ID	Posternumber	Title	Topic	Pesenter first name	Presenter last name
104	P2a.101	Effect of resistivity on the MHD pedestal stability in JET	Magnetic Confinement Fusion	Hampus	Nyström
155	P2a.102	Microtearing turbulence and reduced transport model building in H-mode plasmas	Magnetic Confinement Fusion	Myriam	Hamed
197	P2a.103	Effect of the divertor configuration on the JET edge radial electric field	Magnetic Confinement Fusion	Carlos	Silva
204	P2a.104	Dynamic error fields derivation by inverting a validated interpretative perturbations model	Magnetic Confinement Fusion	Gabriel	Miron
284	P2a.105	Collisional-radiative model for transport simulations of neutrals in detached conditions	Magnetic Confinement Fusion	Francesco	Cianfrani
307	P2a.106	Measuring RF-accelerated fast ions with DD and DT neutron spectroscopy: comparison of velocity-space sensitivity	Magnetic Confinement Fusion	Jacob	Eriksson
309	P2a.107	Exploration of Alfven Eigenmode physics via active antenna excitation in JET Deuterium, Tritium, and DT plasmas	Magnetic Confinement Fusion	Roy Alexander	Tinguely
327	P2a.108	Impurity modelling with European Transport Simulator: implementation and verification	Magnetic Confinement Fusion	Dmitriy	Yadykin
337	P2a.109	Analysis techniques for the simultaneous measurement of impurity ion temperatures and velocities in MAST-U using Coherence Imaging Spectroscopy	Magnetic Confinement Fusion	Rhys	Doyle
344	P2a.110	Observations of confined fast ions in MAST-U with the NCU	Magnetic Confinement Fusion	Marco	Cecconello
376	P2a.111	Linear drive of Fast-ion-driven vertical modes	Magnetic Confinement Fusion	Tommaso	Barberis
419	P2a.112	L-H transitions and intermediate behaviours on MAST and MAST-U	Magnetic Confinement Fusion	Lena	Howlett
421	P2a.113	Confinement dependence on beta/power in the JET ILW hybrid scenario	Magnetic Confinement Fusion	Jörg	Hobirk
427	P2a.114	Neon seeding effects on two JET high performance baseline plasmas	Magnetic Confinement Fusion	Stefano	Gabriellini
442	P2a.115	Predictive modelling of D-T fuel mix control with gas puff and pellets for JET 3.5 MA baseline scenario	Magnetic Confinement Fusion	Vito Konrad	Zotta
448	P2a.116	First MAST-U Equilibrium Reconstructions using the EFIT++ Code	Magnetic Confinement Fusion	Lucy	Kogan
462	P2a.117	Quasi-Linear transport model EDWM: Update and benchmarking	Magnetic Confinement Fusion	Emil	Fransson
472	P2a.118	Fast-ion studies with three-ion ICRF scenarios in non-active JET plasmas	Magnetic Confinement Fusion	Yevgen	Kazakov
481	P2a.119	First divertor Thomson scattering measurements on MAST-U	Magnetic Confinement Fusion	James	Clark
486	P2a.120	Physics informed fast Grad-Shafranov surrogates	Magnetic Confinement Fusion	Emily	Lewis
502	P2a.121	Neural Plasma Reconstruction from Diagnostic Imaging	Magnetic Confinement Fusion	Ekin	Ozturk
503	P2a.122	Microwave current drive for STEP and MAST Upgrade	Magnetic Confinement Fusion	Simon	Freethy
516	P2a.123	An extended-MHD model for peeling-ballooning stability thresholds in spherical tokamaks	Magnetic Confinement Fusion	Andreas	Kleiner
191	P2a.124	Stability analysis of low-n modes for the Divertor Tokamak Test facility Single Null Scenario	Magnetic Confinement Fusion	Valeria	Fusco
552	P2a.124	Validation of a new turbulence probe for MAST-U	Magnetic Confinement Fusion	William	Fuller
26	P2a.201	High-flux neutron generation by laser-accelerated ions from single- and double-layer targets	Beam Plasmas and Inertial Fusion	Vojtěch	Horný
150	P2a.202	Mono-charge super-heavy ion beams accelerated by a multi-PW laser	Beam Plasmas and Inertial Fusion	Jarosław	Domański
182	P2a.203	Acceleration of spin-polarized proton beams from a dual-laser pulse scheme	Beam Plasmas and Inertial Fusion	Lars	Reichwein
233	P2a.204	Adiabatic Focusing of a Long Proton Bunch in Plasma	Beam Plasmas and Inertial Fusion	Livio	Verra
296	P2a.205	Narrow-band, GeV gold ion beams from ultra-thin foils irradiated by intense sub-picosecond pulses	Beam Plasmas and Inertial Fusion	Philip	Martin
301	P2a.206	Direct laser acceleration in plasmas with a density gradients	Beam Plasmas and Inertial Fusion	Robert	Babjak
428	P2a.207	Plasma-based acceleration for non-relativistic particles	Beam Plasmas and Inertial Fusion	Chiara	Badiali
434	P2a.208	PIC Simulations of the Interaction between Self-Modulation in the Front and Rear of an ultra-relativistic Proton Bunch in Plasma	Beam Plasmas and Inertial Fusion	Pablo Israel	Morales Guzman
435	P2a.209	Control of the self-modulation and long-bunch hosing instabilities through plasma frequency detuning	Beam Plasmas and Inertial Fusion	Mariana	Moreira
525	P2a.210	Analysis of electron bunch energy spectra after meter scale over-dense plasma	Beam Plasmas and Inertial Fusion	Kook-Jin	Moon
236	P2a.301	Study of radio frequency breakdown in a device with movable electrodes	Low Temperature and Dusty Plasmas	Leonardo	Zampieri
277	P2a.302	Fluid modelling of the weakly magnetized plasma column MISTRAL	Low Temperature and Dusty Plasmas	Surabhi	Aggarwal
349	P2a.303	Experimental evidence of TIAGO torch dart at atmospheric pressure to be a Surface Wave Discharge.	Low Temperature and Dusty Plasmas	Francisco Javier	Morales-Calero
586	P2a.304	Importance of Electron drag force in EUV induced pulsed plasma	Low Temperature and Dusty Plasmas	Manis	Chaudhuri
131	P2a.401	PIC simulations and reduced model of confined ionising electron clouds relevant to gyrotrons	Basic, Space and Astrophysical Plasmas	Guillaume	Le Bars
355	P2a.402	Models for modulated rotation of a Penning-trapped magnetized electron vortex in a variable-charge regime	Basic, Space and Astrophysical Plasmas	Giancarlo	Maero
499	P2a.403	Gamma-ray flares from magnetic reconnection in relativistically magnetized plasmas: minijets vs. plasmoids	Basic, Space and Astrophysical Plasmas	Krzysztof	Nalewajko
579	P2a.404	Atomic calculations in moderately charged lanthanide ions (from La to Pm) relevant for plasma opacity studies in the context of kilonovae	Basic, Space and Astrophysical Plasmas	Helena	Carvajal Gallego

Effect of resistivity on the MHD pedestal stability in JET

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The pedestal in type I ELMy plasmas is commonly accepted to be limited by ideal peeling-ballooning modes. However, recent JET results obtained in type I ELMy H-modes have shown that the ELM can be triggered also before the ideal peeling-ballooning boundary [1, 2, 3]. In terms of engineering parameters, this typically occurs at high power and high gas rate [2] or, in terms of physics parameters, at high relative shift between the density and temperature pedestals [4]. More recently, the disagreement between experimental results and ideal MHD predictions has been correlated with the resistivity in the middle-bottom of the pedestal [5]. This correlation indicates that resistive MHD might be required to describe the pedestal in plasmas with high relative shift.

In this work, we present the initial results of including resistivity on the MHD stability analysis of an extended JET dataset. In the stability analysis the CASTOR [6] code has been used. The CASTOR code is a linear MHD eigenvalue solver that includes resistivity but does not include diamagnetic effects. The effect of the diamagnetic stabilization is therefore implemented as a critical limit in the growth rate, taken as $\gamma = 0.25\omega^*_{max}$ where ω^*_{max} is the maximum diamagnetic frequency in the pedestal.

The work is focused on two parts. Firstly, the detailed analysis of four different shots with differing gas and power, to understand the effect resistivity has on the peeling-ballooning stability. Secondly, a larger dataset is considered to see if the results obtained in the detailed analysis generalizes to other shots.

The stability boundary in j-α space for JET shot 87342 can be seen in figure 1 where the inclusion of resistivity shifts the stability boundary to within the uncertainty of the experimental point. When a larger dataset is considered, the results of this work indicate that resistivity can significantly improve the model predictions and remove the correlation between relative shift and disagreement between model and experiment. Additionally the shots that are ideally peeling-ballooning limited are only weakly affected by including resistivity. This work therefore suggests that including resistivity is an important first step in reconciling model and experiment in devices with large relative shift where the pedestal does not appear to be ideally peeling-ballooning limited.

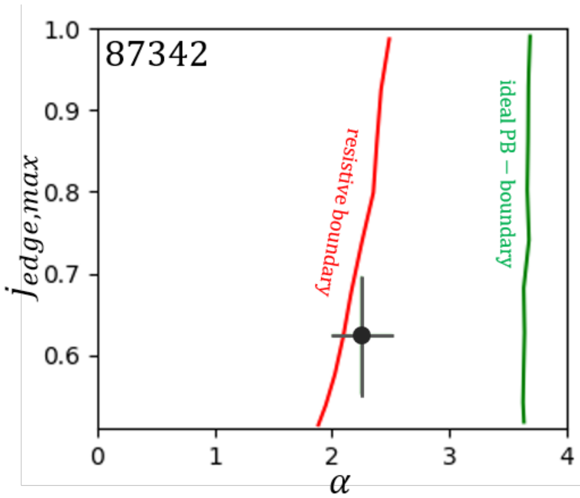

Figure 1. Stability boundary for JET shot 87342 in j-α space including (red) and excluding resistivity (green). Experimental point is shown with error bars.

References

[1] M. Beurskens *et al* 2014 Nucl. Fusion **54** 043001

[2] C.F. Maggi *et al* 2015 Nucl. Fusion **55** 113031

[3] L. Frassinetti *et al* 2021 *Nucl. Fusion* **61** 016001

[4] E. Stefanikova *et al* 2018 *Nucl. Fusion* **58** 056010

[5] L. Frassinetti *et al* 2021 *Nucl. Fusion* **61** 126054

[6] W. Kerner *et al* 1998 *J. Comput.. Phys.* **142** 271

Microtearing turbulence and reduced transport model building in H-mode plasmas

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In many fusion plasmas, microtearing turbulence is a key player, covering core and edge/pedestal scenarios as well as spherical tokamaks. Recent analysis of JET plasmas [1] suggest that microtearing (MT) mode, may be responsible for electron heat transport in the pedestal, and thereby play some role in determining the pedestal characteristics. The stability of MT modes has been extensively studied, showing that a slab current sheet is stable in the absence of collisions [2, 3, 4]. In contrast, recent gyrokinetic simulations in toroidal geometry found unstable MT modes [5, 6], even at low collisionality.

To predict the electron heat transport due to MT in a tokamak pedestal, and to aid with the development of a quasilinear MT transport model, nonlinear simulations were run with the GENE code and analyzed with respect to magnetic fluctuations and the question which kind of physics sets the saturation amplitudes in the quasi-stationary turbulent state. This is a key prerequisite for developing a reduced MT model applicable for flux-driven integrated modeling. A reduced model for microtearing transport is presented that reproduces gyrokinetic trends for a number of parameter regimes, as is demonstrated by comparison with a database of nonlinear gyrokinetic simulations. Using this model, the impact of different physical parameters, in particular the electric potential, has been investigated in nonlinear saturation. The electric potential play an important role in microtearing destabilization by increasing the growth rate of this instability in the presence of collisions, while in electrostatic plasma micro-turbulence, zonal flows can have a strong stabilizing impact in turbulent saturation. Here, instability and saturation physics are examined for different pedestal cases and radial positions, with a special focus on the role of electric field fluctuations and the role of zonal flows and fields. In the saturated state, it is found that removing the zonal flow and zonal fields causes a flux increase, while linearly stabilization had been observed. This model will be coupled to a neural network for sweeping parameter scans, working towards real-time transport modeling in particular of the tokamak pedestal.

References

[1] D.R. Hatch *et al.*, *Nucl. Fusion* **56**: 104003 (2016).

[2] R. D. Hazeltine, D. Dobrott, and T.S. Wang, *Phys. Fluids* **18**: 1778 (1975).

[3] M. Hamed, M. Muraglia, Y. Camenen, and X. Garbet, *Contrib. Plas. Phys.*, 58: 529-533 (2018)

[4] M. Hamed, M. Muraglia, Y. Camenen, and X. Garbet, *J. Phys.: Conf. Ser.* **1125**: 012012, 2018

[5] A.K. Swamy *et al*, *Phys. Plasmas* **21**, 082513 (2014).

[6] D. Dickinson *et al*, *Phys. Rev. Let.* **108**, 135002 (2012).

[7] M. Hamed, M. Muraglia, Y. Camenen, X. Garbet, and O. Agullo, Physics of Plasmas, 26(9):092506, 2019.

Effect of the divertor configuration on the JET edge radial electric field

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The current extrapolations for the ITER L-H threshold power are based on a widely used multi-machine scaling, depending on density, magnetic field and machine size. However, there is a considerable scatter around the scaling law caused by hidden parameters, such as the divertor configuration. Studies in different devices (e.g. [1, 2]) have shown that the divertor configuration can vary the power threshold by up to a factor of two and may therefore have a large impact on future devices that needs to be understood.

The existence of a strong shear in the perpendicular plasma flow, $v_\perp$, caused by a radial electric field, E_r, is thought to be fundamental for the edge turbulence suppression. The origin of the $E_r \times B$ flow is still not fully understood and therefore E_r measurements are essential to better understand the link between flow shear and turbulence suppression.

Over the years, several L–H threshold experiments were performed on JET to investigate the importance of different parameters such as divertor geometry and isotopic mass (e.g. [1, 3]). Here we report on $v_\perp$ measurements obtained by Doppler backscattering in JET experiments with different outer divertor strike-point positions: tile 5 of the horizontal target (V5), vertical target (VT), and in the corner (CC) configuration (between the horizontal and vertical targets close to the pump throat). As reported before (e.g. [3]), VT and CC have similar L-H threshold, which is roughly a factor of two larger than in V5.

A deeper $v_\perp$ well is measured at the L-H transition for the VT configuration, $v_\perp \sim -3$ km/s, which is higher by a factor of about two than for V5. Furthermore, the $v_\perp$ profile for CC does not show a well ($v_\perp \sim 1$ km/s at the expected well location) indicating that the edge E_r profile results from the main ion rotation compensating the diamagnetic term. This may be explained by the existence of an edge toroidal flow most relevant for CC. As reported in [4], the corner configuration shows a stronger pedestal toroidal velocity than in the other configurations, as well as a lower neutral pressure in the main chamber. No clear correlation is seen between the shear flow and the L-H power threshold for different divertor configurations. Our results do not show evidence for the existence of a critical $v_\perp$ needed to achieve H-mode.

References: [1] C. F. Maggi et al., Nucl. Fusion 54 023007 2014; [2] P. Gohil, et al. Nucl. Fusion, 51 103020 2011; [3] H. Meyer et al., EPS Conference on Plasma Physics, P1.013 2014; [4] E. Joffrin et al., Nucl. Fusion 57 086025 2017

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[1]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)”

Dynamic error fields derivation by inverting a validated interpretative perturbations model

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A dynamic perturbations model has been already tested and validated during different discharges at JET [1]. A good match between our calculated perturbations amplitude and frequency and the ones provided by the JET Python code data analysis has been found. In order to obtain our results a presumed very low static error field spectrum has been parametrically used to better match as accurate as possible the perturbations experimental results. This time we intend to perform an inverse approach of our model, starting from the already checked approximate overlap between the calculated and the measured perturbations quantities in order to derive the amplitude of the magnetic error fields influencing the perturbations behavior, the latter playing the role of the input data. Our entire model being dynamic, the expected error fields to be derived are also dynamic. The error field modes are to be introduced into the perturbations differential system of equations in the whole space (plasma, vacuum and plasma column external structures) and searched for as unknowns, whereas the plasma modes of perturbations play an input parametric data role. A quasi-analytic dynamic solution for the error fields are to be delivered. The solution will provide a clear dynamic behavior of the error fields amplitude for various discharges in tokamak devices. We believe that the above mentioned validated *direct* model perturbations results considered as a benchmark starting point for our error field derivation together with a subsequent correct mathematical calculus *inverse* approach will provide reliable results for the magnetic error fields dynamics.

References

[1] I.G. Miron and JET Contributors, Nucl. Fusion 61 (2021) 106016.

*See the author list of “Overview of JET results for optimising ITER operation” Joelle Mailloux et al. 2022 Nucl. Fusion

Collisional-radiative model for transport simulations of neutrals in detached conditions

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The importance of Eirene development for simulating the dynamics of neutrals and ions in the scrape off layer is discussed. As a first step the role of the reactions among molecular and atomic neutrals with ions in a edge tokamak plasma is investigated by using the solver for collisional radiative models Yacora [1]. Two different cases are considered with plasma parameters and reactions deduced from: i) EIRENE-EDGE2D simulations for JET cases [2], ii) the SOLPS-ITER simulations presented in Ref.[3] for a single-null EU-DEMO divertor scenario with kinetic neutrals. Atomic H, molecular H_2 and molecular ions H_2^+ hydrogen species are considered and the extension to deuterium species is envisaged via a proper scaling of reaction rates. The list of reactions includes molecular dissociation, induced ionization and molecular ion dissociation all by electron impact plus a charge-exchange reaction with bulk ions ($H_2 + H^+ \rightarrow H_2^+ + H$). A source term modeling gas puff provides molecules that dissociate into atoms and/or molecular ions, which are then ionized and/or dissociate again. At equilibrium H_2 density exhibits a peak at low temperature ($T < 3eV$) signaling weak molecule dissociation essentially due to charge exchange with protons. By increasing the temperature electron impact reactions become the main dissociation channel and suppress the molecular density. The model is then extended by including vibrationally resolved molecular states $H_2(v)$ and the corresponding electron-induced excitations and de-excitations among neighborhood states, which result to be the dominant reactions at low temperature. Hence, vibrational transitions and charge exchange reactions with bulk ions provide the main channels for the establishment of molecular and atomic equilibrium at low temperature. The relevance of charge exchange reactions with ions can be related with detachment control, while vibrational transitions are useful for setting up molecular spectroscopy as a proper diagnostic in the divertor region.

References

[1] D Wünderlich, M Giacomin, R Ritz and U Fantz 2020 J. Quant. Spectrosc. Radiat. Transfer 240 106695

[2] M. Groth et al. 2013 Nucl. Fusion 53 093016

[3] F Subba, D P Coster, M Moscheni, M Siccinio 2020 Nucl. Fusion 61 106013

Measuring RF-accelerated fast ions with DD and DT neutron spectroscopy: comparison of velocity-space sensitivity

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Two of the most important reactions in a fusion plasma are the $D(d,n)^3He$ (DD) and $T(d,n)^4He$ (DT) reactions. Both these reactions produce neutrons, and if a neutron spectrometer is used to resolve the emitted neutrons in energy it is therefore possible to infer various features of the energy distribution of the D and T fuel ions. Furthermore, if the neutron spectrum is measured along several different sightlines, it is possible to resolve the fuel ions spatially and/or in pitch as well. A common application of neutron spectroscopy is the study MeV-range fast ions, which typically result in distinct high-energy tails in the neutron spectrum.

The DD and DT reaction cross sections exhibit different dependences on the reactant energies. Hence, the neutron spectra of DD and DT neutrons is sensitive to different regions of the fast-ion velocity-space. In this contribution, we examine this velocity-space sensitivity in detail, by means of previously determined velocity-space weight functions. By multiplying the weight functions with various trial distributions representative of radio-frequency (RF) accelerated ions at the JET tokamak, we obtain explicit maps of how much different regions of the fast-ion velocity-space is expected to contribute to the measured neutron spectrum.

For JET-relevant distributions of RF-accelerated deuterons, we find that the average energy of fast ions contributing to the DD signal is about 50-100 percent higher than the average energies of the ions contributing to the DT signal. DD spectroscopy can therefore probe the most energetic part of an RF-accelerated ion distribution (MeV-range ions), while DT spectroscopy is mostly sensitive to more intermediate energies (200-500 keV). The implications of these results for the interpretation and comparison of recent DD and DT neutron spectroscopy results at JET is discussed.

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Exploration of Alfvén Eigenmode physics via active antenna excitation in JET Deuterium, Tritium, and DT plasmas

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While the growth rate of destabilized Alfvén Eigenmodes (AEs) can often be difficult to assess from experimental measurements, the net damping rate of *stable* AEs is readily measured in JET tokamak plasmas by the Alfvén Eigenmode Active Diagnostic [1]: two toroidal arrays of four antennas each [2] are independently powered and phased to resonantly excite stable AEs with toroidal mode numbers $|n| < 20$ [3]. In this poster, we present the novel experimental observation of an unstable-to-stable AE transition in a deuterium plasma and compare with hybrid kinetic-MHD simulations. We also highlight recent tritium operations with new high frequency filters, 165-330 kHz, which allow stability measurements of high-frequency Toroidicity-induced AEs (TAEs, above the previous 250 kHz limit) and even Ellipticity-induced AEs. Finally, we report ~2000 stable AE resonances measured during the 2021 JET DT campaign; radiative damping is inferred from strong correlations with the edge magnetic shear and non-ideal parameter [4]. We will give a first look at the contribution of alpha drive to a subset of these *stable* AEs, as calculated with kinetic-MHD codes.

[1] A. Fasoli et al 1995 Phys. Rev. Lett. 75 645-648

[2] T. Panis et al 2010 Nucl. Fusion 50 084019

[3] P. Puglia et al 2016 Nucl. Fusion 56 112020

[4] W.W. Heidbrink et al 2008 Phys. Plasmas 15 055501

Supported by US DOE grants DE-SC0014264 and DE-AC02-09CH11466. This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 - EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Impurity modelling with European Transport Simulator: implementation and verification

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Model for the evolution of the impurity density included in the European Transport Simulator is described in this work together with the implementation details and the results of the verification studies against the standalone model. European Transport Simulator (ETS) [1] is the integrated modelling tool (workflow) capable to interpret and predict scenarios of the fusion plasma devices. ETS includes several 'building' blocks describing different plasma processes (transport, heating, etc.) that are combined in transport equations describing evolution of the plasma profiles (poloidal flux, density, temperature).

Accurate modelling of the impurity evolution is an important part of the scenario modelling for the present and future fusion devices. Impurity effect on the plasma dynamics (like the impurity accumulation or the imputity effect on the power exhaust) should be included in the scenario modelling to get reliable predictions. Equations for the evolution of the impurity densities are included in ETS. The verification of the impurity model for the ETS version using Consistent Physical Objects (CPOs) for the data transfer was reported in [2]. Recently, ETS is updated to use IMAS framework [3]. This was accompanied by the substantial modification of the impurity model implementation in the simulator. The model details and the implementation scheme are described in this work highlighting the modifications made as compared to the previous version. The results of the verification against the standalone modelling results obtained using the SANCO code [4] for the parabolic kinetic profiles in JET-like geometry are presented.

References

[1] G. Falchetto et al, P1-1081, 46th EPS conference, Milan, 2019

[2] Kalupin D, et al., Nucl. Fusion **53** (2013) 123007

[3] Imbeaux F, et al., Nucl. Fusion **55** (2015) 123006.

[4] Lauro-Taroni L. et al., Proc. 21st EPS (1994) vol 1.

Analysis techniques for the simultaneous measurement of impurity ion temperatures and velocities in MAST-U using Coherence Imaging Spectroscopy

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The ability of Coherence Imaging Spectroscopy (CIS) to quantify 2D profiles of ion flow velocities inside fusion devices such as MAST [1], DIII-D [2], Wendelstein 7-X [3] and ASDEX-U [4] has been well documented. In addition to these studies, we present an extension of the capabilities of CIS to allow for the simultaneous determination of impurity ion flow velocities and temperatures through the demodulation of the phase and contrast, respectively, of interference fringes super-imposed on CIS images. Testing and optimisation of the Fourier demodulation techniques and SART inversion algorithms has been carried out using synthetic CIS images of various MAST-U Super-X divertor plasmas. Synthetic images were generated using single and multi-delay 'pixelated' phase mask (PPM) CIS instruments, developed by Allcock [5], which will be installed on MAST-U during the MU02 experimental campaign. A PPM CIS offers greater spatial resolution when compared to the linear phase mask used in [1] due to the bonding of polarising filters of different orientations directly to the CIS camera sensor. These techniques have wide reaching applications in the validation of future fusion device simulations and detachment studies as CIS is the only diagnostic capable to simultaneous determining 2D ion temperature and velocity profiles. The use of a multi-delay PPM CIS, which encodes interference information in multiple carrier frequencies increasing fringe contrast and thus the accuracy of temperature measurements, is novel and further compounds the effectiveness of CIS as a tool for the direct measurement of the effect Super-X divertor designs have on impurity transport and temperature profiles.

References

[1] S. A. Silburn et al. *Review of Scientific Instruments*, **85**, 11 (2014) 11D703

[2] C. M. Samuell et al. *Review of Scientific Instruments*, **89**, 9 (2018) 093502

[3] V. Perseo et al. *Review of Scientific Instruments*, **91**, 1 (2020) 013501

[4] D. Gradic et al. *Physics and Controlled Fusion*, **60**, 6 (2018) 084007

[5] J. S. Allcock et al. *Review of Scientific Instruments*, **92**, 7 (2021) 073506

*See author list of J. Harrison, et al. Nuclear Fusion **59** 11 (2019) 112011

Observations of confined fast ions in MAST-U with the NCU

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Spherical tokamaks contribute to the design of future fusion reactors in several key areas such as divertor physics, neutral beam current drive and Fast Ion (FI) physics. MAST-U, which was design to address, among other objectives, these issues, has successfully concluded its first experimental campaign providing a wealth of new results. Thanks to its low magnetic field (< 1 T) and high energy (> 50 keV) of the NBI system, MAST-U is suitably poised to study the interaction of super-Alfvénic FIs with a wide range of MHD instabilities including global ones determined by the plasma equilibrium and scenarios such as sawteeth, NTMs and ELMs as well as broad categories of Alfvén instabilities such as TAEs, GAE and CAEs and of energetic particle modes such as fishbones. To further explore the role of the FI distribution function spatial gradient in driving these instabilities, MAST-U is equipped with two tangential NBI systems, one on the equatorial plane (on-axis) and one that is vertically shifted 65 cm above the equatorial plane (off-axis). In order to study the rich physics that was expected, and confirmed in the recent experimental campaign, several FI diagnostics were upgraded and new ones added. Among them, the prototype neutron camera [1] has been upgraded [2] to six sight-lines (all on the equatorial plane). The first observations of the confined FI behaviour in a wide range of plasma scenarios characterized by on-axis and/or off-axis heating and by sawteeth, fishbones and TAEs are presented here. Comparisons with fission chamber measurements are presented and the observed discrepancies discussed. Finally, clear evidence of different FI deposition profiles with off-axis NBI heating only compared to the on-axis only case are presented. In the former case, the neutron emissivity in the core is approximately hundred times smaller than in the latter and its radial profile is hollow, indicative of a regime characterized by high losses of fast ions. These initial results confirm the capabilities of the Neutron Camera Upgrade (NCU) and provide the opportunity, in combination with observations from other FI diagnostics and modeling, for a more constrained description of the FI dynamics in fusion reactor relevant scenarios.

*See author list of J. Harrison, et al. 2019 Nucl. Fusion 59 11201

References

[1] Cecconello M. et al. *Nuclear Instruments and Methods in Physics Research* **A 753** (2014) 72–83

[2] Cecconello M. et al. *Review of Scientific Instruments* **89** 10I110 (2018)

Linear drive of Fast-ion-driven vertical modes

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Recent JET experiments [1] reported the observation of axisymmetric modes (i.e. with toroidal mode number n=0) destabilized in presence of fast ions. Axisymmetric modes in elongated plasmas are normally associated with a well known ideal instability resulting in a vertical shift of the whole plasma column. This vertical instability is stabilized by means of passive feedback consisting of eddy currents induced by the plasma motion in a nearby wall and/or in plasma facing components. When this feedback system is represented by a resistive wall, the n=0 mode dispersion relation can be studied analytically and is cubic. Under relevant tokamak conditions two roots are oscillatory and weakly damped with a frequency proportional to the poloidal Alfvén frequency. These oscillatory modes present a frequency which is below the minimum of the Alfvén continuum, therefore they are not affected by continuum damping. The third root is unstable and represents the so-called resistive wall mode (RWM). We focus on the two oscillatory modes, that can be driven unstable due to their oscillatory character. In fact, even though they are damped by the wall resistivity, they may resonate with fast ions leading to fast-ion-driven vertical modes (in brief FIDVM) as described in Ref. [2]. We derived the cubic dispersion relation for the n=0 modes fully analytically within the so-called reduced ideal MHD model. Thereafter, the effects of energetic particles are added in the framework of hybrid kinetic-MHD model. The mode-particle resonant condition for these modes is $\omega = p\omega_{b/t}$,where p is an integer number labelling harmonics over particle orbit periodicity and $\omega_{b/t}$ is the bounce (or transit) frequency of magnetically confined fast particles. An energetic ions distribution function with $\partial F/\partial E > 0$ is required in order to drive the instability. It is thus possible to drive the FIDVM unstable in presence of a distribution function characterized by an anisotropy in the pitch angle Λ or by a bump-on-tail like distribution in the velocity. In particular the latter situation can be achieved considering losses of fast ions or with a modulation of the fast ion source [3-4]. The growth rate introduced by the resonant interaction with both trapped and passing particles can overcome the damping introduced by wall resistivity. The FIDVM theory presented here is motivated in part by the observation of saturated n=0 fluctuations reported in [1]. These observations were tentatively interpreted in terms of a saturated n=0 Global Alfvén Eigenmode (GAE). It is early for us to conclude whether, in fact, the mode observed at JET is a FIDVM rather than a GAE, nevertheless, we discuss the main points of distinction between GAE and FIDVM that may facilitate the experimental identification.

References

[1] H. J. C. Oliver et al. Phys. Plasmas **24**, 122505 (2017)
[2] T. Barberis et al. submitted for publication to Nuclear Fusion
[3] V. G. Kiptily, et al. , Nucl. Fusion **61**, 114006 (2021).
[4] M. A. Van Zeeland et al. , Nucl. Fusion **61**, 066028 (2021).

L-H transitions and intermediate behaviours on MAST and MAST-U

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Beyond a critical net power threshold P_{LH}, tokamak plasmas transition to a state of reduced turbulence and improved confinement. This high confinement regime (H mode) allows for a higher core pressure and thus fusion power, and is therefore the favoured operating regime for future, reactor-scale tokamaks. One important goal is to predict P_{LH}. There does not yet exist a quantitative model for P_{LH} and attempts at finding an empirical scaling law have not yet produced one which captures all the parameter dependencies.

The work on the density dependence of P_{LH} for a set of experiments on MAST presented at the previous EPS conference [1] has been updated and refined. The components of the net power P_{net} can each be calculated using different methods, including through making use of the EFIT and TRANSP codes and varying smoothing window sizes in the calculation of the rate of change of stored energy. The findings suggest a combination of TRANSP and EFIT used together with diagnostic data provides the best estimates, though the overall trend of a U-shaped density dependence for P_{LH} is captured by all methods. In addition to different types of H modes and L modes, plasmas near the threshold exhibit a variety of behaviours, which have been classified based on a combination of quantitative and qualitative characteristics. The contrasting plasma responses are shown to occupy distinct regions of parameter space.

Recent studies (e.g. [2]) have shown that L-H transitions occur at a critical energy transfer from turbulence to zonal flows. The generality of this result as well as the link between this and divertor configurations will be explored, as separate studies on C-Mod [3] have shown a dependence of P_{LH} on divertor geometry parameters. As part of a study into the effects of divertor configuration on the L-H transition, experiments comparing H-mode access in conventional and Super-X divertors on MAST-U have been set up. First results from L-H transition studies on MAST-U using the Super-X divertor are presented.

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References

[1] L. Howlett et al., Conference proceedings of the 47th EPS conference on plasma physics P3.1073 (2021)

[2] I. Cziegler et al., Nuclear Fusion 55 (2015)

[3] Y. Ma et al., IAEA Conference paper (2012)

Confinement dependence on beta/power in the JET ILW hybrid scenario

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The hybrid scenario on JET has often an improved confinement compared to the H98y2 scaling prediction. This has been observed before on many other experiments, e.g. DIII-D and AUG. From a scaling point of view it is a very interesting question whether this confinement improvement is a consequence of the higher beta operation in the hybrid scenario compared to the traditional H-mode [1] or if the higher normalised confinement is e.g. due to a weaker power degradation as reported in [2]. The H-factor and the plasma β_N are derived both from the stored energy and hence tend to be strongly correlated.

In this paper, results from a database (DB) analysis of about 4500 points from the entire JET ITER- like wall period are shown. Here deuterium, hybrid pulses in a low triangularity lower single null shape are presented. The database is large and diverse enough to allow a derivation of the different scaling dependencies at different β ranges ($0.5<\beta_N<2.7$) under the assumption that all other scaling dependencies are as prescribed in a scaling law ($0.8MA<I_p<3MA$, $1T<B_t<4T$, $2MW<P_{in}<38MW$ dominantly NBI, $2\cdot10^{19}m^{-3}<n_e<7\cdot10^{19}m^{-3}$, geometry factors are constant in DB). This analysis has been done either assuming IPB98(y,2) or ITPA 20 – ITER like (IL20 from now on) [3] scaling properties. It is shown that the IPB98(y,2) exponents fit well to the experimental data as a whole. If only a subset of the data in a reduced beta range for medium beta is considered, the same agreement is found but the multiplication factor needed increases with beta (β_N as well as β_p). Deviations in the exponents are found at low and at high β.

As a further test, the scaling law has been changed to the IL20 properties which results in a better global agreement. The exponents of this scaling fit very well to the low beta part of the DB but not equally well to the medium beta part of the database. This might indicate that the low beta and confinement part of the DB, which is closer to the traditional H-mode operating space, indeed scales more like IL20, whereas the more hybrid like operation space (lower gas fluxes and higher input power) scales more like IPB98(y,2).

The observed deviations compared to the IL20 scaling assumption re-enforces the finding of the good agreement especially with the P_{abs} (but also n_e) dependence of the IPB98(y,2) scaling law despite the better general agreement with the IL20 like scaling. The driving factor of the confinement dependence seems not to be a weaker power degradation but an increase of confinement with beta which is not captured by the other engineering regression variables and would likely require additional variables. This findings might be explained by the observed better pedestal stability and lower turbulence growth rates at higher beta as also been indicated in [2].

References: [1] M. Beurskens *et al*, PPCF **55** 124043, [2] C.D. Challis *et al*, Nucl. Fusion **55** 053031, [3] G. Verdoolaege *et al* , Nucl. Fusion **61** (7) 076007

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Neon seeding effects on two JET high performance baseline plasmas

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On JET Neon injection seems to improve confinement [1] and in addition it is needed in high performance plasmas for mitigating heat fluxes to the divertor and to the first wall. Recent experiments at JET were able to combine low- to mid-Z impurity seeding with high performance baseline H-modes, obtaining an improvement in the confinement when Neon gas was injected with respect to the equivalent unseeded plasmas [1]. Impurity seeding has an impact on plasma dilution and on the radiative power profile, but can also modify the transport. In this paper the results of the modelling of two JET baseline pulses, one with Neon seeding and one without seeding, are presented, including a comparison of their turbulence spectra, in order to understand the effects of Neon seeding on transport and confinement. The baseline is one of the two plasma scenarios explored at JET for stationary high fusion performance, in which the confinement is achieved at high plasma current ($I_p \geq 3.0$ MA) and moderate beta normalized, with a relaxed current profile [2]. The shots modelled in this paper share similar plasma parameters (3.0 MA/2.8 T, $\beta_N \approx 2.2$, $q_{95} \approx 3$) and auxiliary heating powers ($P_{NBI} \approx 28.7$ MW, $P_{ICRH} \approx 3.7$ MW), with the only difference being the Neon seeding, which allows the modelling to investigate the effects of Neon on transport.

The simulations are performed in a fully predictive way in the JINTRAC [3] suite of codes, using JETTO as transport solver and QuaLiKiz [4, 5] as quasilinear gyrokinetic transport model from the magnetic axis up to the pedestal top. The modelling takes into account the pedestal improvement obtained with Neon seeding, also seen in other shots [1]. The pedestal is modelled by adjusting the heat transport in the Edge Transport Barrier (ETB) in order to match the experimental height of the temperature pedestal. The evolution of the plasma current density, electron density, electron and ion temperatures and plasma rotation are computed self-consistently, as well as the equilibrium. The transport of impurities is evolved, considering an impurity mix of Be, Ne, Ni and W. Boundary conditions on the electron and ion temperatures are imposed at the separatrix and equal to 100 eV; initial conditions on the profiles of the electron density and temperature are taken from High Resolution Thomson Scattering (HRTS) measurements, while ion temperature and toroidal rotation are taken from the beam Charge Exchange (CX) spectroscopy.

The results of the predictive simulations are in good agreement with the experimental measurements for both of the analysed shots. QuaLiKiz shows a reduction in the electron and ion thermal diffusivities in the Ne seeded shot for $0.4 < \Psi_N < 0.9$. In order to understand the cause of the transport reduction, QuaLiKiz turbulence spectra are compared. The microstability analysis suggests that Ne injection reduces the growth rates of both ETG and ITG modes, which leads to a decrease of the heat fluxes with respect to the unseeded pulse.

* *See the author list of J Mailloux et al. 2022 Nucl. Fusion* https://doi.org/10.1088/1741-4326/ac47b4

[1] Giroud C. *et al* 2021 *28th IAEA Fusion Energy Conference (FEC 2020)* [2] L. Garzotti *et al* 2019 *Nucl. Fusion* **59** 076037 [3] Romanelli M. *et al* 2014 *Plasma and Fusion Research* **9** 3403023 [4] Bourdelle C. *et al* 2016 *Plasma Phys. Control. Fusion* **58** 014036 [5] Citrin J. *et al* 2017 *Plasma Phys. Control. Fusion* **59** 064010

Predictive modelling of D-T fuel mix control with gas puff and pellets for JET 3.5 MA baseline scenario

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Fuel mix control is a relevant problem in present experiments featuring mixed fusion plasmas, and it will be crucial in future fusion reactors operating with a D-T plasma mixture. To maximise the deuterium-tritium (D-T) thermal reactions the plasma mixture has to be close to 50-50. However, the fusion power can be maximised in presence of D neutral beam injection (NBI) in a T rich plasma, so to favour the beam target component of fusion reactions. Integrated modelling can help explore and compare different fuelling schemes and provide guidance on how to design a suitable recipe in order to achieve the desired experimental condition and minimize the T consumption. In this paper, we present the results of fully predictive simulations done in preparation to the D-T operations of the JET baseline scenario. It is shown that a balanced (50-50) D-T plasma mixture can be obtained by balancing the external particle sources. The different fuelling sources such as NBI, gas puff and pellets are dominant particle sources in different regions of the plasma. In the inner core region ($\psi_N < 0.4$) the fuelling injection associated to the NBI is dominant, while gas puffing is the dominant source from the edge to a $\psi_N \geq 0.6$. The effects of pellets depend on the pellet injection parameters and can be used to control the plasma compositions as shown in [1]. Moreover, a different fuelling efficiency can be expected for different hydrogen isotopes. The simulations are performed in the JINTRAC [2] suite of codes using QuaLiKiz [3, 4] as first-principle transport model to predict the plasma current density, the electron density, the ion densities for D and T, the electron and ion temperatures and the toroidal velocity self-consistently with the equilibrium. The boundary conditions are imposed at the separatrix which allows to investigate the effects of the imbalanced gas puff and the effects on the plasma composition of pure D pacing pellets, required in the baseline scenario. A first group of simulations starts form the extrapolations shown in [5], varying the plasma composition with gas puff only in order to explore the dependence of the fusion performance on the T concentration with balanced D-T NBI injection. Introducing D pacing pellets in the modelling, the gas puff sources have to be adjusted in order to keep the plasma mixture close to the 50-50. The ionization sources (not measured at JET) are computed by FRANTIC. Therefore, the results of this modelling can be trusted in terms of fusion performance but can only estimate the experimental particle sources. The modelling results are in line with the experimental measurement obtained during the last D-T campaign at JET, showing a good prediction capability also in D-T plasma mixture.

* *See the author list of "Overview of JET results for optimising ITER operation" Joelle Mailloux et al. 2022 Nucl. Fusion (preprint).*

References

[1] Valovic M. *et al*, "*Control of H/D isotope mix by peripheral pellets in H-mode plasma in JET*" (2021) at *28th IAEA Fusion Energy Conference (FEC 2020)*
[2] Romanelli M. *et al* 2014 *Plasma and Fusion Research* **9** 3403023
[3] Bourdelle C. *et al* 2016 *Plasma Phys. Control. Fusion* **58** 014036
[4] Citrin J. *et al* 2017 *Plasma Phys. Control. Fusion* **59** 064010
[5] Zotta V. K., Garzotti L. *et al* "Moderate beta baseline scenario in preparation to D-T operations at JET" (2021) at *47th EPS Conference on Plasma Physics*

First MAST-U Equilibrium Reconstructions using the EFIT++ Code

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The MAST-U spherical tokamak has extensive capabilities to produce and explore strongly shaped plasmas and alternative divertor configurations, especially the Super-X. Robust and accurate reconstructions of plasma equilibria are the foundation of many physics analyses, and important intershot for informing operation of the tokamak.

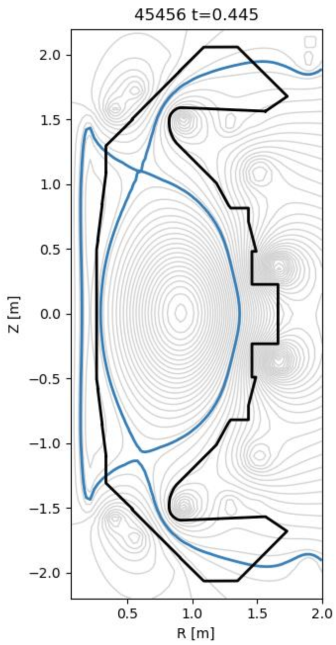

Figure 1: Magnetics only EFIT++ equilibrium reconsruction for MAST-U shot 45456 at t=0.445s.

MAST-U is equipped with a range of magnetic sensors including b-field sensors and flux loops. In this work the Grad-Shafranov equation for the plasma equilibrium is solved using the EFIT++ code[1], which has been updated to provide routine magnetics only reconstructions during the first physics campaign. The results of the analysis show a good agreement with the magnetics data, and the quality of equilibrium reconstructions is further assessed by comparing with diagnostics not used as constraints. For example, in the divertor region there is good agreement between EFIT++ and strike point locations measured with Infra-Red thermography and Langmuir probes, and the divertor leg position measured with Multi-Wavelength Imaging.

The next steps for analysis of MAST-U equilibria are discussed. This includes the first results and impact of adding additional constraints to the EFIT++ reconstructions of the electron pressure profile from Thomson Scattering, ion temperature from Charge Exchange and the magnetic pitch angle from the Motional Stark Effect system to the EFIT++ reconstructions.

[1] Appel, L. C. et al. "Equilibrium reconstruction in an iron core tokamak using a deterministic magnetisation model." *Comput. Phys. Commun.* 223 (2018): 1-17.

Quasi-Linear transport model EDWM: Update and benchmarking

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In this poster we present the latest updates to EDWM [1] and benchmark it against other Quasi-Linear models such as TGLF and QLK for discharges at JET. EDWM is a quasi-linear fluid model which can handle an arbitrary number of ions in arbitrary many charge states [2] and several improvements have been made. Firstly, a new filter which describes the electrostatic potential wave number spectrum has been developed which has significant impact on the fluxes. An updated mixing length assumption has been developed which includes all the spectral dependence in a filter $f(k_y)$ combined with a saturation level at a correlation scale, k_a: $e\phi/T_e = f(k_y)\gamma_{lin,a}/k_a k_a \rho_s c_s$. Here k_y is the wavenumber in the polodial direction, ρ_s and c_s are the sound speed and wave length. To have the correct spectral dependence is especially important for the particle channel, as the major part of the outward diffusion and inward pinch might be located at different spectral scales. Hence, an erroneous filter might quench one and not the other, leading to an incorrect flux. Zonal flows have previously been shown to play a major role for the turbulent transport saturation [3] and its effect are included in the filter. This spectral dependence is verified against non-linear simulations with the gyrokinetic code GENE [4]. Secondly, EDWMs' response to the safety factor has been improved by comparing with safety factor scans done with the gyrokinetic code GYRO [5]. Results show that a stronger response for EDWM is needed which will lead to a larger transport in the outer regions of the plasma. Lastly, a new flux normalization has been performed to accommodate the new features of EDWM by comparing with the fluxes from experiments at JET and GENE simulations. This includes an updated fraction between the ion and electron heat transport.

References

[1] P. Strand et al 31st EPS conferance on Plamsa Phys. 28*G* P-5.187 (2004)

[2] M. Fröjdh et al Nucl. Fusion 32, 419 (1992)

[3] G.M.Staebler et al Phys. Plasmas 23 062518 (2016)

[4] F Jenko and W. Dorland Plasma Phys. Contr. F. 43.12A (2001)

[5] J. Candy and E. Belli General Atomics Technical Report (2010)

Fast-ion studies with three-ion ICRF scenarios in non-active JET plasmas

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Significant progress with the development of three-ion ICRF scenarios in support of the ITER Research Plan has been recently achieved [1]. We report the results of JET studies where the three-ion ^{4}He-(^{3}He)-H scheme was applied for heating non-active H-^{4}He plasmas, both on-axis and off-axis [2], and studying the impact of fast ions on the plasma confinement. The spatial profile of energetic ^{3}He ions was controlled by varying the ICRF antenna phasing, resulting in significant differences in MHD behaviour and sawtooth dynamics. Our results confirm that the three-ion ICRF scenario can be applied to control the radial profile of the safety factor and sustain plasmas with an inverted *q*-profile at JET, complementing earlier observations of its application in D-^{3}He plasmas [3]. Another important highlight of the JET experiments in H-^{4}He plasmas reported here is the demonstration of the capability to measure simultaneously both He isotopes, $n(^4\text{He})/n_e \approx 5$-15% and $n(^3\text{He})/n_e \approx 0.2\%$, using the high-resolution sub-divertor gas spectroscopy [4].

In this contribution, we also report on the successful application of the three-ion ^{9}Be/^{22}Ne/Ar-(^{4}He)-H ICRF scheme at JET. This scenario makes use of intrinsic ^{9}Be ($Z/A \approx 0.44$), and/or extrinsic impurities with a similar charge-to-mass ratio, e.g., ^{22}Ne and Ar ($Z/A \approx 0.45$), to optimize the efficiency of ICRF absorption by a small amount of ^{4}He ions ($n(^4\text{He})/n_e \approx 0.5\%$) in hydrogen plasmas [1]. JET experimental results confirm that an additional injection of a very small amount of ^{22}Ne impurities is beneficial for maximizing the population of MeV-range ^{4}He ions with ICRF in the plasma, as evidenced by gamma-ray spectroscopy [5]. In the absence of a direct control of the level of ^{9}Be impurities, an additional seeding of ^{22}Ne or Ar impurities is a promising technique that can be also applied in future ITER plasmas.

[1] Ye.O. Kazakov et al., *Phys. Plasmas* **28**, 020501 (2021)
[2] M. Schneider et al., *EPJ Web. Conf.* **157**, 03046 (2017)
[3] M. Dreval et al., *Nucl. Fusion* (2022); https://doi.org/10.1088/1741-4326/ac45a4
[4] S. Vartanian et al., *Fusion Eng. Design* **170**, 112511 (2021)
[5] M. Nocente et al., *Plasma Phys. Control. Fusion* **62**, 014015 (2020)

First divertor Thomson scattering measurements on MAST-U

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MAST-U is equipped with a Super-X divertor which aims to promote detachment. Measurements of plasma density and temperature in the Super-X chamber offer insight into the processes at work in this type of divertor. First data has been obtained from the MAST-U divertor Thomson scattering diagnostic [1] designed to measure these quantities. Following a Raman scattering calibration in Nitrogen, the diagnostic operated over a number of plasma pulses in the first physics campaign. Electron density and temperature measurements have been taken in attached and detached conditions and as the strike leg has moved through the field of view of the diagnostic. The system operated with a dedicated 30Hz laser with timing synchronised to 7 similar lasers installed in the core Thomson system.

Electron densities in the range 1×10^{18} - $5 \times 10^{19} m^{-3}$ have been measured by the system throughout these regimes. Although the system was specified to measure from 1eV-100eV [2], electron temperatures in the Super-X divertor in the first campaign were low and measurement down to 0.5eV has been critical, particularly close to the detachment front. This generation of polychromators [1] have been designed with increased stray light rejection compared to those used in the core system. This has proved successful with very low levels of stray light observed.

A range of different operational scenarios were carried out to investigate the capabilities of the Super-X divertor. Magnetic geometry, gas fuelling and magnetic flux expansion were explored to study the access to a detached regime. These measurements have been compared to other diagnostics operating in the divertor such as Langmuir probes and spectral imaging systems and have shown good agreement.

1. J. G. Clark et al, Rev. Sci. Instrum. 92, 043545 (2021)

2. J. Hawke et al, JINST 8, C11010 (2013)

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Physics informed fast Grad-Shafranov surrogates

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The calculation of ideal magnetohydrodynamic (MHD) equilibria is vital to understanding and controlling the behaviour of magnetically confined plasmas. These equilibria provide important integrated tokamak characteristics such as stored energy and edge safety factor in addition to serving as input for subsequent simulation codes. Equilibrium reconstruction is normally performed with numerical solvers. However such methods are computationally costly and inappropriate for real-time plasma control which typically requires calculation times below 100μs. In this work we present neural surrogate models that are able to rapidly reconstruct JET-ILW plasma equilibria. The models were developed to reproduce the poloidal flux function ψ(R,Z) calculated by EFIT, an equilibrium solver used on JET [1]. The surrogate inputs consisted of magnetic signals measured by diagnostic pick-up probes and flux loops. The training and validation dataset was created from 955 experimental JET-ILW pulses, and contained 311914 data points of individual 0.03s timesteps. Both multilayer perceptron (MLP) and convolutional neural network (CNN) architectures were tested [2]. It was found that the latter performed better in terms of Mean Squared Error (MSE) and Mean Structural Similarity (MSSIM) with the true flux geometry. The surrogate loss function was modified to incorporate the Grad-Shafranov equation, introducing a physical understanding of the problem to the network [3]. Figure 1 shows ψ predicted by the surrogate as a series of flux surfaces within the tokamak cross-section, compared to the EFIT ground truth. Model inference time is of the order of milliseconds, demonstrating the viability of surrogate EFIT models for real-time control scenarios.

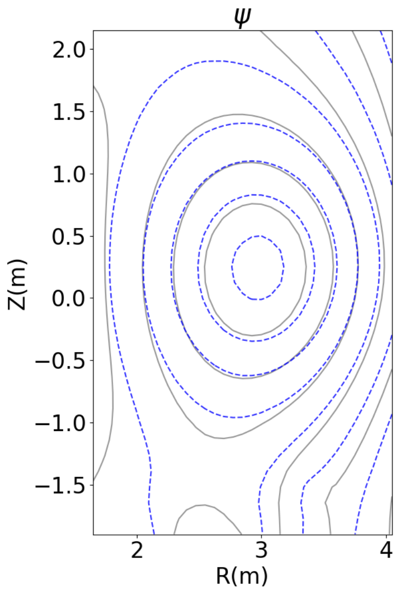

Figure 1: *EFIT (grey) and surrogate (blue) flux surfaces for JET-ILW shot #94257, MSE=0.003 MSSIM=0.967*

References

[1] L.L. Lao et al. Nuclear Fusion **25**, 1611-1622 (1985)

[2] A. Dosovitskiy et al. IEEE Transactions on Pattern Analysis and Machine Intelligence **39**, 692-705 (2017)

[3] M. Raissi, P. Perdikaris and G.E. Karniadakis, Journal of Computational Physics **378**, 686-707 (2019)

Neural Plasma Reconstruction from Diagnostic Imaging

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We leverage a neural network to estimate 2D distributions of neutrals, electrons and temperature from images of plasma obtained via cameras inside the MAST vessel. This is achieved by learning the non-linear mapping between images of the plasma emission and the distributions of the neutrals, electrons, and temperature. Our network, composed of an image encoding block followed by a dense layer, is able to achieve a mean relative RMS error on the test set of $14.6\% \pm 5.0\%$, $27.3\% \pm 5.2\%$, and $15.3\% \pm 3.7\%$ for the neutrals density, electrons density and the electron temperature respectively the results of which an example is shown in Figure 1. Crucially, our network is able to predict not only the electron density and temperature parameters, but also the neutrals density parameters, in only $8ms$ and the full 2D distributions with a spatial resolution of $4mm$ in $6s$ on a laptop RTX 3070 GPU.

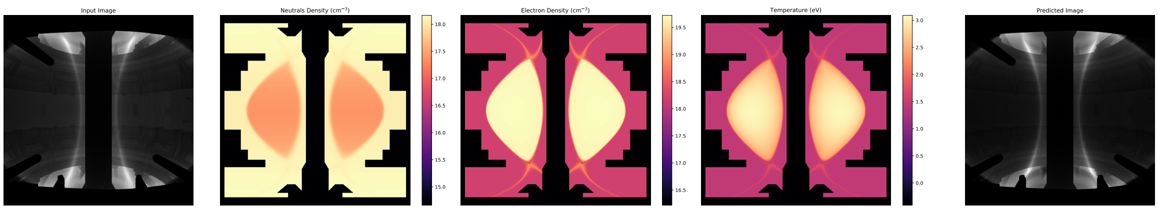

Figure 1: *Input Image (Left), Predicted Cross-Sections (Middle: neutrals density, electron density, temperature), Predicted Image obtained with volume rendering using predicted parameters (Right).*

The success of training a network depends on the richness of the training dataset. Currently, no experimental data exists with a sufficient number of configurations with visually distinct equilibria. To resolve this, we densely sample the space of configuration and simulate the camera image generating process to produce synthetic images of the plasma to train our network.

Our future goal is to further improve the accuracy on simulated data, as well as validate our methods on real diagnostic images. We believe our method has the potential to provide fast feedback of the 2D distributions during physical experiments to improve control.

Microwave current drive for STEP and MAST Upgrade

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The UK's Spherical Tokamak for Energy Production (STEP) reactor design program has recently taken the decision to use exclusively microwave-based heating and current drive (HCD) actuators for its reactor concepts. This is based on a detailed assessment considering all viable HCD concepts, covering the grid to plasma efficiency (η_{grid}), physics applications, technology maturity, integration, maintenance, and costs. Of the two microwave techniques: Electron Cyclotron (EC) and Electron Bernstein Wave (EBW), EC was deemed the lowest risk and EBW is maintained due to its exceptional CD efficiency. To assess the ECCD efficiency, the GRAY beam tracing code was employed to perform detailed scans of the launcher position, toroidal and poloidal launch angle, and frequency over the first 3 cyclotron harmonics. It was found that normalized efficiencies, ζ_{CD}, of 0.45 could be achieved reliably, with $\zeta_{\mathrm{CD}} \simeq 0.9$ for far off-axis Ohkawa current drive. For EBW, GENRAY/CQL3D were used to estimate the CD efficiency. Efficiencies of $\zeta_{\mathrm{CD}} > 0.9$ were found over 1/3 of the plasma radius, peaking more than a factor of 2 greater than ECCD in this range. EBW-CD is not as widely used or as mature as ECCD. To reduce the physics uncertainties in present models for EBW coupling and current drive, MAST Upgrade will install 2 x dual frequency (28, 34.8 GHz), 900kW, 5s gyrotrons from Kyoto Fusioneering, as part of the MAST Upgrade enhancements package. This will be accompanied by a flexible 2D steering launcher system to allow midplane co- and counter-CD and above midplane launch for co-direction off-axis CD. Coupling efficiency is quantified by measuring the heating induced by reflected (i.e. non-coupled) power to a plate inserted in the reflected beam path. The experiments will also include EBW driven solenoid-free start-up, increasing power and pulse length by a factor of 10 on MAST experiments. This presentation will discuss the STEP microwave studies and the MAST Upgrade physics design and capabilities.

An extended-MHD model for peeling-ballooning stability thresholds in spherical tokamaks*

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We show that non-ideal physics can significantly alter peeling-ballooning (PB) stability thresholds in spherical torus (ST) configurations, such as NSTX and MAST. Novel resistive kink-peeling modes are found to limit macroscopic edge-stability in ELMing NSTX discharges [1], and can possibly be a limiting factor in other ST devices. Edge-localized modes (ELMs) are associated with ideal peeling-ballooning (PB) modes occurring in the edge pedestal due to strong pressure and current density gradients. A long-standing problem has been the reliable modeling of such stability boundaries in spherical tokamaks (STs), where ideal-MHD models often predict stability for ELMing discharges [2]. Some MAST discharges were found to be located on the ballooning stability boundary [3]. Employing the extended-MHD initial value code M3D-C1 [4], we investigate macroscopic edge-stability in ELMing and ELM-free discharges in NSTX and MAST. In ELMing discharges robust resistive peeling-ballooning modes [5] are found well before the ideal stability threshold is met. In contrast, ELM-free wide-pedestal and enhanced-pedestal H-mode discharges in NSTX are limited by ideal ballooning modes. Plasma resistivity is seen to destabilize the kink-peeling components, but not the ballooning components. Finite Larmor radius effects affect the stability limits moderately and can explain experimental access to some ELMing regimes. Based on these extended-MHD calculations ELMing discharges are correctly predicted to be unstable, whereas ELM-free plasmas remain inside the stable domain.

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References

[1] A. Kleiner et al, under review

[2] A. Diallo et al, Nucl. Fusion **53**, 093026 (2013)

[3] A. Kirk et al, Plasma Phys. Control. Fusion **51**, 065016 (2009)

[4] S.C. Jardin et al, Comput. Sci. Discov. **5**, 014002 (2012)

[5] A. Kleiner et al, Nucl. Fusion **61**, 064002 (2021)

Stability analysis of low-n modes for the Divertor Tokamak Test facility Single Null Scenario

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Stability analysis is considered to be of fundamental importance to allow operation of plasma fusion devices and prevent bad confinement with consequent loss of plasma performance and/or plasma wall damages. For these reasons a careful analysis of the plasma stability properties for the DTT (Divertor Tokamak Test) machine [1] is undergoing. DTT is a new facility, under construction in Frascati, Italy, whose aim is to design and test a divertor able to face the problems of thermal loads and power exhaust. In this work the SN (single null) scenario proposed for DTT is studied [2]; our attention is focused on low-n stability for both ideal and resistive plasmas. Such analysis is part of a process where different codes follow each other in a consistent chain; so, equilibrium analysis, which precedes stability, follows the results of electromagnetic analyses (CREATE-NL, [3]) and transport analyses (JETTO, [4]). The code used to study the equilibrium is CHEASE [5], a high-resolution fixed boundary code that solves the Grad-Shafranov equation in toroidal geometry, assuming static MHD equilibria and axisymmetry. MARS [6] is the stability code used. It solves full MHD linear, resistive equations and can also consider a vacuum zone between the plasma last closed surface and a perfectly conducting wall, which is conformal to the plasma last closed magnetic surface. First the reference scenario is carefully analyzed; in this framework, the relevant parameters are the safety factor on axis, q_0=0.7, and at the edge, $q_{95\%}$=2.8, the q=1, located around s≈0.64 (being s the poloidal radial like coordinate), the β=1.9, defined as $2\mu_0\langle p\rangle/B_0$, being p the pressure averaged on the plasma volume and B_0 the on axis magnetic field, the pressure peaking approximately equal to 4. Studies with ideally conducting wall placed at infinity as well as at finite distance have been considered. Moreover β and safety factor profiles have been varied to perform a sensitivity study. The analysis reveals, for the reference scenario, an unstable internal kink (m,n)=(1,1), and infernal modes localized around the low shear and high pressure gradient zone. No external modes were observed unless main quantities, such as the safety factor or the β parameter, are strongly varied.

[1] R. Martone, R. Albanese, F. Crisanti, A. Pizzuto, P. Martin. "DTT Divertor Tokamak Test facility Interim Design Report, ENEA (ISBN 978-88-8286-378-4), April 2019 ("Green Book")" https://www.dtt-dms.enea.it/share/s/avvglhVQT2aSkSgV9vuEtw. [2] Casiraghi et al, Nucl.Fusion 61, 2021, 116068. [3] R. Albanese et al., Fusion Engineering and Design 96–97 (2015) 664–667.[4] Cenacchi G. and Taroni A. 1988 ENEA-RT-TIB 88-5 ENEA. [5] H. Lütjens, et al., 97, Issue 3, 1996, Pages 219-260. [6] A. Bondeson, G. Vlad, and H. Lütjens. Physics of Fluids, B4:1889–1900, 1992.

Validation of a new turbulence probe for MAST-U

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MAST-U's 1st experimental campaign demonstrated a reduced heat flux to divertor surfaces by a factor of 10 [1] due to the super-X divertor. There is a need to characterise the relationship between alternate divertor geometries and the subsequent transport fluxes present in the Scrape-Off Layer (SOL). It is known that turbulence plays a key role in the SOL. In recent years new experimental techniques have been developed to better characterise the SOL, like fast sweeping Ball-Pen probes to obtain T_i measurements [2]. This work presents a new Langmuir probe array mounted on a reciprocating probe system specifically designed to measure properties of turbulence in SOL of MAST-U. The new probe design includes: Two Ball-Pen probes (BPP) in close proximity to regular probes allowing direct measurement of T_i, Φ_{plasma}, E_r, and $q_{||}$; A 5-pin balanced triple probe array[4], allowing real-time measurements of both T_e and n_e and, when combined with poloidal electric field measurements from the BPP array, estimates of particle and heat transport fluxes; Logarithmically spaced probes to increase scale resolution for the detection of various turbulence modes and structures, and; An array consisting of three poloidally spaced probes with one probe radially offset to estimate poloidal and radial velocity distributions for plasma filaments. Prior to operation, this versatile probe design has been validated using a synthetic representation of the probe array in a variety of turbulence models, including a 2D Hasegawa-Wakatani drift wave model, a 2D stochastic filament model and the STORM2D interchange turbulence slab model in BOUT++. The simulation quantities taken at the probe positions were converted into relevant probe signals using probe equations from [2, 3, 4]. This paper will report on the results of this synthetic probe validation exercise, alongside plans for initial testing and exploitation in the upcoming MAST-U 2nd experimental campaign.

References

[1] J. R. Harrison, T. Farley, G. M. Fishpool, A. Kirk, B. Lipschultz, J. Lovell, F. Militello, D. Moulton, P. Ryan, R. Scannell, A. J. Thornton, K. Verhaegh, L. Xiang, Phys. Rev. Lett, [Preprint], (2022).

[2] J. Adamek, D. Cipciar, A. Devitre, J. Horacek, J. Cavalier, M. Komm, J. Krbec, M. Tich4, D. Trunec, P. Böhm, R. Panek and the COMPASS team, Nucl. Fusion, **61**, 036023, (2021).

[3] I. H. Hutchinson, Principles of plasma diagnostics, 2. ed. Cambridge: Cambridge University Press, (2002).

[4] H. Y. W. Tsui, R. D. Bengtson, G. X. Li, H. Lin, M. Meier, Ch. P. Ritz, and A. J. Wootton, Review of Scientific Instruments, **63**, 4608, (1992).

High-flux neutron generation by laser-accelerated ions from single- and double-layer targets

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Contemporary ultraintense, short-pulse laser systems provide extremely compact setups for the production of high-flux neutron beams, such as required for nondestructive probing of dense matter or research on neutron-induced damage in fusion devices. Here, by coupling particle-in-cell and Monte Carlo numerical simulations, we examine possible strategies to optimize neutron sources from ion-induced nuclear reactions using 1-PW, 20-fs-class laser systems such as the recently commissioned Apollon laser [1]. To improve ion acceleration, the laser-irradiated targets are chosen to be ultrathin solid foils, either standing alone or preceded by a near-critical-density plasma to enhance the laser focusing.

We compare the performance of these single- and double-layer targets, and determine their optimum parameters in terms of energy and angular spectra of the accelerated ions. These are then sent into a converter to generate neutrons, either traditionally through (p,n) reactions in beryllium or through spallation in lead. Overall, we identify configurations that result in a neutron yield as high as $\sim 10^9\,\mathrm{n\,sr^{-1}}$ and an instantaneous neutron flux above $10^{23}\,\mathrm{n\,cm^{-2}\,s^{-1}}$. Considering a realistic repetition rate of one laser shot per minute, the corresponding time-averaged neutron flux is predicted to reach record values of $7 \times 10^6\,\mathrm{n\ sr^{-1}\,s^{-1}}$, even with a simple thin foil as a primary target. A further boost up to above $5 \times 10^7\,\mathrm{sr^{-1}\,s^{-1}}$ is foreseen using double-layer targets with a deuterated solid substrate. Our results draw a pathway for improvement at upcoming 10 PW lasers in which case neutron generation will be more strongly dominated by spallation [2].

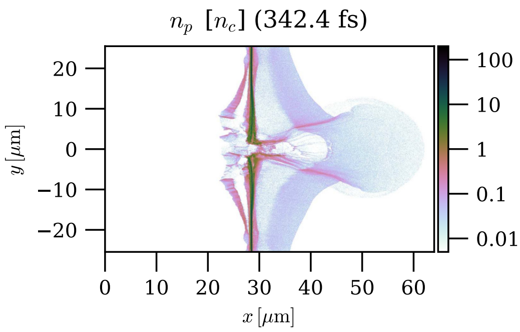

Figure 1: *PIC simulation of proton acceleration in relativistic transparency regime.*

References

[1] K. Burdonov *et al.*, Matter Radiat. Extremes **6**, 064402 (2021).

[2] B. Martinez *et al.*, Matter Radiat Extremes **7**, 024401 (2022).

Mono-charge super-heavy ion beams accelerated by a multi-PW laser

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Recent developments in short-pulse laser technology made it possible to generate femtosecond pulses with multi-PW power and the intensity of a focused laser beam of 10^{23} W/cm^2. Laser beams with such high powers and intensities can potentially accelerate ions to multi-GeV energies, including super-heavy ions with mass numbers A ≥ 200 [1,2]. However, the laser-driven heavy ion beams demonstrated in both numerical simulations [1-3] and experiments [4,5] are multi-charge beams and contain a large number of ion species with different charge states and energy spectra. Such multi-charge ion beams suffer from a number of disadvantages that make their practical use difficult.

In this contribution, the acceleration of super-heavy ions from a 100-nm lead target irradiated by a femtosecond laser pulse with an intensity in the range of ~ 10^{22} - 10^{23} W/cm^2 was investigated using an advanced 2D3V particle-in-cell code. It was found that by properly selecting the laser pulse parameters, it is possible to produce a practically mono-charge Pb ion beam with multi-GeV ion energies and the laser-to-ions energy conversion efficiency approaching 30%. At the laser intensity of 10^{23} W/cm^2, Pb ions with the charge state Z = 72 carry over 90% of the total energy of all ions, while the peak intensity and peak fluence of the Pb^{+72} ion beam are at least two orders of magnitude higher than for other types of ions. Moreover, the Pb^{+72} ion beam is more compact and has a smaller angular divergence than those for other types of ions. The intensity of the beam is much higher and its duration is much shorter than that achieved in conventional accelerators.

The unique properties of mono-charge super-heavy ion beams demonstrated in our work, create a prospect for the application of these beams in high energy-density physics and in new areas of nuclear physics as well as in accelerator technology as an intense ion source for large RF-driven heavy ion accelerators.

[1] J. Domanski and J Badziak, *Phys. Lett. A* **382,** 3412 (2018).

[2] J. Badziak and J. Domanski, *Laser and Particle Beams* **37,** 288 (2019).

[3] G. M. Petrov et al., *Phys. Plasmas* **23,** 063108 (2016).

[4] J. Braenzel et al., *Phys. Rev. Lett.* **114,** 124801(2015).

[5] P. Wang et al., *Phys. Rev. X* **11,** 021049 (2021).

Acceleration of spin-polarized proton beams from a dual-laser pulse scheme

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Particle beams of high energy and spin-polarization are necessary for various experiments, i.a. in order to test the Standard Model of particle physics. Over the last few years, several setups for spin-polarized electron and proton beams from laser-plasma interaction have been proposed [1]. In the case of protons, setups are limited to ones with gaseous targets, a solid-state setups cannot be pre-polarized. In this talk, we present a mechanism based on magnetic vortex acceleration (MVA), where the interaction of a single laser pulse with a plasma delivers high spin-polarization of the final beam [2]. In our new scheme, we consider two laser pulses propagating in parallel, forming two separate plasma channels [3]. Besides the proton filaments created in each channel, a third in the space between the pulses is formed. At the end of the target, the strong azimuthal magnetic field inside the channels can expand in the direction transverse to propagation. In turn, a displacement between electrons and protons arises, leading to electric fields that collimate and accelerate the proton beam. Our particle-in-cell simulations show that for a normalized laser vector potential of $a_0 = 100$ proton energies > 100 MeV can be obtained. Compared to single-pulse MVA, our scheme exhibits better spin polarization ($\sim 80\%$) of the final proton beam due to the different field structure over the course of the acceleration process.

References

[1] M. Büscher, A. Hützen, L. Ji and A. Lehrach, High Power Laser Sci **8**, e36 (2020).

[2] L. Reichwein, A. Hützen, M. Büscher and A. Pukhov, Plasma Phys. Control. Fusion **63**, 085011 (2021).

[3] L. Reichwein, M Büscher and A. Pukhov, arXiv:2201.11534 (2022).

Adiabatic Focusing of a Long Proton Bunch in Plasma

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We show in experiments that a long, relativistic p^+ bunch is focused by the plasma adiabatic response. The free plasma electrons migrate so as to neutralize the space-charge field of the bunch [1], and the bunch is therefore focused by the azimuthal magnetic field generated by its own current, that is not balanced by the radial electric field [2, 3, 4]. Since the length of the bunch is much longer than the plasma electron wavelength, the bunch also undergoes the self-modulation instability [5, 6]. Thus, the amplitude of the wakefields grows along the bunch and along the plasma, and the defocusing effect of the self-modulation can become dominant over the adiabatic focusing effect. We show that, when seeding the self-modulation with a preceding e^- bunch [7], the transition between the effect of the adiabatic response and that of the self-modulation depends on the amplitude of the seed wakefields.

References

[1] P. Chen, J. M. Dawson, R. W. Huff, and T. Katsouleas, Acceleration of electrons by the interaction of a bunched electron beam with a plasma, Phys. Rev. Lett. 54, 693 (1985)

[2] P. Chen, K. Oide, A. M. Sessler, and S. S. Yu, Plasma-based adiabatic focuser, Phys. Rev. Lett. 64, 1231 (1990)

[3] G. Hairapetian, P. Davis, C. E. Clayton, C. Joshi, S. C. Hartman, C. Pellegrini, T. Katsouleas, Experimental Demonstration of Dynamic Focusing of a Relativistic Electron Bunch by an Overdense Plasma Lens, Phys. Rev. Lett. 72, 2403 (1994)

[4] J. S. T. Ng et al., Observation of Plasma Focusing of a 28.5 GeV Positron Beam, Phys. Rev. Lett. 87, 244801 (2001)

[5] AWAKE Collaboration, Experimental observation of proton bunch modulation in a plasma at varying plasma densities, Phys. Rev. Lett. 122, 054802 (2019)

[6] M. Turner et al. (AWAKE Collaboration), Experimental observation of plasma wakefield growth driven by the seeded self-modulation of a proton bunch, Phys. Rev. Lett. 122, 054801 (2019)

[7] L. Verra et al. (AWAKE Collaboration), to be submitted.

Narrow-band, GeV gold ion beams from ultra-thin foils irradiated by intense sub-picosecond pulses

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Narrow energy band bunches of ions were produced from the interaction of intense (>10^{20} W/cm^2), sub-picosecond-duration laser pulses with ultra-thin (15 nm) gold foils. These included the bulk target species, in particular the Au ions which are accelerated with spectral peaks centred at 1.5 GeV and with fluxes on the order of 10^{12} particles per steradian, far surpassing Au ion fluxes reported by previous works by orders of magnitude [1,2]. 2D particle-in-cell simulations show a complex interplay between different acceleration mechanisms at different stages of interaction, suggesting the Au bunches stem from strong radiation pressure acceleration on a heavy-ion dominant plasma in the moments just before transparency, followed by an efficient acceleration due to transparency-enhanced mechanisms. We show that this effect is scalable to future multi-PW systems, where Au ion bunches at energies of several GeV are feasible.

[1] P. Wang, Z. Gong, S. G. Lee, Y. Shou, Y. Geng, C. Jeon, I. J. Kim, H.W. Lee, J. W. Yoon, J. H. Sung, S. K. Lee, D. Kong, J. Liu, Z. Mei, Z. Cao, Z. Pan, I. W. Choi, X. Yan, C. H. Nam, and W. Ma, Physical Review X **11**, 21049 (2021).

[2] F. H. Lindner, E. McCary, X. Jiao, T. M. Ostermayr, R. Roycroft, G. Tiwari, B. M. Hegelich, J. Schreiber, and P. G. Thirolf, Plasma Physics and Controlled Fusion **61**, 055002 (2019).

Direct laser acceleration in plasmas with a density gradients

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The interaction of high-intensity laser pulses with plasmas can be used to accelerate particles. Among the many mechanisms proposed to achieve effective acceleration is direct laser acceleration (DLA). The main advantage of DLA compared to other mechanisms is its ability to provide high charge ($\sim$ 100 nC) electron beams with a broad Maxwellian-like energy spectrum.

When an intense laser pulse propagates through an underdense plasma, it creates a plasma channel that triggers betatron oscillations of electrons around its central axis. When conditions are favorable, the resonance between betatron oscillations and oscillations in the field of the laser pulse can lead to electron acceleration. The mechanism has been well-described for an ideal case of a constant plasma density considering an immobile ion background. However, the potential advantages of using plasmas with a varying density profile are still not well understood.

In our work, we describe the most important differences between the regimes with constant and varying density using quasi 3D geometry of particle-in-cell code OSIRIS. We show that the density profile influences the self-focusing of the laser pulse which strongly impacts the resulting interaction with the plasma electrons. Furthermore, we propose a way how to utilize the varying density profile to maximize the electron beam energy and charge.

Acknowledgements:

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Plasma-based acceleration for non-relativistic particles

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In these past years, the study of plasma-based accelerators has been of great interest as they provide a route to more compact, ecological yet powerful accelerators. Currently established acceleration methods, such as Laser Wake Field Acceleration [1] and Plasma Wake Field Acceleration [2], are only applicable to particles whose velocities are close to the speed of light (relativistic particles). Heavier particles, e.g. muons, are thus excluded from the acceleration mechanism, because they are produced with non-relativistic velocities, even though these particles could particularly benefit from plasma acceleration since conventional acceleration techniques are not fast enough to accelerate them before their decay [3]. State-of-the-art techniques to sculpt the spatio-temporal spectrum of electromagnetic wave-packets leading to pulses with arbitrary group velocities have been recently developed [4]. These pulses can drive superluminal ionization fronts, and are promising drivers for plasma acceleration, being able for example to circumvent dephasing. At the same time, they can propagate with a subluminal group velocity, making them suitable candidates to drive acceleration wakes for heavier particles.

In this work, we propose a plasma-based acceleration technique for non-ultra-relativistic particles using pulses with non-relativistic group velocities, and discuss the role of the evolution of these pulses in a plasma on the acceleration. We first investigated the acceleration using an external field with a non-relativistic group velocity analytically and in 2D particle-in-cell simulations using OSIRIS [5]. Subsequently, we investigated the evolution and wakefield properties using optical space-time wave-packet drivers, traveling with group velocities smaller than the speed of light. We have found that these pulses are able to drive plasma wakes that travel slower than the speed of light. However, they are prone to plasma instabilities, e.g. Raman scattering. We discuss the onset and potential mitigation strategies for these instabilities.

References

[1] T. Tajima and J. M. Dawson, Physical Review Letters **43**, 267 (1979)

[2] P. Chen, J. M. Dawson, Robert W. Huff, and T. Katsouleas, Physical Review Letters **54**, 693 (1985)

[3] K. R. Long et al., Nature Physics volume **17**, 289 (2021)

[4] H. E. Kondakci and A. F. Abouraddy, Nature Communications **10**, 929 (2019)

[5] Fonseca R.A. et al., Lecture Notes in Computer Science **2331**, 342-51 (2002)

PIC Simulations of the Interaction between Self-Modulation in the Front and Rear of an ultra-relativistic Proton Bunch in Plasma

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An ultra-relativistic long proton bunch propagating in plasma can undergo self-modulation (SM) [1], which transforms it into a train of microbunches that resonantly drive wakefields [2]. These wakefields can be used to accelerate particle bunches to high energies [3]. To produce accelerated bunches with reproducible properties, the SM must be seeded [4], so that its phase and amplitude can be repeated event by event. When there is more than one seed, two SM processes could develop simultaneously and interact. This is particularly interesting for the future of the Advanced Wakefield Acceleration Experiment (AWAKE) [5].

We present here a numerical study using particle-in-cell simulations with parameters similar to those in the experiment. To create two seeds at different positions, we first place a density cut at the bunch front. Second, we change the density of the bunch front, creating two sharp density steps along the bunch. We show that the phase of the wakefields at the bunch rear follows that of one seed or of the other, depending on the amplitude and growth rate of the wakefields driven by the bunch front, which depend on its density. We also show that at the transition between following one seed or the other, the phase of the wakefields from the front has a significant effect on the microbunches in the rear.

References

[1] N. Kumar et al., PRL 104, 255003 (2010)
[2] A. Caldwell et al. (AWAKE Collaboration), NIM A, 829, 3-16 (2016)
[3] AWAKE Collaboration, Nature 561, 363–367 (2018)
[4] F. Batsch et al. (AWAKE Collaboration), PRL 126, 164802 (2021)
[5] P. Muggli (AWAKE Collaboration), J. Phys.: Conf. Ser. 1596 012008 (2020)

Control of the self-modulation and long-bunch hosing instabilities through plasma frequency detuning

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The success of plasma-based acceleration schemes often relies on the ability to manipulate complex beam-plasma interactions. In one of these concepts – the single-stage plasma wakefield accelerator driven by a long, highly energetic particle bunch [1] – the key interactions are two modes (symmetric and asymmetric) of the transverse two-stream instability called self-modulation and hosing, respectively. The self-modulation instability (SMI) [2, 3] can be harnessed to produce high-amplitude wakefields from a very long driver (compared to the plasma skin depth k_p^{-1}), but the fields tend to decay quickly after the instability has saturated. The hosing instability (HI) [4] is undesirable due to its potential disruption of the bunch, and we therefore need ways to mitigate it [5, 6].

During their growth phase, both of these instabilities can be understood as driven harmonic oscillators. In this work we show that it is possible to control their growth rates if the plasma oscillation responding to either the beam radius (SMI) or centroid (HI) perturbation is detuned early enough. The detuning can be achieved by varying the background plasma density, as we demonstrate with particle-in-cell simulations. Using plasma density steps [7], we apply this idea to mitigating the HI and optimizing the amplitude decay of the SMI after saturation. This novel approach to controlling the growth of beam-plasma instabilities could have important implications for plasma-based accelerators.

References

[1] E. Adli, *et al.* (the AWAKE collaboration), Nature **561**, 363–367 (2018)

[2] N. Kumar, A. Pukhov, and K. V. Lotov, Phys. Rev. Lett. **104**, 255003 (2010)

[3] C. B. Schroeder, C. Benedetti, E. Esarey, F. J. Grüner, and W. P. Leemans, Phys. Rev. Lett. **107**, 145002 (2011)

[4] C. B. Schroeder, C. Benedetti, E. Esarey, F. J. Grüner, and W. P. Leemans, Phys. Rev. E **86**, 026402 (2012)

[5] J. Vieira, W. B. Mori, and P. Muggli, Phys. Rev. Lett. **112**, 205001 (2014)

[6] R. Lehe, C. B. Schroeder, J.-L. Vay, E. Esarey, and W. P. Leemans, Phys. Rev. Lett. **119**, 244801 (2017)

[7] K. V. Lotov, Phys. Plasmas **18**, 024501 (2011)

Analysis of electron bunch energy spectra after meter scale over-dense plasma

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The proton driven plasma wakefield acceleration experiment at CERN uses the self-modulatio n mechanism of a long proton bunch in an over-dense plasma. In order to seed the modulation and control its phase, the use of a short and low energy electron bunch which precedes the lon g proton bunch in the plasma to seed self-modulation has been studied experimentally. Both el ectron and proton bunch densities are much lower than the ambient plasma density. Particle-in -cell simulations are used to reverse-engineer the process. The electron bunch loses a significa nt fraction of its energy driving seed wakefields. As a result, electrons can be lost along the pl asma and along transport through the energy spectrometer and the electron bunch parameters s trongly evolve along the plasma. In both experimental and simulation results, we found that th e larger charge of electron bunch leads to the more energy loss of bunch particles, which impli es the larger amplitude of the seed wakefield. We compare simulation and experimental result s for the electron bunch energy spectrum after 10 m of plasma.

Study of radio frequency breakdown in a device with movable electrodes

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Radio frequency (RF) capacitively coupled plasmas represent an important part of the plasmas used in the laboratory for applications and basic studies. The issues of how breakdown of such plasmas takes place and of the related Paschen-like curves are of clear interest. Several authors have experimentally found that breakdown voltage curves as a function of pressure display a minimum, as in the DC case, and that on the low-pressure side of this minimum a multi-valued region occurs [1]. This has been associated to a transition from the γ regime, where secondary electron emission from the electrode plays an important role, to the α regime, where new electrons are originated only by ionization taking place in the bulk [2]. Beyond this dependence, the transition is also function of the electrode distance.

In this contribution we have studied Paschen-like curves for breakdown between plane parallel electrodes as a function of the gas pressure p and of the electrode distance d, for different RF frequencies (an example of the plasma produced in the device is shown in Fig. 1). This has allowed to build Paschen-like curves and to compare them with the Kihara equation [3, 4] and with the criterion proposed by Sato and Shoji [5]. The experimental data and the similarities and discrepancies with the theoretical curves have been discussed also in terms of the transition between γ and α modes, which turns out to be related both to the electrode distance and to the applied voltage frequency. The study has been performed for both helium and argon gases.

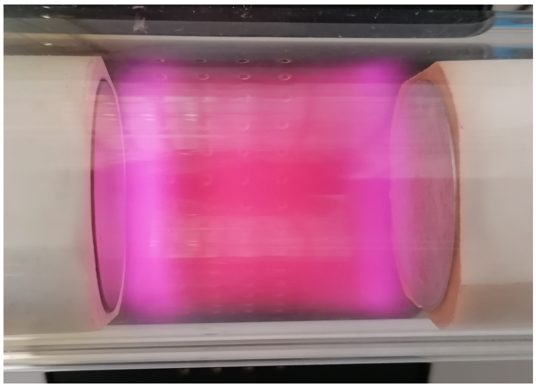

Figure 1: *Example of helium plasma produced between the electrodes, after breakdown.*

References

[1] V. A. Lisovskiy and V. D. Yegorenkov, J. Phys. D: Appl. Phys. **31**, 3349 (1998)

[2] M. U. Lee, J. Lee, J. K. Lee and G. S. Yun, Plasma Sources Sci. Technol. **26**, 034003 (2017).

[3] T. Kihara, Rev. Mod. Phys. **24**, 45 (1952)

[4] V. A. Lisovsky and V. D. Yegorenkov, J. Phys. D: Appl. Phys. **27**, 2340 (1994)

[5] M. Sato and M. Shoji, Jpn. J. Appl. Phys. **36**, 5729 (1997)

Fluid modelling of the weakly magnetized plasma column MISTRAL

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Cross-field configurations are used in a variety of applications, including ions sources and Hall thrusters for satellites, magnetron discharges, Penning gauges and fusion plasmas. Understanding and ultimately controlling anomalous transport is a crucial issue for these applications.

MISTRAL is a linear magnetized plasma column based at the PIIM laboratory used to study ExB plasmas with magnetized electrons and weakly or not magnetized ions. MISTRAL is a versatile device in which the following typical plasma parameters can be achieved: plasma length (L) = 1m, plasma diameter = 8 cm, column radius (a) = 10 cm, T_e = 1-6 eV, $n_e = 10^{14}$ - 10^{16} m^{-3}, B = 10-30 mT, P = 10^{-4}-10^{-2} Pa, Gas: H, He, Ar, Kr, Xe. The MISTRAL plasma has been characterized experimentally [1] with several diagnostics (Langmuir probe, fast camera, emission spectroscopy). Coherent structures rotating in the azimuthal direction have been observed in MISTRAL rotating at a frequency comparable to the ExB rotation frequency with azimuthal wave number m = 1, 2. Simon-Hoh type of instabilities [3,4] are one of the candidates to explain the coherent rotating structures observed in MISTRAL, with a complete theoretical picture remaining to be developed.

Our goal is to complete the characterisation of the observed instabilities along with the theoretical modeling in order to understand the origin of coherent structures in MISTRAL. The spatio-temporal acquisitions of plasma parameters (n_e, T_e, V_{plasma}, V_{float}) have been performed with the help of Langmuir probes for Ar and Xe plasma along with fast camera acquisitions. The linear stability of MISTRAL plasma has been explored with the two-species fluid model developed in [5] showing that these plasmas are prone to the centrifugal instability. Extensions of the fluid model to include ion-neutral friction and relax the small Larmor radius ordering are presently in progress.

References

[1] M. Matsukuma, Th. Pierre, A. Escarguel, D. Guyomarc'h, G. Leclert, F. Brochard, E. Gravier, Y. Kawai, Phys. Lett. A 314, 163 (2003)

[2] S. Jaeger, Phd thesis, Université de Provence, Marseille

[3] A Simon, Phys. Fluids 6, 382 (1963)

[4] F. C. Hoh, Phys. Fluids 6, 1184 (1963)

[5] F. F. Chen, Phys. Fluids 9, 965 (1966)

Experimental evidence of *TIAGO torch* dart at atmospheric pressure to be a Surface Wave Discharge.

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Surface Wave Discharges (SWD) are characterized by an increase of its length with the power supplied, the existence of a radiative zone and a sharp and linear decrease of electron density along the discharge whose slope does not vary with applied power [1]. TIAGO (*Torche à Injection Axiale sur Guide d'Ondes*) torch [2] creates a plasma that shows two different luminous regions: a bright plasma column (dart) and a tenuous shell (plume). It has been suggested [1] that this dart is a SWD, with the surrounding air acting as a virtual dielectric cylinder for the propagation of the electromagnetic surface wave [1,2]. However, this has still not been experimentally proven. In this work, the dart and the plume generated by the TIAGO device have been studied by optical emission spectroscopy. The discharge is demonstrated to be a SWD by the analysis of the axial distribution of electron density (Figure 1). Secondly, a radiative zone has been identified, which is further evidence that the dart from TIAGO plasma is a SWD. In addition, it has been found the plume to behave as a postdischarge, similar to that formed at the end of discharges containing nitrogen [3].

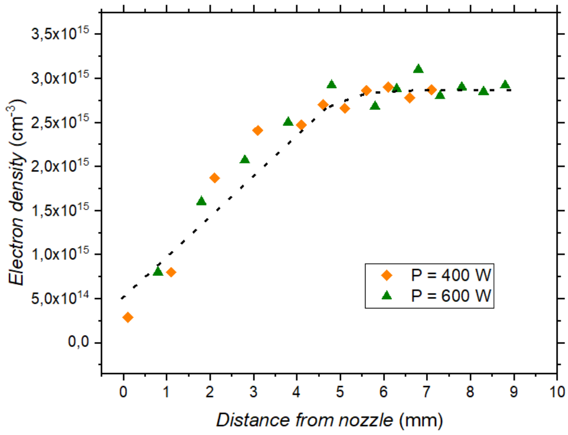

Figure 1: Axial distribution of the electron density in the TIAGO torch exhibiting a typical SWD behavior. The origin of the coordinates system has been placed at the end of the dart, taking positive sense towards the nozzle.

References:

1. Moisan, M., & Nowakowska, H. (2018). *Plasma Sources Science and Technology*, *27*(7), 073001.
2. Moisan, M., Zakrzewski, Z., & Rostaing, J.C. (2001). *Plasma Sources Science and Technology*, *10*(3), 387.
3. Bravo, J. A., Rincón, R., et *al*. (2015). *Plasma Chemistry and Plasma Processing*, *35*(6), 993-1014.

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Importance of Electron drag force in EUV induced pulsed plasma

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To continue with Moore's law in semiconductor technology with shrinking transistor sizes, the EUV lithography has been introduced which uses highly energetic photons (energy $\sim$ 92 eV). One of the unavoidable side effect of this development is the generation of EUV induced plasma due to the interaction of such highly energetic EUV photons with the low pressure (1-10 Pa) background hydrogen gas in scanner. Extreme ultraviolet (EUV) induced pulsed plasma is unique due to its transient characteristics: the plasma switches between non-thermal state (when EUV power is ON at the beginning of the pulse for $\sim$ few 100's ns) and thermal state (end of the pulse at $\sim$ few 10's μs). It is shown that although electron drag force acting on nm-μm size partilces is negligible compared to ion drag force at the beginning of the pulse, however it can be dominant at the end of the pulse and can play important role in particle transport.

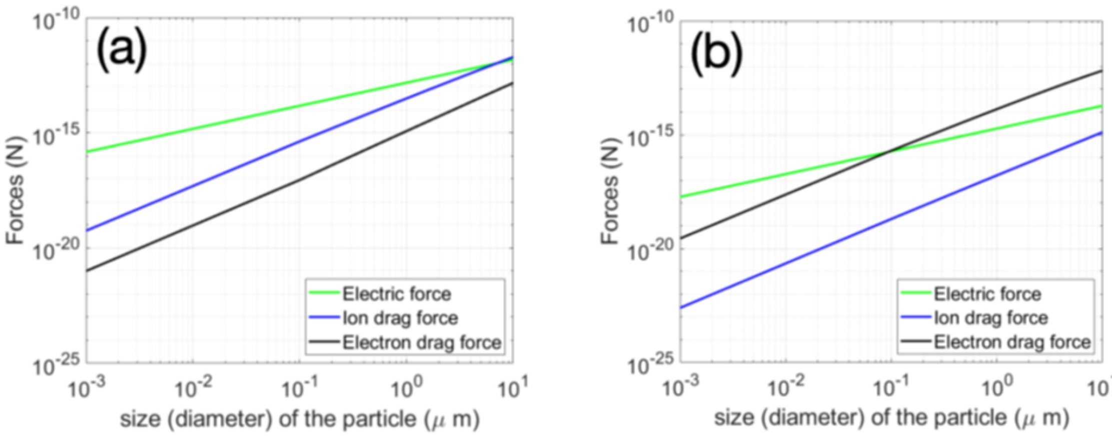

Figure 1: *Force balance plots: (a) beginning of pulse and (b) end of pulse*

References

[1] M. van de Kerkhof, J. P. H. Benschop, and V. Y. Banine. "Lithography for now and the future." Solid-State Electronics, **155**, 20 (2019).

[2] S. A. Khrapak and G. E. Morfill, "Dusty plasmas in a constant electric field: Role of the electron drag force", Phys. Rev. E **69**, 066411 (2004).

[3] M. Chaudhuri, S. A. Khrapak, and G. E. Morfill, "Effective charge of a small absorbing body in highly collisional plasma subject to an external electric field", Physics of Plasmas, **14**, 054503 (2007).

PIC simulations and reduced model of confined ionising electron clouds relevant to gyrotrons

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Nonneutral plasmas are of broad interest for antimatter physics, particle accelerators and high power microwave sources such as gyrotrons. Indeed, the study of charged particle confinement is crucial for developing long-term antimatter storage (Penning traps) or to avoid arcing and improve the overall efficiency of particle accelerators and microwave sources. In gyrotrons specifically, operation has been seen to be limited by the presence of localized trapped electrons (i.e. not belonging to the main electron beam) in the gyrotron gun region [1]. Such trapped electrons can ionise the residual neutral gas present in the vacuum vessel which can lead to arcing and preventing the electron gun from operating at nominal electron acceleration voltage [2]. The trapping of particles is the consequence of crossed electric and magnetic fields and has some analogies to a Penning trap.

We present an exhaustive numerical study that characterizes trapped electron clouds in a magnetron injection gun with different magnetic field amplitudes, electrode shapes and biases, residual gas compositions and pressures. The electron cloud shape and maximum density, as well as the evolution of the self-consistent trapping potential well are obtained by using a 2D axisymmetric electrostatic particle-in-cell code with Dirichlet boundary conditions on elliptic boundaries, where realistic electron gun geometries and their non-trivial electromagnetic field topologies can be simulated. The self-consistent electron cloud build-up is simulated by considering electron-neutral collisions and the resulting ionisation using a Monte Carlo approach [3]. A reduced analytical model describing the electron cloud equilibria is then presented that explains the parametric dependences obtained from the simulations and provides insight into the control parameters that can be used to simplify the design and remove operation limitations of gyrotrons gun assemblies.

References

[1] Pagonakis I Gr, Piosczyk B, Zhang J, Illy S, Rzesnicki T, Hogge J-P, et al 2016 *Phys. Plasmas* **23** 023105.

[2] Piosczyk B, Dammertz G, Dumbrajs O, Kartikeyan M V, Thumm M K and Yang X 2004 *IEEE Trans. Plasma Sci.* **32** 853-60.

[3] Birdsall C K 1991 *IEEE Transactions on Plasma Science* **19** 65-85.

Models for modulated rotation of a Penning-trapped magnetized electron vortex in a variable-charge regime

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We routinely confine and study electron plasmas in a Penning-Malmberg trap generated by means of a quite unconventional production scheme, i.e. using a low-amplitude radio-frequency (RF) drive on one of the trap electrodes [1, 2]. This weak RF drive can effectively heat up the few free electrons in the residual gas - at pressures in the high to ultra-high vacuum regime - and initiate a discharge and accumulation of an electron plasma. Interesting stationary states are reached within some seconds. A peculiar example is the creation of a single column (vortex) of electrons displaying a radial displacement with respect to the longitudinal symmetry axis and thus rotating around it. Total charge and density profile show very robust stability to perturbations and usual instabilities, e.g., ion-induced instability and the relevant loss of confinement, as long as the ionizing drive is maintained. Even more peculiar is the occurrence of stable low-frequency ($\sim$ 1 Hz) oscillations of both charge and radial offset in these rotating vortices [3, 4]. In this contribution, we discuss the interpretation of these oscillations. We start from a simple predator-prey scheme for the electron charge and displacement, where we plug in realistic parameters extracted from experiments, and address the complicated roles of the ionizing RF drive and of the other species present in the trap during the formation process. We notice that an oscillating behaviour of the system variables is observed in a number of other multispecies plasma environments, such as the breathing oscillations seen in Hall thrusters. We show that, although the complete dynamics is highly complicated and spans a range of time scales from microseconds to seconds, we can reproduce to a quantitative level the main features observed in the experiments.

References

[1] B. Paroli, F. De Luca, G. Maero, R. Pozzoli and M. Romé, Plasma Sources Sci. Tecnol. **19**, 045013 (2010)

[2] G. Maero, S. Chen, R. Pozzoli and M. Romé, J. Plasma Phys. **81**, 495810503 (2015)

[3] B. Paroli, G. Maero, R. Pozzoli and M. Romé, Phys. Plasmas **21**, 122102 (2014)

[4] G. Maero, Il Nuovo Cimento C **40**, 90 (2017)

Gamma-ray flares from magnetic reconnection in relativistically magnetized plasmas: minijets vs. plasmoids

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The main cosmic sources of high-energy (HE; GeV-scale) gamma-ray radiation are (1) blazars, the most luminous class of active galactic nuclei (AGN), the broad-band emission of which is produced in powerful narrowly collimated jets attaining relativistic bulk speeds and anchored at supermassive black holes; (2) pulsars (rotating neutron stars with strong magnetic fields) and associated wind nebulae (PWN). These sources are also characterized by strong time variability, with rapid gamma-ray flares posing a particular theoretical challenge. A common feature of these gamma-ray emitters is relativistically magnetized collisionless plasma. Efficient gamma-ray emission requires an efficient mechanism of energy dissipation and non-thermal particle acceleration, and relativistic magnetic reconnection is a primary candidate. To explain the production of rapid gamma-ray flares, two aspects of magnetic reconnection received particular attention: outflows from the magnetic diffusion regions attaining relativistic bulk velocities – so-called minijets, and plasmoids (flux ropes) resulting from the tearing instability. The relative importance of minijets and plasmoids is investigated [1] by means of particle-in-cell (PIC) numerical simulations of antiparallel magnetic fields in relativistically magnetized plasma. The algorithm includes radiative cooling due to synchrotron process, and radiative signatures in the form of observer-dependent light curves are calculated. It is demonstrated that minijets and plasmoids co-exist in the same reconnection layer. While minijets can accelerate particles to higher energies, plasmoids dominate the radiative output due to higher particle density. Hierarchical tail-on plasmoid mergers (smaller and faster plasmoids capturing larger plasmoids) can explain the production of rapid gamma-ray flares.

[1] J. Ortuño-Macías & K. Nalewajko „Radiative kinetic simulations of steady-state relativistic plasmoid magnetic reconnection", 2020, MNRAS, 497, 1365, arXiv:1911.06830

Atomic calculations in moderately charged lanthanide ions (from La to Pm) relevant for plasma opacity studies in the context of kilonovae

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On August 17, 2017, the LIGO-VIRGO collaboration observed gravitational waves from a neutron star merger for the first time [1]. In this coalescence, hot and radioactive matter is ejected causing a very luminous explosion called kilonova. In this latter, they are nuclear reactions forming heavy elements such as lanthanides (Z = 57 – 71). They play an important role because, given their rich spectra, they contribute intensely to the opacity affecting radiation emission [2]. To interpret the spectrum of a kilonova, it is crucial to precisely know the atomic data characterizing these elements. Some studies determined these parameters but only for the first degrees of ionisation (up to 3+). Unfortunately, there is almost no data available for ions higher than 3+. Therefore, our project aims to make a significant contribution in this field as it consists of a detailed study of the radiative processes characterizing moderately charged lanthanide ions (from 4+ to 9+) and to deduce the corresponding astrophysical opacities. Our calculations are based on a multi-platform approach involving different independent theoretical methods, namely the pseudo-relativistic Hartree-Fock (HFR) [3,4], the fully relativistic Multi-Configuration Dirac-Hartree-Fock (MCDHF) [5-8] and Configuration Interaction Many-Body Perturbation Theory (CI+MBPT) [9,10] methods. In the absence of sufficient experimental data, this approach is the only way to estimate the accuracy of the results obtained through systematic comparisons between distinct computational procedures. In the present contribution, we report the results obtained as regards the atomic structures and radiative parameters in moderately lanthanide ions (La to Pm) and the corresponding monochromatic opacities for application to early phases of kilonovae emission spectra observed following neutron star mergers.

1. B. Abbott et al., Phys. Rev. Lett. 119, 161101 (2017).
2. D. Kasen, B. Metzger, J. Barnes, E. Quataert and E. Ramirez-Ruiz, Nature 551, 80 (2017).
3. R.D. Cowan, The Theory of Atomic Structure and Spectra (U. of California Press, Berkeley, 1981).
4. P. Quinet et al., Mon. Not. Roy. Astron. Soc. 307, 934 (1999).
5. I.P. Grant, Relativistic Quantum Theory of Atoms and Molecules (Springer-Verlag, Berlin, 2007).
6. P. Jönsson, G. Gaigalas, J. Biéron, C. Froese Fischer and I.P. Grant, Comput. Phys. Commun. 184, 2197 (2013).
7. C. Froese Fischer et al., J. Phys. B : At. Mol. Opt. Phys. 49, 182004 (2016).
8. C. Froese Fischer, G. Gaigalas, P. Jönsson and J. Bi´eron, Comput. Phys. Commun. 237, 184 (2019).
9. V.A. Dzuba, V.V. Flambaum and M.G. Kozlov, Phys. Rev. A 54, 3948 (1996).
10. E.V. Kahl and J.C. Berengut, Comput. Phys. Commun. 238, 232 (2019).