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Report of Contributions

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Contribution ID: **15** Type: **Plenary and Invited Presentation**

Functional Nanocomposites Synthesized through Atmospheric Pressure Plasma Induced Liquid Chemistry

The development of functional bionanocomposites has gained significant attention due to their potential in sustainable materials, biomedical applications, and advanced functional coatings [1-4]. Non-thermal Atmospheric Pressure Plasma Induced Liquid Chemistry (PiLC) is an emerging green synthesis route that enables the fabrication of nanocomposites with tailored functionalities, eliminating the need for hazardous chemicals or extreme processing conditions.

This talk summarizes the work carried out at Queen's University Belfast on the synthesis and functionalization of various bio-based nanocomposites using PiLC, leveraging natural polymers such as nanocellulose and chitosan in combination with inorganic nanofillers like gold and silver nanoparticles. The plasma-liquid interaction plays a crucial role in generating reactive species, leading to nanocomposite with desirable structure and properties. Key physicochemical properties of the resulting nanocomposites such as microstructure, surface chemistry, thermal property and mechanical integrity have been investigated thoroughly. Preliminary results demonstrate the resulting materials have tunable functional properties, making these nanocomposites highly promising for applications in such as biosensing, photothermal conversion and anti-microbial coatings. The study further highlights the potential of PiLC in engineering next-generation bionanocomposites with controlled morphology and superior functionality.

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Track Classification: Low Temperature and Dusty Plasmas (LTDP): Plasma Processing and Applications (LTDP)

Contribution ID: **21** Type: **Plenary and Invited Presentation**

Strong-Field QED Studies with multi PW lasers

State-of-the-art high-power laser systems are now enabling the exploration of quantum electrodynamics (QED) in the nonperturbative, strong-field regime, where electromagnetic fields approach or surpass the so-called critical "Schwinger"limit of QED [1]. In this extreme regime, phenomena such as nonlinear Breit-Wheeler pair production, vacuum birefringence, and quantum radiation reaction effects are predicted to emerge —effects that remain experimentally unobserved under controlled laboratory conditions. Achieving the required field strengths demands laser intensities around 2.3×10^{29} W/cm^2, which greatly exceed the current maximum of 10^{23} W/cm^2 [2]. A promising approach to access this regime involves nonlinear Compton scattering between ultra-relativistic electron beams and ultra-intense laser pulses, offering a practical platform to investigate strong-field QED effects. Resent advances in laser-plasma accelerator technology, particularly laser wakefield acceleration (LWFA) [3], has opened new possibilities for all-optical investigation of strong-field QED, now actively pursued by several research groups worldwide. In our previous study, we experimentally investigated nonlinear Compton scattering in intense laser fields, where a multi-GeV electron simultaneously interacts with hundreds of laser photons. Using LWFA, we generated an ultra-relativistic electron beam and collided it with a high-intensity laser pulse, reaching the quantum nonlinearity parameter corresponding to about half of Schwinger field strength. This interaction produced GeV-scale gamma rays via multiphoton Compton scattering, extending well beyond the linear Compton limit and marking the onset of the strongly nonlinear regime [4]. Here, we present our latest experimental results demonstrating interactions at effective field intensity exceeding the Schwinger limit. We utilized CoReLS 1 PW beamline for scattering laser, increasing its ɑ0 by a factor of four, and collided with 2.2 GeV LWFA-driven electron using another multi PW beamline. The resulting post-collision electron spectra show signatures consistent with radiation reaction effects, calculated using experimental parameters.

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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: **28** Type: **Plenary and Invited Presentation**

Ultrarelativistic radiative spin-polarized plasmas

Ultrarelativistic radiative plasmas represent an extreme state of matter in which radiation reaction and high-energy gamma-ray emission play a central role. When an ultrarelativistic electron emits a gamma-ray photon, radiative spin-flip processes can induce electron spin polarization, implying that such plasmas may become intrinsically spin polarized. This introduces spin polarization as a new carrier of physical information beyond conventional charge and energy diagnostics. In this talk, we focus on the correlation between transient plasma dynamics and the associated spin-polarization signatures. By exploiting spin-polarization signals, we identify several nontrivial plasma phenomena, including asymmetric magnetic structures in laser-driven plasma channels [1], nonlinear filament dynamics driven by Weibel-like instabilities [2], the electron slingshot acceleration mechanism in relativistic collisionless shocks [3], and the emergence of spiral attractors in plasma phase space during magnetic reconnection [4].

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[4] Z. Gong, K. Hatsagortsyan, C. Keitel, PRL 135, 045101 (2025)

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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: **29** Type: **Plenary and Invited Presentation**

3D multiscale modelling of the interaction of structured light with inhomogeneous plasmas: applications to plasma diagnosis.

The use of structured light is opening exciting paths in several fields, taking advantage of the different geometrical and topological structures of these beams. This work presents recent results on the interaction of structured IR, UV, and XUV beams with plasmas. Experimental and modelling results unveil its potential applications in plasma diagnosis, in the fields of Inertial Confinement Fusion (ICF), plasma-based lasers and Laboratory Astrophysics. Using our multiscale, multiphysics computational framework [1] it is possible to model the full process undergone by the system: plasma creation and hydrodynamic expansion; collisional and radiative processes; and the propagation and interaction of UV/XUV beams.

The presentation will focus in recent modelling and experimental results on the interaction of structured light with plasmas: the use of spatio-temporal couplings to create a flying focus and improve the amplification of High Order Harmonics (HOH) in dense plasmas [2] and boost the UV emission of nitrogen filaments; the emission and amplification of structured UV light by cavity-free nitrogen plasmas, with applications in atmospheric air lasing; and the application of HOH beams carrying OAM towards diagnosing hot, dense plasmas [3,4,5], by measuring the perturbation of the wavefront after propagation through the plasma and relating this perturbation to the electron density and its gradient.

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[5] S. López, et al, Opt. Exp., 33, 22, 46285-46303 (2025)

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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: **31** Type: **Plenary and Invited Presentation**

Laser high-harmonic generation in plasma: the new beat wave

In recent years, we have developed a novel framework to describe laser harmonic generation in plasma as an advanced beatwave process [1]. In our framework, all laser pulses are decomposed into modes with pure circular polarisation and "signed"frequencies and wave numbers. Each spectral step in the harmonic generation process can then be described as the beating between two such modes. The resulting harmonic spectrum will then show peaks with regular distribution along a 1-D line or a 2-D grid. We have also developed a novel method to analyse the harmonic radiation that will bring out this regular spectral structure. We apply our framework to the problem of generating harmonics via the interaction of a powerful laser pulse with solid targets with a structured surface and aperture targets with a structured inner edge [1]. We show that regular harmonic spectra are obtained in all cases, and that the spectral peak spacing can be tuned via the structure of the target. We also show how a laser frequency comb can be obtained by first generating a 2-D harmonic spectrum (e.g. frequency and OAM level, or frequency and transverse wave number) and then preferentially selecting a 1-D subset from this spectrum, for which the harmonic peak spacing is wider than in the full 2-D spectrum [2]. The wide range of configurations returning a 2-D harmonic spectrum (laser hitting a complex aperture or a corrugated target, or two laser beams hitting a flat target) guarantees a wide choice of potential frequency combs. Finally, we elucidate the role of symmetries of the original laser-target configuration in predicting the resulting harmonic spectrum [3]. Including these symmetries in our framework allows us to show the connection between our work and well-known mathematical theorems (Noether, Jacobi-Anger) as well as various spectral theorems known from solid-state physics (Laue, Mathieu, Floquet, Bloch).

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[2] R. Trines et al., arXiv:2410.03599 (2024).

[3] R. Trines et al., arXiv:2507.08635 (2025).

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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: **32** Type: **Plenary and Invited Presentation**

Research progress of laboratory astrophysics based on large laser facilities in China

Large laser facilities now enables human to generate extreme conditions in the laboratory that can mimick astrophysical environments, creating a new research field known as "laboratory astrophysics." This field is a primary goal for major international facilities like NIF, Omega, Vulcan, and LULI. In China, large laser facilities such as Shenguang-II (SG-II), SG-III, and Xingguang-III (XG-III) have seen major capability enhancements, opening new opportunities for groundbreaking laboratory astrophysics research. Recently, a series of great achievements have been made on these facilities for experimental simulations of various key astrophysical problems, including the origin of magnetic fields in plasmas, particle acceleration in turbulent plasmas, turbulent magnetic reconnection, and accretion disk and jet formation dynamics. Results indicate the kinetic Weibel instability as a fundamental mechanism for cosmic magnetic field generation [1], reveal inherent particle acceleration mechanisms in turbulent plasmas and magnetic reconnections [2-4], and identify the critical role of magnetorotational instability in accretion processes [5,6]. This talk will summarize these advancements and future plans for laboratory astrophysics in China. [1] Z.H. Zhao et al., Sci. Adv. (2024); [2] D.W. Yuan et al., Nat. Commun. (2024); [3] Y. L. Ping et al., Nat. Phys. (2023); [4] Z.H. Zhao et al., Astrophys. J. Letts. (2025); [5] Z. Lei et al., Commun. Phys. (2024); [6] L.X. Li et al., submitted (2025).

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

Contribution ID: **37** Type: **Plenary and Invited Presentation**

Quantum effects in dense plasmas and how to simulate them

The year 2025 had been designated by UNESCO as the International Year of Quantum Science and Technology. By now, quantum mechanics is the theoretical foundation of most fields of physics. Plasma physics, on the other hand, got away with classical physics methods for a long time. This has changed radically with the growing importance of dense plasmas, both in astrophysics and in the laboratory. The most important current application is inertial confinement fusion that is seeing a dramatic surge of activity in the U.S. and in Europe and where progress crucially depends on reliably taking into account quantum effects.

Starting with a brief historical overview the talk will discuss the broad parameter range that is characteristic for plasmas and where quantum effects are relevant. It will discuss the quantum methods that are available and which of them are of relevance for plasma physics, finishing with an outlook on future developments.

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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: **43** Type: **Plenary and Invited Presentation**

Kinetic plasma turbulence: recent insights from 3D (hybrid-)kinetic simulations

Understanding the properties of turbulent fluctuations and the mechanisms underlying their transfer through scales and dissipation is crucial to understand how turbulence feeds back on the macroscale evolution and energetics of a wide range of space and astrophysical plasmas. In this context, the solar wind and the near-Earth environment are probably the best laboratory for the study of plasma turbulence. Over the past decades, in-situ measurements from space missions have indeed uncovered a complex scenario whereby several collisionless plasma processes may be simultaneously at play within the turbulent cascade (e.g., from magnetic reconnection to wave-particle interaction and cascades in velocity space). Alongside observations, direct numerical simulations have always played a key role in providing a test ground for the existing theories and models of plasma turbulence and turbulent heating.
In this talk, I will discuss recent advances in our understanding of sub-ion-range turbulence and turbulent heating via hybrid-kinetic simulations.

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

Contribution ID: **47** Type: **Plenary and Invited Presentation**

First observation of RMP ELM suppression in a Spherical Tokamak

Edge Localised Modes (ELMs) - a periodic MHD instability ubiquitous in H-mode tokamak plasmas - are projected to degrade the plasma facing components of reactor scale devices, and so pose a threat to the viability of tokamak based commercial fusion power[2]. By applying Resonant Magnetic Perturbations (RMPs) ELMs can be mitigated, in which the ELM frequency is increased and energy content decreased, or suppressed, in which the ELMs vanish entirely and the peaked heat loads of ELMs are replaced by continuous transport[3]. ELM suppression has been demonstrated on many conventional aspect ratio tokamaks, but full suppression was not achieved in any spherical tokamak despite concerted efforts[4], posing a challenge in extrapolating suppression access from current tokamaks to the power plant scale. This work reports the first instances of RMP induced ELM suppression observed on a spherical tokamak –MAST Upgrade –and its interpretation supported by linear MHD modelling of the plasma response to the applied field using the MARS-F code. The application of a dominantly n=3 RMP caused a global deceleration of the toroidal rotation, density pump out and the disappearance of ELM activity, in a stationary ELM suppressed regime maintained for over 300ms. The core electron temperature was unaffected, and plasma pressure stabilised at βN~2.0. While the ne and Te pedestal heights were reduced, H mode was maintained. The evolutions of these and further experiments to explore this regime, and modelling results, will be reported.

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[4] A Kirk et al, 2013, Plasma Physics and Controlled Fusion, 55, 124003

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

Contribution ID: **59** Type: **Plenary and Invited Presentation**

Hall MHD turbulence: implications for intermittency and multiscaling in space plasma physics

Space- and solar-plasma physics continue to pose major challenges for the characterization of turbulence in these systems. Satellite observations of solar-wind-plasma turbulence have shown a fluid energy spectrum with an inertial range with a -5/3 exponent. However, the magnetic-energy spectrum displays MHD- and sub-ion-scale power-law ranges, the former consistent with the -5/3 power, but the latter characterized by an exponent that is approximately -2.8. These observations have examined (a) the multiscaling of velocity- and magnetic-field structure functions and (b) the alignment of velocity- and magnetic-field fluctuations. One study has found simple scaling of magnetic structure–functions in the sub-ion range, but multiscaling in the MHD range. By carrying out simulations of three-dimensional (3D) Hall magnetohydrodynamics (HMHD) turbulence, we show that it provides a natural framework for understanding solar-wind turbulence, and its dependence on non-dimensional parameters in the sub-ion scale. We present several statistical properties of 3D HMHD turbulence and compare them with their counterparts in solar-wind turbulence. We compute (a) the wave-number dependence of spectra and the scale-dependent Alfven ratio on ion-cyclotron and whistler waves and (b) different measures of the intermittency and multiscaling. The power-laws in the energy spectra are under influences of the Alfven ratio, magnetic Prandtl number, and others. We present relationships between the power-laws and these parameters. Intermittency and multiscaling natures are typically characterized by probability distribution functions and structure functions of magnetic field and current density field. We present the intermittency and multiscaling natures not only by the analysis of magnetic and current density fields, but also by relating these quantities to ion-cyclotron modes and whistler modes.
Our analysis can be related to space- and solar-plasma observations, some of which report relevant multi-fractal, multiscaling nature of turbulence. A comparison of such observatory reports with our simulation results with various settings highlights essences of multiscaling nature of turbulence.

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

Contribution ID: **71** Type: **Plenary and Invited Presentation**

Axions in plasmas: from the lab to astrophysics

Axions constitute one of the most elegant and theoretically well motivated extensions of the standard model. Despite the fact of being so far elusive, they have been proposed to solve the apparent breaking of the charge-parity (CP) symmetry in QCD - the famous strong CP problem - by promoting the small CP angle observed in experiments to a field: the axion restores the CP symmetry in QCD dynamically, via a mechanism that is reminiscent to that of the Higgs boson when giving mass to the gauge fields.
On the other hand, the smallness of such CP breaking implies an extremely weak coupling to photons, which renders axions one of the most appealing candidates for dark matter. Altogether, the axion is a most-hunted particle, and a plethora of experiments are currently devoted to its searches. One critical limitation to the current experimental platforms is that they rely on axion-photon conversion, which is a non-resonant process.
A natural way to circumvent this issue is to design experiments using plasmas, thus relying on the resonant axion-plasmon conversion. We show that, by exploiting the physics of electrostatic instabilities taking place in plasmas, we are allowed to increase the conversion probability (or, equivalently, the axion decay rate) by several orders of magnitude. Moreover, by replacing real plasmas by synthetic (meta material) plasmas, we might be able to probe the axion within the parameter region predicted by the QCD.
Finally, given the ubiquity of plasmas in the different astrophysical scenarios, we investigate some consequences of the axion-plasmon conversion in the production of axions in magnetars and discuss the importance of axion conversion in intergalactic plasmas.

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

Contribution ID: **87** Type: **Plenary and Invited Presentation**

Overview and recent results of the Helically Symmetric eXperiment (HSX) stellarator

The Helically Symmetric eXperiment (HSX) is a mid-sized stellarator designed to investigate quasi-symmetry as an approach to stellarator optimization. With its major radius of 1.2 m and magnetic fields up to 1.25 T, HSX routinely achieves electron temperatures above 1 keV, making it a valuable platform for addressing key scientific and technological challenges on the path toward a fusion power plant.

HSX began operation in 2001 and was designed using the same tools and methodologies employed in the development of the W7-X stellarator. Early research centered on demonstrating its neoclassical optimization, which was confirmed through the observation of strong plasma flows, excellent fast-particle confinement, and low core heat fluxes. Current studies focus on validating theories and numerical models of neoclassical, turbulent, and MHD-driven transport, exploring novel divertor configurations, advancing millimeter-wave heating schemes, and developing next-generation fusion diagnostics.

The device's operation flexibility is one of its key strengths. HSX allows rapid installation and testing of new components, and its magnetic geometry can be tailored using a set of 48 planar auxiliary coils. This flexibility has enabled the experimental investigation of quasi-symmetric turbulence-optimized configurations with reduced transport, identified previously using gyrokinetic simulations. HSX can also be configured to operate in deliberately MHD-unstable states, resulting in reduced confinement and strong mode activity measurable with magnetic pickup coils and density and temperature fluctuation diagnostics.

Looking ahead to the needs of the public sector and the broader push toward fusion power plant technologies, the HSX program is preparing for island divertor operation through the installation of new first wall components. Moreover, the device is being upgraded with a new 70-GHz gyrotron to enable increased heating power and higher density operation.

By combining its experimental flexibility with a strong programmatic focus on plasma confinement and technology development, HSX has become a collaborative platform that actively pursues and welcomes partnerships across the public and private sectors to help close key gaps on the path toward a stellarator-based fusion power plant.

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Track Classification: Magnetic Confinement Fusion (MCF): Stellarator Physics and Optimisation (MCF)

Contribution ID: **89** Type: **Plenary and Invited Presentation**

Global gyro-kinetic Ion Temperature Gradient and Trapped Electron Mode turbulence modelling in X-point geometry in negative and positive triangularity.

Tokamak plasmas with sufficiently strong negative triangularity (NT), in contrast to the conventional positive triangularity (PT) shaping, have been shown to suppress the transition to H-mode while still achieving high confinement regimes comparable to H-mode plasmas, but without harmful for plasma facing components (PFC) Edge Localized Modes (ELMs). Comparative modelling of Ion Temperature Gradient and Trapped Electron Modes (ITG/TEM) turbulence in NT and PT plasma shapes was performed using the nonlinear global gyrokinetic electrostatic particle code JOREK-GK in realistic X-point tokamak geometry including the Scrape Off Layer (SOL) for TCV, DIII-D and WEST tokamaks parameters. The numerical scans of upper (□up□ and lower (□low) triangularities at the same plasma profiles demonstrated the existence of the averaged negative triangularity threshold 0.5(□up□□low) < □av□th , showcasing the beneficial stabilizing effect of NT compared to PT on ITG/TEM turbulence. For the WEST parameters tested here the threshold was about □av□th < -0.25. Existence of longer correlation length of density fluctuations in PT compared to NT was demonstrated similar to experimental measurements on DIII-D. Stronger and more sheared zonal flows are generated in NT compared to PT. These factors are stabilizing for TEM/ITG turbulence and lead to smaller heat fluxes and heat conductivities in NT compared to PT plasmas. Bohm-like confinement scaling with normalized ion gyro-radius □* was obtained both in NT and PT, however with better confinement for NT compared to PT which could be a favorable factor for future reactor size machines operation in negative triangularity without triggering ELMs.

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

Contribution ID: **95** Type: **Plenary and Invited Presentation**

The shock-augmented ignition route to high gain inertial fusion energy

With the achievement of ignition at the National Ignition Facility (NIF), the focus of inertial confinement fusion research is turning to schemes relevant to inertial fusion energy. In particular, the move from indirect drive currently used at NIF to direct drive in which lasers illuminate the fusion fuel directly. This is expected to increase the coupling efficiency and reduce driver energy requirements. Novel implosion designs are being sought that can robustly achieve high fusion energy gain.

In the shock-augmented ignition (SAI) approach, the implosion is driven at reduced velocities that provides hydrodynamic stability and is more energetically efficient. With this reduced velocity though, ignition requires the supplemental energy of a late-timed shock wave that is launched by a sudden increase in laser intensity at the end of the pulse. However, high laser intensities stimulate laser-plasma instabilities that direct energy away from driving the shock. The novel feature of SAI is that the igniting shock wave can be launched with substantially reduced laser intensities by introducing a drop in laser power before rapidly increasing again.

The effectiveness of the scheme was experimentally demonstrated on the OMEGA laser system by the performance increase achieved by optimally timing the shock launch. Key performance metrics, such as fusion yield and hot-spot pressure, saw substantial increases when the shock was timed to arrive at the implosion centre at the point of peak convergence. The optimal timing range and trend in performance were closely matched by simulations.

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

Contribution ID: **101** Type: **Plenary and Invited Presentation**

High performance plasmas of the TJ-II stellarator: Experiments and validation of first-principles models

In stellarators and tokamaks, transport of energy and particles in the plasma core critically determines device performance. Therefore, it is essential to identify advanced operational regimes that yield high-performance conditions and understand the mechanisms governing such regimes. In the TJ-II stellarator several routes to improved confinement have been identified, including L–H transitions driven by turbulence suppression via sheared flows and more recently, enhanced confinement induced by pellet injection, resembling pellet-fueled high-performance plasmas in W7-X. A better confinement is achieved already after the injection of a single pellet as well as after multiple pellets. In order to understand the mechanisms behind this confinement improvement a series of gyrokinetic simulations (using stella and EUTERPE) complemented by neoclassical simulations (using SFINCS) have been carried out and compared with power balance analysis estimates and source modeling using HPI2 and ASCOT. The results show that in TJ-II the physical mechanisms behind the improved confinement do not seem to be so tightly linked to a reduction in turbulent transport due to an increase in the density gradient as demonstrated in W7-X. This work contributes to the interpretation and validation of TJ-II high-performance scenarios in the broader context of stellarator research.

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Track Classification: Magnetic Confinement Fusion (MCF): Stellarator Physics and Optimisation (MCF)

Contribution ID: **102** Type: **Plenary and Invited Presentation**

Laser-plasma interactions driven by flying-focus pulses

The flying focus refers to a family of techniques for creating laser pulses with dynamic focal points. The peak intensity of a flying-focus pulse can move independently of the group velocity—along, against, or transverse to the propagation direction—while maintaining a near-invariant profile over distances far exceeding a Rayleigh range. These features enable and enhance laser-plasma applications that benefit from a tunable velocity or an extended interaction length. This talk will summarize the concepts underlying flying-focus pulses, the conventional and plasma optics-based configurations used for their formation, and recent theoretical and experimental advances in their application to laser–plasma interactions. Applications to be discussed include laser wakefield acceleration, nonlinear Thomson scattering, free-electron lasing, direct laser acceleration, THz generation, and tests of vacuum polarization and radiation reaction.

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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: **128** Type: **Plenary and Invited Presentation**

Novel measurements of plasma conditions with a high bandwidth ultraviolet laser using cross-beam energy transfer

The Fourth-generation Laser for Ultrabroadband eXperiments (FLUX) was recently activated at the Laboratory for Laser Energetics to study the effects of laser bandwidth on laser-plasma instabilities. FLUX delivers a spectrally incoherent beam with 5 nm of bandwidth centered around 351 nm to the target chamber of the Omega Laser Facility. FLUX was initially used was used to demonstrate a novel plasma diagnostic that can measure spatially localized plasma conditions. By crossing the FLUX beam with a narrow 351-nm beam in a nitrogen/hydrogen plasma, a broadband electromagnetic beat wave excited ion-acoustic waves in a ~0.004 mm^3 volume was created. The response of the ion-acoustic waves to this beat wave was imprinted on the spectrum of the transmitted FLUX beam. The ion-acoustic resonances transfer energy between the FLUX beam and the narrow band beam (i.e., cross-beam energy transfer (CBET) moves energy between the two beams). The locations and width of the resonant peaks in the output spectrum provide a measure of the electron and ion temperature, respectively, and the magnitude of transfer was used to determine the plasma density. This technique provides an alternative to Thomson scattering and can have powerful advantages in many situations. It also greatly accelerates our ability to validate CBET models, because the entire CBET gain curve is now captured in a single shot. FLUX is poised to deliver data on laser-plasma instability suppression paving the way for next generation ICF designs.
This work is supported by the Department of Energy under contract numbers: DE-NA-0004144 and DE-SC0024863.

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

Contribution ID: **143** Type: **Plenary and Invited Presentation**

On the Way to a Self-Consistent Target Design for Laser Direct Drive Inertial Fusion Energy

Inertial Fusion, proved by the NIF's milestone achievement of ignition and gain of ~4, is a scientifically mature concept for Inertial Fusion Energy (IFE). However, the NIF's indirect-drive method faces challenges in scaling to a commercially required gain of ~100. Laser-Direct Drive (LDD) is a compelling alternative, offering high efficiency gain by coupling ~5× more laser energy directly to the target. This path needs solutions for mitigating Laser-Plasma (LPI) and hydrodynamic instabilities and will need to implement design constraints from target manufacturability and target survival during the injection process. This talk details Focused Energy's program to develop a self-consistent LDD implosion target for an IFE Pilot Plant. Such a target needs to satisfy critical constraints across implosion physics, target fabrication, laser and reactor design. Achieving high confidence in ignition and high gain relies on developing a target manufacturing method that ensures high quality and scales to mass production and additionally on optimizing the laser system for high wall-plug efficiency and robust LPI/hydrodynamic mitigation. Key laser requirements are the implementation of broad spectral bandwidth and temporal beam smoothing. Paired with careful target design choices, these laser system improvements promise to suppress LPI and laser imprint. We will show the concept for our multi-color broadband laser and its implementation within our coming experimental laser facility, designed for LPI and hydrodynamic mitigation studies. Besides, we will present results from LPI experiments using spectrally broadband lasers at PHELIX and FLUX, which are vital to demonstrate the technological feasibility of this LDD mitigation strategy.

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

Contribution ID: **149** Type: **Plenary and Invited Presentation**

Plasma-enabled nanoarchitectures: from synthesis to devices

Plasma and vacuum deposition technologies are transforming the possibilities in nanoengineering, particularly for porous thin films and low-dimensional materials, while also emphasizing sustainability and energy efficiency. In this presentation, we will share our latest advances in applying these techniques to design complex, supported nanoarchitectures with control over composition, morphology, and functionality. A key component of our strategy is the integration of the one reactor concept for vacuum and plasma assisted deposition methods with a soft template approach.[1,2] This technique involves growing single crystal small molecule nanowires under mild conditions compatible with the substrate. These crystalline templates facilitate the fabrication of nanowires and nanotubes with precisely tailored core@multishell configurations, where each shell introduces novel physical responses or synergistic multifunctionality. We will discuss how plasma assisted and vacuum based methods allow for the integration of these nanoarchitectures as supported platforms and device ready architectures while preserving structural integrity and enabling scalable processing. The versatility of these techniques enables the deposition of a remarkable range of materials, including organic molecules, polymer layers, hybrid perovskites, metals, and metal oxides, which can function as conductors, semiconductors, dielectrics, photoabsorbers, piezoelectrics, triboelectric components, or plasmonic elements. The presentation will focus on two application domains where these nanoengineered systems have recently achieved breakthrough results. First, we will demonstrate how these nanoarchitectures facilitate multisource energy harvesting, combining piezoelectric, solar, pyroelectric, and triboelectric mechanisms within a unified platform.[3–5] Our latest achievements involve solar and indoor light photovoltaic cells,[6–8] pyroelectric,[9] piezoelectric and triboelectric nanogenerators,[3–5] and hybrid devices[10] that leverage the complementary nature of these transduction pathways. Second, we will present innovative concepts for smart surfaces, including semi transparent nanoelectrodes,[1] tunable wetting layers,[11] and advanced de icing/anti icing coatings activated by acoustic waves.[12] This emerging area showcases where plasma engineered materials offer unique advantages in terms of robustness, transparency, and energy efficiency.

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Track Classification: Low Temperature and Dusty Plasmas (LTDP): Plasma Processing and Applications (LTDP)

Contribution ID: **151** Type: **Plenary and Invited Presentation**

The transport challenge for fusion power plants at high β_{pol}

Electromagnetic microinstabilities are expected to dominate core transport in the high-β_e conditions targeted by next-generation fusion pilot plants (FPPs) such as STEP [1], where β_e denotes the ratio of electron thermal pressure to magnetic pressure. In the absence of strong sheared flow, nonlinear local gyrokinetic simulations indicate that unstable electromagnetic modes can drive heat fluxes exceeding the available heating power. Predicting transport in this regime is challenging, as such simulations often fail to attain a robust steady state. Instead, as β_e increases, the turbulence becomes more electromagnetic and undergoes a transition from a low-transport state dominated by strong zonal flows to a high-transport state in which zonal-flow regulation is weakened and transport rises sharply.

This work addresses these challenges in the context of STEP. Using the stress-balance framework of Zhang *et al.* [2] and Kennedy *et al.* [3], we provide a predictive description of this transition in terms of the *zonal-flow torque balance*. We confirm that the onset of extreme transport correlates with a critical value of $q^2\beta_e$ (equivalently a limit in β_{pol}), where q is the safety factor, which can lie well below any relevant linear stability boundary in (q, β_e) space. Extensive nonlinear simulations show that the transition is governed by a competition between electrostatic and magnetic-flutter zonal torques: below threshold, the net torque reinforces zonal flows and supports saturation, whereas above threshold electromagnetic torques counteract the electrostatic drive, suppress zonal-flow regulation, and enable electromagnetic runaway. We further show that access to a second-stable regime at sufficiently high β' permits re-saturation at larger β_e, with the ideal ballooning mode threshold providing a useful proxy for delineating this region, with direct implications for flux-driven simulations.

This talk will review these results with a primary focus on their implications for next-generation FPPs. We discuss how the predicted transport regimes constrain viable high-β_{pol} operating scenarios and examine multiple high-performance MAST-U discharges to assess how close present-day experiments approach the predicted $q^2\beta_e$ threshold. Implications for scenario design, including tailoring the q-profile, achieving sufficient heating power, or exploiting profile control to avoid the transition, are discussed.

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

Contribution ID: **152** Type: **Plenary and Invited Presentation**

New Frontier in Aurora Optical Observation by Hyperspectral Camera for Aurora Imaging (HySCAI)

The hyperspectral camera for auroral imaging (HySCAI), which can provide a two-dimensional (2D) aurora image with full-spectrum coverage, was developed to explore a new frontier in auroral optical observation. HySCAI consists of an all-sky lens, a monitor camera, a galvanometer scanner that scans a slit image of the spectrograph onto the all-sky image plane, a grating spectrograph, and an electron-multiplying charge-coupled device (EM-CCD). HySCAI has two gratings: one with 500 grooves/mm for a wide spectral coverage of 400–800 nm and a spectral resolution (FWHM) of 2.1 nm, and the other with 1500 grooves/mm for a higher spectral resolution of 0.73 nm and a narrower spectral coverage of 123 nm. This system was installed at the KEOPS (Kiruna Esrange Optical Platform Site) of the SSC (Swedish Space Corporation) in Kiruna, Sweden, in 2023 [1]. Unlike conventional filter-based cameras, HySCAI captures more than 25 monochromatic images simultaneously, enabling quantitative auroral measurements even under twilight conditions by accounting for background emission. It also provides the spectral shapes of molecular bands. Three key results have been obtained: 1) The two-dimensional distribution of precipitating electron energy, derived from intensity ratios I(427.8nm)/I(630.0nm) and I(557.7nm)/I(630.0nm), shows a sudden increase to 1–2 keV during auroral breakup [2]. 2) The altitude profile of N_2^+ density, determined from the 427.8 nm resonance scattering emission, peaks at 200 km [3], significantly higher than the 130 km predicted by the GLOW model. 3) The rotational temperature of nitrogen, obtained from N_2 1PG and Meinel band spectra, is higher on the north (polar) side and increases with time during red auroral expansion. Data and related resources are available at the Data Repository Aurora Imaging Spectroscopy (DRAIS) in the National Institute for Fusion Science (NIFS) [4]. A second system, HySCAI-2, is under development for installation at Showa Station, Antarctica. It will offer higher spectral resolution for proton aurora velocity measurements and polarization-resolved measurements to investigate electron anisotropy.

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

Contribution ID: **157** Type: **Plenary and Invited Presentation**

Investigation of multi-ion heat transport using new edge main ion measurements at the ASDEX Upgrade tokamak

A high-resolution main ion charge exchange recombination spectroscopy system has been used to characterize the deuterium temperature at the edge of H-mode plasmas in the ASDEX Upgrade tokamak, enabling new advances in edge physics and heat transport studies [1]. Both main ion (TD) and impurity (Tz) temperatures have been measured, revealing temperature differences up to 80 eV, with TD>TZ. These findings, identified at the pedestal top in cases with higher ECRH power, challenge the conventional assumption of TD=TZ due to strong ion collisional coupling [2].
To interpret these observations, the flexibility of the ASTRA code [3] has been exploited, as it allows for independent implementation of the main ion and impurity heat transport equations. Power balance analysis has been carried out to characterize the experimental deuterium and impurity heat conductivities, revealing a significantly higher χz/χD ratio when TD>TZ.
The properties of χz/χD have been explored using gyrofluid (TGLF) [4] and gyrokinetic (GKW) models [5], showing that χz/χD depends on the ion to the electron heat flux (Qi/Qe), in agreement with analytical theory [6]. The compatibility of the theoretical results with the experimental observations have been tested via predictive modeling with ASTRA. The predictive simulations successfully reproduce a temperature difference of 60 eV, consistent with experimental results, providing first-of-a-kind validation of multi-ion heat transport physics at the plasma edge [2].

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

Contribution ID: **160** Type: **Plenary and Invited Presentation**

Stellarator island divertor physics in Wendelstein 7-X: Current understanding and remaining challenges towards a reactor exhaust concept

In recent years, the stellarator concept has attained increasing attention as an alternative path to a fusion reactor. The Wendelstein 7-X (W7-X) experiment has successfully demonstrated power and particle exhaust with the island divertor, achieving high-performance operation and homogeneous detachment. However, the current open divertor geometry suffers from an unfavorable scalings of divertor density and neutral pressure with upstream density, posing challenges for power and particle exhaust towards a reactor. Despite these limitations, W7-X has significant flexibility in operational and magnetic configuration parameters, allowing for a better understanding of the complex 3D geometry and relevant physics, both in full and simplified models. Recent advancements in imaging diagnostics have provided clear signatures of the 3D structure of the island divertor plasma, and emerging reactor-relevant scaling approaches are being developed. Advances in modeling capabilities enable mean-field and turbulence simulations with the drift-reduced Braginskii model, which are paired with W7-X observations to gain insight into island divertor physics. The boundary island geometry is becoming part of magnetic configuration optimization for future reactor designs, and refined insights into geometric island parameters are being developed to tailor properties for new concepts. Initial results suggest promising paths towards reactor-relevant exhaust performance.

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Track Classification: Magnetic Confinement Fusion (MCF): Stellarator Physics and Optimisation (MCF)

Contribution ID: **169** Type: **Plenary and Invited Presentation**

Ultraintense laser-driven terahertz pulses from plasmas

Ultraintense laser-plasma interactions offer a novel approach to generating high-power terahertz (THz) radiation, and have aroused ever-increasing interest. This talk will review the latest progress on the ultraintense laser-driven THz radiation from plasmas. TW-scale THz bursts have been demonstrated experimentally by irradiating a thin foil with a high-intensity femtosecond or picosecond laser pulse. By tuning the laser or target parameters, the THz spectra can be tuned effectively over a wide range of 1~20 THz, and the laser-to-THz energy conversion efficiency can be boosted up to ~1%. Recently, the tens-of-femtoseconds duration and ultrafast recirculation dynamics of fast electrons have been revealed from the THz self-emission, demonstrating a novel in-situ diagnostic of laser plasmas. Such extreme THz pulses enable the previously inaccessible relativistic optics in the THz regime. Recent studies on the THz plasmas, including the strong-field THz ionization of dielectrics, anomalous plasma-induced THz self-focusing, and ionization-induced THz transparency, will also be presented.

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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: **176** Type: **Plenary and Invited Presentation**

ELM suppression and confinement properties in negative triangularity plasmas in ASDEX Upgrade

Recent studies during the 2025 experimental campaign in ASDEX Upgrade (AUG) have achieved negative triangularity (NT) shaping beyond previous limits. This new set of experiments, guided by the ideal-MHD stability calculations using the BALOO code and supported by predictive results from TCV, have demonstrated a transition to an edge more stable against
peeling ballooning modes, leading to ELM-free plasmas. In some of the AUG cases, a dithery behavior is observed similar to the limit cycle oscillations observed in DIII-D during shaping ramps. In this work we provide the details on the operational boundaries for the NT regime
at various heating mixes and density values. AUG profiles and confinement are compared to a DIII-D discharge similar in shaping and key parameters, although the two machines operate at different values of edge safety factor and have different wall materials. This AUG/DIII-D similarity experiment serves as a basis for comparison of confinement quality and the underlying turbulence regimes using linear and nonlinear gyrokinetic simulations. Achieved ELM avoidance on AUG confirms the universality of the ballooning limited pedestals, previously addressed
on TCV and DIII-D in strongly shaped NT plasmas. Overall, these findings support the feasibility of ELM-free operation in future metal-wall tokamaks using negative-triangularity shaping, offering a viable path forward for high-performance, steady-state fusion scenarios.

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

Contribution ID: **185** Type: **Plenary and Invited Presentation**

Bifurcated states of particle transport driven by regulatory energetic ions in LHD plasmas

Control of particle transport is a prerequisite for sustaining burning plasmas, necessitating a precise balance between fuel confinement and helium ash removal. This study investigates the transport bifurcation phenomena in the Large Helical Device (LHD), demonstrating that the velocity-space anisotropy of energetic ions serves as a deterministic control knob to regulate the directionality of radial particle transport.
Initially, bifurcation of electron density profiles into peaked or flattened steady states was observed following carbon pellet injection. Gyrokinetic analysis suggests that Ion Temperature Gradient (ITG) turbulence remains active in these states, implying a complex interaction between turbulence and transport fluxes. To isolate the regulatory role of energetic ions from pellet fueling effects, systematic experiments were conducted by varying the heating power ratio of energetic neutral beams ($P_\perp/P_\parallel$) from 0 (tangential) to ∞ (perpendicular) without pellet injection.
A clear transition in the transport regime was observed: electron density profiles became hollow in tangential-dominant regimes ($P_\perp/P_\parallel \approx 0 - 1.2$) and shifted to strongly peaked profiles in perpendicular-dominant regimes ($P_\perp/P_\parallel \rightarrow \infty$). Carbon impurity profiles exhibited a synchronized response. Crucially, this bifurcation is interpreted as a transition in the radial electric field structure. The velocity-space anisotropy modifies the non-ambipolar flux of energetic ions, which reconfigures the ambipolar condition and overrides the intrinsic neoclassical transport governed by bulk temperatures. These findings establish that energetic-ion phase-space physics can decouple particle transport from bulk thermal regimes, offering a novel and robust methodology for optimizing confinement and impurity control in future fusion reactors.

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

Contribution ID: **195** Type: **Plenary and Invited Presentation**

Unravelling the nature of H-mode access at ASDEX Upgrade using gyrokinetic simulations

The physical mechanism behind the difference in the H-mode power threshold between favourable and unfavourable drift configurations is still not fully understood and remains an active field of research in view of ITER operation. Experimental evidence indicates that the radial electric field (Er) shear facilitates H-mode access in the favourable configuration, while it is weaker in the unfavourable case [1]. However, the role of turbulence in the self-consistent interplay between transport, equilibrium profiles, and Er has not yet been clarified.
Here, we leverage the recent computational boost in the full-f gyrokinetic code GENE-X [2–4] to perform first-of-their-kind edge and scrape-off layer (SOL) turbulence simulations with X-points of a matched pair of L-mode ASDEX Upgrade discharges in favourable and unfavourable drift configurations [1]. The simulations are validated against experimental measurements and show excellent agreement. In particular, the experimental Er profiles are reproduced, and the simulations demonstrate that poloidal flows provide the dominant contribution to the radial force balance. Most importantly, while these simulated flows remain close to the neoclassical level in the unfavourable configuration, they significantly exceed neoclassical predictions in the favourable case, producing the experimentally observed stronger Er shear. We identify turbulence-driven poloidal flows [5], arising from enhanced nonlinear turbulence–mean-flow energy transfer driven by the radial gradient of the total velocity stress (a full-f generalization of the Reynolds stress [6]), as the key mechanism underlying the observed difference in Er between favourable and unfavourable configurations. This nonlinear energy transfer is much weaker in the unfavourable configuration, yielding a shallower Er well. Edge turbulence and geodesic acoustic mode activity are also found to be weaker in the favourable configuration. The universality of these findings is demonstrated by extending the present analysis to the TCV tokamak. Within the turbulence–flow shear suppression paradigm, the deeper Er well and reduced turbulence intensity in the favourable configuration may underlie the observed configuration dependence of the H-mode power threshold. Extensions toward H-mode are presented by attempting a sudden increase in the input power [7].
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Track Classification: Magnetic Confinement Fusion (MCF): Edge and Pedestal Physics (MCF)

Contribution ID: **212** Type: **Plenary and Invited Presentation**

Systematic multi-machine analysis of the exhaust time-dependent behavior in tokamaks

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This work presents an overview of experimental investigations of the exhaust dynamics in TCV, MAST-U, ASDEX-Upgrade, WEST, DIII-D, and JET. Using various different perturbations such as gas-injection, impurity injection, and power modulations and corresponding responses on various outputs is analyzed. From these experiments, a clear picture arises on properties of the exhaust dynamics across machines. Particularly, we observe that the scrape-off layer equilibrates on fast time-scales and strong similarities across scenarios (H-mode, L-mode), injected species, and injection locations. On the other hand, we see clear differences when analyzing different exhaust properties. This is all summarized in a database that is for the validation of dynamic exhaust models for reactor design. Moreover, some measurements presented have formed the basis for systematic exhaust control on the considered devices.

https://iopscience.iop.org/article/10.1088/1741-4326/ae30f1

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

Contribution ID: **213** Type: **Plenary and Invited Presentation**

On the closure of the BBGKY hierarchy

The fundamental closure of the BBGKY hierarchy is based on largeness of the plasma parameter, g, the number of particles in a Debeye sphere. Closure yields the Hamiltonian [1] Vlasov-Maxwell (VM) equations and/or the metriplectic [2] VM equations with the Landau-Lenard-Balescu (LLB) collision operator. Both models are used with arbitrary initial conditions, with the latter model having a formal H-theorem to thermal equilibrium. Here we address two issues: i) Because g depends on a temperature, for any initial condition, what is meant by this approximation? ii) The LLB collision operator derivation uses the Bogoliubov (B) assumption on the decay of correlations. Given that structures can appear in phase space, to what degree is this assumption valid. With regard to issue i) we can consider alternative closure procedures. However, issue ii) is problematic given the lack of rigor and numerical testing, which is prohibitive because of high dimensionality. A 1D electrostatic plasma model that can bring computations within reach has been proposed [3]. This model replaces particles by disks that exhibits 1-D features at short distances, but retains 3-D features at large distances. The dynamics of this model is investigated analytically, implementation for numerical validation of the B assumption is formulated, and recent results described.

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

Contribution ID: **224** Type: **Plenary and Invited Presentation**

The Physics and Operational Limits of Runaway Electron Mitigation: Multi-Machine Validation for ITER

We present a validated framework and physics basis for low-Z benign termination of runaway electrons (RE). This strategy uses hydrogenic injection as a first step, followed by a low q-edge MHD instability to deconfine and disperse the RE beam. Our multi-machine experimental campaign (AUG, COMPASS, DIII-D, JET, TCV) confirmed this robust two-step process. We established a minimum required neutral pressure for ITER (0.2-0.8 Pa) and identified an upper limit of ~1 Pa, where the termination efficacy begins to reduce. Experimental H and D secondary gas injection comparisons above 1 Pa revealed an unexpected offset in background plasma electron density (ne) dependence on mode growth.

Multi-code modeling was done with SOLPS-ITER, JOREK and M3D-C1. The SOLPS-ITER simulations, modelling the power balance of the REs and background plasma, reproduced the experimental non-monotonic ne trend with neutral pressure. The resulting profiles were ported to JOREK and M3D-C1 to model the MHD collapse phase. Results showed that lower ne and higher resistivity accelerate the m/n=2/1 mode growth, in line with experimental observations. The instability was shown to grow fast enough to induce strong magnetic stochasticity and significant RE transport within 0.1ms in the ASDEX simulations with M3D-C1.

This work provides the essential operational boundary map and multi-code physics validation necessary to implement this scheme on ITER, addressing one of the most critical challenges for the realization of fusion energy.

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

Contribution ID: **225** Type: **Plenary and Invited Presentation**

The ITER Research Plan and its Operational Scenarios

One of the key elements of the 2024 ITER baseline is a revised ITER Research Plan (IRP) that has been developed in collaboration with experts from the ITER Members'fusion institutes. It outlines the new strategy and timeline to reach the ITER Project specifications (including 500 MW of fusion power production with $Q \geq 10$ for durations longer than 300 s in a reproducible way) through a three-phase programme in which incremental steps are taken towards the full D-T performance with a more realistic management of nuclear licensing constraints. The strategy and sequence to develop the operational scenarios specified in the IRP have been significantly impacted by the switch of first wall armour from Be to W in the new baseline. This change can be both favourable and unfavourable for plasma operations. Although the consequences for $Q = 10$ performance have been analysed in detail using a wide range of high-fidelity modelling tools, the development and control of the IRP scenarios is a complex process, requiring sophisticated plasma control and protection systems (a central component of which is disruption mitigation) which must be in an advanced state of readiness at the start of operations. This talk will describe how the plasma scenarios necessary for the success of the IRP staged approach are constructed from the operational point of view, including how the return on experience from current devices and the particular constraints imposed by the ITER machine itself impact their design.

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

Contribution ID: **229** Type: **Plenary and Invited Presentation**

Spatio-temporal evolution of the edge flows and turbulence across the L-H transition on JET

A validated, physics-based model of the L–H transition threshold is essential for estimating heating requirements in future burning-plasma experiments. However, no consensus has yet been reached on the mechanisms that trigger the transition, particularly regarding the generation of the initial flow shear believed to be required for turbulence suppression.
The aim of this work is to improve understanding of turbulence reduction at the L–H transition. The JET correlation reflectometer allows determination of the perpendicular velocity, v , and density fluctuation level, A_n, slightly above the outer midplane, from the SOL to inside the pedestal top. L–H transitions were induced at JET using NBI or ICRH in plasmas with different main ion masses and divertor configurations. Earlier studies found no universal edge flow shear across the JET dataset, suggesting that H-mode access is not solely set by the v profile [C. Silva NF 2021]. No significant variation in v was detected during the heating ramp, though fast dynamics (<10 ms) near the transition were not explored at that time.
New high-temporal-resolution results, obtained in both single-step and long-dithering L–H transitions, indicate that v and A_n are strongly intermittent, yet show no clear trend in the milliseconds preceding the transition. A robust feature of the L–H transition is the sharp reduction of turbulence on a timescale shorter than 50 µs, localized from the separatrix to the pedestal top. Simultaneously, the density profile steepens, though in a narrower radial region. No clear changes in the edge flow shear are observed before the L–H transition, nor immediately afterward, when turbulence suppression begins. These results highlight current limitations while also defining a path forward, namely the need to characterize turbulence in order to enable validation of physics-based models of the L–H transition.

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

Contribution ID: **231** Type: **Plenary and Invited Presentation**

Numerical Investigation of Spin-Resolved Dynamics for Polarized Particle Generation in Strong-Field QED

Polarized positrons and gamma rays are pivotal for probing fundamental physics, yet their generation has long been constrained by a fundamental trade-off between yield, polarization, and efficiency. Conventional methods suffer from low yields or significant depolarization, while existing laser-driven approaches typically produce only transversely polarized particles.
This talk presents a unified theoretical framework for modeling spin and polarization dynamics in strong-field QED interactions [1-3]. Building on this foundation, they propose novel all-optical schemes to generate polarized high-brightness gamma-ray sources [3] and spin-polarized positron beams using ultra-intense lasers [1,5]. They works also reveal new polarization physics arising from QED radiative corrections in laser-electron interactions. They demonstrate a method to generate highly polarized GeV gamma-rays and a compact, single-stage scheme producing longitudinally polarized positrons with high yield and polarization. These advanced beams open the way for laboratory-scale investigations of astrophysical radiation mechanisms—such as gamma-ray bursts and black hole jet emissions—by enabling controlled studies of polarization-dependent, high-energy interactions. This work also establishes a practical route toward compact polarized positron sources for next-generation high-energy physics.

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

Contribution ID: **234** Type: **Plenary and Invited Presentation**

Key Physics Gaps on the Path from W7-X to a HELIAS Reactor

Advancing a HELIAS-type stellarator toward DEMO requires a systematic reduction of critical physics uncertainties that directly impact reactor performance. This work discusses and prioritizes these uncertainties based on their influence on machine design, the urgency for near-term decisions, and the feasibility of closing knowledge gaps through current experimental access and tool maturity. The analysis focuses on five key areas: core transport, MHD stability, fast-ion confinement, plasma exhaust, and plasma-material interactions.

While W7-X has successfully validated neoclassical transport optimization, significant gaps remain. Turbulent transport must be characterized across diverse density-gradient regimes to fully understand configuration-dependent confinement. Furthermore, advanced core turbulence modelling is needed to incorporate electromagnetic effects at high pressure and Alfvénic mode coupling, both of which can significantly alter heat transport. As W7-X is currently a predominantly carbon device, establishing impurity-tolerant operation compatible with a metallic wall remains a critical challenge; multi-species impurity transport must therefore be addressed to ensure core-edge compatibility.

Fast-ion confinement at high-β, particularly regarding losses driven by Alfvén eigenmode coupling, represents another critical uncertainty affecting first-wall loading and requires high-fidelity quantitative predictions. Finally, island divertor physics presents several open questions: drift effects on heat and particle transport must be quantified, and the necessity of divertor closure for HELIAS needs validation. Ensuring consistent detachment, assessing helium ash removal against dilution limits, and verifying the robustness of divertor topology under finite-β variations are essential for defining a stable exhaust geometry. Addressing these priorities —specifically by executing integrated scenarios at 5–7 T with coupled core–edge modelling —will establish the physics foundation for next-step stellarator reactors.

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

Contribution ID: **249** Type: **Plenary and Invited Presentation**

Achievements in LHD Project and Development to Post-LHD Project

The reconsideration of stellarator–heliotron programs is discussed in light of a review of key highlights from the LHD (Large Helical Device) and the plans for the post-LHD project. The LHD, based on the heliotron concept and employing superconducting coils, has been in operation since 1998 and will complete its mission in 2025. The LHD project has significantly advanced plasma science across a broad range of fields, both theoretically and through experimental achievements. The steady-state sustainment of 2-keV plasmas for 50 minutes and the achievement of beta values as high as 5% have demonstrated the feasibility of disruption-free, stable plasmas. A unique feature of the LHD is its ability to produce plasmas that are resistant and resilient to external disturbances, enabling novel experiments such as impurity injection and the application of magnetic perturbations. Advanced diagnostics with high spatiotemporal resolution have clarified the roles of electric fields and non-local effects in transport mechanisms. These physics lessons accumulated over 27 years will be transferred to the new machine, CHD-U (Compact Helical Device-U), a compact yet more flexible stellarator. The post-LHD project, including CHD-U, aims to explore micro-collective plasma phenomena, which are considered critical physics in the challenge toward a comprehensive understanding of toroidal plasmas. The knowledge and skills cultivated through the LHD project underpin this paradigm shift.

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Track Classification: Magnetic Confinement Fusion (MCF): Stellarator Physics and Optimisation (MCF)

Contribution ID: **270** Type: **Plenary and Invited Presentation**

From startup to burn: plasma-wall interaction implications for Q=10 in the full tungsten ITER

The new 2024 ITER baseline introduces a tungsten (W) first wall (FW), requiring renewed assessments of plasma-wall interactions and their impact on achieving the Q=10 performance target. This contribution provides a brief update of the status of ITER, and focusses on assessments of how the new wall material will impact key phases of ITER scenarios, from burn-through in limiter configuration, through diverted L-modes and finally, to the principal objective of burning plasma operation in H-mode. It details the implementation of risk mitigation measures, in particular the boronization system, which is critical for plasma start-up as demonstrated in dedicated experiments performed in WEST and ASDEX Upgrade. This overview also addresses the important issue of fuel retention and recovery strategies.

Throughout the limiter phase of ITER plasma scenarios, W erosion, core W contamination and edge power flow are coupled in an experimentally confirmed strongly self-regulated system, resulting in high core radiation and advantageously lowering power fluxes to the FW surface, but requiring central electron cyclotron heating (ECH) to prevent uncontrolled W accumulation. For L-mode diverted plasmas, central ECH also enables operation with moderate core radiated fractions from W wall sources, consistent with the range observed in current experiments with W plasma-facing components. For Q ≥ 10 H-mode scenarios, assumed to have no ELMs (either by active control or by access to naturally ELM-free plasmas compatible with Q ≥ 10), the full W pathway from source to core is quantified by combining new wide grid plasma boundary simulations, where wall and divertor loads are set within design specifications, with erosion source modelling to predict the W concentration at the separatrix, coupled to the core through state-of-the-art integrated modelling. This approach improves on the first studies performed for the re-baseline by maintaining consistent W transport assumptions across codes to provide a realistic assessment of the W source and transport. The analysis confirms, with greater confidence in the W source modelling, the key finding of the initial physics studies in support of the re-baseline, that the risk to the 500 MW fusion power target of switching to an all-W ITER is mitigated by the increased ECH power in the re-baseline, although with a reduction of Q for the highest W erosion sources for wall loads reaching their design limits.

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

Contribution ID: **272** Type: **Plenary and Invited Presentation**

Comprehensive data set of cross sections for molecular hydrogen and its application in fusion and low temperature plasmas

The development of the molecular convergent close-coupling (MCCC) method has enabled large-scale convergence studies to be performed for molecular targets for the first time. Over the last decade we have been applying this technology to the electron-H_2 scattering system, with the long-term goal of producing a complete collision data set for application in collisional-radiative models. Previously, the majority of available data were either from small close-coupling calculations valid only at low energies, or semi-classical calculations valid only at high energies. There was also little vibrationally- and rotationally-resolved data available.

Motivated by fusion and astrophysical applications, we have produced cross sections numbering in the hundreds of thousands for electrons scattering on H_2 and its five isotopologues, considering vibrational levels in the first 20 electronic states, and rovibrational levels in the first 10. These data have allowed detailed collisional-radiative models for low-temperature hydrogen plasmas to be constructed for the first time. This talk will provide an update on the MCCC project and its applications, including new results for proton collisions with H_2.

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

Contribution ID: **278** Type: **Plenary and Invited Presentation**

Seeing the Invisible: A decade of small angle x-ray scattering diagnostics at XFELs for high-intensity-laser plasmas

Understanding how matter behaves under extreme conditions is a central challenge in plasma physics, with implications ranging from laboratory astrophysics to fusion energy research. Over the past decade, small-angle X-ray scattering (SAXS) at X-ray free-electron lasers (XFELs) has emerged as a powerful diagnostic for studying laser-driven plasmas. Extreme states of matter are created when intense laser pulses rapidly heat and compress solid materials into dense, transient plasma conditions. Unlike traditional diagnostics, SAXS provides direct access to nanometer-scale density structures and their ultrafast evolution, enabling us to observe processes that previously could only be inferred indirectly from simulations.

Early experiments demonstrated that coherent X-ray scattering could reveal microscopic filamentary structures, return-current dynamics, and shock formation inside optically opaque targets. These observations have significantly advanced our understanding of energy transport in dense plasmas, especially the propagation and stability of energetic electron beams. Such processes are central to the fast ignition approach to inertial fusion, where efficient coupling of laser energy into the fuel depends critically on controlling electron transport and instability growth. SAXS measurements provide unique insight into the underlying density modulations and collective plasma behaviour that influence beam guiding, energy deposition, and compression symmetry.

At large-scale facilities such as European XFEL and LCLS, the success of SAXS has helped to develop integrated experimental platforms combining scattering, imaging, spectroscopy, and synchronized high-power laser drivers. These multi-modal environments enable simultaneous observation of structural evolution and plasma dynamics across multiple scales, strengthening the link between theory, simulation, and experiment.

This plenary talk will present a ten-year perspective on SAXS as a plasma diagnostic, highlighting key discoveries, methodological advances, and interdisciplinary connections with photon science and condensed matter physics. The presentation will place these developments within the broader context of fusion research, illustrating how scattering-based diagnostics are contributing to the understanding of fast ignition physics and outlining future opportunities enabled by next-generation high-repetition-rate XFEL facilities.

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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: **288** Type: **Plenary and Invited Presentation**

Impact of resonant second-harmonic generation on helicon-wave damping

Helicon discharges are widely used to produce high density, low temperature, moderate magnetic field plasmas and are central in a broad range of applications, such as plasma-material interaction studies, electric propulsion, fundamental plasma physics investigations, auxiliary heating in tokamaks, and wake-field particle acceleration. In such plasmas, helicon wave damping is commonly assumed to be dominated by collisional dissipation.

In this work, we combine a normal-mode analysis with spatially resolved magnetic field measurements using a movable B-dot probe to investigate helicon wave damping over a broad parameter space. While collisional models accurately describe most operating regimes, we identify a specific parameter window in which the damping of the fundamental helicon mode is reduced by approximately a factor of two relative to collisional predictions. In this regime, a coherent magnetic-field component at the second harmonic frequency 2ω becomes clearly detectable, contributing up to ~10% of the total magnetic signal.

Using a weakly nonlinear perturbative framework, we show that this second-harmonic component arises from a resonant wave–wave interaction of the form $\omega + \omega \rightarrow 2\omega$. Importantly, the analysis reveals a nonlinear back-coupling from the second harmonic to the fundamental mode, which quantitatively accounts for the observed reduction in damping. Although second-harmonic helicon waves have been reported previously, their role has not been identified as a resonant nonlinear mechanism with a measurable impact on helicon wave dissipation.

Based on this analysis, we derive a simple predictive criterion that identifies the parameter range in which this nonlinear interaction is important. Preliminary measurements from the CERN AWAKE Helicon Plasma Source exhibit similar harmonic signatures, suggesting that this mechanism may be robust across different helicon devices.

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

Contribution ID: **298** Type: **Plenary and Invited Presentation**

Tungsten in tokamaks, how one of the elements producing largest radiation losses can be compatible with a nuclear fusion plasma

Tungsten is becoming the leading solution as first wall material of magnetic confinement fusion reactors, as confirmed by the recent decision of ITER to also adopt tungsten in the main chamber. Tungsten is the metal with the highest melting point and combines low erosion rates with low fuel retention. However, tungsten is also one of the elements which leads to the highest radiation losses in a wide range of fusion relevant temperatures. In this plenary talk, progress in experiments, theory and predictive modelling dedicated to tungsten transport in tokamak plasmas is retraced, highlighting the main milestones.
These in particular include: the development of appropriate strategies to reduce tungsten erosion and limit the tungsten concentration in the plasma; the positive role of central wave heating to prevent central accumulation, through modifications of the tungsten transport and of the main plasma profiles; the complicated impact of plasma rotation on collisional transport, which is understood to be particularly unfavorable in usual plasma conditions in present tokamaks. All transport mechanisms, collisional, turbulent and MHD-driven, are involved and can compete. The understanding of these processes has helped to identify effective actuators to mitigate the risk of excessive core radiation and to increase the predictive capability for present and future tokamaks. Some aspects are still challenging the scientific community, particularly to predict turbulent transport at the plasma edge.
These achievements have progressively allowed the integration of tungsten in tokamak operation, overcoming the challenges provided by the need to successfully combine competing requirements of the plasma edge, where tungsten originates, and the plasma core, where strong accumulation can occur. A successful core-edge coupling is essential for the high plasma performance required in a fusion reactor, but which tungsten makes more difficult to achieve. However, strategies to limit tungsten erosion and edge plasma contamination practically coincide with those which are in any case imposed by the heat exhaust and a long lifetime of the plasma-facing components.
Experimental and theoretical research have advanced together, converging on deeper physics knowledge, controlled plasma operation and more reliable reactor predictions, enabling more future tokamak projects to confidently choose tungsten as plasma-facing material.

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

Contribution ID: **311** Type: **Plenary and Invited Presentation**

From fundamental plasma characterization to technological optimization: Maximizing graphene production in a microwave plasma torch

The global demand for high-quality graphene continues to drive the search for sustainable, scalable, and cost-effective synthesis methods. Among the most promising emerging technologies, microwave-induced plasmas generated by the TIAGO torch (Torche à Injection Axiale sur Guide d'Ondes) offer a streamlined, catalyst-free, and environmentally friendly approach to producing few-layered graphene nanosheets through ethanol decomposition at atmospheric pressure. While this technology represents a significant leap forward in green nanomaterial manufacturing, unlocking its full industrial potential requires a deeper understanding of the fundamental physics governing its energy transport mechanisms.

Using optical emission spectroscopy techniques, the fundamental characteristics of the TIAGO torch have been investigated, revealing that it behaves as a surface wave discharge (SWD), where electromagnetic wave sustaining it propagates along the plasma-dielectric (air) interface. More importantly, a distinct "radiation zone" located near the nozzle exit has been identified for the first time at atmospheric pressure, highlighting a critical inefficiency: nearly 43% of the input microwave energy can be dissipated as non-guided radiation. This fundamental insight serves as the cornerstone for technological optimization of graphene synthesis.

By implementing a custom-designed metallic electromagnetic shielding around the reaction chamber it is possible to suppress these radiation losses. This strategic modification results in a significant volumetric expansion of the plasma and a more efficient decomposition of carbon precursors. Quantitative analysis demonstrates a remarkable 22.8% increase in graphene production alongside a 21% improvement in overall energy yield.

Critically, this boost in productivity does not come at the expense of material integrity. Extensive multi-technique characterization, including Raman spectroscopy, X-ray photoelectron spectroscopy (XPS), and High-Resolution Transmission Electron Microscopy (HRTEM), confirms that the synthesized powder maintains its high-quality, few-layered structure with low defect density and high sp2 hybridization. Ultimately, the bridge between fundamental plasma diagnostics and industrial optimization proves that understanding basic energy loss mechanisms is the key to achieving the energy efficiency and scalability required for the next generation of sustainable nanostructure manufacturing.

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Track Classification: Low Temperature and Dusty Plasmas (LTDP): Plasma Processing and Applications (LTDP)

Contribution ID: **483** Type: **Plenary and Invited Presentation**

Understanding the features of high power impulse magnetron sputtering plasma for the synthesis of nanostructured materials

High power impulse magnetron sputtering is a new and promising physical vapor deposition technique. In this technique, differently from DC magnetron sputtering, the use of proper voltage pulses, in the microsecond regime, leads to the formation of a plasma population made of sputtered species in addition to the usual Ar ones. The evolution of such plasma plays a pivotal role in determining the features of the growing film. Thanks to the presence of the metal ion population, the deposition of more compact and crystalline films, as well as formation of compounds at low temperature, is possible [1]. If, on one side, this technique is very promising, on the other many parameters determine the generation of a so complex plasma (e.g. pulse features, magnetic field, gas composition, pressure, etc.) and their role need to be understood. To properly investigate this phenomenon, a multi technique approach is presented focused on metallic and nitride nanomaterials for energy applications [2]. The features of the grown films (morphology and crystallinity) are studied using a material science approach, by SEM and XRD, allowing to link materials feature and process parameters. Then plasma is characterized by OES determining the generated ionic species and monitoring the plasma current during the voltage pulse. The composition of such current is modelled by means of an Ionization Region Model [3,4] that allows the prediction of temporal evolution of every single species. Combining the data it's possible to envisage the evolution of plasma. This, in turn, allows to predict the coating growth conditions depending on the composition of the impinging ion flux.

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Track Classification: Low Temperature and Dusty Plasmas (LTDP): Plasma Processing and Applications (LTDP)

Contribution ID: **503** Type: **Plenary and Invited Presentation**

Engineering Surfaces for Sustainability and Health with Low Temperature Plasmas

Nature's ingenuity is epitomised by nanometre-scale architectures, as for example the lotus leaf' s self-cleaning surface and the moth eye's anti-reflective design. Following nature's example, surfaces of materials can be manipulated and modified with plasmas to alter properties such as colour, wettability, reactivity, or to influence the interface and the interactions of surfaces with proteins, cells, bacteria, and viruses. My key area of interest is plasma bionanotechnology, where I aspire to control the behaviour of cellular and protein systems at their interfaces with plasma modified material surfaces. My work aims to influence the growth and development of living tissues and organs, contributing to advancements in areas such as artificial organ development, and regenerative medicine. In parallel, I am committed to driving sustainability in the broader context of materials science and engineering. This involves investigating and simplifying the mechanisms needed to facilitate the sustainable transition of manufacturing processes, laboratory practices, and advanced material preparation and characterisation methods. By addressing both the biological and engineering aspects of materials science, my work provides innovative solutions to global challenges, such as improving healthcare outcomes and reducing the environmental impact of industrial and scientific processes, necessary not only for future technological developments, but also the survival of our species.

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Track Classification: Low Temperature and Dusty Plasmas (LTDP): Plasma Processing and Applications (LTDP)

Contribution ID: **520** Type: **Plenary and Invited Presentation**

Kinetic effects on heat transport in direct-drive ICF simulations

Predictive simulations of inertial confinement fusion (ICF) require accurate modeling of electron transport, particularly in regimes where temperature gradients become comparable to the electron mean free path. In these conditions, diffusive transport models commonly used in radiation-hydrodynamics codes fail to capture non-local effects. These inaccuracies compromise predictions of shock timing, laser-plasma coupling and the thermal smoothing of perturbations. We have recently developed the coupled *K2-Gorgon* code which allows tractable two-dimensional simulations of ICF relevant experiments with high-fidelity kinetic modeling of electron transport. *K2* solves the Vlasov-Fokker-Planck (VFP) equation to evolve the electron distribution function, and provides a kinetic electron transport model for use in the multiphysics hydrodynamics code *Gorgon*.

We present results from 1D planar simulations of plastic target ablation using K2-Gorgon at direct-drive relevant laser intensities, benchmarking the VFP model against flux-limited diffusion and Schurtz-Nicolai-Busquets (SNB) transport models. These results demonstrate the inadequacy of the flux-limited model, revealing substantial differences in predicted coronal temperatures (> 200 eV). SNB more accurately captures observables, including shock velocity, coronal temperature and non-local preheat, with minor quantitative differences. We will discuss the extension of this work to 2D, including the role of self-generated magnetic fields and their influence on thermal transport (complementary to recent results in indirect drive hohlraums [1]). Finally, we examine the role of non-local transport in the smoothing of perturbations in the corona, a critical factor for the design of next-generation ICF facilities.

[1] M. Sherlock et al., APS-DPP Abstracts (APS, 2025)

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

Contribution ID: **543** Type: **Plenary and Invited Presentation**

Negative triangularity plasma shapes: how bad ideal MHD properties can lead to excellent perspectives for a fusion power plant

This contribution will first review the history of tokamak plasma physics research related to negative triangularity (NT), starting by explaining why it was disregarded early on, based on ideal MHD considerations [1]. Nevertheless, leveraging on the pioneering work on TCV, NT studies have been extended to larger tokamaks among which DIII-D, AUG and even JET on its last day of plasma operation, and significant progress was made. For the three main pillars considered to design a reactor (plasma confinement, heat exhaust and integrated design), no showstopper is identified so far. While the baseline scenario for ITER and next step devices relies on the H-mode confinement regime, and its harmful edge localized modes, the promise of NT is that plasma confinement is as good as H-mode PT (positive triangularity) but in Lmode [see papers in 2 and refs therein]. This benefit alleviates the problem of ELM suppression but also the request to ensure a certain level of power crossing the separatrix to maintain the Hmode.

The H-mode avoidance for NT shapes is explained by a closed path to the second stability region for ballooning modes, hence the benefit of "bad"ideal stability, and allows robust predictions. The example of JET experiments will be used to illustrate these aspects. Another breakthrough is that operation at much larger densities than the "density limit"in tokamaks has been demonstrated in DIII-D. Here also, theoretical advancements are supporting the experimental findings. Prospects for an optimized DEMO-NT will be explained.

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a B.P. Duval et al 2024 Nucl. Fusion 64 112023
b K E Thome et al 2024 Plasma Phys. Control. Fusion 66 105018
c H. Zohm et al 2024 Nucl. Fusion 64 112001
d C.F. Maggi et al 2024 Nucl. Fusion 64 112012
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Track Classification: Magnetic Confinement Fusion (MCF): Scenario Development, Heating and Current Drive (MCF)

Contribution ID: **545** Type: **Plenary and Invited Presentation**

High-power laser interaction with micro-structured materials: experiments and simulations

In the context of Inertial Confinement Fusion (ICF), micro-structured low-density materials, or foams, have been shown to be able to reduce the effects of hydrodynamic instabilities, while increasing the laser absorption efficiency and enhancing the pressure at the shock front. 3D-printing represents the new manufacturing method for controlling the morphology, gradients in density and pore size, and sample shapes, opening the way to realizing wetted foams.
In this work, the results of experiments in which different kinds of micro-structured materials have been irradiated at the ENEA-ABC laser facility at high intensity of 10^{14} W/cm^2 will be discussed. The irradiated samples included chemical, 3D-printed and innovative micro-structured materials. The results of 3D simulations for 3D-printed foams obtained with the FLASH code will be discussed.

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

Contribution ID: **553** Type: **Plenary and Invited Presentation**

The Sun and the solar wind: Linkage science with Solar Orbiter

The ESA/NASA Solar Orbiter mission started its nominal science phase at the end of 2021, after a little less than two years of cruise phase. By June 2026, 9 remote-sensing observation campaigns will have taken place, with coordination with other international space missions as well as ground-based infrastructures. On top of this, Solar Orbiter regularly monitors the Sun and the heliosphere with its 10 suites of remote-sensing and in situ instruments.

The mission therefore gives an unprecedented linkage between the activity of the Sun and measurements of dynamic processes happening in the solar wind.

Recent observations reveal that tiny plasma jets in coronal holes, only a few hundred kilometers wide and lasting about a minute, may contribute to both the fast and slow solar wind, suggesting that similar small-scale processes can feed multiple outflow regimes. Coordinated campaigns have also shown that variations in the elemental and charge-state composition of the solar wind correspond to specific source regions on the Sun, from open coronal holes to boundary layers between open and closed magnetic field structures. These regions, shaped by magnetic reconnection, provide escape channels for plasma with distinctive composition "fingerprints"that ultimately can flow into interplanetary space.

On top of this, the Sun's atmosphere is highly dynamical: they are the locations of energetic events such as solar flares, which can accelerate particles in the interplanetary medium. These solar energetic particle (SEP) events can have strong enrichments in certain heavy ions, helping connect their source regions via remote composition diagnostics and therefore constrain models of acceleration processes.

Throughout this talk, we will thus see how Solar Orbiter provides an unparalleled opportunity to observe how processes in the solar atmosphere, and in particular its various magnetic regions, shape and modulate events in the heliosphere.

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

Contribution ID: **559** Type: **Plenary and Invited Presentation**

Review of Power Exhaust Studies in European Tokamaks and Application to SPARC

Understanding and controlling power exhaust is crucial for the success of SPARC and other future tokamaks. This work presents a comprehensive review of power exhaust studies conducted across European tokamaks. The analysis integrates data from both carbon-based and metallic-wall regimes to characterize divertor heat fluxes. We detail the foundational research that established the empirical multi-machine scaling law for the inter-ELM scrape-off layer (SOL) power decay length. This parameter is needed to predict the steady-state heat flux to the divertor, which in turn determines the level of power dissipation needed to protect the divertor targets from excessive damage or erosion.

We then review the experimental efforts from JET, ASDEX Upgrade, and MAST to characterize transient heat loads caused by Edge Localized Modes (ELMs). A relationship between the ELM energy fluence and the upstream pedestal-top pressure was identified and later validated on several other tokamaks, including COMPASS, allowing for the prediction of transient heat fluxes in next-step devices. Using these scalings, we show that SPARC and ITER will have similar steady-state and ELM-transient heat fluxes.

To link these exhaust challenges to operational constraints, we have developed the Separatrix Operational Space (SepOS) framework. This framework describes operational domains such as LH transition and density limit in terms of separatrix parameters which are key for power dissipation and detachment access. In addition, it has been shown to correlate with the transition between large "type-I"ELMs and the small-ELM QCE/EDA regime. This allows us to identify conditions where both the steady-state and transient heat fluxes can be tolerated in high-performance regimes on future tokamaks.

However, the studies on SepOS do not yet include impurity seeding cases. Furthermore, SOLPS modeling for ITER has shown that the highest achievable separatrix density is limited by the presence of impurities in the divertor region. The application of this methodology to SPARC yields similar results, identifying a corresponding reduction in the available separatrix operational space. Thus, the presentation concludes with both a discussion on these remaining gaps in our understanding, as well as a brief outlook to the boundary digital twin for SPARC, which incorporates the extensive heritage and data from European tokamaks.

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

Contribution ID: **561** Type: **Plenary and Invited Presentation**

Multiscaled Aeromaterial Reactor for Plasma Catalysis

The intermittency of renewable energy sources such as wind and solar often results in electricity generation when demand is low, leading to curtailment and energy losses. Converting this surplus power into chemical energy carriers, such as ammonia, offers a viable storage route. Conventional ammonia synthesis via the Haber-Bosch process is efficient but inflexible and centralized. Non-thermal plasma catalysis provides a promising alternative, enabling ammonia production under mild conditions and direct coupling to intermittent renewable electricity.

Among reactor concepts, packed-bed designs offer high catalytic surface area but suffer from plasma penetration limits, pressure drops, and heat management challenges. Honeycomb reactors, while exhibiting low pressure drop and uniform gas flow, struggle to sustain stable discharges in narrow channels. Here, we present a novel reactor concept based on multiscaled aeromaterials that merges the advantages of both configurations. The open, hierarchical architecture promotes uniform plasma generation and enhanced plasma-surface coupling. When combined with advanced catalytic materials, these reactors could provide a versatile platform for studying discharge dynamics, plasma-surface interactions, and catalytic enhancement mechanisms. This approach represents a step toward efficient, renewable-energy-driven plasma catalysis and decentralized ammonia synthesis.

Recent results utilizing the novel reactor with optical access to study the fundamental plasma penetration through aeromaterials will be presented. For the proof-of-concept non-catalytic aeroglass (SiO_2) was used to confirm the plasma penetration in this material.

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

Contribution ID: **575** Type: **Plenary and Invited Presentation**

Pedestal dynamics at the shape driven transition to QCE: a multi-scale analysis

Experiments on ASDEX Upgrade investigate how plasma shaping and the poloidal beta (βpol) affect pedestal behaviour in H-mode plasmas. The focus is placed on the transition from type-I ELMy H-mode to the quasi-continuous exhaust (QCE) regime, which is accessed experimentally by increasing plasma shaping while keeping βpol approximately constant. The dataset spans a wide range of shaping parameters and covers the full transition between these confinement regimes, providing a controlled framework to isolate the role of geometry in pedestal formation and stability.
A versatile combination of experimental diagnostics and numerical tools is employed to analyse this dataset. High-resolution profile measurements are used to reconstruct kinetic pedestal profiles, which are then assessed using a comprehensive modelling approach. This includes local and global MHD stability analysis, transport simulations, and gyrokinetic calculations addressing both ion- and electron-scale turbulence. The joint application of these complementary methods allows stability limits, transport channels, and profile evolution to be examined, offering a detailed view of pedestal dynamics across the ELMy–QCE transition.
The analysis demonstrates that pedestal formation is not governed by a single dominant mechanism, but rather by the interplay of multiple instabilities and stabilising effects acting across different radial regions of the pedestal. The interplay between local magnetic shear is found to strongly stabilise kinetic ballooning modes (KBMs), which play a central role in regulating both the density gradient and turbulent ion heat transport. Increased shaping facilitates access to the second stability regime, allowing larger pressure gradients while simultaneously shifting the most unstable region radially.
The behaviour of KBMs at the pedestal foot emerges as a key element in setting the boundary conditions for accessing and sustaining the QCE regime. Complementary MHD and gyrokineticanalysis, further elucidates the role of shaping in modifying magnetic shear and stability boundaries.
Taken together, these results provide a detailed, multi-scale view of pedestal structure and establish a foundation for understanding the transition from ELMy H-mode to QCE. The presented analysis is used as the groundwork for the development of a predictive pedestal model for QCE-relevant regimes, with direct relevance for future devices and reactor-oriented operation.

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

(MCF)

Contribution ID: **595** Type: **Plenary and Invited Presentation**

Fusion reactivity enhanced by turbulence

Turbulence increases the reactivity of fusion plasma, allowing ignition at lower temperature. This "shear flow reactivity enhancement"[1] occurs because in plasmas, as opposed to other fluids, particles'collisional mean free paths increase rapidly with their velocity. In sheared flows, and in solenoidal turbulent flows [2], energetic particles can travel long distances and pass between regions with large differences in flow, ending up at higher velocities relative to the local fluid. Such a velocity boost greatly increases the number of tail particles available to participate in energy-sensitive processes, such as fusion reactions. Furthermore, because the mean free paths of thermal ions and tail ions are widely separated, the effect can appear even in highly collisional plasmas; in fact, because thermal ions determine viscosity, their short mean free paths help to support strong flow gradients.

A central paradigm in inertial confinement fusion (ICF) –that imploding kinetic energy should thermalize to maximize fusion reactivity –must therefore be revised. In some cases, driving micron-scale turbulence inside ICF hot spots allows ignition at lower energy density [3]. Colder fuel improves the confinement of alpha particles, allowing for a smaller hot spot and offering particularly large energy savings in fast-ignition and shock-ignition configurations [1]. The shear flow reactivity enhancement effect raises the prospect of a new scheme for ICF in which targets are seeded with perturbations to generate turbulence on optimal scales during compression, reducing thermal losses and potentially enabling higher gain. Beyond the implications for high-yield experiments, consequences of the effect with broader scientific relevance will be discussed, including modifications to yield ratios and fusion-product spectra (affecting, for example, diagnostics based on these quantities).

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

Contribution ID: **599** Type: **Plenary and Invited Presentation**

Quantifying inner beam Cross Beam Energy Transfer in a Hohlraum like platform at the National Ignition Facility

Cross beam energy transfer (CBET) is central to controlling implosion symmetry in all ignition designs at the National Ignition Facility (NIF), and can possibly be even more critical as laser driver energies increase from the current multi megajoule regime toward next generation facilities operating at approximately 10 MJ. In indirect drive inertial confinement fusion (ICF) experiments at NIF, CBET redistributes laser power among the 192 beams via ion wave mediated coupling in the hohlraum plasma, strongly influencing the spatial and temporal drive symmetry on the fusion capsule. While CBET has been essential to achieving ignition, its quantitative behavior remains poorly constrained; current radiation hydrodynamics simulations cannot reliably predict low mode shape and symmetry, and an empirical plasma wave amplitude limiter is routinely applied to CBET models. This limiter must be retuned for each design, laser pulse, and wavelength detuning configuration, creating ambiguity as to whether it compensates deficiencies in the CBET physics or other inaccuracies in hohlraum and capsule modeling. These uncertainties increase the number of required tuning shots and limit confidence in extrapolations to higher energy facilities.
We report on a new suite of NIF experiments, conducted in 2025 and 2026, designed to directly measure CBET in a hohlraum-like environment. A novel experimental platform has been developed that, for the first time, quantifies the time resolved transfer of power from outer to inner beam cones, as a function of wavelength detuning $\Delta\lambda$ and hohlraum gas fill density. High fidelity time gated x-ray images of the inner cone footprint provide unprecedented maps of post CBET beam powers and intensities over an entire NIF hemisphere.
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Track Classification: Beam Plasmas and Inertial Fusion (BPIF): Inertial Confinement Fusion (BPIF)

Contribution ID: **607** Type: **Plenary and Invited Presentation**

Unveiling plasma energization and energy transport in the Magnetospheric System through multi-scale observations: the Plasma Observatory mission

The comprehension of particle energization and energy transport is a grand challenge of plasma physics that has implications on research fields that span from space weather to the understanding of the farthest astrophysical plasmas. The Earth's Magnetospheric System, where strong energization and energy transport occurs, is the best natural laboratory to study these processes through in situ measurements. Theory, numerical simulations and previous multi-point observations from missions such as ESA/Cluster, NASA/MMS and THEMIS evidenced that cross-scale coupling has a fundamental role in plasma energization and energy transport. Therefore, simultaneous in situ measurements at both large, fluid and small, kinetic scales are required. Such measurements are currently not available. Here we present the Plasma Observatory (PO) multi-scale mission tailored to study plasma energization and energy transport in the Earth's Magnetospheric System through simultaneous measurements at both fluid and ion scales. PO baseline mission employs seven identical smallsat Sister Space Craft (SSC) in two nested tetrahedral formation in an HEO 7.2x17 RE orbit, enabling observations in all the key regions of the Magnetospheric System including the foreshock, the bow shock, the magnetosheath, the magnetopause, the transition region and the magnetotail current sheet. The nominal mission duration is 3.5 years with 3 Nominal Science Phases during which the scale of the inner/outer tetrahedra are increased in three steps: 30-60/150-300 km, 100-200/500-1000 km, and 3500-6500 km, covering all typical ion and fluid scales of interest in the magnetospheric key regions. The SSC payload provides a complete characterization of electromagnetic fields and particles simultaneously at multiple locations with measurements tailored to ion and fluid scales. PO is the next logical step after Cluster and MMS and will allow us to resolve for the first time scale coupling in the Earth's Magnetospheric System, leading to transformative advances in the field of space plasma physics. Plasma Observatory PO has been recently recommended by ESA as the Medium-class mission M7 of the ESA scientific
program. The ESA Science Program Committee will make the formal decision at its next meeting in November 2026. The launch of PO is expected in 2037.

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

Contribution ID: **620** Type: **Plenary and Invited Presentation**

Phase-Space Turbulence in Space and Fusion Plasmas

The velocity distribution functions (VDFs) of space plasmas typically exhibit non-Maxwellian features owing to the extremely low level of collisionality. Fine velocity-space gradients in the VDFs may play a crucial role in plasma heating and dissipation, as they can inhibit the reversibility of energy exchange between fields and particles once a sufficient degree of phase-space complexity is reached.

A powerful way to quantify this complexity is through the Hermite spectrum of the VDFs. In velocity space, a Hermite cascade—analogous to the turbulent cascade in real space—has been identified in both numerical simulations and observations in the terrestrial magnetosheath.

Here, we present new results on this phenomenon using measurements from Parker Solar Probe and Solar Orbiter, together with gyrokinetic Vlasov simulations of fusion plasmas. These findings advance our understanding of the development of phase-space turbulence in both space and laboratory (fusion) plasma environments.

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

Contribution ID: **624** Type: **Plenary and Invited Presentation**

Physics Understanding and Solutions to Key Issues of Long Pulse High Performance Operation on EAST

EAST has achieved a pivotal breakthrough by sustaining a steady-state high-confinement plasma for 1066 seconds with an injected energy of 3.05 GJ, setting a world record for both pulse duration and cumulative energy input. This major achievement integrates high-confinement performance with low momentum input, efficient heating and current drive, water-cooled tungsten divertors, active control of heat fluxes, precise recycling and particle balance regulation, magnetic configuration and equilibrium for long-duration operations. With this result, EAST has become the first tokamak that can operate with a pulse length in thousand-second scale, with plasma temperatures in the tens of million degrees Celsius and self-driven current.

Key technical solutions were developed to overcome the challenges of long-pulse H-mode plasma operation over 1066 seconds, which was achieved in a lower single-null configuration with $\beta_p = 2.0$ and $f_{\mathrm{BS}} \sim 50\%$, driven by $P_{\mathrm{LHCD}} = 1.1\,\mathrm{MW}$ and $P_{\mathrm{ECRH}} = 1.9\,\mathrm{MW}$. A no/small ELM regime was realized by positioning the outer strike point on the horizontal target, which not only facilitates efficient radio frequency (RF) power coupling but also mitigates tungsten (W) sputtering and erosion. Fully non-inductive current drive was achieved at an electron density equivalent to 63\% of the Greenwald density, with a confinement enhancement factor $H_{98y2} = 1.3$ enabled by an electron temperature internal transport barrier (e-ITB). The synergistic effects between on-axis ECRH and LHCD are critical for maintaining high-confinement plasmas.

The e-ITB H-mode discharge exhibits nonlinear self-organization characteristics, emerging near the magnetic axis without external momentum injection. This long-term operational stability provides a unique opportunity to investigate the anomalous energy fluxes driven by plasma turbulence. Active control of a high-field side flux loop maintained zero loop voltage for non-inductive operation. Low-Z material wall coating and real-time powder injection techniques were implemented to enhance particle control capability. The evolution of wall materials was systematically studied through plasma-wall integrated modeling, while core-edge integration in high-performance steady-state operation scenarios compatible with metallic walls was experimentally explored.

This paper also presents the detailed physical mechanisms and technological advancements associated with the upgrade of EAST's operational capabilities, which are tailored to the development of future fusion reactors such as ITER-relevant configurations.

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

Contribution ID: **646** Type: **Plenary and Invited Presentation**

Time dependent advanced scenario modelling on present and future fusion devices

The high poloidal beta (βp) scenario [Ding_Nature2024] is one of reactor-relevant advanced tokamak regimes, combining high confinement (H98y2 > 1.5) with operation at Greenwald fraction ≥ 1. The most specific feature of this scenario is the formation of an internal transport barrier (ITB) at large radius (⊠≥ 0.5), enabled by an optimized current ramp-up phase and current profile shaping that establish favorable magnetic shear conditions to suppress core turbulence.
First demonstrated in JT-60U [Takenaga_NF2005] and subsequently developed in DIII-D, the high βp scenario has been reproduced in several devices as EAST, ASDEX-U, JET and, more recently, also explored in MAST-U, establishing a solid experimental and physics basis. In this invited talk, we focus on how integrated modelling can be used to study the performance and robustness of this scenario, with particular emphasis on access conditions, density evolution toward the Greenwald limit, and the sustainment of the ITB condition during the flat-top phase.
Using an ASTRA–TGLF integrated modelling framework [Bonanomi_NF2025], we study the time-dependent evolution of high βp plasmas in DIII-D, from current ramp-up through flat-top. The analysis highlights the key role of the turbulence stabilization in the formation and sustainment of the ITB, a feature consistently captured by both gyrokinetic studies and the quasi-linear TGLF model. Particular attention is paid to magnetic shear and pressure gradient, and their dominant impact on transport, as well as the effect of the toroidal velocity and its minor role in the formation and sustainment of the ITB.
The validated DIII-D analysis opens the possibility to extend such approach to MAST-U cases to provide insights on the influence of low aspect ratio on current diffusion, turbulence stabilization, and ITB physics.
Finally, the physics understanding gained from present devices is applied to the design of a high βp scenario for the DTT tokamak, currently under construction in Italy. The results illustrate how integrated modelling can guide the development of high-performance, reactor-relevant scenarios in next-step, high-field superconducting machines.

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

Contribution ID: **663** Type: **Plenary and Invited Presentation**

Field-aligned Clebsch-type flux coordinates for rectangular magnetrons

Large-scale rectangular magnetrons are central to industrial high-throughput coating, yet their theoretical description remains challenging due to the complex topology of their non-axisymmetric magnetic fields. We construct field-aligned Clebsch-type flux coordinates for the confinement region above the cathode, starting from a physically admissible vacuum field generated by an optimized ensemble of sub-surface magnetic dipoles. The magnetic flux partitions the domain into core, return region, and halo, bounded by neutral curves that form the geometric backbone of the construction. In contrast to axisymmetric devices with a single apex null and magnetic dome, elongated rectangular configurations may, beyond a critical aspect ratio, undergo a symmetry-breaking bifurcation of the central null and develop additional off-axis null points. Below the corresponding bifurcation height we identify a regular domain in which field lines remain arc-like and connect core and return region. The technically relevant active region is a subset of this domain and comprises those arc-like field lines along which the magnetic field strength exceeds a prescribed threshold. Within the regular domain, a magnetic flux function and a generalized azimuth are constructed that label flux surfaces and individual field lines and reproduce the magnetic field in Clebsch form, while an arc-length coordinate completes the system.

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

Contribution ID: **670** Type: **Plenary and Invited Presentation**

Towards on-demand production of 18F radiopharmaceuticals via high-rep rate laser-driven accelerator and microfluidic systems

Advances in laser technology have made it possible to deliver energies of the order of a joule in tens of femtoseconds at relatively high repetition rates (e.g., 100 Hz). When focused onto a thin solid target, such lasers can generate multi-MeV proton beams with fluxes exceeding 10^{10} particles per shot. These sources are promising for producing the ^{18}F radioisotope via the ^{18}O(p,n)^{18}F nuclear reaction. This development could significantly benefit the wider adoption of Positron Emission Tomography, which relies on the availability of short-lived positron-emitting radiopharmaceuticals. At present, these compounds are mainly produced at selected cyclotron facilities and then transported to hospitals, limiting the geographical availability of PET and making economically viable only the production in large batches. We investigate, through Monte Carlo simulations, the feasibility of employing laser-driven proton sources combined with microfluidic systems for on-demand production of ^{18}F radiopharmaceuticals. The simulations were benchmarked against results obtained in a dedicated experiment carried out at low repetition rate. Proton beams obtained through TNSA were directed onto a [^{18}O]H_2O sample contained within a custom PDMS microfluidic target chip intended for direct integration with the radiochemical apparatus used in radiopharmaceutical synthesis. During the experiment, a peak activity of ~5 Bq was measured, while tens of MBq are expected for HRR operation and adopting an optimized irradiation scheme aimed at maximizing the proton flux reaching the enriched water sample.

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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: **692** Type: **Plenary and Invited Presentation**

Optimizing the physics of quasi-isodynamic stellarators

The non-axisymmetric toroidal magnetic geometry of a stellarator presents a vast space, in which one can find designs of different shapes and properties, filling a number of different stellarator classes. This talk focuses on the quasi-isodynamic (QI) stellarator, which promises a number of uniquely attractive properties that make it a front-runner for future stellarator power plants. Although the Wendelstein 7-X stellarator, whose design can be thought of as an early precursor of the QI variant, has validated a number of these expectations, it is only over recent years that advances in stellarator optimization have demonstrated that the full potential of QI stellarators could be realized in practice. We will discuss the physics of QI stellarators, and how this understanding is being used to design the next generation of experiments and fusion reactor designs. These designs combine intrinsic stability, excellent confinement of fusion-born alpha particles, and the resilience in shape needed for reliable and predictable operation. Our deepening understanding of the turbulence in QI stellarators has also enabled us to incorporate key physics into the optimization, such as zonal flows, flux compression, and maximum-J stabilization. Understanding the strong coupling of heat and particle transport channels has lead to designs with a tendency to draw fuel inward, with strong consequences for performance and economics of future devices.

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Track Classification: Magnetic Confinement Fusion (MCF): Stellarator Physics and Optimisation (MCF)

Contribution ID: **706** Type: **Plenary and Invited Presentation**

Kinetic ballooning modes in high-beta stellarators: theory and experiment

High-performance stellarator operation increasingly approaches regimes where electromagnetic effects become essential for confinement. In this context, kinetic ballooning modes (KBMs), driven by total pressure gradients and finite-beta effects, can emerge as the dominant electromagnetic instability, linking ideal magnetohydrodynamic ballooning physics with kinetic microturbulence.
The present contribution provides a combined theoretical and experimental overview of KBMs, with a primary focus on stellarators. To establish the physical foundations, the discussion briefly revisits the ballooning mode framework in tokamaks, starting from simplified cases that illustrate the essential physics of curvature-driven instabilities at finite beta. This perspective is then extended to three-dimensional stellarator geometry, where additional geometric effects modify stability properties.
Within this framework, the impact of increasing beta on the microinstability spectrum is examined. As beta rises, electrostatic instabilities can be mitigated, while KBMs are destabilized and may eventually dominate the electromagnetic response. Gyrokinetic simulations are employed to identify KBM thresholds and to characterize their dependence on pressure gradients and magnetic configuration. Particular attention is paid to the role of magnetic geometry properties (iota, mirror ratio, shear) in determining KBM stability.
These theoretical and numerical findings are complemented by experimental observations in W7-X high-performance discharges, where coherent electromagnetic activity consistent with KBM dynamics is detected. Fluctuation measurements and equilibrium reconstructions reveal systematic trends in frequency and mode structure that align with theoretical expectations, indicating that KBMs set a practical boundary for high-performance operation.
Taken together, these findings indicate that KBMs may define an important electromagnetic stability boundary in high-beta stellarator regimes, although the nature of this boundary, whether gradual or more abrupt, remains an active subject of investigation. Linear stability maps appear to offer a useful framework for identifying KBM-prone operational scenarios and exploring configuration optimization. Incorporating KBM physics into stellarator design and profile control strategies is therefore likely to play an important role in achieving reactor-relevant steady-state performance.

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Track Classification: Magnetic Confinement Fusion (MCF): Stellarator Physics and Optimisation (MCF)

Contribution ID: **716** Type: **Plenary and Invited Presentation**

From data-integrated physical simulation to machine learning analysis of plasma processing of resistive switching devices

The field of machine learning (ML) in plasma science has experienced an immense development in the past decade [1], advancing low-temperature plasma modeling and simulation, as well as experiments and diagnostics [2,3]. Part of this development relates to plasma processing, enabling fine control over tailored material properties at the nanoscale. In this study, plasma processing of SiO_x/Cu resistive switching devices [4] is investigated for reactive radio-frequency magnetron sputter deposition with Ar/O_2 through ML surrogate modeling, data-integrated physical simulations, and a data-driven classification of corresponding wafer-level measurements. Initially, Tridyn simulations [5] of the reactive plasma-surface interaction (PSI) during Ar and O_2 ion impingement on SiO_x are conducted to establish an extensive data set. This is leveraged to devise a ML PSI surrogate model. The latter is subsequently utilized in an axially symmetric 2D particle-in-cell/Monte Carlo collision simulation with dynamical chemical surface coverage for the comprehensive prediction of discharge and surface conditions during reactive sputter deposition. Insights from this simulation study are correlated with a data-driven classification of measured electrical device characteristics. Specifically, a statistical analysis at the wafer-level is applied to over 50,000 devices to identify how processing conditions relate to device characteristics. The analysis reveals distinct device types attributed to the local process conditions during deposition, highlighting the importance of plasma process control in determining functional outcomes in nanoscale electronic devices.

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Track Classification: Low Temperature and Dusty Plasmas (LTDP): Plasma Processing and Applications (LTDP)

Contribution ID: **744** Type: **Plenary and Invited Presentation**

Plasma acceleration, extreme focusing and SFQED using petawatt electron beams

With today's accelerator and laser facilities, such as the 10 GeV FACET-II facility at SLAC National Accelerator Laboratory or laser-accelerated electron beams at multipetawatt laser facilities, extreme beam physics is emerging as a promising science area where ultrashort and dense electron beams can be used as a source of TV/m fields, enabling high field matter interaction and new applications in photon science and particle acceleration. In this talk I will present an overview of recent experimental progress, prospects and physics opportunities for the FACET-II accelerator facility and the multipetawatt laser facilities APOLLON and ELI-NP. By delivering extreme electron beams with peak current reaching 100 kA, corresponding to petawatt peak power at 10 GeV, these facilities enable a broad science program ranging from high-field plasma-based acceleration, laboratory astrophysics, extreme focusing and attosecond sources, and probing quantum electrodynamics at the scale of the Schwinger critical field in the so-called strong-field quantum electrodynamics (SFQED) regime. I will highlight recent breakthroughs achieved at FACET-II, such as the most precise measurements of quantum radiation reaction to date, the generation of 100-kA class beams by laser-electron beam shaping, the demonstration of a brightness and energy transformer, efficient plasma acceleration with percent-level field uniformity, and extreme beam focusing by leveraging intense coherent transition radiation in beam-multifoil collisions. At laser facilities, I will show that extreme beam focusing is also possible thanks to the high current of the laser-accelerated electron beams, and I will highlight how plasma mirrors can be used to generate self-aligned nonlinear inverse Compton scattering from high-energy electron beams, opening the way to the study of SFQED at fields well above the Schwinger critical field.

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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: **757** Type: **Plenary and Invited Presentation**

Electron spin dynamics and spin polarisation preservation in direct laser acceleration (DLA)

The interaction of a high-intensity laser pulse with a near-critical plasma target can lead to the generation of electron beams via direct laser acceleration (DLA) in a plasma channel [1]. This mechanism yields electron beams that are relatively collimated (divergence ~0.1 rad), with charge in the tens of nC, (up to μC [2]) and an exponential energy spectrum with 'temperatures'in the tens of MeV. These electron beams are drastically different from the ones obtained by laser wakefield acceleration (LWFA) and are uniquely suited for applications requiring high particle fluxes, such as neutron generation, nuclear physics studies and industrial imaging.

While electron acceleration dynamics in DLA have been well-studied analytically and in particle-in-cell (PIC) simulations [3,4], the spin dynamics of electrons in this regime have remained largely unexplored. In this work, we analytically investigate electron spin dynamics in DLA based on the Thomas-Bargmann-Michel-Telegdi (T-BMT) equation. We demonstrate that for the most energetic, planar electron trajectories, the spin projection perpendicular to the plane of motion remains conserved. Furthermore, we show that under the ultra-relativistic assumption ($\gamma \gg 1$) the net spin precession averaged over a single betatron oscillation period is negligible, i.e., spin averaged over a betatron oscillation period is conserved. These findings are corroborated by the test particle simulations and 3D EPOCH PIC simulations. Finally, we address the practical feasibility of generating and preserving spin-polarized electron beams in realistic DLA experimental scenarios.

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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: **770** Type: **Plenary and Invited Presentation**

A Laboratory Analogue of Cosmic Ray Interactions in Magnetised Plasma

Understanding how cosmic rays gain energy and scatter in astrophysical environments remains one of the central open questions in plasma astrophysics. We report on an experiment at the GSI Helmholtz Centre for Heavy Ion Research, in which a monoenergetic 450 MeV chromium ion beam was propagated through a magnetized plasma formed by the collision of two counter-propagating, laser-ablated flows. The plasma, diagnosed using interferometry and ion deflectometry, showed an interaction region largely free from fluid-scale turbulence, consistent with magnetohydrodynamic simulations performed with FLASH [Moczulski et al., Phys. Plasmas 31, 122105 (2024)]. Despite this, time-of-flight diagnostics revealed both velocity-space diffusion and bulk acceleration of the ion beam.

The absence of strong, fluid-scale turbulence rules out Fermi acceleration as the cause of the observed scattering and energization. An analytical treatment, constrained by experimental observations, suggests wave–particle scattering by short-wavelength electrostatic kinetic turbulence as an alternative explanation. A forthcoming beamtime campaign at GSI will directly probe these electrostatic fluctuations using collective optical Thomson scattering, providing a quantitative test of the proposed mechanism. These experiments establish a new laboratory platform for studying cosmic-ray-like transport and pre-acceleration in magnetized plasmas. See [arXiv:2509.07880] for initial results.

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

Contribution ID: **771** Type: **Plenary and Invited Presentation**

Progress and plans of the Wendelstein 7-X project and its role in developing the stellarator concept

Wendelstein 7-X (W7-X) is the first comprehensively optimised stellarator and the first magnetic fusion device to follow design principles derived from fundamental physics criteria, such as minimising neoclassical transport losses and plasma currents. As such, W7-X is a rigorous realisation of the stellarator concept, in which the plasma equilibrium depends only weakly on the plasma pressure. It is equipped with superconducting coils that demonstrate the stellarator's ability to confine plasmas in a stationary manner, ensuring plasma discharges are long enough to achieve steady-state equilibria. Thanks to neoclassical optimisation, W7-X has achieved triple product values that were previously unattainable for stellarators. With continuous pellet fuelling, plasma performance parameters can now be maintained over longer periods of time —a capability that was previously only accessible in much larger fusion experiments. These successes are based not only on a significantly better understanding of plasma transport, particularly turbulent plasma losses, but also on technical advances such as an actively cooled divertor and the power control of a multi-gyrotron ECRH facility. The future focus of the W7-X programme will be to advance the duration of high-performance plasmas further (with the aim of achieving 30 minutes at 10 MW of heating power), to improve the understanding of heat and particle exhaust (by employing a magnetic island divertor) and to investigate the crucial role of plasma edge transport and high-beta experiments in exploring stability limits and fast ion confinement. Nevertheless, the success of W7-X must not distract from the fact that many questions remain unanswered on the path to achieving burning fusion plasma or a fusion power plant, despite the conceptual advantages of stellarators. A strategy is currently being developed to address open physics questions, including those relating to divertor physics and first wall materials. The success of W7-X has significantly increased worldwide interest in the stellarator concept among governments and fusion start-ups alike. A key question is how this interest will impact stellarator development and what concrete steps are currently being considered.

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Track Classification: Magnetic Confinement Fusion (MCF): Stellarator Physics and Optimisation (MCF)

Contribution ID: **848** Type: **Plenary and Invited Presentation**

Effect of internal magnetic islands on confinement and transport in Wendelstein 7-X plasmas

A quantitative understanding of the impact of magnetic islands (MIs) on transport and their possible role in enhanced confinement is important for the design and optimization of future stellarator devices. The Wendelstein 7-X stellarator allows for magnetic configurations where static 5/5 MIs form near the separatrix inside the confined region. These configurations have been found to provide improved confinement compared to equivalent configurations where MIs are placed in the scrape-off layer. Confinement transitions associated with MI growth beyond a critical width, $w > w_c$ with w the MI width, can be triggered in turbulence-dominated scenarios by scanning w with external control coils. In turbulence-suppressed regimes, where ITG turbulence is suppressed with density gradients, these transitions are observed spontaneously. Upon these transitions, the plasma diamagnetic energy decreases by ~30-40 %, associated with a flattening of both ion (T_i) and electron (T_e) temperature profiles. The Coherence Imaging Charge Exchange Recombination Spectroscopy (CICERS) diagnostic is employed to characterize the impact of these transitions within one MI on T_i, carbon impurity density (n_C) and flow velocity (v_C), delivering poloidally resolved 2D images of such parameters. While turbulence-dominated regimes show only minor changes in n_C and v_C, associated with the flattening of the profiles, the turbulence-suppressed scenarios display a strong n_C accumulation centered around the O-point of the MI, with n_C increasing up to a factor of 4. Additionally, an island inboard-outboard flow asymmetry is observed, potentially linked to the development of $E \times B$ flows inside the MI. Maintaining w below w_c via strong coil-driven island reduction prevents the spontaneous temperature flattening and associated confinement degradation observed in these configurations in high-performance turbulence-suppressed operation; under these conditions, the current record of Stellarator triple product is obtained.

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Track Classification: Magnetic Confinement Fusion (MCF): Stellarator Physics and Optimisation (MCF)

Contribution ID: **870** Type: **Plenary and Invited Presentation**

Single-shot spatiotemporal plasma density measurements with a chirped probe pulse

High-power (>TW), short-pulse (<ps) laser systems are generating significant interest worldwide due to their numerous applications in science, technology, medicine and industry. Each of these applications relies upon the plasma that is initially produced by the laser's interaction with the target matter. These laser-plasmas range widely in spatial scales from microns to millimeters, and their dynamics can evolve on femtosecond to nanosecond timescales. Due to the sensitivity with which the plasma properties depend on the laser system, and the downstream effects of this initial plasma on the subsequent secondary sources and physics applications, diagnostics that capture a robust picture of their temporal and spatial evolution on a single shot must be developed for and demonstrated on high-power laser systems.

Studies of high-power-laser plasmas to-date have been limited by either temporal or spatial resolution or rely on scanning a variable, such as time or delay. Such measurements that use multiple laser shots to form a measurement cannot reliably distinguish between changes due to shot-to-shot variations and changes due to the variable being scanned. To address this problem, we present the development and demonstration of a diagnostic for the measurement of the spatial and temporal evolution of plasma density in a single shot 2. Single-shot Advanced Plasma Probe HolographIc REconstruction (SAPPHIRE) uses a chirped probe pulse, a diffractive optical element, a self-referenced interferometer, and an interference bandpass filter to achieve high-fidelity electron density measurements suitable for underdense plasmas that exhibit cylindrical symmetry. It overcomes limitations in conventional diagnostics, such as reliance on shot-to-shot reproducibility, while capturing plasma dynamics on picosecond timescales with micron-level spatial resolution. The capabilities of SAPPHIRE are demonstrated through measurements of laser-driven plasma channels in gas jets, including the formation and expansion of plasma channels and the propagation of supersonic ionization fronts while revealing shot-to-shot variations in the plasma profiles. Experimental results are validated against theoretical models and scaling laws, underscoring the robustness and accuracy of this technique. By enabling ultrafast, high-resolution plasma diagnostics in a single exposure, SAPPHIRE represents a transformative advancement in plasma measurement technology.

1 E Grace et al. Optica 12 1522 (2025).

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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: **885** Type: **Plenary and Invited Presentation**

The physics of the energy cascade in magnetohydrodynamic turbulence

In turbulent plasma flows, magnetic field and flow fluctuations interact, resulting in complex multi-scale energy transfer and conversion processes. Here, I discuss an analytical method to decompose the energy flux across scales in magnetohydrodynamic (MHD) turbulence into terms that are physically interpretable and measurable from numerical and observational data. Applying this method to data from three-dimensional direct numerical simulations, we identify the physical MHD processes that drive the energy cascade, akin to vortex stretching and strain amplification in hydrodynamic turbulence. Independent of the level of anisotropy, magnetic energy is transferred from large to small scales mainly by current-sheet thinning, a process where current sheets are stretched by large-scale straining motion into regions of magnetic shear at smaller scales –a process with a natural relation to magnetic reconnection. Contributions from current-filament stretching –the analogue to vortex stretching –is negligible. The small-scale magnetic shear generated by current-sheet thinning in turn drives extensional flows at smaller scales, while hydrodynamic processes such as vortex stretching and strain self-amplification are strongly depleted. Hence, magnetic and kinetic energy are transferred from large to small scales almost exclusively by magnetic effects, connected with the generation of regions of small-scale intense strain induced by the Lorentz force. These results become exact in the limit of very strong background magnetic fields. In consequence, we show that all relevant physics driving the energy cascade are present in reduced MHD, as processes that enter at higher order are negligible, irrespective of the plasma beta. I discuss applications of the method to helicity fluxes and Hall physics and present an exact mathematical analogy between the Hall flux and the kinetic helicity flux, and show in the strong-field limit that magnetic energy transfer due to Hall physics is given by current-sheet thinning, now due shear currents, again a process with a natural relation to magnetic reconnection. Implications of these results for subgrid-scale modelling of magnetohydrodynamic turbulence are discussed.

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

Contribution ID: **896** Type: **Plenary and Invited Presentation**

CIEMAT-QI4X: a reactor-candidate quasi-isodynamic stellarator configuration

The stellarator offers key advantages over the tokamak as a magnetic fusion reactor concept, including intrinsic steady-state operation capability and immunity to current-driven instabilities and disruptions. Unlike in tokamaks, good confinement is not guaranteed in a generic stellarator but requires a careful design of the three-dimensional magnetic field, usually known as stellarator optimization. Owing to its inherent advantages, together with progress in theory and computational optimization, the stellarator has emerged as a solid contender for fusion reactors 1.
In this talk, CIEMAT-QI4X 2 is presented, a new four-field-period quasi-isodynamic configuration featuring low neoclassical and electrostatic turbulent transport, good fast-ion confinement across a wide β range, and a small bootstrap current. CIEMAT-QI4X has been obtained by building on the optimization strategy and sophisticating the methods employed in [3] to achieve high-quality nested flux surfaces in the confinement region and a robust island structure at the edge compatible with an island divertor. A set of filamentary coils wil be presented that generate the configuration with enough accuracy to preserve the aforementioned physics properties. In terms of physics performance, CIEMAT-QI4X establishes as a strong candidate for stellarator
fusion reactor designs.

1 Global Fusion Industry Report 2025. The Fusion Industry Association. 2025.
2 Sánchez E. et al. Nuclear Fusion 2026 (submitted).
[3] Sánchez E. et al. 2023 Nucl. Fusion 63 066037.

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Track Classification: Magnetic Confinement Fusion (MCF): Stellarator Physics and Optimisation (MCF)

Contribution ID: **901** Type: **Plenary and Invited Presentation**

Genesis, amplification, and decay of cosmic magnetic fields

Astronomical observations suggest pervasive, dynamically important magnetic fields in our Galaxy and the intracluster medium, yet their origin remains a long-standing question in astrophysics and cosmology. It is widely believed that such fields first arose as weak "seeds" generated by cosmic batteries and were subsequently amplified by turbulent plasma flows to current levels via the dynamo process; however, a complete understanding of these processes in weakly collisional plasmas, as well as the sustenance of magnetic fields once turbulent stretching subsides, is still lacking. This work presents a unified paradigm for the origin and evolution of cosmic magnetism by incorporating the effects of nonequilibrium microphysics of collisionless plasmas into macroscopic astrophysical processes. Using analytical theory and first-principles numerical simulations, it is demonstrated that seed magnetic fields can spontaneously emerge under generic turbulent motions through kinetic plasma instabilities, implying that cosmic plasmas are ubiquitously magnetized. The cross-scale, nonlinear coupling between microscopic magnetic fields and macroscopic flows enhances turbulence and accelerates the plasma dynamo, rapidly amplifying the field to energy equipartition with the turbulent flow. The subsequent relaxation of these fields after turbulent stretching subsides is regulated by pressure-anisotropy-driven instabilities. The ab initio production of equipartition-strength fields from an initially unmagnetized plasma, together with their relaxation, provides a predictive explanation for the prevalence of cosmic magnetism, a key target of upcoming observations such as those by the Square Kilometer Array.

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

Contribution ID: **903** Type: **Plenary and Invited Presentation**

Holographic gaseous lenses for high-power lasers

Constructing next-generation lasers with energies exceeding several megajoules, or peak powers greater than ten petawatts, will require optical elements that tolerate significantly higher intensities than
solid-state media. For use in practical inertial confinement fusion energy plants or miniaturized particle
accelerators, these optics must also withstand harsh environments with intense backscattered light and
energetic particles. Structured gases, rather than solids, can meet these stringent requirements [1,2]. We
present the first experimental demonstration of a diffractive gas lens for steering and focusing high-energy
nanosecond to high-power femtosecond beams [3]. These lenses were constructed holographically via the
interference of two ultraviolet "write"beams (6 mJ, 5 ns, 266 nm) in an ozone-doped gas mixture. The
write beams drove a structured density profile via spatially-varied heat deposition through ultravioletinduced photodissociation of ozone [4]. The resulting lenses manipulated the focus of a third "read"beam
that was substantially more energetic (220 mJ, 5 ns, 532 nm) at an incident fluence of 35 J/cm2 with greater
than 50% efficiency. These lenses also exhibited sufficient spectral bandwidth to diffract ultrashort 35-fs
800-nm pulses. As holograms, we tuned these lenses to focus, collimate, and defocus the read beam. The
optic showed stable beam pointing and diffraction efficiency without degradation during 10 Hz operation
over sustained periods of time. These results suggest that gaseous optics may enable arbitrary, damageresistant manipulation of intense light.
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Track Classification: Beam Plasmas and Inertial Fusion (BPIF): Inertial Confinement Fusion

(BPIF)

Contribution ID: **904** Type: **Plenary and Invited Presentation**

Laboratory benchmark experiments for stellar opacities

Opacity quantifies the absorption of photons in matter and is essential for understanding energy transport through radiation in high-energy-density (HED) plasmas, such as those found in stars and inertial confinement fusion. While opacity models provide local thermodynamic equilibrium (LTE) opacities for all elements based on temperature and density, they depend on multidisciplinary physics and include untested approximations. Calculating opacities under HED conditions is challenging due to density effects and the overwhelming number of excited states involved. This raises questions about the accuracy of calculated opacities, especially when discrepancies arise between simulations and observations. For instance, solar models have shown inconsistencies with helioseismic observations, raising concerns about the opacities being used. Experimental validation of HED opacity is difficult due to the need for a bright backlight to overcome self-emission from hot, dense plasmas. In 2015, we utilized the Z-machine at Sandia National Laboratories, which is the most energetic X-ray source on Earth, to test iron opacity at solar interior temperatures for the first time. The measurements revealed significant discrepancies between calculated and measured iron opacities, raising significant concerns within the HED and astrophysics communities. We will summarize experimental and theoretical challenges associated with HED opacity, as well as our recent progress in our time-resolved measurements and first oxygen opacity measurements. Systematic experimental investigations into opacity issues will help resolve the solar problem and reduce uncertainty in radiation-hydrodynamic simulations.

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

Contribution ID: **906** Type: **Plenary and Invited Presentation**

Laser driven radioisotope production for medical applications

Laser generated sources of TNSA protons and alpha particles (produced by proton boron fusion reactions) can be used for the production of radioisotopes of medical interest. The present work discusses the results from experiments performed using the PW-class, short duration and high repetition laser VEGA-III at CLPU, Spain. In the experiment, we used the pitcher-catcher scheme, using thin Al foils to produce accelerated protons, which were directed on various targets including boron catchers (BN, BNH6) to produce alpha particles through proton boron fusion reactions. We used a High Purity Germanium (HPGe) detector to trace gamma ray emission lines from the activated catcher showing emission lines from 7Be, 11C, and 18F, measuring their lifetime and estimating their activity [1, 2]. We also used high density calcium
silicate (Ca2SiO4) catchers to produce scandium radioisotopes either by the interaction with alpha-particles produced by proton-boron fusion or directly by the accelerated proton beam. The results indicate the presence of the scandium radioisotopes: 43Sc, 44Sc, and 48Sc. We are reporting on two experiments. The first one demonstrated possibility of radioisotope production [1, 2], the second one put light on developments, which might allow developing laser-driven sources of radioisotopes for medical applications.

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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: **921** Type: **Plenary and Invited Presentation**

Modelling the particle dynamics in turbulent plasmas using the innovative multi-scale Box-In-Box (BIB) approach

The particle dynamics in plasmas has a highly multi-scale nature in terms of spatial scales, temporal scales, and energy range. In the solar wind, it spans about eight orders of magnitude in length (from fractions of the electron gyroradius to the Sun-Earth distance) and about five in energy. These ranges are way more extreme in astrophysical systems. Tackling the particle dynamics is thus a very challenging task, especially when the background plasma is highly turbulent.

We have developed an innovative approach, the multi-scale Box-in-Box (BIB), to model particle energisation in turbulent plasmas over a massive range of scales. First, we model the turbulent energy cascade from very large to very small scales coupling different models (MHD, hybrid, and fully kinetic), using a portion of a large simulation as initial condition for one with higher resolution multiple times in sequence. Then, we advance the trajectories of hundreds of millions of test particles on the evolving turbulent background from small to large scales while their gyroradius (and energy) increases. Our BIB approach allows for modelling the large-scale propagation of energetic particles in turbulent plasmas while retaining a realistic and self-consistent description of the microphysics responsible for particle energization. BIB simulations are key tools for developing new visualisation and analysis techniques for future multi-scale space missions such as NASA HelioSwarm and ESA Plasma Observatory.

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

Contribution ID: **922** Type: **Plenary and Invited Presentation**

Kinetic Instabilities in Extreme Plasma Physics: Laboratory and Astrophysical Dynamics

Extreme plasma physics concerns regimes in which strong electromagnetic fields, intense radiation, and matter–antimatter pair production fundamentally alter kinetic plasma behaviour. Such conditions arise in pulsar and black-hole magnetospheres, relativistic shocks, and are increasingly accessible in laboratory experiments. This thesis addresses two central components of this field: radiative plasma kinetics and electron–positron pair-plasma dynamics.
A kinetic model for radiatively dominated plasmas is developed using analytical theory and large-scale particle-in-cell simulations. Synchrotron cooling in strongly magnetized collisionless plasmas is shown to drive phase-space bunching, generically producing anisotropic ring-shaped momentum distributions with population inversion, i.e., $\partial f / \partial p_\perp > 0$. These non-equilibrium states are unstable to the electron cyclotron maser instability (ECMI). Radiation reaction sustains the phase-space bunching, maintaining coherent emission beyond classical saturation. An analogous radiation-reaction–driven mechanism also arises in plasma wakefield accelerators, where betatron cooling induces amplitude bunching and ring-like phase-space structures in relativistic beams, enabling coherent emission via the ion-channel laser instability.
The thesis further investigates the collective behaviour of relativistic electron–positron plasmas, with contributions to the first laboratory generation of high-density, quasi-neutral pair beams at CERN's SPS and led three-dimensional kinetic simulations demonstrating that realistic energy spread and angular divergence suppress current-filamentation growth. Additional non-ideal effects, including charge imbalance and multi-species components, were also analysed. This improved understanding of pair-beam instabilities establishes experimental constraints relevant to γ-ray–induced pair cascades and limits on the intergalactic magnetic field.
Together, these studies advance a unified kinetic description of extreme plasmas encompassing both radiative effects and pair-plasma dynamics.

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

Contribution ID: **923** Type: **Plenary and Invited Presentation**

Theory-based integrated modelling of impurity transport in tokamaks

Impurities play a critical role in the integration of a hot plasma core with a cold plasma edge, which are simultaneous requirements for the viable operation of a fusion reactor. Core radiation and fuel dilution set stringent limits on the tolerable impurity concentrations to sustain thermonuclear conditions or even for the survival of the plasma itself. At the same time, injected impurities will be essential to safely dissipate excess heat before it reaches the reactor walls.
An integrated modelling workflow including impurities and their radiation has been developed, combining all presently known theoretical elements in the local description of quasi-linear turbulent and collisional impurity transport. An analytical model which describes the crucial effects of toroidal rotation on the neoclassical transport of impurities is introduced and shown to be accurate with respect to more complete codes but better suited for fast applications.
The workflow is validated against experimental data from a variety of plasmas in the ASDEX Upgrade tokamak. The modelling is able to reproduce measurements of the main plasma profiles, the impurity densities, and the radiated powers of L-mode discharges in full-radius simulations, including a discharge with impurity seeding and a high radiated power fraction.
Furthermore, the control of impurity accumulation with central wave heating is investigated for H-mode plasmas with dominant neutral beam heating. The workflow is shown to quantitatively reproduce the experimentally observed reduction of tungsten (W) peaking at increasing wave heating power, and the physics behind this important experimental technique is analyzed.
Having validated the physics-based modelling workflow, a predictive study of the 15 MA ITER baseline scenario is presented, investigating the interplay between the edge concentration, transport and radiation of W, the auxiliary heating required to sustain H-mode operation, and the fusion performance. It is shown that heavy impurities are in a different core transport regime in reactors compared to present-day devices. Furthermore, the transport and effects of W in electron-heated ITER plasmas at lower currents and fields, as well as during the current ramp-up, are investigated. Overall, this analysis contributes to a more solid definition of the domain of operational conditions which allow the achievement of the main ITER targets, in particular in view of its recently proposed full-tungsten walls.

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

Contribution ID: **924** Type: **Plenary and Invited Presentation**

Probing Ion Drag and Electric Field Forces in 2f CCPs using Optically Trapped Microparticles

Boundary regions of low-pressure capacitively coupled plasmas (CCPs) –the presheath and sheath –govern ion acceleration, momentum transfer, and plasma–surface interactions, yet remain challenging to probe experimentally. In dual-frequency (2f) CCPs, the Electrical Asymmetry Effect (EAE) allows global tuning of plasma parameters via the relative phase between driving frequencies, but its local impact on boundary-layer forces has remained largely unexplored.
In this work, optically trapped microparticles are employed as spatially
resolved, minimally invasive force probes to investigate boundary-layer dynamics in dual-frequency CCPs. A single SiO2 microparticle (7 μm diameter) is confined in a three-dimensional optical tweezer and scanned vertically through the discharge. By tuning the trap stiffness, strong electrostatic forces in the sheath and weaker ion drag forces in the presheath are selectively resolved (Fig. 1).
The measured force profiles reveal a clear spatial separation of dominant forces: ion drag emerges in the presheath, reaches a maximum near the sheath edge, and is overtaken by the rapidly increasing electric field force inside the sheath. Under dual-frequency excitation, both force magnitude and spatial distribution exhibit pronounced asymmetry with respect to the RF phase, reflecting phase-dependent modifications of
electron heating and plasma density.
Particle charges derived from the sheath force profiles are consistent with orbital-motion-limited theory and literature estimates.
This approach establishes optically trapped microparticles as highly sensitive, force-resolved probes of boundary-layer physics, directly linking bulk plasma behavior with sheath dynamics.
It provides quantitative insight into local force balances, ion acceleration, and momentum transfer in phase-controlled 2f CCPs, and opens new experimental pathways toward force-resolved studies of plasma–surface interaction in technologically relevant RF discharges.

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

Contribution ID: **925** Type: **Plenary and Invited Presentation**

Quasi-Isodynamic Stellarator Optimisation

Quasi-isodynamic (QI) magnetic fields are a uniquely attractive feature for stellarator power plants due to their low neoclassical transport and small toroidal currents 1, the latter offering robust plasma stability. It is for this reason that several stellarator companies, including Type One Energy 2 and Proxima Fusion [3], have based their power plant designs around QI magnetic fields. Like most properties in stellarators, one must use numerical optimisation techniques to find plasma equilibria that are QI. In this work, we begin by presenting the first method ever developed that is able to find stellarator equilibria with sufficient QI quality for a fusion power plant [4]. Any stellarator reactor must be resilient to magnetohydrodynamic (MHD) and turbulent instabilities, the latter of which limits the performance of Wendelstein 7-X [5], itself a roughly QI stellarator. As such, we next merged our QI optimisation methodology with other novel methods to find a new class of stellarators, "SQuIDs"(Stable Quasi-Isodynamic Designs) [6], which satisfy these conditions alongside excellent QI quality. Findings from Kappel et al. [7] can be included in SQuID designs, yielding configurations that are compatible with relatively simple electromagnetic coils. The final publication in this work therefore presents coil-compatible SQuIDs [8], which additionally feature an island divertor concept, along with other new and interesting physics properties such as an electron root —a region of outward pointing radial electric field —which may result a transport barrier akin to an H-mode placed the plasma radius of the designer's choosing [9]. Future work on SQuIDs includes introducing an inward particle pinch [10], resulting in further improved fusion power output and plasma confinement.

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