THE EuPRAXIA FILES

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FOREWORD

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

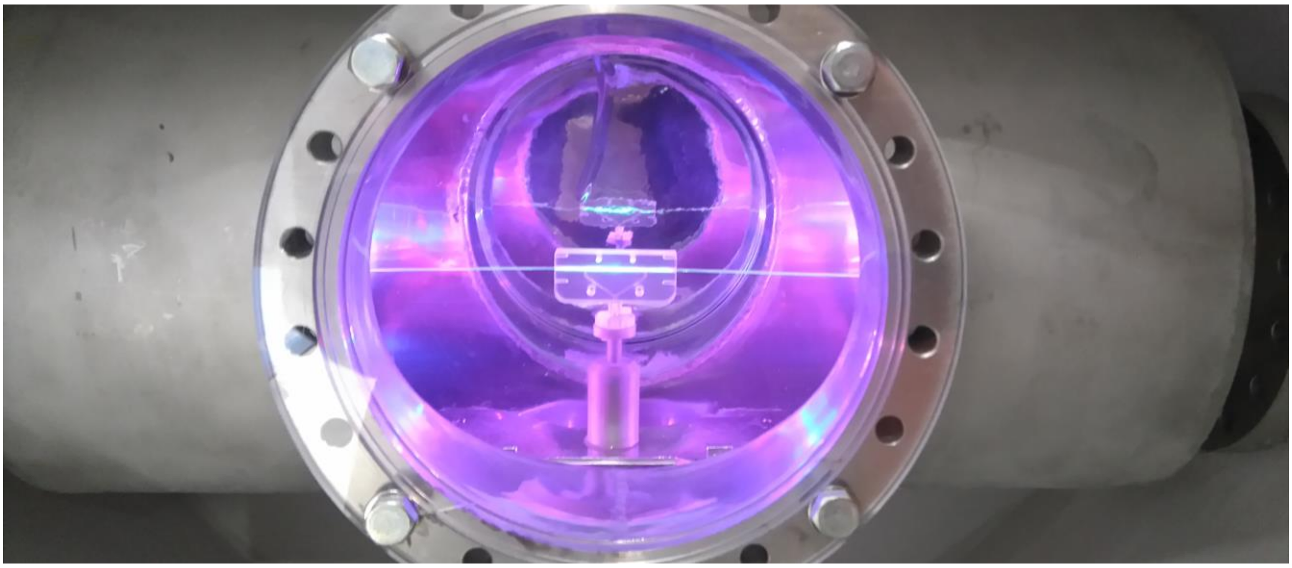
The EuPRAXIA Preparatory Phase grant has turned mid-way of work last November, and a bit less than two years are ahead to the Consortium to set-up the ESFRI Research Infrastructure. Several challenges must be still tackled, and among them, the nearest one is the choice of the second site, the Laser-driven one. A dedicated expert panel is working on it, and three sites have shown interest in becoming hosting lab. A decision will be taken by the end of March.

Once again, The EuPRAXIA files show us how deep is the worldwide interest in novel technologies of acceleration, based on plasma. EuPRAXIA teams represent more and more a substantial part of R&D efforts.

I wish you an interesting reading,

Pierluigi Campana, *EuPRAXIA-PP Coordinator*

CONTENTS



FUNDAMENTALS

Matched Guiding and Controlled Injection in Dark-Current-Free, 10-GeV-Class, Channel-Guided Laser-Plasma Accelerators

Picksley, A.; Stackhouse, J.; Benedetti, C.; Nakamura, K.; Tsai, H. E.; Li, R.; Miao, B.; Shrock, J. E.; Rockafellow, E.; Milchberg, H. M.; Schroeder, C. B.; van Tilborg, J.; Esarey, E.; Geddes, C. G. R.; Gonsalves, A. J.
PHYSICAL REVIEW LETTERS 133(25), 255001 (DEC 2024)
https://doi.org/10.1103/PhysRevLett.133.255001

We measure the high-intensity laser propagation throughout meter-scale, channel-guided laser-plasma accelerators by adjusting the length of the plasma channel on a shot-by-shot basis, showing high-quality guiding of 500 TW laser pulses over 30 cm in a hydrogen plasma of density $n_0 \approx 1x10^{17}$ cm^{-3}. We observed transverse energy transport of higher-order modes in the first ≈ 12 cm of the plasma channel, followed by quasimatched propagation, and the gradual, dark-current-free depletion of laser energy to the wake. We quantify the laser-to-wake transfer efficiency limitations of currently available petawatt-class lasers and demonstrate via simulation how control over the laser mode can significantly improve beam parameters. Using 21.3 J of laser energy, and triggering localized electron injection, we observed electron bunches with single, quasimonoenergetic peaks up to 9.2 GeV with charge extending beyond 10 GeV.

Laser Wakefield Acceleration of Ions with a Transverse Flying Focus

Gong, Zheng; Cao, Sida; Palastro, John P.; Edwards, Matthew R.
PHYSICAL REVIEW LETTERS 133(26), 265002 (DEC 2024)
https://doi.org/10.1103/PhysRevLett.133.265002

The extreme electric fields created in high-intensity laser-plasma interactions could generate energetic ions far more compactly than traditional accelerators. Despite this promise, laser-plasma accelerator experiments have been limited to maximum ion energies of 100 MeV/nucleon. The central challenge is the low charge-to-mass ratio of ions, which has precluded one of the most successful approaches used for electrons: laser wakefield acceleration. Here, we show that a laser pulse with a focal spot that moves transverse to the laser propagation direction enables wakefield acceleration of ions to GeV energies in underdense plasma. Three-dimensional particle-in-cell simulations demonstrate that this relativistic-intensity "transverse flying focus" can trap ions in a comoving electrostatic pocket, producing a monoenergetic collimated ion beam. With a peak intensity of 10^{20} W/cm^2 and an acceleration distance of 0.44 cm, we observe a proton beam with 23.1 pC charge, 1.6 GeV peak energy, and 3.7% relative energy spread. This approach allows for compact high-repetition-rate production of high-energy ions, highlighting the capability of more generalized spatiotemporal pulse shaping to address open problems in plasma physics.

Energy depletion and re-acceleration of driver electrons in a plasma-wakefield accelerator

Pena, F.; Lindstrom, C. A.; Beinortaite, J.; Svensson, J. Bjoerklund; Boulton, L.; Diederichs, S.; Foster, B.; Garland, J. M.; Caminal, P. Gonzalez; Loisch, G.; Schroeder, S.; Thevenet, M.; Wesch, S.; Wood, J. C.; Osterhoff, J.; D'Arcy, R.
PHYSICAL REVIEW RESEARCH 6(4), 043090 (NOV 2024)
https://doi.org/10.1103/PhysRevResearch.6.043090

For plasma-wakefield accelerators to fulfill their potential for cost effectiveness, it is essential that their energy-transfer efficiency be maximized. A key aspect of this efficiency is the near-complete transfer of energy, or depletion, from the driver electrons to the plasma wake. Achieving full depletion is limited by the

process of re-acceleration, which occurs when the driver electrons decelerate to nonrelativistic energies, slipping backward into the accelerating phase of the wakefield and being subsequently re-accelerated. Such re-acceleration is unambiguously observed here for the first time. At this re-acceleration limit, we measure abeam driver depositing (57 +/- 3)% of its energy into a 195-mm-long plasma. This suggests that the energy-transfer efficiency of plasma accelerators could approach that of conventional accelerators.

Optical ionization effects in kHz laser wakefield acceleration with few-cycle pulses

Monzac, J.; Smartsev, S.; Huijts, J.; Rovige, L.; Andriyash, I. A.; Vernier, A.; Tomkus, V.; Girdauskas, V.; Raciukaitis, G.; Stankevic, V.; Cavagna, A.; Kaur, J.; Kalouguine, A.; Lopez-Martens, R.; Faure, J.
PHYSICAL REVIEW RESEARCH 6(4), 043099 (NOV 2024)
https://doi.org/10.1103/PhysRevResearch.6.043099

We present significant advances in laser wakefield acceleration (LWFA) operating at a 1 kHz repetition rate, employing a sub-TW, few-femtosecond laser and a continuously flowing hydrogen gas target. We conducted a comprehensive study assessing how the nature of the gas within the target influences accelerator performance. This work confirms and elucidates the superior performance of hydrogen in LWFA driven by few-cycle, low-energy laser pulses. Our system generates quasimonoenergetic electron bunches with energies up to 10 MeV, bunch charges of 2 pC, and angular divergences of 15 mrad. Notably, our scheme relying on differential pumping enables continuous operation at kHz repetition rates, contrasting with previous systems that operated in burst mode to achieve similar beam properties. Particle-in-cell simulations explain hydrogen's superior performances: the ionization effects in nitrogen and helium distort the laser pulse, negatively impacting the accelerator performance. These effects are strongly mitigated in hydrogen plasma, thereby enhancing beam quality. This analysis represents a significant step forward in optimizing and understanding kHz LWFA. It underscores the critical role of hydrogen and the imperative need to develop hydrogen-compatible target systems capable of managing high repetition rates, as exemplified by our differential pumping system. These advances lay the groundwork for further developments in high-repetition-rate laser plasma accelerator technology.

Efficient laser wakefield accelerator in pump depletion dominated bubble regime

Horny, V.; Bleotu, P. G.; Ursescu, D.; Malka, V.; Tomassini, P.
PHYSICAL REVIEW E 110(3), 035202 (SEP 2024)
https://doi.org/10.1103/PhysRevE.110.035202

With the usage of the postcompression technique, few-cycle joule-class laser pulses are nowadays available extending the state of the art of 100 TW-class laser working at 10 Hz repetition. In this Letter, we explore the potential of wakefield acceleration when driven with such pulses. The numerical modeling predicts that 50% of the laser pulse energy can be transferred into electrons with energy above 15 MeV, and with charge exceeding several nanocoulombs for the electrons at hundreds of MeV energy. In such a regime, the laser pulse depletes its energy to plasma rapidly driving a strong cavitated wakefield. The self-steepening effect induces a continuous prolongation of a bubble resulting in a massive continuous self-injection that explains the extremely high charge of the beam rending this approach suitable for promoting Bremsstrahlung emitter and generator of tertiary particles, including neutrons released through photonuclear reactions.

Wakefield-driven filamentation of warm beams in plasma

Walter, Erwin; Farmer, John P.; Weidl, Martin S.; Pukhov, Alexander; Jenko, Frank
PHYSICAL REVIEW E 110(3), 035208 (SEP 2024)
https://doi.org/10.1103/PhysRevE.110.035208

Charged and quasineutral beams propagating through an unmagnetized plasma are subject to numerous collisionless instabilities on the small scale of the plasma skin depth. The electrostatic two-stream instability, driven by longitudinal and transverse wakefields, dominates for dilute beams. This leads to modulation of the beam along the propagation direction and, for wide beams, transverse filamentation. A three-dimensional spatiotemporal two-stream theory for warm beams with a finite extent is developed. Unlike the cold beam limit, diffusion due to a finite emittance gives rise to a dominant wave number and a cutoff wave number above which filamentation is suppressed. Particle-in-cell simulations with quasineutral electron-positron beams in the relativistic regime give excellent agreement with the theoretical model. This paper provides deeper insights into the effect of diffusion on filamentation of finite beams, crucial for comprehending plasma-based accelerators in laboratory and cosmic settings.

Coherent high-harmonic generation with laser-plasma beams

Antipov, S. A.; Agapov, I.; Brinkmann, R.; Pousa, A. Ferran; de la Ossa, A. Martinez; Schneidmiller, E. A.; Thevenet, M.
PHYSICAL REVIEW ACCELERATORS AND BEAMS 27(10), 100704 (OCT 2024)
https://doi.org/10.1103/PhysRevAccelBeams.27.100704

Active energy compression scheme is presently being investigated for future laser-plasma accelerators. This method enables generating laser-plasma accelerator electron beams with a small, 10^{-5}, relative slice energy spread. When modulated by a laser pulse, such beams can produce coherent radiation at very high, 100th harmonics of the modulation laser wavelength, which are hard to access by conventional techniques. The scheme has a potential of providing additional capabilities for future plasma-based facilities by generating stable, tunable, narrow-band radiation.

Self-consistent effects in the ponderomotive acceleration of electron beams

Almansa, I.; Russman, F.; Peter, E.; Marini, S.; Rizzato, F. B.
JOURNAL OF PLASMA PHYSICS 90(4), 905900413 (SEP 2024)
https://doi.org/10.1017/S0022377824000758

In the present work, we extend the results of a previous investigation on the dynamics of electrons under the action of an inverse free-electron-laser scheme (Almansa *et al.*, Phys. Plasmas, vol. 26, 2019, 033105). While the former work examined electrons as single test particles subject to the combined action of a modulated wiggler plus a laser field, we now look at electrons as composing a particle beam, where collective space-charge effects are relevant and included in the analysis. Our previous work showed that effective acceleration is achieved when the initial velocities of the particles are close enough to the phase velocity of the beat-wave mode formed by the laser and the wiggler fields. Electrons are then initially accelerated by a ponderomotive uphill effect generated by the beat mode and, once reaching the phase velocity of the beat, undergo a final strong resonant acceleration step resembling a catapult effect. The present work shows that, under proper conditions, space-charge effects play a similar role as the initial (or injected) velocity of the beam. Even if acceleration is absent when space charge is neglected, it may be present and effective when charge effects are taken into account. We also discuss how far the space charge can grow without affecting the sustainability of the acceleration process.

Electron Acceleration in Nitrogen Clusters by Terawatt Femtosecond Laser

Nazarov, M. M.; Semenov, T. A.; Tausenev, A. A.; Chaschin, M. V.; Shcheglov, P. A.; Lazarev, A. V.; Sidorov-Biryukov, D. A.; Mitrofanov, A. V.; Gordienko, V. M.; Panchenko, V. Ya.
JETP LETTERS 120(7), 470-476 (OCT 2024)
https://doi.org/10.1134/S0021364024601957

Narrowly divergent high-energy electron beam is experimentally demonstrated during the interaction of terawatt Ti:Sa laser radiation with a nitrogen gas-cluster jet at gas pressure corresponding to the boundary of the condensation region. A collimated electron beam with an energy of up to 10 MeV and a divergence of 10 mrad at a plasma concentration of $\sim 10^{19}$ cm^{-3} is obtained. The use of nitrogen instead of argon or krypton significantly improves the spatial (divergence) and energy (charge and spectrum shape) properties of the generated electron beam. The formation of clusters in a supersonic jet is observed and their composition is thermodynamically analyzed.

Direct laser acceleration in varying plasma density profiles

Babjak, R.; Martinez, B.; Krus, M.; Vranic, M.
NEW JOURNAL OF PHYSICS 26(9), 093002 (SEP 2024)
https://doi.org/10.1088/1367-2630/ad7280

Direct laser acceleration has proven to be an efficient source of high-charge electron bunches and high brilliance x-rays. However, an analytical description of the acceleration in the interaction with varying plasma density targets is still missing. Here, we provide an analytical estimate of the maximum energies that electrons can achieve in such a case. We demonstrate that the maximum energy depends on the local electron properties at the moment when the electron fulfills the resonant condition at the beginning of the acceleration. This knowledge enables density shaping for various purposes. One application is to decrease the required acceleration distance needed to achieve the maximum electron energy. Another use for density tailoring is to achieve acceleration beyond the radiation reaction limit. We derive the energy scaling law that is valid for arbitrary density profile that varies slowly compared with the betatron period. Our results can be applied to electron heating in exponential preplasma of thin foils, ablating plasma plumes, or gas jets with long-scale ramp-up.

Direct Acceleration of an Electron Beam with a Radially Polarized Long-Wave Infrared Laser

Li, William H.; Pogorelsky, Igor V.; Palmer, Mark A.
PHOTONICS 11(11), 1066 (NOV 2024)
https://doi.org/10.3390/photonics11111066

Direct laser acceleration with radially polarized lasers is an intriguing variant of laser-based particle acceleration that has the potential of offering GeV/cm-level energy while avoiding the instabilities and complex beam dynamics associated with plasma wakefield accelerators. A major limiting factor is the difficulty of generating high-power radially polarized beams. In this paper, we propose the use of CO_2-based long-wave infrared (LWIR) lasers as a driver for direct laser acceleration, as the polarization insensitivity of the gain medium allows a radially polarized beam to be amplified. Additionally, the larger waist sizes, Rayleigh lengths, and pulse lengths associated with the long wavelength could improve the injection efficiency of the electron beam. By comparing acceleration simulations using a near-infrared laser and an LWIR laser, we show that the injection efficiency is indeed improved by up to an order of magnitude with the longer wavelength. Furthermore, we show that even sub-TW peak powers with an LWIR laser can provide MeV-level energy gains. Thus, radially polarized LWIR lasers show significant promise as a driver of a direct laser-driven demonstration accelerator.

Coherent Control of Relativistic Electron Dynamics in Plasma Nanophotonics

Dulat, Ankit; Rakeeb, S. K.; Dam, Sagar; Lad, Amit D.; Ved, Yash M.; Kruk, Sergey; Kumar, G. Ravindra
LASER & PHOTONICS REVIEWS 2401570 (NOV 2024)
https://doi.org/10.1002/lpor.202401570

Intense femtosecond laser pulses interacting with solids can drive electrons to relativistic energies, enabling miniaturized particle accelerators and bright extreme-UV light sources. In-situ space-time control of these electrons is crucial for developing next-generation laser-based accelerators but remains extremely challenging. A novel approach is presented to achieve such control by manipulating the local fields driving these electrons using a nanoengineered dielectric nanopillar target. Via experiments and simulations, it is demonstrated that this sub-femtosecond and nanometer-scale control enables enhanced electron acceleration and control of the directionality of relativistic electrons over a wide angular range and predicts the coherent formation of sub-femtosecond electron bunches from the nanopillars. This research bridges nanophotonics and strong-field plasma physics, offering new opportunities for in-situ control of high-energy particles and advancements in plasma technology.

Summary of Working Group 1: Laser-driven plasma wakefield acceleration

Lehe, R.; Miao, B.; Shrock, J. E.; Hidding, B.
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH SECTION A-ACCELERATORS SPECTROMETERS DETECTORS AND ASSOCIATED EQUIPMENT 1072, 170133 (MAR 2025)
https://doi.org/10.1016/j.nima.2024.170133

Working Group 1 discussed progress and advanced concepts in laser-driven wakefield acceleration (LWFA). LWFA technology has potential applications for e.g., future TeV-scale colliders, as well as compact high-energy light sources (e.g. plasma-based FEL). This working group included presentations of experimental, simulation, and theoretical results towards improving the performance of LWFA for these and other applications.

Summary of Working Group 2: Laser-driven plasma acceleration of ions

Kemp, Andreas; Palmer, Charlotte
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH SECTION A-ACCELERATORS SPECTROMETERS DETECTORS AND ASSOCIATED EQUIPMENT 1072, 170156 (MAR 2025)
https://doi.org/10.1016/j.nima.2024.170156

This article summarizes contributions in WG2 (Laser-driven plasma acceleration of ions) made at AAC24. Topics include advancing the maximum proton energy beyond 100 MeV; repetition rate, innovative targets; and characterisation and improvement of shot-to-shot stability, beam quality, and conversion efficiency. Applications of interest for ion beams presented at AAC24 include radiobiology, materials science, fundamental physics, and fast-ignition inertial confinement fusion (ICF).

Summary of Working Group 3: Beam-driven plasma acceleration

O'Shea, Brendan; Muggli, Patric
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH SECTION A-ACCELERATORS SPECTROMETERS DETECTORS AND ASSOCIATED EQUIPMENT 1072, 170130 (MAR 2025)
https://doi.org/10.1016/j.nima.2024.170130

We briefly summarize presentations that were made in the four sessions of the working group on beam-driven plasma acceleration (WG 3) that spanned over six hours.

PLASMA TECHNOLOGY, TARGETS & DIAGNOSTICS

Experimental Demonstration of an Emittance-Preserving Beam Energy Dechirper Using a Hollow Channel Plasma

Liu, Shuang; Li, Fei; Du, Yingchao; Peng, Bo; Fang, Yu; Ning, Xiaonan; Zhang, Tianliang; Chen, Jiucheng; Song, Zhi; Xiao, Hengyuan; Zhou, Linyi; Zhou, Bing; Hua, Jianfei; Lu, Wei
PHYSICAL REVIEW LETTERS 133(17), 175001 (OCT 2024)
https://doi.org/10.1103/PhysRevLett.133.175001

Plasma-based acceleration has emerged as a highly promising candidate for future colliders and compact x-ray free electron lasers owing to its capability to efficiently accelerate electron and positron beams with high brightness over short distances. However, a major obstacle to its application in free electron lasers and colliders is the imposition of a substantial energy chirp on the output beams, resulting from the longitudinally dependent acceleration field. This Letter presents the first experimental demonstration of a beam energy dechirper using a hollow plasma channel. This novel approach simultaneously enables the mitigation of energy chirp and preservation of beam emittance. Experimental results demonstrate a substantial reduction in energy spread by nearly 1 order of magnitude (from 0.93% to 0.11% FWHM), while maintaining a negligible increase in emittance. Simulation suggests that the corrected energy spread may have been reduced to 10 keV (0.025%), thereby meeting the stringent requirement of colliders or x-ray free electron lasers.

Development of an ultrathin liquid sheet target for laser ion acceleration at high repetition rates in the kilohertz range

M. Füle, A. P. Kovács, T. Gilinger, M. Karnok, P. Gaál, S. Figul, G. Marowsky, and K. Osvay
HIGH POWER LASER SCIENCE AND ENGINEERING 12, E37 (2024)
https://doi.org/10.1017/hpl.2024.19

A colliding microjet liquid sheet target system was developed and tested for pairs of round nozzles of 10, 11 and 18 µm in diameter. The sheet’s position stability was found to be better than a few micrometers. Upon interaction with 50 mJ laser pulses, the 18 µm jet has a resonance amplitude of 16 µm at a repetition rate of 33 Hz, while towards 100 Hz it converges to 10 µm for all nozzles. A white-light interferometric system was developed to measure the liquid sheet thickness in the target chamber both in air and in vacuum, with a measurement range of 182 nm – 1 µm and an accuracy of ±3%. The overall shape and 3D shape of the sheet follow the Hasson–Peck model in air. In vacuum versus air, the sheet gradually loses 10% of its thickness, so the thinnest sheet achieved was below 200 nm at a vacuum level of 10^{-4} mbar, and remained stable for several hours of operation.

Laser interactions with gas jets: electromagnetic pulse emission and nozzle damage

Bradford, P. W.; Ospina-Bohorquez, V.; Ehret, M.; Henares, J.L.; Puyuelo-Valdes, P.; Chodukowski, T.; Pisarczyk, T.; Rusiniak, Z.; Salgado-Lopez, C.; Vlachos, C.; Sciscio, M.; Salvadori, M.; Verona, C.; Hicks, G. S.; Ettlinger, O. C.; Najmudin, Z.; Marques, J.R.; Gremillet, L.; Santos, J. J.; Consoli, F.; Tikhonchuk, V. T.
HIGH POWER LASER SCIENCE AND ENGINEERING 12, e98 (JAN 2025)
https://doi.org/10.1017/hpl.2024.73

Understanding the physics of electromagnetic pulse (EMP) emission and nozzle damage is critical for the long-term operation of laser experiments with gas targets, particularly at facilities looking to produce stable sources of radiation at high repetition rates. We present a theoretical model of plasma formation and electrostatic charging when high-power lasers are focused inside gases. The model can be used to estimate the amplitude of gigahertz EMPs produced by the laser and the extent of damage to the gas jet nozzle. Looking at a range of laser and target properties relevant to existing high-power laser systems, we find that EMP fields of tens to hundreds of kV/m can be generated several metres from the gas jet. Model predictions are compared with measurements of EMPs, plasma formation and nozzle damage from two experiments on the VEGA-3 laser and one experiment on the Vulcan Petawatt laser.

Target sensitivity study of density transition-injected electrons in laser wakefield accelerators

Cobo, C. C.; Arran, C.; Bourgeois, N.; Calvin, L.; Carderelli, J.; Cavanagh, N.; Colgan, C.; Dann, S. J. D.; Fitzgarrald, R.; Gerstmayr, E.; Kettle, B.; Los, E. E.; Mangles, S. P. D.; Mckenna, P.; Najmudin, Z.; Rajeev, P. P.; Ridgers, C. P.; Sarri, G.; Streeter, M. J. V.; Symes, D. R.; Thomas, A. G. R.; Watt, R.; Murphy, C. D.
PHYSICAL REVIEW ACCELERATORS AND BEAMS 27(11), 111301 (NOV 2024)
https://doi.org/10.1103/PhysRevAccelBeams.27.111301

While plasma-based accelerators have the potential to positively impact a broad range of research topics, a route to application will only be possible through improved understanding of their stability. We present experimental results of a laser wakefield accelerator in the nonlinear regime in a helium gas jet target with a density transition produced by a razor blade in the flow. Modifications to the target setup are correlated with variations in the plasma density profile diagnosed via interferometry and the shot-to-shot variations of the density profile for nominally equal conditions are characterized. Through an in-depth sensitivity study using particle-in-cell simulations, the effects of changes in the plasma density profile on the accelerated electron beams are investigated. The results suggest that blade motion is more detrimental to stability than gas pressure fluctuations, and that early focusing of the laser may reduce the deleterious effects of such density fluctuations.

Implementation of a single-shot metrology system for a TW-class laser in a particle accelerator facility

Rondepierre, Alexandre; Espinos, Driss Oumbarek; Jin, Zhan; Hosokai, Tomonao
OPTICS AND LASER TECHNOLOGY 180, 111523 (JAN 2025)
https://doi.org/10.1016/j.optlastec.2024.111523

Electron generation from a laser-plasma accelerator (LPA) requires a good knowledge of the laser beam delivered on target, as many parameters are involved and represents a complex non-linear system. The next step towards a high repetition rate generation of stable and high-quality electron beams also requires to measure and monitor in real time and in single-shot the laser parameters, which may be a tough task for fs high-power laser systems. In this article, conducted at the LAPLACIAN LPA facility, we propose a simple way to measure all important laser parameters in real time without disturbing the main beam delivered on target, while ensuring to thwart intrinsic issues such as aberrations and dispersion. The beam leakage from the last mirror, just after the focusing optics, is used and sent towards a dedicated setup where, mainly, the energy, the pulse duration, the FF and NF profile (implying beam pointing and size), the spectrum and the M^2 are measured. A prismatic blade has been designed to compensate aberrations introduced during the leakage process, and also chirped mirrors are used to compensate the dispersion. This real-time laser metrology system is fully operational to monitor what is reaching the target, and it should help in the future to have a better understanding on the electron beam generation and its instabilities.

Characterization of kHz Repetition Rate Laser-Driven Electron Beams by an Inhomogeneous Field Dipole Magnet Spectrometer

Zymak, Illia; Favetta, Marco; Grittani, Gabriele Maria; Lazzarini, Carlo Maria; Tassielli, Gianfranco; Grenfell, Annika; Goncalves, Leonardo; Lorenz, Sebastian; Slukova, Vanda; Vitha, Filip; Versaci, Roberto; Chacon-Golcher, Edwin; Nevrkla, Michal; Sisma, Jiri; Antipenkov, Roman; Sobr, Vaclav; Szuba, Wojciech; Staufer, Theresa; Gruener, Florian; Lapadula, Loredana; Ranieri, Ezio; Piombino, Michele; Hafz, Nasr A. M.; Kamperidis, Christos; Papp, Daniel; Mondal, Sudipta; Bakule, Pavel; Bulanov, Sergei V.
PHOTONICS 11(12), 1208 (DEC 2024)
https://doi.org/10.3390/photonics11121208

We demonstrate a method to characterize the beam energy, transverse profile, charge, and dose of a pulsed electron beam generated by a 1 kHz TW laser-plasma accelerator. The method is based on imaging with a scintillating screen in an inhomogeneous, orthogonal magnetic field produced by a wide-gap magnetic dipole. Numerical simulations were developed to reconstruct the electron beam parameters accurately. The method has been experimentally verified and calibrated using a medical LINAC. The energy measurement accuracy in the 6-20 MeV range is proven to be better than 10%. The radiation dose has been calibrated by a water-equivalent phantom, RW3, showing a linear response of the method within 2% in the 0.05-0.5 mGy/pulse range.

PIC Simulation of Enhanced Electron Acceleration in a Double Nozzle Gas Target Using Spatial-Temporal Coupling with Axiparabola Optics

Girdauskas, Valdas; Tomkus, Vidmantas; Abedi-Varaki, Mehdi; Raciukaitis, Gediminas
APPLIED SCIENCES-BASEL 14(22), 10611 (NOV 2024)
https://doi.org/10.3390/app142210611

In this paper, the results of a Particle-in-Cell (PIC) simulation of electrons accelerated using a 10 fs Top-hat (TH) beam with a limited pulse energy of 85 mJ, focused on a double nozzle gas target using an off-axis parabola (OAP), an axiparabola (AXP), and an axiparabola with additional spatial-temporal coupling (AXP+STC), are discussed. The energy of accelerated electrons was predominantly determined through self-focusing and the ionisation injection effects of the laser beam propagating in plasma. The maximal energy of electrons accelerated using an AXP+STC could be higher by 12% compared to the energy of electrons accelerated by the regular OAP.

Effect of dielectric wakefields in a capillary discharge for plasma wakefield acceleration

Verra, L.; Galletti, M.; Pompili, R.; Biagioni, A.; Carillo, M.; Cianchi, A.; Crincoli, L.; Curcio, A.; Demurtas, F.; Di Pirro, G.; Lollo, V.; Parise, G.; Pellegrini, D.; Romeo, S.; Silvi, G. J.; Villa, F.; Ferrario, M.
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH SECTION A-ACCELERATORS SPECTROMETERS DETECTORS AND ASSOCIATED EQUIPMENT 1072, 170157 (MAR 2025)
https://doi.org/10.1016/j.nima.2024.170157

Dielectric capillaries are widely used to generate plasmas for plasma wakefield acceleration. When a relativistic drive bunch travels through a capillary with misaligned trajectory with respect to the capillary axis, it is deflected by the effect of the dielectric transverse wakefields it drives. We experimentally show that the deflection effect increases along the bunch and with larger misalignment, and we investigate the decay of dielectric wakefields by measuring the effect on the front of a trailing bunch. We discuss the implications for the design of a plasma wakefield accelerator based on dielectric capillaries.

Compact laser wakefield acceleration toward high energy with micro-plasma parabola

Geng, Xuesong; Xu, Tongjun; Zhang, Lingang; Kostyukov, Igor; Pukhov, Alexander; Shen, Baifei; Ji, Liangliang
MATTER AND RADIATION AT EXTREMES 9(6), 067203 (NOV 2024)
https://doi.org/10.1063/5.0202964

Laser wakefield acceleration (LWFA) promises compact accelerators toward the high-energy frontier. However, the approach to the 100 GeV milestone faces the obstacle of the long focal length required for optimal acceleration with high-power lasers, which reaches hundreds of meters for 10-100 PW lasers. The long focal length originates from optimal laser intensity required to avoid nonlinear effects and hence large spot size and Rayleigh length. We propose a "telescope" geometry in which a micro-plasma parabola (MPP) is coupled with a short-focal-length off-axis parabola, minimizing the focal length to the meter range for LWFA under optimized conditions driven by lasers beyond 1 PW. Full-dimensional kinetic simulations demonstrate the generation of a 9 GeV electron bunch within only 1 m optical length-only one-tenth of that required with the conventional approach with the same performance. The proposed MPP provides a basis for the construction of compact LWFAs toward single-stage 100 GeV acceleration with 100 PW class lasers.

Combined plasma lens and rephasing stage for a laser wakefield accelerator

Gustafsson, Cornelia; Lofquist, Erik; Svendsen, Kristoffer; Angella, Andrea; Persson, Anders; Lundh, Olle
SCIENTIFIC REPORTS 14(1), 26286 (NOV 2024)
https://doi.org/10.1038/s41598-024-78143-6

Electrons from a laser wakefield accelerator have a limited energy gain due to dephasing and are prone to emittance growth, causing a large divergence. In this paper, we experimentally show that adjusting the plasma density profile can address both issues. Shock-assisted ionisation injection is used to produce 100 MeV quasi-monoenergetic electron bunches in the primary part of the accelerator. Downstream from the accelerator, a second, independently tuneable density region is added, which can be used to either boost the energy of the electron bunches or as a plasma lens for significant divergence reduction. An additional energy gain of 25% and a 40% divergence reduction are obtained. Theoretical models validate the effects.

Oscillation damper for misaligned witness in plasma wakefield accelerator

Lotov, Konstantin V.; Kargapolov, Ivan Yu.; Tuev, Petr V.
PHYSICS OF PLASMAS 31(12), 123103 (DEC 2024)
https://doi.org/10.1063/5.0239380

If a laser- or particle beam-driven plasma wakefield accelerator operates in the linear or moderately nonlinear regime, injecting an externally produced particle bunch (witness) to be accelerated may encounter an alignment problem. Witness alignment tolerances can be relaxed by using a damper, an additional particle bunch produced by the same injector and propagating at a submillimeter distance ahead of the witness. If misaligned, the damper perturbs the wakefield in such a way that the witness shifts on-axis with no quality loss.

LASERS & OPTICS

Design of very-large area photonic crystal surface emitting lasers with an all-semiconductor photonic crystal

King, Ben; Wenzel, Hans; Kuhn, Eduard; Radziunas, Mindaugas; Crump, Paul
OPTICS EXPRESS 32(25), 44945-44957 (DEC 2024)
https://doi.org/10.1364/OE.537452

We report on the design of a photonic crystal surface emitting laser (PCSEL) with an all-semiconductor (InGaP/GaAs) photonic crystal suitable for very-large-area emission and high-power operation. Using coupled-wave theory for PCSELs we model infinite- and finite-size cavity PCSELs and show that a photonic crystal unit cell with square lattice periodicity and a rotated and stretched triangular feature is suitable for the realization of PCSELs with very large areas (1 mm < *L* < 3 mm for a square cavity of size *L* x *L*) while maintaining high mode discrimination between the fundamental laser mode and higher order cavity modes as well as high external efficiency. This was achieved by exploiting a single-lattice photonic crystal unit cell design that minimizes one-dimensional coupling in the photonic crystal, providing a promising alternative to double-lattice PCSELs.

Compression of high-power laser pulse leads to increase of electron acceleration efficiency

Vais, O. E.; Lobok, M. G.; Bychenkov, V. Yu.
PHYSICAL REVIEW E 110(6), 065202 (DEC 2024)
https://doi.org/10.1103/PhysRevE.110.065202

Propagation of ultrarelativistically intense laser pulses in a self-trapping mode in a near critical density plasma makes it possible to produce electron bunches of extreme parameters appropriate for different state of the art applications. Based on three-dimensional particle-in-cell (PIC) simulations, it has been demonstrated how the best efficiency of electron acceleration in terms of the total charge of high-energy electrons and laser-to-electron conversion rate can be achieved. For a given laser pulse energy the universal way is a proper matching of laser hot spot size and electron plasma density to the laser pulse duration. The recommendation to achieve the highest yield of high-energy electrons is to compress the laser pulse as much as possible. As an example, compression of a pulse of a few tens of femtoseconds to the ∼ 10 fs pulse leads to generation of the high-energy electron bunch with the highest total charge to exhibit conversion efficiency exceeding 50% for the Joule-level laser pulse energies.

Efficient, High Power, Wide-Aperture Single Emitter Diode Lasers Emitting at 915 nm

Arslan, Seval; King, Ben; Della Casa, Pietro; Martin, Dominik; Thies, Andreas; Knigge, Andrea; Crump, Paul
IEEE PHOTONICS TECHNOLOGY LETTERS 36(16), 977-980 (AUG 2024)
https://doi.org/10.1109/LPT.2024.3419552

We present single emitter laser diodes with high optical output power (P_{out}), conversion efficiency (η_E), and lateral beam quality in quasi-continuous-wave (QCW) and continuous-wave (CW) operations enabled by using very wide stripe width (ranging from 400 to 1500 μm) and laterally structured p-side contact to prevent higher order and unwanted ring modes. We show that the maximum QCW P_{out} increases for wider stripe and P_{out} of ∼ 290 W (limited by facet failure) is obtained at η_E =60 % for 1500 μm stripes using 500 μs pulse width and 10Hz repetition-rate at a heatsink temperature of T_{HS}=25° C. In contrast, the maximum CW P_{out} of 71W

(limited by the available cooling of the test set-up) at η_E =59 % is obtained for 1000 μm stripes, with lateral-beam-parameter-product (BPPLat.) < 75mm · mrad, which is suitable for coupling into 1mm core 0.15NA fiber.

Power and Efficiency Scaling of GaAs-Based Edge-Emitting High-Power Diode Lasers

Crump, Paul; Boni, Anisuzzaman; Elattar, Mohamed; Khamari, S. K.; Marko, Igor P.; Sweeney, Stephen J.; Arslan, Seval; King, Ben; Miah, Md. Jarez; Martin, Dominik; Knigge, Andrea; Casa, Pietro Della; Traenkle, Guenther
IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS 31(2), 1502512 (MAR-APR 2025)
https://doi.org/10.1109/JSTQE.2024.3484669

Current progress in the scaling of continuous wave optical output power and conversion efficiency of broad-area GaAs-based edge emitters, broad-area lasers (BALs), operating in the 900...1000 nm wavelength range is presented. Device research and engineering efforts have ensured that BALs remain the most efficient of all light sources, so that in the past 10 years, power conversion efficiency at 20 W continuous wave (CW) output power from BA lasers with a 90...100 μm wide stripe has increased 1.5-fold to 57% (via epitaxial layer design developments), whilst peak CW power per single emitter has increased around 3-fold to 70 W (via scaling of device size), with further scaling underway, for example via use of multi-junction designs. However, the peak achievable CW power conversion efficiency and CW specific output power (defined here as peak output power from a 100 μm stripe diode lasers with a single p-n junction) has changed remarkably little, remaining around 70% and 25 W, respectively, for the past decade. Fortunately, research to understand the limits to peak efficiency and specific output power has also shown progress. Specifically, recent studies indicate that spatial non-uniformity in optical field and temperature play a major role in limiting both power and conversion efficiency. Technological efforts motivated by these discoveries to flatten lateral and longitudinal temperature profiles have successfully increased both power and efficiency. In addition, epitaxial layer designs with very high modal gain successfully reduce threshold current and increase slope at 25 degrees C to values comparable to those observed at 200 K, offering a path toward the 80% conversion efficiency range currently seen only at these cryogenic temperatures. Overall, whilst operating efficiency and power continue to scale rapidly, a technological path for increased specific power and peak efficiency is also emerging.

Finite-Element Thermal Simulation of High-Power Diode Laser Stacks for High-Duty-Cycle Pump Applications

Elattar, Mohamed; Huebner, Marko; Wilkens, Martin; Ginolas, Arnim; Crump, Paul
IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS 31(2), 1500407 (MAR-APR 2025)
https://doi.org/10.1109/JSTQE.2024.3431293

The two-dimensional heat distribution (steady-state and transient) within high-power diode laser stacks is simulated using a newly-developed model, based on finite element analysis and calibrated against prior experimental results. The model is then used to estimate the average temperature and thermal impedance of the stack elements under quasi-continuous-wave pulsed operation and investigate the impact of variations to the pulse conditions (pulse width and duty cycle). It is also used to show how using improved heat-spreading materials and increasing cooling efficiency can significantly reduce thermal impedance, thereby enabling duty cycle and optical power scaling.

BEAMLINES & APPLICATIONS

Compact Compton γ-ray source from a spatiotemporal-modulated pulse scattering a high-energy electron beam

Yu, Q.; Gu, Y. J.; Zhang, Y.; Kong, Q.; Kawata, S.
PHYSICS OF PLASMAS 31(8), 083101 (AUG 2024)
https://doi.org/10.1063/5.0211695

A novel plasma mirror is proposed for realizing all-optical Compton scattering, and its performance is compared with that of planar and concave plasma mirrors. Compared to a planar mirror, a concave mirror augments the radiation energy, but it decreases the collimation of the emitted photon beam. With the aid of the increased pulse length of the reflected laser, our proposed plasma mirror boosts the radiation energy and simultaneously improving the collimation of the emitted radiation. The pulse length and radius of the reflected laser can be controlled by adjusting the parameters of the proposed plasma mirror. The dependences of the pulse length and radius on the mirror parameters have been demonstrated. The impact of non-ideal conditions encountered in real experiments on the proposed mechanism has been discussed, which precisely demonstrates the robustness of the proposed mechanism. Additionally, the required gas density for a wakefield accelerator is derived to achieve optimal scattering under the given plasma mirror configurations.

Elevating electron energy gain and betatron x-ray emission in proton-driven wakefield acceleration

Saberi, Hossein; Xia, Guoxing; Liang, Linbo; Farmer, John Patrick; Pukhov, Alexander
PHYSICS OF PLASMAS 31(9), 093104 (SEP 2024)
https://doi.org/10.1063/5.0216713

The long proton beams present at CERN have the potential to evolve into a train of microbunches through the self-modulation instability process. The resonant wakefield generated by a periodic train of proton microbunches can establish a high acceleration field within the plasma, facilitating electron acceleration. This paper investigates the impact of plasma density on resonant wakefield excitation, thus influencing the acceleration of a witness electron bunch and its corresponding betatron radiation within the wakefield. Various scenarios involving different plasma densities are explored through particle-in-cell simulations. The peak wakefield in each scenario is calculated by considering a long pre-modulated proton driver with a fixed peak current. Subsequently, the study delves into the witness beam acceleration in the peak wakefield and its radiation emission. Elevated plasma density increases both the number of microbunches and the accelerating gradient of each microbunch, consequently resulting in heightened resonant wakefield. Nevertheless, the scaling is disrupted by the saturation of the resonant wakefield due to the nonlinearities. The simulation results reveal that at high plasma densities, an intense and broadband radiation spectrum extending into the domain of the hard x-rays and gamma rays is generated. Furthermore, in such instances, the energy gain of the witness beam is significantly enhanced. The impact of wakefield on the witness energy gain and the corresponding radiation spectrum is clearly evident at elevated densities.

High brightness betatron x-ray source driven by chirped laser pulses

Mishra, S.; Rao, B. S.; Moorti, A.; Chakera, J. A.
PHYSICS OF PLASMAS 31(10), 103105 (OCT 2024)
https://doi.org/10.1063/5.0214213

We demonstrate high brightness betatron x-ray generation from a chirped laser pulses driven plasma accelerator. It is shown that positively chirped laser pulse leads to the initiation and enhancement of collective oscillations of electrons inside plasma bubbles, due to associated pulse front tilt (PFT). The PFT causes transverse drift of the bubbles with respect to the laser axis, which results in high brightness x-ray generation. At an optimum chirp, enhanced x-ray emission of >10^8 photons/pulse/sr in 0.1% BW with a critical energy of ∼ 18 keV was observed by a factor >2 in comparison to the case of no chirp. The role of collective oscillation in enhancing x-ray emission is also validated in the Geant4 simulations.

On estimation of betatron radiation spectrum characteristics of DLA electrons in NCD plasma

Veysman, M. E.
PHYSICS OF PLASMAS 31(10), 103112 (OCT 2024)
https://doi.org/10.1063/5.0182247

Action of a relativistically intense subpicosecond laser pulse on the near critical density (NCD) plasma can give rise to the formation of ion channel inside the plasma and effective acceleration of background electrons. Thus, one can produce high current (electron charges from tens nCl to several mkCl), high energy (from several MeV to several hundreds of MeV) electron bunches, demanded in different practical applications. Synchrotron (betatron) radiation of these electrons can serve as an important tool both for practical applications and also for diagnostic of the process in laser plasma, which is important for better understanding of these processes and for optimization of experimental conditions. For the last goals, an approximate model is proposed for calculating the spatial and energy characteristics of a bunch of DLA (direct laser accelerated) electrons in the ion channel formed in the NCD plasma and the characteristics describing the spectrum of their synchrotron radiation. For the considered example of a powerful laser pulse action on NCD plasma, the predictions of the proposed model are in good agreement with the results of particles in cell simulations and with the experimental measurements of the synchrotron radiation specter. It is shown that with the assumption of the rotation of the initial plane of motion of DLA electrons, the experimental data on the measurements of synchrotron radiation specters can be explained on the basis of the concept of betatron radiation of electrons accelerated in NCD plasma by DLA mechanism.

Efficient backward x-ray emission in a finite-length plasma irradiated by a laser pulse of picosecond duration

Yeh, I. -L.; Tangtartharakul, K.; Tang, H.; Willingale, L.; Arefiev, A.
PHYSICS OF PLASMAS 31(11), 113108 (NOV 2024)
https://doi.org/10.1063/5.0221672

Motivated by experiments employing picosecond-long, kilojoule laser pulses, we examined x-ray emission in a finite-length underdense plasma irradiated by such a pulse using two-dimensional particle-in-cell simulations. We found that, in addition to the expected forward emission, the plasma also efficiently emits in the backward direction. Our simulations reveal that the backward emission occurs when the laser exits the plasma. The longitudinal plasma electric field generated by the laser at the density down-ramp turns around some of the laser-accelerated electrons and re-accelerates them in the backward direction. As the electrons collide with the laser, they emit hard x rays. The energy conversion efficiency is comparable to that for the forward emission, but the effective source size is smaller. We show that the picosecond laser duration is required for achieving a spatial overlap between the laser and the backward energetic electrons. At peak laser intensity of 1.4×10^{20} W/cm^2, backward-emitted photons (energies above 100 keV and 10 degrees divergence angle) account for 2×10^{-5} of the incident laser energy. This conversion efficiency is three times higher than that for similarly selected forward-emitted photons. The source size of the backward photons (5 μm) is three times smaller than the source size of the forward photons.

Plasma-guided Compton source

Meir, Talia; Cohen, Itamar; Tangtartharakul, Kavin; Cohen, Tamir; Fraenkel, Moshe; Arefiev, Alexey V.; Pomerantz, Ishay

PHYSICAL REVIEW APPLIED 22(4), 044004 (OCT 2024)
https://doi.org/10.1103/PhysRevApplied.22.044004

We investigated numerically the emission properties of an x-ray source based on direct laser acceleration of electrons interacting with an intense counterpropagating laser pulse. The source was realized by irradiating from both sides a high atomic number plasma-plume target. The resulting x-ray beam was analyzed through three-dimensional particle-in-cell simulations for its spectral content, source size, angular divergence, and temporal structure. For simulated experiments in which the total laser-pulse energy was 1.5 J, we obtained a peak brightness of approximately 10^{22} (s $mrad^2$ mm^2 0.1%BW)$^{-1}$ of x-ray photons peaking at an energy of 25 keV. The results and their competitiveness in applications are discussed and compared with other laser-based x-ray generation methods.

Research progress on advanced positron acceleration

Si, Meiyu; Huang, Yongsheng

EUROPEAN PHYSICAL JOURNAL A 60(10), 210 (OCT 2024)
https://doi.org/10.1140/epja/s10050-024-01433-0

Plasma Wakefield Acceleration (PWFA) is a highly promising method that can reduce the scale and cost of future electron-positron collider experiments. While significant breakthroughs have been achieved in electron acceleration both theoretically and experimentally, generating high-quality positron beams in plasma presents greater challenges. This paper reviews advanced positron acceleration schemes, including particle beam-driven wakefield acceleration, laser-driven wakefield acceleration, radiation acceleration, and hollow plasma channel acceleration. The hollow plasma channel scheme is a promising method that can provide stable and efficient acceleration of positrons, making it more advantageous for experimental implementation.

Towards a 10^{10} n/s neutron source with kHz repetition rate, few-cycle laser pulses

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EUROPEAN PHYSICAL JOURNAL PLUS 139, 574 (2024)
https://doi.org/10.1140/epjp/s13360-024-05338-1

A project has been launched for the development of a laser-based neutron source with the few-cycle lasers available at ELI ALPS. Here we show the first experiments, when deuterons were accelerated from ultrathin deuterated foils at 1 Hz repetition rate with the use of 12 fs, 21 mJ laser pulses. The energy spectra of the accelerated deuterons were measured with Thomson ion spectrometers both in forward and backward directions. The accelerated deuterons induced 2H + 2H fusion reaction in a deuterated polyethylene disk. The resulting fast neutrons were measured with a time-of-flight (ToF) detector system, within which each detector consisted of a plastic scintillator and a photomultiplier, at four different angles relative to the normal of the neutron converter disk. We found good agreement with the simulated angular distribution and energy spectra. Here, we also present preparations for the next phases when the repetition rate is increased to 10 Hz. The developed flat liquid jet was demonstrated to accelerate protons over 0.6 MeV cutoff energy with a stability better than 4% for 15 min. We developed two further neutron measurement techniques: a

liquid scintillator, the ToF signal of which was evaluated with the pulse shape discrimination method, and a bubble detector spectrometer calibrated against a conventional PuBe source. One of the first upcoming applications is the irradiation of zebrafish embryos with laser-generated ultrashort bunch neutrons. As this experiment needs to be implemented in vacuum, the steps of careful preparation and calibration measurements are also discussed.

Compact ultrafast neutron sources via bulk acceleration of deuteron ions in an optical trap

Lei, Zhiyu; Ma, Hanghang; Zhang, Xiaobo; Yu, Lin; Zhang, Yihang; Li, Yutong; Weng, Suming; Chen, Min; Zhang, Jie; Sheng, Zhengming
MATTER AND RADIATION AT EXTREMES 9(5), 057202 (SEP 2024)
https://doi.org/10.1063/5.0208901

A scheme for a quasi-monoenergetic high-flux neutron source with femtosecond duration and highly anisotropic angular distribution is proposed. This scheme is based on bulk acceleration of deuteron ions in an optical trap or density grating formed by two counter-propagating laser pulses at an intensity of $\sim 10^{16}$ W/cm^2 in a near-critical-density plasma. The deuterons are first pre-accelerated to an energy of tens of keV in the ambipolar fields formed in the optical trap. Their energy is boosted to the MeV level by another one or two laser pulses at an intensity of $\sim 10^{20}$ W/cm^2, enabling fusion reactions to be triggered with high efficiency. In contrast to previously proposed pitcher-catcher configurations, our scheme can provide spatially periodic acceleration structures and effective collisions between deuterons inside the whole target volume. Subsequently, neutrons are generated directly inside the optical trap. Our simulations show that neutron pulses with energy 2-8 MeV, yield 10^{18} - 10^{19} n/s, and total number 10^{6} - 10^{7} in a duration $\sim$ 400 fs can be obtained with a 25 μm target. Moreover, the neutron pulses exhibit unique angularly dependent energy spectra and flux distributions, predominantly along the axis of the energy-boosting lasers. Such microsize femtosecond neutron pulses may find many applications, such as high-resolution fast neutron imaging and nuclear physics research.

Preliminary investigation of a Higgs factory based on proton-driven plasma wakefield acceleration

Farmer, J.; Caldwell, A.; Pukhov, A.
NEW JOURNAL OF PHYSICS 26(11), 113011 (NOV 2024)
https://doi.org/10.1088/1367-2630/ad8fc5

A Higgs Factory is considered the highest priority next collider project by the high-energy physics community. Very advanced designs based on radio-frequency cavities exist, and variations on this approach are still being developed. Recently, an option based on electron-bunch driven plasma wakefield acceleration has also been proposed. In this article, we discuss a further option based on proton-driven plasma wakefield acceleration. This option has significant potential advantages due to the high energy of the plasma wakefield driver, simplifying the plasma acceleration stage. Its success will depend on further developments in producing compact high-energy proton bunches at a high rate, which would also make possible a broad range of synergistic particle-physics research.

FACILITIES

The EuAPS Betatron Radiation Source: Status Update and Photon Science Perspectives

Galdenzi, Federico; Anania, Maria Pia; Balerna, Antonella; Bean, Richard J.; Biagioni, Angelo; Bortolin, Claudio; Brombal, Luca; Brun, Francesco; Coreno, Marcello; Costa, Gemma; Crincoli, Lucio; Curcio, Alessandro; Del Giorno, Martina; Di Pasquale, Enrico; di Raddo, Gianluca; Dompe, Valentina; Donato, Sandro; Ebrahimpour, Zeinab; Falone, Antonio; Frazzitta, Andrea; Galletti, Mario; Ghigo, Andrea; Lauciani, Stefano; Liedl, Andrea; Lollo, Valerio; Marcelli, Augusto; Principi, Emiliano; Rossi, Andrea R.; Stocchi, Federica; Villa, Fabio; Zottola, Marco; Cianchi, Alessandro; Stellato, Francesco; Ferrario, Massimo
CONDENSED MATTER 9(3), 30 (SEP 2024)
https://doi.org/10.3390/condmat9030030

The EuPRAXIA EU project is at the forefront of advancing particle accelerator research and the development of photon sources through innovative plasma acceleration approaches. Within this framework, the EuAPS project aims to exploit laser wakefield acceleration to build and operate a betatron radiation source at the INFN Frascati National Laboratory. The EuAPS source will provide femtosecond X-ray pulses in the spectral region between about 1 and 10 keV, unlocking a realm of experimental ultrafast methodologies encompassing diverse imaging and X-ray spectroscopy techniques. This paper presents a description of the EuAPS betatron source, including simulations of the photon beam parameters, outlines the preliminary design of the dedicated photon beamline, and provides an insightful overview of its photon science applications.

Optimizing beam dynamics in the EuPRAXIA@SPARC_LAB RF injector

Silvi, G. J.; Bacci, A. L.; Carillo, M.; Chiadroni, E.; Faillace, L.; Giribono, A.; Mostacci, A.; Ferario, M.; Vaccarezza, C.
NUOVO CIMENTO C-COLLOQUIA AND COMMUNICATIONS IN PHYSICS 47(5), 323 (SEP-OCT 2024)
https://doi.org/10.1393/ncc/i2024-24323-5

The EuPRAXIA@SPARC_LAB RF injector provides high-brightness electron beams accelerated and longitudinally manipulated in the velocity bunching regime (VB). The RF injector works in the so-called comb configuration. It foresees a 30 pC witness and a 200 pC driver longitudinally compressed in the first two accelerating structures both operated in the VB regime. The beam stability can be improved by adding a High Harmonic Cavity (HHC), interposed between the Gun and the first accelerating structure, to shorten and flatter the charge distribution and manipulate the beams to reach proper transverse and longitudinal parameters. The paper reports on beam dynamics studies performed with the insertion of the X-band RF cavity that is proposed to shape the beam current distribution, linearize the longitudinal phase space, and stabilize it with respect to RF jitters.

Overview and Recent Developments of the Frascati Laser for Acceleration and Multidisciplinary Experiments Laser Facility at SPARC_LAB

Galletti, Mario; Stocchi, Federica; Costa, Gemma; Curcio, Alessandro; Del Giorno, Martina; Pompili, Riccardo; Cacciotti, Luciano; Di Pirro, Giampiero; Dompe, Valentina; Verra, Livio; Villa, Fabio; Cianchi, Alessandro; Anania, Maria Pia; Ghigo, Andrea; Zigler, Arie; Ferrario, Massimo
APPLIED SCIENCES-BASEL 14(19), 8619 (OCT 2024)
https://doi.org/10.3390/app14198619

An overview of the 200 TW Frascati Laser for Acceleration and Multidisciplinary Experiments (FLAME) at the SPARC_LAB Test Facility at the National Laboratories of Frascati (LNF-INFN) is presented. The FLAME laser is employed to investigate different laser-matter interaction schemes, i.e., electron acceleration and secondary radiation sources through Laser Wakefield Acceleration (LWFA) or ion and proton generation through Target Normal Sheath Acceleration (TNSA), for a wide range of scientific areas including the biomedical applications. Finally, recently performed experimental campaigns within the EuAPS and EuPRAXIA frameworks are reported.

Experimental measurements of gamma-photon production and estimation of electron/positron production on the PETAL laser facility

Brun, F.; Ribotte, L.; Boutoux, G.; Davoine, X.; Masson-Laborde, P. E.; Sentoku, Y.; Iwata, N.; Blanchot, N.; Batani, D.; Lantuejoul, I.; Lecherbourg, L.; Rosse, B.; Rousseaux, C.; Vauzour, B.; Raffestin, D.; D'Humieres, E.; Ribeyre, X.
MATTER AND RADIATION AT EXTREMES 9(5), 057203 (SEP 2024)
https://doi.org/10.1063/5.0206416

This article reports the first measurements of high-energy photons produced with the high-intensity PETawatt Aquitaine Laser (PETAL) laser. The experiments were performed during the commissioning of the laser. The laser had an energy of about 400 J, an intensity of 8 x 10^{18} W cm^{-2}, and a pulse duration of 660 fs (FWHM). It was shot at a 2 mm-thick solid tungsten target. The high-energy photons were produced mainly from the bremsstrahlung process for relativistic electrons accelerated inside a plasma generated on the front side of the target. This paper reports measurements of electrons, protons and photons. Hot electrons up to ≈ 35 MeV with a few-MeV temperature were recorded by a spectrometer, called SESAME (Spectre ÉlectronS Angulaire Moyenne Énergie). K- and L-shells were clearly detected by a photon spectrometer called SPECTIX (Spectromètre Petal à Cristal en TransmIssion pour le rayonnnement X). High-energy photons were diagnosed by CRACC-X (Cassette de RAdiographie Centre Chambre-rayonnement X), a bremsstrahlung cannon. Bremsstrahlung cannon analysis is strongly dependent on the hypothesis adopted for the spectral shape. Different shapes can exhibit similar reproductions of the experimental data. To eliminate dependence on the shape hypothesis and to facilitate analysis of the data, simulations of the interaction were performed. To model the mechanisms involved, a simulation chain including hydrodynamic, particle-in-cell, and Monte Carlo simulations was used. The simulations model the preplasma generated at the front of the target by the PETAL laser prepulse, the acceleration of electrons inside the plasma, the generation of MeV-range photons from these electrons, and the response of the detector impacted by the energetic photon beam. All this work enabled reproduction of the experimental data. The high-energy photons produced have a large emission angle and an exponential distribution shape. In addition to the analysis of the photon spectra, positron production was also investigated. Indeed, if high-energy photons are generated inside the solid target, some positron/electron pairs may be produced by the Bethe-Heitler process. Therefore, the positron production achievable within the PETAL laser facility was quantified. To conclude the study, the possibility of creating electron/positron pairs through the linear Breit-Wheeler process with PETAL was investigated.

Technical Design Report for the LUXE experiment

Abramowicz, H. et al. (LUXE Collaboration)
EUROPEAN PHYSICAL JOURNAL-SPECIAL TOPICS 233(10), 1709-1974 (OCT 2024)
https://doi.org/10.1140/epjs/s11734-024-01164-9

This Technical Design Report presents a detailed description of all aspects of the LUXE (Laser Und XFEL Experiment), an experiment that will combine the high-quality and high-energy electron beam of the European XFEL with a high-intensity laser, to explore the uncharted terrain of strong-field quantum electrodynamics characterised by both high energy and high intensity, reaching the Schwinger field and beyond. The further implications for the search of physics beyond the Standard Model are also discussed.

First Thomson scattering results from AWAKE's helicon plasma source

Stollberg, C.; Guittienne, Ph; Karimov, R.; Sublet, A.; Furno, I; Vincent, B.; Andrebe, Y.; Buttenschoen, B.
PLASMA PHYSICS AND CONTROLLED FUSION 66(11), 115011 (NOV 2024)
https://doi.org/10.1088/1361-6587/ad7d36

We present the first results of electron density and temperature measurements obtained from Thomson scattering at the helicon plasma source (HPS) for the AWAKE project. These measurements are compared to simulation results from a 1D power and particle balance model (PPM), confirming that the plasma can be fully sustained by collisional power dissipation. The variations in plasma parameters under different experimental conditions are evaluated in the PPM framework. We discuss current limitations of the model and propose possible improvements. Additionally, we suggest modifications to the existing HPS setup to enhance axial plasma homogeneity.

THEORY & SIMULATION

The collisional particle-in-cell method for the Vlasov-Maxwell-Landau equations

Bailo, Rafael; Carrillo, Jose A.; Hu, Jingwei
JOURNAL OF PLASMA PHYSICS 90(4), 905900415 (OCT 2024)
https://doi.org/10.1017/S0022377824001077

We introduce an extension of the particle-in-cell method that captures the Landau collisional effects in the Vlasov-Maxwell-Landau equations. The method arises from a regularisation of the variational formulation of the Landau equation, leading to a discretisation of the collision operator that conserves mass, charge, momentum and energy, while increasing the (regularised) entropy. The collisional effects appear as a fully deterministic effective force, thus the method does not require any transport-collision splitting. The scheme can be used in arbitrary dimension, and for a general interaction, including the Coulomb case. We validate the scheme on scenarios such as the Landau damping, the two-stream instability and the Weibel instability, demonstrating its effectiveness in the numerical simulation of plasma.

Acceleration of the particle-in-cell code OSIRIS with graphics processing units

Lee, Roman P.; Pierce, Jacob R.; Miller, Kyle G.; Almanza, Maria; Tableman, Adam; Decyk, Viktor K.; Fonseca, Ricardo A.; Alves, E. Paulo; Mori, Warren B.
JOURNAL OF PLASMA PHYSICS 91(1), E8 (JAN 2025)
https://doi.org/10.1017/S0022377824001569

Fully relativistic particle-in-cell (PIC) simulations are crucial for advancing our knowledge of plasma physics. Modern supercomputers based on graphics processing units (GPUs) offer the potential to perform PIC simulations of unprecedented scale, but require robust and feature-rich codes that can fully leverage their computational resources. In this work, this demand is addressed by adding GPU acceleration to the PIC code OSIRIS. An overview of the algorithm, which features a CUDA extension to the underlying Fortran architecture, is given. Detailed performance benchmarks for thermal plasmas are presented, which demonstrate excellent weak scaling on NERSC's Perlmutter supercomputer and high levels of absolute performance. The robustness of the code to model a variety of physical systems is demonstrated via simulations of Weibel filamentation and laser-wakefield acceleration run with dynamic load balancing. Finally, measurements and analysis of energy consumption are provided that indicate that the GPU algorithm is up to ∼ 14 times faster and ∼ 7 times more energy efficient than the optimized CPU algorithm on a node-to-node basis. The described development addresses the PIC simulation community's computational demands both by contributing a robust and performant GPU-accelerated PIC code and by providing insight into efficient use of GPU hardware.

Pseudospectral particle-in-cell formulation with arbitrary charge and current-density time dependencies for the modeling of relativistic plasmas

Shapoval, Olga; Zoni, Edoardo; Lehe, Remi; Thevenet, Maxence; Vay, Jean-Luc
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This paper introduces a formulation of the particle-in-cell (PIC) method for the modeling of relativistic plasmas, that leverages the ability of the pseudospectral analytical time-domain solver (PSATD) to handle arbitrary time dependencies of the charge and current densities during one PIC cycle (applied to second-order polynomial dependencies here). The formulation is applied to a modified set of Maxwell's equations that was proposed earlier in the context of divergence cleaning, and to recently proposed extensions of the PSATD-PIC algorithm. Detailed analysis and testings revealed that, under some condition, the formulation can expand the range of numerical parameters under which PIC simulations are stable and accurate when modeling relativistic plasmas such as, e.g., plasma-based particle accelerators.

Thermal fluid closures and pressure anisotropies in numerical simulations of plasma wakefield acceleration

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We investigate the dynamics of plasma-based acceleration processes with collisionless particle dynamics and non-negligible thermal effects. We aim at assessing the applicability of fluid-like models, obtained by suitable closure assumptions applied to the relativistic kinetic equations, thus not suffering from statistical noise, even in the presence of a finite temperature. The work here presented focuses on the characterization of pressure anisotropies, which crucially depend on the adopted closure scheme, and hence are useful to discern the appropriate thermal fluid model. To this aim, simulation results of spatially resolved fluid models with different thermal closure assumptions are compared with the results of particle-in-cell simulations at changing temperature and amplitude of plasma oscillations.

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