| ID | Posternumber | Title | Topic | Pesenter first name | Presenter last name |
|---|---|---|---|---|---|
| 61 | P1b.101 | Effect of edge ion temperature on the divertor W sputtering on WEST | Magnetic Confinement Fusion | yongliang | Li |
| 63 | P1b.102 | Predicting the physics of ion cyclotron emission from neutral beam-heated plasmas in the Wendelstein 7-X stellarator | Magnetic Confinement Fusion | Omstavan | Samant |
| 84 | P1b.104 | The helically-trapped electron mode in W7-X stellarator | Magnetic Confinement Fusion | Javier H. | Nicolau |
| 108 | P1b.105 | Plasma perturbation by active probes in the SOL of W7-X | Magnetic Confinement Fusion | Carsten | Killer |
| 127 | P1b.106 | A statistical analysis approach of plasma dynamics in gyrokinetic simulations of stellarator turbulence | Magnetic Confinement Fusion | Johan | Anderson |
| 135 | P1b.107 | Investigation of tungsten EUV line and background emission and determination of its density in the WEST tokamak | Magnetic Confinement Fusion | Mohamed Yaakoub | BOUMENDJEL |
| 160 | P1b.108 | Analysis of divertor fluxes with proper orthogonal decomposition method in Wendelstein 7-X | Magnetic Confinement Fusion | Marcin | Sleczka |
| 165 | P1b.109 | Upgrades of the Phase Contrast Imaging Diagnostic at Wendelstein 7-X | Magnetic Confinement Fusion | Jan-Peter | Bähner |
| 184 | P1b.110 | 2D X-ray spectrometer on WEST: diffracting crystals study and first temperatures profiles | Magnetic Confinement Fusion | Adrien | Da Ros |
| 200 | P1b.111 | Correlation microwave diagnostics on the Wendelstein 7-X stellarator for Operational Phase 2 | Magnetic Confinement Fusion | Gavin | Weir |
| 215 | P1b.112 | On symplectic integration of the guiding-center equations in general 3D toroidal fields using GORILLA | Magnetic Confinement Fusion | Michael | Eder |
| 222 | P1b.113 | ICRH heating and turbulent transport modelling of the WEST L-mode plasma using ETS: interpretative and predictive code validation | Magnetic Confinement Fusion | philippe | huynh |
| 239 | P1b.114 | Analysis of 3D filament structures in various magnetic configurations of the W7-X stellarator | Magnetic Confinement Fusion | Attila | Buzás |
| 248 | P1b.115 | Radial correlation reflectometry analysis in high-turbulence plasma scenario | Magnetic Confinement Fusion | Stephane | Heuraux |
| 252 | P1b.116 | KBM and Finite-β ITG Turbulence in the Wendelstein 7-X stellarator | Magnetic Confinement Fusion | Paul | Mulholland |
| 278 | P1b.117 | Compatibility of high-Z impurity accumulation with high plasma performance in ECR-heated W7-X plasmas | Magnetic Confinement Fusion | Daihong | Zhang |
| 322 | P1b.118 | A special case of long-pulse high performance operation in W7-X | Magnetic Confinement Fusion | Glen | Wurden |
| 356 | P1b.119 | Power exhaust in high-performance plasmas in Wendelstein 7-X | Magnetic Confinement Fusion | Yu | Gao |
| 366 | P1b.120 | The universal instability in optimised stellarators | Magnetic Confinement Fusion | Paul | Costello |
| 425 | P1b.121 | Parametric decay of microwave beams in the edge island of Wendelstein 7-X: theoretical modelling and correlation with edge fluctuations | Magnetic Confinement Fusion | Andrea | Tancetti |
| 429 | P1b.122 | Novel methods for evaluating Thomson scattering data to improve the accuracy of the electron density and its error estimate | Magnetic Confinement Fusion | Golo | Fuchert |
| 514 | P1b.123 | Fast diagnostic mapping in non-nested magnetic topologies using 3D field compliant magnetic surface labels and neural network based interpolation | Magnetic Confinement Fusion | Alexander | Knieps |
| 96 | P1b.201 | Turbulence Generation in High - power Laser - Plasma Interaction Relevant to Astrophysical Scenarios | Beam Plasmas and Inertial Fusion | Indraj | Singh |
| 249 | P1b.202 | Enhancement of nuclear reactions via the kinetic Weibel instability in plasmas | Beam Plasmas and Inertial Fusion | Zhenyu | Liu |
| 389 | P1b.204 | A hybrid (ablation-expansion) model for low-density foams | Beam Plasmas and Inertial Fusion | Lubomír | Hudec |
| 391 | P1b.205 | Calculation on the stopping power of the warm dense matter at the Bragg peak | Beam Plasmas and Inertial Fusion | Francisco | Chacón Rubio |
| 398 | P1b.206 | Hydrodynamic modeling of self-generated magnetic fields by ALE methods | Beam Plasmas and Inertial Fusion | Milan | Kucharik |
| 537 | P1b.208 | Self-generated magnetic fields during nanosecond laser-target interaction | Beam Plasmas and Inertial Fusion | Jan | Nikl |
| 420 | P1B.209 | Investigation of magnetized plasma created in snail targets at the PALS facility | - | Tadeusz | Pisarczyk |
| 172 | P1b.301 | Quantum sensing of microparticle charges in plasmas | Low Temperature and Dusty Plasmas | Mikhail | Pustylnik |
| 219 | P1b.303 | Design and optimization of a radio frequency plasma jet for biomedical applications | Low Temperature and Dusty Plasmas | Leonardo | Zampieri |
| 582 | P1b.304 | Modeling of gas breakdown with “particle in cell” method | Low Temperature and Dusty Plasmas | Stanislav | Dudin |
| 57 | P1b.401 | Community structure of Earth’s magnetic field measurements. | Basic, Space and Astrophysical Plasmas | Sebastián | de la Maza |
| 88 | P1b.402 | On stochastic electron dynamics in colliding plane waves | Basic, Space and Astrophysical Plasmas | Alexey | Knyazev |
| 141 | P1b.403 | Nonlinear growth of Rayleigh Taylor Instability single mode structure under the effect of collision with a second fluid | Basic, Space and Astrophysical Plasmas | Quentin | Cauvet |
| 432 | P1b.404 | PICSAR-QED: a Monte Carlo module to simulate strong-field quantum electrodynamics in particle-in-cell codes for exascale architectures | Basic, Space and Astrophysical Plasmas | Luca | Fedeli |
| 440 | P1b.405 | Ionization and electron capture processes induced in collisions between singly charged ions and nitrogen atom | Basic, Space and Astrophysical Plasmas | Musab | Al-Ajaleen |

# Effect of edge ion temperature on the divertor W sputtering on WEST

Y. Li[1], N. Fedorczak[2], G. S. Xu[1], Y. Liang[3], S. Brezinsek[3], J. Morales[2], and the WEST team[4]

[1]*Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China*

[2]*CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France*

[3]*Forschungszentrum Jülich GmbH, Institut für Energie- und Klimaforschung – Plasmaphysik, Partner of the Trilateral Euregio Cluster (TEC), 52425 Jülich, Germany*

[4]*See (http://west.cea.fr/WESTteam) for the WEST team*

Email (speaker): ylli@ipp.ac.cn

Due to the lack of routinely ion temperature measurement at the SOL, the study of tungsten erosion and transport is usually limited to the electron temperature measurement, and the effect of the ion temperature is barely considered in theoretical simulations [1]. This presentation introduces a study of the edge ion temperature effect on the tungsten (W) sputtering in the WEST tokamak by means of the retarding field analyzer [2], the divertor Langmuir probe array [3] and the divertor visible spectroscopy [4]. By gradually decreasing the SOL electron density and maintaining a constant SOL power, the upstream ion temperature and its ratio over the electron temperature both gradually increase. This increment is observed to enhance the energy transfer from ions to electrons, which in turn increases the downstream electron temperature and enhances the downstream W sputtering. The energy transfer rate was estimated to gradually decrease with the increase of the normalized electron collisionality. Its value comparing with the perpendicular ion and electron energy transport rate are roughly $Q_{eq}/Q_{\perp,i}\sim 1/5$ and $Q_{eq}/Q_{\perp,e}\sim 1$. This indicates that the energy transfer from ions to electrons play an important role in governing the edge plasma energy balance. An analytical equation considering the ion and electron coupling term is introduced to predict the upstream and downstream electron temperature ratio ($T_{eu}/T_{ed}$). The result is more precise than the traditional analytical equation [5] in comparing with the experimental measurement. Based on the new analytical equation, increasing the upstream $T_i/T_e$ ratio or electron collisionality would decrease the $T_{eu}/T_{ed}$ ratio and potentially increase the W material sputtering risk. This work may help to facilitate the understanding of the effect of the coupled ion and electron energy on the W sputtering.

**Reference:**

[1]Brezinsek S. et al. 2019 Nucl. Fusion 59 096035

[2]Kočan M. et al. 2008 Rev. Sci. Instrum. 79 073502

[3]Dejarnac R. et al. 2021 Fusion Eng. Des. 163 112120

[4]Meyer O. et al. 2018 Rev. Sci. Instrum. 89 10D105

[5]Stangeby P. C., The plasma boundary of magnetic fusion devices (CRC Press, 2000).

# Predicting the physics of ion cyclotron emission from neutral beam-heated plasmas in the Wendelstein 7-X stellarator

O Samant[1], R O Dendy[2,1], S C Chapman[1,3], D Moseev[4] and R Ochoukov[5]

[1]*Centre for Fusion, Space and Astrophysics, Department of Physics, Warwick University, Coventry CV4 7AL, UK*

[2]*CCFE, Culham Science Centre, Abingdon, Oxfordshire OX14 3DB, UK*

[3]*Department of Mathematics and Statistics, University of Tromsø, Norway*

[4]*Max-Planck-Institut für Plasmaphysik*, *Wendelsteinstr. 1, 17491 Greifswald, Germany*

[5]*Max-Planck-Institut für Plasmaphysik*, *Boltzmannstr. 2, 85748 Garching, Germany*

Recent observations of spontaneously generated radiation in the ion cyclotron range of frequencies from the KSTAR and DIII-D tokamaks, and from the LHD heliotron-stellarator, show that energetic neutral beam injected (NBI) ion populations can relax collectively in the edge plasma near their injection point, resulting in ion cyclotron emission (ICE). Its spectrum has strongly suprathermal peaks at harmonics of the local ion cyclotron frequency. Edge NBI ICE is due to the magnetoacoustic cyclotron instability (MCI), which has been simulated [for KSTAR, B Chapman *et al*., *Nucl. Fusion* **59**, 106021 (2019); for LHD, B C G Reman *et al*., *Nucl. Fusion* **59**, 096013 (2019)] from first principles, using particle-in-cell (PIC) kinetic codes which solve the Maxwell-Lorentz system of equations self-consistently for tens of millions of gyro-orbit-resolved particles. Comparison of ICE spectra from tokamaks and stellarators sheds light *inter alia* on the relative importance of overall magnetic field structure compared to spatially localised physics. Here we report PIC simulations that predict ICE spectra from imminent observations from NBI-heated plasmas in the Wendelstein 7-X stellarator. These simulations are computationally resource-intensive, partly due to the low ratio of the perpendicular velocity of the NBI ions to the local Alfvén velocity, requiring typically 200,000 CPU-hours apiece. Our simulations capture the entire frequency range from ion cyclotron through lower hybrid and well beyond, with high fidelity. It appears that both the MCI and the lower hybrid drift instability, found in related simulations (J W S Cook *et al*., *Phys. Rev. Lett.* **105**, 255003 (2010)), may operate simultaneously in the Wendelstein 7-X scenario. We explore how far they embody similar underlying physics, perhaps linked, at the level of first principles kinetics. The development of a predictive, as distinct from *ex post facto* interpretive, capability for linking ICE spectral structure to the velocity-space structure of the emitting ion population is important for the diagnostic exploitation of ICE in present and future fusion experiments.

This work received support from the RCUK Energy Programme grant no. EP/T012250/1. It was carried out within the framework of the EUROfusion Consortium and received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreements 633053 and 101052200. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

# The helically-trapped electron mode in W7-X stellarator

J.H. Nicolau[1], Z. Lin[1], X.S. Wei[1], P.F. Liu[1] and G. Brochard[1]

[1] *Department of Physics and Astronomy, University of California, Irvine, USA*

This work reports the discovery of a new driftwave eigenmode in the W7-X from the first ever nonlinear gyrokinetic simulation of microturbulence in the stellarator incorporating both full flux-surface and kinetic electrons. Global simulations are necessary to study key physics of the non-axisymmetric stellarator such as linear toroidal coupling of multiple-n toroidal harmonics (e.g., localization of eigenmodes to discrete magnetic field lines, linear coupling between zonal flows and low-n harmonics etc), turbulence spreading, and secular radial drift of helically-trapped particles. In this work, global gyrokinetic simulations using the GTC code [1] find a new electrostatic helically trapped electron mode (HTEM) driven by a realistic density gradient in the W7-X. The HTEM is excited by helically trapped electrons at the toroidal section with a weak magnetic field. The linear eigenmode is localized to discrete field lines on the inner side of the torus. Nonlinear simulations find that the HTEM saturates by inverse cascade of the toroidal harmonics from a linear range of n=[100,300] to a nonlinear range of n=[0,200] and by turbulence spreading to the damped region across the whole flux-surface and in the radial direction. Zonal flows play a secondary role in the HTEM saturation. The saturated HTEM turbulence drives a large particle diffusivity comparable to the heat conductivity driven by the ion temperature gradient (ITG) turbulence [2] with similar gradient scale lengths. The HTEM can only be captured by full flux-surface simulations since helically trapped electrons residing in different flux-tubes can either drive or damp the HTEM. The full flux-surface simulations with kinetic electrons only become feasible thanks to the GTC global field-aligned mesh in real space, which reduces the number of parallel grid points by a factor of 150 in these W7-X simulations.

## References

[1] Z.Lin *et al*, Science **281**, 1835 (1998)

[2] H.Y. Wang *et al*, Phys. Plasmas **27**, 082305 (2020)

# Plasma perturbation by active probes in the SOL of W7-X

C. Killer[1], O. Grulke[1], W7-X Team[1]

[1] *Max Planck Institute for Plasma Physics, Greifswald, Germany*

Electric (Langmuir) probes are a common diagnostic tool for the investigation of plasma edge physics in magnetized fusion plasmas. While they offer several advantages, such as highly localized measurements and typically good temporal resolution, they have the inherent drawback of being an invasive diagnostic, potentially perturbing the plasma.

Experiments involving electrically biased reciprocating probes in the test divertor operation phase of the Wendelstein 7-X stellarator (2017-2018) reveal a variety of (unintended) phenomena attributed to perturbations by the probes:

Firstly, negatively biased probes, drawing ion saturation current, affect the fluctuation characteristics in the 100kHz range of nearby unbiased probes.

Secondly, a single swept Langmuir probe can strongly affect the signals of all nearby electric probes while it is at electron collection (positive) bias. The effects include a strong modulation of both time-averaged values and fluctuation characteristics. In particular, electron collection currents of ~1A by the swept probe at positive bias voltages can clearly affect plasma conditions measured by divertor target probes on flux tubes passing closely nearby the reciprocating probes at a parallel distance of ~10m.

Finally, the insertion of a reciprocating probe head into a magnetic island can redistribute heat and particle fluxes within the island, causing factor 2 changes (both increases and decreases) in density and temperature at the divertor targets, presumably by acting as a field-line limiting object.

This contribution summarizes these observations, infers scenarios to minimize perturbations in future experiments, and explores potential exploitations of perturbations: As an example, the clear response on target probes due to a reciprocating swept probe can help in mapping magnetic field lines. Furthermore, the propagation of active perturbations provides insight into the SOL plasma physics. Finally, modification of plasma conditions and particularly $E_r$ shear by biased electrodes with the goal of tailoring SOL heat and particle fluxes has been attempted in several fusion devices, e.g. [Zweben PPCF **51** 105012 (2009), Grenfell NF **59** 016018 (2019)].

# A statistical analysis approach of plasma dynamics in gyrokinetic simulations of stellarator turbulence

A. D. Papadopoulos[1], J. Anderson[2], E-J. Kim[3], M. Mavridis[4] and H. Isliker[4]

[1] *School of Electrical and Computer Engineering, National Technical University of Athens, 157 80, Greece*

[2]*Department of Space, Earth and Environment, Chalmers University of Technology, SE-412 96 Göteborg, Sweden*

[3]*Centre for Fluid  Complex Systems, Coventry University, Priory St, Coventry CV1 5FB, UK*

[4]*Dept. of Physics, Aristotle University of Thessaloniki, 541 24, Thessaloniki, Greece*

A geometrical method is used for the analysis of stochastic processes in plasma turbulence. Distances between thermodynamic states can be computed according the thermodynamic length methodology which allows the use of a Riemannian metric on the phase space. The geometric methodology is suitable in order to understand stochastic processes involved in e.g. order-disorder transition, where a sudden increase in distance is expected. Gyrokinetic simulations of Ion-Temperature-Gradient (ITG) mode driven turbulence in the core-region of the stellarator W7-X, with realistic quasi-isodynamic topologies using the *GENE* [1] software are considered. In gyrokinetic plasma turbulence simulations avalanches, e.g. of heat and particles, are often found and in this work a novel method for detection is investigated. This new method combines the Singular Spectrum Analysis algorithm [2, 3], formulated for 1D and 2D data, and Hierarchical Clustering such that the gyrokinetic simulation time series is decomposed into a part of useful physical information and noise. The informative component of the time series is used for the calculation of the Hurst exponent, the Information Length and the Dynamic Time. Based on these measures the physical properties of the time series is revealed.

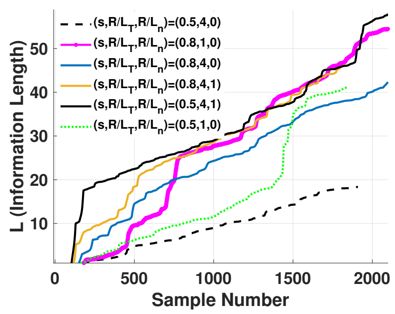


Figure 1: *Information length for the heat flux Q time series for various values of the normalized flux radius, s, temperature gradient,* $\Delta T$*, and density gradient,* $\Delta n$*.*

## References

[1] The GENE Development Team, ”The Gyrokinetic Plasma Turbulence Code Gene: User Manual”, http://genecode.org/

[2] N. Golyandina, V. Nekrutkin, A. Zhigljavsky, ”Time Series Structure SSA and Related Techniques”, CHAPMAN & HALL/CRC, (2001).

[3] J. Anderson, F. D. Halpern, P. Xanthopoulos, P. Ricci, and I. Furno, Phys. Plasmas. **21**, 122306 (2014).

# Investigation of tungsten EUV line and background emission and determination of its density in the WEST tokamak

M.Y. Boumendjel[1], R. Guirlet[1], C. Desgranges[1], E. Popov[2], J. L. Schwob[3], O. Peyrusse[4]

*[1] CEA/Institut de Recherche sur la Fusion Magnétique, 13108 Saint paul Lez Durance Cedex, France*

*[2] Aix-Marseille Université, Ecole Centrale Marseille, Institut Fresnel UMR 7249, Marseille, France.*

*[3] Racah Institute of Physics, Hebrew University of Jerusalem, Israel*

*[4] Aix-Marseille Université, Laboratoire Lasers Plasmas Procédés Photoniques, Marseille, France*

The inner walls of current (AUG, JET, WEST) and future (ITER) tokamaks use tungsten W. In many devices with W wall components, plasma scenarios have been developed aimed at minimizing W erosion from the plasma facing components and W contamination of the confined plasma. A crucial criterion for the success of those scenarios is the core W density. For this reason, it is important to determine the W density experimentally [1]. However, little attention has been given to the tungsten spectrum background that may affect its density determination. The aim of this work is to analyze the tungsten spectral emission in the EUV region measured in the WEST tokamak by a grazing incidence spectrometer [2] and to extract from the spectrum background some information complementary to the spectral line intensities for the determination of tungsten density in the plasma core.

In a recent work [3], a method was developed to compute the local tungsten density from its line brightness in the EUV region in WEST tokamak. The density of the $W^{42+}$ to $W^{45+}$ ions was computed from isolated strong lines emitted in the 120-135 Å region. In the present work, we model the spectrum background. It appears to be complex, because in addition to the Bremsstrahlung and the radiative recombination, higher diffraction orders of the quasi-continuum emission may contribute to the background. We have calculated the grating efficiency, and in our spectral region of interest (120-160 Å), the results show that the contribution of the second and third orders is negligible compared to the other emission types. The bremsstrahlung and the radiative recombination emissions are computed with the help of the experimental $Z_{eff}$ and the W density deduced from the EUV line measurements. Assuming three types of impurities: light (C, N, O), mid (Fr, Cu) and W, we can thus assess the impurity mix from the consistent modeling of the background and of the spectral lines by fitting it to the measurements. This allowed us to develop a fitting method for the EUV spectra and evaluate the impact on the derived line intensities. The method is used to resolve the tungsten blended lines, to extract properly the line characteristics and to determine the tungsten density. It is also used here to show that W accumulation triggered by ICRH is responsible for a radiative collapse in a WEST plasma.

[1] Asmussen, Knut, et al. "Spectroscopic investigations of tungsten in the EUV region and the determination of its concentration in tokamaks." *Nuclear fusion* 38.7 (1998): 967.

[2] Schwob, J. L., et al. "High-resolution duo-multichannel soft x-ray spectrometer for tokamak plasma diagnostics." *Review of scientific instruments* 58.9 (1987): 1601-1615.

[3] R. Guirlet, et al. To be submitted.

# Analysis of divertor fluxes with proper orthogonal decomposition method in Wendelstein 7-X

M. Ślęczka[1], M. Jakubowski[2], H. Niemann[2],

A. Puig Sitjes[2], H. Tanaka[3], B. Zamorski[1] and W7-X team

[1] *Institute of Physics, University of Szczecin, Szczecin, Poland*

[2] *Max-Planck-Institut für Plasmaphysik, Greifswald, Germany*

[3] *Graduate School of Engineering, Nagoya University, Nagoya, Japan*

Wendelstein 7-X uses a so-called island divertor for heat and particle exhaust, which uses large magnetic islands to form strike lines on ten divertor units: five on top, five on bottom. This leads to specifics, strongly three-dimensional structure of the heat flux distribution, which is sensitive to magnetic configuration and plasma parameters. During the last campaign, OP1.2b (2018), a few programs were performed where a set of 10 so called control coils (located behind each divertor units) were used to modify edge islands geometry and by that strike line shape and position. Data collected during the discharge by 10 infrared camera systems were analysed by the 2D THEODOR code in order to obtain heat flux distribution across all 10 divertors. However, the analysis is very complicated due to the large amount of data to be considered. The Proper Orthogonal Decomposition (POD) [1, 2] method was implemented to find the correlation between strike line parameters and the additional magnetic field generated by the control coils.

POD method has been applied to investigate multidimensional problem allowing to reduce the number of dimensions in the description. For these studies the time evolution of the heat peak profile and the wetted area were investigated. It was shown that POD modes changed as the considered parameters changed. Comparison of both, heat profile and evolution in time wetted area, with proper time coefficient show clear relation between these quantities.

## References

[1] Tanaka H. et al, Plasma Phys. Control. Fusion **60** (2018) 125001

[2] Tanaka H. et al, Nuclear Materials and Energy **19** (2019) 378-383

# Upgrades of the Phase Contrast Imaging Diagnostic at Wendelstein 7-X

J.-P. Bähner[1], A. von Stechow[1], S. K. Hansen[2], Z. Huang[2], E. M. Edlund[3],
M. Porkolab[2], O. Grulke[1,4] and the Wendelstein 7-X Team[1]

[1] *Max-Planck-Institut für Plasmaphysik, Greifswald, Germany*

[2] *MIT Plasma Science and Fusion Center, Cambridge, MA, USA*

[3] *SUNY Cortland, Cortland, NY, USA*

[4] *Technical University of Denmark, Kongens Lyngby, Denmark*

This contribution presents the details of the technical diagnostic upgrades and proposed experiments for the phase contrast imaging (PCI) diagnostic [1, 2] on the optimised stellarator Wendelstein 7-X (W7-X). The PCI system, which measures line-integrated and wavenumber-resolved density fluctuations throughout the entire plasma (e.g. [3]), is a central tool for turbulence characterisation. In preparation for the upcoming long pulse, high performance experiments at W7-X, technical upgrades of the diagnostic have been implemented including a new infrared $CO_2$ laser, improved optical design, spatial mask filters for radially localised measurements and a feedback system for suppression of low frequency noise due to mechanical vibrations. Additionally, a heterodyne detection scheme using an acousto-optical modulator will be added for measurements in the ion cyclotron frequency range. Various experimental proposals making use of these capabilities are planned for the upcoming experiment campaign: a radial localisation of fluctuations previously inferred despite the line-integrated nature of the measurements [3] will be further validated using the mask filters. Zonal-flow-like oscillations of the poloidal flow velocity have previously been observed. Their nature and origin will be investigated as well as possible connections to coherent MHD modes. A direct comparison of dedicated experimental measurements to global gyrokinetic simulations is envisioned using a synthetic PCI diagnostic [4]. Finally, the improved confinement after pellet injection [5] and other means of profile shaping will be further investigated, in particular with respect to the spatial distribution of fluctuations.

## References

[1] E. M. Edlund *et al.*, *Rev. Sci. Instrum.* **89**, 10E105 (2018)

[2] Z. Huang *et al.*, *J. Inst.* **16**, P01014 (2021).

[3] J.-P. Bähner *et al.*, *J. Plasma Phys.* **87**, (2021).

[4] S. K. Hansen *et al.*, submitted to *Plasma Phys. Control. Fusion* (2022)

[5] S. A. Bozhenkov *et al.*, *Nucl. Fusion* **60**, 066011 (2020).

# 2D X-ray spectrometer on WEST: diffracting crystals study and first temperatures profiles

A.Da Ros[1], D. Vezinet[1], G. Colledani[1], F. Bombarda[2] and the WEST Team[1]

[1]*CEA, IRFM, F-13108 Saint Paul-lez-Durance, France*

[2]*ENEA-FSN, Frascati (Rome), Italy*

A 2D X-ray spectrometer has been installed and operated on WEST. Based on the Bragg's diffraction law, three crystals, mounted on a rotating table, give access to physical parameters such as Te and Ti through the Ar XVII K-α spectrum (~3.97 Å), the Ar XVIII Lyman-α spectrum (~3.73 Å) and the Fe XXIV K-α spectrum (~1.86 Å).

During the first campaigns, the spectrometer results for the ArXVII crystal revealed doubled spectra, presumably because the crystals have been manufactured as two independent pieces standing next to each other on the same curved support. These doubled spectra can be fitted with two parameters, an amplitude ratio and a spectral shift, essentials to extract the temperature profiles of the plasma.

This paper present experimental and ray-tracing evidence that the observed spectral shift is indeed due to the double crystal but also to an intrinsic defect, a non-parallelism between the crystal's optical surface and its inner mesh. Then, it shows how to best model and fit the doubled spectrum by studying how the doubling parameters vary on the surface of the detector. Indeed, significant variations over the entire detector area in spectral shift are demonstrated.

Regarding the variations in the amplitude ratio, several hypothesis are being investigated among which a vignetting by a spectrometer element and an effect of the polarization of the X-rays. Although an absolute calibration of the detector has not been done yet, a rocking curve is numerically estimated in order to characterize the reflectivity power with respect to the incident angle, the wavelength and the polarization of incident photons. Depending exclusively on crystallographic properties, this technique can reveal the influence of crystal defects, and more importantly the non-parallelism, on the diffraction pattern. Numerical curves are used to estimate the effect of the polarization on the rocking curve.

Finally, systematic analysis of the electronic temperature proxy profile estimated by the spectrometer will be carried out, in comparison with the ECE measurements, confirming that the spectrometers yields very valuable profile measurements.

# Correlation microwave diagnostics on the Wendelstein 7-X stellarator for Operational Phase 2

G.M. Weir[1], A. Krämer-Flecken[2], T. Windisch[1], O. Grulke[1], M. Hirsch[1], T. Klinger[1] and the Wendelstein 7-X team[1]

[1]*Max-Planck-Institute for Plasma Physics, Greifswald, Germany*

[2]*Forschungszentrum Jülich, Institut für Energie- und Klimaforschung/Plasmaphysik, Jülich, Germany*

Correlation microwave radiometry and reflectometry diagnostics are used to measure electron temperature and plasma density fluctuations on Wendelstein 7-X (W7-X) [1] and the capabilities of these diagnostics are being extended for the second operational phase of W7-X. The ZOOM device [2] is a 16-channel, frequency scannable radiometer extension that is used as a high-resolution radial correlation electron cyclotron emission (CECE) diagnostic when connected to the ECE radiometer on W7-X [3]. A new toroidally displaced radial correlation system with a focusing antenna has been installed that is optimized for core electron temperature fluctuation measurements between 30% and 70% of the plasma minor radius. A secondary CECE antenna has also been installed for plasma density-electron temperature cross phase measurements in the outer 80% of the plasma minor radius. The poloidal correlation reflectometer (PCR) diagnostic [4] measures plasma density fluctuations in the same toroidal plane as the new CECE antennas and has overlapping measurement volumes. A second frequency synthesizer and detection system has been added to the PCR system allowing access to plasma densities up to $4.5 \times 10^{19}$ $m^{-3}$ and radial correlation length measurements in the outer 80% of plasma minor radius.

[1] T. Klinger *et al., Plasma Phys. Control. Fusion* **59** 014018 (2017).

[2] Ch. Fuchs and H.J. Hartfuss, *Rev. Sci. Instrum.* **72** 383 (2001).

[3] M. Hirsch *et al.,* EPJ Web of Conferences **203**, 03007 (2019).

[4] A. Krämer-Flecken, S. Soldatov, B. Vowinkel, and P. Müller*, Rev. Sci. Instrum.* **81** 113502 (2010).

# On symplectic integration of the guiding-center equations in general 3D toroidal fields using GORILLA

M. Eder[1], C.G. Albert[1], M.F. Heyn[1], S.V. Kasilov[1,2], W. Kernbichler[1]

[1] *Fusion@ÖAW, Institut für Theoretische Physik - Computational Physics, Technische Universität Graz, Petersgasse 16, A-8010 Graz, Austria*

[2] *Institute of Plasma Physics, National Science Center "Kharkov Institute of Physics and Technology", 61108 Kharkov, Ukraine*

In Ref. [1], a method for quasi-geometric integration of the guiding-center equations in general 3D toroidal fields was introduced. Realized in the GORILLA code [2], this method reduces the set of guiding-center equations to a linear ODE set with piece-wise constant coefficients by approximating the guiding-center Lagrangian with a continuous piece-wise linear function of the coordinates. The latter is achieved by representing the electro-magnetic field quantities with a 3D linear interpolation within tetrahedral cells which can be built on the basis of the spatial discretization of edge plasma codes, in particular, of the kinetic neutral code EIRENE. Thus, direct data exchange with these codes is facilitated. Since this method is not limited by field topology, its primary target is to model edge plasmas of toroidal devices with a general 3D geometry. Originally, the method has been realized for the approximate, lowest order time dynamics such that the shape of the orbits in the phase space was corresponding to a Hamiltonian system but the evolution in time could lead to minor artifacts in dwell time averages which are required for the computation of the spatial distribution of macroscopic parameters (density, plasma flows, pressure tensor). In the present work, the accurate time dynamics outlined in [1] has been realized in GORILLA resulting in orbits fulfilling the Hamiltonian properties in the whole extended phase space. The correctness of time dynamics is implicitly verified by computing the 1$^{st}$ Poincaré invariant in the extended phase space and by directly demonstrating the preservation of the symplectic form by the GORILLA flow map. The symplectic feature of the present integration method is also shown analytically in the case that the linear ODE set is integrated exactly. In GORILLA, a polynomial expansion of this linear set is used, however, computer accuracy of the resulting guiding-center orbits is achieved by employing a mild refinement of the integration time step within a tetrahedral cell, if necessary.

Furthermore, the application of the method to guiding-center orbit computation using the spatial discretization of the EIRENE code for the WEST tokamak geometry is presented as well.

**References**

[1] M. Eder *et al*, Physics of Plasmas 27, 122508 (2020), `doi.org/10.1063/5.0022117`

[2] M. Eder *et al*, zenodo (2021), `doi.org/10.5281/zenodo.4593661`

# ICRH heating and turbulent transport modelling of the WEST L-mode plasma using ETS: interpretative and predictive code validation

P. Huynh[1], E.Lerche[2,3], D. Van Eester[3], J. Garcia[1], G. Frazzoli[1], P.Maget[1], J.F. Artaud[1], J. Ferreira[4], T. Johnson[5], D. Yadykin[6], P. Strand[6] and WEST team[*]

*[1] CEA, IRFM, F-13108 St-Paul-Lez-Durance, France*
*[2] CCFE, Culham Science Centre, Abingdon OX14 3DB, United Kingdom,*
*[3] Laboratory for Plasma Physics, ERM/KMS, B-1000 Brussels, Belgium,*
*[4] IPFN, Instituto Superior Tecnico, Universidade de Lisboa, 1049-001 Lisbon, Portugal,*
*[5] KTH, Royal Institute of Technology, Stockholm, Sweden,*
*[6] Chalmers University of Technology, Gothenburg, Sweden*
*[*] see http://west.cea.fr/WESTteam*

The European Transport Simulator ("ETS") [1] is a suite of codes designed to simulate tokamak plasma discharges. Not only it highlights the evolution of particle density and energy due to transport effects accounting for particle, heat and current sources, but it equally provides insight into fast ion dynamics resulting from ICRH (and - if present - beams), and the impact these high-energy populations have on the plasma core [2]. This tool allows to help understand the plasma dynamics in WEST and is being used for optimizing the plasma discharge. In particular, attention is being devoted to identify means to avoid a radiative collapse by ensuring an efficient electron RF induced heating and to help finding favourable conditions to enable the L-H transition.

The first step was to verify and validate the simulator in interpretative and predictive mode for some relevant WEST L-mode plasmas. CYRANO [3] and StixRedist [4] are used as ICRH modules [5, 6], while transport is assumed to be due to turbulence and is described exploiting the TGLF module [7]. Collisional electron power computeded with the ICRF modules was compared with the experimental one obtained by using the Break In Slope method. Scans in minority density and ICRF power were performed in *interpretative* mode in order to determine the electron/ion heating ratio, revealing dominant electron heating and highlighting that the neutron rate is a sensitive function of the power absorbed by the deuterons. Seeking for the highest possible compatibility between the various available measurements (electron temperature profiles, stored energy and neutron rate) while staying within realistic error bars, *predictive* modelling which describes the evolution of particle density and temperatures allowed to estimated the ion temperature profiles and to establish a firm link between the WEST experimental data (e.g. energy & neutron rate) on the one hand and the thermal and fast particle profiles resulting from simulation on the other, yielding a better insight in the scenario dynamics allowing to better steer upcoming experiments.

[1] Kalupin D. et al 2013 Nucl. Fusion 53 123007
[2] Huynh P. et al 2021 Nucl. Fusion 61 09601
[3] Lamalle P.U. 1994 PhD Thesis Universite de Mons LPPERM/KMS Report 101
[4] Van Eester D. and Lerche E. 2011 Plasma Phys. Control. Fusion 53 09200
[5] Huynh P. et al 2020 AIP Conf. Proc. 2254 060003
[6] Van Eester D. et al 2021, J. Plasma Phys. vol. 87, 855870202
[7] Staebler G.M., Kinsey J.E. and Waltz R.E. 2007 Phys. Plasmas 14 055909

# Analysis of 3D filament structures in various magnetic configurations of the W7-X stellarator

A. Buzas[1,2], C. Biedermann[3], G. Cseh[1], B. Csillag[1], G. Kocsis[1], T. Szepesi[1], S. Zoletnik[1] and the W7-X Team *

[1] *Centre for Energy Research, Budapest, Hungary*

[2] *Institute of Nuclear Techniques, BME, Budapest, Hungary*

[3] *Max-Planck-Institute for Plasma Physics, Greifswald, Germany*

Filaments in fusion plasmas are high-density structures aligned with magnetic field lines and can be responsible for a significant portion of particle transport in the plasma edge. Their origin is often linked to density perturbations caused by interchange modes, in which curvature and $\nabla B$ drifts result in charge separation. This polarized structure is moved by E $\times$ B drift [1]. Such filaments have been observed on W7-X by multiple diagnostics, including fast-cameras [2], alkali beam emission spectroscopy [3] and reciprocating probes [4].

Due to the complex magnetic geometry, the 2-D description of filaments in W7-X, as it is common on tokamaks, is insufficient, a 3-D treatment is necessary. Most diagnostics offer a 1 or 2-D view on filaments, focusing on radial or poloidal motion. To reveal 3-D behaviour, the W7-X fast-camera system [5] offers a tangential vantage point, from where both poloidal movement and toroidal structure are visible, including toroidal turn around.

In this study, an analysis of W7-X fast-camera images from various divertor configurations is presented. The gathered light is filtered to different atomic emission lines, such as $H_\alpha$ and C III (due to the carbon divertors, it is a common impurity in the edge plasma). Pixel-wise correlations of images from various shots of standard, high and low $\iota$ configurations are compared to highlight differences in filament geometry and dynamics. Shape and toroidal extent is examined and showcased in the context of the magnetic geometry by overlaying the projection of magnetic field lines and flux surfaces. Poloidal rotation of filaments is often seen. Localization and direction of movement is mapped, its velocity estimated. Results are compared to those of other diagnostics.

## References

[1] D'Ippolito D. A. *et al* Phys. Plasmas **18**, 060501 (2011)

[2] Kocsis G. *et al* 44th EPS Conf. on Plasma Phys. ECA vol. **41F**, O2.102 (2017)

[3] Zoletnik S. *et al* Plasma Phys. Control. Fusion **62**, 014017 (2020)

[4] Killer C. *et al* Plasma Phys. Control. Fusion **62**, 085003 (2020)

[5] Kocsis G. *et al* Fus. Eng. Des. **96-97**, 808, (2015)

*See Pedersen *et al* 2021 (https://doi.org/10.1088/1741-4326/ac2cf5) for the W7-X Team.

# Radial correlation reflectometry analysis in high-turbulence plasma scenario

S. Heuraux[1], P.V. Tretinnikov[1,2], E. Z. Gusakov[2]

[1]*Institut Jean Lamour CNRS, Univ. de Lorraine, BP 50840, 54011 Nancy, France*

[2]*Ioffe Institute, 26 Politekhnicheskaya, 194021, St Petersburg, Russia*

The radial correlation reflectometry (RCR) is a widely used technics that provides information on plasma turbulence characteristics. Probing plasma with multiple frequencies can simply determine the turbulence radial correlation length by the difference in the cut-off positions where the correlation of the signals disappears. It turned out that this approach is not always correct [1]. That stimulated theoretical investigation of the RCR and resulted in the non-linear theory of the RCR in 1D [2] and 2D [3] models. According to the developed models in the case of strong turbulence or small plasma density gradient the signal spatial correlation length is a function of both the turbulence correlation length and its amplitude. Another method of the reflectometry signal analysis was developed for extracting information on the turbulence spectrum thus the turbulence amplitude [4]. This approach is based on the relation between the radial wave-number spectrum of the density fluctuations and the phase fluctuation wave-number spectrum of a reflectometer signal via a transfer function or a relation established under the Born approximation [5]. Assuming that the main contribution comes mainly from the vicinity of the cut-off layer, the Parceval's theorem is used to recover the density fluctuation level, and thus the density fluctuation profile.

Theoretically the two methods can be combined for obtaining the information on both the turbulence amplitude and its radial correlation length under the conditions when the non-linear regime of the RCR takes place. Nevertheless this idea has not been used in practice yet.

This paper is devoted to the demonstration and verification of the possibility to use the two approaches of the RCR signal interpretation simultaneously. On the base of 2D simulation of a RCR experiment it is shown that this method allows us to resolve the turbulence amplitude and the turbulence radial correlation length.

[1] A. Costley et al (1990) *Rev. Sci. Instrum.* **61** 2823.

[2] E. Z. Gusakov and A. Yu. Popov (2002) *Plasma Phys. Control. Fusion* **44** 2327-2337.

[3] E. Z. Gusakov and A. Yu. Popov (2004) *Plasma Phys. Control. Fusion* **46** 1393-1408.

[4] S. Heuraux et al (2003) *Rev. Sci. Instrum.* **74** 1501.

[5] C. Fanack et al (1996) Plasma Phys. Cont. Fusion **38** 1915.

# KBM and Finite-$\beta$ ITG Turbulence in the Wendelstein 7-X stellarator

P. Mulholland[1], K. Aleynikova[2], B.J. Faber[3], I.J. McKinney[3], M.J. Pueschel[1,4] and J.H.E. Proll[1]

[1]*Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands*

[2]*Max-Planck-Institut für Plasmaphysik, D-17491 Greifswald, Germany*

[3]*Department of Engineering Physics, University of Wisconsin-Madison, Madison, WI 53706, USA*

[4]*Dutch Institute for Fundamental Energy Research, 5612 AJ Eindhoven, The Netherlands*

The impact of fluctuations of the confining magnetic field – brought about by finite plasma pressure – has been studied in detail in axisymmetric toroidal fusion devices (i.e., in tokamaks) [1, 2]. One consequence of finite pressure is the possible destabilisation of electromagnetic plasma waves such as the kinetic ballooning mode (KBM). Much remains to be better-understood in terms of linear and nonlinear KBM physics in more complex three-dimensional magnetic geometries [3, 4, 5, 6].

Here, we study the behaviour of finite-$\beta$ ion-temperature gradient (ITG) modes and KBMs - and the ensuing turbulence - in the Wendelstein 7-X (W7-X) stellarator. Using the gyrokinetic Vlasov code GENE [7], we determine the onset of KBMs by varying the plasma pressure $\beta$. Of particular interest is how changes in the magnetic equilibrium or the driving gradients influence the KBM onset. From linear simulations, we find that increasing the magnitude of magnetic shear delays the onset of KBMs in W7-X (i.e., increases the $\beta_{\mathrm{crit}}^{\mathrm{KBM}}$ threshold). This effect of magnetic shear on the onset of KBMs is in agreement with previous work [6].

We further report on the nonlinear behaviour of KBMs, as this regime is of particular interest for high-performance operation. Here, we present the first-ever nonlinear KBM turbulence simulations in W7-X geometry, and we discuss the numerical prerequisites for achieving a quasi-stationary state. Scalings of heat flux with $\beta$ in the ITG-dominated regime as well as above the KBM threshold are reported.

**Acknowledgements**

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

**References**

[1] M.J. Pueschel *et al.*, Phys. Plasmas **15**, 102310 (2008)

[2] M.J. Pueschel *et al.*, Phys. Plasmas **17**, 062307 (2010)

[3] A. Ishizawa *et al.*, Phys. Plasmas **21**, 055905 (2014)

[4] A. Ishizawa *et al.*, Phys. Plasmas **26**, 082301 (2019)

[5] K. Aleynikova *et al.*, J. Plasma Phys. **84**, 745840602 (2018)

[6] I. McKinney *et al.*, J. Plasma Phys. **87**, 905870311 (2021)

[7] F. Jenko *et al.*, Phys. Plasmas **7**, 1904 (2000)

# Compatibility of high-Z impurity accumulation with high plasma performance in ECR-heated W7-X plasmas

D. Zhang, M.N.A. Beurskens, J.A Alcusón[1], G. Wurden[2], B. Buttenschön, S. Jablonski[3] , M. Kubkowska[3], A. Langenberg, K. Rahbarnia, F. Reimold, A. Pavone, S. Kwak, H. M. Smith, C.D. Beidler, S.A. Bozhenkov, O. Ford, C. Biedermann, K.J. Brunner, Y. Feng, G. Fuchert, Y. Gao, J. Geiger, U. Höfel, M. Hirsch, Z. Huang[4], M. Jakubowski, J. Knauer, P. Kornejew, T. Kremeyer, M. Krychowiak, R. König, H.P. Laqua, R. Laube, D. Naujoks, N. Pablant[5], E. Pasch, A von Stechow, H. Thomsen, Th. Wegner, G. Weir, V. Winters and the W7-X team

*Max-Planck-Institut für Plasmaphysik, 17489 Greifswald Germany*
*[1]University Carlos III of Madrid, 28911, Leganes, Spain*
*[2]Los Alamos National Laboratory, Los Alamos, USA*
*[3]Institute of Plasma Physics and Laser Microfusion (IPPLM), 01-497 Warsaw, Poland*
*[4]Plasma Science and Fusion Center, MIT, Cambridge, MA 02139, USA*
*[5]Princeton Plasma Physics Laboratory, Princeton, NJ, US*

In the neoclassically optimized W7-X stellarator, particle and energy transport has so far been dominated by turbulent transport, especially in gas-fueled plasmas generated by ECRH, where the transport time for impurities is much shorter than predicted by neoclassical theory and the energy confinement time is somewhat below the ISS04 stellarator scaling [1-4]. During these experimental programs (usually lasting ~10 s), no evident impurity accumulation has been observed up to now.

Recently, plasma phases with prominent radiation from the inner plasma region have been revealed by bolometer tomography in two long-pulse discharges (up to ~50 s; ECRH power 1.2 MW in the initial phase and later halved), which were performed shortly after wall boronization during the first divertor operational phase. In such discharges, gas refueling is alternately turned on and off. The radiation intensities (at r/a~0.3) are comparable to that at the plasma edge (r/a≥0.8), which is usually associated with intrinsic low-Z impurities (typically carbon from the plasma facing components). Spectroscopic diagnostics show an increasing of high-Z impurity content (mainly Fe ions) and their accumulation in the plasma core. During the accumulation phases of a few seconds long, a clear increase of the effective ion charge ($Z_{eff}$ ~1.8) has been observed. At the same time, the plasma stored energy is increasing (also the ion temperature exceeds the typical limitation of ~1.5 keV [5]) and the energy confinement time is reaching the ISS04 scaling. This scenario remains in a quasi-steady state for several tens of seconds and occurs at different power levels in the respective experimental programs. Further analyses show that 1) a common condition for the occurrence of this scenario is the peaking of the plasma density profile which has a low edge plasma density ($<1.0\times10^{19}$ m$^{-3}$); 2) this scenario favors a plasma phase fueled solely by recycling neutrals from the divertors, without any additional gas-fueling. The impurity accumulation observed is believed to be a neoclassical effect as a result of turbulence suppression which is driven by density gradient increments [6] (similar to pellet injection experiments at W7-X [7]). The electrostatic instabilities at ion scales are analyzed through linear gyrokinetic simulations; the transport of impurities is studied using radiation profiles measured with bolometers. Detailed results are presented and the sources of high-Z impurities are discussed.

**References:**

[1] Beidler, C.D., et al., Nature, 2021. **596**(7871): p. 221-226.
[2] Geiger, B., et al., Nuclear Fusion, 2019. **59**(4): p. 046009.
[3] Langenberg, A., et al., Physics of Plasmas, 2020. **27**(5): p. 052510.
[4] Fuchert, G., et al., Nuclear Fusion, 2020. **60**(3): p. 036020.
[5] Beurskens, M.N.A, et al., Nuclear Fusion, 2021.
[6] Alcusón, J., et al., Plasma Physics and Controlled Fusion, 2020. **62**(3): p. 035005.
[7] von Stechow, A., et al., arXiv preprint arXiv:2010.02160, 2020.

# A Special Case of Long-Pulse High Performance Operation in W7-X

G. A. Wurden[1], S. A. Bozhenkov[2], G. Fuchert[2], D. Zhang[2], S. Jablonski[3], M. Kubkowska[3], A. von Stechow[2], M. Beurskens[2], C. Brandt[2], K. J. Brunner[2], B. Buttenschoen[2], M. Hirsch[2], P. Kornejew[2], A. Krämer-Flecken[4], Y. Gao[2], M. Krychowiak[2], N. Pablant[5], E. Pasch[2], K. Rahbarnia[2], H. Thomsen[2], T. Windisch[2], V. Winters[2], and the W7-X Team

*[1] Los Alamos National Laboratory, Los Alamos, NM 87545 USA*

*[2] Max-Planck-Institut für Plasmaphysik, 17489 Greifswald Germany*

*[3]Institute of Plasma Physics and Laser Microfusion (IPPLM), 01-497 Warsaw, Poland*

*[4]Institute of Energy and Climate Research, Forschungszentrum Jülich GmbH, D-52425*

*[5] Princeton Plasma Physics Laboratory, Princeton, NJ 08543, USA*

In a W7-X discharge (3rd shot of the morning, pulse 20180808005) during the previous campaign, an accidental dropout of one of two ECRH heating gyrotrons, at 15 seconds into a 55 second planned pulse, allowed a remarkable transition to occur. Initial heating power was only 1.1 MW, but the stored plasma energy, after first dropping when the power was cut to 510 kW, actually climbed higher (to 220 kJ) over the next 2 seconds, with only half the heating power remaining. The plasma density, initially rather flat with core density of 3x10^19 cm^3, peaked to >4.5x10^19 cm^3 by itself during the same time. Turbulence was reduced, and regular island-localized mode (ILM) activity, not normally present in high-iota discharges [1] turned on, while the energy confinement time doubled, from 200 msec to 400 msec. The ion temperature climbed to 1.8 keV, approaching the electron temperature, breaking the ion temperature clamping which is often seen in W7-X plasmas [2]. Zeff increased slightly from 1.6 to 1.9, and then held constant for the remainder of the pulse. The edge soft x-rays dropped, but the core soft x-ray emission increased a factor of 5x. Bolometer signals were small, but an increase in the core radiation (due to some high Z accumulation), along with a drop in edge radiation, followed the transition. Line integrated light impurity emission (B, C, O) remained constant. Heat loads on the divertor dropped a factor of 3.7x (more than the factor of 2x one would otherwise expect). The resulting nTTau was within a factor of two of W7-X's best transient performance [3]. A key factor was that the divertor strike points for this high-iota plasma configuration were freshly boronized, and no external gas puffing was enabled. Later in the day, it could not be duplicated. The periodic ILM'ing activity has most of the features of ELM's, which along with the confinement improvement and H-alpha response, suggests the possibility that an H-mode transition occurred. We plan to look for evidence of a pedestal with more diagnostics in the upcoming campaigns, as well as explore further ways to modify the profile during the long flattop (e.g., adding NBI or pellets), hopefully without turning the normal turbulence (ITG's) back on.

*[1]* G. A. Wurden et al. *"Structure of island localized modes in Wendelstein 7-X*", P2.1068, 46th EPS Conference on Plasma Physics (2019)
*[2]* M.N.A. Beurskens et al, *2022* Nucl. Fusion ***62*** *016015*
*[3]* J Baldzuhn et al, *2020* Plasma Phys. Control. Fusion ***62*** *055012*

# Power exhaust in high-performance plasmas in Wendelstein 7-X

Y. Gao[1], J. Geiger[1], M. Jakubowski[1], S. Bozhenkov[1], Y. Feng[1], M. Endler[1], V. Perseo[1], T. Szepesi[2], A. Pandey[1], T. Kremeyer[1], A. Puig Sitjes[1], F. Pisano[3], T.S. Pedersen[1], M. Otte[1], D. Naujoks[1], M. Krychowiak[1], A. Knieps[4], R. König[1] and the W7-X Team[1]

[1] *Max-Planck-Institut für Plasmaphysik, Wendelsteinstraße 1, 17491 Greifswald, Germany*

[2] *Centre for Energy Research, 1121 Budapest, Hungary*

[3] *University of Cagliari, Cagliari 09123, Italy*

[4] *Forschungszentrum Jülich GmbH, 52425 Jülich, Germany*

In the previous experimental campaign on Wendelstein 7-X (W7-X), a spontaneous but transient increase of global energy confinement time $\tau_E$ exceeding the empirical ISS04-scaling after injections of frozen hydrogen pellets was reported [1]. The highest volume averaged plasma $\beta$ was also reached in such post-pellets phase with measured diamagnetic energy above 1 MJ. Strong density peaking leading to a reduction of the turbulence was considered as the main reason for such transition to high-performance plasmas.

In this study, power exhaust in this high-performance phase will be reported. Preliminary analysis shows a clear correlation between the evolution of the divertor heat distributions and the transition to the high-performance phase. A clear second strike line was found on the horizontal divertor plate at the outboard side connecting to the outer leg of the enlarged magnetic island due to the higher $\beta$. A narrower main strike line was also observed in the high-performance phase, which might be attributed to two effects: 1) decreased connection length at the main heat channel with higher $\beta$, and 2) similar to tokamaks, a narrower power decay length caused by the higher confinement. A careful comparison with numerical simulations using experimental equilibrium and different perpendicular heat transport coefficients [2] could in principle disentangle the above two effects, and quantify the heat transport during the high-performance phase.

Furthermore, strong transient heat and particle flows at the degradation of the high-performance phase are measured from various edge diagnostics and will be reported in this study. Potential influence of the mitigation of turbulence on the edge transports will also be discussed. This study would be essential not only as a first understanding of the heat transport at the edge during the high-performance plasmas, but also for the preparation for the next W7-X campaign to prolong the high-performance phase with reliable power exhaust solutions.

## References

[1] S. Bozhenkov *et al. Nuclear Fusion*, **60** (6), 066011 (2020).

[2] Y. Gao *et al. Nuclear Fusion*, **59** (6), 066007 (2019).

# The universal instability in optimised stellarators

P. Costello[1], J.H.E. Proll[2], G.G Plunk[1] M.J Pueschel[2,3,4]

[1] *Max-Planck-Institut für Plasmaphysik, Wendelsteinstraße 1, 17491 Greifswald, Germany*

[2] *Science and Technology of Nuclear Fusion, Department of Applied Physics, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands*

[3] *Dutch Institute for Fundamental Energy Research, 5612 AJ Eindhoven, The Netherlands*

[4] *Institute for Fusion Studies, The University of Texas at Austin, Austin, Texas 78712, USA*

**Abstract**

In tokamaks and neoclassically optimised stellarators, like Wendelstein 7-X (W7-X) and the Helically Symmetric Experiment (HSX), turbulent transport is expected to be the dominant transport mechanism. Among the electrostatic instabilities that drive turbulence, the trapped-electron mode (TEM), which is one of the dominant instabilities in tokamaks, has been shown both analytically [1] and in simulations [2, 3] to be absent over large ranges of parameter space in quasi-isodynamic stellarator configurations with the maximum-*J* property. For some modes of operation of W7-X, the magnetic geometry approximately satisfies the quasi-isodynamic and maximum-*J* properties. It has been proposed that the reduction of the linear TEM growth rate in such configurations may lead to the passing-electron-driven universal instability [4, 5], which is often subdominant to the TEM, becoming the fastest growing instability over some range of parameter space. Here, we show through gyrokinetic simulations using the GENE code [6], that the universal instability is dominant in a variety of stellarator geometries over a range of parameter space typically occupied by the TEM, but most consequentially in maximum-*J* devices like W7-X. We find that the universal instability exists at long perpendicular wavelengths, and as a result dominates the potential fluctuation amplitude and heat-flux spectrum in non-linear simulations. In W7-X, universal modes are found to differ in parallel mode structure from trapped-particle modes which may impact turbulence localisation in experiments.

## References

[1] J.H.E. Proll, P. Helander, J.W. Connor and G. G. Plunk, Physical Review Letters 08 24:245002 (2012)

[2] J. H. E. Proll, P. Xanthopoulos, and P. Helander, Physics of Plasmas, 20(12):122506 (2013)

[3] J.A. Alcusón, P. Xanthopoulos, G. .G Plunk, P. Helander, F. Wilms, Y. Turkin, A. von Stechow and O. Grulke, Plasma Physics and Controlled Fusion 2(3):035005 (2020)

[4] M. Landreman, T.M. Antonsen, and W. Dorland, Physical Review Letters, 114:095003 (2015).

[5] P. Helander and G. G. Plunk, Physics of Plasmas, 22(9):090706 (2015)

[6] F. Jenko, W. Dorland, M. Kotschenreuther, and B. N. Rogers, Physics of Plasmas, 7(5):1904–1910 (2000).

# Parametric decay of microwave beams in the edge island of Wendelstein 7-X: Theoretical modelling and correlation with edge fluctuations

A. Tancetti[1], S.K. Nielsen[1], J. Rasmussen[1], E.Z. Gusakov[2], A.Yu. Popov[2], D. Moseev[3], T. Stange[3], S. Marsen[3], M. Vecsei[4], G. Anda[4], D. Dunai[4], S. Zoletnik[4], C. Brandt[3], H. Thomsen[3], V. Winters[3], P. Kornejew[3], J. Harris[5], H.P. Laqua[3] and the W7-X Team

[1] *Department of Physics, Technical University of Denmark, Kgs. Lyngby, Denmark*

[2] *Ioffe Institute, Saint-Petersburg, Russia*

[3] *Max-Planck-Institut für Plasmaphysik, Greifswald, Germany*

[4] *Center for Energy Research, Budapest, Hungary*

[5] *Oak Ridge National Laboratory, Oak Ridge, USA*

Parametric decay instability (PDI) is the nonlinear decay of a pump wave into a pair of daughter waves when the pump power exceeds a certain threshold. In inhomogeneous plasmas, the power threshold is lowered if the pump trajectory crosses a density bump where daughter waves can be trapped [1]. In tokamaks and stellarators, where high-power microwave beams are employed for plasma heating at the electron cyclotron resonance (ECRH), low-threshold PDI can induce anomalous power deposition and permanently degrade microwave diagnostics and plasma facing probes, if not properly shielded. In this contribution, we present a theoretical model for PDI-related signals measured with a microwave radiometer in the Wendelstein 7-X stellarator. Here, ECRH beams at $f_0 = 140$ GHz cross a density bump detected by alkali beam emission spectroscopy within a stationary magnetic island in the plasma edge. We measure PDI-related sidebands symmetrically arranged around $f_0$ with a fine structure suggesting excitation of ion Bernstein waves. We present a system of equations for the PDI cascade in the density bump which reliably yields the power and the spectrum of the detected signals. The model predicts the PDI power threshold at $\approx 300$ kW in agreement with the experimental value, 320 kW, and a fraction of power drained by the daughter waves $\approx 4\%$. Furthermore, we show correlation of crashes in the PDI-related sidebands with quasi-continuous oscillations, related to island localized modes (ILMs) [2], measured by several edge diagnostics. We propose inhibition of the low-threshold PDI during ILM-like events, when the density bump in the island is observed to flatten [3].

[1] Gusakov, E.Z. and Popov, A.Yu., Phys.Plasmas **23**, 082503, 2016

[2] Wurden G.A. *et al*., *46$^{th}$ EPS Conference on Plasma Physics*, (2019)

[3] Takács R. *et al*., *47$^{th}$ EPS Conference on Plasma Physics* (2021)

# Novel methods for evaluating Thomson scattering data to improve the accuracy of the electron density and its error estimate

G. Fuchert[1], U. Höfel[1],
M.N.A. Beurskens[1], S. Bozhenkov[1], E. Pasch[1], R.C. Wolf[1], and the W7-X team
[1]*Max-Planck-Institut für Plasmaphysik, Wendelsteinstraße 1, 14791 Greifswald, Germany*

Laser Thomson scattering is employed in fusion experiments to determine the electron density and temperature from the measured spectrum of the scattered photons. However, the whole spectrum cannot be measured with sufficient accuracy for a single laser pulse. Instead, so-called polychromators are used. These split the full wavelength range into a number of channels and integrate the spectrum over those channels. The spectrum is then reconstructed from those discrete measurements. Due to noise (electronic and photon shot noise) there is an uncertainty in this reconstruction and, hence, in the density and temperature determiend from it. In reality, however, variations between individual laser pulses or adjacent spatial points are often larger than the uncertainties arising from the reconstruction. This is especially true for the electron density. It is often challenging to identify the exact cause for such additional uncertainties and, consequently, to quantify a reliable estimate for the experimental error.

In the first experimental campaigns of Wendelstein 7-X it was found that misalignment of the laser beam was the dominant reason for uncertainties in the electron density. Besides mechanical improvements of the beam path, a novel calibration technique has been established, which accounts for any remaining alignment variations and substantially improves the profile quality. This technique may be crucial for larger fusion experiments like ITER, which necessarily have long beam paths. But the question remains, how error bars can be quantified reliably, possibly even accounting for unknown error sources. For this, the distribution of measured signal levels during the absolute Raman calibration (with constant conditions) has been determined. This distribution covers all fast changes to the overall sensitivity of the diagnostic (vibrations, detector gain, etc.) and in combination with the calibration uncertainties and the error due to the imperfect reconstruction of the spectrum, this distribution gives a realistic and experimentally accessible error estimate for the electron density. In this regard it was an interesting finding that for some polychromators the error distribution was not symmetric. For such a distribution, the mean value is different from the maximum of the distribution (modus). This implies that the calibration factor relating the intensity to the electron density, which is determined from the mean of the distribution, yields slightly incorrect density values for most of the measurements. This effect can be mitigated by using the empirical distribution as error estimate.

# Fast diagnostic mapping in non-nested magnetic topologies using 3D field compliant magnetic surface labels and neural network based interpolation

A. Knieps[1], M. Brenzke[1], D. Böckenhoff[2], P. Drews[1], M. Endler[2], Y. Gao[2], J. Geiger[2], Y. Liang[1], Y. Suzuki[3], S. Wiesen[1] and the W7-X-Team

[1] *Forschungszentrum Jülich GmbH, Jülich, Germany*

[2] *Max-Planck-Institut für Plasmaphysik, Greifswald, Germany*

[3] *Graduate School of Advanced Science and Engineering, Hiroshima University, 739-8527 Higashi-Hiroshima, Japan*

The Wendelstein 7-X Stellarator uses an island divertor for heat- and particle exhaust. This island divertor induces a complex magnetic topology in the plasma edge, which makes the integrated interpretation of diagnostic measurements a challenging endeavor.

Understanding the mutual agreement or disagreement of plasma parameter measurements in the SOL or boundary requires the separation of magnetic field geometry effects from other physics phenomena like transport effects, e.g. the up- and downstream differences in plasma parameters in the SOL. A commonly used approach to eliminate geometry effects is to find label functions aligned along the magnetic surfaces. Most of these approaches, however, assume tightly nested magnetic flux surfaces, such as this in equilibriy provided by the VMEC [1] code.

This contribution introduces first a new surface label function inspired by the idea of a transport delay from the core to the edge. This function is capable of correctly handling non-nested topologies such as magnetic islands, and provides a physical interpretation of the surface label. Second, a neural network is used to both speed up the label function calculation and interpolate in coordinate and parameter space (coil currents and equilibrium parameters). This allows us to bypass the large bulk computations required to initially compute the surface label, which would otherwise make the calculation prohibitively slow for real-time diagnostic applications.

## References

[1] Hirshmann, Whitson 1983 Phys. Fluids **26** (1983)

# Turbulence Generation in High-power Laser-Plasma Interaction Relevant to Astrophysical Scenarios

Indraj Singh, R. Uma and R. P. Sharma

*Department of Energy Science and Engineering,*

*Indian Institute of Technology Delhi, India*

*Email Address: indraj436@gmail.com*

Many astrophysical scenarios such as supernova remnant (SNR), Cassiopeia A, the collision of galaxies, and turbulent magnetic field amplification in the intergalactic medium, etc has been imitated by utilizing high-power lasers. A hundred times stronger magnetic field has been observed in Cassiopeia A than the adjacent interstellar medium. It is presumed that the surrounding clumpy media near supernova remnant Cassiopeia A support myriads modes, which acts as a source for amplifying the turbulent magnetic field. The origin of magnetic field amplification in the clumpy medium is not fully understood yet. The typical model for this amplification is the seed field amplification due to turbulence generation. Such magnetic field amplification and turbulence generation have been reported experimentally in various laboratory astrophysics. A model is proposed to study the turbulence generation and magnetic field amplification, which ensues due to the high-power laser interaction with plasma. In this study we employed the computational techniques to solve the coupled system of the model equations.

1. Sudipta Mondal, V. Narayanan, Wen Jun Ding, Amit D. Lad, Biao Hao, Saima Ahmad, Wei Min Wang, Zheng Ming Sheng, Sudip Sengupta, Predhiman Kaw, Amita Das, and G. Ravindra Kumar, "Direct observation of turbulent magnetic fields in hot, dense laser produced plasmas," Proc. Natl. Acad. Sci., 109, 8011-8015 (2012).
2. J. Meinecke, H. W. Doyle, F. Miniati, A. R. Bell, R. Bingham, R. Crowston, R. P. Drake, M. Fatenejad, M. Koenig, Y. Kuramitsu, C. C. Kuranz, D. Q. Lamb, D. Lee, M. J. MacDonald, C. D. Murphy, H.-S. Park, A. Pelka, A. Ravasio, Y. Sakawa, A. A. Schekochihin, A. Scopatz, P. Tzeferacos, W. C. Wan, N. C. Woolsey, R. Yurchak, B. Reville, and G. Gregori, "Turbulent amplification of magnetic fields in laboratory laser produced shock waves," Nat. Phys. 10, 520–524 (2014).
3. J. Meinecke, P. Tzeferacos, A. Bella, R. Binghamc, R. Clarke, E. Churazove, R. Crowstong, H. Doylea, R. P. Drakeh, R. Heathcote, M. Koenigi, Y. Kuramitsu, C. Kuranz, D. Lee, M. MacDonald, C. Murphy, M. Notley, H. S. Park, A. Pelka, A. Ravasio, B. Reville, Y. Sakawa, W. Wan, N. Woolsey, R. Yurchak, F. Miniati, A. Schekochihin, D. Lamb, and G. Gregori, "Developed turbulence and nonlinear amplification of magnetic fields in laboratory and astrophysical plasmas," Proc. Natl. Acad. Sci. 112, 8211-8215 (2015).
4. P. Tzeferacos, A. Rigby, A. F. A. Bott, A. R. Bell, R. Bingham, A. Casner, F. Cattaneo, E. M. Churazov, J. Emig, F. Fiuza, C. B. Forest, J. Foster, C. Graziani, J. Katz, M. Koenig, C.-K. Li, J. Meinecke, R. Petrasso, H.-S. Park, B. A. Remington, J. S. Ross, D. Ryu, D. Ryutov, T. G. White, B. Reville, F. Miniati, A. A. Schekochihin, D. Q. Lamb, D. H. Froula, and G. Gregori, "Laboratory evidence of dynamo amplification of magnetic fields in a turbulent plasma," Nat. Commun. 9, 591 (2018).

# Enhancement of nuclear reactions via the kinetic Weibel instability in plasmas

Z. Y. Liu[1], B. Qiao[1*]

[1] *Center for Applied Physics and Technology, HEDPS and State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, China*

**Abstract**: In astrophysics, nuclear reactions take place mostly in the plasma environment, such as the primordial universe, stars and interstellar mediums. However, so far, most of our knowledge of nuclear reactions are from the experiments on conventional particle accelerators, with no plasma effects taken into account. With the rapid progresses of high-power laser facilities, laser-plasma has been regarded as a unique platform for researching nuclear reactions in plasmas. Some colliding laser-produced plasmas experiments have been performed on different laser facilities, and give us strong hints that nuclear reactions in plasmas can be modulated significantly by the self-generated electromagnetic fields and the collective motion of plasma. However, no self-consistent theory or simulation has been given to explain how the kinetic effects influence the nuclear reactions in plasmas.

With the implement of nuclear reactions module in particle-in-cell code, we systematically show that, the kinetic Weibel instability occurring in colliding plasma results in significant enhancement of nuclear reactions. Specifically, the self-generated magnetic fields deflect ion motions to different angles, decreasing the relative velocity and converting plasma kinetic energy to thermal energy. For reactions with sharp resonance peak in the cross-section, like $t(d,n)\alpha$ or ${}^{12}_{6}C(\mathrm{p},\gamma){}^{13}_{7}N$, the enhancement of reaction yield could reach up to several times even orders of magnitudes, which is a meaningful result and deserves more attention and further research.

*Corresponding author: bqiao@pku.edu.cn

**References:**

[1] Liu Z Y, Li K, Yao Y L, et al. Plasma Physics and Controlled Fusion, 2021, 63(12): 125030.

# A hybrid (ablation-expansion) model for low-density foams

L. Hudec[1], A. Gintrand[2], J. Limpouch[1], R. Liska[1], S. Shekhanov[2], V. Tikhonchuk[2,3] and S. Weber[2]

[1] *FNSPE, Czech Technical University in Prague, Prague, Czech Republic*

[2] *ELI-Beamlines Center, Institute of Physics of the ASCR, Dolní Břežany, Czech Republic*

[3] *CELIA, University of Bordeaux, CNRS, CEA, Talence, France*

Low-density foams have a wide variety of applications in the fields of inertial confinement fusion and high energy density physics. However, direct simulations of laser propagation through a foam are difficult due to the large separation of scales, given by the necessity to spatially resolve the density differences in the foam microstructure. Unfortunately, low-density foams also cannot be modeled as a uniform material of an equivalent mean density as such results overestimate the propagation speed of the laser-driven ionization wave.

Recent interests in foam simulations led to the development of two-scale models [1,2], where a simplified interaction model is computed on the scale of an individual foam pore in addition to the conventional macroscale hydrodynamics. These models describe the laser-foam interaction in terms of volumetric heating and expansion of planar or cylindrical, wire-like foam microstructure. However, further analysis of laser absorption in sub-wavelength objects and detailed particle-in-cell simulations show that laser is being absorbed mostly at the surface of the overcritical elements and that ablation plays an important role in the overall dynamics. The mass ablated from the surface layer rapidly fills the empty space in the pores and creates a high-temperature, low-density plasma background. Moreover, it also carries away a significant portion of the absorbed laser energy in the form of ion kinetic energy.

We present a novel approach to the foam modeling that combines a self-similar expansion of cylindrical elements with a surface ablation by laser. In our microscale model, each foam pore is divided into two regions (central cylinder and outer plasma) with separate masses, densities and temperatures. The movement of the boundary between these two environments is controlled by the self-similar expansion while the mass transfer between regions is given by a stationary ablation model. Laser deposition is calculated according to the Mie theory for electromagnetic scattering on cylindrical particles. The proposed model is implemented in the PALE and FLASH hydrodynamic codes for laser-plasma interaction. The simulation results are compared to experimental data available in literature.

## References

[1] M. Cipriani et al., Laser and Particle Beams **36**, 121 (2018)

[2] M.A. Belyaev et al., Physics of Plasmas **27**, 112710 (2020)

# Calculations on the stopping power of the warm dense matter at the Bragg peak

F. Chacón-Rubio, J. Vázquez-Moyano , M.D. Barriga-Carrasco

*E.T.S.I. Industrial Universidad de Castilla-La Mancha, Ciudad Real, Spain*

Dense plasmas in the Warm Dense Matter (WDM) regime are of great interest as a probe of stopping power theories. WDM is extremely difficult to treat theoretically due to the simultaneous appearance of quantum degeneracy, Coulomb correlations, and thermal effects. Also, the coexistence of plasma and condensed phases force stopping power theories to consider both, free and bound electrons. Many stopping power models in plasma use density, temperature, and ionization state as input parameters. Therefore, an accurate description of the plasma is necessary to perform these calculations correctly. As these values are not always available from the real plasma, hydrodynamic simulation become a handy solution to obtain key plasma parameters. In this study, we have performed a hydrodynamic simulation based on a proposed experiment [1] with the help of a hydrodynamic code. The basic physics processes included in the code employed are hydrodynamic equations, thermal flux, electron-ion relaxation, electron collisions and laser energy deposition. We present the profiles of density, temperature and ionization obtained and discuss their validity as well as the shortcomings of the simulation. Finally, stopping power calculations with our and other models using an ad hoc combination of free and bound electrons. The models considered are T-Matrix [3], Li-Petrasso [4], Vlasov [5], SSM [6], Mehlhorn [7] and Zimmerman [8]. With this, we expect to test the validity of the stopping power models considered in general, and of our model [2] in particular, in WDM near the Bragg peak.

[1] J.I. Apiñaniz et al. Scientific Report 11:6881 (2021)
[2] M.D. Barriga-Carrasco, F. Chacón-Rubio, C.C. Montanari. In publication process (2021).
[3] D. O. Gericke and M. Schlanges. Physical Review E, 60,904 (1999).
[4] C.-K. Li and R. D. Petrasso. Physical Review Letters, 70, 3059 (1993).
[5] T. Peter and J. Meyer-ter Vehn. Physical Review, A, 43, 1998 (1991).
[6] C. Deutsch, et al. The open plasma physics journal, 3 (2010)
[7] T.A.Mehlhorn. Journal of Applied Physics 52, 6522 (1981)
[8] G. B. Zimmerman. Tech. Rep. Internal Report No.UCRL-JC-105616 (1990).

# Hydrodynamic modeling of self-generated magnetic fields by ALE methods

M. Kucharik[1], J. Nikl[1,2,3], J. Limpouch[1]

[1] *Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic*

[2] *ELI-Beamlines, Institute of Physics, Czech Academy of Sciences, Prague, Czech Republic*

[3] *Institute of Plasma Physics, Czech Academy of Sciences, Prague, Czech Republic*

Arbitrary Lagrangian-Eulerian (ALE) methods belong to the most popular approaches for hydrodynamic simulations of laser/target interactions [1]. They benefit from improved accuracy of the simulation due to the Lagrangian motion of the computational mesh, as well as robustness resulting from a regular mesh optimization followed by conservative interpolation (remap) of all quantities between the meshes. In recent years, we were interested in modeling of spontaneous magnetic field (SMF) generation [2, 3] resulting from crossed gradients of electron temperature and density, known as the Biermann battery effect. Such models have been implemented in our developed 2D cylindrical Prague ALE (PALE) code [1], containing also all necessary physical models (EOS, laser absorption, thermal conductivity, etc.). Here, we present performance of the second-order accurate extension of the SMF generation model [4] in the ALE framework on selected realistic tests.

## References

[1] R. Liska, M. Kucharik, J. Limpouch, O. Renner, P. Vachal, L. Bednarik, and J. Velechovsky. ALE methods for simulations of laser-produced plasmas. In Jaroslav Fořt, Jiří Fürst, Jan Halama, Raphaèl Herbin, and Florence Hubert, editors, *Finite Volumes for Complex Applications VI Problems & Perspectives*, volume 4 of *Springer Proceedings in Mathematics*, pages 857–873. Springer, 2011.

[2] M. Kucharik, J. Limpouch, and J. Nikl. Development of ALE hydrodynamic code for laser-plasma interactions with self-generated magnetic fields. In *Europhysics conference abstracts, 47th EPS Conference on Plasma Physics, 21 - 25 June 2021*, volume 45A, page P1.2020, 2021.

[3] J. Nikl, M. Kucharik, and S. Weber. Self-generated magnetic fields modelling within high-order Lagrangian magneto-hydrodynamics. In *Europhysics conference abstracts, 47th EPS Conference on Plasma Physics, 21 - 25 June 2021*, volume 45A, page P1.2022, 2021.

[4] M. Kucharik, J. Nikl, and J. Limpouch. Second-order magnetic field generation model for Lagrangian and ALE plasma simulations. *AIP Conference Proceedings*, 2021. Accepted.

# Self-generated magnetic fields during nanosecond laser-target interaction

Jan Nikl[1,2,3], M. Kuchařík[3], and S. Weber[1]

[1] *ELI Beamlines, Institute of Physics, Academy of Sciences of the Czech Republic, 18221 Prague, Czech Republic*

[2] *Institute of Plasma Physics, Academy of Sciences of the Czech Republic, 18200 Prague, Czech Republic*

[3] *Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, 11519 Prague, Czech Republic*

The interaction of a nanosecond laser pulse with a solid target is one of the most common scenarios appearing in many disciplines, like inertial confinement fusion, X-ray plasma sources, laboratory astrophysics and others. The detailed understanding of the involved physical phenomena is crucial for increasing predictive capabilities of the simulations and achieving a better agreement with the experimental results. One of the challenging parts of the physical modelling is description of the self-generated magnetic fields and their role in the process of interaction. The classical approach to their generation relies on the crossed gradients of density and temperature [1]. However, these conditions can occur also on the fronts of propagating shock waves, where the modelling of the magnetic fields has proved to be challenging and numerical instabilities may arise [2]. We propose a stable high-order numerical method, which is integrated to our recently developed multi-dimensional magneto-hydrodynamic code [3]. Moreover, the non-classical processes, which are predominantly given by the non-local transport of electrons and can substantially contribute to the magnetic field generation, are briefly explored too [4].

## References

[1] Ludwig Biermann. Über den Ursprung der Magnetfelder auf Sternen und im interstellaren Raum (miteinem Anhang von A. Schlüter). *Zeitschrift Naturforschung Teil A*, 5:65, 1950.

[2] Carlo Graziani, Petros Tzeferacos, Dongwook Lee, Donald Q. Lamb, Klaus Weide, Milad Fatenejad, and Joshua Miller. The Biermann catastrophe in numerical magnetohydrodynamics. *The Astrophysical Journal*, 802(1):43, 2015.

[3] Jan Nikl, Milan Kuchařík, and Stefan Weber. High-order curvilinear finite element magneto-hydrodynamics I: A conservative Lagrangian scheme. *Journal of Computational Physics*, 2021. Submitted. arXiv:2110.11669 [physics.comp-ph].

[4] Tadeusz Pisarczyk, Sergey Yu. Gus'kov, Tomasz Chodukowski, Roman Dudzak, et al. Kinetic magnetization by fast electrons in laser-produced plasmas at sub-relativistic intensities. *Physics of Plasmas*, 24(10):102711, 2017.

# Investigation of magnetized plasma created in snail targets at the PALS facility

T. Pisarczyk[1], O. Renner[2,3,3a], R. Dudzak[3,2], T. Chodukowski[1], Z. Rusiniak[1], J. Dostal[2,3], M. Krupka[2,3,5], P. Gajdos[2], D. Batani[6], S. Singh[2,3], D. Klir[4], A. Zaras-Szydłowska[1], Iu. Kochetkov[7], M. Rosinski[1], P. Tchórz[1], J. Krasa[2], T. Burian[3,2], M. Pfeifer[3,2], J. Cikhardt[4], S. Jelinek[2,3], G. Kocourkova[3], S. Borodziuk[1] , M. Krus[2], L. Juha[3,2], and Ph. Korneev[7,8]

*[1] Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland*
*[2]Institute of Plasma Physics, Czech Academy of Sciences, 182 00 Prague, Czech Republic*
*[3]Institute of Physics, Czech Academy of Sciences, 182 21 Prague, Czech Republic*
*[3a]Institute of Physics, ELI Beamlines Center, Czech Acad Sci, 252 41 Prague, Czech Republic*
*[4]Faculty of Electrical Engineering CTU, 166 27 Prague, Czech Republic*
*[5]Faculty of Nuclear Sciences and Physical Engineering CTU, 115 19 Prague, Czech Republic*
*[6]Univ. Bordeaux, CNRS, CEA, CELIA, UMR 5107, F-33405 Talence, France*
*[7]National Research Nuclear University MEPhI, 115409 Moscow, Russian Federation8*
*[7]P. N. Lebedev Physical Institute of RAS, 119991 Moscow, Russian Federation*

Magnetized plasma studies are necessary for many applied studies including laser-driven inertial fusion, modeling astrophysical relevant phenomena, as well as innovative industrial and medical applications. One of the main issues met in this research is generation of strong magnetic fields. A particularly interesting alternative to classic pulse magnetic field generators offers the application of spiral-shaped cavity (snail-like*)* targets, in which the magnetized plasma streams are generated. This research continues previous PALS experiments, which principally confirmed the idea of forming the magnetized plasma in snail targets irradiated by moderate intensity laser beams [1]. In the reported extended research, snail targets of various diameters illuminated by ~500 J, 1ω, linearly or circularly polarized radiation of the PALS iodine laser , were used. As the main diagnostic, a 3-frame complex interferometry measured the temporal changes in the distribution of the magnetic fields and electron density in the formed structures of the magnetized plasma. Complementary studies of the electron emission parameters were carried out using 2D imaging of the Cu-Kα line emission and a multi-channel electron spectrometer. A 4-frame X-ray camera was used to visualize the plasma formation process in the X-ray range. The results obtained within this investigation clearly demonstrate the influence of the target size and the laser beam polarization on the structure of the formed magnetized plasma and the emission of electrons and ions. Irradiation of the targets with the linearly polarized laser beam significantly affects the parameters of the electron emission, especially the hot electrons, which reveals in their increased production, temperature and energy deposited along the snail target surface, according to 2D imaging of Kα-Cu emission and to angular measurements of the electron spectra with the multi-channel magnetic electron spectrometer.

[1] T. Pisarczyk, S.Yu Gus'kov, A. Zaras-Szydłowska, R. Dudzak, O. Renner, T. Chodukowski, J. Dostal, Z. Rusiniak, T. Burian, N. Borisenko, M. Rosinski, M. Krupka, P. Parys, D. Klir, J. Cikhardt, K. Rezac, J. Krasa, Y.J. Rhee, P. Kubes, S. Singh, S. Borodziuk, M. Krus, L. Juha, K. Jungwirth, J. Hrebicek, T. Medrik, J. Golasowski, M. Pfeifer, J. Skala, P. Pisarczyk, Ph. Korneev. Magnetized plasma implosion in a snail target driven by a moderate intensity laser pulse. *Scientific Report*, **8**:17895, 2018.

# Quantum sensing of microparticle charges in plasmas

M.Y. Pustylnik[1] , Z. Marvi[2] , J. Beckers[2]

[1] *Institut für Materialphysik im Weltraum, Deutsches Zentrum für Luft- und Raumfahrt, Cologne, Germany*

[2] *Department of Applied Physics, Eindhoven University of Technology, Eindhoven, The Netherlands*

Electrical charge is an important parameter of dust particles immersed in plasmas. It enters into practically all dust-related quantities. In laboratory experiments, the charge is usually measured by means of dynamical methods. Such methods have obvious disadvantages. It is, therefore, very important to develop optical methods of the charge measurements.

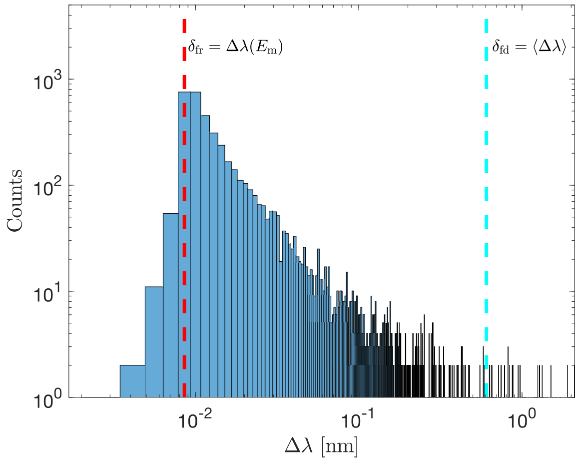


Figure 1: *Statistics of the Stark shift for a CdSe QD of* 3.3 *nm radius on the surface of a microparticle of* 4.6 *µm radius and charge of* $3 \times 10^4$ *elementary charges.*

We propose to use the quantum dots (QDs) deposited on the surface of the microparticles as optical charge sensors [1]. Radiative transitions of the QDs are subject to the so-called quantum-confined Stark effect [2], for which the spectral shift of the photoluminescence wavelength is proportional to the square of the local electric field. Experiments with QDs deposited on large flat plasma-facing surfaces proved the sensitivity of the QDs to the surface charge [3].

As calculations show, the electric field sensed by a QD (and the respective Stark shift) will be subject to large fluctuations (see Figure 1). The value of the Stark shift is of the order of fractions of nm and, therefore, should be accessible for measurement.

Other issues related to the possible experimental realization of such measurement (heating of microparticles and QDs, sputtering of QDs, surface design) will be discussed.

## References

[1] M.Y. Pustylnik, Z. Marvi, J. Beckers, Journal of Physics D **55** 095202 (2022)

[2] A.L. Efros, J.B. Delehanty, A.L. Huston, I.L. Medintz, M. Barbic, T.D. Harris, Nature Nanotechnology **13** 277 (2018)

[3] Z. Marvi, T. J. M. Donders, M. Hasani, G. Klaassen, J. Beckers, Applied Physics Letters **119** 254104 (2021)

# Design and optimization of a radio frequency plasma jet for biomedical applications

L. Zampieri[1], E. Martines[1]

[1] *Department of Physics "G. Occhialini", University of Milano – Bicocca, Milano, Italy*

In the context of plasma medicine, the most widespread tools are represented by small plasma jets operating at atmospheric pressure and very low power, so as to avoid thermal effects on the treated substrate [1]. These devices typically use helium or argon as main process gas, with the elements required for the production of active chemical species provided by small amount of oxygen or nitrogen mixed to the main flow or, more commonly, just by the interaction of the plasma with the surrounding air. The most commonly used technology for the production of such jets is that of Dielectric Barrier Discharge (DBD), powered by sinusoidal or pulsed high voltage waveform. There are however also several examples of jets powered by radio frequency (RF) voltage, including a well known certified device [2]. In this contribution we describe a novel RF plasma jet developed by our group, and we investigate the impact of the applied voltage waveform on the jet characteristics. In particular, the effects of frequency change and of duty cycle are documented, both in terms of electrical and optical measurements. Operation in helium and argon is analyzed, highlighting the differences in discharge features. The effect of the jet on surfaces is described in terms of contact angle change.

**References**

[1] G. Y. Park, S. J. Park, M. Y. Choi, I. G. Koo, J. H. Byun, J. W. Hong, J. Y. Sim, G. J. Collins and J. K. Lee, Plasma Sources Sci. Technol. **21**, 043001 (2012)

[2] S. Bekeschus, A. Schmidt, K.-D. Weltmann and T. von Woedtke, Clinical Plasma Medicine, **4**, 19 (2016)

# Modeling of gas breakdown with “particle in cell” method

V. Lisovskiy, S. Dudin, D. Dudin, R. Osmayev, I. Lesnik, V. Yegorenkov
*V.N. Karazin Kharkiv National University, Kharkiv, Ukraine*

A numerical theoretical model has been developed that allows calculating the breakdown voltage of a gas between electrodes of arbitrary curvilinear shape. Such parameters of the model as boundary conditions for electric field calculation, time step between iterations of the model, distribution of loaded ions, modeling time required for breakdown detection were studied and optimized. A breakdown detection algorithm and a voltage feedback simulation algorithm have been developed that allows simulations to be performed accounting for the accumulation of surface charge on the chamber walls. Methods for acceleration of the modeling process were also proposed, which allowed to speed up the calculations several times. Comparison of the simulation results with previously obtained experimental data for the cases of flat and hemispherical electrodes in a wide range of distances between the electrodes showed a good correspondence at different gas pressures. It is shown that in the case of flat electrodes for a sufficiently large distance between the electrodes, the Paschen similarity law is not satisfied. It is concluded that the reason for this is the loss of charged particles on the dielectric walls of the discharge chamber due to radial diffusion and the defocusing geometry of the electric field lines. For the system with hemispherical electrodes it is shown that the physical reason for the formation of a horizontal section on the breakdown curve is the change in the breakdown path when the gas pressure changes, diffusion processes expand the breakdown channel, and the trajectory of particles in a curved electric field does not repeat the shape of the force line due to the inertia of motion. It is shown that due to the accumulation of surface charge, the losses of charged particles are reduced, and breakdown becomes possible at much lower voltages.

# Community structure of Earth's magnetic field measurements.

Sebastián de la Maza[1,*], Víctor Muñoz[1,†]
[1] *Departamento de Física, Facultad de Ciencias, Universidad de Chile.*
*sebastian.delamaza@ug.uchile.cl, †vmunoz@macul.ciencias.uchile.cl

## Introduction

The Earth's magnetic field has dependence both in the time and spatial domains. Also, due to the underlying physical processes involved, the change of the magnetic field at a given point or at a given instant may induce variations at other points and/or subsequent times. We propose to study this complex dynamics of spatiotemporal correlations by means of tools derived from graph theory and complex networks, which have shown to be useful to describe the behavior of various systems of geophysical interest [1, 2, 3]. In particular, we intend to study the evolution of magnetic field measurements on the Earth's surface along the 23rd solar cycle. Based on records by 59 magnetometers during the 23rd solar cycle (taken from the World Data Center for Geomagnetism, Kyoto, http://wdc.kugi.kyoto-u.ac.jp/hyplt/index.html), we define a complex network where nodes are the magnetometers, and their connection is determined by the correlation between their respective magnetic field time series. Thus, the structure of the complex network is expected to be a representation of the spatiotemporal patterns of the Earth's magnetic field. Since the 59 stations are not uniformly distributed, we will also consider data from a simulation (taken from the Community coordinated modeling center, https://ccmc.gsfc.nasa.gov/modelweb/models/igrf_vitmo.php), where we can sample data on a uniform grid in spherical coordinates. In fact, we consider a network of 234 points with a separation of 12.5° in latitude and 20° in longitude. Thus, we expect to complement the conclusions taken from observed data.

## Methodology

The network is defined by two similarity methods between time series, namely, the Pearson correlation [4, 5] and event synchronization [6]. Complex networks are built for each year from 1996 to 2008, covering the full 23rd solar cycle. Then, the community structure of each network is analyzed, and some of its basic features are analyzed along the cycle: the number of communities, their average coverage area and the value of their modularity.

We find that the community structure for both the real data and the simulation data do indeed have information about solar activity. For example, we observe that both the average coverage area and the value of the modularity of the communities decrease during the solar maximum, with both parameters producing a maximum at the beginning and at the end of the solar cycle. This suggests that the community structure of the network may reveal the changes in correlation length in the magnetic field structure as solar activity evolves. But we also show that results strongly depend on the choice of similarity methods, and the thresholds involved.

## Acknowledgments

V. M. acknowledges support of ANID through Fondecyt Grant 1201967.

# Referencias


[1] L. Orr, S. C. Chapman, J. W. Gjerloev, and W. Guo, Nuovo Cim. **12**, 1842 (2021).

[2] S. Lu, H. Zhang, X. Li, Y. Li, C. Niu, X. Yang, and D. Liu, Nonlinear Proc. Geophys. **25**, 233 (2018).

[3] A. Najafi, A. H. Darooneh, A. Gheibi, and N. Farhang, Astrophys. J. **894**, 66 (2020).

[4] Y. Xu, F. Lu, K. Zhu, X. Song, and Y. Dai, Water **12**, 1739 (2020).

[5] M. J. Halverson and S. W. Fleming, Hydrol. Earth Syst. Sci. **19**, 3301 (2015).

[6] A. Agarwal, N. Marwan, R. Maheswaran, B. Merz, and J. Kurths, J. Hydrol. **563**, 802 (563).

# On stochastic electron dynamics in colliding plane waves

A.R. Knyazev, S. I. Krasheninnikov

*Univeristy of California San Diego*

Stochastic dynamics of the electron interacting with multiple electromagnetic waves is a subject of active research [1-6]. Recently, dynamics of the relativistic electron interacting with two counter-propagating plane waves was described with a 3/2-Hamiltonian, [5] allowing to utilize the techniques used in previous studies of stochastic dynamics in such systems. This novel Hamiltonian approach provided a clear physical picture of the mechanism behind the onset of stochasticity in electron motion. However, the previous analysis [5] did not consider the impact of the electron's canonical momentum $\bar{P}_{\perp}$ perpendicular to the laser propagation axis. Assessing the effects of $\bar{P}_{\perp}$ enables [5] a better understanding of the recent numerical results of stochastic heating in colliding laser pulses, such as the dependence on the initial laser phases [6].

This talk presents a recently published [5] study of stochastic heating of an electron with an arbitrary canonical momentum P in the presence of two counter-propagating linear plane waves with vector potentials $\mathbf{a}_1$ and $\mathbf{a_2}$, with an arbitrary angle between the polarizations. The onset of stochasticity for both parallel and perpendicular polarization setups is demonstrated.

For $a_2 \ll a_1$ case, i.e. when laser amplitude $a_1$ of one of the lasers dominates the other, the stochasticity threshold is derived, showing how the stochastic region of H decreases with an increase of perpendicular canonical momenta $\mathbf{P}_{\perp}$. The physics behind the impact of $\mathbf{P}_{\perp}$ on the stochasticity boundary is revealed. Finally, the Hamiltonian analysis is expanded to include the impact of radiation friction in the classical radiation reaction limits. It is shown that Hamiltonian analysis remains valid within applicability of classical RF approximation. Presented results are useful for understanding the electron dynamics in counter-propagating laser pulses such as, for example, the incident-reflected laser pulses in laser-target interactions.

## References

[1] Mendonça, J. T. "Threshold for electron heating by two electromagnetic waves." Physical Review A **28**, 3592 (1983).

[2] J.-M. Rax, Physics of Fluids B: Plasma Physics **4**, 3962 (1992).

[3] Z.-M. Sheng, K. Mima, Y. Sentoku, M. Jovanovi c, T. Taguchi, J. Zhang, and J. Meyerter Vehn, Physical review letters **88**, 055004 (2002).

[4] S. Bochkarev, E. d'Humi'eres, V. Tikhonchuk, P. Korneev, and V. Y. Bychenkov, Plasma Physics and Controlled Fusion **61**, 025015 (2019).

[5] Y. Zhang and S. Krasheninnikov, Physics of Plasmas **26**, 050702 (2019).

[6] Knyazev, A. R., and S. I. Krasheninnikov. "Stochastic electron motion in colliding plane waves." Physical Review E **103**.6 (2021): 063213.

# Nonlinear growth of Rayleigh Taylor Instability single mode structure under the effect of collision with a second fluid

Q. Cauvet[1], B. Bernecker[1,2], S. Bouquet[1,2,3], B. Canaud[1,2], F. Hermeline[1], S. Pichon[1]

[1] *CEA, DAM, DIF- 91297 Arpajon, FRANCE*

[2] *Université Paris-Saclay, CEA, Laboratoire Matière en Conditions Extrêmes) (LMCE), 91680 Bruyères-le-Châtel, FRANCE*

[3] *Observatoire de Paris, PSL Research University, CNRS, Université Paris Diderot, Sorbonne Paris Cité, 92190 Meudon, FRANCE*

The Rayleigh-Taylor instability (RTI) occurring at the interface between two fluids subject to an external force pointing from heavy to light fluid is widely encountered in plasma physics, playing an important role in inertial confinement fusion, astrophysics, and geophysics. A particular case appears when the fluid is partially ionized plasma interacting through collision with a predominantly neutral background.

In this configuration, the non-linear growth of RTI structures is investigated using Goncharov's [1] potential model for a single mode RTI. It gives the temporal evolution of the position, the curvature, and the velocity of the top of the bubble or of the tip of the spike. In the case where the RTI dynamics is dominated by collisions between neutrals and ions, the terminal bubble and spike velocities are derived from the non-linear equations. Direct Numerical Simulations (DNS), with the code MHD CLOVIS [2] and electrostatic ERINNA [3], are used to justify the use of Goncharov's model in this regime and observe its limitations or transition to the classical (inertial) regime.

In the collisional regime and at any arbitrary Atwood number, the terminal velocity obtained with this model appears to agree well with DNS. As a conclusion, Goncharov's potential model applied to this particular case yields promising and unexpected results.

## References

[1] V. N. Goncharov, Analytical model of nonlinear, single-mode, classical Rayleigh-Taylor instability at arbitrary Atwood numbers, Physical review letters **88**, 134502 (2002).

[2] T. Miyoshi and K. Kusano, A multi-state hll approximate Riemann solver for ideal magnetohydrodynamics, Journal of Computational Physics **208**, 315-344 (2005)

[3] F. Hermeline, A finite volume method for the approximation of convection-diffusion equations on general meshes, International journal for numerical methods in engineering **91**, 1331-1357 (2012)

# PICSAR-QED: a Monte Carlo module to simulate strong-field quantum electrodynamics in particle-in-cell codes for exascale architectures

L. Fedeli[1], N.Zaïm[1], A.Sainte-Marie[1], M.Thévenet[2], A.Huebl[3], A.Myers[3], J.-L.Vay[3], H.Vincenti[1]

[1] *Université Paris-Saclay, CEA, CNRS, LIDYL, 91191 Gif-sur-Yvette, France*

[2] *Deutsches Elektronen-Synchrotron, Notkestraße 85, D-22607 Hamburg, Germany*

[3] *Lawrence Berkeley National Laboratory, Berkeley, CA 94720, United States of America*

Physical scenarios where the electromagnetic fields are so strong that quantum electrodynamics (QED) plays a substantial role are one of the frontiers of contemporary plasma physics research. Investigating those scenarios requires state-of-the-art particle-in-cell (PIC) codes able to run on top high-performance computing (HPC) machines and, at the same time, able to simulate strong-field QED processes. This contribution presents the PICSAR-QED library[1], an open-source, portable implementation of a Monte Carlo module designed to provide modern PIC codes with the capability to simulate such processes, and optimized for HPC. We present detailed tests and benchmarks that we carried out to validate the physical models in PICSAR-QED, to study how numerical parameters affect such models, and to demonstrate its capability to run on different architectures (CPUs and GPUs). We also discuss its integration with WarpX[2, 3], a state-of-the-art PIC code designed to deliver scalable performance on upcoming exascale supercomputers. Finally, we present the results of some production simulations carried out with WarpX and PICSAR-QED to investigate strong-field QED effects in ultra-intense laser-solid interaction[4] (see Fig. 1).

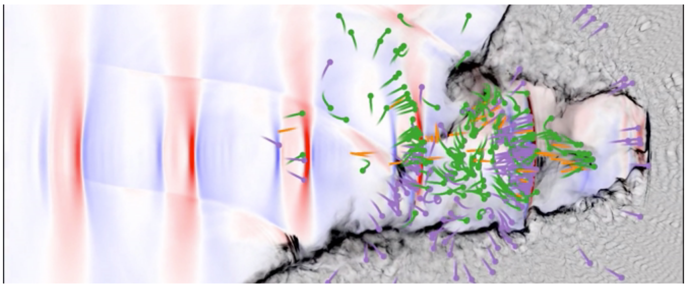

Figure 1: *Snapshot of a 2D Particle-In-Cell simulation performed with WarpX+PICSAR-QED. The interaction of an ultra-intense beam (blue-red scale) between a solid target (grayscale) results into the emission of high-energy photons (orange rays) and the generation of electron/positron pairs (green and purple particles), two processes simulated with PICSAR-QED.*

## References

[1] L.Fedeli et al. New Journal of Physics, in press, DOI: https://doi.org/10.1088/1367-2630/ac4ef1 (2022)

[2] A.Myers et al., Parallel Computing **108**, 102833 (2021)

[3] WarpX github repository: https://ecp-warpx.github.io/

[4] L.Fedeli et al., Physical Review Letters **127**, 114801 (2021)

# Ionization and electron capture processes induced in collisions between singly charged ions and nitrogen atom

M. Al-Ajaleen[1,2], A Taoutioui [1], and K. Tőkési [1]

[1] *Institute for Nuclear Research (ATOMKI), Debrecen, 4026, Hungary*

[2] *Doctoral School of Physics, University of Debrecen, Debrecen, 4032, Hungary*

The electron processes induced in ion-atom collisions are crucial and central in various research domains such as fusion plasma in tokamak reactors and interstellar space [1]. The modeling and control of these processes rely on the accurate cross sections of the induced electron processes. In particular, we are interested in presenting accurate cross sections for single electron processes, mainly ionization and electron capture in collision between $Li^+$ and $Na^+$ ions with nitrogen atom. For sake of simplicity, the considered collisional systems are treated as three-body problem. The nitrogen atom target is described within the single active electron approximation using Garvey model potential where only the outermost electron is involved in the collision dynamics [2]. Regarding the projectile, in the first approximation, it is treated as a frozen core model and the charge of the projectiles are +1 in the entirely time of the collision. In the second approximation, the projectile-target interaction is described by a model potential which takes into account the screening effect by the projectile electrons [2]. The scattering problem is solved within the frame of the classical trajectory Monte Carlo (CTMC) [3].

We present total, angular, and energy differential cross sections for single ionization and single capture processes from intermediate to high impact projectile energies (10 keV-10 MeV). Our results are compared to the available experimental data which allowed us to test the validity of the frozen core approximation.

## REFERENCES

[1] R Isler et al., Nucl. Fusion 31 245 (1991).

[2] R. H. Garvey et al., Phys. Rev. A 12, 1144 (1975).

[3] K. Tőkési et al., Nucl. Instrum. Methods Phys. Res. B: Beam Interact. Mater. At. 86, 201 (1994).