# European Physical Society Plasma Physics Conference 2026


# Report of Contributions

Contribution ID: **27** Type: **Oral Presentation**

# High-intensity laser-driven surface plasmon for coherent synchrotron radiation and TV/m-level plasma wakefield acceleration

Recent research into the high-intensity laser-driven surface plasmon excitation has revealed the significant potential of generating extremely strong (~TV/m) fields for particle acceleration and radiation production. This new approach has emerged by overcoming several challenges in laser-solid interactions. It therefore holds great promise for reshaping the research direction of large-scale facilities that pursue the energy frontier and micro-scale facilities that require great flexibility. At the same time, this research can provide new insights into the extremely complex nonlinear dynamics of surface plasmons (SPs) in strong fields and a new, unexplored regime of plasma-based particle acceleration.

In this study, we theoretically and numerically investigate the high-intensity laser-driven excitation of relativistic surface plasmons on the micro-scaled surfaces of structured nanomaterials, such as vertically aligned carbon nanotube (VACNT) forests. This enables the TV/m-level plasma wakefield generation for both negatively and positively charged particle acceleration [1-3]. By investigating SP mode selection on cylindrical surfaces, we have proposed a new principle for coherent radiation generation that differs fundamentally from traditional superradiance [4]. Our research offers a new approach to the development of ultrahigh-gradient and ultra-compact particle accelerators.

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[1] Bifeng Lei et al. 2025 Plasma Phys. Control. Fusion 67 065036
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**Track Classification:** Beam Plasmas and Inertial Fusion (BPIF): Laser-plasma Acceleration of Particles and Plasma-based Radiation Sources (BPIF)

Contribution ID: **39** Type: **Oral Presentation**

# The Role of High-Power X-ray Pulses in Pursuing Inertial Fusion Energy

The pursuit of controlled energy gain by nuclear fusion took a huge leap forwards with the 2022 demonstration of multi-megajoule energy gain from deuterium-tritium implosions at the National Ignition Facility. Attention has now turned to applying these breakthroughs to realize commercially-viable energy production, in particular through the IFE-STAR and FIRE programs from the US Department of Energy.

As part of this decadal effort, the High Energy Density Science (HEDS) division at SLAC is applying its expertise in using pulses from X-ray Free Electron Lasers to study extreme states of matter. These deliver femtosecond pulses with tunable wavelength, which we have used to probe bulk properties of matter and in order to observe phase transitions, ultrafast dynamics and temperature evolution with greater fidelity than can be delivered by any other approach.

A leading design for delivering fusion targets at Hz-level repetition rates uses polymer foam capsules wetted with liquid nuclear fuels. A new program at SLAC will study these targets in high precision experiments with powerful X-ray sources to provide the required equation of state (EoS) data for validation of hydrodynamic simulations.

This talk will cover some of the ways that our existing experiments have begun answering questions about fusions targets and drivers, and what new diagnostics and analysis techniques will still need to be developed. Our recent studies have developed sub-micron resolution X-ray imaging techniques and measured shock propagation, instability growth, and heating of foam targets. Inelastic X-ray scattering with spectral resolution of $\Delta E/E$ = 10-6 can resolve the ion feature and plasmons and measure the physical properties of fusion plasmas. I will show examples that use self-seeded X-rays, stochastic correlation of SASE spikes, and Quantum-entangled X-ray photons to accomplish these goals. These results motivate upgrades to the optical drives lasers at MEC at LCLS, and the proposed IFE end station at European XFEL. These future experimental capabilities will couple XFELs to higher-energy and -power lasers than ever before, accessing the pressure conditions found in fusion capsule implosions.

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**Track Classification:** Beam Plasmas and Inertial Fusion (BPIF): Inertial Confinement Fusion (BPIF)

Contribution ID: **65** Type: **Oral Presentation**

# Experimental characterisation of suppressed thermal conduction in weakly collisional, magnetised plasma

Classical transport theory predicts that, in a magnetised, collisional plasma, the heat flux parallel to magnetic field lines is given by Spitzer's theory of heat conduction for unmagnetised plasmas. Numerous recent theoretical and computational studies have called this prediction into question for weakly collisional magnetised plasmas in which thermal pressure dominates magnetic pressure (so-called high-$\beta$ plasmas). Such plasmas, notable examples of which include the intra-cluster medium of galaxy clusters and inertial-confinement-fusion deuterium-tritium hotspots, are thought to be susceptible to a host of anisotropy-driven microinstabilities that can suppress parallel heat conduction. Various attempts have been made to construct revised theories of heat conduction in such plasmas, relying on kinetic simulations, but there is a lack of experimental data to benchmark them. In this talk, we report a new experiment at the Orion Laser Facility in which the temporal evolution of the temperature in a high-$\beta$, weakly collisional plasma is primarily dependent on the magnitude of the thermal conductivity along its laminar magnetic field. This temperature evolution, along with the plasma's density and magnetic field, is characterised with a suite of plasma diagnostics: x-ray spectroscopy and imaging, and proton radiography. Our data indicate significant suppression of thermal conduction compared to predictions from Spitzer once stochastic magnetic fluctuations develop. These results have important implications for transport modelling in both astrophysical and laser plasma physics.

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**Track Classification:** Basic, Space and Astrophysical Plasmas (BSAP): Laboratory Astrophysics (BSAP)

Contribution ID: **90** Type: **Oral Presentation**

# Buffering and Burn Through of Transients in the MAST-U Super-X Divertor

The MAST Upgrade super-X divertor [1,2] creates ideal conditions for detachment with a long connection length and high neutral pressure in the divertor region. While results have shown the super-X strongly mitigates heat flux during steady state plasma conditions, the survivability of the divertor during transient events is a key requirement for future plasma devices[3]. Although large transients such as ELMs are not expected to be tolerable in future devices, certain types of transients, such as H-L back transition, are unavoidable and the ability to tolerate slightly larger transients may open up useful operational regimes.

The impact of transients in the Super-X configuration has been investigated on MAST-U using advanced diagnostics, focused experiments and improved modelling. An Ultra Fast Divertor Spectroscopy providing fast Fulcher measurements of the detachment front position has offered new insight into what is occurring during transients. This has been combined with fast Infra-Red camera data, divertor Thomson scattering at the target and camera imaging. Dedicated experiments have been performed on both ELMs and Sawteeth transients, scanning neutral deuterium gas pressure, performing nitrogen seeding in the Super-X chamber and using X-point Target Configuration to mitigate the heat flux, as well as dedicated comparisons with conventional divertor configurations.

The experimental results have quantified the dependence of the buffering on transient energy and neutral deuterium gas pressure. An approximately linear increase in peak power flux is observed with transient energy, or reducing neutral gas pressure, up to a certain point where it enters a second regime with larger increase in target heat flux. It may be that the second regime is where the neutral inventory has been depleted and after which point additional energy causes proportionately greater increase in heat flux. Comparing Super-X with the conventional divertor has shown reduced heat flux in line with the improved geometry of the Super-X divertor. Very strong mitigation of transients with Nitrogen gas have also been demonstrated albeit with some impact on core performance, offering a promising path forward using impurities to mitigate transients. The heat flux from transients greatly increase Te and ne in the divertor. These increases have been captured in Thomson scattering data and are compared with modelling in the ReMKiT1D framework[4]. This modelling has shown that recycling plays a key role in understanding the transient heat flux.

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). It has also been supported by the EPSRC Energy Programme (grant number EP/W006839/1).

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**Track Classification:** Magnetic Confinement Fusion (MCF): SOL, Divertor and PWI (MCF)

Contribution ID: **94** Type: **Oral Presentation**

# Zonal Flows driven by Toroidicity-induced Alfven Eigenmodes, mitigating core turbulence in DIII-D*

The interaction of fast-ion-driven Alfven Eigenmodes with axisymmetric Zonal shear flows in toroidal plasmas has recently received significant attention due to the potential stabilization of microturbulence and reduction of radial transport [1,2,3]. Here, we present clear experimental evidence that multiple simultaneous Toroidicity-induced Alfven Eigenmodes [4] drive mesoscale ($\rho_i$ < $1/k_r$ <$L_n, L_T$), radially localized Zonal shear flows and suppress ITG turbulence in DIII-D. An upper single null diverted target plasma ($B_t = 1.25T, I_p \approx 0.61MA, q_{95} \approx 5.4$) is heated via neutral beam injection ($P_{NBI} \approx 4MW$), intermittently destabilizing TAE modes. Multi-channel Doppler Backscattering (DBS [5]) probes the local ExB flow, flow shear, and turbulence (density fluctuation) levels at normalized radii $0.2\ \rho\ 0.8$. Using two multi-channel DBS systems located 180° apart toroidally, the axisymmetric nature of the measured Zonal shear flows has been confirmed. Near mid-radius, the local ExB shearing rate increases by roughly an order of magnitude (from $\omega_{ExB} \approx 2 - 3$x$10^4 rad/s -$2x$10^5 rad/s$) and exceeds the plasma frame turbulence decorrelation rate intermittently when multiple TAE modes are present. Simultaneously, density fluctuation levels ($k_\theta \rho_s \approx 0.4 - 0.8$) are reduced by 35-50%, with almost perfect anti-correlation between fluctuation level and local shearing rate. The observed shear flows are not localized to low order rational surfaces. DBS measurements confirm causality (the TAE amplitude leads the maximum ZF shearing rate); in turn the local ExB shearing rate leads ITG fluctuation suppression (by ~70$\mu s$) near mid-radius ($\rho \approx 0.55$). In contrast, the shearing rate lags fluctuation suppression in the inner core ($\rho \approx 0.35$), potentially indicating shear flow drive from the turbulence spectrum at this radius. Further work will be presented to elucidate the coupling and energy exchange between TAE modes, Zonal Flows and drift wave turbulence via bispectral/transfer entropy analysis.

*This work supported by US DoE under DE-FC02-04ER54698, DE-SC0020287, DE-SC0020337, DE-SC0019352 and DE-FG02-08ER54999.

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**Track Classification:** Magnetic Confinement Fusion (MCF): Energetic Particles and MHD (MCF)

Contribution ID: **98** Type: **Oral Presentation**

# Plasma shape effects on L-H power threshold and H-mode in JET-ILW

Early studies in JET-C already indicated that the power threshold for the L-H transition (PLH) depends on plasma magnetic configuration [1]: PLH is lower in plasmas with strike points on horizontal targets (HT) when compared with vertical target (VT) plasmas. Initial studies in the JET-ILW have shown that even small changes in outer strike location can affect both PLH, and the density at which PLH is minimum (ne,min) [2,3].
Further detailed studies have confirmed these trends, expanding the shapes being studied and pointing out differences in transition dynamics [4]. Configurations with both inner and outer strikes on Vertical tiles (VT, vertical target) and with strikes on the corners of the divertor (CC, corner-corner) both have higher PLH and lower ne,min than those with the outer strike on the tilted central divertor tile (HT, horizontal target). The perpendicular rotation of the turbulence before the L-H transition differs significantly amongst configurations [5]. For any configuration, lower plasma current reduces ne,min, which in general is related to fGW,min= ne,min/nGW [6]. Additionally, it has been shown that for given configuration fGW,min depends on plasma content, being lowest for Tritium, followed by Deuterium, D+T, Hydrogen [6,7].
The configuration effect on PLH and ne,min introduces factor of 2 uncertainties on the prediction of PLH in future devices [7]. No explanation is available yet.
Interestingly, once in the ELMy H-mode regime, the configurations with higher PLH exhibit considerably better confinement and lower type I ELM frequency, the latter being affected even by small strike sweeps. Therefore, the ratio of input power over PLH is not a good indicator of the power required to obtain good H-mode confinement, indicating that the mechanisms responsible for triggering the formation of an edge transport barrier don't determine its evolution in a well-established H-mode.
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**Track Classification:** Magnetic Confinement Fusion (MCF): Edge and Pedestal Physics (MCF)

Contribution ID: **106** Type: **Oral Presentation**

# Physics basis of a Volumetric Neutron Source (VNS) for component testing and qualification

A study is being carried out within EUROfusion to address the feasibility of a Volumetric Neutron Source (VNS). VNS is a medium-size tokamak (R = 2.67 m, B0 = 5.6 T, A = 4.25, Ip = 2.54 MA) operating D-T plasmas, able to achieve a significant neutron wall load (approximately 0.5 MW/m2) on long pulses, to be built and operated in parallel to ITER. Purpose is to test and qualify in-vessel components, in particular the breeding blanket and the divertor, under large neutron irradiation, fluence and heat flux in a reactor-relevant environment. VNS is based on beam-target fusion reactions, which enable a significant fusion power despite the reduced device size. Neutral Beams are employed both to generate the beam-target reactions (as in JET D-T fusion energy record [Maslov, NF 2023, PPCF2026 submitted]), and to drive the plasma current to sustain the requested long pulses. Additional EC power is installed to keep the electron temperature high (a fundamental aspect in beam-target driven devices), and for control reasons. This work illustrates the design-driving criteria according to which the current VNS design point has been identified. A series of scans performed with the plasma simulator METIS [Artaud, NF 2018] coupled with the code MADE [Giannini, FED 2023] for preliminary magnets sizing is also presented. The results highlight the impact of relevant machine parameters on the VNS performance.

In addition, this work reviews the VNS plasma scenario, with focus on its critical features. This is currently being investigated with codes of different level of fidelity, both looking at some particular aspect in isolation, but also with integrated modelling –e.g. for tungsten accumulation. Further analyses deal with MHD stability (with particular attention on the interplay with energetic particles), power exhaust, fast particles confinement (both beams and alpha's) and beam deposition, as well as magnetic equilibrium and control. In the near future, a study of the dynamic phases and of the machine controllability in a broad sense via Pulse Design tools (e.g. Fenix [David, OPS 2025]) is planned, following what has recently been carried out for EU-DEMO [Di Grazia, FED 2025].

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**Track Classification:** Magnetic Confinement Fusion (MCF): Power Plant Design (MCF)

Contribution ID: **138** Type: **Oral Presentation**

# Overview of High beta experiments on JET in preparation of JT60SA

High beta discharges with normalized Larmor radius (ρ*), and normalized beta (βN) relatively close to JT-60SA scenarios hybrid and advanced were realized in a new series of experiments on JET-ILW[1]. The strategy of these experiments was to explore high normalized beta (βN) values, MHD effects at different BT ( Toroidal Magnetic field on axis) and find discharges with mild MHD. JET/JT-60SA 'similarity experiments'can be done with plasma parameters on JT-60SA, at BT/Ip=1.45T/1.4MA and heating power less than 10MW. Deuterium plasmas were realized in hybrid scenario at BT = 1.7, 2, 2.4 T, Ip = 1.4 MA, elongation k = 1.7, triangularity $\delta \approx 0.4$, q95=4-6, and central safety factor q0>1 at NBI ( Neutral Beam Injection) start, with NBI power PNBI = 16-25 MW. The preliminary results of the JET high beta experiments were presented in [1]. Here an overview is presented on the following topics : i) confinement properties of high beta discharges versus input power and scaling of confinement improvement with beta; ii) dynamics of formation of the Internal Transport Barriers(ITB) while approaching high beta; iii) pedestal structure and its evolution at high beta ; iv) current profile evolution. It is found that the maximum normalized beta ( βN) obtainable, increases with input power and depends ( decreases with ) on the magnetic field . These effects are compatible with a small dependence of the confinement time on the input power. Looking into the electron kinetic spatial profiles , the progress toward the high beta is characterized by the formation of an ITB. The confinement dynamics can be related to the critical gradient scale length of the ITG turbulence, which is depending on the ratio Ti/Te and magnetic shear. The confinement properties of these discharges indicate that the H98Y ( the improvement confinement factor with respect to the ITER confinement scaling ) has a linear dependence on the βN, changing with the magnetic field. TRANSP analysis done for the pulse 103116 (B=2.4T) shows that the spatial profile of the diamagnetic current increases from negative values toward zero while βN increases toward the maximum.

1. F P Orsitto et al , High beta experiments on JET in preparation of JT-60SA , Proc. 50th EPS Conf on Plasma Physics , 8-12 july 2024, Salamanca , Spain , paper P1-151

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**Track Classification:** Magnetic Confinement Fusion (MCF): Scenario Development, Heating and Current Drive (MCF)

Contribution ID: **145** Type: **Oral Presentation**

# Extreme Astrophysics with Laboratory electron-positron jets

Relativistic electron–positron (pair) plasmas play a central role in extreme astrophysical environments, including gamma-ray bursts and pulsar winds, yet their microphysics remains poorly constrained by observations. The Fireball programme generates dense, relativistic electron–positron beams in the laboratory, enabling controlled studies of pair-plasma instabilities and particle acceleration under astrophysically relevant conditions.

Fireball is hosted at CERN's High Radiation Materials facility (HiRadMat) and is currently the only scheme capable of producing relativistic pair plasmas terrestrially. In this talk, we present results from the two most recent experimental campaigns, Fireball II and Fireball III. Fireball II delivered the first experimental measurements of the magnetic-field amplification associated with beam plasma instabilities involving a relativistic pair jet. Fireball III revealed significant modifications to the longitudinal beam profile and energy spectrum, consistent with electron acceleration and positron deceleration during the beam–plasma interaction.

These results provide new experimental constraints on kinetic processes thought to operate in extreme astrophysical sources and demonstrate the potential of laboratory pair plasmas as a platform for testing relativistic plasma theory.

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**Track Classification:** Basic, Space and Astrophysical Plasmas (BSAP): Laboratory Astrophysics (BSAP)

Contribution ID: **158** Type: **Oral Presentation**

# Understanding the impact of the divertor configuration on the L-H transition in the ASDEX Upgrade tokamak

Future tokamak devices, will operate in high-confinement mode (H-mode) in order to achieve the plasma confinement required for sustained net energy production. A key parameter describing H-mode is the power threshold for the L-H transition ($P_{LH}$), which has been shown to depend on various parameters, such as the plasma density, main isotope and plasma shaping. Experiments on different tokamaks, including JET [E. Delabie, 2014], DIII-D [P. Gohil, 2011] and MAST [H. Meyer, 2011] showed that $P_{LH}$ can vary by up to a factor of two depending on the divertor configuration, indicating the importance of the edge and divertor conditions in the L–H transition. Despite this sensitivity, the widely used $P_{LH}$ scaling law [Y.R. Martin, 2008] does not include the divertor configuration as a parameter, which leads to a significant uncertainty in the predictions. In the ASDEX Upgrade tokamak, during the 2024 campaign, dedicated upper single null (USN) discharges with different divertor configurations were performed at low and high densities. Together with a set of lower single null (LSN) plasmas from a previous campaign, these discharges provide a dataset with similar operational parameters (plasma current, magnetic field and heating scheme) to study the divertor configuration dependence of $P_{LH}$ in ASDEX Upgrade. Significant variations in $P_{LH}$ were observed between the different divertor configurations in both the LSN and USN discharges and in both density branches. The analysis focuses on the divertor conditions and the evolution of the midplane kinetic profiles prior to the L–H transition. This study can help us to understand the underlying physics of the L-H transition, to clarify the role of the divertor configuration on the $P_{LH}$ and to improve our ability to optimize H-mode access in future fusion reactors.

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**Track Classification:** Magnetic Confinement Fusion (MCF): Edge and Pedestal Physics (MCF)

Contribution ID: **159** Type: **Oral Presentation**

# Stimulated scattering of a spectrally broadened laser beam in inhomogeneous plasma

Spectral smoothing of laser pulses is considered a promising approach for controlling parametric instabilities and improving laser plasma coupling in inertial fusion research. A limited number of experiments with broadband lasers and contradicting theoretical results motivate a more general assessment of the pump bandwidth on the excitation of parametric instabilities in a spatially inhomogeneous plasma. Here, we report on the studies of the forward and backward scattering in inhomogeneous plasma by comparing a monochromatic pump, a phase-modulated pump, and a pump with random phase modulations. In the time domain, phase-modulated and random pumps produce a qualitatively similar effect, reducing the temporal growth rate approximately inversely proportional to the bandwidth, in agreement with theoretical predictions following from the random phase approximation. Significant differences are observed, however, in the case of convective amplification in a spatially limited pump and in an inhomogeneous plasma. The level of saturation of the scattered light is enhanced and is associated with large temporal and statistical fluctuations if the pump correlation time is larger or comparable to the instability growth time. These fluctuations are associated with high-intensity spikes or groups of spikes in the pump field. The one-dimensional analysis of parametric instabilities is extended to speckled laser beams, assuming that each speckle generates scattered light independently. The laser bandwidth can suppress scattering from low-intensity speckles, but the high-intensity speckles may still dominate the response. A criterion for the bandwidth suppression of stimulated scattering in a speckled beam is proposed.

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**Track Classification:** Beam Plasmas and Inertial Fusion (BPIF): Laser and Particle Beam Interaction with Plasmas, Hydrodynamics and Instabilities (BPIF)

Contribution ID: **171** Type: **Oral Presentation**

# Gyrokinetic electrostatic ITG-TEM simulation of H-mode plasmas in COMPASS-like geometry

Considerable progress has been made in modelling edge turbulence and the L-H transition using fluid and kinetic approaches. However, the gyrokinetic simulation of a complete transition from steady-state
L-mode turbulence to a quasi-stationary H-mode remains a challenge. To simulate the transport properties of the H-mode pedestal, an alternative approach, avoiding the L-H transition is to start the simulation with profiles (density, temperature, current density) approximating the expected H-mode profiles. This approach has, for example, been successfully applied in [1] using the GRILLIX drift-fluid code. In this paper, we apply the gyro-kinetic model from the JOREK code (named JOREK-GK) to obtain quasi steady-state H-mode solutions.
The JOREK-GK code builds on the C1 finite element discretisation and the discrete particle module to implement the well-established electro-static gyrokinetic model including ions and electrons. The conservative collision model from [2] is included, together with a small-angle scattering model for the e-i collisions. In this paper, only ion-ion and small angle electron-ion collisions are retained. A simple model for the divertor sheath is also used. This implementation allows global, full-f, gradient driven, electrostatic simulations in x-point geometry.
Simulations are initialised with H-mode density and pressure profiles in COMPASS-like geometry, as in [3], followed by an axisymmetric phase with collisions, i.e. without turbulence, to establish the neoclassical flows. Adding the toroidal harmonics allows to obtain a quasi-steady H-mode solution including ITG-TEM turbulence, and the stabilisation in the pedestal. The pedestal width is ~1.5cm, in reasonable agreement with experimental observations [3]. The resulting radial electric field is ~36 kV/m. The reduced turbulent transport inside the pedestal is associated with both a decrease in fluctuation amplitudes by a factor of 2–3 and a comparable modification of the cross-phase between pressure and electrostatic potential fluctuations, leading to a local reduction of turbulent transport by about an order of magnitude. In absence of MHD and kinetic ballooning (KBM) modes in the electrostatic model, the pedestal height grows well above the experimental value. A medium-n discrete mode, localised within the pedestal and initially at low amplitude, is found to grow and eventually trigger a rapid collapse of the pedestal radial electric field.

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**Track Classification:** Magnetic Confinement Fusion (MCF): Plasma Turbulence and Transport (MCF)

Contribution ID: **178** Type: **Oral Presentation**

# Link between edge radial electric field and confinement improvement in negative triangularity plasmas in TCV

Negative triangularity (NT) has emerged as a promising alternative to the conventional positive triangularity (PT) shape of tokamak plasmas. Owing to the suppression of large ELMs, combined with outstanding L-mode confinement, NT appears as a suitable candidate for core-edge integration [1,2]. While the fundamental reason for the NT L-mode performance improvement over PT remains unclear, experiments emphasize the role of the NT edge region [3,4]. This contribution investigates the edge radial electric field (Er) and its shear as possibly relevant distinguishing features between the NT and PT edge. The study is based on recent experiments on the TCV tokamak that, for the first time, compare the edge Er profile in matched NT/PT discharges [5]. Measurements using a Doppler backscattering diagnostic [6] reveal an Er well that is deeper in NT than in PT, along with improved L-mode confinement. The stronger edge Er × B shear in NT is observed systematically under Ohmic, NBI, or ECRH heating. It coincides—at equal heating power—with higher edge density and temperature. Notably, a deeper Er well is still observed in NT, even when the auxiliary power in PT is adjusted to match the edge density and temperature profiles of NT. Implications of this decoupling of Er from kinetic profile differences are dicussed. Overall, the results are compatible with edge Er × B shear stabilization as a possible cause for the beneficial L-mode confinement properties of the NT edge. Turbulent transport modelling based on the presented data is underway to elucidate the origin of the differing Er behavior between NT and PT.

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**Track Classification:** Magnetic Confinement Fusion (MCF): Edge and Pedestal Physics (MCF)

Contribution ID: **180** Type: **Oral Presentation**

# On the conservation of orbital angular momentum in laser-plasma interactions

Orbital angular momentum (OAM) transfer in laser-plasma interactions is a fundamental process far less understood than energy or linear momentum transfer. However, it has important direct applications, such as the production of strong magnetic fields.

Previous studies of angular momentum transfer in laser–plasma interactions have investigated both dissipative processes, as well as single electron motion in laser fields carrying OAM.

In this work, we present a novel ray-based approach of laser OAM transfer to plasmas. In this framework, refraction in plasmas with azimuthal density gradients enables non-dissipative transfer of OAM between the laser and plasma. These gradients can be pre-existing in the plasma, or self-generated by a spatiotemporally shaped laser pulse. This process is analogous to the mechanism behind orbital AM transfer in spiral phase plates. Our model provides a simple unified interpretation of OAM transfer in many laser-plasma interactions and can be used to explain previous results.

Utilizing recent breakthroughs in spatio-temporal shaping of high power laser systems, we show that light springs - lasers carrying multiple OAM modes in multiple frequency bands, can indeed drive plasma waves with helical density gradients, and self couple into the plasma driving strong axial magnetic fields. Using SMILEI particle-in-cell simulations, we validate this model and show that light springs are efficient at transferring the AM to electrons, leading to the generation of strong longitudinal magnetic fields (a few 100s of Tesla) at moderate laser power (a few 100s of GW to a few TW).

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**Track Classification:** Beam Plasmas and Inertial Fusion (BPIF): Laser and Particle Beam Interaction with Plasmas, Hydrodynamics and Instabilities (BPIF)

Contribution ID: **189** Type: **Oral Presentation**

# Disruption mitigation in EAST with metal walls: a comparative study of shattered pellet injection and massive gas injection

The EAST superconducting tokamak, with Mo first walls and ITER-like W divertors, has developed and tested a Shattered Pellet Injection (SPI) system [1,2] and two Massive Gas Injection (MGI) systems [3] for disruption mitigation. Neon SPI experiments revealed key disruption dynamics including helical impurity transport and radiation evolution. Compared with MGI, SPI shows superior performance: a shorter TQ, longer CQ, stronger core radiation, and ~40% lower electron temperature with ~50% reduced divertor heat flux [4]. It also generates a more uniform poloidal radiation profile near the plasma core and avoids cold VDEs seen in MGI disruptions. Impurity injection, by either SPI or MGI, can trigger MHD mode switching from an inherent n=1/2 to a new n=1 with reversed rotation, attributed to impurity–plasma interactions [5]. SPI parameter scans showed smaller fragments ablate rapidly at the edge, while larger ones penetrate deeper and ablate slowly. Although ISPI generated more uniform TQ radiation, its poorer assimilation caused a longer pre-TQ phase and weaker halo current mitigation [6]. Finally, RE plateau formation was achieved with Ar-MGI, critically dependent on pre-disruption non-Maxwellian seed electrons and suppressed by MHD activity during TQ. These EAST results provide key data and insights for ITER disruption mitigation system design and operation.

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**Track Classification:** Magnetic Confinement Fusion (MCF): Disruptions and Runaway Electrons (MCF)

Contribution ID: **240** Type: **Oral Presentation**

# Particle transport modelling for D/T ratio control experiments in JET

This study presents particle transport modelling results for D/T ratio control experiments conducted during the JET DTE3 campaign [1]. Interpretative TRANSP and predictive JETTO simulations were performed to analyse the evolution of the D/T mixture [2] in these experiments [3]. Using simplified Bohm–gyroBohm-based transport models, the simulations successfully reproduced electron density, steady-state D/T ratio, and neutron rate evolution. However, during the transient phases the predicted D/T ratio responded to control requests faster than observed experimentally. Additional scenarios, including cases which could not be realised experimentally where gas injection and pellet sources were swapped, were also investigated, and the corresponding simulation results are discussed.
The findings in this study demonstrate that simple models and assumptions regarding D and T transport and sources can be successfully adopted to predictively model the behaviour of Real Time (RT) controllers for D/T ratio. Detailed modelling of the SOL and core across all channels is not required for such tasks. It has been demonstrated that a simplified approach can be effective, using (i) measured Te, Ti, (ii) not modelling the SOL physics, and (iii) adopting simplifying particle transport assumptions. This conclusion is crucial for developing numerical tools to test future controllers.
In general, the proposed approach for developing and testing real-time D/T controllers should be directly applicable to future conventional tokamaks, such as ITER, SPARC, and DEMO, where simplified assumptions about energy and particle transport are valid. For devices where the transport models require validation —such as STEP —applicability largely depends on the extent to which transport can be reasonably simplified. Regarding source terms, the proposed model appears broadly applicable. The simulations presented here indicate that particle sources from pellet injection and NBI can be reliably captured by the models employed in this work. However, for gas injection sources, the simplified treatment used in this study code may not be adequate for devices or scenarios characterized by significantly different SOL physics.
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**Track Classification:** Magnetic Confinement Fusion (MCF): Plasma Control (MCF)

Contribution ID: **250** Type: **Oral Presentation**

# Boronisation at AUG: Investigations in view of the ITER operation

With the recent ITER rebaseline decision introducing a full-tungsten first wall configuration, the efficacy of wall conditioning via boronisation has become a high priority issue in the ITER operational planning. ASDEX Upgrade (AUG), equipped with tungsten (W) plasma facing components and using deuterated diborane, has the unique capability to investigate the main issues arising for ITER: These include the influence of boronisation on plasma start up, homogeneity of the boron coating, lifetime of boronisation and tritium inventory in the boron hydride layers.
The ITER plasma start-up scenario was adapted to AUG, matching all relevant plasma parameters. First experiments without boronisation did not lead to stable plasma conditions. Applying even a partial boronisation by intentionally using only two of the installed four glow anodes immediately allowed reliable plasma start-ups and stable discharges.
Quartz microbalance sensors installed at seven different locations and a manipulator system to expose witness samples offer investigations of layers produced by the coating. The layer thickness at different locations varies only by a factor of three. Switching off one anode reduces the nearby deposition by only about 60 % as opposed to a factor ~100 reduction predicted by initial simulations carried out by ITER. The discrepancy is attributed to the sticking of borane radicals, which was measured to be ~30% while the simulations assumed 100% sticking. The in-situ measurements were complemented by 54 long term samples exposed during the entire campaign. For typical plasma edge temperatures at AUG, W is sputtered mainly by light residual impurity species. These are reduced by boronisation and by this also the W source. The deposited layers on the long-term samples were analysed by ion beam techniques to get information on the elementary composition. A typical D/B ratio of 0.3 is found. This yields a T inventory of less than 2 gr T per boronisation in ITER.

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**Track Classification:** Magnetic Confinement Fusion (MCF): SOL, Divertor and PWI (MCF)

Contribution ID: **266** Type: **Oral Presentation**

# Record H-mode pedestal pressure in high triangularity, high elongation discharges leveraging the new "Shape and Volume Rise"divertor on DIII-D

A new divertor geometry enabling high shaping on DIII-D has been leveraged to achieve the highest pressure pedestals observed to date on the device. Peeling-ballooning model calculations suggested increased plasma triangularity and volume would allow the pedestal stability boundary to develop a broad channel of operation at high density and pressure simultaneously, leading to a state of a low collisionality pedestal top at high density. This state is rarely achieved in present devices and represents a path for significant gains in future devices, highlighting it as a key challenge for core-edge integration physics.

ELMy H-mode, QH-mode, and RMP ELM suppressed regimes were developed to access high pedestal pressure through the Super H-mode channel, with each scenario exploration leading to novel pedestal physics insights. ELMy H-modes and co-Ip QH-modes resulted in the highest pedestal pressure and core performance observed to date in DIII-D, yielding Pped of 37-40kPa, roughly 2-4 times typical ELMy H-mode values, and Ptau/IaB of 11-14, about twice typical values.

Counter-Ip QH-mode discharges reached record QH densities of ~1.4x1020m-3. QH-mode persisted as the density was raised, shifting from the peeling to ballooning stability boundary. This phenomenon is likely due to significantly decoupling of low-n peeling and intermediate/high-n ballooning instabilities as a result of the strong shaping.

RMP experiments established full ELM suppression in the SVR configuration at moderate plasma current (1.2–1.6 MA) with odd-parity n=3 fields. These discharges sustained high performance (βN up to 2.8, H98 up to 2, and ⌧E up to 0.4 s) with total pedestal pressures up to 26 kPa and extended suppression windows (q95 ≈ 4.2–5.3). Optimization of dRsep and coil configuration enabled stationary ELM-free operation close to double-null shapes, highly relevant for future pilot plant designs.

The pedestal width in these experiments for all three regimes did not conform to the EPED1 width scaling typical of H-modes in DIII-D and other devices and instead were found to be consistent with n=60 ballooning mode critical gradient as a proxy for the KBM.

This work was supported in part by the US Department of Energy under DE-FC02-04ER54698, DE-SC0014264, DE-AC02-09CH11466, DE-AC05-00OR22725, DE-SC0019302, DE-AC52-07NA27344, DE-SC0022270, and DE-FG02-04ER54761.

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**Track Classification:** Magnetic Confinement Fusion (MCF): Edge and Pedestal Physics (MCF)

Contribution ID: **271** Type: **Oral Presentation**

# DIII-D–WEST Hybrid Scenario Similarity Experiments for Long-Pulse Operation

For the first time, identity and similarity experiments between DIII-D and WEST were performed in the ITER “hybrid-like” regime during dedicated campaigns on the two facilities in 2025. These experiments exploit the complementary capabilities of the two facilities and aim to illuminate the path toward combined high fusion performance with high-normalised pressure ⊠N (DIII-D) and long-pulse scenarios (WEST) in a tungsten environment.
The matched parameters include elongation, positive triangularity, ion ∇B drift direction toward X-point, safety factor profile, and core dimensionless physics quantities such as normalized pressure, ⊠⊠⊠normalized gyroradius, electron collisionality, and the ion to electron temperature ratio, Ti/Te. Core transport physics is explored across different aspect ratios (R/a) (3 at DIII-D and 5 on WEST). DIII-D accessed high-⊠ regimes (strong electromagnetic effects) under low injected torque (~0 ± 0.5 N·m) using high heating power, while scanning heating mix (ion vs electron), ⊠, Ti/Te, core radiation via controlled tungsten injection using the Laser Blow-Off system. WEST extended operation toward long duration pulses using its actively cooled tungsten divertor. Boron impurity injection was scanned on WEST to control edge conditions and core performance.
It is found that core confinement improves—manifested in higher electron temperature, total energy content, neutron rate, and ion temperature —under conditions of low separatrix density, consistent with previous observations. The ratio of the thermal energy confinement time (τE) to the volume-averaged electron–ion collisional heat exchange time (τe-i) emerges as a key parameter for enhancing ion heating and potentially facilitating H-mode access in electron-heated regimes. Conditions for both H-mode access and ion heating in electron-dominated regimes on WEST and DIII-D are compared (role of aspect ratio, ion heating versus electron heating). An outlook is also provided on extending the campaign by matching aspect ratio, increasing the ECRH power level, or replicating the dimensionless studies in negative-triangularity configurations with similar L-mode edges.
The first-of-a-kind coordinated DIII-D and WEST experiments provide a unique multi-machine dataset to validate predictive models and support extrapolation toward ITER and future fusion power plants, leveraging the complementary strengths of the two facilities.

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**Track Classification:** Magnetic Confinement Fusion (MCF): Scenario Development, Heating and Current Drive (MCF)

Contribution ID: **294** Type: **Oral Presentation**

# Energetic Particle Physics and Control in the TCV Tokamak: From Alfvén Eigenmodes to Ion Cyclotron Emission

Energetic particles (EPs) provide plasma heating and current drive in fusion devices, but their confinement can be strongly affected by Alfvén eigenmodes (AEs) and other instabilities, with implications for performance and plasma–wall interactions in ITER and DEMO. Recent experiments on the Tokamak à Configuration Variable (TCV) have advanced the physics basis for AE excitation and control in plasmas with supra-Alfvénic fast ions. Scenarios were established using both co- and counter-injected neutral beams, enabling controlled variation of fast-ion drive and systematic characterization of AE activity.

Dedicated control experiments demonstrate reproducible AE suppression using electron-cyclotron heating and current drive (ECRH/ECCD). The observations indicate that multiple mechanisms contribute, including (i) temperature and density profile modifications affecting damping and resonance conditions, (ii) magnetic-shear changes driven by localized ECCD, and (iii) direct fast-ion redistribution associated with AE dynamics and EC actuation. Comparative studies in positive and negative triangularity further show that fast-ion confinement is similar during MHD-quiescent phases, while AE activity during flat-top conditions differs between shapes, highlighting sensitivity of EP-driven stability to equilibrium and profile details.

Finally, first observations of ion cyclotron emission (ICE) on TCV open a new diagnostic window on EP dynamics, complementing established fast-ion measurements and enabling access to high-frequency signatures linked to EP populations and wave–particle coupling. The results are discussed in the context of recent findings on other tokamaks, emphasizing common trends and constraints for robust AE control and improved EP confinement in reactor-relevant regimes.

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**Track Classification:** Magnetic Confinement Fusion (MCF): Energetic Particles and MHD (MCF)

Contribution ID: **296** Type: **Oral Presentation**

# Turbulence simulations of the Quasi-Continuous Exhaust regime

The H-mode in tokamaks brings fusion performance within reach but faces two major challenges: damaging ELMs and excessive divertor heat loads. Recent results across tokamak experiments identified an ELM-free H-mode—the quasi-continuous exhaust (QCE) regime—combining high pedestal pressure, reactor-relevant separatrix density, and a broadened the scrape-off layer (SOL) heat width, making it promising for a fusion reactor [1]. A first-principles understanding of the turbulence dynamics in QCE plasmas has been elusive, given the complexities of nonlinear, separatrix-spanning electromagnetic modes and their interactions with large-amplitude, intermittent filaments in the SOL.

We address the challenge using two-fluid turbulence code GRILLIX [2,3]. We conduct global simulations of the QCE regime across the pedestal and SOL in realistic ASDEX Upgrade geometry. The results reveal a quasi-coherent mode (QCM) [4] spanning the separatrix and launching ballistic, filamentary blobs into the SOL, reproducing not only mean profiles but also fluctuation spectra and mode structure seen in experiments.
We identify QCM as a kinetic ballooning mode (KBM) with a long radial correlation length, which yields transport levels exceeding those of a KBM-unstable ELMy pedestal foot. The transport by QCM in the pedestal foot is regulated by two key ingredients: the self-consistent formation of a broad Er well, and the finite Larmor radius physics. The resistivity remains prominent near the X-point and triggers a secondary resistive X-point mode (RXM) [5]. The emergence of RXM strengthens interchange dynamics at the outermost extent of the QCM, thereby launching blobs into the SOL. The blob-dominated SOL temperature fall-off is then well decoupled from the pedestal-foot gradient set by the QCM. Together, these dynamics outline a pathway to self-sustained H-mode confinement with manageable heat exhaust.

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**Track Classification:** Magnetic Confinement Fusion (MCF): Edge and Pedestal Physics (MCF)

Contribution ID: **299** Type: **Oral Presentation**

# The Interplay Between the Bell and Firehose Instabilities

In astrophysical shocks, instabilities driven by the streaming of energetic particles into the upstream medium amplify magnetic fields and generate turbulence, enabling efficient cosmic-ray (CR) acceleration (Malkov et al., 2010). However, a complete and self-consistent picture of CR acceleration, spanning the initial generation of magnetic fields through their subsequent amplification and the resulting particle acceleration, remains incomplete. These magnetic fields are expected to arise from the interplay, competition, and nonlinear evolution of several instabilities, notably the Bell (Bell, 2004) and firehose instabilities. These interactions happen across a wide range of scales, making both analytical and numerical investigations challenging. Our work aims at providing a tentative picture of such interplay through a simplified analytical and numerical framework, offering insight into mechanisms responsible for large-scale magnetic-field amplification.

We present kinetic simulations performed with the SMILEI particle-in-cell (PIC) code (Derouillat et al., 2018) to study the nonlinear evolution of the Bell and firehose instabilities in counter-streaming monoenergetic proton beams, used here as a minimal model for cosmic-ray–driven turbulence. By varying the beam density ratio, we probe regimes where either the Bell or the firehose instability dominates.

Our results constitute, to our knowledge, the first observation in fully kinetic PIC simulations of nonlinear self-coupling of the dominant linear mode, leading to growth of large-scale magnetic fields at twice the linear growth rate, in agreement with earlier magnetohydrodynamic simulations (Bykov et al., 2013). We develop an analytical interpretation of this behavior based on the growth of density perturbations, which drive nonlinear electrostatic modes that subsequently feed back into electromagnetic modes. This mechanism provides a potential pathway for the generation of large-scale magnetic fluctuations required to approach Bohm diffusion regimes for CRs, and thus for efficient particle acceleration in astrophysical shocks.

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**Track Classification:** Basic, Space and Astrophysical Plasmas (BSAP): Astrophysical Plasmas (BSAP)

Contribution ID: **305** Type: **Oral Presentation**

# Integrated core-SOL simulations of H-mode access in ITER SRO scenarios

The start of research operation (SRO) in ITER will explore H-mode operation as well as commission control and protection systems including ELM mitigation systems [1]. For successful commissioning of the ELM mitigation systems, operation in stable ELMy H-mode is required. To inform the development of the plasma control system, fully integrated core, edge, scrape-off layer (SOL), divertor simulations are performed with the JINTRAC suite of codes analysing the access to ELMy H-mode across SRO scenarios. The scenarios studied are 5MA/2.65T and 7.5MA/2.65T deuterium plasma including the L-mode, L-H transition and H-mode ELMy phases. A range of densities are analysed, and deuterium gas puff is used to fuel the plasma to the specified Greenwald density fraction with the potential of adding pellets where gas fuelling is insufficient to provide the required density [2].
Simulations performed so far show that even for the lower current scenario of 5MA a 60% Greenwald density fraction plasma is marginal for pedestal development using 30MW EC assuming that the ITPA 2008 scaling law holds. Heating schemes available during SRO operation consists of 40MW of ECRH and 10 MW ICRH [1]. At the same current a high-density plasma of 80% Greenwald density fraction needs 40MW EC together with additional IC to access a good quality H-mode.

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**Track Classification:** Magnetic Confinement Fusion (MCF): Scenario Development, Heating and Current Drive (MCF)

Contribution ID: **319** Type: **Oral Presentation**

# Demonstration of shattered pellet injection schemes at ASDEX Upgrade for disruption mitigation in ITER

ITER will rely on shattered pellet injection (SPI) to mitigate the damaging consequences of plasma disruptions. Its disruption mitigation system (DMS) is designed to support various injection schemes and geometries to maximise material assimilation across the evolving plasma conditions during a disruption. The SPI system at ASDEX Upgrade has been adapted for the recent campaign to test a variety of injection schemes and to assess post thermal quench (TQ) injections which mimic the limited fragment plume-plasma intersection as expected for upper port injection in ITER. Experiments show that post-TQ injections suffer from weak fragment ablation due to the low plasma temperature, reducing densification and acceleration of the current quench (CQ) for minimising electromagnetic loads. In ohmic density limit disruptions, neon assimilation decreases by ~50% when fragments arrive 2 ms into the CQ compared with pre-TQ injection, leading to only partially mitigated CQs due to the comparatively low plasma resistivity.
Early deuterium injection aimed at avoiding the triggering of MHD activity and subsequent global reconnection event can dilute the plasma and reduce hot-tail runaway seeds. However, initial assimilation remains low (≈20%) and is further reduced by transport losses before TQ onset. Adding neon improves assimilation without shortening the pre-TQ phase to below the injection duration. Although smaller and faster fragments in general lead to a steeper density rise, their preferential edge deposition increases material losses by the time of the TQ. Intrinsic impurities, particularly tungsten in degraded H-mode plasmas, strongly influence mitigation performance. Longer pre-TQ phases and lower temperatures enhance fragment penetration and assimilation, and the presence of intrinsic impurities relaxes CQ mitigation requirements. Multiple Ne/D SPI has revealed that the assimilation deteriorates if the fragment plumes arrive more than 1 ms apart, which can be attributed to the already initiated plasma cooling. This imposes a strict requirement on the allowable fragment arrival jitter when material must be injected from several locations.
This contribution summarises results from recent ASDEX Upgrade SPI experiments and their implications for ITER's disruption mitigation strategy.

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**Track Classification:** Magnetic Confinement Fusion (MCF): Disruptions and Runaway Electrons (MCF)

Contribution ID: **328** Type: **Oral Presentation**

# Laser-produced tin plasmas for EUV lithography: Experiment and modeling

Extreme ultraviolet (EUV) lithography at 13.5 nm, driven by laser-produced tin (Sn) plasmas, has become the foundational technology in semiconductor manufacturing. A primary challenge is the control of plasma parameters: electron density, electron temperature, and ion charge state distribution, which define the spectral purity and conversion efficiency of the EUV source. Here, we present our experimental and modeling efforts on comprehensively characterizing laser-produced tin plasmas and the resulting EUV emission.

On the experimental side, we introduce ''SparkLight", a new platform for generating and characterizing laser-produced plasmas. Tin plasmas are generated by irradiating a continuously moving tin-coated wire with a 1064 nm Nd:YAG laser. The facility integrates three complementary diagnostics: EUV emission spectroscopy, laser interferometry, and coherent Thomson scattering.

We devote particular attention to Thomson scattering, which allows for space- and time-resolved characterization of laser-produced plasmas. To reject stray light and isolate Thomson signal from the plasma self-emission, we utilize a compact and cost-effective design based on a Wollaston prism, volume Bragg grating notch filters, and a single-grating spectrometer.

On the modeling side, we use the radiation hydrodynamics code FLASH to study how laser pulse shaping can be optimized to improve EUV source performance. We also develop the collisional Particle-in-Cell code PSC to simulate fast ion debris acceleration in current EUV sources and in future, shorter wavelength sources.

This work demonstrates an integrated and practical approach for experimental and modeling characterization of plasmas in EUV source development.

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**Track Classification:** Low Temperature and Dusty Plasmas (LTDP): Other - LTDP

Contribution ID: **335** Type: **Oral Presentation**

# 3D hot tail runaway electron generation modelling with JOREK: validation and predictions for ITER

Disruptions in ITER present the risk of generating large Runaway Electron (RE) beams that may cause untolerable damage when impacting plasma facing components. Assuming short Thermal Quenches (TQs) lasting around 1 ms, the hot tail mechanism, driven by the rapid temperature drop and the resulting non-Maxwellian electron population, may produce dangerous amounts of RE seeds [1]. This motivates modelling with 3D non linear MHD codes to accurately account for electron losses due to magnetic field stochasticity and other 3D aspects of the dynamics. The related physics is highly difficult to capture and remains virtually unexplored.

We leverage the JOREK 3D non-linear MHD code to post-process MHD simulations with test electrons. A dedicated computational framework has been developed to simulate a hot test electron population evolving in the pre-calculated MHD fields and undergoing collisions with the bulk electrons and ions. It has been verified in a reduced phase space against DREAM, and preliminary tested with 3D fields [2].

To approach experimental validation, the DIII-D discharge 178682, identified as producing a hot-tail RE seed [3], is modelled. A 3D MHD simulation including pellet injection is first performed, capturing phenomena typically observed during disruptions, such as stochasticity, double tearing modes, helical cooling, and ⊠⊠ × ⊠⊠ mixing. By using markers, and considering or neglecting the 3D components of the fields, the simulations demonstrate the critical role of stochastic losses in reducing the RE seed by orders of magnitude.

Finally, the new framework is employed to perform the first full-geometry estimates of mitigated ITER 15 MA H-mode scenarios, using MHD simulations presented in [4]. We observe that Shattered Pellet Injection (SPI) enables, for a degraded H-mode case, a safe disruption with a seed current below 10e−10 A. However, the baseline H-mode case produces a potentially dangerous seed. Unlike the DIII-D case, including the 3D effects increases the generated seed from 10 mA to 670 A. For the first time, these simulations reveal a generation boost caused by the formation of acceleration cells due to the (1,1) helical cooling, as well as the transport of hot electrons from the core into these regions which overcome stochastic losses.

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**Track Classification:** Magnetic Confinement Fusion (MCF): Disruptions and Runaway Electrons (MCF)

Contribution ID: **349** Type: **Oral Presentation**

# Measuring vacuum birefringence using the dark-field concept at the European XFEL

Quantum field theory predicts that the vacuum exhibits a nonlinear response to strong electromagnetic fields, giving rise to phenomena such as vacuum birefringence. Despite its fundamental significance, this effect has remained experimentally inaccessible and has yet to be observed in the laboratory. Detecting it would provide a distinct signature of the optical activity of the quantum vacuum and enable a precision test of nonlinear quantum electrodynamics in an unexplored regime.

A central difficulty in such experiments is isolating the weak signal from the photon background of the probe beam. In the strong-field region created by a tightly focused IR pump pulse, the X-ray probe acquires a tiny vacuum-induced polarization rotation and an angular deflection. Conventional approaches rely on ultra-high-contrast polarimetry to suppress the background and reveal the signal.

We introduce here the dark-field concept, a promising alternative that creates a controlled shadow in the probe's near field, enabling a clean angular separation between the vacuum-induced signal and the background. We report on the recent experimental campaign at the European XFEL's High Energy Density (HED) instrument, where this technique was implemented using the X-ray beam as the probe and the ReLaX IR laser as the pump. The dark-field configuration reduced the background by roughly 15 orders of magnitude. This design not only increases the sensitivity of the measurement, but also gives access to both the polarization-flipped and non-flipped components of the probe, enabling a direct determination of the fundamental QED parameters that can be confronted with theoretical predictions. We present an overview of the setup, the experimental results from the last campaing, the expected measurable signal for the upcoming campaign, and the current status of the advanced simulation framework that models both the vacuum birefringent signal and its background.

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**Track Classification:** Beam Plasmas and Inertial Fusion (BPIF): Ultra-high Intensity Laser-matter Interaction and High-field Physics (BPIF)

Contribution ID: **354** Type: **Oral Presentation**

# Proton acceleration efficiency via ultra-short PW-class lasers

Proton beams generated via Target Normal Sheath Acceleration1,2 (TNSA) using the VEGA PW-class laser at CLPU were studied by covering pulse durations from 30–500 fs at fixed laser energies, spanning intensities from 2 × 1018 to 2 × 1020 W/cm2. This provided a unique, consistent dataset from a single campaign. Results show cut-off proton energies distribution versus pulse duration exhibit a maximum that scales with laser energy, occurring at intensities within 1 × 1019 and 2 × 1019 W/cm2, thus revealing a saturation mechanism in proton acceleration which differ with several published scaling from picosecond-driven experiments. Data analysis, supported by theoretical models and simulations, indicates this behaviour is linked to VEGA high contrast driving ultra-short scale-length plasma expansion. Consequently, pulse duration strongly impacts efficiency, decreasing sharply for shorter pulses. Updated electrostatic model, Bayesian analysis rand numerical simulations reproduce the trend, yielding a new scaling law that identifies optimal pulse duration for given laser energies. These results3 enable improved optimization of proton beams from ultrashort femtosecond high-power lasers, with potential applications in compact ion and neutron sources, inertial confinement fusion, radioisotope production and medical physics.

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List item

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**Track Classification:** Beam Plasmas and Inertial Fusion (BPIF): Laser-plasma Acceleration of Particles and Plasma-based Radiation Sources (BPIF)

Contribution ID: **370** Type: **Oral Presentation**

# Tungsten dust ingress in WEST: an integrated modelling approach

Tokamak operation with tungsten walls, as foreseen in ITER and future fusion-based power plants, faces the potential strong impact of tunsgten dust ingress in the plasma. This was documented on the WEST tokamak [Bucalossi2024], equipped with an ITER-grade tungsten divertor, during a high fluence campaign in attached divertor condition: the erosion of tungsten monoblocks generated deposits that could detach and trigger plasma disruptions [Gaspar2024]. The operation in a radiative divertor regime mitigates the risk of building tungsten deposits [Gaspar2026], but a deterioration of plasma operation could be seen after cumulating the equivalent of a single ITER pulse (Q=10, 400s) in attached divertor condition. Being able to predict the impact of such dusts in present tokamaks is therefore instrumental, although the task is on many aspects extremely complex [Smirnov2020]. The modelling of tungsten dust penetration in WEST is performed with the DUSTTRACK code [Gervasini2027], investigating the tungsten deposition dependence on the dust size and speed. It shows that for similar range of size and speed, the dust is penetrating further inside in WEST compared to JET [Lazzaro2022], due to the lower plasma temperature. The impact on the plasma evolution is then modelled with the High Fidelity Pulse Simulator (HFPS) based on JINTRAC [Romanelli2024], with different levels of complexity, from a prediction of current diffusion only, up to a prediction of particle (D, N and W) and heat transport using TGLF [Staebler2021]. With current diffusion only, resistive MHD mode triggering on q=2/1 is found for a dust mass above 20µg, consistent with experimental observations [Maget2024]. With the more complete simulation scheme, we find that the localization of the tungsten source inside the plasma boundary plays an essential role in the observed plasma evolution. The validation of this workflow on WEST is a first step towards the evaluation of the maximum allowed dust size in larger tokamaks and the associated mitigation strategies.

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**Track Classification:** Magnetic Confinement Fusion (MCF): Other - MCF

Contribution ID: **372** Type: **Oral Presentation**

# First demonstration of X-mode reflectometry as a sensor for density and plasma position control on the WEST tokamak

This work presents the first use of real-time (RT) sensors provided by the eXtraordinary mode (X-mode) reflectometry for density and plasma position control. Density control using Ordinary (O-mode) reflectometry as a sensor was demonstrated in Asdex-Upgrade in 2010 \[1\], but requires an assumption on the density profile position. On the contrary, the X-mode reflectometry enables to detect the plasma edge radial position, which is used to start the density profile reconstruction and was planned on ITER \[2\].

A new acquisition system and a new algorithm dedicated to RT measurements were implemented on the WEST X-mode edge reflectometer. The world first electron density profiles were reconstructed in real-time during 2024, providing profiles every few ms \[3\].

Real-time density profiles can provide several sensors for plasma control. The first sensor is the local density at a fixed radial position. The second sensor is the edge plasma position deduced from the major radius of a fixed density. Thirdly, the plasma position knowledge allows to compute the density at given distance to the plasma edge, roughly the density at a fixed flux surface.

The first control experiments using X-mode reflectometry sensors have been performed on WEST in 2025. Density control is usually achieved using the interferometry line integrated density (every ms), the actuator is the gas injection. First, we replaced the line integrated sensor with the density at a fixed radial position, to perform control of the local edge density. Secondly, we replaced the density sensor by the density at a given relative position, allowing to control the local edge density during a plasma radial translation. These two control experiments were successful, without any specific issue. Lastly, we replaced the magnetic sensor used to control the plasma position by the radial position obtained from RT reflectometry. The actuators are the PF coils. The first experiments showed radial position oscillations due to a latency of about 30 ⊠⊠ on the measurements, specific to reflectometry plasma position control. We improved all the RT data processing to shorten this latency to a few milliseconds, and the new plasma position control experiments were performed successfully without any radial oscillations.

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**Track Classification:** Magnetic Confinement Fusion (MCF): Plasma Control (MCF)

Contribution ID: **381** Type: **Oral Presentation**

# Characterizing the dynamics of dust clouds in dusty plasmas under weightlessness

The dynamical properties of extended clouds of dust particles in a dusty plasma under the microgravity conditions of parabolic flights is studied. Here, micrometer-sized dust particles are immersed into a gaseous plasma of a capacitively coupled radio-frequency discharge. There the particles become confined in a large extended, nearly force-free dust cloud. The particles are illuminated by lasers and the scattered light is recorded by (high-speed) video cameras. For the dynamical analysis, features of the dust cloud are derived either directly from the image data or from physical data extracted from the dust cloud. From a comparison of different features the cloud dynamics (dust-density waves, void formation, structure formation) is characterized.

Financial support from the German Aerospace Center DLR (Contract No. 50WM2161) is gratefully acknowledged.

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**Track Classification:** Low Temperature and Dusty Plasmas (LTDP): Dusty and Strongly Coupled Plasmas (LTDP)

Contribution ID: **388** Type: **Oral Presentation**

# Ultra-intense neutron source production using laser-driven photonuclear reactions on the LMJ-PETAL facility.

This work tackles the production and experimental characterization of a broad-range ultra-intense neutron source on the LMJ-PETAL facility. Using the PETAL laser (700 J, 500 fs) as a driver of laser-plasma accelerated electron beams, bremsstrahlung gamma-rays were radiated by the relativistic electrons in a $5\ \mathrm{cm}$-thick lead (Pb) converter in a pitcher-catcher configuration. The high-energy photons were then able to induce the emission of photoneutrons through $(\gamma, xn)$ photonuclear reactions with Pb. The primary electrons were accelerated in the self-modulated laser-wakefield acceleration (SM-LWFA) regime within a supersonic helium gaz jet. This acceleration mechanism is known to generate high electron charges approaching the microCoulomb ($\mu$C), hence its potential for secondary source generation. Using time-of-flight neutron (nToF) scintillator detectors, nuclear activation diagnostics and Geant4 simulations, the setup is shown to have produced up to $2 \times 10^{10}$ fast neutrons per shot with energies reaching about $20\ \mathrm{MeV}$. Such high-flux sources could find application in nuclear physics and astrophysics, as well as in material science.
Moreover, traces of high-energy gamma-induced nuclear fragmentation were recorded on our nuclear activation diagnostic, demonstrating the potential of this scheme to produce radioisotopes akin to conventional spallation facilities but with a more compact setup and a lower overall production cost.

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**Track Classification:** Beam Plasmas and Inertial Fusion (BPIF): Laser-plasma Acceleration of Particles and Plasma-based Radiation Sources (BPIF)

Contribution ID: **432** Type: **Oral Presentation**

# Sustaining long-pulse, high-performance plasmas in the optimized stellarator W7-X by repetitive pellet injection

We report on the development of discharge scenarios that enable long-term stabilization ($t > \tau_{L/R}$) of equilibrated high-performance plasmas in the optimized stellarator W7-X. The scenarios exploit repetitive pellet injection combined with second-harmonic O-mode heating, which together may raise the ion temperature beyond the ion-temperature clamping limit (>1.5 keV) and sustain a quasi-stationary operational cycle at high density and plasma energy up to the available heating duration.

Surprisingly, these plasmas exhibit indications of central fueling and the plasma ions appear to contribute to the thermalisation of the injected pellet material. Targeted impurity seeding mitigates heat loads on critical components without impurity accumulation thereby enabling longer pulses. As a consequence of pellet injection, the plasma parameters oscillate within a limited range. In particular, under constant and optimized pellet fueling and plasma heating, good confinement is achieved over several dozen pellet cycles. This PULSE (Pellet-Utilized Long-Pulse Steady-State Enabled) regime proves robust: if irregularities in pellet size temporarily reduce plasma performance, recovery to high performance is observed once the nominal fueling rate is restored.

In initial experiments, central ion temperatures exceeding 2 keV and central densities above $1.5 \times 10^{20}\ m^{-3}$ were obtained at the maximum of the pellet-induced cycles. During these phases, central beta values of up to 4 % were achieved, together with confinement consistent with the ISS04 scaling ($f_{ren}$ 1). The improved confinement appears to be related to a local reduction of transport that remains stabilized over a pellet cycle in the PULSE regime. For the first time, dimensionless parameters of reactor relevance have been achieved in stellarator plasmas sustained for up to 43 s.

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**Track Classification:** Magnetic Confinement Fusion (MCF): Scenario Development, Heating and Current Drive (MCF)

Contribution ID: **460** Type: **Oral Presentation**

# Charging dynamics of single and clustered microparticles in spatiotemporal afterglow plasmas

As semiconductor devices continue to shrink, maintaining ultra-clean fabrication environments becomes increasingly critical. To eliminate unwanted particles from low-pressure, high-purity processing systems, a novel technique known as the "plasma seal"has been proposed. This method uses plasma to electrically charge contaminant particles, enabling their removal through an externally applied electric field. However, because the plasma screens the particles from the electric field, effective deflection can only take place either outside the active plasma region, immediately after the plasma is switched off or during the spatiotemporal afterglow, which combines aspects of both regimes.

Recent research has advanced the understanding of particle charging mechanisms in the spatiotemporal afterglow, yet the role of particle clustering remains largely unexplored. In this contribution, we examine how cluster size influences particle charging behavior. Optical emission spectroscopy is employed to link particle charge to key plasma parameters. The findings provide experimental validation of established theoretical models describing particle charging processes.

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**Track Classification:** Low Temperature and Dusty Plasmas (LTDP): Dusty and Strongly Coupled Plasmas (LTDP)

Contribution ID: **468** Type: **Oral Presentation**

# Mitigation of Stimulated Raman Scattering and Stimulated Brillouin Scattering in kinetic regime using Smoothed Broadband Laser

High-energy laser beams used in inertial confinement fusion (ICF) experiments are subject to phase aberrations as they propagate through numerous optical elements. These aberrations induce large non-uniformities at the focal spot and significant shot-to-shot variations, which can compromise implosion symmetry. While Random Phase Plates (RPP) are routinely employed to improve beam stability, this spatial smoothing technique inherently creates small-scale hot spots known as speckles. These speckles strongly affect laser-plasma interaction by seeding deleterious instabilities, specifically Stimulated Brillouin Scattering (SBS) and Backward Stimulated Raman Scattering (SRS). These processes lead to potential optics damage, target pre-heating via supra-thermal electrons, and a reduction in the energy effectively delivered to the capsule. To mitigate these effects, the speckle coherence time, tc, must be shorter than the growth rate of the instabilities. Currently, standard Smoothing by Spectral Dispersion (SSD) appears insufficient to reach this regime. Using 2D and 3D Particle-In-Cell (PIC) simulations optimized for CPU and GPU architectures, we investigate several schemes to break spatial and temporal coherence in the kinetic regime. We focus on Broadband Laser configurations and the Induced Spatial Incoherence (ISI) method. Our results demonstrate that while reducing SBS is achievable, certain configurations can dramatically increase SRS, highlighting limitations of using "moderate bandwidth" approaches.

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**Track Classification:** Beam Plasmas and Inertial Fusion (BPIF): Laser and Particle Beam Interaction with Plasmas, Hydrodynamics and Instabilities (BPIF)

Contribution ID: **472** Type: **Oral Presentation**

# A unified description of spatiotemporal ultrarelativistic beam-plasma instabilities under the quasistatic approximation

Plasma streaming instabilities driven by ultrarelativistic charged particle beams in dense ambient plasmas play a central role in astrophysical and laboratory settings 1. However, their numerical modeling is hampered by the large disparity in dynamical scales between the beam and plasma particles.

Here, we leverage the quasistatic approximation (QSA)–widely used in the context of plasma accelerators 2–to develop a unified model of unstable modes in the realistic case where the beam continuously encounters fresh plasma at its leading edge. Unlike previous works [3,4], we do not adopt the slowly varying envelope approximation (SVEA). This allows us to capture the unstable modes developing throughout the beam region, and thus to clarify the interplay of the current filamentation (CFI) and oblique-two-stream (OTSI) instabilities, under conditions where standard theory predicts dominance of the OTSI 1. By contrast, we find that spatiotemporal CFI modes prevail near the front–precisely where the SVEA breaks down–and are superseded by the spatiotemporal OTSI further away.

We benchmark our theory against high-resolution particle-in-cell (PIC) simulations and QSA-based PIC (QS-PIC) simulations performed using our newly developed QuaSSis code [5]. We demonstrate that the dramatic computational speedup offered by the QS-PIC method makes it possible to probe extreme beam-plasma interactions, such as those expected in the context of blazar jets.

Finally, we extend our theory to collisional systems. We show analytically that the collisionality of the background plasma entails a more complex instability dynamics, involving a succession of spatiotemporal and temporal variants of the CFI and OTSI, which is well reproduced by low-noise collisional QS-PIC simulations.

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**Track Classification:** Beam Plasmas and Inertial Fusion (BPIF): Laser and Particle Beam Interaction with Plasmas, Hydrodynamics and Instabilities (BPIF)

Contribution ID: **474** Type: **Oral Presentation**

# Full reconstruction of the energy partitioning in 2-μm-wavelength-laser-driven plasma sources of extreme ultraviolet light

State-of-the-art nanolithography uses extreme ultraviolet (EUV) radiation at 13.5 nm emitted from tin laser-produced plasma (LPP), driven by a 10.6 μm-wavelength CO2-gas laser, to create the smallest features on semiconductor devices. Advances in solid-state laser technologies have led to the alternative concept of a 2 μm-wavelength-driven LPP as a promising candidate for a more efficient and more powerful EUV source. At this drive laser wavelength a high conversion efficiency of laser energy into EUV radiation of 4% has been demonstrated [Appl. Phys. Lett. 123, 234101 (2023)], but a full picture of the plasma has not been shown to date.
In this study we characterize the partitioning of all emissions of a 2 μm laser driven plasma to have a full picture of the energy sinks. We use our custom-built high energy 2 μm laser system, developed at ARCNL, to heat a tin sheet into an EUV emitting plasma. Plasma emissions are measured by an extensive diagnostic suite: In-band EUV light (13.5nm±1%) is measured, correcting for the emission anisotropy, by a set of EUV photodiodes. The EUV emission is combined with the emission spectrum measured in 5-260nm in order to reconstruct the full radiative emission. Ion emissions are measured with a set of retarding field analyzers, reconstructing the charge-state-resolved ion kinetic energy spectrum. Together with laser reflection and kinetics of the remaining neutral tin this accounts for the energy sinks in the plasma.
We can for the first time reconstruct 100% of the incoming laser energy. With ~70%, most of the energy goes into photons, the largest part of which is emitted in the 5-80 nm wavelength range. Plasma ions contribute ~30% of the energy, and, contrary to available theory and numerical simulations, we find that this fraction decreases as a function of the laser intensity. This is a key insight in finding pathways to optimize plasma for industrial application. Our results offer insight into the energy partitioning of EUV-emitting plasmas for research and industrial nanolithography alike, and provide a benchmark for plasma light source development.

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**Track Classification:** Beam Plasmas and Inertial Fusion (BPIF): Laser-plasma Acceleration of Particles and Plasma-based Radiation Sources (BPIF)

Contribution ID: **493** Type: **Oral Presentation**

# COMPACT: the future facility for complex (dusty) plasma research in space

Experiments under microgravity conditions are a cornerstone of complex (dusty) plasma research. In microgravity, large particle systems can be generated and studied, without sedimentation overshadowing particle interaction and dynamics.

Thus, a series of facilities (PKE-Nefedov, PK-3 Plus, PK-4) were and are operated onboard the International Space Station since the early 2000s, providing dedicated research platforms.

An international science definition team (SDT) recently identified so-far unanswered scientific questions from the areas statistical physics, phase transitions, nonlinear dynamics, active matter, planetary physics and the use of particles as diagnostics in the plasma. The SDT compiled an extensive research program for the future facility COMPACT: an international, multi-user facility for the community with strong support by multiple agencies (DLR, NASA, ESA, NSF).

COMPACT offers a wide range of experimental capabilities such as manipulation of particles by laser, UV-light, or low-frequency electric signals, a pulsed rf discharge mode, a multi-electrode system, and a variable discharge volume. Advanced optical diagnostics include a stereoscopic camera setup for 3D particle diagnostics, and spatially and spectrally resolved plasma glow observation.

A phase B study (preliminary definition) was finished successfully in early 2026, with major components identified and tested. We will present the scientific program and project status, alongside with first scientific results obtained during preliminary investigations using the COMPACT hardware on parabolic flight campaigns.

This work is funded by DLR/BMWi FKZ 50WM2161, FKZ 50WM2561.

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**Track Classification:** Low Temperature and Dusty Plasmas (LTDP): Dusty and Strongly Coupled Plasmas (LTDP)

Contribution ID: **495** Type: **Oral Presentation**

# X-ray phase contrast Imaging of propagating shocks within TMPTA using the SACLA x-ray free electron laser

Direct drive inertial confinement fuison are especially susceptible to driver non-uniformities that imprint structure of on to the target surface. The imprinted structure seed hydrodynamic isntabilities whilst launching non-uniform shocks. This talk presents the results of using x-ray phase contrast imaging of a propagting shock within TMPTA foam using the x-ray free electron laser present at SACLA.

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**Track Classification:** Beam Plasmas and Inertial Fusion (BPIF): High Energy Density Plasmas, Warm Dense Matter, and Atomic Physics in Plasmas (BPIF)

Contribution ID: **497** Type: **Oral Presentation**

# Dark-Field Shadowgraphy: An Ultra-Sensitive Diagnostic for Probing Plasma-Based Particle Accelerators

Plasma wakefield accelerators driven by ultra-intense laser pulses (LWFA) or relativistic particle beams (PWFA) have emerged as a promising route toward compact next-generation accelerators. Precise characterization of the plasma wave is essential for understanding and optimizing these schemes. Optical shadowgraphy techniques already enable direct imaging of plasma density perturbations and wakefield structures 1. Despite these advances, the sensitivity of conventional shadowgraphy limits its application to high plasma densities, typically in the $10^{18} - 10^{19}$ $\mathrm{cm}^{-3}$ range.

Here, we introduce a dark-field or Schlieren shadowgraphy diagnostic that greatly enhances the sensitivity of optical shadowgraphy and enables probing ultra-low plasma densities down to the $10^{16}$ $\mathrm{cm}^{-3}$ range, where plasma waves are invisible to conventional shadowgraphy. Furthermore, we show with this new diagnostic that we clearly observe for the first time several detailed features of the plasma accelerator: (i) the position of the laser driver that typically appears as the brightest signal, (ii) the ion cavities with the plasma electrons circulating around, and (iii) the plasma electron crossing points at the back of the cavities, characterized by particularly high plasma densities and strong gradients, yielding a strong diagnostic signal. The method was experimentally tested first in Salle Jaune at LOA and more recently during campaigns at the Apollon (3 PW) facility. Our study further demonstrates the capability of this diagnostic to track the temporal evolution and damping of the wakefield with a relaxation time estimated to be on the order of 10 ps after the laser passage in good agreement with numerical simulations, together with the formation and expansion of the associated ion channel. This high-contrast, non-intrusive diagnostic thus provides a powerful tool for investigating and optimizing plasma-based particle accelerators.

Finally, double gas-jet targets combining a low-density stage followed by a higher-density region are considered for optimizing ultra-bright gamma-ray production aimed at probing strong-field quantum electrodynamics processes such as nonlinear Breit–Wheeler pair production 2. Dark-field shadowgraphy proves particularly well suited to characterize laser propagation and wakefield generation in such complex density profiles.

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**Track Classification:** Beam Plasmas and Inertial Fusion (BPIF): Laser-plasma Acceleration of Particles and Plasma-based Radiation Sources (BPIF)

Contribution ID: **498** Type: **Oral Presentation**

# Bridging plasma microphysics to macroscopic ammonia synthesis with machine learning

Low-temperature plasmas enable electron-driven plasma NH3 synthesis, yet a quantitative understanding of microphysical characteristics relative to reactor-scale performance remains elusive. Building on a systematic experimental $N_2$–$H_2$ dataset spanning varied reactor configurations and operating conditions, we developed a machine-learning-based framework that links plasma microphysics to macroscopic ammonia synthesis, using electrical diagnostics (Lissajous analysis, micro-discharge statistics), optical emission spectroscopy, and colorimetric NH3 quantification. These charge and excitation descriptors, along with varied operational conditions, were used to train a Random Forest model. The model reveals that total charge per pulse and median micro-discharge energy are the most informative descriptors of the plasma characteristics, which are governed by barrier thickness, gap geometry, voltage, and plasma on time, altering the reactor capacitance and electric field. Further, it is observed that when the discharge gap is fixed, increasing barrier thickness reduces the total micro discharge charge but increases the median energy. On the contrary, fixing the electrode gap and increasing the barrier thickness decreases both total charge and median energy, producing fewer, less energetic filaments. Further, the model showed that the resulting total charge per pulse is the dominant predictor of NH(A–X) and H Balmer intensities intern related to ammonia synthesis. Thus, these insights translate into mechanistic design rules: reducing the discharge gap or increasing barrier thickness increases reactor capacitance and micro discharge energy, which boosts NH(A–X)/H emission and $NH_3$ concentration but at the expense of energy efficiency, whereas higher total flow may produce less power-dense micro discharges, improving energy efficiency. Overall, this data-driven framework shows how machine learning can deconvolute complex multidimensional plasma behaviour into physically interpretable guidelines for optimising non-thermal plasma reactors for sustainable, decentralised ammonia synthesis.
This work builds on Ref. 1.

Reference:

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**Track Classification:** Low Temperature and Dusty Plasmas (LTDP): LTP Plasmas for Sustainability (LTDP)

Contribution ID: **499** Type: **Oral Presentation**

# Impact of edge cooling on current profile evolution and resistive wall tearing stability in JET

Edge cooling is frequently observed in tokamak plasmas prior to disruptions and can lead to significant changes in the current density profile, potentially destabilizing magnetohydrodynamic (MHD) activity 1. Understanding whether such cooling can drive the plasma toward instability, and whether/how the presence of a resistive wall affects this process, is essential for interpreting pre-disruption dynamics and improving disruption prediction.
In this work, we first investigate linear MHD stability in the presence of a resistive wall using a newly developed linear solver 2, with particular emphasis on resistive wall tearing modes (RWTMs). These modes correspond to tearing instabilities that would be stable in the presence of an ideal wall but become unstable in the no-wall limit 3. The results from this fast solver are benchmarked against extended MHD simulations using JOREK–STARWALL and CASTOR3D, providing cross-code validation and establishing confidence in the modeling of RWTMs. This framework enables a systematic study of the effect of current density profile and resistive wall on MHD stability.
Building on this, we further investigate a realistic JET plasma in which edge cooling was experimentally observed prior to a disruption [4] via simulations with the JOREK-STRAWALL code. The simulations are initialized by modeling the edge cooling via impurity radiation and subsequently track the evolution of the current density profile and the onset of MHD activity. Experimental measurements indicate the presence of unusual and intermittent MHD signatures prior to the disruption, motivating a detailed numerical investigation of the underlying dynamics. In this work, we aim to assess whether edge cooling can modify the current profile sufficiently to move the plasma into an unstable regime and to identify the role of the resistive wall in the resulting MHD activity. In particular, by comparing simulated behavior with experimental observations, this work seeks to clarify whether RWTMs provide a consistent interpretation of the observed pre-disruption dynamics in the JET discharge.
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**Track Classification:** Magnetic Confinement Fusion (MCF): Disruptions and Runaway Electrons (MCF)

Contribution ID: **502** Type: **Oral Presentation**

# Reexamination of collisional ionization cross sections including double ionization processes

Collisional ionization and recombination rates remain a major source of uncertainty in the spectroscopic modelling of solid-density plasmas. X-ray free-electron lasers (XFELs) provide a unique platform to generate warm dense matter with well-defined density and ultrafast energy deposition, enabling K-shell emission spectra to be used as sensitive diagnostics of ionization dynamics. However, the interpretation of these spectra depends critically on the treatment of non-thermal electron distributions, degeneracy effects, and competing atomic processes that may produce similar spectral signatures.

In this work, we revisit previously reported K-shell emission spectra from XFEL-irradiated solid-density aluminium. The experiment used 3 keV, 35 fs XFEL pulses to photoionize aluminium foils, producing K-shell vacancies and subsequent fluorescence emission. We analyse these data using the collisional-radiative model BigBarT, which self-consistently evolves the electron continuum, including non-thermal electron populations and Fermi–Dirac degeneracy effects [1, 2].

We further include shake-off processes following primary photoionization. These processes create additional L-shell vacancies and generate satellite emission features that can mimic those usually attributed to collisional ionization 3. Our simulations show that shake-off contributes significantly to the observed satellite structure. Nevertheless, when standard collisional cross sections are used, the calculated spectra underestimate the satellite emission, mainly because rapid three-body recombination refills L-shell vacancies on too short a timescale.

To assess the sensitivity of the spectra to these rates, we performed simulations with reduced collisional cross sections. Lowering these rates by an order of magnitude substantially improves agreement with the experimental data, as longer-lived L-shell holes allow shake-off-driven configurations to contribute more effectively to the emitted spectrum. These results suggest that commonly used IPD-scaled collisional models may overestimate three-body recombination rates in low-temperature, solid-density XFEL-driven plasmas.

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**Track Classification:** Beam Plasmas and Inertial Fusion (BPIF): High Energy Density Plasmas, Warm Dense Matter, and Atomic Physics in Plasmas (BPIF)

Contribution ID: **505** Type: **Oral Presentation**

# Microwave Cavity Resonance Spectroscopy as a diagnostic technique for plasmas and electron beams

One of the main defining characteristics of a plasma is the electron density. Conventional electron density diagnostic techniques, such as Langmuir probes or Thomson scattering are generally relatively invasive. As an alternative, Microwave Cavity Resonance Spectroscopy (MCRS) can be used as a minimally invasive diagnostic technique for the electron density. MCRS relies on measuring the eigenfrequency of a cylindrical cavity using microwaves. As the permittivity of the medium inside the cavity changes, the eigenfrequency of the cavity shifts.

This work will give an overview of the working principles of MCRS, and highlights three of its key capabilities across various applications. First, its high temporal resolution is demonstrated through measurements on pulsed plasmas. Second, a method for obtaining qualitative spatial information is shown using nanodusty plasma experiments and FEM simulations. Finally, the high sensitivity of MCRS is illustrated through the characterization of an electron beam.

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**Track Classification:** Low Temperature and Dusty Plasmas (LTDP): Other - LTDP

Contribution ID: **513** Type: **Oral Presentation**

# Core tungsten transport of internal transport barrier scenarios in JET with Be/W wall

Avoiding tungsten (W) accumulation in the core plasma will be vital for successful operations of next generation tokamaks. For the development of high-performance scenarios, which target steady state operation, it is essential that core W transport and the plasma conditions required for impurity screening at the confined plasma periphery are understood. Spontaneous formation of internal transport barriers (ITBs) may also occur in burning plasma scenarios, motivating the need to understand ITB physics to maintain control of the barrier's strength or prevent it entirely. Studies of core impurity transport in ITB plasmas in JET-C found evidence of core impurity accumulation due to neoclassical transport, which dominates inside the ITB where the turbulent transport is stabilised [1, 2]. Previous analysis of JET-ILW (Be/W wall) hybrid scenarios demonstrated peripheral tungsten screening in D and DT plasmas [3, 4]. This analysis builds upon previous work by investigating core W transport in ITB scenarios in JET-ILW.
Strong ITBs have been produced in low density $n_\mathrm{e}$ JET-ILW plasmas with high NBI heating that generates high core ion temperature $T_\mathrm{i}$, high toroidal Mach number $\Omega_\phi$ and a peaked $n_\mathrm{e}$ profile [5]. The resulting steep $T_\mathrm{i}$ and $n_\mathrm{e}$ gradients have substantial effects on the neoclassical transport that dominates core W transport. Due to the sizeable concentrations of Be and Ni in these pulses, impurity-impurity collisions must be retained for accurate core W transport predictions. The drift-kinetic code NEO [6] used in this modelling captures this important physics, predicting core W accumulation after the formation of the strong ITB, which weakens outward convection of W. An integrated impurity analysis tool [7] enables interpretative analysis of the plasma impurity composition, using experimental measurements from multiple diagnostics. This tool provides input Be and Ni density profiles, which are the dominant contributors to $Z_\mathrm{eff}$, as well as W density profiles. NEO predictions are consistent with the experimental measurements, indicating core W accumulation, which codes using simplified approximations of neoclassical transport are unable to reproduce. Sensitivity scans on the gradients of key driving parameters $\nabla T_\mathrm{i}$, $\nabla n_\mathrm{e}$ are performed within experimental uncertainties to enhance confidence in the model predictions.

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**Track Classification:** Magnetic Confinement Fusion (MCF): Plasma Turbulence and Transport (MCF)

Contribution ID: **517** Type: **Oral Presentation**

# Experimental Application of Laser–Plasma Radiation Sources to Cultural Heritage Studies at ELI Beamlines

Laser-plasma particle acceleration based on solid targets 1 is promising for many applications, from nuclear medicine to materials characterization. Laser-plasma sources can generate different radiations (e.g., ions and photons), allow for energy tuning, and can operate within potentially compact setups. Control over the laser (e.g., intensity) and target parameters (e.g., thickness) enables one to tune the maximum energy of accelerated ions. Therefore, laser-plasma sources represent promising alternatives to conventional accelerators which, although based on mature technologies, remain limited in terms of flexibility and compactness.
Particle Induced X-Ray Emission (PIXE) and X-Ray Fluorescence Spectroscopy (XRF) are complementary materials characterization techniques used in several fields including artworks analysis 3. They rely on the irradiation of samples with protons and photons to induce characteristic X-ray emission. PIXE and XRF could benefit from the use of laser-plasma sources [4]. Indeed, the energies of the laser-driven protons and photons are suitable for the characterization of cultural heritage materials.
Here, we present artworks characterization with laser-plasma sources via laser-driven PIXE and XRF. We performed a campaign at the ELIMAIA beamline [5] (ELI Beamlines) driven by the HAPLS laser. Using a proof-of-principle setup 2, laser-driven protons and photons were transported in air to irradiate certified materials, medieval bronzes, and Iron Age ceramics. We measured the characteristic X-rays emitted by the sample, and the spectra were analysed with a numerical tool that integrates the theoretical description of PIXE in the PyMCA code [6] for XRF analysis. In this way, it is possible to determine the elements present in the samples and their concentrations. This study lays the foundation for the development of laser-plasma accelerators tailored to the characterization of cultural heritage materials, suggesting that this suorces could achieve results comparable to conventional accelerators while maintaining their inherent versatility.

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**Track Classification:** Beam Plasmas and Inertial Fusion (BPIF): Laser-plasma Acceleration of Particles and Plasma-based Radiation Sources (BPIF)

Contribution ID: **541** Type: **Oral Presentation**

# Surface Dielectric Barrier Discharge characterization based on mass spectrometry diagnostic techniques

Surface Dielectric Barrier Discharge characterization
based on mass spectrometry diagnostic techniques
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Non-thermal plasmas in atmospheric air have been proposed as a tool aimed to various applications, including air purification, food packaging, textile finishing and new materials development, owing to its capacity to generate highly reactive species under ambient conditions. Surface Dielectric Barrier Discharges (SDBD) are particularly promising because the plasma state is almost two-dimensional and confined to region facing the dielectric surface, with only indirect interactions with the surrounding gas-phase or with the to be exposed surfaces aimed for functionalization. One key aspect is the generation of reactive oxygen and nitrogen species (RONS), which play a fundamental role in oxidative processes. The relative concentrations of these species determine the overall oxidative potential of the plasma and its effectiveness in biological and chemical applications. Therefore, the accurate identification and quantification of these species are essential for any optimization strategy to enhance the efficiency of the plasma. Mass spectroscopy could be used to gain insight into such gas-phase composition. Our mass-spectrometer (HPR60 by Hiden) in particular, with its ability to change the electron energy in an extended range (namely 4-150 eV), their intensity (about four decades between 0.2 to 2000 uA) and the electrical optics (so that it is able to collect native positive and negative ions from the discharge region), could aim to a a comprehensive characterization of plasma gas-phase. Here we presents the results of an experimental campaign aimed to this.
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**Track Classification:** Low Temperature and Dusty Plasmas (LTDP): Plasma Processing and Applications (LTDP)

Contribution ID: **549** Type: **Oral Presentation**

# Control of nonlinear Breit-Wheeler positrons created in multi-PW strong field QED showers

Continued developments in high-power lasers will enable intensities beyond 10^23 W/cm^2. At such intensities, a laser pulse colliding with an ultra-relativistic electron beam subjects the electrons to fields nearing the Schwinger limit, triggering strong-field QED (SFQED) processes. The dominant processes in the collision are nonlinear Compton scattering, where a charged particle emits a high-energy photon, and nonlinear Breit-Wheeler pair creation, where a photon decays into an electron-positron pair. Harnessing these processes for positron generation requires control over the processes themselves and the positrons they produce. Here, we demonstrate two approaches to controlling the properties of positrons produced during nonlinear Breit-Wheeler pair creation. In the first, the asymmetric fields of a bichromatic, circularly polarized laser pulse enable simultaneous spin-polarization and angular isolation of the created positrons, producing a positron signal that is over 50% spin-polarized and nearly devoid of electrons. In the second, the collision of a monochromatic, linearly polarized laser pulse and relativistic electron beam occurs in a plasma, where the magnetic fields excited by the laser pulse focuses the positrons and expels electrons. This focusing is energy-dependent and results in smaller energy spreads than could be achieved in a vacuum collision.

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**Track Classification:** Beam Plasmas and Inertial Fusion (BPIF): Ultra-high Intensity Laser-matter Interaction and High-field Physics (BPIF)

Contribution ID: **557** Type: **Oral Presentation**

# Measurements of LPI growth in smoothed and unsmoothed beam interactions of relevance to direct drive ICF

The focus of the inertial confinement fusion (ICF) community post-ignition is shifting towards practical schemes for inertial fusion energy production (IFE). Direct drive, where the intense lasers irradiate the fuel pellet exterior directly, and related variants such as shock ignition 1 and fast ignition is a primary candidate for IFE. A critical limitation facing direct drive is the excitation of laser-plasma instabilities (LPI) which act to couple laser waves into scattered light and hot electrons, reducing the efficiency of implosions. The growth of LPI is non-linear with laser intensity, making it a particular issue for shock ignition. Additionally LPI growth is highly dependent on the plasma parameters and kinetic effects, making predictive modelling challenging. Experiments at high power laser facilities with planar targets therefore offer a valuable tool for understanding the fundamental growth of these instabilities.

In this paper we present results from an experimental study performed at ELI-Beamlines measuring the Stimulated Raman Scattering (SRS) and Stimulated Brillouin Scattering (SBS) instabilities. A full-aperture backscatter (FABS) diagnostic station 2 was used to measure LPI driven under irradiation of thick and thin "exploding foil"targets by the L4n laser in 2⊠ (λ = 526.5 nm) up to intensities ~3 x 1015 W/cm2. In addition, a Distributed Phase Plate (DPP) was used to spatially smooth the focal spot in conditions more relevant to ICF. Filamentation and self-focusing are found to play a significant role in driving LPI considering the larger f-number (f/10.8) of the laser focusing optic. Our measurements highlight the critical role of focal spot statistics and self-focusing in governing LPI growth and demonstrate the utility of exploding foils for expanding the parameter space accessible at high-power laser facilities 3.

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**Track Classification:** Beam Plasmas and Inertial Fusion (BPIF): Laser and Particle Beam Interaction with Plasmas, Hydrodynamics and Instabilities (BPIF)

Contribution ID: **566** Type: **Oral Presentation**

# Helicon modes triggered by axially peaked density perturbation

Radio-frequency (RF) helicon sources usually display three modes of operation: a capacitive mode at low RF power $P_{RF}$, an inductive mode at intermediate power and a wave-sustained (W) mode, above a critical power $P_c$. The W-mode is reached when the plasma density allows for solutions to the dispersion relation of the natural helicon/Trivelpiece Gould (W) modes, which depend on the antenna design and the cavity geometry. A large density jump occurs at the transition to the W mode. A strong hysteresis is usually observed, and high-density natural W-modes are triggered in the ramp-down, when $P_{RF}$ is further decreased.

We demonstrate that W-modes are triggered well below the critical power $P_c$, when transiently and locally increasing the plasma density, either by current injection on-axis, or using a small secondary axial inductive source. When the perturbation stops, the primary RF source maintained at $P_{RF} < P_c$ sustains the high-density natural W-modes observed during the ramp-down. A thorough experimental characterization of spatially-resolved plasma density and wave magnetic fields structure is detailed for a half-helical antenna in a $1\,\mathrm{m}$ long, $20\,\mathrm{cm}$ in diameter plasma vessel, operating in the range of $0.1\,\mathrm{Pa}$ with a static magnetic field of $180\,\mathrm{G}$. We stress that a few tens of Watts of auxiliary power allows to trigger a W-mode at $P_{RF} = 500\,\mathrm{W} = 0.5P_c$.

The underlying mechanism lies in the modification of the density profile, which is more centrally peaked in the presence of the axial perturbations, and modifies the wave coupling. This mechanism has been validated using the HELIC code, which solves Maxwell's equations with boundary conditions for given plasma density profiles and antenna design. The computation of the absorbed power using experimentally informed density profiles demonstrates that high density W-modes are triggered at lower $P_{RF}$ in the presence of peaked profiles. In this simplified model, the predicted steady-state working points reproduce the experimental features. When injection is stopped, the high density in the cavity allows the sub-critical natural modes to be maintained. These results potentially open new avenues for the development of efficient helicon sources at low RF power.

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**Track Classification:** Low Temperature and Dusty Plasmas (LTDP): Other - LTDP

Contribution ID: **572** Type: **Oral Presentation**

# Electron heat flux and whistler instability in the Earth's magnetosheath

In collisionless plasma, several processes contribute to plasma heating and energy dissipation. One such example is wave-particle interactions between electromagnetic whistler waves and electrons. In the solar wind, the whistler-heat flux instability is known to regulate the electron heat flux by pitch-angle scattering of strahl electrons. Similar instabilities are believed to operate in various astrophysical plasma, but most such systems can only be studied remotely and through simulations. The Earth's magnetosheath downstream of the bow shock is accessible to high-quality *in situ* spacecraft measurements, allowing the measurement of heat flux and detailed studies of wave-particle interactions. The heat flux properties and evolution across the magnetosheath have not yet been explored.

We present Magnetospheric Multiscale (MMS) observations from 18 hours of high-resolution burst-mode measurements. We quantify the electron heat flux in the magnetosheath and examine the role of whistler instabilities in regulating it. Our results show that the heat flux follows the magnetosheath magnetic field as it drapes around the magnetosphere. We find that the heat flux is constrained by whistler instability thresholds and is aligned with the propagation of low-frequency whistler waves. We also present a case study investigating direct evidence for the whistler-heat flux instability in the magnetosheath.

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**Track Classification:** Basic, Space and Astrophysical Plasmas (BSAP): Solar and Space Plasmas (BSAP)

Contribution ID: **576** Type: **Oral Presentation**

# Propagation-based X-ray phase contrast imaging of laser-driven shocks in planar targets at the GSI PHELIX laser facility

X-ray phase contrast imaging (XPCI) is a cutting-edge diagnostic technique based on the phase shift of x-ray photons induced by a density gradient. By enhancing contrast through refraction and diffraction at material interfaces and density gradients, XPCI is particularly well-suited for imaging laser-driven shock propagation inside targets. In this work, we advanced the platform originally developed by *L. Antonelli et al* [EPL 125, 35002 (2019)] at the GSI PHELIX laser facility. We have compared different X-ray sources and geometries to optimize the backlighter performance. Results demonstrate high-quality imaging of shock waves propagating through planar plastic and foam targets. We will also discuss the next step of extending this platform toward direct imaging of early-time, laser-imprinted perturbations.

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**Track Classification:** Beam Plasmas and Inertial Fusion (BPIF): Laser and Particle Beam Interaction with Plasmas, Hydrodynamics and Instabilities (BPIF)

Contribution ID: **582** Type: **Oral Presentation**

# Study of the X divertor on MAST Upgrade: development, control and impact on power exhaust

Plasma scenarios with an X divertor configuration 1 developed on MAST Upgrade exhibit a reduction in heat and particle fluxes at the divertor targets compared with conventional divertor configurations. We use the Toksys 2 and TED 3 frameworks to modify a conventional divertor magnetic equilibrium to increase poloidal flux expansion at the target and apply feed-forward changes to poloidal field coil currents to realise these configurations in Ohmic and beam-heated L-mode and H-mode plasmas.

The highest target poloidal flux expansion is achieved by zeroing the radial and vertical magnetic field components just below the strike point; this strategy is however very sensitive to plasma evolution and cannot be sustained by feed forward control. Moving the field null further from the target reduces the peak flux expansion but gives a more robust scenario. Designing solely for target flux expansion instead of imposing a field null constraint also achieves a robust scenario at the cost of with lower peak flux expansion. Adding strike point position feedback control after forming the X divertor maintains acceptable flux expansion for longer durations, but only for lower poloidal flux expansion scenarios.

In Ohmic and NBI-heated L mode plasmas using the field-null strategy, we achieved high peak flux expansion only in the far SOL, with modest flux expansion at the strike point. Increased interaction of the SOL with the divertor entrance and a corresponding increase in upstream neutral influx and radiated power precluded isolating the impact of the divertor geometry from the impact of the increased wall interaction at the divertor entrance. Moving the location of the peak flux expansion closer to the strike point and sacrificing peak flux expansion avoided excessive wall interaction. This scenario achieved a 10%-30% reduction in peak parallel heat flux and earlier detachment onset in N2-seeded H mode plasmas compared with the conventional divertor.

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Work supported by EPSRC EP/W006839/1 and US-DOE DE-AC05-00OR22725.

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**Track Classification:** Magnetic Confinement Fusion (MCF): SOL, Divertor and PWI (MCF)

Contribution ID: **606** Type: **Oral Presentation**

# Optimising non-linear Breit-Wheeler pair production in simulated laser experiments

High laser intensities enable the production of electron-positron pairs from bright gamma rays passing through strong fields. Potentially the most promising approach for all-optical experiments in the near term uses dense but higher divergence electron beams from laser wakefield acceleration to produce gamma rays through inverse Compton scattering. Achieving many-photon collisions between these gamma rays and the high intensity laser pulse in practice is extremely difficult, however, due to significant shot-to-shot jitter in laser pointing and timing. In practice, this jitter reduces the yield of electron-positron pairs by orders of magnitude.

We model these practical difficulties using simulated Monte-Carlo experiments. By using a more efficient algorithm for sampling infrequent pair production with particle splitting, we enable the exploration of a multi-dimensional parameter space. Using Gaussian Process Regression we then efficiently find optimal conditions for maximising pair production by changing the laser spot size, the energy in the colliding beam, and the stand-off distance between the laser wakefield accelerator and the focus of the colliding laser pulse. We find that the optimal stand-off distance increases with the degree of laser jitter and that the best conditions for producing electron-positron pairs are not the same as the best conditions for maximising the energy in the gamma rays. With 100 J of laser energy, we estimate realistic rates of pair production of around 1 pair per 100 electrons are achievable even with jitter of 10s of microns and 10s of femtoseconds.

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**Track Classification:** Beam Plasmas and Inertial Fusion (BPIF): Ultra-high Intensity Laser-matter Interaction and High-field Physics (BPIF)

Contribution ID: **621** Type: **Oral Presentation**

# An Updated Plasma Scenario for the Spherical Tokamak for Energy Production

The UK's Spherical Tokamak for Energy Production (STEP) programme, aiming to provide a prototype fusion power plant (SPP) based on the spherical tokamak concept targeting 2040 1, has now moved from the conceptional to preliminary design phase. Key objectives of the SPP, which will drive the creation of a UK fusion economy, are to deliver net electric power $P_{\mathrm{net}}100\mathrm{MWe}$ and demonstrate tritium self-sufficiency. Choosing a fully non-inductive flat top operating point without inboard breeding drives the design to low aspect ratio A~1.8, high elongation κ~3 and high normalised plasma pressure $_N \sim 4$ 2 as fusion power scales like $P_{\mathrm{fus}} \propto (_N \cdot B_t)^{45}(R_{\mathrm{geo}}/A)^3$ at high bootstrap current fraction $f_{\mathrm{BS}} = I_{\mathrm{BS}}/I_{\mathrm{p}} \sim 0.8-0.9$. The high $f_{\mathrm{BS}}$ reduces the demand on the auxiliary microwave based heating and current drive system on STEP. In addition to the usual electromagnetic electron cyclotron wave current drive (ECCD), the use of electrostatic electron Bernstein waves current drive (EBCD) in combination is considered3. EBCD provides a 3 times higher normalised current drive efficiency than ECCD and opens opportunities to potentially access scenarios at commercial power plant relevant fusion gain of $Q = P_{\mathrm{fus}}/P_{\mathrm{aux}} \sim 30$. The ECCD scenario operates at Q~11. Since publishing the original design base (SPP-1) ($R_{\mathrm{geo},1} = 3.6\mathrm{m}$ , $B_{t,1} = 3.2\mathrm{T}$ , $I_{p,1} \sim 20\mathrm{MA}$ , $1.5\mathrm{GW} \leq P_{\mathrm{fus}} \leq 1.8\mathrm{GW}$ in 2025) 1, to reduce the risk the centre column, the design has moved to a larger baseline (SPP-2) with $R_{\mathrm{geo},2} = 4.3\mathrm{m}$ , $B_{t,2} = 3\mathrm{T}$ but with the same fusion power range and aspect ratio, leading to a similar $I_p$. Plasma solutions for the larger design have proven to be more challenging in some areas, while making it easier to find an exhaust solution. To handle the heat load in the divertor at this high fusion power a core radiation fraction $f_{\mathrm{rad}} = P_{\mathrm{rad}}/P_{\mathrm{heat}} \sim 0.7$ is adopted. Recent efforts to explore solutions with lower recirculating power have led to plasma flat-top operating points at lower $f_{\mathrm{rad}} \geq 50\%$ and lower fusion power $P_{\mathrm{fus}} \geq 1\mathrm{GW}$ that open attractive opportunities for the plasma and the machine design, whilst still meeting the objectives. The physics basis for STEP has grown considerably, reducing uncertainties in plasma core performance, divertor performance, control and operations without type-I ELMs. The onset of high core transport fluxes in high β regimes with low torque input due to the dominant hybrid kinetic ballooning mode (hKBM) turbulence is now understood. The competition between the Reynolds and Maxwell stresses with respect to zonal flow generation leading to these high fluxes is governed by a a threshold ${q^2}_e = f(\hat{s}, \gamma_E)$ ($\hat{s}$: magnetic shear, $\gamma_E$: E×B flow shear). This has been used to optimise the flat-top solution in SPP-2. Although, most of the scenario exploration is done with using JETTO or RAPTOR with $_N$ feedback used to achieve the required $P_{\mathrm{fus}}$ , codes like an ST optimised version of TGLF or a newly developed quasilinear model for hKBM transport provide flux driven predictive capabilities. Machine learning has been used to provide surrogates for faster scenario evaluation. An optimised divertor design has been developed to provide good detachment access and efficient He exhaust at the same time. The first coupled core edge simulations are being used to understand the impact of He and Ar on the scenario performance. A novel scheme for vertical control in double null has been developed and tested on TCV. A runaway electron (RE) beam mitigation coil (REMC) has been incorporated into the design to provide a feasible solution to dissipate the RE current in combination with shattered pellet injection. This reduces a key risk to the STEP plasma scenario by deconfining >75% of the REs in less than 0.1 ms . A manageable R&D programme to develop key diagnostic systems for STEP is being established. This paper will give an overview of the most important aspects in which risk and uncertainty in of the STEP plasma scenario has been reduced. Considerable progress has been made in STEP scenario modelling capability but still many challenges remain. The burning plasma solution is driving physics development at the forefront of fusion research.

*This work has been funded by STEP, a major technology and infrastructure programme led by UK Industrial Fusion Solutions Ltd (UKIFS), which aims to deliver the UK's prototype fusion powerplant and a path to the commercial viability of fusion. To obtain further information on the data and models underlying this paper please contact PublicationsManager@ukaea.uk.*

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**Track Classification:** Magnetic Confinement Fusion (MCF): Scenario Development, Heating and Current Drive (MCF)

Contribution ID: **638** Type: **Oral Presentation**

# Development of High-$\beta_p$ Scenarios towards High-Q on EAST in Support of ITER Steady-state Operation

To advance the steady-state operation of ITER and achieve high fusion gain (high-$Q$) in tokamak devices, experimental research on high poloidal beta ($\beta_p$) plasma scenarios was conducted on EAST, focusing on ITER-relevant compatibility, fully non-inductive operation, and tungsten (W) divertor adaptation. High-performance high-$\beta_p$ plasma was successfully demonstrated via radio frequency only heating (ECRH, LHCD, ICRF), with key parameters including excellent confinement $H_{98y2} = 1.5$, bootstrap current fraction $f_{\mathrm{BS}} = 50\%$, Greenwald fraction $n_e/n_G = 0.82$, and $\beta_p \sim 3.0$ / $\beta_N \sim 1.8$ maintained for 100 seconds at $B_t = 2.5\,\mathrm{T}$ and $q_{95} \sim 7.0$.

For steady-state operation of W-divertors towards high-$Q$, fully non-inductive high-$\beta_p$ plasmas with a boron-coated wall were developed at $q_{95} = 6.0$, $n_e/n_G = 0.65$, $B_t = 2.5\,\mathrm{T}$. Driven by dominant electron heating, this plasma achieved $H_{98y2} = 1.35$ and $\beta_p = 2.1$ / $\beta_N = 1.85$, and exhibited a series of superior physical characteristics: an internal transport barrier (ITB) that effectively suppresses plasma turbulence, small edge-localized modes (ELMs) with a frequency $f_{\mathrm{ELM}} > 2.5\,\mathrm{kHz}$, effective control of tungsten impurity accumulation, a flat core current density profile with $q_{\min} > 1$, and suppression of $3/2$ tearing modes via ICRF heating. Transport simulation results showed that $\alpha$-stabilization induced by Shafranov shift is the dominant factor governing turbulent transport. The electron thermal ITB is mainly controlled by trapped electron mode (TEM) turbulence, and zonal flow shearing in the ITB region exerts a regulatory effect on TEM-induced energy transport. Notably, increased plasma density and $\beta_p$ were found to elevate the bootstrap current fraction $f_{\mathrm{BS}}$, broaden the current density profile, and further improve plasma energy confinement.

Subsequent experiments were performed with ITER-like heating and ITER-shaped (LSN) combinations (ECRH, ICRH, NBI), alongside plasma current scanning in the range $q_{95} = 5.0$–$6.0$. The results indicated that increased plasma current caused $H_{98y2}$ to decrease from 1.35 to 1.1 and reduced the SOL density. Additionally, edge plasma parameters were found to exert a significant influence on the coupling and absorption efficiency of RF heating.

For further optimization of ITER-configuration plasma scenarios with enhanced capability on EAST, future research will focus on adopting a moderate safety factor $q_{95} = 5.0$ to extend fusion performance, employing ITER-like heating configurations, adjusting the ion-to-electron temperature ratio $T_i/T_e$ via ion heating, and broadening the current density profile $j(r)$ to form a full-channel ITB with $q_{\min} > 2.0$, which can effectively prevent the onset of low-order tearing modes.

The experimental results obtained on EAST provide important technical support for ITER's new research plan, including the material switch of the first wall to tungsten. Furthermore, these findings offer critical physical insights for the development of high-performance plasma scenarios in future fusion power plants.

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**Track Classification:** Magnetic Confinement Fusion (MCF): Scenario Development, Heating and Current Drive (MCF)

Contribution ID: **641** Type: **Oral Presentation**

# Gyrokinetic investigation of microturbulence in the edge of ELM suppressed H-modes in ASDEX Upgrade

High confinement mode (H-mode) access in tokamaks is based on the formation of a radially narrow steep gradient region in the plasma edge and a concomitant radial electric field ($E_r$).
There is growing evidence that the profiles of temperature and density in the H-mode edge are partly determined by turbulent transport connected with microinstabilities driven by the steep gradients and its interplay with the $E \times B$ shear flow related to the $E_r$-well.
Through a gyrokinetic investigation with the code GKW it is shown that the slab branch of the ion temperature gradient (ITG) driven instability is dominantly unstable under edge conditions of edge localized mode (ELM) suppressed H-modes in ASDEX Upgrade (AUG).
This work explicitly takes into account the gyroaverage in the background $E \times B$ shear flow model.
It is shown that this has significant impact on linear stability and turbulent transport:
The slab ITG is then hardly stabilized and turbulent transport is not reduced when a gyroaveraged $E \times B$ shear flow is added.
This lack of stabilization renders the slab ITG a strong candidate for setting the ion temperature profile in the steep gradient edge region.
Furthermore, a sign sensitive $E \times B$ shear flow induced radial symmetry breaking of slab ITG Eigenmodes is discussed.
In the inhomogeneous $E_r$-well this symmetry breaking mechanism determines the most unstable Eigenmode and renders linear stability and turbulent transport highly sensitive to the sign of the $E \times B$ shear flow.
Hence, it is not only the magnitude of the $E \times B$ shear rate, but also its sign which determines microturbulence in the steep gradient edge region.
Finally, three-dimensional (3d) magnetic perturbations (MPs), applied in the considered AUG scenario to suppress ELMs, are shown to impact slab ITG turbulence:
Single helicity 3d MPs with high mode number parallel to the ambient magnetic field destabilize the slab ITG and thereby augment turbulent transport.
The 3d MP aided increase of slab ITG turbulence and connected particle transport might relate to the density pump-out responsible for ELM suppression.

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**Track Classification:** Magnetic Confinement Fusion (MCF): Edge and Pedestal Physics (MCF)

Contribution ID: **644** Type: **Oral Presentation**

# Control the intensity of the induced flow in a liquid by a dual-frequency APPJs

Dual-frequency atmospheric pressure plasma jets (APPJs) represent a promising method to manipulate the ion transportation and the plasma propagation on a surface 1. Despite the potential shown by these unique devices, the fundamental mechanisms through which such systems interact with a liquid substrate and govern the induced liquid flow have not been investigated yet. In this work, we implemented a coaxial dual-frequency configuration employing an upstream high-frequency electrode (HF) at 17kHz and a downstream radio-frequency (RF) electrode at 27.12 MHz 1.
Within this configuration, the plasma discharge is mainly sustained by the RF Ω-mode ionisation regime at twice the RF oscillation frequency (54 MHz). Concomitantly, the HF high-voltage electrode modulates the thickness of the sheath at the liquid interface, triggering the RF γ-regime through secondary electron emission. Time-resolved measurements of the electrode voltage, surface charge on the substrate and optical emission above the liquid substrate demonstrated the transition between the two RF ionisation modes.
To quantify the electrohydrodynamic forces (EHD) within the liquid phase, Particle image velocimetry (PIV) was performed using graphene oxide (GO) as tracers in solutions of varying conductivity.
A significant finding in our work has been revealed by comparing different operational modes. Pulsed HF signal combined with continuous RF excitation led to a discharge with electrical features dominated by the HF component, while the upward induced flow observed is consistently similar to the RF-only operation. These flows remain lower compared to the non-pulsed dual-frequency condition. Moreover, evaporation rate measurements exhibit a strong correlation with the applied RF power, opening possibilities for a precise flow control by reducing the applied RF power combined with micro- or nanosecond pulse generation techniques.

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**Track Classification:** Low Temperature and Dusty Plasmas (LTDP): Liquid Plasma Interaction (LTDP)

Contribution ID: **647** Type: **Oral Presentation**

# Hyper Boris integrators for kinetic plasma simulations

Particle-in-cell (PIC) simulations are important research tools in theoretical plasma physics. Inside the PIC code, the particle integrator is extensively used to solve the Newton-Lorentz equation to advance charged particles. The Boris method (Boris 1970; also known as the Buneman-Boris method) has been the de facto standard particle integrator for more than a half century. It has second-order accuracy in time — the numerical error is proportional to the square of the timestep, ~ (dt)^2.
In this presentation, we propose three extensions to the nonrelativistic Boris solver. First, we introduce n-times subcycling: we repeat the numerical procedure n-times, with an n-times smaller timestep of dt/n. This allows us to solve the equation with better second-order accuracy, ~ (dt/n)^2. Second, we extend the second-order Boris method to higher order. In addition to the well-known "gyrophase correction" to the magnetic field, we use an anisotropic correction to the electric field, to achieve fully higher-order accuracy, ~ (dt)^N [N = 2, 4, 6…]. Third, we combine these two methods to amplify their benefits. We call the hybrid method the hyper Boris solvers, because it has two hyperparameters of the subcycling number n and the order of accuracy, N. The accuracy of the n-cycle Nth-order solver is remarkably high, ~ (dt/n)^N, even though its computational cost is affordable.
For further details, see S. Zenitani & T. N. Kato, *Comput. Phys. Commun.* 2025, doi:10.1016/j.cpc.2025.109695.

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**Track Classification:** Basic, Space and Astrophysical Plasmas (BSAP): Fundamental Plasma Physics - Theory (BSAP)

Contribution ID: **665** Type: **Oral Presentation**

# Innovative Ignition Concepts in Laser-Driven Inertial Fusion: Toward High-Gain Regimes

Inertial Fusion Energy (IFE) is increasingly regarded as a credible long-term option for large-scale, carbon-free power production. The recent demonstration of ignition with net target gain at the National Ignition Facility (NIF) marks a decisive scientific milestone for laser-driven inertial confinement fusion (ICF). Since 2022, repeated ignition shots have been achieved, with fusion gains increasing from ~1.5 1 to above ~4 by 2025. These results validate decades of theoretical and experimental efforts devoted to implosion symmetry control, instability mitigation, and ignition physics. Yet single-shot ignition at gain of a few is not equivalent to a viable energy pathway. An economically relevant fusion system delivering >750 MW of electricity would ultimately require repetition rates of the order of 10 Hz and target gains exceeding 100. Although advances in laser efficiency, target production and injection, and reactor technologies are indispensable, the achievable fusion gain remains fundamentally conditioned by the underlying ignition physics. In this respect, the central question is not merely how to scale present approaches, but whether alternative ignition regimes offer intrinsically more favorable gain margins and robustness.
This talk will therefore focus on a comparative assessment of advanced ignition concepts aimed at substantially increasing target gain beyond conventional central hot-spot ignition. Concepts proposed over the past three decades –including shock 2 and shock-augmented ignition 3, electron- [4] and proton-driven fast ignition [5], and magnetized inertial confinement fusion [6] –will be evaluated in terms of physical robustness, scalability toward high gain (>100), sensitivity to asymmetries and instabilities, and compatibility with existing or emerging large-scale laser infrastructures.
Drawing on 25 years of research and teaching experience and a synthesis of key reference works, I will propose an independent perspective on the most promising physics-driven strategies for substantially increasing fusion gain within the current international academic and emerging semi-industrial ecosystem. Particular emphasis will be placed on identifying the critical physical bottlenecks that may ultimately determine which approaches can realistically mature in the coming decades.

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**Track Classification:** Beam Plasmas and Inertial Fusion (BPIF): Inertial Confinement Fusion (BPIF)

Contribution ID: **673** Type: **Oral Presentation**

# Confined microparticle displacement caused by electrode-photon interaction

When confined in a horizontally near-flat potential well in the plasma sheath region, microparticles are very sensitive to perturbations in their horizontal force balance. In this contribution we present experiments where glass microparticles confined in the sheath region of a radio frequency driven parallel plate argon plasma, react to laser light hitting surfaces near the potential well. The bottom electrode in this configuration has a shallow groove to create a potential well to confine the microparticles. When the sides of this groove are illuminated, the confined microparticles move away from the illuminated area. This displacement caused by the interaction of the light and the electrode is unexpected as the energy of the laser photons are well below the work function of the illuminated electrode surface.

To find an explanation for these observations, multiple parameters have been varied. In the presented experiments variations in laser wavelength, surface material, illumination direction, and surface geometry were considered. The confined microparticle displacement is dependent on the wavelength of the light, and stronger displacement is seen for higher intensities. Furthermore, the location and direction of illumination also influence the amount of displacement together with the surface geometry. The results of these experiments are presented, along with hypotheses for possible explanations of the observed effect and plans for future research to understand this phenomenon.

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**Track Classification:** Low Temperature and Dusty Plasmas (LTDP): Dusty and Strongly Coupled Plasmas (LTDP)

Contribution ID: **687** Type: **Oral Presentation**

# Reconstructing plasma density structure from shadowgraphic images of a pulsed-power-driven reconnection layer

We present updated results from magnetic reconnection experiments with both strong radiative cooling and the plasmoid instability [1,2]. These two plasma processes are intertwined with reconnection events across a wide range of astrophysical environments, including the interstellar medium, the solar chromosphere, and black hole accretion disks. The MARZ (Magnetic Reconnection on Z) experiments at Sandia National Laboratories investigate these key physics of astrophysically-relevant reconnection in the laboratory. The MARZ pulsed-power platform consists of two exploding aluminum wire arrays, through which a large current (20 MA, 300 ns rise time) is driven by the Z Machine, to generate a reconnection layer. In three separate MARZ experiments, the spacing between the two arrays was shifted; in changing the inflow parameters (velocity, density, field), we vary the reconnection layer formation and evolution. Using a laser imaging diagnostic, we take time-resolved measurements of the density structures in and near the layer. We gain a qualitative understanding of the features in these experimental images by comparison to synthetic shadowgrams produced from 3-D MHD simulations. These features include: a dense layer with temporally-increasing density gradients due to radiative collapse; standing MHD shocks outside the layer; and apparent nonuniformities along the axial direction consistent with instabilities. Quantitative measurements of these time-evolving density structures is challenging; our experimental shadowgraphic data exhibits large intensity variations, caustics, and noise. As-such, we have adopted a forward model approach: we fit our experimental intensity profiles to model profiles, which are quickly computed from a simple parameterized model of the layer structure. Fitting techniques, such as differential evolution and nonlinear least-squares, survey the multidimensional parameter space to find the best-estimates of the layer density jump, width, and length.

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*Funding Acknowledgements:*

This work is supported by the Department of Energy's NNSA Stewardship Science Graduate Fellowship (SSGF) program under Cooperative Agreement DE-NA0003960. We also acknowledge funding through NSF EAGER PHY2213898. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

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**Track Classification:** Basic, Space and Astrophysical Plasmas (BSAP): Laboratory Astrophysics (BSAP)

Contribution ID: **697** Type: **Oral Presentation**

# Permanent magnet-based focusing setup for MeV/c electron-positron pair beams

Relativistic outflows enriched with electron-positron pair plasma can be found in various highly energetic astrophysical environments, such as those around active galactic nuclei, black holes, or in the jets of gamma ray bursts. Understanding the mechanisms involved in the generation of particular types of plasma instabilities during the propagation of such jets is important in order to explain the radiative signature of their outflows observed on Earth. Until now, the understanding of electron-positron pair plasmas has been based on numerical studies limited in the quasi-linear regime, while experimental realizations of high charge density, quasi-neutral beams have been challenging. In our experiments, inaugurating and improving a newly developed experimental platform for such studies at the HiRadMat facility of CERN, high intensity, high density, ultra-relativistic, quasi-neutral electron-positron pair beam production was achieved, opening up the possibility to study the microphysics of such pair plasmas via experimental means.

In our experiments, we confirmed that the growth of plasma instabilities as the pair beam propagates through ambient plasma is greatly affected by the divergence and momentum spread of the pair beams. We present a study on the implementation and the performance limitations of a beam focusing setup used in one of our experiments. We designed a quadrupole triplet, based on custom-made permanent magnet quadrupoles, aiming to improve the optical and momentum properties of the electron-positron pair beam towards an increased e-/e+ density. A comparison between the experimental results and the expected performance given by different computational tools, along with the challenges of such a setup that should be considered for future implementations, is presented in this work.

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**Track Classification:** Basic, Space and Astrophysical Plasmas (BSAP): Laboratory Astrophysics (BSAP)

Contribution ID: **713** Type: **Oral Presentation**

# Experimental Investigation and Numerical Multi-scale Modelling of Weakly Collisional Shocks

Shocks are fundamental drivers of energy dissipation in both astrophysical and laboratory plasmas. A quantitative understanding of how shock dynamics evolve as particle collisions become infrequent, transitioning from collisional to collisionless regimes, remains a frontier problem. Even in the collisional regime, the thermal precursor acts as a critical region where non-thermal effects may emerge [1, 2]. Non-thermal ions can counter-stream against the bulk flow, modifying the shock structure and potentially driving kinetic instabilities.
We present high-resolution, time-resolved measurements of shock profiles with Mach numbers ranging from 3 to 5, obtained from experiments at the LULI2000 and GEKKO XII facilities. Using collective optical Thomson scattering, we have mapped the evolution of electron and ion temperatures and densities to resolve both the forward and a reverse shock with unprecedented detail. To analyze these data, we developed a Bayesian analysis framework that self-consistently accounts for multiple ion species, resolving their individual temperatures and relative fractions.
To interpret the experimental results, we employ a dual-modeling approach: extended-MHD3 simulations to capture large-scale plasma dynamics and fully kinetic particle-in-cell simulations[4] to isolate the underlying microphysics. Our results reveal a broad forward shock transition and significant interpenetration between the piston and the background plasma in the downstream region. Furthermore, we observe strong heating of the carbon population immediately ahead of the forward shock, suggesting a significant modification of the energy partition across the shock front driven by kinetic ion behavior.
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**Track Classification:** Basic, Space and Astrophysical Plasmas (BSAP): Laboratory Astrophysics (BSAP)

Contribution ID: **718** Type: **Oral Presentation**

# Characterization of a high-repetition-rate laser filament-induced plasma in air using optical emission spectroscopy

When ultrafast laser pulses with sufficient peak power propagate through transparent media, laser filamentation arises from the dynamic interplay between self-focusing and photoionization-induced plasma defocusing. The plasma can be described as an initial primary photoionization-driven plasma and a secondary plasma, governed solely by plasma kinetics. As modern laser systems reach higher repetition rates, interpulse times approach plasma-kinetic timescales, and accumulation effects may arise 1. As such, simulation and characterization of plasma-chemical kinetics in laser-induced filamentation are becoming increasingly important to account for the plasma's molecular composition and its influence on optical properties.

In this work, we investigate how accumulation effects at elevated repetition rates affect photochemical reactions and alter the molecular composition of filament-induced plasmas. We measure the time-dependent plasma dynamics and key parameters—including gas temperature, electron temperature, electron density, and species-specific decay times—for filaments generated at a repetition rate of 10 kHz.

The experimental setup employs a Yb-based thin-disk regenerative amplifier (DIRA 500-10, TRUMPF Scientific Lasers) delivering sub-picosecond pulses at a central wavelength of 1030 nm and pulse energies of 2.5 mJ, 5 mJ, and 10 mJ. The pulses are tightly focused to promote filamentation and plasma ignition. Plasma characterization is performed using optical emission spectroscopy with an echelle spectrometer coupled to an intensified charge-coupled device (ICCD) camera, providing a resolution of 500 ps.

Analysis of the vibrational distributions and temporal evolution of molecular nitrogen emission bands enables identification of the excitation mechanisms responsible for nitrogen photoemission 2. Electron density, electron temperature, and gas temperature are quantitatively determined from emission spectra and optical filament images within a collisional-radiative modeling framework, which was adapted from the diagnosis of electrically driven plasmas 2.

This diagnostic approach complements conventional optical probing techniques commonly used in filamentation studies 3, offering a comprehensive characterization of the plasma wake from a single measurement. It provides insight into changes in optical properties caused by the formation and extinction of molecular species. To our knowledge, this represents the first study of laser-filament-driven plasma at a 10 kHz repetition rate, where plasma wake characterization becomes particularly important due to reduced interpulse times and potential accumulation effects.

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**Track Classification:** Low Temperature and Dusty Plasmas (LTDP): Other - LTDP

Contribution ID: **759** Type: **Oral Presentation**

# Influence of a soft plasma wall on the millimeter sized low pressure argon plasmas

Electrodes and other solid boundaries are invariably separated from a plasma by a non-neutral transition region known as the plasma sheath. Depending on the discharge pressure and plasma parameters, the sheath has a minimum thickness on the order of the electron Debye length.The intrinsic properties of the wall material, including its electrical conductivity, surface roughness, and chemical composition, may affect the plasma facing the wall. Macroscopic gaps, pores, or cavities in the surface are effectively filled with plasma only if their characteristic size is comparable to or larger than the sheath thickness; otherwise, the sheath may span across these features, preventing l plasma infusion.
To investigate how aeroglass 1 affects low-pressure (10 - 1000 Pa) argon plasmas, we generated a plasma inside a central millimeter-wide hole in an aeroglass cylinder. The cylinder had a height of 8 mm and a diameter of 8 mm. As the bore radius decreases, the ratio of the interface area to the plasma volume increases, thereby enhancing the relative influence of surface-related processes. Under such conditions, any material-specific effects of the aeroglass on plasma density, electron temperature, or discharge stability should become more pronounced and experimentally accessible.
Plasma diagnostic was performed using electrostatic double probes, enabling local measurements of plasma parameters without the need for an external reference electrode. At discharge pressures of < 700 Pa, we observed the emergence of a high-density plasma mode that was not present when conventional wall materials were used under otherwise identical conditions. This finding suggests that the aeroglass walls play an active role in the modification of the plasma wall interaction.

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**Track Classification:** Low Temperature and Dusty Plasmas (LTDP): LTP Plasmas for Sustainability (LTDP)

Contribution ID: **766** Type: **Oral Presentation**

# Hamiltonian simulation of spectrally truncated ideal fluids on quantum computers

The ongoing development of quantum computers may pave the way for
improvements in the state of the art of fluid and plasma simulations. While the Hamiltonian nature of quantum mechanics makes quantum computers natural tools for simulating Hamiltonian dynamics, we propose an approach to fluid dynamics that explicitly exploits the underlying Hamiltonian structure of ideal fluids.

More precisely, we consider the simulation of spectrally truncated fluid equations, such as the inviscid Burgers'equation and the multidimensional Euler equations. We embed the nonlinear fluid dynamics into a Liouville equation defined in a configuration space, describing the linear evolution of the probability density. This linear evolution can be efficiently implemented on a digital quantum computer, as it is both linear and unitary.

The proposed quantum algorithm relies on three main steps: (i) efficient and physically motivated state preparation, (ii) Hamiltonian-based time evolution, and (iii) recovery of the original fluid variables through measurement of the averaged position of the probability density.

These results open new perspectives for encoding and simulating fluid dynamics on quantum computers, and pave the way toward the quantum simulation of ideal magnetohydrodynamics.

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**Track Classification:** Basic, Space and Astrophysical Plasmas (BSAP): Fundamental Plasma Physics - Theory (BSAP)

Contribution ID: **797** Type: **Oral Presentation**

# Turbulence-Driven Magnetic Reconnection: From Cluster and Magnetospheric Multiscale to Plasma Observatory

Both magnetic reconnection and turbulence are fundemental plasma phenomena active across laboratory, space, and astrophysical plasmas. Magnetic reconnection events initiated within the tangled magnetic fields produced in turbulent plasmas have long been thought to play an important role in turbulent dynamics. These events have traditionally been challenging to examine from either a numerical or experimental perspective due to their small-scale nature and the complex magnetic topologies involved. However, multi-spacecraft measurements from the natural plasma environments in near-Earth space have provided a step-change in understanding this complex phenomenon. Since the days of ESA's Cluster mission, evidence has been found for turbulence-driven magnetic reconnection embedded within the turbulent fluctuations of Earth's magnetosheath, making it an ideal location for studying the physics and importance of turbulence-driven magnetic reconnection. In this presentation, we will highlight the observational insights into turbulence-driven reconnection that have been enabled by the systematic identification and analysis of reconnection events in Earth's magnetosheath by missions such as NASA's Magnetospheric Multiscale (MMS) and ESA's Cluster missions –including the importance of so-called electron-only reconnection and estimates that suggest magnetic reconnection can account for a significant fraction of the energy dissipated in turbulent plasmas. Using kinetic simulations of turbulence reminiscent of the plasmas found in Earth's magnetosheath, we will further demonstrate and evaluate how multi-scale measurements from a mission such as ESA's proposed seven-spacecraft Plasma Observatory mission will enable key observational constraints characterizing the 3D structure and distribution of turbulence-driven magnetic reconnection events that will usher in a new era of advancements on the subject.

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**Track Classification:** Basic, Space and Astrophysical Plasmas (BSAP): Solar and Space Plasmas (BSAP)

Contribution ID: **798** Type: **Oral Presentation**

# First electron acceleration from a tunable-velocity laser wakefield

Laser-wakefield accelerators (LWFAs), which accelerate electrons in plasma waves driven by short intense laser pulses, have demonstrated the ability to produce high-quality electron beams with energies up to several GeV. One of the fundamental limitations for reaching ever higher energies is dephasing, when ultrarelativistic electrons outrun the wakefield and slip into its decelerating phase. A promising approach to overcoming this limitation is the use of structured light pulses to control the on-axis intensity propagation velocity of the laser pulse [1, 2].

Here, we report on the first experimental observation of electron acceleration in a tunable-velocity wakefield and mitigation of dephasing using structured light pulses 3. In the experiments, a 1.5 J, 27 fs laser pulse is focused using an axiparabola, a specialized mirror that produces quasi-Bessel beams with an extended focal line. The on-axis intensity propagation velocity is further modified by applying pulse-front curvature (PFC) before reflection. Through its interaction with a gas jet, we demonstrate that this structured light pulse creates coherent plasma wakefields capable of injecting and accelerating electrons to high energies. We further show that changing the PFC value induces a statistically significant shift in the cutoff energy of the accelerated electron spectrum, demonstrating experimental control over the wakefield velocity and partial mitigation of dephasing. The experimental results are supported by comprehensive simulations including FLUENT simulations of the gas density profile, axiprop simulations of the reflected laser pulse propagation from the axiparabola to the focal region, followed by particle-in-cell simulations of the structured light pulse with the obtained gas density and laser profiles.

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**Track Classification:** Beam Plasmas and Inertial Fusion (BPIF): Laser-plasma Acceleration of Particles and Plasma-based Radiation Sources (BPIF)

Contribution ID: **800** Type: **Oral Presentation**

# Efficient gamma-ray generation via relativistic two-wave resonance driven by ultra-intense lasers

We investigate an efficient mechanism for gamma-ray generation based on relativistic two-wave resonance driven by ultra-intense counter-propagating laser pulses in a strongly magnetized plasma. In the presence of a sufficiently strong external magnetic field, electrons can simultaneously resonate with both laser fields, enabling sustained and coherent energy transfer from the electromagnetic waves to relativistic particles. This dual-resonance configuration leads to rapid electron energization and enhanced high-frequency radiation.

Using a combination of analytical modeling and particle-in-cell simulations that incorporate radiation reaction effects, we identify the parameter regime in which relativistic two-wave resonance is established and maintained. When the resonance condition is satisfied, electron trajectories become strongly phase-correlated with the laser fields and exhibit pronounced transverse oscillations. These dynamics significantly enhance synchrotron emission, resulting in efficient gamma-ray production. The energy conversion occurs on timescales comparable to the laser period, demonstrating a rapid channel for transferring laser energy into high-energy photons.

Our simulations show that a substantial fraction of the incident laser energy can be converted into gamma-ray radiation under optimized conditions. The resulting photon spectra depend sensitively on key plasma and laser parameters, including plasma density, magnetic field strength, and laser intensity, indicating that the emission characteristics can be tuned in a controllable manner.

The mechanism explored here is closely related to resonant wave–particle interactions in extreme astrophysical environments, where relativistic particles interact with intense electromagnetic and Alfvénic fluctuations. Relativistic two-wave resonance thus provides a laboratory-accessible analogue of these high-energy processes.

These results establish relativistic two-wave resonance as a robust and controllable pathway for laser-driven gamma-ray generation, bridging laboratory high-energy-density plasma physics and astrophysical gamma-ray emission mechanisms, and opening new prospects for compact, high-brilliance gamma-ray sources.

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**Track Classification:** Basic, Space and Astrophysical Plasmas (BSAP): Laboratory Astrophysics (BSAP)

Contribution ID: **805** Type: **Oral Presentation**

# Spectroscopic characterization of hydrogen pellet ablation clouds at LHD: analysis of Balmer emission including opacity effects

The use of solid hydrogen pellets in magnetically confined fusion plasmas has been proposed both as a promising fueling technique and as a tool to investigate the effect of impurities on plasma dynamics. Pellets are typically injected at high speed, depositing fuel in the denser inner plasma regions, where the evaporation rate is higher. In this work, we present a spectroscopic model for the characterization of the resulting ablation cloud by analyzing the Balmer emission in the 300–700 nm wavelength range. Atomic level populations were calculated assuming local thermodynamic equilibrium. An extensive dataset of line shapes for transitions up to n = 9 ⟶ 2 was computed using state-of-the-art Stark-broadening simulations. The spectral intensity was obtained by solving the radiation transport equation for a spherical plasma source under uniform conditions. Instrumental broadening was accounted for by convolving the synthetic spectra with a Gaussian function of appropriate width. The model successfully reproduces measured pellet ablation cloud spectra at the Large Helical Device across the entire Balmer region, including both the optically thick Balmer $\alpha$ line and the emission beyond the ionization limit. The inclusion of opacity effects enables an independent estimate of the pellet core radius during the vaporization process. Additionally, it is shown that the use of the Inglis–Teller approach, together with detailed Stark-broadened line profiles, successfully describes line merging and continuum lowering phenomena, whereas other models, such as the widely used Stewart–Pyatt formulation, fail to reproduce the experimental observations.

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**Track Classification:** Magnetic Confinement Fusion (MCF): Plasma Diagnostics and Data Analysis (MCF)

Contribution ID: **813** Type: **Oral Presentation**

# A new instrument for fusion research at the European XFEL

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X-ray radiation in the range of 5 - 20 keV provided by high brightness Free-Electron Laser (FEL) sources offer unprecedented new opportunities for studying phenomena and materials of high relevance to laser-driven fusion. Initial imaging experiments have shown the capability to study how matter is compressed by laser irradiation and how instabilities form and propagate [1,2]. In order to perform such studies more systematically in a dedicated experimental environment, an instrument for fusion research has been proposed for the European XFEL.
European XFEL is an international large-scale user facility for research using x-ray FEL radiation. This radiation is characterized by very intense, ultrashort and coherent pulses, complementary to both synchrotron and visible laser radiation. European XFEL currently offers x-ray FEL radiation in the range from 0.25 to 25 keV (0.05 −5 nm) to seven science instruments, each dedicated to a specific area of application 3. We now proposed a new instrument, coupled to a nanosecond laser with kJ pulse energy at the 3rd harmonic and pulse shaping capabilities, and a complementary femtosecond laser of PW-class pulse intensity. These lasers allow to excite and dynamically compress fusion relevant materials while the coherent, ultrashort and intense XFEL pulse will be used to diagnose the targets by a variety of different x-ray methods with O(200 nm) spatial and femtosecond temporal resolution.
Experiments will address the microphysics and dynamic behaviour of fusion targets during several, early states of compression: Non-uniformities arising from laser imprint, the development of laser-plasma instabilities, plasma formation and the onset of hydrodynamic instabilities, the launch of a shock wave into the target or ablator and, if present, shock propagation in the target, and finally hydrodynamic instability growth leading to mixing. As major x-ray techniques full-field imaging, small angle-scattering, and as well spectroscopic techniques will be available. Using these techniques the experiments will allow investigating the behaviour of different targets materials, e.g. foam or similar, under compression and laser excitation. The time- and spatially-resolved experimental data will provide important benchmarking of high-resolution rad-hydro simulations.
The instrument is expected to start operation before the end of this decade and an increase of the drive laser pulse energy, as well as a dedicated x-ray source, are planned for a second phase.

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**Track Classification:** Beam Plasmas and Inertial Fusion (BPIF): Inertial Confinement Fusion (BPIF)

Contribution ID: **817** Type: **Oral Presentation**

# First laboratory observations of residual energy generation in strong Alfvén wave interactions

In the MHD inertial range (scales larger than ion-kinetic scales) turbulent fluctuations in the solar wind are often Alfvénic in character, meaning that their magnetic and flow velocity fluctuations are proportional to each other and predominantly perpendicular to the background magnetic field. However, observations of the solar wind have shown that there is a significant difference in the energy in velocity fluctuations and normalized magnetic fluctuations. This difference, called the residual energy, should be zero for linear Alfvén waves, but is consistently observed to be negative in the solar wind, with magnetic fluctuations dominating. This work investigates the energy partition in strong three-wave interactions through an experimental campaign on the LArge Plasma Device (LAPD) in an MHD-like regime. Primary (driven) modes are launched from antennas, and secondary modes generated by a strong three-wave interaction are observed. The primary modes are shown to have no residual energy, while the secondary modes have significant residual energy - negative in the "sum"mode and positive in the "difference"mode. These results constitute the first laboratory demonstration that residual energy can indeed be generated by nonlinear mode coupling.

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**Track Classification:** Basic, Space and Astrophysical Plasmas (BSAP): Fundamental Plasma Physics - Laboratory (BSAP)

Contribution ID: **823** Type: **Oral Presentation**

# Counterpart-induced millisecond-scale truncation mechanism of fast radio bursts

The observed millisecond-scale duration is an essential yet mysterious feature of fast radio bursts (FRBs). In this work, we link the observed soft gamma-ray counterpart of FRB 200428 to electron-positron pair cascades driven by Compton scattering and the Breit-Wheeler process. We demonstrate that such pair cascades can truncate FRBs to durations down to millisecond-scale, thereby establishing millisecond-scale upper bounds on their durations. The physical processes involved in the truncation mechanism occur during the propagation of FRBs after their production. Consequently, this mechanism is independent of the specific production mechanism or origin of the FRBs, suggesting that it could potentially operate in all FRBs. Our results lift the constraint on FRB production mechanisms that they must inherently generate bursts lasting only milliseconds.

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**Track Classification:** Basic, Space and Astrophysical Plasmas (BSAP): Astrophysical Plasmas (BSAP)

Contribution ID: **826** Type: **Oral Presentation**

# Core-edge-SOL modelling of density and fuel mix control in JET high current and high-performance baseline plasmas in D, T and D-T

The experiments performed at the Joint European Torus (JET) in the final years of operation give the unique opportunity to investigate future reactor relevant issues. In preparation to the second deuterium–tritium campaign (DTE2) JET team developed a high-current baseline scenario capable of sustaining high performance for 5 s. The scenario was developed in D plasmas through a step-wise increase in plasma current (2.5-4.0 MA), optimised for high performance and repeatability, while minimising particle throughput. However, when reproduced in T and D-T mixtures, with Ip=3.5 MA and BT=3.3 T, the discharge duration was limited to 2–3 s due to weakened ELM activity.
The modelling presented starts from predictive core simulations of these D, T and D-T pulses, performed with JINTRAC equipped with the reduced first-principle based transport model QuaLiKiz. Plasma kinetic profiles, core performance as well as the isotope mixture are well reproduced with a realistic impurity mixture of beryllium, nickel and tungsten. Using COCONUT we extend the simulation domain from core-pedestal to the Scrape-off layer imposing the nominal gas puffing throughput to investigate the role of fuelling in achieving a 50-50 D-T mixture via T gas, D pellets, and neutral beam injection. We are presenting a novel framework of validation with the state-of-the-art models that are being used in ITER re-baselining with D-T isotope segregation and impurities (including W). COCONUT modelling results across isotope mixtures reveal a reduction of core ionisation sources in T and D-T (particularly at low particle throughput) consistent with the experimentally observed weakened ELM activity. Moreover, experiments performed during DTE3 confirmed within the same plasma scenario the possibility of sustaining the pulse in D-T with higher gas puff nominal throughput. Despite the critical importance of density and fuel mix control for future devices, these aspects remain only sporadically explored due to large uncertainties in edge particle sources. The JET baseline scenario offers a unique opportunity to address these ITER relevant conditions (e.g. small compound ELMs, competition between pellet and gas puffing), as it employs multiple fuelling channels with different isotopes, enabling the measured isotope ratio to serve as a constraint for the analysis.

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**Track Classification:** Magnetic Confinement Fusion (MCF): Plasma Turbulence and Transport (MCF)

Contribution ID: **838** Type: **Oral Presentation**

# Verification and validation of AE dynamics with realistic energetic particle distributions in DIII-D plasmas

The linear stability and nonlinear dynamics of Energetic Particle (EP)-driven modes is strongly dependent on the phase space gradients of EP distributions, since these modes are driven unstable by wave-particle resonances locally in phase space 1. Even though EPs are far from thermodynamic equilibrium, their distribution function is often reduced in numerical modelling to local Maxwellians, or more realistic analytical forms taking into account the EP slowing-down physics, which tends to under-estimate the instabilities drive at high EP energy 2. Therefore, for accurate predictions of EP-driven modes dynamics in upcoming burning plasmas and more importantly their cross-scale interaction with microturbulence, which depends heavily on the drive ratio between drift-waves and EP-driven modes 3, realistic numerical distributions are required in kinetic-MHD/gyrokinetic modelling.
In this contribution, we report progress made within the ITPA-EP activities, on the numerical verification and experimental validation of gyrokinetic and kinetic-MHD codes using realistic EP distributions. A DIII-D discharge has been chosen for this activity [4], where the stability of BAEs is influenced by changes in beam injection direction. Realistic EP distributions are obtained from NUBEAM [5]. Such inputs are generally too noisy to initialise $\delta F$ or full-F codes. They are therefore transformed into $\mathcal{C}^2$ distributions in the 3D constants of motion (CoM) space $(E, \mu, P_\varphi)$ by the EPCoM code [6]. In addition to providing numerically smooth distributions, this approach enables a direct identification of instability drive in a phase space where wave-particle resonances can be explicitly identify.
In particular, results from the gyrokinetic codes GTC [7] and the kinetic-MHD codes M3D-C1 [8] and XTOR-K [9] will be presented. These codes agree well regarding the AE linear stability using either EP realistic distributions or equivalent Maxwellians. The AE drive with realistic beam distributions is much stronger than with equivalent Maxwellians. CoM space analysis reveals that although anisotropic beam EPs have less wave-particle resonances available, they lead to stronger drive because the local gradient drive $(n\partial_{P_\varphi} + \omega\partial_E)F_{EP}$ is 10 times stronger than its equivalent Maxwellian. The dependence of AE stability on beam injection angle will be compared between simulations and the experiment, as well as the modes nonlinear saturation and the associated EP transport.

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**Track Classification:** Magnetic Confinement Fusion (MCF): Energetic Particles and MHD (MCF)

Contribution ID: **887** Type: **Oral Presentation**

# Experimental measurement of strong-field QED effects at the ZEUS facility

Strong-field QED (SFQED) is the regime of physics where effective fields are comparable to E<sub>c</sub> = 1.3 x 10<sup>18</sup> V/m, the critical field of QED. In this regime several exotic processes can be observed such as non-linear Compton scattering and non-linear Breit-Wheeler pair production. In addition, radiation reaction - the recoil experienced by particles radiating in these fields - takes a different form from classical predictions and exhibits stochasticity. Such fields and physics are relevant to astrophysical objects like magnetars and pulsars, but experimental investigation of this area is limited by the difficulty in generating such large fields.

Currently the highest power laser beams tightly-focused can still only reach fields of order 10<sup>14</sup> V/m, but when combined with a counter-propagating relativistic particle beam the fields in the frame of the particles are upshifted to order 10<sup>17</sup>-10<sup>18</sup> V/m, close to E<sub>c</sub>. These relativistic beams can be generated by laser-wakefield acceleration, allowing SFQED experiments to be carried out using lasers only as drivers, with the additional advantage that achieving spatial and temporal overlap of the beams is easier. Our collaboration has previously carried out experiments of this type on the Gemini facility [1,2,3], but the ZEUS facility provides higher power beams and therefore access to stronger field interactions.

In this talk we will present an experiment carried out in September 2025 in which electron beams up to 2 GeV were generated by laser-wakefield acceleration and collided with a 200 TW beam focused to intensity ~5 x 10<sup>20</sup> W/cm<sup>2</sup>. The electrons were diagnosed by a magnetic spectrometer, and the gamma rays generated by the collision by a LYSO profiler and CsI stack spectrometer. We will present combined analysis of these, with supporting simulations, to estimate collision parameters and SFQED effects observed.

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**Track Classification:** Beam Plasmas and Inertial Fusion (BPIF): Ultra-high Intensity Laser-matter Interaction and High-field Physics (BPIF)

Contribution ID: **902** Type: **Oral Presentation**

# Plasma facing material in inertial confinement fusion reactors operated in the direct drive dry wall approach

Nuclear fusion is a promising option for future large-scale energy supply. There are two main approaches to fusion energy: magnetic confinement fusion (MCF) and inertial confinement fusion (ICF). In 2022 ICF achieved, by the first time, ignition with gain at the National Ignition Facility (NIF). Since then, several campaigns carried out in it have replicated this milestone, achieving successive increases in gain in each of them. These breakthroughs have motivated a notable increase in public and private funding for the development of projects aimed at the conceptualization of commercial power plants.

Despite the achievements, there are still several challenges that need to be addressed prior to upscaling to a commercial facility. One of them is the development of plasma facing materials (PFMs) able to withstand the combined effects of large thermal loads and radiation environments taking place in these reactors.

In this contribution, we will show the different radiation environments that PFMs have to withstand in ICF reactors operated in the direct drive dry wall approach 1. We briefly introduce the limitations of coarse-grained W acting as PFM 2. Finally, based on a combination of experimental and multiscale computer simulation data, we will discuss the capabilities and limitations of alternative W-based materials to act as PFM: nanostructured W, with a large density of grain boundaries [3–7], and W nanocolumns, with a large surface area [8].

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**Track Classification:** Beam Plasmas and Inertial Fusion (BPIF): Inertial Confinement Fusion (BPIF)

Contribution ID: **929** Type: **Oral Presentation**

# Experimental evidence of in vitro sparing effects for single-pulse, picosecond radiation from a laser-plasma accelerator

Laser-driven plasma accelerators generate ultra-short (picosecond-femtosecond) and extremely high dose-rate ($10^{10}$ -$10^{13}$ Gy/s) radiation sources that can induce unique cellular responses. These beams deliver multi-Gy doses on timescales overlapping with the earliest physico-chemical stages of radiation interaction. We present the in vitro cell response of biological samples to single-pulse, multi-Gy electron radiation, delivered over picosecond timescales.

Single-pulse doses of up to 8 Gy (dose-rates of $10^{10}$ -$10^{12}$ Gy/s), were delivered to two healthy and two cancer human cell lines. Dosimetric characterisation from radiochromic film and Monte Carlo simulations confirmed high beam uniformity across samples, with transverse and longitudinal dose variations of <10 % and 1%, respectively. Biological outcomes were compared with conventional (CONV) 160 kVp X-ray irradiation (2.4 Gy/min).

At doses <3 Gy, responses were consistent with CONV irradiation ($RBE_{50}$ ~ 1 for all cell lines). At doses >3 Gy, a consistent departure was observed, with reduced radiosensitivity indicative of a FLASH-like sparing effect. This was reflected in decreased $RBE_{10}$ values ($RBE_{10}$ ~ 0.84 for all cell lines).

These results establish the potential of laser-driven plasma sources for investigating radiation responses at previously inaccessible timescales, providing a pathway to mechanistic insight into the earliest radiochemical processes involved in high dose-rate radiobiology.

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**Track Classification:** Beam Plasmas and Inertial Fusion (BPIF): Laser-plasma Acceleration of Particles and Plasma-based Radiation Sources (BPIF)

Contribution ID: **932** Type: **Oral Presentation**

# The effect of the Isotope Mass on Divertor Detachment and Pedestal Performance

This work presents a new integrated study of hydrogen isotope effects on scrape-off layer (SOL) transport, divertor performance, and pedestal fueling combining dedicated DIII-D H-mode experiments together with SOLPS-ITER simulations with full drifts. Matched H and D discharges were specifically designed to isolate isotope effects providing a systematic comparison of pedestal structure and divertor detachment behavior. Increasing isotope mass significantly reduces divertor particle and heat fluxes prior to detachment, with particle fluxes decreasing from H to D. Detached conditions occur at ~15% higher upstream density in H after SOLPS-ITER modeling constrained by experiment indicates that carbon sputtering, rather than neutral mean free path effects, is the primary driver of the observed isotope dependence of detachment access. To isolate the fundamental mass dependence from impurity effects, simulations are extended to pure H, D, and T plasmas with both carbon and tungsten walls. The isotope effect is shown to arise primarily from parallel momentum balance: while pressure and electric-field forces are nearly identical across isotopes, heavier ions experience lower acceleration due to increased inertia, producing slower SOL parallel flows and reduced convective transport. From H to T, target particle fluxes decrease by nearly a factor of two, while divertor heat fluxes decrease by ~10% for each increase in isotope mass. These results provide a comprehensive, experimentally validated predictions of isotope effects for DT operation in future fusion devices.

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**Track Classification:** Magnetic Confinement Fusion (MCF): SOL, Divertor and PWI (MCF)

Contribution ID: **933** Type: **Oral Presentation**

# Turbulence characterization from density fluctuations velocity in fusion plasma using Doppler Backscattering diagnostic

Turbulence-driven transport and its self-regulation by plasma flows play a central role in confinement in magnetised fusion plasmas [1,2]. The perpendicular mean flow velocity ($v_\perp$) and its radial shear facilitate turbulence reduction and transport barrier formation 3. Radial profiles of $v_\perp$ are accessible with Doppler Backscattering (DBS) [4], using density fluctuations as tracers. The measured $v_\perp$ is typically interpreted as the local E×B flow [5–7], but actually includes a contribution from the phase velocity of turbulent structures, usually neglected. Previous experiments have shown a systematic velocity increase at lower wavenumbers, suggesting a scale-dependent contribution on top of the mean flow [8,9].

Characterising the turbulent phase velocity provides access to the turbulence regime and flow-turbulence interaction. Here, such a characterisation is achieved for the first time, with the $k_\perp$ dependence of $v_\perp$ from DBS compared against quasilinear predictions using TGLF with saturation rule 2 [10,11]. A systematic increase of $v_\perp$ at lower wavenumbers is observed across L-mode configurations on WEST [12] and TCV, consistent with a finite phase velocity. This interpretation is verified using a synthetic DBS diagnostic based on full-wave simulations [13] applied to Kolmogorov-like spectra and Hasegawa-Wakatani turbulence [14], consistently recovering phase velocity signatures. The comparison with TGLF-sat2 simulations shows good quantitative agreement, establishing a robust framework for characterising turbulence phase velocity and interpreting DBS measurements.

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**Track Classification:** Magnetic Confinement Fusion (MCF): Plasma Turbulence and Transport (MCF)

Contribution ID: **934** Type: **Oral Presentation**

# Shock propagation in cryogenic deuterium-wetted foams

Low-density polymer foams wicked with cryogenic liquid hydrogen are prime candidates to deliver nuclear fuel in inertial fusion power plants. These targets allow fast filling and uniform distribution of the fuel on the inside of a spherical capsule that is required for high-convergence implosions using laser-driven shock waves driven by ablation pressure. Their design requires high-precision equation of state data and understanding of instability hydrodynamics.
In April 2026, we completed the first cryogenic wetted foam experiment that visualizes shock wave propagation through foams that have been wicked with liquid deuterium at 25K. We utilized high-resolution X-ray imaging measurements at the Titan laser facility at Lawrence Livermore National Laboratory that delivered a 150-J, 600 fs short-pulse laser beam to drive a Cu K-alpha X-ray backlighter source at 8 keV. This setup provides X-ray phase-contrast images with 100 picosecond temporal resolution and 20-micron spatial resolution of the shock-compressed plasma driven by a second long-pulse laser beam at 450 J energies and smoothed with a 600-micron continuous phase plate. Our measurements provide new results on the shock speed and the shock uniformity for various types of foam structures revealing a path towards approaching the uniformity achieved in a pure deuterium liquid. The data further visualize the mixing of foam material with the liquid behind the shock, providing important benchmark data for hydrodynamic simulations of laser-driven fusion targets for inertial fusion energy.
These experiments provide the first measurements of the equation of state of wetted foams and comparisons with liquid deuterium. The results are of critically importance to design inertial fusion targets for public and private fusion efforts.

This work was funded by the DOE Office of Science, Fusion Energy Science under FWP100182. We acknowledge support from Department of Energy (DOE), Office of Science, Fusion Energy Sciences, under Award No. DE-SC 0024882: IFE-STAR was issued as SLAC FWP 101126. The work of XX, JV., SM, and RC was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. DE-AC52-07NA27344.

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