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# A flexible linear gyro-fluid eigensolver with Onsager symmetry

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Gyro-fluid equations are velocity space moments of the gyrokinetic equation. Special gyro-Landau-fluid closures have been developed to include the damping due to kinetic resonances fit to the collisionless local response functions [1,2]. This damping allows for accurate linear eigenmodes to be computed, even in the collisionless limit, with a relatively low number of velocity space moments compared to gyrokinetic codes. An analysis of the gyro-Landau-fluid closure schemes finds that the Onsager symmetries [3] of the resulting quasilinear fluxes are not preserved. Onsager symmetry guarantees that the matrix of diffusivities is positive definite, an important property for a transport model. The constraints on the closure due to Onsager symmetry and other considerations are shown to be very restrictive. A new, simpler scheme for regularizing the gyro-fluid equations that preserves the Onsager symmetry and is scalable to higher velocity space moments without change of the damping model is presented. Linear eigenmodes from the new system of equations are compared with gyrokinetic results, with and without collisions, including parallel and perpendicular electromagnetic fluctuations at high beta. The new linear gyro-fluid equation eigensolver (GFS) will be used to extend the TGLF quasilinear transport model [4] so that it can compute the energy and momentum fluxes due to parallel magnetic fluctuations, completing the transport matrix. The GFS equations do not use a bounce average approximation to the magnetic mirror force. General flux surface magnetic geometry is included. Only pitch angle scattering for electron collisions are included and equilibrium rotation is restricted to be subsonic. The Onsager symmetries will enable faster transport solvers since the matrix of convection and diffusion coefficients will all be computed by a single call to the quasilinear transport model.

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# Formulation and numerical benchmark of improved magneto fluid-dynamics boundary conditions for 3D nonlinear MHD code SPECYL

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3D nonlinear MHD code SpeCyl [1] is a spectral tool, operating in zero-$\beta$ approximation and in cylindrical geometry to advance in time the magnetic field and the plasma flow. The traditional formulation of its boundary conditions would see the plasma as if in direct contact with an ideally conducting shell. However, a recent reformulation [2] introduced the presence of a rigid thin shell and a tuneable-width vacuum region between the plasma and the outer conductor.
With suitable parameters choice, the resistive shell can be made transparent to the magnetic field, so to simulate a free-interface between plasma and vacuum. Numerical benchmark performed in this regime against current-driven linear MHD instabilities found good agreement concerning the internal modes, yet quantitatively poor for external modes of MHD [3], motivating a reformulation of fluid boundary conditions, as well.
We present here the resulting set of boundary conditions, which combines the chance for finite flow at plasma edge with the already present thin shell-like modelling of magnetic plasma-vacuum matching conditions. We also illustrate numerical benchmarks, mainly against some well known results of the theory of linear MHD instabilities [4, 5]. Finally, we include a mutual-benchmark between our formulation of SpeCyl and another MHD nonlinear simulations code, Pixie3D [6], with analogous physical assumptions at plasma edge. This extends the nonlinear benchmark, already performed between the two codes in the past [7].

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# Ballooning stability in negative and positive triangularity spherical tokamak plasmas

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A particularly promising magnetically confined fusion reactor concept is the spherical tokamak (ST). To be economically competitive, ST power plant designs require a high $\beta$ (plasma pressure/magnetic pressure) and sufficiently low turbulent transport to enable steady-state operation. A novel approach to tokamak optimisation is for the plasma to have negative triangularity, with experimental results indicating this reduces transport in L-mode, and avoids the deleterious impact of Edge-Localised Modes (ELMs) experienced in standard H-mode operation. However, negative triangularity is known to close access to the "second stability" region for ballooning modes (a pressure-driven plasma instability) [**?**], and thus are expected to impose a hard $\beta$ limit. Second stability access is likely important in ST reactor design, and this raises the question as to whether negative triangularity is feasible. We address this question by presenting a linear gyrokinetic study of three hypothetical (but reasonable) high $\beta$ ST equilibria with similar size and fusion power in the range 500-800MW. We find that, by closing the second stability window, the negative triangularity case becomes strongly unstable to long-wavelength kinetic ballooning modes (KBMs) across the plasma, likely driving unacceptably high transport. By contrast, positive triangularity can completely avoid the ideal ballooning unstable region whilst having reactor-relevant $\beta$, provided the on-axis safety factor is sufficiently high. Nevertheless, the dominant instability still appears to be KBM, and we explore the role of kinetic effects in destabilising the mode. The KBM growth rate in the ideal MHD-stable region is low, and this could feasibly be stabilised by flow shear or may impose a soft $\beta$ limit for ST reactors.

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## The synergetic effects of three-dimensional magnetic perturbations and finite beta on collisionless trapped electron mode in tokamak plasmas

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The effects of three-dimensional (3D) magnetic perturbations (MPs) and finite beta ($\beta$, i.e., the ratio of plasma kinetic pressure to magnetic pressure) on the instability of collisionless trapped electron mode (CTEM) have been studied [1]. Based on the local 3D equilibrium model [2], we have derived general expressions for longitudinal invariant and the corresponding precession drift frequency of trapped electrons, which include the synergetic effects of MPs and finite $\beta$. It is found that 3D effects can either stabilize or destabilize CTEM instability by analytically solving the linear dispersion relation of CTEM. These effects depend on the poloidal and toroidal mode numbers as well as the phase of 3D MPs. Specially, for the destabilizing phase of MPs, the stabilizing effect of finite $\beta$ on CTEM [3] can be even reversed when the displacement of magnetic flux surface exceeds a critical value. Moreover, the synergetic effects of 3D MPs with stabilizing phase and finite $\beta$ can further reduce the required absolute value of negative magnetic shear to completely stabilize CTEM instability. This indicates that 3D MPs might be used as an actuator for lowing the level of anomalous electron heat transport, and thus facilitate the formation of electron internal transport barrier (eITB).

**Key words**: 3D magnetic perturbations, finite $\beta$, precession drift frequency, CTEM, tokamak plasmas

**Reference:**

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# Energetic decomposition of modes in resistive plasmas

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In magnetically confined fusion plasmas, magnetohydrodynamic (MHD) instabilities can cause massive losses of confinement. The analysis of MHD stability is, therefore, crucial for the operation of future fusion devices.

While solving the set of linearized MHD equations yields the structure and growth rate of instabilities, there is no information on the energetic drives of the instability. The energy functional relates the kinetic energy of the perturbation to the driving and restoring forces in the plasma [1]. For ideal MHD, the energy functional can be transformed to an "intuitive form", where the energetic contributions are separated into different sources of energy (pressure drive, current drive and stabilizing terms) [2]. However, for some equilibria, the presence of finite resistivity can influence MHD stability, lowering the critical parameters relative to the ideal MHD case and changing the mode structure. In order to analyze the energy sources driving these resistive instabilities, the intuitive form of the ideal energy functional must be generalized to plasmas with finite resistivity.

In this work, we extend the intuitive form of the ideal energy functional to include resistive instabilities. Since the resistive energy functional is not in the form of a solvable eigenvalue problem, it cannot be used to search for resistive instabilities directly, but it can be used to analyze the different energetic drives of resistive instabilities. The intuitive form of the resistive energy functional has been implemented in the stability code CASTOR3D in general curvilinear coordinates [3][4]. The functional has also been applied to a numerical test case showing equality of the kinetic and potential energy terms in different coordinate systems as well as the change of the different energetic contributions with increasing resistivity.

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# Energetic particle nonlinear equilibria and transport processes in burning plasmas

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The purpose of ITER and of magnetic confinement fusion is to investigate burning plasmas approaching ignition. In ideal conditions, $\alpha$ particles thermalize and sustain the fusion process although collective electromagnetic fluctuations might lead to increased energetic particle (EP) losses. Therefore, being able to accurately describe EPs transport is of main importance. Fluctuations resonantly excited by EPs and ensuing transport have different spatiotemporal scales compared with thermal plasma. More generally, EPs play a critical role as mediators of plasma cross scale couplings [1]. Consequently, a self consistent, first-principle-based theoretical description is mandatory, such as a global gyrokinetic approach. Self-consistent analysis of meso-scales and the weak collisional nature of EPs suggest a full$-f$ formulation, which is computationally demanding, especially on the transport time scales [2]. This is very challenging and, at the same time, calls for reduced descriptions.

A general theoretical framework to describe EPs transport, dubbed the Dyson-Schrödinger model (DSM), has been recently proposed by the authors [2-4] and will be discussed in this work. The necessity of developing a gyrokinetic theory for energetic particle phase space transport will be underlined first [2]. The main differences with multi-scale gyrokinetics [5] will be analyzed, with a special emphasis on the assumption of scale separations between equilibrium and fluctuations, which cannot be assumed for EPs. Then, we will elucidate how defining this theoretical framework leads to a renormalization of the usual plasma equilibrium in the presence of a finite level of electromagnetic fluctuations, dubbed the zonal state. The governing Dyson-like transport equations will be derived, consisting of a novel full $f$ / $\delta f$ mixed approach. In particular, the nonlinear slowly evolving equilibrium distribution will be described by a full $f$ scheme in a reduced $3D$ phase-space, i.e. the unperturbed constants of motion space, while a $\delta f$ approach will describe symmetry breaking fluctuations. The significance of this new formulation will be highlighted in particular for long time scale (transport) calculations where the non-Maxwellian features and the role of wave-particle resonances are particularly relevant. The relation with other commonly adopted EPs reduced descriptions, e.g., resonance line broadened quasi-liner model and kick model, and with the usual formalism based on the wave kinetic equation will be discussed. To show the generality of the present approach, which ranges from Tokamak [2-4] and Stellarator [7] studies to the recent analysis of chorus emission [6], we will apply it to explore the effects of sources and collisions on Energetic particle mode (EPM) burst dynamics [6]. Similarities and differences with the energetic-particle driven Geodesic Acoustic Modes (EGAM) will also be illustrated.

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## Kinetic Structure of Low Frequency Continuous Spectrum in General Tokamak Geometry

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The low frequency kinetic continuous spectra of shear Alfvén waves (SAW) and ion acoustic waves (IAW) in magnetic confinement devices are widely used for identification of frequency gaps and discrete modes. The drift Alfvén energetic particle stability (DAEPS) code [1], which is an eigenvalue code using the finite element method, is used to calculate the low frequency fluid and kinetic continuous spectra. The model equations, consisting of quasi-neutrality condition and Schrödinger-like form of vorticity equation, are derived within the general fishbone-like dispersion relation (GFLDR) theoretical framework [2, 3]. The mode structure decomposition approach and asymptotic matching between the inertial/singular layer and ideal regions are adopted. In this work, the numerical model of the DAEPS code is further extended to include general axisymmetric geometry. Numerical results of fluid and kinetic continuous spectra are benchmarked with FALCON [4] and LIGKA [5, 6], respectively. The comparison of circular (model) and experimental ITER profiles shows that the structure of the kinetic continua is sensitive to the shaping effect. Comparing kinetic and MHD continuous spectra also suggests that the structure of the kinetic and MHD continua share a similar frequency behavior, while the damping rate of the kinetic continua reflects the SAW/IAW coupling and/or the polarization of the fluctuation structure. It is also suggested that the ion diamagnetic frequency, corresponding to the plasma nonuniformity, not only changes the frequency, but also destabilizes the kinetic ballooning mode/Alfvén ITG branch near the accumulation point. The use of DAEPS as building block of a hierarchy of reduced energetic particle transport models, which are presently being developed, will also be discussed.

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# Nonlinear evolutions of energetic particle modes in tokamak plasmas with reversed magnetic shear configuration

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The effects of energetic particles (EPs) on magnetohydrodynamic instabilities has been investigated using CLT-K code [1] in tokamak plasmas with reversed magnetic shear configuration. So far, the investigation of energetic particles modes (EPMs) has been limited to the theoretical analysis and linear simulation [2-3]. The role of nonlinear evolution of EPMs has not been considered.

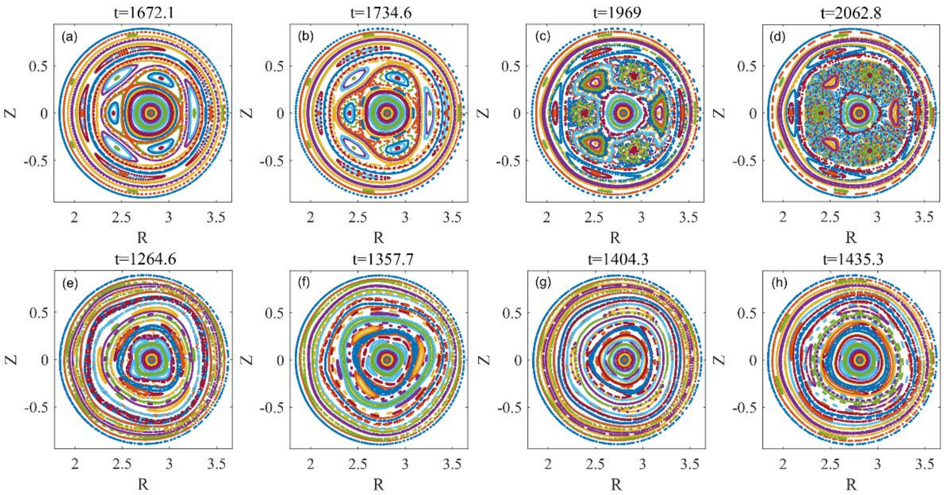


*Figure 1.* *(Top) Poincaré plot of magnetic field lines for* $m/n = 3/1$ *DTM with* $\beta_h = 0$, *and (bottom) Poincaré plot of magnetic field lines for* $m/n = 3/1$ *EPM with* $\beta_h = 0.01$.

Once the EP beta is larger than a critical value, a global EPM can be excited with high mode frequencies [4-5]. As shown in Fig. 1, owing to the absence of overlapping of two m/n=3/1 rational surfaces, the magnetic flux surfaces of EPMs well keep in the nonlinear saturation stage, which is different from the result of DTMs. It means that the EPMs appear like an ideal MHD mode rather than a resistive mode. Meanwhile, the distances and positions of the two rational surfaces effect on the mode are also studied in detail.

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# Can a monotonic electrostatic potential exist in the Debye sheath at very shallow magnetic field angles?

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A Debye sheath forms in a plasma right next to a solid target in order to repel electrons, which are lighter and more mobile than ions. It is characterised by a strong electric field varying on the scale of the Debye length. The presence of a magnetic field with an oblique angle of incidence with the wall causes the appearance of a quasineutral magnetic presheath. This is characterised by a strong electric field varying on the scale of the ion gyroradius, much larger than the Debye length. It affects any magnetised plasma which interacts with a solid target, such as in fusion devices, Hall thrusters, magnetic filters and near probes. We present numerical results of the steady state electrostatic potential profile across the magnetic presheath and Debye sheath, treated on their respective length scales assuming an asymptotic scale separation between Debye length and ion gyroradius. Ion and electron trajectories in the magnetic presheath and Debye sheath, respectively, are treated as quasi-periodic non-circular gyro-orbits by assuming a small magnetic field angle (particularly relevant to fusion devices). This approximation greatly expedites the density calculation for a given electrostatic potential profile. The steady state profile is obtained in both regions using an iterative scheme which converges to a numerical solution of both the quasineutrality equation and Poisson's equation. The ratio of Debye length to electron gyroradius, which is a measure of the magnetic field strength, is varied in the simulations. We find a critical angle below which no monotonic potential profile can exist in the magnetised sheath. The dependence of the critical angle with magnetic field strength, ion-to-electron temperature ratio and mass ratio is found numerically, and shown to follow an analytical scaling. What happens to the sheath below the critical angle is not understood yet. However, in most fusion-relevant cases the critical angle is expected to be too low to matter.

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# The Chaotic Nature of Three-dimensional Magnetic Topology Revealed by Transversely Intersecting Invariant Manifolds

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Although adopted by Grad-Shafranov equation, EFIT, VMEC, *etc.*, the nested closed flux surface assumption does not necessarily hold when the axial symmetry of magnetic field is absent. An abundant amount of research has focused on how to stimulate a stochastic field layer at the plasma boundary to mitigate distructive type-I edge localized modes [1]. With regard to the influence of topology change on the scrape-off layer, a spiral ribbon-like pattern of heat deposition has also been reported and investigated in experiments. Based on the theory of dynamical system and chaos [2], we formalized relevant notions concerning magnetic topology and revealed the global structure of three-dimensional magnetic field. *The invariant manifold growth formula in cylindrical coordinates* is deduced and essential to determine the chaotic field regions (used to be called stochastic field), which induce a mixing effect inside plasma. It is proposed that the well-known notion of the last closed flux surface is substituted by more accurate invariant manifolds of the outmost hyperbolic cycle(s). The transverse intersection of invariant manifolds is a signature of chaos, indicating the intrinsic unpredictability (of field line tracing) in the long run. Having acquired the analytical form of invariant manifolds, we further regard the whole magnetic field as a functional argument of Poincaré map and utilize the functional derivative from functional analysis to obtain *the X-point shift under perturbation ($\delta\mathscr{B}$) formula*. Undoubtedly, the most important perturbation field is the derivative of magnetic field itself *w.r.t.* time, *i.e.* $\partial\mathscr{B}/\partial t$, giving the shift velocity of X-points when $\delta\mathscr{B}$ is substituted for $\partial\mathscr{B}/\partial t$ in the formula above.

In conclusion, a systematic analytic theory of three-dimensional magnetic fields has been established to facilitate comprehending the field structure and to provide guidance on control.

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# Kinetic effects in tokamak scrape-off layer plasmas - nonlocal parallel transport and plasma-atomic reactions

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In tokamak scrape-off layer (SOL) plasmas, accurate modelling of heat transport to the divertor region and plasma-facing components is critical to the successful operation of future devices. These plasmas are often assumed to be highly collisional, so Braginskii-like fluid models are used. However, there are two important aspects of SOL physics for which this assumption may be violated. First, the presence of steep parallel temperature gradients, as would be expected in devices like ITER, means electron heat transport may be dominated by fast, low-collisionality particles and so becomes 'non-local'. Secondly, enhanced high-energy tails of electron distributions close to the walls, where most plasma-atomic interactions take place, may modify reaction rates (e.g. electron-impact ionisation), and therefore affect the particle, momentum and power balance.

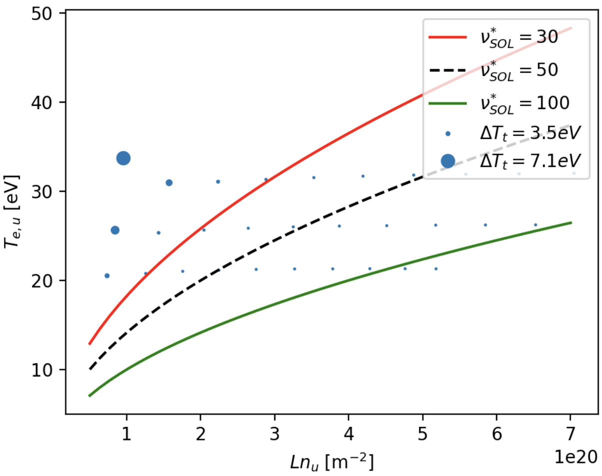


Figure 1: *Difference in target temperature for SOL simulations with kinetic vs. fluid electrons.*

For these reasons, electron kinetics in SOL plasmas has been investigated using the 1D code SOL-KiT [1]. SOL-KiT has been extended to model background ions and neutral atoms more realistically, with the aim of studying SOL plasmas in reactor-relevant conditions. Results from simulations will be presented comparing fluid and kinetic electron treatments, looking in particular at modifications to the electron heat flux and atomic reaction rates. To ascertain the tokamak regimes where kinetic effects may be most important, we have performed upstream collisionality scans, looking at both equilibrium and transient/ELM-y conditions. We find large differences in electron heat conductivity at reactor-relevant collisionalities, as well as small modifications to plasma-neutral reaction rates with atomic hydrogen.

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# A new turbulent transition in a toroidal plasma


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We study the LH transition. This transition between a low confined turbulent state named L-mode and a higher quality confined state named H-mode has been observed since 1982 [1] in tokamaks. It is characterized by a drop of turbulent fluctuations which usually causes loss of confinement of the plasma. The understandig of this phenomenon is still incomplete [2]

We propose that the LH transition can be linked to a transition between two turbulent states in an axisymmetric flow. This transition was first observed numerically in a cylindric system [3] between two two-dimensional states with two (2D2C state) and three (2D3C state) velocity components, that we link to the H-mode and the L-mode respectively.

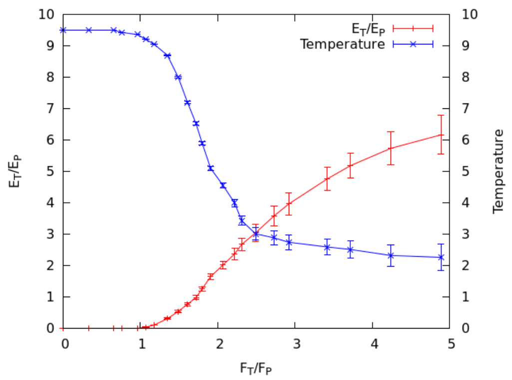


Figure 1: *Drop in temperature at the center of the tokamak section and growth in the $E_T/E_P$ ratio by increasing toroidal-poloidal forcing ratio $F_T/F_P$.*

We performed direct numerical simulations with the code Nek5000 in toroidally axisymmetric geometry. A scalar field is added in order to study the confinement quality of the flow. We can show (Fig. 1) that an increase of toroidal fluctuating velocity induces both a loss of confinement of the scalar and an increase of the toroidal-polidal energy ratio $E_T/E_P$ indicating a 2D3C state. We conclude that this simple model induces a transition which reproduces the key properties of the LH transition.

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# Energy confinement time in a magnetically confined thermonuclear fusion reactor

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The single most important scientific question in fusion research may be confinement in a fusion plasma [1]. A recently-developed theoretical model [2] is reviewed for the confinement time of ion kinetic energy in a material where fusion reactions occur. In the theoretical model where ion stopping was considered as a key mechanism for ion kinetic energy loss, an estimate was obtained for the confinement time of ion kinetic energy in a D-T plasma - and found to be orders of magnitude lower than required in the Lawson criterion. As ions transfer their kinetic energies to electrons via ion stopping and thermalization between the ions and the electrons takes place, spontaneous electron cyclotron radiation is identified as a key mechanism for electron kinetic energy loss in a magnetically confined plasma. The energy confinement time is obtained and found in agreement with measurements from TFTR [1] and Wendelstein 7-X [3]. An advanced Lawson criterion is obtained for a magnetically confined thermonuclear fusion reactor.

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# Plasma flow in tokamaks: unraveling the competition and synergy between turbulence and 3D magnetic perturbations

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The present study addresses the complex issue of flow control in tokamak plasmas. Flow shaping in large size magnetized plasmas is not easily achievable with external momentum sources. Flows are rather determined by intrinsic physics that combine competing turbulent and collisonal effects in presence of 3D magnetic perturbations. Usually those effects are handled separately in numerical simulations. In this work, they are treated on an equal footing, which allows addressing possible synergies for the first time. To this aim, both analytical theory and gyrokinetic simulations with the GYSELA code [1] are used. The methodology consists in three steps. First, GYSELA simulations with only neoclassical contribution and including non-axisymmetric magnetic perturbations are successfully compared to the neoclassical theory [2]. Secondly, in simulations of Ion Temperature Gradient driven turbulence without magnetic perturbation, turbulent momentum transport is analyzed and compared with available models of turbulent transport [3, 4]. Finally, all effects are self-consistently accounted for to assess the resulting flow. As expected – although never confirmed up to now by means of self-consistent first principle numerical simulations – magnetic braking due to the magnetic perturbation prevails over turbulence above a critical amplitude of perturbation. Moreover, interplay mechanisms between magnetic braking and turbulent momentum drive are addressed. The main mechanism is the enhancement of the rotation-driven radial electric field shear $E_r'$ when this perturbation is present. This effect indirectly results in a significant change in magnitude of the turbulent stress tensor – quite sensitive to $E_r'$. Conversely, the turbulent intensity is only mildly affected in our simulations. All in all, turbulence-dominated L-mode plasmas are expected to overcome the neoclassical effects. Edge flows however are likely to be dominated by magnetic braking in H-mode.

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# Study of Electrode Biasing in the Edge and SOL regions of a Tokamak

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A theoretical study is made of the effect of edge biasing on the dynamics of the interchange turbulence [1,2,3] in the edge and scrape-off layer (SOL) regions. A linear analysis of a set of model fluid equations shows that biasing stabilizes the small $k_y$ modes. The model equations are next solved numerically, using the BOUT++ framework, to explore the nonlinear dynamics in the presence of positive or negative bias. Positive biasing is found to lead to a larger increment in plasma density and temperature as compared to negative biasing. It is observed that cross-correlation between density and poloidal electric field at different radial positions decreases for positive biasing and in the case of negative biasing it is almost similar to that of no biasing. Plasma density and poloidal electric field fluctuations have been investigated which show that the density fluctuations increase (decrease) for positive (negative) biasing but the radially outward flux for these biasing cases always decreases mainly due to the decrease of cross-correlation between density and poloidal electric field fluctuations. The edge electrode biasing also affects the power spectral density (PSD) in the edge and SOL regions. PSD in the edge region before the position of electrode is higher for the positive bias in the 5-70kHz frequency range. In the SOL region, PSD for both the biasing is lower in comparison to no biasing. Analysis of the $k_y$ spectrum for both the bias cases shows a reduction of $k_y$ in the edge and SOL regions in comparison to the case of no bias. Edge biasing is also shown to impact the heat and particle loads on the plasma-facing components by decreasing the SOL width as a function of the applied voltage.

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# Interaction of Alfvénic modes and turbulence via the nonlinear modification of the equilibrium profiles

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A key step towards the achievement of controlled nuclear fusion in magnetic confinement devices is the mitigation of turbulence. Turbulent tokamak plasmas are intrinsically multiscale systems. Microturbulence generates meso-scale zonal flows. Additionally, energetic particles drive Alfvénic modes (AM) unstable, on meso- or macro-scales, and zonal structures.

In this work, we investigate the possible interaction of AMs and turbulence via the evolution of the equilibrium profiles. Turbulence is known to strongly depend on the gradients of the equilibrium profiles, for example plasma density and temperature. AMs can nonlinearly modify the equilibrium profiles [1, 2, 3], and therefore affect turbulence. Viceversa, with the same mechanism, turbulence can affect the AM dynamics.

We present results obtained by means of global gyrokinetic simulations with the particle-in-cell code ORB5 [4]. In recent simulations with ORB5, AMs have been shown to carry substantial heat and particle fluxes [5, 6]. Here, we extend that analysis by showing how the profile modification due to those fluxes can affect turbulence.

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# Transport barrier using a vorticity source in 5D gyrokinetic simulations

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The present work addresses the necessary preparatory step in view of exploring impurity transport across transport barriers which characterize improved confinement regimes. Two ways of producing a strong shear of the $\mathbf{E}\times\mathbf{B}$ poloidal flow have been investigated using GYSELA gyrokinetic simulations[1] in a flux-driven regime. The first one uses an external vorticity source[2] that polarizes locally the plasma, and the second one enforces a steep density profile. In both cases a transport barrier is created as a result of a reduced magnitude of turbulence. This reduction is strongly correlated with the shearing of turbulent structures[3] as attested by the reduction of the auto-correlation length of the potential fluctuations as well as a reduction of the large scale structures of the $k_\perp$ spectra. By discriminating neoclassical and turbulent contributions to the total heat flux through effective transport coefficients

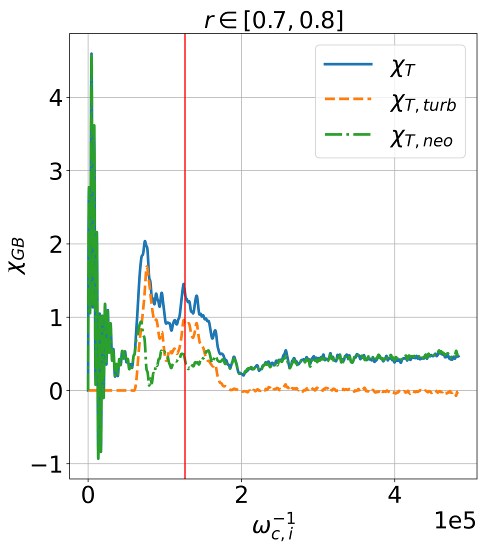


Figure 1: $\chi_T$ *(See Eq(1)) in* $\chi_{GB} = \rho^\star \rho_i c_{s,i}$ *units as a function of time near the vorticity source (*$r = 0.75$*). Red line is the activation time of the vorticity source.*

$$Q = Q^{turb} + Q^{neo} = -n\left(\chi_T^{turb} + \chi_T^{neo}\right)\nabla T \tag{1}$$

we can monitor the evolution of the $\chi_T$ radially averaged coefficients. The reduction in heat diffusivity near the source (See Fig.1) caused a core temperature increase. The turbulence intensity appears to be reduced not only in the vicinity of the vorticity source, but also in the core region. A detailed analysis of the physical mechanisms at work will be presented.

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# An active learning pipeline for surrogate models of gyrokinetic turbulence.

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One of the bottlenecks in integrated models of tokamak plasmas is the plasma turbulence module. Even quasilinear gyrokinetic reduced order models such as QualiKiz [1] still result in long runtimes that are undesirable for many applications. In previous work, QLKNN [2], a simple feed-forward neural network (NN) surrogate model of Qualikiz, has been shown to provide a speedup of up to a factor of 10,000 in the turbulence module of some integrated models. However, the Qualikiz runs needed to simulate extensive databases used to train the NN involved a considerable computational burden. Moreover, specific regions of the input parameter space turned out to be invalid for numerical or physical reasons. Lastly, only a minority of points in the input parameter space resulted in unstable turbulent modes. Similar brute-force approaches are not feasible for more computationally-intensive models, for which a more optimised methodology would be required. Overall, it is hypothesized that the amount of training points needed to obtain a performant surrogate can be reduced by orders of magnitude. The proposed solution is to train a surrogate using Active Learning (AL, e.g, [4]), a method that allows to sample the input space of Qualikiz only at the points that will most likely result in an improvement of the surrogate model by reducing its output uncertainty or a related metric. We start from a subsample of the existing jetexp-15D database [3] consisting of only a few thousands data points ($\ll 1\%$). These are used to pre-train a NN to predict the Qualikiz fluxes, as well as two NNs tasked with identifying regions in the parameter space that are invalid or that do not result in turbulent fluxes (preliminary work indicates that a 80% accuracy is achievable for the two latter NNs). The three networks are uncertainty-aware, which enables AL, and they are retrained after each time a sampling of the input space is performed. With this technique, we expect the size of the original dataset to be significantly reduced while retaining the performance of the original QLKNN surrogate. This method may be used to scale up the number of dimensions required to obtain an improved surrogate compared to the state of the art, and it may be applied to other, potentially more computationally expensive gyrokinetics simulations where a vast simulated database is unavailable.

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# Growth of electron hole in 1D Vlasov plasma and 4D gyro and bounce averaged kinetic Vlasov simulation

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Electron holes (EH) are frequently observed in collisionless electrostatic and magnetized plasmas. Once formed, such structures can grow by extracting free energy and by momentum exchange, or velocity scattering by other species. In the first part, the growth/stability of electron hole in the subcritical [1] and supercritical regimes, are investigated using a 1D Vlasov-Poisson simulation. At cold ion temperature the stability of electron holes are accompanied by an ion compression that yields phase velocity of electron holes above $C_s$ (ion acoustic velocity) and accelerates them, forcing a jump over a forbidden velocity gap, and settle on the high velocity tail of the electron distribution. This acceleration is observed both in subcritical and supercritical regime of plasma instability. Therefore inside the supercritical regime, two stages of evolution of electron-hole's growth are observed (Fig. 1). In the first stage EH accelerates to higher velocity, and in the second stage EH starts to grow in amplitude due to the presence of sufficient free energy.

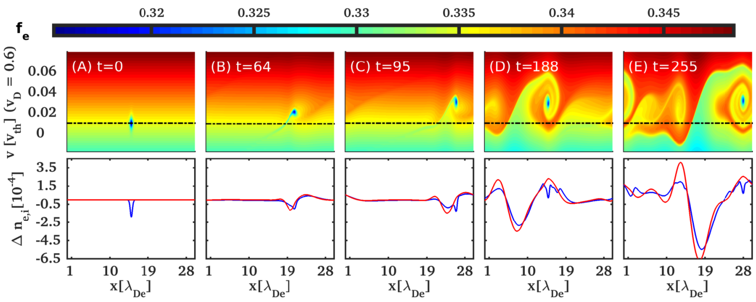


Figure 1: *Evolution of distribution $f_e$, $n_e$ (blue) and $n_i$ (red).*

In the second part a brief study on electron and ion-hole like coherent structures formation in a 4D $(\alpha, \psi, \kappa, E)$ gyrophase and bounce-motion averaged kinetic model [2] of trapped electron and ion modes (TEM and TIM) simulations of magnetically confined tokamak plasmas using TERESA code is presented. From a very small amplitude initial density perturbation, unstable TEM and TIM are excited due to resonance with the electron and ion precessional frequency of the banana-centric motion in presence of temperature inhomogeneity. Initially these modes grow and finally saturate due to energy cascading through turbulent mode-mode interactions and particle trapping in the potential profile of TEM/TIM. These trapped particle coherent-structures accelerate along the energy $E$ direction.

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# Resonance broadening in quasilinear theory: towards Kubo >1

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Charged particle velocity-space diffusion is investigated in a one-dimensional Gaussian turbulent electric field. Measurement from numerical trajectories are compared with quasi-linear theory including resonance broadening [1] [2]. Ion acoustic and Langmuir dispersion relations are investigated.

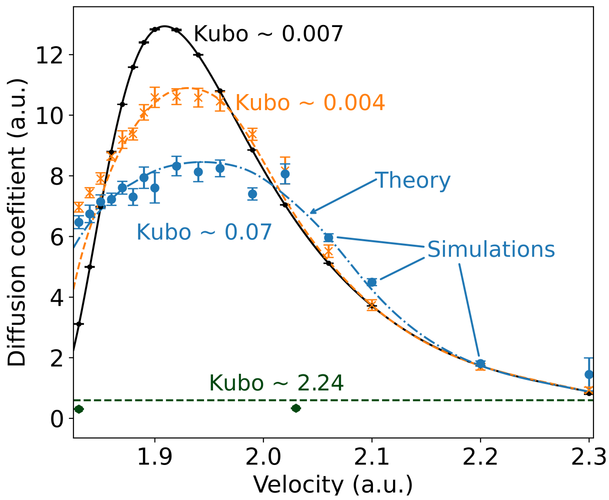


Figure 1: *Quasi-linear diffusion coefficient and numerical diffusion in the small Kubo number regime for a random electric field of Gaussian amplitude with Langmuir dispersion.*

First we initialize $N$ test particles in a turbulent electric field. We then calculate the mean square velocity of these test particles as a function of time in order to determine the numerical diffusion coefficient. We observe quantitative and qualitative agreements between theory and numerical results, as shown in Fig. (1) for the Langmuir case, in the regime of Kubo number $K \ll 1$. The impact of resonance broadening becomes significant for Kubo of the order of a few percent.

In addition, we study the diffusion of particles outside quasi-linear theory regime $K \geq 1$, for a larger range of particle velocities. We find qualitative agreement with theory around the resonance velocity ($v < 4v_T$). For fast particles ($v > 4v_T$), we measure a non-zero diffusion from numerical simulations, while negligible diffusion is predicted by quasi-linear theory and resonance broadening.

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# Stochastic simulations of the L-H transition in fusion plasmas

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The Low-to-High confinement (L-H) transition is an extremely important phenomenon in magnetic confinement fusion (MCF) research. It involves a sudden improvement in the confinement conditions of a fusion device when an input power threshold is reached. The work here presents a stochastic prey-predator model of the L-H transition, and builds on the work carried out in [1]. The model involves the interplay of turbulence, zonal flow shear, mean flow shear and the (ion) pressure gradient. The (transformed) turbulence and zonal flow shear are treated as stochastic variables and a corresponding Fokker-Planck equation for the time-dependent probability density function (PDF) is solved numerically. As well as studying the time evolution of the PDF, information length and entropy diagnostics are employed to study the changes to the system and the environment. Hysteresis associated with the L-H transition and its backward, H-L transition is studied by using three input power functions, which are symmetric around a time $t_*$. The results highlight the importance of non-Gaussian PDFs and time-varying fluctuations in the transitions.

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# Causality analysis of turbulent structures in the stellarator TJ-K.

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Convergent cross mapping [1] (CCM) as a causality inference technique is used to unveil causal coupling between variables measured in the same dynamical system. CCM measures how well the mapping – from a small region within a multidimensional phase space reconstruction of one variable (obtained from time-delay embedding) – compares to the actual representation of the second variable in its reconstructed phase space. Thus, CCM allows for the identification of causal links and direction of influence between variables. In this work, turbulent plasma fluctuations across different scales and positions are analyzed for magnetically confined plasmas of the stellarator TJ-K. To this end, conditional averaging and bandwidth filtering is used to isolate spatial and temporal scales in relation to turbulent phenomena such as blobs and zonal flows.

Langmuir-probe measurements of plasma potential and density fluctuations across TJ-K's whole poloidal cross-section are used as input for the CCM. This way, a two-dimensional mapping of the causal link existing between the fluctuations can be reconstructed. Recent studies revealed a distinct spatial region in which density perturbations appear to cause zonal potential structures. This is consistent with the localized tilt of vortices in the drift-wave – zonal-flow system previously observed as poloidally local Reynolds-stress maximum in this region [2].

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# Confinement of fast ions and FLR effects in presence of magnetic islands

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Fast ions are very important in many aspects of toroidal devices for plasma confinement. They appear mainly in relation to plasma heating from auxiliary sources such as NBI and ICRH where the injected energy is concentrated in a small population of energetic particles which have to transfer their energy to thermal particles by collisions. Fast ions have to be well confined before thermalizing in order to optimize heating. However, the presence of magnetic perturbations such as magnetic islands may increase the transport and reduce the confinement time which would reduce heating efficiency and produce energy waste. On the other hand, for moving perturbations, such as rotating magnetic islands, the associated poloidal flow may reduce the transport. For that reason it is of great interest to study the effect of magnetic islands on the transport of fast ions crossing the island region under different circumstances. Islands can be formed spontaneously by neoclassical tearing modes (NTM) or created from the outside by resonant magnetic perturbations.

We have initiated a study of transport of fast ions across the magnetic island region using both guiding center (GC) and full orbit (FO) computations. The goal is to determine how important the finite Larmor radius (FLR) effects are on the radial transport and figure out if resonant effects are relevant when this radius is of the order of the island width. The codes are validated by computing the transport coefficients and comparing with neoclassical computations. The simulations presented here consider a population of fast ions inside the radius of the rational surface that contains the island chain and measure the flux of crossing particles as they thermalize when collisions with a Maxwellian plasma background are included consisting of electrons and a single species of ions, which are described by Lorentz scattering.The equations of motion for each case (GC and FO) of a charged particle in a strong magnetic field are solved using an analytical model for the tokamak magnetic field and the magnetic island typical of a medium size tokamak. The initial particle distribution is monoenergetic and has a given pitch angle dispersion. The results of the GC and FO codes are compared in order to identify the differences ascribed to FLR. The presence of an electric field associated with the island itself resulting from the NTM is included, which leads to an increase in the particle flux beyond the one without the E-field, which indicates a predominance of the poloidal components of these fields. Island rotation is taken as a free parameter and we found a resonant-like effect where the flux is maximum when the rotation frequency is of the order of a characteristic particle frequency.

# Recent enhancements of ICRF modelling code PION

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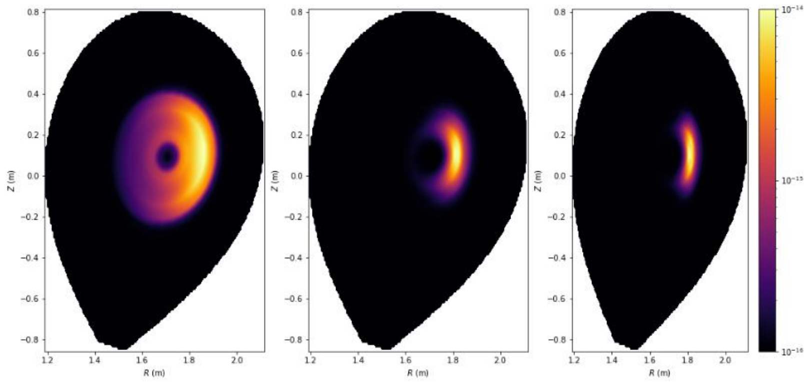
Ion Cyclotron Resonance Frequency (ICRF) heating is one of the auxiliary heating methods used in present day fusion devices. An ICRF heating system is also being prepared for ITER. ICRF physics involves a complex coupled system of time-evolving resonant ion distributions and electromagnetic wave fields with non-linear dependencies. Moreover, there are often various ICRF heating schemes to consider, optimize and choose from for a given target plasma and an ICRF system. Numerical modelling has proven to be a useful approach to increase understanding of ICRF heating in present fusion devices and it is also used to make predictions for new experiments in present and future devices. While numerous numerical tools for simulating ICRF heating exist, in this work we focus on ICRF modelling code PION [1]. Prior to this work, PION has been extensively compared against experimental data for a large variety of minority ion, majority ion and three-ion heating schemes on JET, AUG, DIII-D and Tore Supra. In this work, we will review recent enhancements in the evaluation of the resonant ion distribution functions using PION to improve its capabilities. They include a simple model to account for its pitch-angle dependence and an improved ICRF diffusion operator. They have enabled the calculation of the spatial 2D resonant ion density (c.f. Fig) and improved agreement with fast ion measurements.




Resonant ion density (a.u.) in the poloidal plane of a tokamak at energies of 100 keV (left), 350 keV (middle) and 600 keV (right) as given by PION for a synthetic case following recent code enhancements.

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# Particle Transport Barriers Dependence on the Magnetic Configuration

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For some discharge configurations in tokamaks, transport barriers reduce particle transport, improving plasma confinement. In this context, a model has been applied to describe the turbulent transport by drift waves, attributing this transport to $\mathbf{E} \times \mathbf{B}$ chaotic drift orbits [1]. In the present work we use this model to investigate the influence of magnetic safety factor on creation, maintaining and destruction of particle transport barriers. The model results in a set of differential equations that describe the motion of a test particle on the plasma, that we integrate numerically and analyze the behavior of trajectories using Poincaré sections [2]. Introducing a nonmonotonic safety factor profile, the phase space structure is deeply modified and a shearless invariant curve appears. Such curves are robust under electrostatic fluctuations, so they act like Shearless Transport Barriers (STB) [3].

We obtained a bifurcation diagram of the rotation number [2] of the STB as a function of the safety factor at plasma edge, $q_a$ . In this bifurcation diagram, we identify intervals of the parameter with or without STB. In some intervals of $q_a$, more than one STB are present in phase space. The results obtained show that nonmonotonic safety factor profiles creates STB and its variation results in an intermittent sequence of STB breakup and resurgence.

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# Onset of shearless transport barriers in a magnetically confined plasma

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An $\mathbf{E} \times \mathbf{B}$ drift waves transport model was implemented to investigate the onset and break-up of shearless transport barriers (STBs) when considering a non-monotonic electric field radial profile for a magnetically confined plasma. These barriers were found by using the rotation number profile, since they are located in the profile's equal-zero derivative position. So, considering as a control parameters the amplitude of the electrostatic potential perturbation non-resonant mode and the radial position of the electric field extreme value, we found intervals of the parameters for which the barrier exists, breaks-up or even bifurcates into one or two secondary shearless curves. Also, we found effective transport barriers related with stickiness regions which appear both after the STB breaks up or before the STB arises. In general, we discovered that the STB can emerge recurrently even if we are increasing the perturbation or displacing the electric field profile.

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# Spatially resolved x-ray spectroscopy of high energy density plasmas at the European XFEL

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In high energy density physics experiments, dense plasmas with large, one-dimensional gradients in temperature, density and ionization state can be created by the intense laser irradiation. Measurements of these plasma parameters are essential to investigate equation of state (EOS) and transport properties in astrophysically relevant matter. Spatially resolved x-ray spectroscopy is a powerful technique for diagnosing the internal conditions of inhomogeneous high energy density plasmas. A multipurpose imaging x-ray crystal spectrometer is developed at the HED instrument of European XFEL, providing high-resolution, space-resolved spectral measurements for x-rays in the energy range of 5 – 10 keV. The preliminary results are present from a isochorically heated Cu experiment using the XFEL beam, demonstrating the high spatial and spectral resolution properties of the spectrometer. Other potential applications, such as x-ray Thomson scattering (XRTS) measurements for radiative shocks in dense plasmas [1], x-ray emission spectroscopy for the isochoric heating of wire targets with the RELAX laser [2], are discussed as well.

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# Basic Commissioning of the Laser-Plasma Ion accelerator at the ELIMAIA user beamline

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We report on the basic commissioning experiment of the ELIMAIA beamline laser-plasma accelerator [D. Margarone et al., Quantum Beam Sci. 2018, 2, 8], using the high-repetition-rate, high peak-power L3-HAPLS laser system at the ELI Beamlines user facility in the Czech Republic. The laser beam (10 J, 30 fs) was tightly focused (~2 μm, FWHM) to reach ultrahigh intensity on target (~$10^{21}$ W/cm$^2$). Thin targets (10-20 μm) of different composition (e.g. Mylar, Al, Au, and Ni) were investigated to optimize the Ion Accelerator performances.

The proton beam characteristics were monitored using a complete set of ion diagnostics (Thomson Parabola spectrometer, Time-Of-Flight detectors, nuclear track detectors, and radiochromic films). Additionally, the laser-target interaction and plasma features were characterized through various optical and X/γ-ray diagnostics.

The laser, plasma, and ion performances were monitored at full power and on a shot-to-shot basis. The capability and reliability of the ELIMAIA Ion Accelerator was demonstrated at a repetition rate approaching 1 Hz for several hundred consecutive laser shots, along with automatic target positioning systems and online data analysis.

# Simulation of X-ray sources driven by the picosecond PETAL laser pulse interacting with a solid target

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Understanding X-ray sources driven by ultra-intense lasers is important for the development of shot-pulse backlighters suitable for radiography of rapidly evolving dense objects. For instance, the X-ray flashes generated by the Petawatt picosecond PETAL laser installed at the LMJ facility make it possible to image the dense plasmas created by the high-energy nanosecond LMJ laser pulses. We will present a simulation effort to model such X-ray sources from relativistic laser-plasma interactions under PETAL irradiation conditions. Three different codes are used successively. (i) The hydrodynamic TROLL code [1] simulates the effect of the laser prepulse on the backlighter solid-density target and notably the resulting pre-plasma formation. (ii) The particle-in-cell (PIC) CALDER code [2] describes the generation of fast electrons from the interaction of the main laser pulse with the expanded target. (iii) Finally, the Monte Carlo GEANT4 code computes the Bremsstrahlung and $K_\alpha$ photon emission produced by the fast electrons through the dense part of the target. This simulation chain enables us to understand the sensitivity of the X-ray source properties to the laser parameters (e.g. energy or pulse duration) as well as to the shape and composition of the backlighter target.

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# EMP measurements from MF to UHF at VEGA

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We present and compare experimental studies of electromagnetic pulses (EMP) produced at the high-power 30 fs lasers VEGA-2 with 200 TW and VEGA-3 with 1 PW. The seed space charge fields are triggered by the interaction of the laser pulses focused to relativistic intensities onto solid density and gas targets, at intensities ranging from several $10^{19}$ W/cm$^2$ to several $10^{20}$ W/cm$^2$. The detection of EMP is achieved by passive calibrated B-field and E-field antennas with large bandwidth from 9 kHz to 400 MHz and 300 MHz to 8 GHz respectively.

Outstanding features are the excited cavity modes, clearly detected by the compact antenna system, that can be tailored by modification of the experimental geometry. The detected magnetic fields inside the interaction chamber show amplitudes ranging from tens to hundreds of µm, which is up to ten times stronger than earth's magnetic field. Electric fields in the vicinity of the interaction chamber show amplitudes of hundreds of V/m, which is of the order of fields encountered in cm distance to GSM mobile phones. In the experimental hall, amplitudes hint at a dipole-like radiation field that bears the order of one ten-thousandth of the laser pulse energy.

Building upon the study, we present prospects for a target geometry mitigating EMP and perspectives to make use of systematic quantitative evaluation of EMP.

# The first results from the x-ray emission measurements at Draco PW laser facility

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Laser-produced plasmas are widely studied complex systems. In order to get better understanding of their inner processes, advanced diagnostics methods have to be used to get a valuable insight – for example, x-ray emission spectroscopy has the capability to unfold atomic processes and plasma conditions and reveal information about the hot electron population.

Recently, two x-ray crystal spectrometers were installed in the Ion Acceleration Lab at Draco PW laser facility, which allows to acquire characteristic emission spectra including Ti K-$\alpha$ and He-$\alpha$ lines from Ti targets. While quartz spectrometer offers wide spectral range and excellent spectral resolution of $\sim$ 0.3 eV, Ge spectrometer focuses on Ti K-$\alpha$ emission lines and provides 1D spatial imaging with resolution below 10 μm.

Here, we present the first results from the x-ray spectroscopic measurements from proton acceleration targets at the DRACO PW laser facility uncovering the plasma conditions and electron dynamics for various target and laser configurations including inclusion artificial prepulse or the use of reduced mass targets.

## Results on the commissioning of the 1 PW experimental area at ELI-NP

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Last year at the ELI-NP (Extreme Light Infrastructure - Nuclear Physics) research facility, the commissioning of the 1 PW experimental area has been successfully performed with a TNSA experiment on proton acceleration. A 23 fs laser beam was focused to a peak intensity of the order of $I_0 \sim 10^{21}$ Wcm$^{-2}$ in a spot size of ~3.5 µm FWHM via an F/3.7 parabolic mirror. The beam's pointing was stable at ±2 µm during a full day's run. We have run the experiment in a configuration without and with a plasma mirror. We assessed the systems' performance through a wide parametric scan of different target materials and thicknesses ranging from hundreds of nm to micrometers. Multiple laser and plasma diagnostics were deployed to characterize the laser beam and the by-products of the interaction on a shot-to-shot base. We diagnosed the ion beam spectrum using standard plasma diagnostics, for instance: Thomson parabola, stacks of Radiochromic films, CR39 and activation methods. We also characterized the laser properties such as: near-field and far-field profiles, laser spectrum and pulse duration at full energy in the interaction chamber and the laser temporal contrast via optical plasma probing and third order auto-correlator diagnosis. We evaluated the reflected and back-scattered laser light from target. We obtained proton and carbon energies greater than 40 MeV and 15 MeV/n respectively. We are performing hydrodynamic and PIC simulations to evaluate the effects of the laser temporal contrast on the ion acceleration. A short overview of the next steps and upcoming commissioning experiments will be also presented.

# Electromagnetic emissions at LMJ-PETAL facility: understanding, mitigation and measurement.

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The LMJ-PETAL is a large-scale facility that combines high energy nanosecond laser beams (300 kJ/3 ns in 2022) and high-power picosecond beam (400 J/0.6 ps in 2021). A combination of these beams is able to generate MV/m electromagnetic pulses (EMP) in GHz domain in the interaction chamber that may produce equipment failures, diagnostic damages, and spurious signals in detectors. The main mechanism of EMP generation is due to the return current through the target holder, induced by electron ejection from the laser-irradiated target [1]. However, other processes may also strongly contribute to the electromagnetic emissions [2].

The upgrade of PETAL up to energy of 1 kJ cannot be achieved without an efficient EMP mitigation strategy. By performing in-situ measurements on smaller-scale laser facilities and multiphysics, multiscale large scale numerical simulations, we further improved the understanding EMP generation processes and developed an efficient mitigation device [3]. We present in this paper a new resistive and magnetic target holder designed to reduce the current discharge. It is tested and validated in experiments showing the robustness and efficiency of this device at kJ energies.

Moreover, we present two recent advances in the understanding of EMP generation and detection: First, a THz emission makes a significant contribution to the signal when the main EMP source is efficiently mitigated. Second, the discharge current a few cm from the target can be measured with a good precision 4 m away from the target in the experiment chamber. This observation, validated by PIC simulations and near field measurements, may lead to a new efficient hot electron diagnostic.

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# Update on development of Laser based hard X-ray sources at ELI Beamlines

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We report the laser-plasma accelerator-based X-ray sources development at ELI beamlines. One of the main objectives of ELI Beamlines, is to provide beams of ultrashort particle and hard X-ray sources to the users from various fields of research [1,2]. Two hard X-ray betatron sources with high photon flux [3,4] based on laser plasma acceleration (LPA) are being commissioning. First source is Gammatron beamline [5] located in Experimental Hall E2. It provides X-ray pulses of energies from 1-100 keV in betatron and up to a MeV in Compton scheme. A novel X-ray optics has been designed as a focusing optics of these hard X-ray source for the user application [6]. The second hard X-ray source based on LPA, is being developed in the ELI plasma physics platform (P3) [7,8] that will serve as an active diagnostics HED and Laboratory astrophysics [9, 10], multi-beam experiments [11], and fundamental research. This source is now being commissioning, we will present the first experimental results.

Besides, we have proposed a novel scheme for enhancing the X-ray flux based on betatron oscillations enhanced from nonlinear resonances due to interaction with two-color laser field [12]. In addition, we will also introduce a novel optical probing technique with high sensitivity for characterization of low-density gas target for laser plasma accelerator. It has been achieved employing multiple passes of the probe beam through the object and relay-imaging of the object between the individual passes [13]. We will summaries these new results as well.

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# Effect of surface porosity on plasma assisted catalysis for ammonia synthesis

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The fundamental understanding of plasma-catalytic interaction and reaction mechanism is important in optimizing the catalyst design and increasing the efficiency of plasma-enhanced catalytic process for ammonia ($NH_3$) synthesis. In this work, we have reported the effect of surface porosity of catalytic support on plasma- assisted ammonia synthesis from nitrogen and hydrogen. The experiments were performed using a coaxial dielectric barrier discharge (DBD) plasma reactor with variable applied voltage at room temperature and near atmospheric pressure (550 torr) where porous silica (SiO2) and smooth soda lime glass beads of equal diameter are used for comparison. $N_2$ conversion, ammonia synthesis and energy yield were traced at varying voltage and were found to be higher in the case of silica which suggest that porous materials are better as compared to smooth surfaces for plasma-enhanced ammonia synthesis. The discharge characteristic shows that the effect of different catalytic support on the physical properties of the discharge was almost negligible. High resolution optical emission spectra (OES) were used to explore the evolution of reactive gas phase species ($N_2^+$, N, $H_\alpha$, $H_\beta$, $N_2$) in presence of both materials. The relative concentration of these gas phase species was higher in the case of glass regardless of applied voltage which suggests that gas phase reactions were dominant for smooth surfaces. However, higher conversion of ammonia with porous material signifies that chemistry of the catalyst surface is dominant over the gas phase reactions and physical effects of the catalysts in the plasma-catalytic synthesis of ammonia. A zero-dimensional (0D) kinetic model [1,2] has been performed to understand the underlying mechanism of porosity effect on plasma assisted ammonia synthesis.

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# Gliding arc discharge for $CO_2$ conversion: An experimental study of different discharge configurations

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This experimental study examines the usage of low current ($10^2$ mA) gliding arc discharges (GAD) for $CO_2$ dissociation, at atmospheric pressure. Several types of discharges are tested and compared. These include the traditional diverging electrode setup, and modifications of that concept which employ the use of a constant external magnetic field to stabilize [1] or accelerate the arc.

The discharge device consists of two diverging electrodes, placed between quartz glass plates. The $CO_2$ gas is introduced from a nozzle, located at the closest distance between the electrodes. The quartz glasses channel the gas flow, so that most of the inlet gas passes through the arc. In the magnetically stabilized configuration, the magnetic field pushes the arc in a direction opposite to the gas flow and the arc is stabilized at a certain location along the electrodes and remains at a fixed length.

The two main quantities of interest are the percent of converted $CO_2$ gas, and the energy efficiency of the conversion process. The main input parameters are the gas flow rate and the discharge current.

The results presented in this work show how the values of the conversion and efficiency depend on the inlet flow rate and the input power. Generally, the conversion decreases with the flow rate and increases with power. The decrease in the conversion with the increase in the gas flow is more pronounced in the magnetically stabilized setup, when compared to the traditional gliding types. The efficiency increases with the flow rate, for all types of discharges. The measured values for the conversion and efficiency strongly depend on the profile of the flow, which influences the arc behaviour – its length (voltage drop), attachment, etc. The magnetically stabilized configuration is generally more stable and efficient, but has poor performance at high flow rates. The non-stabilized configurations show good conversion for a larger range of inlet flow rates, but are generally more unstable and less efficient.

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# Measurements and determination of breakdown voltage in DC discharges at low pressure

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Breakdown measurements in non-equilibrium discharges in gases and vapours provide insight into elementary processes (ionization, secondary electron emission, surface interactions) that participate in discharges, which can be crucial in the development and optimization of new and existing applications of non-equilibrium discharges. In our experiment, the breakdown voltage is determined by igniting discharge in a low-current regime and extrapolating the Volt-Ampere characteristic to zero-current [1,2]. While the advantage of this technique is in the elimination of overvoltage in the pre-breakdown, it can have limitations under certain conditions due to oscillations of voltage and current in the Townsend regime of discharge.

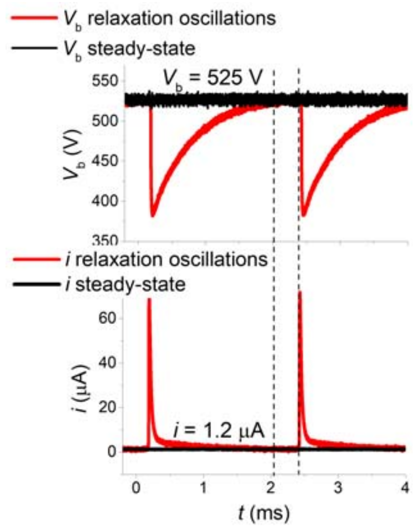


Figure 1. Estimation of breakdown voltage from relaxation oscillations in water vapour.

Here we present a method of estimation of breakdown voltage from relaxation oscillations in the Townsend regime of discharge [1]. The main feature of such oscillations is that the current briefly passes through the high-current mode and then relaxes to the Townsend low-current mode. The breakdown voltage can be estimated from the part of the period corresponding to the lowest current values (fig.1). The reproducibility and reliability of results were tested in conditions in which it was possible to obtain a breakdown, both in steady-state mode and in oscillations for similar discharge parameters, by varying the elements of the electrical circuit. Results were also verified by time-resolved ICCD imaging of the discharge emission. The presented technique enables breakdown measurements in a considerably wider range of gas pressures and electrode gaps.

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# Higher Order Solutions for Dust Ion Acoustic Solitons in Complex Plasmas with Relativistic Ions and Cairn's Distributed Electrons

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For this supercritical composition of complex plasma, relativistic ions and Cairn's distributed electrons are introduced to investigate dust ion-acoustic (DIA) solitons by reductive perturbation approach. For this investigation, higher order non-linearity (upto cubic) for the plasma is incorporated to derive Modified Korteweg-de Vries (mKdV) equation and expressions for amplitude and width of solitary waves are obtained and examined under different plasma parameter regimes. The non-thermal parameter ($\beta$) and the number of dust charge contained in a dust particle ($Z_d$) reflexes a new light in the formation of compressive and rarefactive relativistic DIA mKdV solitons. For some values of the electron to ion temperature ratio ($\Omega$) only compressive mKdV soltons exists and rarefactive solitons exists for another mode but for the same set of values of the other plasma parameters. Also, for some set of parametric values of the plasma, the nature of solitons becomes compressive, rarefactive and rarefactive to compressive for three different modes which is a salient feature of this investigation. Application of this plasma model to astrophysical and space plasma are also briefly discussed.

Keywords: Relativistic mKdV solitons, Cairn's distributed electrons, Complex plasma.

# A Two-photon Absorption Laser Induced Fluorescence diagnostic for atomic H in a helicon plasma device

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The Resonant Antenna Ion Device (RAID) [1] is a linear basic plasma experiment at the Swiss Plasma Center. Among its research goals are the study of helicon plasmas as a source of negative ions for Neutral Beam Heating for fusion devices, the investigation of neutral dynamics which may limit the plasma density in high-power helicon discharges, as well as the study of plasma detachment, a regime of operation in tokamak divertors characterized by low heat and particle flux to the walls. Owing to the possibility of steady-state operation and ease of access for diagnostics, RAID is particularly well suited to perform detailed measurements in plasmas similar to those in the divertor and scrape-off layer of tokamaks.

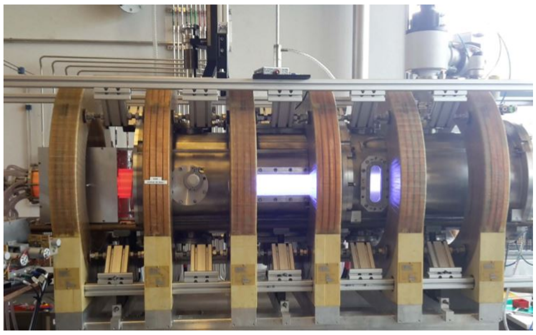

Figure 1: *An argon plasma generated in RAID*

The design of a Two-photon Absorption Laser Induced Fluorescence (TALIF) diagnostic is presented along with first measurements performed in $H_2$ plasmas. The TALIF diagnostic uses a picosecond pulsed laser to excite ground state atomic H. The excited states decay by emitting fluorescence at the $H_\alpha$ wavelength which is detected by an Intensified Charge Coupled Device (ICCD camera), thus allowing spatially resolved measurements of the density and temperature of atomic H [2, 3]. The width of the fluorescence emission line, mainly determined by Doppler broadening, is related to the neutral temperature. The intensity of the fluorescence line can be related, through calibration with Kr gas [4], to the density of atomic H. The density measurements must be corrected for collisional quenching, which includes all other decay mechanisms of the pumped state apart from fluorescence emission. The quenching rate can be experimentally determined from the fluorescence decay time, requiring time-resolved measurements.

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# Positron acceleration in a plasma channel with multi-Petawatt-class lasers

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The electron-positron colliders of the future will measure tens of kilometres and cost billions of euros. The alternative offered by plasma accelerators is promising since they can sustain accelerating fields which are orders of magnitudes higher than these conventional radio-frequency accelerators, providing relativistic beams in shorter distances and for reduced costs. Experiments have already shown that positron wakefield acceleration is possible when the wake structure is driven by a single and long positron beam [1], and numerical investigations indicate that positron wakefield acceleration is possible either using a Laguerre-Gaussian laser pulse driver [2] or a hollow plasma channel [3]. It is worth noting that all the mentioned numerical studies assume an idealised positron beam injection. Multi-Petawatt lasers are now expected to be able to both, create and accelerate positrons [4]. This is predicted for a 90 degree collision between a multi-PW laser and a GeV-class electron beam, where positrons are created via the multi-photon Breit-Wheeler process and are then accelerated on a short distance by the laser in vacuum.

In this work, we suggest a new scheme based on the propagation of a multi PW pulse in a preformed plasma channel. It stands out from previous attempts since it addresses the three key steps of creation, injection and acceleration of the positrons within a single 3D self-consistent numerical framework. In this setup, positrons generation takes place at the focus of a multi-PW laser and is stimulated by a perpendicularly propagating electron beam via the inverse Compton and Breit-Wheeler processes. Although positrons are created in the same direction as the incident electrons, a fraction of them is deflected by the laser pulse toward its propagation axis and injected in the plasma channel. The positron acceleration takes place in the plasma channel over a distance of  400 μm. The fields focusing positrons on the channel axis are mediated by a dense central electron beam, formed self-consistently along the pulse propagation. Although unexpected at lower laser power, such focusing and accelerating fields for positive charges have already been observed in numerical simulations but where never exploited for positron acceleration [5, 6]

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# Preliminary space and time resolved characterization of X-ray emission from an ECR magneto-plasma in the PANDORA project frame

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Theoretical predictions suggest that the behavior of β decays can dramatically change in relation to the ionization state of in-plasma isotopes [1]. The PANDORA project [2] aims at measuring nuclear β-decays in stellar-like conditions in high-temperature plasmas confined in B-minimum magnetic traps, which require a continuous monitoring of plasma parameters. X-ray space-resolved emission characterization can provide relevant features of the magneto-plasma [3] in terms of distribution of its density and temperature. We arranged a full-field X-ray pin-hole setup consisting in a 400μm hole in a lead disk embedded inside a multi disk collimation system coupled with a 4MP X-ray (2 – 20 keV) CCD camera. For the first time the system was coupled to a Pt-Ir shutter to suppress the readout noise, thus permitting sPhC (single photon counting) acquisitions at low exposure times, $t_e \sim$ ms. During the experiment $t_e$ was varied in a range 30ms-60s. In addition, the shutter enables time-resolved acquisitions during plasma discharge or plasma turbulence. An X-Ray measurement line on the so called Flexible Plasma Trap (used as test bench for the PANDORA project) was arranged. A set of measurements has been performed at different plasma conditions (pumping frequency, RF power, magnetic field profile, gas pressure and composition). First collected images will be processed by an original algorithm [4] to perform space-resolved spectroscopy and spectrally resolved imaging.

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# Evolution of plasma conditions within capillary discharges, with application to plasma accelerators

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The ability to characterize and manipulate the plasma conditions within capillary discharge devices, such as plasma accelerator modules, laser waveguides (LWs), and active plasma lenses (APLs), is paramount to the development and optimization of next generation compact particle accelerator technology.

The FLASHForward [1] experiment at DESY aspires to use beam-driven plasma wakes to accelerate GeV electron beams of sufficient quality to generate free-electron laser gain. Experimental parameters, such as the discharge current pulse shape, alter the plasma properties, and the relaxation time of these properties places a limit on the repetition rate [2]. In LWs, the radially non-uniform current heating from the discharge forms a plasma channel that can be used for guiding ultrashort, high-intensity lasers [3]. In APLs, the current is utilized to provide strong axi-symmetric focusing of charged-particle beams [4]. Unlike LWs, the formation of radially non-uniform plasma conditions is detrimental to APL quality. In both cases, the evolution of the radially-varying plasma properties is critically important.

In this study, we simulate the evolution of the electron temperature and density in plasma capillaries after the initiation of a current discharge, to comment on the operation of high-repetition-rate plasma-wakefield accelerators, development of LWs, and operation of aberration-free APLs.

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