scientific Research Institute of Electrophysical Apparatus, Saint Petersburg, Russia

[3] National Research Centre «Kurchatov Institute», Moscow, Russia

The first ITER non-active (H or He fuel) Pre-Fusion Power Operation phase (PFPO-1) will also be the first in which the full blanket first wall and divertor will be installed and in which the ITER Research Plan foresees the achievement of diverted plasma scenarios potentially up to plasma currents of I_p = 10 MA in L-mode and 5 MA in Type I ELMing H-mode. This in turn requires that the Plasma Control System (PCS), in particular for plasma current, position and shape control, be developed with the full required functionality well in advance of the campaign. This PCS PFPO-1 design activity is now underway, with completion expected in 2025. Scenario simulations with specific focus on plasma magnetic control and taking into account the engineering limits of the ITER machine, are a key input to this PCS design. As will be described in this paper, they are being performed with the DINA code, which incorporates a 2D free boundary equilibrium solver, and is now fully integrated into the ITER Integrated Modelling Analysis Suite. The various controllers used in DINA for the scenario development are also being ported into the PCS Simulation Platform (PCSSP). To perform sensitivity studies of the impact of plasma internal inductance on magnetic control, the DINA transport module has recently been updated.

Magnetic control on ITER is complicated as a result of long settling times caused by the thick vacuum vessel walls, the high inductance of the poloidal field coils and the relatively low voltage limits allowed by the superconducting magnets. There are also many additional requirements which impose detailed optimization of magnetic control scenarios (for example the generation of oscillations in power consumed from the electric grid). Plasma density waveforms are optimized to be high enough to reduce the possibility of locked modes, but not too high as to exceed the Greenwald limit. The achievable stable plasma elongation is estimated respecting the minimum allowed distance between the inner and outer separatrices, and vertical stability with the presence of noise in the vertical position control. In the low I_p PFPO-1 scenarios, the initial charge of the Central Solenoid (CS) is reduced to save lifetime. Even for a half-charged CS, I_p flattop durations of ~100 s are found to be possible.

Towards multi-machine large-scale integrated modelling validation

A. Ho[1], C. Bourdelle[2], J.-F. Artaud[2], Y. Camenen[3], F. J. Casson[4], J. Citrin[1], F. Koechl[4], M. Marin[5], J. Morales[2], G. Tardini[6], JET Contributors*, the AUG team, the TCV team, and the WEST team

[1] *DIFFER, De Zaale 20, 5612 AJ, Eindhoven, The Netherlands*
[2] *CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France*
[3] *Aix-Marseille Univ., PIIM UMR7345, Marseille, France*
[4] *EURATOM-CCFE Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK*
[5] *Swiss Plasma Center, EPFL, 1015 Lausanne, Switzerland*
[6] *Max Planck Institute for Plasma Physics, D-85748 Garching, Germany*
* *See the author list of 'Overview of JET results for optimising ITER operation' by J. Mailloux et al. to be published in Nuclear Fusion Special issue: Overview and Summary Papers from the 28th Fusion Energy Conference (Nice, France, 10-15 May 2021)*

To prepare ITER operation and contribute to DEMO design, a cohesive plan to extend the state-of-the-art in predictive integrated tokamak simulation and associated validation methodologies has been endorsed by E-TASC (*EUROfusion-Theory and Advanced Simulation Coordination*) initiative under the acronym of TSVV11 (*Theory, Simulation, Validation and Verification task on 'Validated frameworks for the Reliable Prediction of Plasma Performance and Operational Limits in Tokamaks'*). The JINTRAC simulation suite, primarily used at the Joint European Torus (JET) facility, was selected as a base to build the required simulation functionality. A sub-task of the project focuses on standardizing and automating the modelling validation and uncertainty quantification pipelines of the JINTRAC simulation suite and its components across multiple experimental regimes and multiple EUROfusion devices. This task also stress tests the existing ITER IMAS architecture, the IDS data structure, and any developed tools for facilitating cross-domain data communication and large-scale data analysis.

The first stages of this validation task are presented here, including developing a rudimentary procedure for configuring the code accounting for current best practices in the modelling community and defining suitable validation metrics. The strict definition and subsequent automation of the simulation setup reduces the undesired impact of human errors and subjectivity on the validation results. Also, the amalgamation of multiple pre-existing 0D metrics (e.g. V_{loop}, l_i, stored energy, radiated power, neutron flux, etc.) allows a comparison to direct experimental measurements for more meaningful validation results.

The upcoming stages in this work intend to incorporate of 1D profiles and 2D line-of-sight information to extend the depth of validation possible. The large-scale study results can also be leveraged to categorize potential model discrepancies by their physical origins, possibly helping to identify or prioritize missing but crucial physics within the simulation suite. Finally, this exercise is currently limited to steady-state plasma conditions but expanding this methodology into time evolution simulations is recommended for future work within this project.

On linear analysis of turbulence growth rates

T.P.Kiviniemi, S. Leerink

Department of Applied Physics, Aalto University

P.O. Box 11100, 00076 AALTO, Finland

Linear growth rate is routinely used for benchmarking activities of turbulence codes. For gyrokinetic full-f code ELMFIRE [1] this poses a challenge as it is intrinsically nonlinear full-f code where the linear growth rates of single modes can only be observed by filtering nonlinear data during the simulation, not by turning off terms like in other codes [2]. Another option is to look at the linear growth of macroscopic quantities like heat diffusivity or the growth of potential fluctuations in total without limiting the analysis to single modes. In a recent verification effort it was also noticed that global effects have an influence on linear analysis close to the edge [2].

In present paper, we discuss these difficulties and, also, test the code in a box-type geometry by neglecting the drifts caused by toroidal geometry in the equations of motion. Results are compared to the results including toroidal effects and, also, to recently published results on box-simulations with fully-kinetic 6D code [3].

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Analysis of ITER performance with different heating schemes using predictive integrated plasma modelling

T. Bensadón[1], M. Mantsinen[1,2], J. Manyer[1], T. Jonnson[3], D. Yadykin[3,4]

[1] *Barcelona Supercomputing Center, Barcelona, Spain*

[2] *Catalan Institution for Research and Advanced Studies (ICREA), Barcelona, Spain*

[3] *KTH Royal Institute of Technology, Stockholm, Sweden*

[4] *University of Gothenburg, Sweden*

In order to achieve a suitable fusion performance and reach the H-mode in the Pre-Fusion Power Operation Phase (PFPO) at ITER, auxiliary heating power systems such as Ion Cyclotron Resonance Frequency (ICRF) heating are needed. Although extensive research has gone into ICRF modelling, most of the modelling has been done for heating scenarios relevant for the D, T and D-T plasmas in the Fusion Operation stage of ITER, focusing on second harmonic T heating and fundamental minority ^{3}He resonance heating schemes. There is a need to improve our understanding on the performance of ICRF in H and He in the non-active phase of ITER, and on the most effective heating schemes for this phase.

We use the heating code PION [1] integrated into the European Transport Solver (ETS) [2] to study and predict how the plasma transport will be affected when ICRF heating is applied to ITER non-active plasmas. The integration into a transport modelling workflow is relevant because a transport modelling workflow such as ETS, which has been developed inside the ITER Integrated Modelling & Analysis Suite (IMAS) [3], can calculate the evolution of the plasma discharge and provide the capabilities for self-consistent predictive simulations. In this work, the PION+ETS integration was used to model JET high performance baseline discharge 92436 with D-H plasma composition at full field, and was validated against PION results of this discharge. Synthetic METIS ITER shot 110005 with ^{4}He-H plasma composition was also modelled and validated against results from our earlier PION results in IMAS [4]. In both cases the ICRF heating scheme used was fundamental minority H heating. We present results of time dependent predictive simulations at different H concentrations of the ITER synthetic shot using the PION+ETS integration. Fundamental minority H heating was found to be an effective heating scheme, yielding increasing power absorption with increasing H concentration and reaching a maximum of 80.2% at [H] $\sim$ 5%.

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Analysis of Ion Temperature in High Intense Gas Puffing Experiment on Heliotron J

CY. Wang[1], S. Kobayashi[2], K. Nagasaki[2], DC. Qiu[1], MY. Luo[1], R. Fukushima[1], PF. Zhang[1],
K.Y. Watanabe[3], R. Seki[3], R. Matoike[1], A. Miyashita, [1] Y. Kondo[1], K. Inoshita[1], T. Minami[2], S. Kado[2],
S. Ohshima[2], S. Konoshima[2], T. Mizzuchi[2], H. Okada[2]

[1]*Graduate School of Energy Science, Kyoto University, 611-0011 Uji, Kyoto, Japan*

[2]*Institute of Advanced Energy, Kyoto University, 611-011 Uji, Kyoto, Japan*

[3]*National Institute for Fusion Science, 509-5292 Toki City, Gifu, Japan*

A fueling method named high intense gas puffing (HIGP) has been applied to obtain high-performance plasmas on the Heliotron J helical device. The fueling method puffs deuterium gas in a short period (~10-20ms) with high intensity. The electron density reached up to $6\times10^{19}m^{-3}$, depending on the HIGP intensity, with a steep density gradient at the peripheral region[1]. With a moderate HIGP, the improvement of core ion temperature T_i has been observed in NBI plasmas. Besides, the electron density profile is more peaked at the peak density of $2.5\text{-}3.5\times10^{19}m^{-3}$, and the electron temperature profile was also peaked. We studied the ion temperature profile measured with a charge exchange recombination spectrum (CXRS) system equipped on Heliotron J [2,3]. We compared the T_i profile to that obtained in a conventional gas puffing (GP) with a similar electron density. The plasma was initiated by electron cyclotron heating first and then heated by neutral beam injection (NBI).

Several differences in T_i between the HIGP and GP cases were observed. The T_i profile is improved after HIGP turn-off compared with GP case. After HIGP turn-off, T_i increased in a rather high rate while the increase was suppressed when HIGP was operating. We observed that the relation between T_i and n_e was also different. In the HIGP case, when n_e starts to decrease, T_i is kept increasing for about 10 ms. We also observed that shape of T_i profile and NBI absorption profile was related to the shape of n_e profile. A similar relationship was also observed between T_e and n_e profiles. These phenomena suggest that HIGP may improve the ion heat transport in the core plasma with a peaked n_e profile. In a further study, we will do the heat transport analysis.

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High accuracy Landau collision operator and transport coefficients for gyrokinetic and fluid turbulence simulations

K. Hallatschek

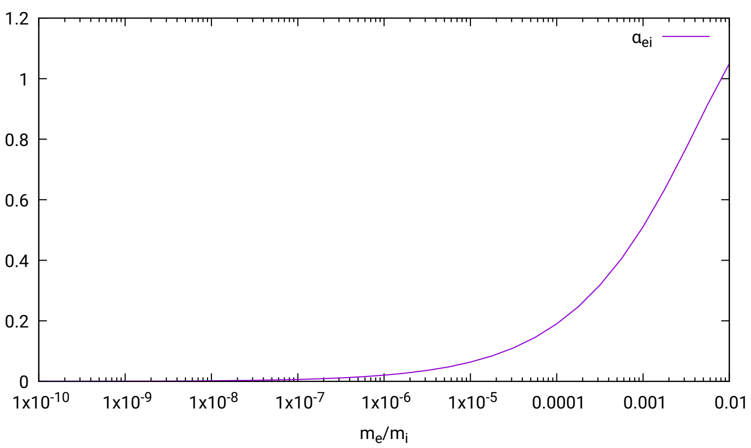
Max-Planck-Institute for Plasma Physics, Boltzmannstr. 2, 85748 Garching, Germany

A code for the gyro-transformed (pulled-back) matrix elements of the linearized but otherwise complete Landau operator required by gyrokinetic (GK) [1] edge turbulence simulations was developed, inspired by the advantageous use of half-sided Hermite (or related) polynomials P_i as velocity space basis functions in [1, 2].

This approach turned out to be amazingly successful. It takes only seconds to calculate the Landau matrix elements for hundreds of polynomials for all normally required perpendicular wavenumbers of a turbulence simulation up to machine precision, automatically fulfilling all applicable conservation laws and the H-theorem. In the case that extremely high wavenumbers are to be computed $k\rho_i \gtrsim 100$ (e.g. for ETG turbulence) nevertheless a cut-off was required. For these a novel fast asymptotic approximation procedure is presented.

With the code it is also possible to calculate Braginskii-style transport coefficients, much more precise than so far published [3, 4] and study alternative *definitions* of fluid transport coefficients – those are usually based on the particular ordering scheme used, and cannot provide more than the first order in the expansion parameters.

This way, certain analytically overlooked, transport coefficients can be computed, such as the mass-ratio dependent ion electron cross heat flux $q_{i,e} = \alpha_{ei} n T_i \tau_{ii} / m_i \partial_\| T_e$, the coefficient of which (α_{ei}) is shown on the side.



Clearly these effects are significant and should be taken into account in any fluid turbulence simulation of realistic collisional Deuterium plasmas, not the least to arrive at a meaningful comparison between fluid and kinetic simulations.

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Application of FIDA as a charge exchange loss measurement for NB-produced fast ions in small or medium-size devices

S. Nishimura[1], H. Yamaguchi[1], S. Kobayashi[2], S. Kado[2], T. Minami[2], S. Ohshima[2],
H. Okada[2], Y. Nakamura[3], K. Nagasaki[2]
[1] *National Institute for Fusion Science, Toki, Japan*
[2] *Institute of Advanced Energy, Kyoto University, Uji, Japan*
[3] *Graduate School of Energy Science, Kyoto University, Uji, Japan*

In NBI heating experiments in small or medium-size toroidal devices such as Heliotron-J and CFQS, the charge exchange loss of NB-produced fast ions is not negligible in the determination of the fast ions' slowing down velocity distribution function. Although it may be possible for many numerical simulation methods for the fast ions to include this loss mechanism, experimental measurements of the neutral particle density profile in the 3-dimmensional real space as the input to such calculations are almost impossible. On the other hand, the FIDA (Fast Ion D-alpha) measurement[1] are widely used in various devices for investigating the local fast ion velocity distribution. In situations where the charge exchange loss is not negligible and the neutral particle density profile is unknown, this method is not useful for the purpose of the experimental validation of theoretical calculations of the velocity distribution. For the studies of beam-driven phenomena such as that in Refs.2-3, and the anisotropic pressure MHD equilibrium mentioned in Ref.4, however, the requirement on the velocity distribution is not in the detailed understanding on the slowing down process including the charge exchange loss but in the reduction factor of the lower Legendre order structures of the velocity distribution. In both the direct solving using the eigenfunction[3] and the indirect solving based on the adjoint equation method[4], it can be shown that for this purpose that the effect of the charge exchange loss on the velocity distribution will not appear in the pitch-angle space structure but will appear only in the energy space structure. When we find the substantial neutral particle density by comparison of the FIDASIM[1] calculation including this energy space reduction factor and the experimentally observed Balmer-alpha spectrum, we should include this reduction factor also in calculations of the beam-driven effects. [2−4] The measurement example in the Heliotron-J will be presented.

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Preliminary ab-initio calculations of the mean excitation energy of ions with relativistic effects for deriving their stopping power in fusion plasmas

J. Walkowiak[1], A. Jardin[1], J. Bielecki[1], Y. Peysson[2], D. Mazon[2], D. Dworak[1], K. Król[1] and M. Scholz[1]

[1] Institute of Nuclear Physics Polish Academy of Sciences, PL-31342 Krakow, Poland
[2] CEA, IRFM, F-13108, Saint-Paul-lez-Durance, France

The use of tungsten as a material for plasma-facing components introduced new challenges for plasma simulation codes. High-Z impurities like tungsten (Z = 74) are not fully ionized in tokamak plasmas in existing devices, nor in the planned ones like ITER or DEMO. Bound electrons strongly influence collisions in different ways, e.g. by introducing new energy loss mechanism by excitation and ionization [1,2].

The effects of impurities on suprathermal electrons dynamics can be calculated using the Fokker-Planck equation with modifications [3] to the collision operator. However, this approach requires knowledge of the Mean Excitation Energy (MEE) of the ions, which precise value can only be obtained from the spectroscopic properties of the ions. Since direct measurements of the required quantities for ions are not possible, the only way to obtain accurate estimates of the MEE is to calculate the transition properties of the ions. This has already been done in non-relativistic approach, but high-Z elements require advanced atomic models that account for relativistic and correlation effects in atoms. Modern computational methods, such as Multiconfigurational Dirac-Hartree-Fock, brings the possibility to obtain required data from ab-initio calculations of atomic properties. Since tungsten is an important element for the spectroscopy of the tokamak plasma, calculations of some tungsten lines are already available [4]. However, no systematic study to obtain the MEE has been done. The presented work shows possible ways to fill this gap and preliminary results of the MEE calculation for ions where relativistic effects are noticeable.

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On Relativistic Braginskii Transport Equations: Mixed Approach

I. Marushchenko[1], N. A. Azarenkov[1]

[1] *V. N. Karazin Kharkiv National University, Krarkiv, 61022, Ukraine*

It is well known that the relativistic and ultra-relativistic effects are important in astrophysics for description of transport processes in space plasmas. In last decades it was also recognized that the relativistic effects can play the significant role for transport processes in the laboratory fusion plasmas, where typical temperature are about tens of keV (see, for example, [1, 2, 3]). In particular, the physics of electron transport processes in hot plasmas requires a special attention in calculation of plasma fluxes [2, 3]. Nevertheless, practically all transport codes which are in use for simulation of the fusion reactor scenarios are based on the non-relativistic limit of transport theory; see, for example [4].

The present work is focused on transport processes in hot plasmas with relativistic electrons with $v_{te} < c$ and relatively slow macroscopic fluxes $V \ll c$. Formally, the required equations can be obtained from the general co-variant formulations (see, for example, [5]). However, it was found that it's more physically transparent to derive the Braginskii equations from the first principles. A presence of the hydrodynamic flow is accounted in weakly relativistic approach, neglecting the terms of the order higher than V^2/c^2 and $V v_{te}/c^2$, while the bulk electrons are considered rigorously, i.e. in fully relativistic approach. The ions are taken as classical. This mixed approach makes possible to omit the requirements of Lorentz invariance, while including the relativistic effects related to the kinetics of hot electrons.

For the closure of the relativistic transport equations, the linearized kinetic equation has to be solved. It is proposed to apply for this procedure the generalized Laguerre polynomials $L_n^{(\alpha)}(\mu(\gamma-1))$ of order $\alpha = 3/2 + \mathscr{R}(\mu)$ with $\mathscr{R}(\mu) = 15/8\mu + \mathscr{O}(\mu^{-2})$ and $\mu = m_e c^2/T_e \gg 1$. In contrast to earlier attempts to apply Sonine polynomials for relativistic transport (see [6]), generalised Lagguerre polynomials allows to use a finite number of terms for the right-hand-side of the relativistic linearized kinetic equation.

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PIC simulations of strongly magnetized parallel collisionless shocks in pair plasmas

Antoine Bret[1,2], Colby C. Haggerty[3], Damiano Caprioli[4]

[1] *ETSI Industriales, Universidad de Castilla-La Mancha, E-13071 Ciudad Real, Spain*

[2] *Instituto de Investigaciones Energéticas y Aplicaciones Industriales, Campus Universitario de Ciudad Real, E-13071 Ciudad Real, Spain*

[3] *Institute for Astronomy, University of Hawai'i, Honolulu, HI 96822, USA*

[4] *Enrico Fermi Institute, The University of Chicago, 5640 S Ellis Ave, Chicago, IL 60637, USA*

Collisionless shock waves are frequently treated/modelled as a collisional, fluid MHD discontinuity. In light of this, using PIC simulations of non-relativistic, parallel collisionless shocks, we detail the deviation of collisionless shocks form MHD predictions for varying magnetization/Alfvénic Mach numbers. We show that for sufficiently large upstream magnetic fields, the shock compression ratio is dramatically reduced, in agreement with the predictions of Bret & Narayan 2018 [1]. Additionally, we examine the role of field strength on the shock width and on the generation of energetic particles. This work reinforces a growing body of work that suggest that modelling many astrophysical systems with only a fluid plasma description omits potentially important physics [2].

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Injection tolerances for a quasilinear wakefield accelerator

J. P. Farmer[1,2], L. Liang[3], R. Ramjiawan[2], F. M. Velotti[2], M. Weidl[4], E. Gschwendtner[2], and P. Muggli[1].

[1] *Max Planck Institute for Physics, Munich, Germany*

[2] *CERN, Geneva, Switzerland*

[3] *University of Manchester, Manchester, UK*

[4] *Max Planck Institute for Plasma Physics, Garching, Germany*

The AWAKE project at CERN harnesses a high-energy proton beam as a driver for wakefield acceleration. Run 2 will allow improved control over the acceleration process by using a separate plasma stage for the self-modulation of the proton driver. The modulated driver will then be injected into a second plasma stage where it is used to accelerate a witness bunch. Although statistical quantities such as emittance and energy spread are useful for describing the witness evolution, the accelerated bunch is ultimately best characterised in terms of its suitability for applications. We here present a figure of merit based on an electron-proton collider, and show how this leads naturally to constraints on both the tunability and stability of the witness bunch parameters at the point where it is injected into the wakefield.

Theoretical and Numerical Study of Stimulated Raman Scattering in a Finite Plasma

M.S.Wong[1], S.H.Chen[2]

[1] *Department of physics, National Central university, Taoyuan, Taiwan*

[2] *Department of physics, National Central university, Taoyuan, Taiwan*

In a one-dimension, finite-length plasma, the behavior of stimulated Raman scattering(SRS) is performed by three-wave-interaction and Vlasov simulation. Via two-scale expansion, the analytical dispersion relation for absolute instability in a finite-length plasma system is derived and validated by linear growth rate with three-wave-interaction(TWI) simulation. The scaling of the linear growth rate of the scattered wave with the system length(L) and pump intensity(A_0) has been examined and demonstrated. The linear and nonlinear behavior of SRS has been also studied by the TWI simulation. In the nonlinear region, the pump depletion plays an important role in SRS, which results in the contraction of the field profile of the scattered wave. The start oscillation and the stationary oscillation can be achieved while the finite system reaches the energy balance condition. By considering a kinetic effect, such as Landau damping and Wave breaking, the Vlasov simulation is developed. In the Vlasov simulation, the wave breaking breaks the stationary oscillation of SRS. Via Vlasov simulation, the difference between wave-breaking threshold in theory and simulation varies by changing the plasma length. The Landau damping has also been studied in Vlasov simulation and examined in different plasma lengths. In this poster, we point out the plasma length changes the linear growth rate, field profile contraction in the nonlinear region, and the wave breaking threshold.

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Plasma potential control in a weakly magnetized plasma column using negatively-biased emissive electrode

F. Pagaud[1], B. Trotabas[2], R. Gueroult[2], V. Dolique[1], N.Plihon[1]

[1] *Laboratoire de Physique - ENS de Lyon & CNRS, Lyon, France*

[2] *LAPLACE, Université de Toulouse, CNRS, INPT, UPS, 31062 Toulouse, France*

The possibility to control plasma parameters such as the density n, the electron temperature T_e or the plasma potential V_p is of crucial importance for applications (for instance plasma centrifuges [1]). We present an extensive investigation of the influence of a hot and negatively-biased emissive electrode on the plasma parameters of a pre-existing magnetized plasma column.

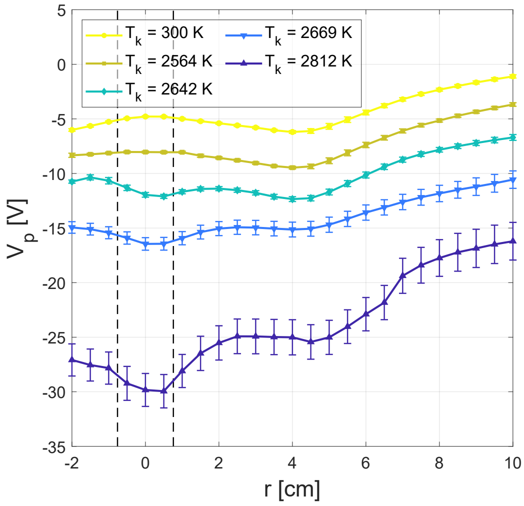

Figure 1: *V_p along r with various temperatures T_k. $r = 0$ is the center of the column, dashed lines indicate the electrode.*

Experiments using a negatively-biased emissive electrode were conducted in an Argon plasma column [2] at pressures p_0 around 1 mTorr and magnetic fields $B \sim 20$ mT. The 10 cm in diameter plasma column is created by an RF source (power P_w from 1 to 3 kW) resulting in ionization rates up to 20%, while the biased emissive electrode faces the opposite side of the column. The cathode is biased at a fixed potential V_b up to -60 V (i.e. $\sim 20\ T_e$) and heated at temperatures T_k up to 2900 K.

A comprehensive dataset spanning the parameters space (p_0, B, P_w, V_b and T_k) was obtained with measurements of density and electron temperature using an advanced triple probe, and plasma potential measurements using emissive probes.

A typical example (Fig. 1 with $V_b = -60$ V) shows that electron emission is an efficient mean to control the plasma potential: as the temperature of the cathode T_k increases, the cathode sheath reduces, allowing to control the value V_p from the external bias V_b. Our dataset is interpreted in light of recent models [3, 4], and refinements of these models will be discussed.

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Dust Ion Acoustic Modified Korteweg-de Vries Solitons in Dusty Plasmas with Boltzmann Electrons

Samiran Das[1] and D. C. Das[2]

[1]*Department of Mathematics, Central Institute of Technology Kokrajhar, BTR, Assam 783370, India*

[2]*Department of Mathematics, Barnagar College, Sorbhog, Barpeta 781317, India*

For this multicomponent dusty plasma consisting of ions, Bolzmann electrons and mobile dusts, interesting results of dust ion-acoustic KdV solitons were already shown. In this paper we incorporate higher order nonlinearity and more interesting characteristics of dust ion acoustic solitons by deriving modified Korteweg-de Vries (mKdV) equation. We observe that for inclusion of higher order nonlinearity, compressive or rarefactive mKdV solitons of much higher amplitudes exists. The drastic change in growth of amplitudes of the mKdV solitons for different pairs of ions and electrons streaming in presence of mobile dusts is a salient feature of this investigation. Mobile dusts and number of charges contained in a dust particle (Z_d) also plays very important role in the formation of mKdV solitons in this plasma model.

Plasma characterisation for nonlinear wave-plasma interaction experiments

L. Selman[1], K. Wilson[1], P. MacInnes[1], C.G. Whyte[1], A.R. Young[1], A.D.R. Phelps[1], A.W. Cross[1], L. Zhang[1], B. Eliasson[1], D.C. Speirs[1], C.W. Robertson[1], K. Ronald[1], R.A. Cairns[1,2], R. Bingham[1,3], R. Bamford[3], M.E. Koepke[1,4]

[1] SUPA and Department of Physics, University of Strathclyde, Glasgow, G4 0NG UK

[2] School of Mathematics and Statistics, University of St Andrews, St Andrews, KY16 9SS, UK

[3] STFC Rutherford Appleton Laboratory, Oxford, OX11 0QX, UK

[4] Department of Physics, West Virginia University, Morgantown, WV26506-6315, USA

Electromagnetic (EM) waves propagating in a plasma can non-linearly excite plasma oscillations, other EM waves and transfer energy to the plasma, especially at plasma resonances. Raman and Brillouin scattering, where two EM waves, coupled via a Langmuir or ion-acoustic wave respectively, are relevant to intense laser plasma interactions. In magnetised plasma, beat-waves may couple to hybrid and cyclotron resonances of the electrons and ions. This may be useful in delivering energy in overdense magnetically confined fusion plasma.

The paper presents progress on a low temperature plasma apparatus for multifrequency microwave interaction experiments. Using microwaves in a tenuous cool plasma will enable enhanced active control and diagnostic accessibility. An RF source driving a flat spiral antenna is used to ionize an unmagnetised plasma by inductive coupling or a magnetised plasma ($T_e \sim$ few eV, $n_e \sim 10^{15} - 10^{18}$ m^{-3}) by helicon waves [1] in a vessel 3m long and 1 m in diameter. Equilibrium T_e, n_e, and electrostatic fluctuations will be measurable.

High power microwaves are launched between a pair of horn antennae, which launch a Gaussian beam, at ~ 9.5 GHz, into the plasma. The antennae have been fabricated and will be compared to numerical predictions. The microwaves may be generated by compact magnetron oscillators and TWT amplifiers, or fast wave Gyro-TWT amplifiers. The amplifiers are tuneable to provide frequency differences corresponding to plasma resonances. The paper will also present simulations of relevant beat wave interactions. Combining measurement, simulation and theoretical analysis, an enhanced understanding of the physics is anticipated.

The project builds on previous research in [2-4]. The authors gratefully acknowledge support from the UK EPSRC through grants EP/R004773/1 and EP/R034737/1.

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Investigation of tin plasma driven by high-energy 2-µm-wavelength light

L. Behnke[1], Y. Mostafa[1], Z. Bouza[1], L. Poirier[1], A. Lassise[1], R. Schupp[1], R. Hoekstra[2], W. Ubachs[3], O.O. Versolato[1]

[1] *Advanced Research Center for Nanolithography, Amsterdam, The Netherlands*

[2] *Zernike Institute for Advanced Materials, Groningen, The Netherlands*

[3] *Department of Physics and Astronomy and LaserLaB, Amsterdam, The Netherlands*

Tin laser-produced plasmas are used as sources of extreme ultraviolet (EUV) light at 13.5 nm wavelength in nanolithography [1]. Tin plasmas driven by lasers operating at wavelengths of 1 and 10 µm are widely studied with respect to their emission characteristics in the EUV regime. We present experimental data from tin plasmas driven by a 2-µm-wavelength laser operating in the range between the 1 and 10 µm cases. Plasmas driven by a 2-µm laser provide intermediate plasma densities that help to understand the role of fundamental atomic properties in the generation of usable EUV light.

We conduct experiments where we irradiate different mass limited tin targets with a 2-µm drive laser. In these experiments, small droplets of molten Sn are dispensed from a droplet generator inside a vacuum vessel. These droplets can be deformed to a thin sheet of tin by means of an additional laser pulse, called pre-pulse. Relevant plasma characteristics such as emission spectra and the emitted in-band energy around 13.5 nm are observed for different target dimensions and laser parameters. Those parameters include pulse duration, laser intensity distribution, target -diameter and -thickness. The experiments show a significant reduction of spectral line broadening at 13.5 nm in going from 1- to 2-µm drive laser wavelength (λ) under otherwise similar conditions. The change in line broadening is attributed to a near-linear scaling of the relevant plasma mass density with λ^{-1} and thus a corresponding scaling of optical depth at 13.5 nm [2]. The 2-µm-driven plasma with reduced relevant density paired with controllable drive-laser-pulse duration and plasma dimension allows for further detailed studies of the opacity-related broadening that may limit future solid-state-laser driven sources of EUV light. Further, controlling the thickness of the target and the pulse duration allows for an investigation of laser ablation rates. The experiments provide insight into the fundamental atomic opacity limits of converting drive laser light to useful EUV photons.

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Numerical investigation of non-homogeneous ECR plasma opacities assuming an external black-body radiation

M. Bezmalinovich[1,2], G. Emma[3,4], G. Finocchiaro[3,4,6], G. S. Mauro[4], M. Mazzaglia[4], B. Mishra[3,4], E. Naselli[4], A. Pidatella[4], D. Santonocito[4], G. Torrisi[4], A. Galatà[5], A. Saltarelli[1,2], S. Simonucci[1,2] and D. Mascali[4]

[1] *Università degli studi di Camerino, Camerino, Italy*

[2] *INFN, Sezione di Perugia - Perugia, Italy*

[3] *Università degli studi di Catania, Catania, Italy*

[4] *INFN, LNS - Catania, Italy*

[5] *INFN, LNL - Legnaro, Italy*

[6] *CSFNSM, Catania, Italy*

Laboratory plasma may become an attractive environment for making innovative research activities impacting Astrophysics and Nuclear Physics in the context of the Multi-messenger Astronomy. In this scenario, the PANDORA project [1] aims at investigating nuclear β-decays under plasma conditions resembling astrophysical scenarios, following theoretical predictions [2] and allows to better address the study of s-process nucleosynthesis. In addition, the project aims at measuring, for the first time, plasma opacities which are relevant for addressing the opacity input, arising from freshly synthesized r-process elements in post-merging plasma ejecta, relevant for the Kilonovae signal interpretation [3]. In this paper, we numerically estimated the electron densities and temperatures of the non-homogeneous laboratory Electron Cyclotron Resonance (ECR) plasma in non Local Thermodynamical Equilibrium conditions through a Particle-In-Cell (PIC) code [4]. Moreover, by means of the population kinetics code FLYCHK [5], we also simulated the optical properties of an Ar plasma using the PIC simulation results together with an input black-body radiation, to establish and characterize the opacities, along 1-D line of sight. Finally, we studied the behaviour of the outcoming intensity as impacted by the opacity arising from both radiation-perturbed and not optically thin plasma, according to the population levels distribution of the excited Ar atoms. Results presented can offer benchmarks about plasma induced radiation field distortion, useful for supporting laboratory spectral characterizations.

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High-resolution Optical Emission Spectroscopy characterization of hydrogen and argon laboratory magneto-plasmas of astrophysical interest

G. Emma[1,2], M. Bezmalinovich[4,5], G. Finocchiaro[1,2,3] , G. S. Mauro[2], M. Mazzaglia[2], B. Mishra[1,2], E. Naselli[2], A. Pidatella[2], D. Santonocito[2], G. Torrisi[2], R. Reitano[1,2] and D. Mascali[2]

[1] *Università degli studi di Catania, Catania, Italy*

[2] *INFN - LNS, Catania, Italy*

[3] *CSFNSM, Catania, Italy*

[4] *Università degli studi di Camerino, Camerino, Italy*

[5] *INFN - Sezione di Perugia, Perugia, Italy*

In the last decades there has been a growing interest in the nuclear astrophysics' community to investigate the origin of elements heavier than iron in the Universe produced via r-process nucleosynthesis. Merging of compact binary objects, leading both to high-neutron flux and gravitational wave (GW) events, are among the most favorable astrophysical loci for this production [1]. In this context, it is relevant the study of kilonovae (KN). These are electromagnetic transients powered by freshly synthesized elements and radioactivity and can be used as spectral signatures of nucleosynthetic yields inside the expanding post-merging plasma ejecta [2]. To this aim, in the framework of the PANDORA project [3] we are developing a new plasma trap where it will be attempted the emulation of kilonovae ejecta properties at a specific stage of their evolution. This setup will allow measurements of plasma opacity providing new insights about the most relevant species produced via r-process nucleosynthesis [4]. In order to verify the feasibility of this kind of measurements in terms of required temperature and density (order of eV and 10^{12} cm^{-3}, respectively), we are using the flexible plasma trap (FPT), operative at INFN-LNS, as testbench for PANDORA, characterizing gaseous plasma (H_2, Ar) discharge, stability, and parameters by Optical Emission Spectroscopy. In this work, we will present the experimental results, concerning estimates of plasma density and temperature, deduced by means of the line-ratio method [5], from the analysis of the spectra measured in the visible range under different conditions, i.e., by tuning microwave frequency and power, pressure and magnetic field profile.

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