FOREWORD

A new issue of the EuPRAXIA Files is presented here, recollecting the most relevant books and papers recently appeared in literature about accelerators, lasers and plasma science and strictly correlated with technologies that will be used at EuPRAXIA.

EuPRAXIA Consortium is preparing the implementation of the two sites at Frascati (INFN) and Prague (ELI-ERIC), together with the general future organization of the EuPRAXIA network for user access.

EuPRAXIA was inserted in the ESFRI 2021 Roadmap, and since then, it has a window of opportunity of ten years to complete the necessary steps in terms of governance, creation of a legal entity, setting a sustainable program and launching the operation of sites.

EuPRAXIA files is a golden reference source of material for the work to be done in EuPRAXIA!

Thanks to Hannah and Debdeep who did a great job!

I wish you an interesting reading

Pierluigi Campana

CONTENTS

FUNDAMENTALS

On the impact of short laser pulses on cold diluted plasmas

G. Fiore, S. De Nicola, T. Akhter, R. Fedele, D, Jovanovi´c
PHYSICA D: NONLINEAR PHENOMENA 454, 133878 (NOV 15 2023)

We analytically study the impact of a (possibly, very intense) short laser pulse onto an inhomogeneous cold diluted plasma at rest, in particular: the duration of the hydrodynamic regime; the formation and the

features of plasma waves (PWs); their wave-breakings (WBs); the motion of test electrons injected in the PWs.
If the pulse is a plane wave travelling in the z-direction, and the initial plasma density (IPD) depends only on z, then suitable matched bounds on the maximum and relative variations of the IPD, as well as the intensity and duration of the pulse, ensure a strictly hydrodynamic evolution of the electron fluid during its whole interaction with the pulse, while ions can be regarded as immobile. This evolution is ruled by a family (parametrized by $Z \geq 0$) of decoupled systems of non-autonomous Hamilton equations with 1 degree of freedom, which determine how electrons initially located in the layer $Z \leq z < Z + dZ$ move; $\xi = ct - z$ replaces time t as the independent variable. This family of ODEs is obtained by reduction from the Lorentz–Maxwell and continuity PDEs for the electrons' fluid within the spacetime region where the change of the pulse is negligible. After the laser–plasma interaction the Jacobian of the map from Lagrangian to Eulerian coordinates is linear-quasi-periodic in ξ . We determine spacetime locations and features of the first wave-breakings of the wakefield PWs, the motion of test electrons (self-)injected in the PWs. The energy of those trapped in a single PW trough grows linearly with the distance gone, where the IPD is constant.
If the pulse has cylindrical symmetry and a not too small radius, the same conclusions hold for the part of the plasma enclosed within the causal cone swept by it.
This computationally light approach may help in a preliminary study of extreme acceleration mechanisms of electrons (LWFA, etc.), before 2D or 3D PIC simulations.

High-order Mie resonance and transient field enhancement in laser-driven; plasma nanoshells

Gao, XH
PHYSICAL REVIEW A 112(6), 063537 (DEC 22 2025)
https://doi.org/10.1103/z4sw-kxlf

We demonstrate substantial field enhancement in plasma nanoshells through high-order Mie resonances using combined Mie theory and particle-in-cell simulations. Optimal shell geometries yield approximately threefold electric field enhancement for 800-nm irradiation, with transient buildup times of tens of femtoseconds before plasma expansion disrupts resonance. Few-cycle pulses produce reduced enhancement due to insufficient resonance establishment. These findings enable optimized laser-plasma interactions for applications including diagnostics of laser-cluster interaction and energetic ion production from engineered core-shell targets, highlighting the critical role of temporal dynamics in nanoplasma resonances.

Threshold effects in the development of highly ionized plasma channels; in a pulsed nanosecond discharge in air at pressures of 100-760 Torr

Parkevich, EV; Khirianova, AI; Shpakov, K; Khirianov, TF; Popov, NA
PHYSICAL REVIEW E 112(6), 065211 (DEC 30 2025)
https://doi.org/10.1103/bq1x-2p4t

The formation processes of highly ionized plasma channels (filaments), with an electron concentration of Ne similar to 1018-1019cm-3, in a pulsed nanosecond discharge in air at a pressure of 100-760 Torr are investigated. The studies are carried out for millimeter-sized gaps with a point cathode and flat anode. It is established that explosive processes at the cathode give rise to the emergence of an ionization wave propagating toward the anode with a velocity of similar to 106-107 cm/s and initiating the development of highly ionized filaments. The wave's propagation velocity is practically independent of the air pressure. At pressures 400-760 Torr, the ionization wave front is unstable and splits into numerous microchannels with typical diameters of similar to 20 mu m and electron concentrations Ne = (1-5) x 1019cm-3. The microchannel formation ceases to be observed when the air pressure decreases from 400 to 300 Torr, whereas the discharge development occurs mainly through the development of a uniform highly ionized plasma filament. A decrease in pressure entails the drop in the maximum values of electron concentrations, which, however, are close to the values corresponding to complete ionization. Theoretical estimates of characteristic filamentation times are presented together with the analysis of the possible mechanism responsible for generating plasma with a high degree of ionization. The findings can be helpful in refining the models of plasma-chemical kinetics and the formation mechanisms of a system of highly ionized microchannels in high-pressure discharges at nanosecond times.

Fiber-laser-induced cavitation: Transition from plasma formation to; bubble nucleation

Xu, ZR; Yang, XL; Ge, Y; Tang, XQ; Chen, Y; Liu, YX; Li, HY; Zhong, XH; Guo, CY

APPLIED PHYSICS LETTERS 128(1), 011104 (JAN 5 2026)
https://doi.org/10.1063/5.0304814

Despite extensive research on laser-induced cavitation bubble dynamics based on the given bubble nucleus assumption, the mechanism linking laser energy-induced optical breakdown to bubble nucleation dynamics remains poorly explored. In this Letter, we investigate the coupled dynamics of plasma and bubble formation induced by various laser energies using fiber lasers. Our findings show that the initial growth of the laser-induced bubble nucleus is driven by ionization-induced phase transitions, with plasma diffusion forming a pressure field that triggers secondary fluid expansion. We find that the oscillatory variations of the Weber number (We) and Mach number (Ma) span values from approximately 10(-5)-10(5) for We and from 10(-6) to 10(-1) for Ma, reflecting the wide range of dynamical regimes encountered across different stages in the laser-induced cavitation process. In addition, vortex ring formation is observed during the bubble evolution stage. The breakdown threshold and nucleation critical conditions are determined through parameterized energy, with the maximum of bubble radius R-b,R-max at low energies consistent with experimental results. This study offers a physical interpretation for optical breakdown nucleation dynamics and extends the quantitative application of laser-induced cavitation technology in diverse fluid fields.

Ultrafast laser-induced anharmonic lattice dynamics and nonlinear; optical modulation in croconic acid

Cheng, YH; Zhang, H; Tang, R

APPLIED PHYSICS LETTERS 127(24), 241102 (DEC 15 2025)
https://doi.org/10.1063/5.0298932

Ultrafast laser excitation offers a powerful means to modulate material properties on femtosecond timescales. Here, we investigate croconic acid, a hydrogen-bonded organic ferroelectric, using real-time time-dependent density functional theory to uncover the microscopic mechanisms of light-induced structural transitions and nonlinear optical responses. High-order harmonic generation in croconic acid is found to be highly sensitive to proton displacement within hydrogen bonds, with polarization switching reshaping internal electronic asymmetry and modulating intersite electron currents. Subangstrom-scale lattice distortions induce marked enhancements or suppressions in the harmonics, highlighting the extreme sensitivity of the nonlinear response to hydrogen-bond configuration. These results reveal a light-driven electron-proton-lattice interaction mechanism in organic ferroelectrics, providing a route toward tunable ultrafast photonic and optoelectronic devices based on molecular materials.

Ultrafast Laser-Induced Defects in β-Gallium Oxide Below Ablation; Threshold

Deangelis, E; Chae, C; Alam, S; Gao, HT; Noor, MY; Su, ZY; Clink, L; Brillson, L; Hwang, J; Chowdhury, E

ACS APPLIED MATERIALS & INTERFACES 18(1) 2892-2904 (JAN 14 2026)
https://doi.org/10.1021/acsami.5c16451

In this work, (201)beta-Ga2O3 was irradiated with 95 fs, 1030 nm laser pulses in order to investigate ultrafast laser-induced morphological and crystalline defects, which play an important role in the controlled transformation of materials at the nanomicro-scale. Kelvin probe force microscopy and depth-resolved cathodoluminescence spectroscopy (DRCLS) revealed laser-induced subsurface crystallographic defects below the ablation threshold that were undetectable by optical and atomic force microscopy. While DRCLS probed depths of 58-180 nm, scanning transmission electron microscopy provided complementary insights into regions beyond the reach of DRCLS, enabling direct imaging of the crystal structure and defects at or just below the surface. The analysis revealed a depth-dependent modification of the material, with an amorphous layer forming closest to the surface and damage site, transitioning to a defective region exhibiting a phase change to gamma-Ga2O3, and further transitioning to a region rich in point defects, with defect concentrations decreasing with depth. A Keldysh ionization-based FDTD simulation of the single pulse interaction was carried out as well, revealing high density of carrier generation consistent with the depth scales observed by the measurements. These findings contribute to a deeper understanding of defect formation mechanisms in beta-Ga2O3 and highlight the potential of ultrashort laser pulses for precision subsurface modification in wide bandgap semiconductors.

Amplification of terahertz radiation in inhomogeneous plasma produced by; multiphoton ionization of inert gas in a magnetic field

Mamontova, TV; Uryupin, SA
PHYSICAL REVIEW E 112(6), 065207 (DEC 17 2025)
https://doi.org/10.1103/pt3c-cwkk

The reflection and transmission coefficients of an electromagnetic wave interacting with an inhomogeneous plasma layer produced by multiphoton ionization of an inert gas in a magnetic field are determined. The possibility of terahertz radiation amplification is revealed. If the frequency of the probe radiation matches the electron cyclotron frequency, the field strength of the transmitted and reflected radiation can be amplified by more than two orders of magnitude. The amplification arises due to the Ramsauer-Townsend effect and the non-equilibrium energy distribution of the photoelectrons. Blurring the plasma boundary by an amount equal to a few percent of the uniform layer width results in a small decrease in radiation amplification. The energy spread of photoelectrons reduces the amplification by several times.

Diffusive plasma jet vs. conventional linear plasma jets: physical; properties, chemical production, in vitro effects on cell; proliferation and collagen production

Saugé, L; Labérie, B; Gautreau, AM; Rousseau, A
JOURNAL OF PHYSICS D-APPLIED PHYSICS 59(2), 025213 (JAN 16 2026)
https://doi.org/10.1088/1361-6463/ae2aea

Cold atmospheric plasma jets show promising results in chronic wound healing. In this study, three AC kHz helium plasma jet configurations are characterized: two standard linear plasma jets and an innovative large area diffusive jet. The latter consists of a linear tube with an expansion bell closed at its end by sintered glass material generating a 50 mm2 uniform plasma. First, three configurations are compared with respect to their physicochemical aspects: the ionization front propagation and interaction with dielectric and liquid target is monitored using an electric field (E-field) probe, and the production of H2O2 and NO2- in liquid target as a

function of the energy dose is measured. Second, a preliminary study is conducted on simple biological models in vitro: collagen secretion from primary fibroblasts and proliferation from keratinocytes (HaCaT) are assessed. It results that collagen secretion and cell proliferation are enhanced when treated with the diffusive jet, contrary to linear jets. The diffusive jet produces higher E-field and lower concentration of H_2O_2 and NO_2^- compared to standard linear jets. This suggests that the balance between E-field and reactive oxygen and nitrogen species is critical to stimulate cell responses.

CONTROL & OPMIZATION

ENERGY SPREAD & EMITTANCE

Mitigating emittance and longitudinal profile degradation of non-ideal; bunches caused by CSR in multi-bend deflecting beamlines

Chen, XJ; Chen, S; Deng, HX; Wang, D

NUCLEAR SCIENCE AND TECHNIQUES 37(3), 50 (JAN 10 2026)
https://doi.org/10.1007/s41365-025-01869-z

Preserving beam quality during the transport of high-brightness electron bunches is crucial for advanced accelerator applications, such as particle colliders, free-electron lasers, and recirculating linacs. However, coherent synchrotron radiation (CSR) significantly degrades beam quality when electron bunches pass through multi-bend isochronous beamlines, particularly for short bunches with non-ideal longitudinal profiles. Although several methods have been proposed to mitigate CSR effects, most rely on small-angle approximations or are limited to idealized bunch profiles. In this study, we present two improved methods for designing isochronous triple-bend achromat (TBA) beamlines that effectively mitigate CSR-induced emittance growth and longitudinal profile distortion without relying on small-angle approximations. The first method, an enhanced integral optimization approach, simplifies numerical optimization and can accurately handle larger deflection angles, making it suitable for practical applications that require flexible lattice configurations. The second method, an optimized I-matrix approach, completely cancels steady-state and transient CSR kicks through specific matrix constraints and higher-order dispersion optimization, enabling effective CSR suppression even with very large deflection angles. Systematic simulations demonstrate that both methods achieve excellent preservation of transverse emittance and longitudinal profiles.

Enhanced generation of single-spike hard x-ray free-electron laser; pulses with lower charge and shorter electron beams in the injector

Prat, E; Malyzhenkov, A; Orlandi, GL; Weilbach, T; Reiche, S

PHYSICAL REVIEW RESEARCH 7(4), L042060 (DEC 10 2025)
https://doi.org/10.1103/t8qq-h31p

Standard x-ray free-electron lasers (FELs) produce pulses with total durations of tens of femtoseconds and with time and spectral profiles consisting of multiple randomly distributed spikes. Strongly compressing an electron beam is a typical approach to produce shorter and coherent FEL pulses. We have advanced this method by starting at the injector of the FEL facility with electron beams with lower charges and shorter durations than in standard configurations. This leads to shorter electron beams with reduced energy spread after full compression and, consequently, to shorter and higher-quality FEL pulses. By operating with electron beams at the injector with charges of a few pC and rms durations of 360 fs, we show the generation of hard x-ray FEL radiation with practically all pulses having a single spike and a duration estimated from spectral measurements of about 300 as (full-width-at-half-maximum values). The demonstration was conducted at SwissFEL, the FEL at the Paul Scherrer Institute in Switzerland. Our work represents a simple way to enhance the production of single-spike events in x-ray FEL facilities, paving the way to achieve fully coherent hard x-ray FEL pulses with unprecedented durations.

ENERGY GAIN

Effect of laser prepulse on proton acceleration driven by femtosecond; intense lasers

Guo, XJ; Xu, S; Zhang, H; Wang, QS; Li, S; Xu, DR; Yu, LH; Xu, Y; Wang, C; Liu, XY; Liu, YQ; Liang, XY; Leng, YX; Shen, BF; Ji, LL; Li, RX

HIGH POWER LASER SCIENCE AND ENGINEERING 13, e99 (JAN 12 2026)

https://doi.org/10.1017/hpl.2025.10092

We present an experimental study of proton acceleration driven by femtosecond multi-PW lasers of three different prepulse parameters with the peak laser intensity of 1.2 x 1021 W/cm2 irradiating micrometre-thick metal foils. For 4-mu m-thick copper foils, the highest-energy proton beam of 58.9 MeV is generated with the moderate-contrast laser, while the low-contrast or high-contrast lasers result in the lower proton cutoff energies. The one-dimensional hydrodynamic and two-dimensional particle-in-cell simulations indicate that the front preplasma of foils induced by the laser prepulse can enhance electron acceleration and in turn improve proton acceleration, while the rear preplasma will weaken the sheath field and be unfavourable for accelerating ions. For the case of the moderate contrast, the scale length of the front preplasma is long enough to generate high-temperature electrons compared to the high-contrast case, and the scale length of the rear preplasma is so short that the sheath field still remains strong compared with the low-contrast case, which is advantageous for generating high-energy protons. Meanwhile, a concrete map is theoretically given for accelerating higher-energy protons. This work extends the concept of the prepulse effect on target normal sheath acceleration (TNSA) to a wider range of laser parameters (multi-PW, 1021 W/cm2), representing an important step towards potential applications of TNSA-driven proton sources, especially considering that PW and even 10 PW laser facilities exist all around the world.

Evidence of electron microbunching in laser-driven modulated downramp; injection and prospects for beam-driven implementation

Zhang, CJ; Farrell, A; Marsh, KA; Su, QQ; Joshi, C

PLASMA PHYSICS AND CONTROLLED FUSION 68(1), 015009 (JAN 1 2026)

https://doi.org/10.1088/1361-6587/ae2b33

Plasma accelerators can generate high-energy, high-brightness electron beams over centimeter-scale distances, offering novel pathways to compact x-ray free-electron lasers. Generating beams pre-bunched at the desired radiation wavelength would significantly enhance longitudinal coherence and reduce saturation length. Plasma density-modulated downramp injection offers an in-situ way to generate such beams with nanometer-scale bunching. Here we report the first experimental evidence of this mechanism in a laser-driven wakefield accelerator, showing that modulated density downramps generate modulated electron energy spectra absent in unmodulated cases. Particle-in-cell simulations reproduce these observations and reveal bunching factors of 0.05 at 0.4 mu m, with a compression factor of approximately 7. Building on this demonstration, we propose a beam-driven implementation for FACET-II to generate multi-GeV beams pre-bunched at hundreds of nanometers wavelength, with sub-micrometer emittance, kiloampere peak current, and sub-percent slice energy spread. Two-stage magnetic compression enables tunable bunching from optical to extreme ultraviolet wavelengths while achieving peak currents exceeding 100 kA. Coherent transition radiation calculations confirm diagnostic feasibility. This approach offers a promising path towards compact, high-energy pre-bunched electron sources for advanced photon science applications.

BEAM CHARGE & LUMINOSITY

Superradiant terahertz free-electron laser driven by electron microbunch; trains

Liang, YF; Li, T; Sun, JT; Liu, ZY; Yang, JY; Wang, XF; Yu, Y; Tian, QL; He, ZG; Wang, HF; Zeng, L; Yi, HQ; Sun, H; Dai, YJ; Deng, XJ; Wu, GR; Zhang, WQ; Yang, XM; Tang, CX; Yan, LX

LIGHT-SCIENCE & APPLICATIONS 15(1), 60 (JAN 8 2026)
https://doi.org/10.1038/s41377-025-02156-7

Superradiance, an enhanced radiation phenomenon stemming from the phase synchronization of emitters, features a radiation intensity proportional to the number of emitters squared. The pursuit of superradiance from free electrons has long been a goal for generating intense radiation across a broad spectrum, from terahertz (THz) to the X-ray regime. However, achieving superradiance in the THz spectral range has been hindered by the lack of effective microbunching techniques. Here, we demonstrate an ultra-widely tunable superradiant THz free-electron laser (FEL) driven by high-peak-current electron microbunch trains. The emission efficiency is substantially improved as the ultra-short electron microbunches emit in phase and engage in strong interactions with the generated THz waves within the undulator. We further demonstrate that the implementation of a tapered undulator configuration leads to a two-fold enhancement in emission intensity compared to the non-tapered case, elevating the pulse energy of the narrow-band THz radiation to the millijoule level in a one-meter-long undulator. This experimental breakthrough represents a critical step toward realizing a compact, high-power, narrow-band THz source capable of fully bridging the 'THz gap' and will unlock numerous opportunities across a wide range of scientific disciplines.

Study of Gain Enhancement by Managing Betatron Oscillations Using; Multi-Stage Optical Klystrons in Free Electron Lasers

Gajbhiye, A; Jain, D

JOURNAL OF EXPERIMENTAL AND THEORETICAL PHYSICS (DEC 18 2025)
https://doi.org/10.1134/S1063776125601028

This research paper explores the dynamics of a cascaded optical klystron with betatron oscillations in free-electron lasers theoretically. By integrating multiple optical klystron stages in sequence, energy extraction efficiency and electron bunching are improved. An analytical treatment has been employed to evaluate spectral properties of the free electron lasers. The results demonstrate that the proposed configuration significantly enhances free-electron laser gain and intensity compared to the conventional single-stage optical klystron setup. The Liénard-Wiechert potentials and generalized Bessel functions have been introduced in the analysis. This study reveals that the cascaded optical klystron configuration serves as a highly effective method for improving gain efficiency and enhancing stability in free-electron lasers, even in the presence of the adverse effects of betatron oscillations.

Study of spectral brightness of THz radiation produced by longitudinally; polarized harmonic undulator

Kumar, M; Kumar, S; Jewariya, M

JOURNAL OF OPTICS-INDIA (DEC 29 2025)

https://doi.org/10.1007/s12596-025-02976-1

Spectral brightness in a Terahertz (THz) free electron laser (FEL) is a critical parameter that measures the brilliance of the emitted radiation within a defined wavelength range. In this article, we present a detailed numerical and analytical investigation of key FEL parameters on THz radiation, considering a longitudinally polarized harmonic undulator. The study examines the dynamics of the ponderomotive force and stimulated emission mechanisms in the context of THz radiation generation. Our numerical results offer comprehensive insights into the on-axis and off-axis spectral brightness, average power, and total power of the harmonic undulator, highlighting its efficiency in producing THz radiation. LU-based FEL emerges as a promising alternative, offering a tunable and high-intensity platform for advancing high-power laser systems and applications in the THz regime.

TECHNOLOGY

DIAGNOSTICS

Design of Spectrometer Energy Measurement Setups for the Future; EuPRAXIA@SPARC_L and SSRIP Linacs

Quartullo, D; Alesini, D; Cianchi, A; Demurtas, F; Faillace, L; Franzini, G; Ghigo, A; Giribono, A; Pompili, R; Sabbatini, L; Stella, A; Vaccarezza, C; Vannozzi, A; Verra, L

INSTRUMENTS 9(4), 34 (DEC 17 2025)

https://doi.org/10.3390/instruments9040034

EuPRAXIA@SPARC_L is an FEL (Free-Electron Laser) user facility currently under construction at INFN-LNF in the framework of the EuPRAXIA collaboration. The electron beam will be accelerated to 1 GeV by an X-band RF linac followed by a plasma wakefield acceleration stage. This high-brightness linac requires diagnostic devices able to measure the beam parameters with high accuracy and resolution. To monitor the beam energy and its spread, magnetic dipoles and quadrupoles will be installed along the linac, in combination with viewing screens and CMOS cameras. Macroparticle beam dynamics simulations have been performed to determine the optimal energy measurement setup in terms of accuracy and resolution. Similar diagnostics evaluations have been carried out for the spectrometer installed at the 100 MeV RF linac of the radioactive beam facility SSRIP (IFIN-HH, Romania), whose commissioning, foreseen for 2026), will be performed by INFN-LNF in collaboration with IFIN-HH. Optics measurements have been performed to characterize the resolution and magnification of the optical system that will be used at SSRIP, and probably also at EuPRAXIA@SPARC_L, for beam energy monitoring.

Composite velocity imaging spectrometer on Shanghai soft X-ray free; electron laser facility

Liao, JF; Feng, YF; Wu, KF; Tao, JF; Zhu, WT; Huang, JY; Ding, BC; Liu, XJ

ACTA PHYSICA SINICA 74(24), 243203 (DEC 20 2025)

https://doi.org/10.7498/aps.74.20251176

Temporal- and angular-resolved photoionization experiments are essential for probing the geometric configuration and electronic state evolution of atoms and molecules, which requires measuring the full spatial angular distributions of electrons and ions in free electron laser (FEL) experiments. Here, we present the first experimental results from the composite velocity imaging spectrometer (CpVMI) on the Shanghai soft X-ray free electron laser facility (SXFEL). The study demonstrates its ability to capture energy and angular information of electrons and ions with high resolution and full solid-angle collection. Krypton (Kr) atoms and carbon tetrachloride (CCl4) molecules are ionized using FEL pulses at 263.8 eV. Electron momentum images are recorded with an Andor Zyla 4.2 PLUS camera, and ion time-of-flight mass spectra and momentum distributions are acquired using a TPX3CAM. For Kr, the electron spectrum contains peaks from 3p, 3d, and 4p photoionization, as well as the Auger electrons from 3d and 3p levels. The measured anisotropy parameters (b) of these electrons show good agreement with previous theoretical Hartree-Fock calculations. The ion abundance in the time-of-flight mass spectra of Kr is consistent with the ratio derived from the intensities of the corresponding photoelectron peaks. For CCl4, the electron spectrum contains Cl 2p photoelectrons, 2p Auger electrons, and valence-shell photoelectrons, with their angular distribution parameters also aligning with theoretical predictions. The TPX3CAM can directly measure the momenta of fragment ions without the need of inverse Abel transformation. By integrating the high-resolution flight time mass spectrometry and momentum imaging data obtained from TPX3CAM, we successfully visualize and analyze the key photodissociation pathways of CCl4 molecules under the action of soft X-ray FEL. In particular, it can distinguish between direct two-body dissociation and multi-step dissociation processes, and observe the unique angular distributions and kinetic energy release characteristics of different dissociation channels. In conclusion, the experimental results clearly show that the CpVMI fully meets the technical requirements for FEL user experiments in terms of energy, angular distribution, and momentum measurement, providing a platform for FEL light-induced dynamics research. Future enhancements, including improved light focusing and the use of supersonic molecular beams, are expected to further improve the performance of the instrument

Tracking Ultrashort Electron Processes in Matter With X-Ray Chronoscopy

Fanselow, R; Blachucki, W; Szlachetko, J

X-RAY SPECTROMETRY (JAN 2 2026)

https://doi.org/10.1002/xrs.70073

The development of X-ray Free Electron Lasers (XFELs) unlocked new possibilities in many areas of science. These facilities routinely produce femtosecond X-ray pulses with extremely high peak brilliance, enabling time-resolved X-ray spectroscopy experiments to study ultrashort phenomena in matter. However, many fundamental electron processes in atoms, molecules, and clusters are still unreachable by the XFEL-based time-resolved methods. Recently, an innovative methodology called X-ray Chronoscopy was introduced to address some current time resolution limits typically encountered at XFEL. Herein, we assess the ability of X-ray Chronoscopy to track electron dynamics in an optical pump/X-ray probe XFEL experiment. By employing numerical simulations, we showed that the proposed method could determine femtosecond relaxation rates in matter while mitigating the main issues related to optical pump/X-ray probe experiments at XFELs, such as pump-probe arrival time jitter. We anticipate that with the ongoing advent of temporal diagnostic tools, the implementation of X-ray Chronoscopy at XFEL would complement the information obtained from X-ray spectroscopy, providing a complete picture of the sample's electronic structure.

Demonstration of full-scale spatiotemporal diagnostics of solid-density; plasmas driven by an ultra-short relativistic laser pulse using an X-ray; free-electron laser

Huang, LE; Smíd, M; Yang, L; Humphries, O; Hagemann, J; Engler, T; Pan, XY; Cui, YZ; Kluge, T; Aguilar, R; Baehtz, C; Brambrink, E; Eren, E; Falk, K; Garcia, AL; Göde, S; Gutt, C; Hassan, M; Heuser, P; Höppner, H; Kozlova, M; Lu, W; Metzkes-Ng, J; Masruri, M; Mishchenko, M; Nakatsutsumi, M; Ota, M; Öztürk, Ö; Pelka, A; Prencipe, I; Preston, TR; Randolph, L; Rehwald, M; Schlenvoigt, HP; Schramm, U; Schwinkendorf, JP; Starke, S; Stefaníková, R; Thiessenhusen, E; Toncian, M; Toncian, T; Vorberger, J; Zastrau, U; Zeil, K; Cowan, TE

MATTER AND RADIATION AT EXTREMES 11(1), 017201 (JAN 2026)

https://doi.org/10.1063/5.0279974

Understanding the complex plasma dynamics in ultra-intense relativistic laser-solid interactions is of fundamental importance for applications of laser-plasma-based particle accelerators, the creation of high-energy-density matter, understanding planetary science, and laser-driven fusion energy. However, experimental efforts in this regime have been limited by the lack of accessibility of over-critical densities and the poor spatiotemporal resolution of conventional diagnostics. Over the last decade, the advent of femtosecond brilliant hard X-ray free-electron lasers (XFELs) has opened new horizons to overcome these limitations. Here, for the first time, we present full-scale spatiotemporal measurements of solid-density plasma dynamics, including preplasma generation with tens of nanometer scale length driven by the leading edge of a relativistic laser pulse, ultrafast heating and ionization at the main pulse arrival, the laser-driven blast wave, and transient surface return current-induced compression dynamics up to hundreds of picoseconds after interaction. These observations are enabled by utilizing a novel combination of advanced X-ray diagnostics including small-angle X-ray scattering, resonant X-ray emission spectroscopy, and propagation-based X-ray phase-contrast imaging simultaneously at the European XFEL-HED beamline station.

PLASMA TARGETS

Demonstration of a tandem lens for producing shaped laser-ionized; plasmas for plasma wakefield acceleration

Ariniello, R; Lee, V; Litos, MD

OPTICS EXPRESS 33(25), 52019-52034 (DEC 15 2025)

https://doi.org/10.1364/OE.578053

We demonstrate a tandem lens optical setup, comprising two diffractive optics, that focuses a high-power ultrafast laser with a shaped on-axis intensity profile, producing a meter-long Bessel focus. The intended use of the optical setup is to produce a laser-ionized plasma source for plasma wakefield acceleration. By controlling the on-axis intensity, the density profile of the plasma ramps at the entrance and exit of the plasma can be tailored to optimize the matching of the electron beam into the plasma. In addition to demonstrating the optical system, we describe the algorithm used to calculate the lens phases and present detailed calculations of the lenses' expected performance.

LASERS & OPTICS

Demonstration of Mode-Locked Frequency Comb for an X-Ray Free-Electron; Laser

Hu, WX; Aeppli, G; Arrell, C; Calvi, M; Carbajo, S; Dax, A; Deng, YP; Dijkstal, P; Dunning, D; Gerber, S; Huppert, M; Neppl, S; Reiche, S; Schietinger, T; Thompson, N; Trisorio, A; Vicario, C; Zholents, A; Prat, E

PHYSICAL REVIEW LETTERS 135(26), 265001 (DEC 31 2025)
https://doi.org/10.1103/wn8d-l7sh

X-ray free-electron lasers (FELs) are powerful photon sources offering a wide wavelength range, subfemtosecond pulse duration, and high brightness. Most x-ray FELs are based on self-amplified spontaneous emission (SASE). SASE-FEL radiation has excellent transverse but only limited longitudinal coherence, with power and spectral profiles consisting of multiple randomly distributed spikes. In this Letter, we present the first experimental demonstration of mode-locked SASE, which generates periodic trains of phase-locked subfemtosecond pulses, thus providing an x-ray analog of the optical frequency comb. Our approach combines the mode-coupled SASE scheme, where magnetic chicanes between the undulator modules of the FEL increase the coherence of the output radiation, and an external optical laser that restricts the FEL amplification to periodic and short regions of the electron bunch. The work relies on evidence in the frequency and time domains for photons and electrons, respectively, and will benefit investigations of ultrafast dynamics as well as coherent spectroscopy, and enable new types of experiments requiring phase-correlated x-ray pulses.

Single Attosecond Extreme Ultraviolet Pulse Source via; Light-Wave-Controlled Relativistic Laser-Plasma Interaction: Thomson; Backscattering Scheme

Shirozhan, M; Quéré, F; Kahaly, S
ULTRAFAST SCIENCE 6, 0130 (JAN 7 2026)
https://doi.org/10.34133/ultrafastscience.0130

Reflecting light off a mirror moving near light speed offers a powerful method for generating bright, ultrashort pulses in the extreme ultraviolet range. Several investigations show that dense relativistic electron mirrors can be created by striking a nanometer-scale foil with a high-intensity, sharp-fronted laser pulse, forming a single relativistic electron sheet (RES). This RES coherently reflects and upshifts a counterpropagating laser beam from the infrared to the extreme ultraviolet with efficiency exceeding incoherent scattering by over several orders of magnitude. Here, we demonstrate that optimizing the drive laser waveform can reliably produce a single RES, leading to the generation of isolated attosecond pulses enhancing both the intensity and temporal compression of the back-reflected light in a controlled manner. Simulations reveal that tuning parameters like timing delay enables control over the amplitude, duration, and bandwidth of the resulting attosecond Thomson backscattering pulse. Together, these advances meet key experimental challenges and pave the way for compact, tunable sources of isolated attosecond pulses for probing ultrafast phenomena.

BEAMLINES & APPLICATIONS

FELs

Simulation study of energy chirp induced effects in; laser-wakefield-accelerator-driven free electron lasers

Teng, SY; Lau, WK; Chen, SH; Chiang, WY
NEW JOURNAL OF PHYSICS 28(1), 014301 (JAN 1 2026)
https://doi.org/10.1088/1367-2630/ae3206

Beam energy compression via chicane magnets has been proved to be an effective method to reduce the slice energy spread of electron beams generated by laser wakefield accelerators (LWFAs). This technique has been widely adopted by leading research teams in experiments targeting future compact, high-gain free electron lasers (FELs). However, after energy compression, a strong beam energy chirp is introduced into the electron beam, which substantially hinders the microbunching process and impairs spectral coherence. Here, we present a detailed, unaveraged three-dimensional simulation that examines the effects of this energy chirp, and the results can be applied to the design of a proposed LWFA-driven VUV FEL. The energy chirp in a LWFA-produced electron beam causes FEL interactions at multiple resonant frequencies across the entire electron bunch, simultaneously, which prevents sustained radiation power growth at the designed frequency along the undulator. Consequently, spectral purity is significantly degraded. Additionally, due to undulator dispersion, the energy chirp leads to an elongation of the bunch length, which increases microbunch separation. This results in a noticeable redshift in the radiation frequency and further disruption of spectral purity. These effects are compared to the ideal scenario in which the energy chirp is removed following energy compression. Simulation results indicate that the implementation of a beam dechirper is a crucial step for improving the saturation of radiation power. Insights gained from this simulation of energy chirp-induced mechanisms will aid in the development of more effective compensation strategies, ultimately optimizing LWFA-driven FEL designs.

LASER-MATERIALS & MANUFACTURING

Correlative microscopy and energy dispersive X-ray spectroscopy for; comprehensive surface characterization before and after laser treatment; of tungsten carbide-cobalt material

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Comprehensive correlative characterization of material surfaces is essential for understanding how certain treatments, such as laser treatments, can modify their properties and overall performance. This study employs a multi-modal correlative microscopy approach, combining Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Spectroscopy (EDX), Optical Microscopy (OM), Focus-Variation Optical Microscopy (F-V OM) and Atomic Force Microscopy (AFM) to characterize laser-textured Tungsten Carbide-Cobalt (WC-Co) surfaces. The characterization was carried out on the same area before and after pulsed laser treatment at ambient atmosphere. The experiments revealed the persistence of surface defects, presumably caused by Wire Electrical Discharge Machining (WEDM) during sample preparation, which were further accentuated by the subsequent laser treatment. In addition, significant and non-uniform surface oxidation was observed, with elevated levels on specific flanks of laser-ablated grooves. This analysis demonstrated that spatial property decoupling is key, as the maximum topographic height, nearing 7 mu m height from the lowest surface point, did not spatially coincide with the extremes of the chemical composition or total deformation curves. Specifically, point analysis showed that oxygen concentrations varied sharply, reaching 29.0 atomic oxygen percentage on high-deformation zones, contrasting with 21.2 at.% O found at adjacent low-deformation zones. Finally, the relationship among topography, chemical composition and nanomechanical properties was demonstrated, and the value of applying multi-modal correlative microscopy for

understanding laser-material interactions was underscored. The insights gained highlight the potential of the methodology for optimizing laser parameters to achieve targeted surface functionalities.

Effect of laser parameters on microstructural evaluation and wear; properties of A713-Al2O3-CaCO3 hybrid; composite processed by laser surface melting

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MATERIALS RESEARCH EXPRESS 13(1), 016505 (JAN 14 2026)
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The microstructural and wear behaviour of the stir cast A713-15wt-%Al2O3-5wt-%$CaCO_3$ aluminium hybrid composite processed using laser surface melting process was investigated. The A713 matrix reinforced with Al2O3 and CaCO3 was initially fabricated using stir casting process. The effects of laser beam power and scanning speed on the microstructure, hardness, and wear behaviour were studied in samples processed at a constant energy density. The investigation revealed superior wear resistance, with wear loss was reduced by 42% than that of as-cast A713-15wt-%Al2O3-5wt-%$CaCO_3$ aluminium hybrid composite. The maximum micro hardness of the laser treated sample was increased from 44 HV to 164 HV, which is 3.7 times than that of substrate material. As a results, wear rate was substantially reduced from 3.8 x 10(-3) mm(3) m(-1) to 1.2 x 10(-3) mm(3) m(-1). It was observed that shortest interaction time of 0.2 s during laser melting was most effective for achieving optimal grain refinement and improved wear resistance.

In-situ technique for absorptivity evaluation from surface temperature; measurements in direct laser metal deposition

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INTERNATIONAL JOURNAL OF ADVANCED MANUFACTURING TECHNOLOGY (JAN 6 2026)
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Direct Laser Metal Deposition (DLMD) is an additive manufacturing process in which a laser and metallic powder are used to build or repair metal components. The mechanical performance and microstructure of DLMD parts are governed by the thermal conditions during processing, which are commonly monitored using in-situ infrared pyrometers and thermal cameras to record surface temperature fields. Bulk temperature evolution and final material response can be predicted with thermal models that couple material properties, measured surface temperatures, and energy conservation. However, the reliability of these models strongly depends on accurate knowledge of the material's laser absorptivity. Absorptivity governs the interaction between the laser and the material, offering critical insight into the high-temperature, transient, and highly localized phenomena occurring near the laser spot. This work proposes novel in-situ technique for numerically estimating the material's absorptivity to the laser beam by using surface temperature data from the solid region of the substrate, where reliable calibration of the thermal-camera measurements is possible. In contrast to conventional approaches, the method does not rely on estimating the optical properties of the molten material. Instead, it exploits calibrated temperatures outside the melt pool, detailed knowledge of the thermal properties of the solid material, and the specific characteristics of Rosenthal's analytical approximation of the temperature field for a moving point heat source. The approach was validated using experimental surface temperature data acquired during the deposition of a nickel-based superalloy. The absorptivity values obtained using our method closely match those reported in the literature using established techniques.

Data-driven optimization of the quality and efficiency of silica glass; microchannels in femtosecond laser processing via Gaussian process; regression

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PRECISION ENGINEERING-JOURNAL OF THE INTERNATIONAL SOCIETIES FOR; PRECISION ENGINEERING AND NANOTECHNOLOGY 97, 828-838 (JAN 2026)
https://doi.org/10.1016/j.precisioneng.2025.11.002

Silica glass, renowned for its exceptional physical, chemical, and biocompatible properties, serves as a critical substrate for microfluidic devices. However, its inherent hardness and brittleness present significant challenges for achieving precise and efficient fabrication. Although femtosecond lasers offer remarkable advantages in precision machining, achieving simultaneous enhancements in machining quality and processing efficiency remains a complex challenge. This study introduces a data-driven framework that integrates a Gaussian Process Regression (GPR) model with an improved Non-dominated Sorting Genetic Algorithm II (NSGA-II) for the multiobjective optimization of femtosecond laser-based microchannel fabrication. The GPR model systematically captures the relationships between processing parameters, surface roughness (Sa), and material removal rate (MRR), effectively addressing nonlinear interactions during multi-pass scanning. The enhanced NSGA-II algorithm incorporates adaptive parameter adjustments and improved population diversity to robustly explore the solution space, enabling the identification of optimal trade-offs between surface quality and processing efficiency. Experimental validation of the optimization results reveals strong agreement between predicted and actual outcomes, demonstrating the framework's effectiveness in simultaneously minimizing surface roughness and maximizing material removal rate. This work underscores the potential of combining GPR and NSGA-II to optimize femtosecond laser micromachining, offering a robust methodology to significantly improve both the quality and efficiency of microfabrication processes.

Effects of laser scanning speeds on ablation mechanism occurred on; low-index lattice planes of single crystal diamond

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FUNCTIONAL DIAMOND 5(1), 2490141 (DEC 31 2025)
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The speed of laser scanning significantly influences the temporal and energetic distribution of the interaction between the laser and the material, thereby impacting both the material removal rate and processing quality. For the purposes of improving the laser machining efficiency on the (100), (110), and (111) low-index lattice planes of single crystal diamond, laser ablation experiments have been carried out under the laser scanning speeds of 10, 20, 30, 40, and 50 mm/s. The effects of laser scanning speed on the depth, width, material removal rate (MRR) and surface morphology of the ablation microgrooves have been investigated to reveal ablation mechanism of single crystal diamond with anisotropy performances. The experimental findings indicate that a high laser scanning speed leads to the formation of narrow and shallow microgrooves with a rougher edge and a low material removal rate, owing to combined effects of oxidation and graphitization occurred on the low-index lattice planes of single crystal diamond. Compared with the (110) and (111) lattice planes, the microgrooves on the (100) lattice plane exhibit a greater width, a less depth, a low depth-to-width ratio and a higher material removal rate, attributed to the small atomic planar density, large interplanar spacing, and small binding energy between the adjacent crystal planes. As the laser scanning speed reduce to 20 mm/s, the material removal rate on the (100), (110), and (111) low-index lattice

planes of single crystal diamond grow slowly, resulting from the progressively intensified plasma shielding effects during laser-material interaction.

Unravel melt pool and bubble dynamics during laser powder bed fusion of; polyamides using synchrotron X-ray imaging and process simulation

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VIRTUAL AND PHYSICAL PROTOTYPING 20(1), e2465905 (DEC 31 2025)
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Laser powder bed fusion (LPBF) of Polyamide 12 (PA12) using a near-infra-red (NIR) beam is largely unexplored; therefore, the beam-matter interaction, evolution mechanisms of the melt pool and defects remain unclear. Here, we employed a combination of in situ synchrotron X-ray imaging, ex situ materials characterisation techniques, and high-fidelity process simulations to study these behaviours during LPBF of PA12. Our results demonstrate that the NIR absorption of PA12 can be improved by 600 times through powder surface modification with C, P and Al species. In situ X-ray images reveal that the PA12 powders undergo melting, viscous merging, volume expansion, warping, solidification, and shrinkage before forming a solid track. Our results uncover the bubble evolution mechanisms during LPBF of PA12. During laser scanning, the high-energy laser beam produces organic substances/vapours which are trapped inside bubbles during viscous merging. These bubbles continue to shrink due to vapour condensation as the polymer cools under a cooling rate range of 200 - 600 K s-1. Using the collected data, we have developed a data-driven bubble shrinkage criterion to predict the bubble shrinkage coefficient using the bubble half-life, improving the build quality of LPBF polymeric parts.

Effect of Er:YAG Laser Irradiation on the Flexural Fatigue Strength of a; 4YSZ Ceramic

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JOURNAL OF BIOMEDICAL MATERIALS RESEARCH PART B-APPLIED BIOMATERIALS 114(1), e70028 (JAN 2 2026)
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This study aimed to evaluate the effect of Er:YAG laser surface treatment on the flexural fatigue strength of 4YSZ ceramics, with or without resin cement application. Disk-shaped zirconia ceramic specimens (Ø = 15 mm, thickness = 1.2 mm of IPS e.max ZirCAD MT BL) were prepared and randomly assigned to 10 groups based on two factors: "surface treatments" (Ctrl-, no surface treatment, only polished with silicon carbide [SiC] papers; Ctrl+, CAD/CAM simulation in the laboratory; AirAbr, air abrasion with alumina oxide; Laser, Er:YAG laser; and AirAbr + Laser, combination of air abrasion with alumina oxide + Er:YAG laser); and "resin cement" (with or without). Surface topography ($n = 2$), surface roughness ($n = 15$), and flexural fatigue strength were evaluated ($n = 15$). Specimens with resin cement were tested after 24 h of its application. Fractographic and topographic characteristics were qualitatively analyzed. Specific statistical tests ($\alpha = 0.05$) were applied for each outcome. Surface treatment ($F = 125.75$, $p < 0.001$), cement application ($F = 6.25$, $p = 0.014$) and their interaction ($F = 2.71$, $p = 0.033$) were statistically relevant for flexural fatigue outcomes. Ctrl- presented the highest performance, with or without resin cement. AirAbr showed better performance than Laser. Resin cement was relevant only when associated with AirAbr or Laser. Air abrasion notably improved flexural fatigue strength when combined with resin cement, whereas laser Er:YAG alone did not significantly enhance the results. None of the surface treatments, with or without cement application, replicated the flexural fatigue strength of a polished surface. There were no differences in roughness (Ra and Rz) seen among surface treated conditions, only Ctrl- was smoother ($p < 0.05$).

Dynamic simulation of the helium cryo-plant for the test facility of; Shanghai High repletion rate X-ray free electron laser and Extreme Light

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APPLIED THERMAL ENGINEERING 284, 129067 (JAN 30 2026)
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The helium cryo-plants at the hard X-ray free electron laser (XFEL) and Extreme Light (SHINE) facility test station operate under demanding variable conditions. To analyze their dynamic characteristics, develop robust control strategies, and ensure operational safety during extreme events, dynamic simulation technologies have been implemented. A comprehensive dynamic simulation model is established in EcosimPro software. Key equipment such as compressors, heat exchangers, valves, phase separators, and turbines are encompassed to the model. The actual control strategies from Programmable Logic Controllers (PLCs) are translated to EcosimPro language and implemented within Experiment blocks to control valve operations. The model was validated by simulating the cool-down process from 300 K to 4.5 K and comparing the results with experimental data. The analysis included investigating the reasons for trend changes in temperature, pressure, liquid level, and turbine speed profiles. Based on this, dynamic behavior under thermal shock and new control strategies are simulated, providing suggestions for optimizing the cryo-plant.

THEORY & SIMULATION

Full-fluid modelling of rotating plasma instabilities in Penning-like; configurations

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PLASMA SOURCES SCIENCE & TECHNOLOGY 35(1), 015007 (JAN 1 2026)
https://doi.org/10.1088/1361-6595/ae33ef

A novel time-dependent full-fluid 2D model of E x B discharges is presented. The model is based on the finite volume method with the addition of a threshold-based vacuum tracking algorithm. These tracking capabilities enable unprecedented fluid simulations of E x B plasma instabilities with near-vacuum regions. Two test cases are presented: the plasma layer (a semi-periodic domain resembling a hollow beam) and a square cross-section Penning-like discharge. In the two cases, an electron beam is injected into a background of neutrals, and ions are solely produced by impact ionisation. In both geometries, the simulations are performed from the limit of a pure electron plasma to a quasineutral plasma by increasing the background neutral density, showing a distinct transition from diocotron modes at low pressures to rotating spokes at high pressures. In line with theoretical and experimental results, the saturated regime of the diocotron mode results in the formation of electron vortices. The structure of the discharge in the different regimes is analysed, and the main spoke characteristics are assessed. In the square Penning configuration, the discharge transitions from vortices to the long-wavelength m = 1 rotating spoke. Finally, a variation of the square configuration is used to demonstrate the onset of the short-wavelength spiral structure observed in particle-in-cell simulations.

Accelerating kinetic plasma simulations with machine-learning-generated; initial conditions

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PHYSICS OF PLASMAS 33(1), 013902 (JAN 2026) https://doi.org/10.1063/5.0304576

Computational models of plasma technologies often solve for the system operating conditions by time-stepping an initial value problem to a quasi-steady solution. However, the strongly nonlinear and multi-timescale nature of plasma dynamics often necessitate millions, or even hundreds of millions, of steps to reach convergence, reducing the effectiveness of these simulations for computer-aided engineering. We consider acceleration of kinetic plasma simulations via data-driven machine-learning-generated initial conditions, which initialize the simulations close to their final quasi-steady-state, thereby reducing the number of steps to reach convergence. Three machine-learning models are developed to predict the density and ion kinetic profiles of capacitively coupled plasma discharges relevant to the microelectronics industry. The models are trained on kinetic simulations over a range of device operating frequencies and pressures. Best performance was observed when simulations were initialized with ion kinetic profiles generated by a convolutional neural network, reducing the mean number of steps to reach convergence by 17.1x when compared to initialization with a zero-dimensional global model. We also outline a workflow for continuous data-driven model improvement and simulation speedup, with the aim of generating sufficient data for full device digital twins.

EONet: a neural operator method for efficiently predicting the; electronic energy distribution function

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JOURNAL OF PHYSICS D-APPLIED PHYSICS 59(1), 015207 (JAN 9 2026)
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Electron energy distribution function (EEDF) is a critical descriptor of the electron energy characteristics in plasmas, directly governing the rates of core electron-impact reactions, such as excitation, ionization, and dissociation, thereby determining the chemical reactivity and energy efficiency of plasmas. However, the precise determination of the EEDF relies on solving the computationally intensive Boltzmann equation. While traditional numerical methods like Monte Carlo simulations are reliable, their high computational cost can limit their efficiency in some engineering applications. To address these limitations, we propose Electron energy distribution function Operator Network (EONet), a deep learning methodology. This approach employs a neural operator model to learn the mapping from the reduced electric field (E/N) to the function space of EEDF, enabling efficient prediction of the EEDF and addressing the computational limitations of traditional methods. An assessment of EONet is conducted, and the results showed that EONet not only can accurately predict EEDF, but also maintains a prediction error of less than 7 parts per thousand even when the input parameters are subjected to +/- 20% noise. Furthermore, after a brief pre-training phase, the model enables millisecond-level extrapolative prediction across multiple operating conditions, achieving an end-to-end computational speedup of approximately two orders of magnitude compared to Monte Carlo methods. This effectively resolves the efficiency bottleneck associated with repetitive computations in multi-parameter scenarios. This method is readily generalizable to other engineering problems characterized by prohibitively expensive data acquisition or computationally intensive simulations, thereby offering a novel efficient solution to this class of challenges.

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