THE EuPRAXIA FILES

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FOREWORD

I have the pleasure and the honor to present a new issue of The EuPRAXIA Files, collecting the most relevant papers recently appeared in the literature about accelerators, lasers and plasma science, and strictly correlated with technologies that will be used at EuPRAXIA. This is an important tool for the EuPRAXIA community and, at large, for worldwide scientists involved in such advanced accelerator technologies.

In the past week, EuPRAXIA Preparatory Phase held its first in-person General Meeting in the wonderful location of Elba island. It was the moment to make a wrap-up, at nearly mid way to the end of the EU grant, on the relevant amount of work performed by working packages. It was evident that EuPRAXIA is steadily heading toward its final configuration of an European Large Research infrastructure.

We also heard from distinguished guests the latest news about plans for plasma-based future linear colliders, new high gradient horizons opened by dielectric accelerators, and initiatives in less favoured countries for new photon sources, which should help in innovation and development of various regions (Latin America and Africa, in primis). Also in this case, the EuPRAXIA community can provide not only intellectual endorsement, but also practical initiatives: training, exchange of scientists, political support. This chapter of the EuPRAXIA storyboard would be as important and strategic as the one related to drive a FEL with a beam originated from a plasma.

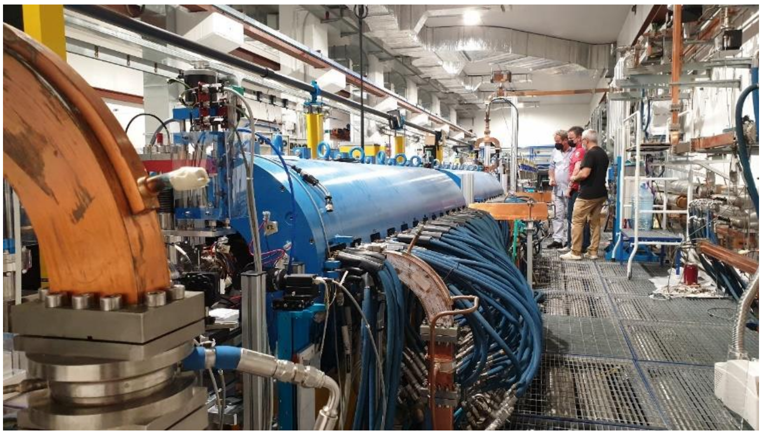
I wish you a fruitful reading,

Pierluigi Campana

CONTENTS

RESEARCH HIGHLIGHTS

Taking the pulse of plasma-based Free Electron Lasers



FEL at SPARC_LAB, Laboratori Nazionali di Frascati. Photo by Alexandra Welsch.

A group of researchers including distinguished members of EuPRAXIA published a review article in Nature Photonics summarizing the recent advances and challenges in developing plasma-driven Free Electron Lasers (FEL), a valuable source of high-brilliance ultrashort coherent light for the study of subatomic matter, ultrafast dynamics of complex systems and X-ray nonlinear optics, among other applications.

Plasma-wakefield-based acceleration technology provides a new approach for driving FELs, with the potential to reduce the material and economic footprint of current FEL facilities and enhance their performance using the unique properties of plasma-accelerated electron beams. First author of the review, Dr Mario Galletti (INFN-LNF/University of Rome Tor Vergata) shared that *"With the advent of plasma wakefield acceleration, we are entering a new era where particle accelerators become more powerful and compact. This technology holds the key to developing next-generation free-electron lasers, enabling unprecedented studies of matter at the most fundamental levels. As international efforts advance, the progress in plasma-driven FELs marks a major step forward, bringing us closer to unlocking a wide range of applications in science and industry."*

The review describes the operating principles of plasma accelerators, and gives an overview of recent experimental milestones for plasma-driven FELs in self-amplified spontaneous emission and seeded configurations. It also highlights the remaining major challenges in the field, in particular to improve the electron beam quality and shot-to-shot stability and to increase the repetition rate to achieve plasma-based X-FEL operational facilities. The ultimate goal is to create dedicated plasma-FEL user facilities, expanding global access to FEL photon sources and enabling new areas of research.

The article describes the vision for the future of the three plasma-based accelerator facilities that have successfully operated a FEL, exploring different configurations for the plasma wakefield driver beam, plasma stage design and operational regime: the Shanghai Institute of Optics and Fine Mechanics, COXINEL at Helmholtz-Zentrum Dresden-Rossendorf, and SPARC_LAB at Laboratori Nazionali di Frascati.

The authors conclude by introducing EuPRAXIA as a joint effort towards the realization of an operational plasma-driven FEL facility, stating that close collaboration with existing FEL user communities is essential to identify key applications that can benefit from plasma-FEL machines in the near future.

Prospects for free-electron lasers powered by plasma-wakefield-accelerated beams
M. Galletti, R. Assmann, M. E. Couprie, M. Ferrario, L. Giannessi, A. Irman, R. Pompili, and W. Wang
NATURE PHOTONICS 18, 780–791 (2024)
https://doi.org/10.1038/s41566-024-01474-3

FUNDAMENTALS

Emittance preservation in a plasma-wakefield accelerator

Lindstrom, C. A.; Beinortaite, J.; Svensson, J. Bjoerklund; Boulton, L.; Chappell, J.; Diederichs, S.; Foster, B.; Garland, J. M.; Caminal, P. Gonzalez; Loisch, G.; Pena, F.; Schroeder, S.; Thevenet, M.; Wesch, S.; Wing, M.; Wood, J. C.; D'Arcy, R.; Osterhoff, J.
NATURE COMMUNICATIONS 15(1), 6097 (JUL 2024)
https://doi.org/10.1038/s41467-024-50320-1

Radio-frequency particle accelerators are engines of discovery, powering high-energy physics and photon science, but are also large and expensive due to their limited accelerating fields. Plasma-wakefield accelerators (PWFAs) provide orders-of-magnitude stronger fields in the charge-density wave behind a particle bunch travelling in a plasma, promising particle accelerators of greatly reduced size and cost. However, PWFAs can easily degrade the beam quality of the bunches they accelerate. Emittance, which determines how tightly beams can be focused, is a critical beam quality in for instance colliders and free-electron lasers, but is particularly prone to degradation. We demonstrate, for the first time, emittance preservation in a high-gradient and high-efficiency PWFA while simultaneously preserving charge and energy spread. This establishes that PWFAs can accelerate without degradation-an essential step toward energy boosters in photon science and multistage facilities for compact high-energy particle colliders. High beam quality is key for particle-accelerator applications in high-energy physics and photon science. Here, authors demonstrate gigavolt-per meter acceleration of electron bunches in a plasma-wakefield accelerator with no degradation of emittance, while also preserving charge and energy spread.

Direct Laser Acceleration in Underdense Plasmas with Multi-PW Lasers: A Path to High-Charge, GeV-Class Electron Bunches

Babjak, R.; Willingale, L.; Arefiev, A.; Vranic, M.
PHYSICAL REVIEW LETTERS 132(12), 125001 (MAR 2024)
https://doi.org/10.1103/PhysRevLett.132.125001

The direct laser acceleration (DLA) of electrons in underdense plasmas can provide hundreds of nC of electrons accelerated to near -GeV energies using currently available lasers. Here we demonstrate the key role of electron transverse displacement in the acceleration and use it to analytically predict the expected maximum electron energies. The energy scaling is shown to be in agreement with full-scale quasi-3D particle-in-cell simulations of a laser pulse propagating through a preformed guiding channel and can be directly used for optimizing DLA in near-future laser facilities. The strategy towards optimizing DLA through matched laser focusing is presented for a wide range of plasma densities paired with current and near -future laser technology. Electron energies in excess of 10 GeV are accessible for lasers at $I \sim 10^{21}$ W/cm^2.

Experimental Observation of Space-Charge Field Screening of a Relativistic Particle Bunch in Plasma

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.
PHYSICAL REVIEW LETTERS 133(3), 035001 (JUL 2024)
https://doi.org/10.1103/PhysRevLett.133.035001

The space-charge field of a relativistic charged bunch propagating in plasma is screened due to the presence of mobile charge carriers. We experimentally investigate such screening by measuring the effect of dielectric wakefields driven by the bunch in an uncoated dielectric capillary where the plasma is confined. We show that the plasma screens the space-charge field and therefore suppresses the dielectric wakefields when the distance between the bunch and the dielectric surface is much larger than the plasma skin depth. Before full screening is reached, the effects of dielectric and plasma wakefields are present simultaneously.

Guided Mode Evolution and Ionization Injection in Meter-Scale Multi-GeV Laser Wakefield Accelerators

Shrock, J. E.; Rockafellow, E.; Miao, B.; Le, M.; Hollinger, R. C.; Wang, S.; Gonsalves, A. J.; Picksley, A.; Rocca, J. J.; Milchberg, H. M.
PHYSICAL REVIEW LETTERS 133(4), 045002 (JUL 2024)
https://doi.org/10.1103/PhysRevLett.133.045002

We show that multi-GeV laser wakefield electron accelerators in meter-scale, low density hydrodynamic plasma waveguides operate in a new nonlinear propagation regime dominated by sustained beating of lowest order modes of the ponderomotively modified channel; this occurs whether or not the injected pulse is linearly matched to the guide. For a continuously doped gas jet, this emergent mode beating effect leads to axially modulated enhancement of ionization injection and a multi-GeV energy spectrum of multiple quasimonoenergetic peaks; the same process in a locally doped jet produces single multi-GeV peaks with < 10% energy spread. A three-stage model of drive laser pulse evolution and ionization injection characterizes the beating effect and explains our experimental results.

Attosecond and nano-Coulomb electron bunches via the Zero Vector Potential mechanism

Timmis, R. J. L.; Paddock, R. W.; Ouatu, I.; Lee, J.; Howard, S.; Atonga, E.; Ruskov, R. T.; Martin, H.; Wang, R. H. W.; Aboushelbaya, R.; von der Leyen, M. W.; Gumbrell, E.; Norreys, P. A.
SCIENTIFIC REPORTS 14(1), 10805 (MAY 2024)
https://doi.org/10.1038/s41598-024-61041-2

The commissioning of multi-petawatt class laser facilities around the world is gathering pace. One of the primary motivations for these investments is the acceleration of high-quality, low-emittance electron bunches. Here we explore the interaction of a high-intensity femtosecond laser pulse with a mass-limited dense target to produce MeV attosecond electron bunches in transmission and confirm with three-dimensional simulation that such bunches have low emittance and nano-Coulomb charge. We then perform a large parameter scan from non-relativistic laser intensities to the laser-QED regime and from the critical plasma density to beyond solid density to demonstrate that the electron bunch energies and the laser pulse energy absorption into the plasma can be quantitatively described via the Zero Vector Potential mechanism. These results have wide-ranging implications for future particle accelerator science and associated technologies.

The effect of laser pulse evolution on down-ramp injection in laser wakefield accelerators

Jain, Arohi; Yoffe, Samuel R.; Ersfeld, Bernhard; Holt, George K.; Gupta, Devki Nandan; Jaroszynski, Dino A.
SCIENTIFIC REPORTS 14(1), 19127 (AUG 2024)
https://doi.org/10.1038/s41598-024-69049-4

Electron self-injection in laser wakefield accelerators (LWFAs) is an important determinator of electron beam parameters. Controllable and adjustable LWFA beams are essential for applications. Controlled injection by capturing sheath electrons can be achieved using plasma density down-ramps or bumps, which perturb the LWFA bubble phase velocity by varying the plasma frequency and by affecting relativistic self-focussing of the

laser. We report on a comprehensive study, using particle-in-cell simulations, of the effect of laser pulse evolution on injection on density perturbations. We show how the LWFA can be optimised to make it suitable for use in a wide range of applications, in particular those requiring short duration, low slice-emittance and low energy spread, and high-charge electron bunches.

Beam physics studies for a high charge and high beam quality laser-plasma accelerator

Marini, Samuel; Minenna, Damien F. G.; Massimo, Francesco; Batista, Laury; Bencini, Vittorio; Chance, Antoine; Chauvin, Nicolas; Doebert, Steffen; Farmer, John; Gschwendtner, Edda; Moulanier, Ioaquin; Muggli, Patric; Uriot, Didier; Cros, Brigitte; Nghiem, Phu Anh Phi

PHYSICAL REVIEW ACCELERATORS AND BEAMS 27(6), 063401 (JUN 2024)

https://doi.org/10.1103/PhysRevAccelBeams.27.063401

Electron acceleration by laser-plasma techniques is approaching maturity and is getting ready for the construction of particle accelerators with dedicated applications. We present a general methodology showing how beam physics studies can be used to achieve a specific parameter set in a laser-plasma accelerator. Laser systems, plasma targets, and magnetic component properties are designed to optimize the electron beam so as to achieve the required performances. Beam physics in its full 6D phase space is studied from electron injection to beam delivery to the end user, through the plasma acceleration stage and transport line. As each beam parameter can only be modified by specific electric/magnetic field configurations, it is crucial to assign from the beginning specific roles to given accelerator sections in obtaining given beam parameters. These beam physics considerations were successfully applied to the design of a plasma-based electron injector for the AWAKE Run2 experiment. Electron beam parameters were calculated using a global simulation, achieving simultaneously unprecedented high charge (100 pC) and high quality (micrometric beam emittance and size).

Numerical studies of collinear laser-assisted injection from a foil for plasma wakefield accelerators

Wilson, T. C.; Farmer, J.; Pukhov, A.; Sheng, Z. -M.; Hidding, B.

PHYSICAL REVIEW ACCELERATORS AND BEAMS 27(7), 071301 (JUL 2024)

https://doi.org/10.1103/PhysRevAccelBeams.27.071301

We present a laser-assisted electron injection scheme for beam-driven plasma wakefield acceleration. The laser is collinear with the driver and triggers the injection of hot electrons into the plasma wake by interaction with a thin solid target. We present a baseline case using the AWAKE Run 2 parameters and then perform variations on key parameters to explore the scheme. It is found that the trapped witness electron charge may be tuned by altering laser parameters, with a strong dependence on the phase of the wake upon injection. Normalized emittance settles at the order of micrometres and varies with witness charge. The scheme is robust to misalignment, with a $1/10^{th}$ plasma skin-depth offset (20 μm for the AWAKE case) having a negligible effect on the final beam. The final beam quality is better than similar existing schemes, and several avenues for further optimization are indicated. The constraints on the AWAKE experiment are very specific, but the general principles of this mechanism can be applied to future beam-driven plasma wakefield accelerator experiments.

Benchmarking of hydrodynamic plasma waveguides for multi-GeV laser-driven electron acceleration

Miao, B.; Rockafellow, E.; Shrock, J. E.; Hancock, S. W.; Gordon, D.; Milchberg, H. M.

PHYSICAL REVIEW ACCELERATORS AND BEAMS 27(8), 081302 (AUG 2024)

https://doi.org/10.1103/PhysRevAccelBeams.27.081302

Hydrodynamic plasma waveguides initiated by optical field ionization have recently become a key component of multi-GeV laser wakefield accelerators. Here, we present the most complete and accurate experimental and simulation-based characterization to date, applicable to current multi-GeV experiments and future 100 GeV-scale laser plasma accelerators. Crucial to the simulations is the correct modeling of intense Bessel beam interaction with meter-scale gas targets, the results of which are used as initial conditions for hydrodynamic simulations. The simulations are in good agreement with our experiments measuring evolving plasma and neutral hydrogen density profiles using two-color short pulse interferometry, enabling realistic determination of the guided mode structure for application to laser-driven plasma accelerator design.

Direct measurement of the 2D axisymmetric ionization source rate in a helicon plasma for wakefield particle accelerator applications

Zepp, M.; Granetzny, M.; Schmitz, O.
PHYSICS OF PLASMAS 31(7), 070704 (JUL 2024)
https://doi.org/10.1063/5.0211109

A direct measurement of the particle balance and derivation of the underlying particle source rate distribution in a helicon plasma developed for wakefield particle accelerators is presented. Parallel and radial ion fluxes are measured using laser induced fluorescence on single ionized argon. We find that the radial contribution to the source rate is an order of magnitude larger than the axial contribution. We also find that the axial source rate profile closely matches the radial density gradient axial profile, thus indicating the importance of the radial density profile for the particle balance. Notably, the peak ion source rate is located off-axis, about halfway between the axis and the vacuum wall on both sides of the axial center.

Energy stabilization of high-charge bunches from laser plasma accelerators

Shi, Xueyan; Xu, Haisheng; Li, Dazhang; Wang, Jia; Zeng, Ming
NEW JOURNAL OF PHYSICS 26(7), 073045 (JUL 2024)
https://doi.org/10.1088/1367-2630/ad6634

Laser plasma accelerators (LPAs) have become one of the frontiers of the accelerator community, mainly because they promise orders of magnitude improvement in the accelerating gradient. However, the energy stability and spread of the high-charge bunched beams (e.g. several hundred pC per bunch) from LPAs still strongly limit their application. In this work, we propose a novel method utilizing magnetic chicanes combined with both active and passive plasma dechirpers to simultaneously reduce the central energy deviation and the energy spread of high-charge bunched beams from LPAs. Start-to-end simulations demonstrate that the central energy deviation and the energy spread of approximately 500 pC bunches can be simultaneously reduced from approximately 2% and 1.2% to 0.1% and 0.5%, respectively, while maintaining almost perfect transmission efficiency (above 97%).

Recovery of hydrogen plasma at the sub-nanosecond timescale in a plasma-wakefield accelerator

Pompili, R.; Anania, M. P.; Biagioni, A.; Carillo, M.; Chiadroni, E.; Cianchi, A.; Costa, G.; Crincoli, L.; Del Dotto, A.; Del Giorno, M.; Demurtas, F.; Ferrario, M.; Galletti, M.; Giribono, A.; Jones, J. K.; Lollo, V.; Pacey, T.; Parise, G.; Di Pirro, G.; Romeo, S.; Silvi, G. J.; Shpakov, V.; Villa, F.; Zigler, A.
COMMUNICATIONS PHYSICS 7(1), 241 (JUL 2024)
https://doi.org/10.1038/s42005-024-01739-x

Plasma wakefield acceleration revolutionized the field of particle accelerators by generating gigavolt-per-centimeter fields. To compete with conventional radio-frequency (RF) accelerators, plasma technology must demonstrate operation at high repetition rates, with a recent research showing feasibility at megahertz levels using an Argon source that recovered after about 60 ns. Here we report about a proof-of-principle experiment that demonstrates the recovery of a Hydrogen plasma at the sub-nanosecond timescale. The result is obtained with a pump-and-probe setup and has been characterized for a wide range of plasma densities. We observed that large plasma densities reestablish their initial state soon after the injection of the pump beam (< 0.7 ns). Conversely, at lower densities we observe the formation of a local dense plasma channel affecting the probe beam dynamics even at long delay times (> 13 ns). The results are supported with numerical simulations and represent a step forward for the next-generation of compact high-repetition rate accelerators.

On the energy spectrum evolution of electrons undergoing radiation cooling

Bulanov, S. V.; Grittani, G. M.; Shaisultanov, R.; Esirkepov, T. Z.; Ridgers, C. P.; Bulanov, S. S.; Russell, B. K.; Thomas, A. G. R.
FUNDAMENTAL PLASMA PHYSICS 9, 100036 (JAN 2024)
https://doi.org/10.1016/j.fpp.2024.100036

Radiative cooling of electron beams interacting with counter-propagating electromagnetic waves is analyzed, taking into account the quantum modification of the radiation friction force. Central attention is paid to the evolution of the energy spectrum of electrons accelerated by the laser wake field acceleration mechanism. As an electron beam loses energy to radiation, the mean energy decreases and the form of the energy distribution also changes due to quantum-mechanical spectral broadening.

Generation of polarized electron beams through self-injection in the interaction of a laser with a pre-polarized plasma

Yin, L. R.; Li, X. F.; Gu, Y. J.; Cao, N.; Kong, Q.; Buscher, M.; Weng, S. M.; Chen, M.; Sheng, Z. M.
HIGH POWER LASER SCIENCE AND ENGINEERING 12, e28 (FEB 2024)
https://doi.org/10.1017/hpl.2024.7

Polarized electron beam production via laser wakefield acceleration in pre-polarized plasma is investigated by particle-in-cell simulations. The evolution of the electron beam polarization is studied based on the Thomas-Bargmann-Michel-Telegdi equation for the transverse and longitudinal self-injection, and the depolarization process is found to be influenced by the injection schemes. In the case of transverse self-injection, as found typically in the bubble regime, the spin precession of the accelerated electrons is mainly influenced by the wakefield. However, in the case of longitudinal injection in the quasi-1D regime (for example, F. Y. Li et al., Phys. Rev. Lett. 110, 135002 (2013)), the direction of electron spin oscillates in the laser field. Since the electrons move around the laser axis, the net influence of the laser field is nearly zero and the contribution of the wakefield can be ignored. Finally, an ultra-short electron beam with polarization of 99% can be obtained using longitudinal self-injection.

Ultrahigh-brightness 50 MeV electron beam generation from laser wakefield acceleration in a weakly nonlinear regime

Xiang, Zhongtao; Yu, Changhai; Qin, Zhiyong; Jiao, Xuhui; Cheng, Jiahui; Zhou, Qiaoxuan; Axi, Gatie; Jie, Jianghua; Huang, Ya; Cai, Jintan; Liu, Jiansheng
MATTER AND RADIATION AT EXTREMES 9(3), 035201 (MAY 2024)
https://doi.org/10.1063/5.0189460

We propose an efficient scheme to produce ultrahigh-brightness tens of MeV electron beams by designing a density-tailored plasma to induce a wakefield in the weakly nonlinear regime with a moderate laser energy of 120 mJ. In this scheme, the second bucket of the wakefield can have a much lower phase velocity at the steep plasma density down-ramp than the first bucket and can be exploited to implement longitudinal electron injection at a lower laser intensity, leading to the generation of bright electron beams with ultralow emittance together with low energy spread. Three-dimensional particle-in-cell simulations are carried out and demonstrate that high-quality electron beams with a peak energy of 50 MeV, ultralow emittance of ~ 28 nm rad, energy spread of 1%, charge of 4.4 pC, and short duration less than 5 fs can be obtained within a 1-mm-long tailored plasma density, resulting in an ultrahigh six-dimensional brightness $B_{6D,n}$ of ~ 2 x 10^{17} $A/m^2/0.1\%$. By changing the density parameters, tunable bright electron beams with peak energies ranging from 5 to 70 MeV, a small emittance of $\leq$ 0.1 mm mrad, and a low energy spread at a few-percent level can be obtained. These bright MeV-class electron beams have a variety of potential applications, for example, as ultrafast electron probes for diffraction and imaging, in laboratory astrophysics, in coherent radiation source generation, and as injectors for GeV particle accelerators.

Diagnostics

Revealing the three-dimensional structure of microbunched plasma-wakefield-accelerated electron beams

Laberge, Maxwell; Bowers, Brant; Chang, Yen-Yu; Cabadag, Jurjen Couperus; Debus, Alexander; Hannasch, Andrea; Pausch, Richard; Schoebel, Susanne; Tiebel, Jessica; Ufer, Patrick; Willmann, Anna; Zarini, Omid; Zgadzaj, Rafal; Lumpkin, Alex H.; Schramm, Ulrich; Irman, Arie; Downer, M. C.

NATURE PHOTONICS 18(9) (SEP 2024)

https://doi.org/10.1038/s41566-024-01475-2

Plasma wakefield accelerators use tabletop equipment to produce relativistic femtosecond electron bunches. Optical and X-ray diagnostics have established that their charge concentrates within a micrometre-sized volume, but its sub-micrometre internal distribution, which critically influences gain in free-electron lasers or particle yield in colliders, has proven elusive to characterize. Here, by simultaneously imaging different wavelengths of coherent optical transition radiation that a laser-wakefield-accelerated electron bunch generates when exiting a metal foil, we reveal the structure of the coherently radiating component of bunch charge. The key features of the images are shown to uniquely correlate with how plasma electrons injected into the wake: by a plasma-density discontinuity, by ionizing high-Z gas-target dopants or by uncontrolled laser-plasma dynamics. With additional input from the electron spectra, spatially averaged coherent optical transition radiation spectra and particle-in-cell simulations, we reconstruct coherent three-dimensional charge structures. The results demonstrate an essential metrology for next-generation compact X-ray free-electron lasers driven by plasma-based accelerators. Imaging the visible light emitted from accelerated electron bunches reveals important information about the three-dimensional charge structure of the bunches, which strongly influences the performance of free-electron lasers.

Single-Shot Diagnosis of Electron Energy Evolution via Streaked Betatron X Rays in a Curved Laser Wakefield Accelerator

Ma, Y.; Cardarelli, J. A.; Campbell, P. T.; Fourmaux, S.; Fitzgarrald, R.; Balcazar, M. D.; Antoine, A. F.; Beier, N. F.; Qian, Q.; Hussein, A. E.; Kettle, B.; Klein, S. R.; Krushelnick, K.; Li, Y. F.; Mangles, S. P. D.; Sarri, G.; Seipt, D.; V. Senthilkumaran, V.; Streeter, M. J. V.; Willingale, L.; Thomas, A. G. R.

PHYSICAL REVIEW LETTERS 132(22), 225001 (MAY 2024)

https://doi.org/10.1103/PhysRevLett.132.225001

We report on an experimental observation of the streaking of betatron x rays in a curved laser wakefield accelerator. The streaking of the betatron x rays was realized by launching a laser pulse into a plasma with a transverse density gradient. By controlling the plasma density and the density gradient, we realized the steering of the laser driver, electron beam, and betatron x rays simultaneously. Moreover, we observed an energy -angle correlation of the streaked betatron x rays and utilized it in diagnosing the electron acceleration process in a single-shot mode. Our work could also find applications in advanced control of laser beam and particle propagation. More importantly, the angular streaked betatron x ray has an intrinsic spatiotemporal correlation, which makes it a promising tool for single-shot pump-probe applications.

Selective electron beam sensing through coherent Cherenkov diffraction radiation

Senes, E.; Krupa, M.; Mazzoni, S.; Lasocha, K.; Lefevre, T.; Shloegelhofer, A.; Wendt, M.; Davut, C.; Karataev, P.; Pakuza, C.; Spear, B.

PHYSICAL REVIEW RESEARCH 6(2), 023278 (JUN 2024)

https://doi.org/10.1103/PhysRevResearch.6.023278

We exploit the coherent emission of Cherenkov diffraction radiation (ChDR) by a relativistic electron beam to sense its position even in the presence of other particle beams. ChDR is produced in alumina inserts embedded in the vacuum chamber walls and recorded in a narrow band centered at 30 GHz. This nontrivial solution has been implemented for plasma wakefield accelerators, where the electron beam to be sensed can copropagate with another high-energy proton beam that generates the plasma wakefield. In addition, at variance with most existing position detectors, this method is insensitive to spurious electric charges due to the presence of plasma. We present the overall design of the detector as well as experimental results obtained in the AWAKE facility at CERN.

Advanced Diagnostics of Electrons Escaping from Laser-Produced Plasma

Krasa, Josef; Krupka, Michal; Agarwal, Shubham; Nassisi, Vincenzo; Singh, Sushil

PLASMA 7(2), 366-385 (JUN 2024)

https://doi.org/10.3390/plasma7020021

This article provides an up-to-date overview of the problems associated with the detection of hot electrons escaping from laser-produced plasma and corresponding return current flowing from the ground to the target, which neutralises the positive charge occurring on the target due to the escaped electrons. In addition, the target holder system acts as an antenna emitting an electromagnetic pulse (EMP), which is powered by the return target. If the amount of positive charge generated on the target is equal to the amount of charge carried away from the plasma by the escaping electrons, the measurement of the return current makes it possible to determine this charge, and thus also the number of escaped electrons. Methods of return current detection in the mA-10 kA range is presented, and the corresponding charge is compared to the charge determined using calibrated magnetic electron energy analysers. The influence of grounded and insulated targets on the number of escaped electrons and EMP intensity is discussed. In addition to EMP detection, mapping of the electrical potential near the target is mentioned.

Laser drivers

Plasma electron acceleration driven by a long-wave-infrared laser

Zgadzaj, R.; Welch, J.; Cao, Y.; Amorim, L. D.; Cheng, A.; Gaikwad, A.; Iapozzutto, P.; Kumar, P.; Litvinenko, V. N.; Petrushina, I.; Samulyak, R.; Vafaei-Najafabadi, N.; Joshi, C.; Zhang, C.; Babzien, M.; Fedurin, M.; Kupfer, R.; Kusche, K.; Palmer, M. A.; Pogorelsky, I. V.; Polyanskiy, M. N.; Swinson, C.; Downer, M. C.

NATURE COMMUNICATIONS 15(1), 4037 (MAY 2024)

https://doi.org/10.1038/s41467-024-48413-y

Laser-driven plasma accelerators provide tabletop sources of relativistic electron bunches and femtosecond x-ray pulses, but usually require petawatt-class solid-state-laser pulses of wavelength $\lambda_L \sim 1$ μm. Longer-λ_L lasers can potentially accelerate higher-quality bunches, since they require less power to drive larger wakes in less dense plasma. Here, we report on a self-injecting plasma accelerator driven by a long-wave-infrared laser: a chirped-pulse-amplified CO_2 laser $\lambda_L \approx 10$ μm). Through optical scattering experiments, we observed wakes that 4-ps CO_2 pulses with < 1/2 terawatt (TW) peak power drove in hydrogen plasma of electron density down to 4×10^{17} cm^{-3} (1/100 atmospheric density) via a self-modulation (SM) instability. Shorter, more powerful CO_2 pulses drove wakes in plasma down to 3×10^{16} cm^{-3} that captured and accelerated plasma electrons to relativistic energy. Collimated quasi-monoenergetic features in the electron output marked the onset of a transition from SM to bubble-regime acceleration, portending future higher-quality accelerators driven by yet shorter, more powerful pulses.

Stabilization and correction of aberrated laser beams via plasma channelling

Rondepierre, Alexandre; Zhidkov, Alexei; Espinos, Driss Oumbarek; Hosokai, Tomonao
SCIENTIFIC REPORTS 14(1), 12078 (MAY 2024)
https://doi.org/10.1038/s41598-024-62997-x

High-power laser applications, and especially laser wakefield acceleration, continue to draw attention through various research topics, and may bring many industrial applications based on compact accelerators, from ultrafast imaging to cancer therapy. However, one main step towards this is the arch issue of stability. Indeed, the interaction of a complex, aberrated laser beam with plasma involves a lot of physical phenomena and non-linear effects, such as self-focusing and filamentation. Different outcomes can be induced by small laser instabilities (i.e. laser wavefront), therefore harming any practical solution. One promising path to be explored is the use of a plasma channel to possibly guide and correct aberrated beams. Complex and costly experimental facilities are required to investigate such topics. However, one way to quickly and efficiently explore new solutions is numerical simulations, especially Particle-In-Cell (PIC) simulations if, and only if, one is confidently implementing such aberrated beams which, contrary to a Gaussian beam, do not have analytical solutions. In this research, we propose two new advancements: the correct implementation of aberrated laser beams inside a 3D PIC code, showing a great consistency, under vacuum, compared to the calculations with Fresnel theory); and the correction of their quality via the propagation inside a plasma channel. We demonstrate improvements in the beam pattern, becoming closer to a single plasma mode with less distortions, and thus suggesting a better stability for the targeted application. Through this confident calculation technique for distorted laser beams, we are now expecting to proceed with more accurate PIC simulations, closer to experimental conditions, and obtained results with plasma channels indicate promising future research.

Luminal mirror

Esirkepov, T. Z.; Bulanov, S. V.
PHYSICAL REVIEW E 109(2), L023202 (FEB 2024)
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When a refractive index modulation of dispersive medium moves at the speed of light in vacuum, an incident electromagnetic wave, depending on its frequency, either is totally transmitted with a phase shift, or forms a standing wave, or is totally reflected with the frequency upshift. The luminal mirror converts a short incident pulse into a wave packet with an infinitely growing in time local frequency near the interface and with an energy spectral density that asymptotically is the inverse square of frequency. If the modulation disappears, the high frequency radiation is released.

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.

Ultrarelativistic electron beams accelerated by terawatt scalable kHz laser

Lazzarini, C. M.; Grittani, G. M.; Valenta, P.; Zymak, I.; Antipenkov, R.; Chaulagain, U.; Goncalves, L. V. N.; Grenfell, A.; Lamac, M.; Lorenz, S.; Nevrkla, M.; Spacek, A.; Sobr, V.; Szuba, W.; Bakule, P.; Korn, G.; Bulanov, S. V.
PHYSICS OF PLASMAS 31(3), 030703 (MAR 2024)
https://doi.org/10.1063/5.0189051

We show the laser-driven acceleration of unprecedented, collimated (2 mrad divergence), and quasi-monoenergetic (25% energy spread) electron beams with energy up to 50 MeV at 1 kHz repetition rate. The laser driver is a multi-cycle (15 fs) 1 kHz optical parametric chirped pulse amplification system, operating at 26 mJ (1.7 TW). The scalability of the driver laser technology and the electron beams reported in this work pave the way toward developing high-brilliance x-ray sources for medical imaging and innovative devices for brain cancer treatment and represent a step toward the realization of a kHz GeV electron beamline.

On the synergic approach toward the experimental realization of interesting fundamental science within the framework of relativistic flying mirror concept

Jeong, Tae Moon; Bulanov, Sergei V.; Valenta, Petr; Hadjisolomou, Prokopis
REVIEWS OF MODERN PLASMA PHYSICS 8(1), 9 (MAR 2024)
https://doi.org/10.1007/s41614-023-00139-y

The relativistic flying parabolic mirror can provide a higher laser intensity than the intensity a current laser system can reach via the optical-focusing scheme. A weakly relativistic laser intensity (1.8×10^{17} W/cm^2, η = 0.29) can be intensified up to a super-strong intensity of >1×10^{27} W/cm^2 ($\eta \approx 2.2 \times 10^4$) by the relativistic flying mirror. Such a super-strong field can be applied to study the strong-field quantum electrodynamics in perturbative and non-perturbative regimes. In this review, the analytic derivations on the field strength and distribution obtained by the ideal relativistic flying parabolic mirror have been shown under the 4π-spherical-focusing approach. The quantum non-linearity parameter is calculated when such a super-strong field collides with the high-energy γ-photons. The peak quantum non-linearity parameter reaches above 1600 when the 1-GeV γ -photon collides with a super-strong laser field reflected and focused by the relativistic flying mirror driven by a 10 PW laser pulse.

Analysis of plasma wakefield generation by a Laguerre-Gaussian laser beam in laser-plasma accelerators with external injection

Abedi-Varaki, Mehdi

PHYSICA SCRIPTA 99(9), 095611 (SEP 2024)
https://doi.org/10.1088/1402-4896/ad6ebe

This study presents a comprehensive modeling of wakefield generation through external injection utilizing a Laguerre-Gaussian (LG) laser beam in a bubble/blowout regime. The wakefield dynamics are simulated in two dimensions using the particle-in-cell (2D-PIC) method via Wake-T tool, aiming to investigate the underlying mechanisms and characteristics of this process. The simulation results provide insights into the behavior of electrons within the wakefield, their acceleration, phase spaces of the electron beam, velocity distribution, and longitudinal and transversal profiles of the laser electric field in the plasma. The presented model serves as a valuable tool for further investigations into wakefield generation with external injection using LG laser beams, facilitating advancements in this field of study.

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

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IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS 31(2), 1500407 (MAR 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.

Plasma structures

Resonant excitation of plasma waves in a plasma channel

Ross, A. J.; Chappel, J.; van de Wetering, J. J.; Cowley, J.; Archer, E.; Bourgeois, N.; Corner, L.; Emerson, D. R.; Feder, L.; Gu, X. J.; Jakobsson, O.; Jones, H.; Picksley, A.; Reid, L.; Wang, W.; Walczak, R.; Hooker, S. M.
PHYSICAL REVIEW RESEARCH 6(2), L022001 (APR 2024)
https://doi.org/10.1103/PhysRevResearch.6.L022001

We demonstrate resonant excitation of a plasma wave by a train of short laser pulses guided in a preformed plasma channel, for parameters relevant to a plasma-modulated plasma accelerator (P-MoPA). We show experimentally that a train of $N \approx 10$ short pulses, of total energy ~ 1 J, can be guided through 110 mm long plasma channels with on-axis densities in the range 10^{17} - 10^{18} cm^{-3}. The spectrum of the transmitted train is found to be strongly red shifted when the plasma period is tuned to the intratrain pulse spacing. Numerical simulations are found to be in excellent agreement with the measurements and indicate that the resonantly excited plasma waves have an amplitude in the range 3 - 10 GVm^{-1}, corresponding to an accelerator stage energy gain of order 1 GeV.

Emittance preservation for the electron arm in a single PWFA-LC stage using quasi-adiabatic plasma density ramp matching sections

Zhao, Yujian; Hildebrand, Lance; An, Weiming; Xu, Xinlu; Li, Fei; Dalichaouch, Thamine N.; Su, Qianqian; Joshi, Chan; Mori, Warren B.

PHYSICS OF PLASMAS 31(6), 063106 (JUN 2024)
https://doi.org/10.1063/5.0206378

Plasma-based acceleration (PBA) is being considered for a next generation linear collider (LC). In some PBA-LC designs for the electron arm, the extreme beam parameters are expected to trigger background ion motion within the witness beam, which can lead to longitudinally varying nonlinear focusing forces and result in an unacceptable emittance growth of the beam. To mitigate this, we propose to use quasi-adiabatic plasma density ramps as matching sections at the entrance and exit of each stage. We match the witness electron beam to the low density plasma entrance, where the beam initially has a large matched spot size so the ion motion effects are relatively small. As the beam propagates in the plasma density upramp, it is quasi-adiabatically focused, and its distribution maintains a non-Gaussian equilibrium distribution in each longitudinal slice throughout the process, even when severe ion collapse has occurred. This only causes small amounts of slice emittance growth. The phase mixing between slices with different betatron frequencies leads to additional projected emittance growth within the acceleration stage. A density downramp at the exit of an acceleration section can eliminate much of the slice and projected emittance growth as the beam and ion motion adiabatically defocuses and decreases, respectively. Simulation results from QuickPIC with Azimuthal Decomposition show that within a single acceleration stage with a 25 GeV energy gain, this concept can limit the projected emittance growth to only ~ 2% for a 25 GeV, 100 nm emittance witness beam and ~ 20% for a 100 GeV, 100 nm normalized emittance witness beam. The trade-off between the adiabaticity of the plasma density ramp and the initial ion motion at the entrance for a given length of the plasma density ramp is also discussed.

Simulation observation of high effectiveness laser plasma wakefield accelerator using plasma telescope configuration

Zeng, Ming
PHYSICS OF PLASMAS 31(8), 080702 (AUG 2024)
https://doi.org/10.1063/5.0223051

In the laser wakefield accelerators, the energy transfer efficiency from the laser to the electron beam and the energy spread of the electron beam are parameters of contradiction, which people have not been able to improve simultaneously for a long time. To generate quasi-monoenergetic electron beams, the energy transfer efficiencies are up to the 1% level, while for 10% or higher energy transfer efficiencies, the electron spectra are broad in general. In the series of particle-in-cell simulations shown in this paper, we observe the simultaneous improvement of these two parameters by the self-injection mechanism in uniform plasma using the plasma telescope configuration [Zeng et al., Phys. Plasmas 27, 023109 (2020)]. The energy transfer efficiency is increased to more than 10%, and the energy spread of the electron beam is less than 5%. We also show the possibility to produce an electron beam with the energy of 1.871 GeV, the charge of 2.13 nC, and the energy spread of 2.5% by a 30 J laser.

A Scalable, High-Efficiency, Low-Energy-Spread Laser Wakefield Accelerator Using a Tri-Plateau Plasma Channel

Liu, Shuang; Li, Fei; Zhou, Shiyu; Hua, Jianfei; Mori, Warren B.; Joshi, Chan; Lu, Wei
RESEARCH 7, 0396 (AUG 2024)
https://doi.org/10.34133/research.0396

The emergence of multi-petawatt laser facilities is expected to push forward the maximum energy gain that can be achieved in a single stage of a laser wakefield acceleration (LWFA) to tens of giga-electron volts, which begs the question-is it likely to impact particle physics by providing a truly compact particle collider? Colliders

have very stringent requirements on beam energy, acceleration efficiency, and beam quality. In this article, we propose an LWFA scheme that can for the first time simultaneously achieve hitherto unrealized acceleration efficiency from the laser to the electron beam of > 20% and a sub-1% energy spread using a stepwise plasma structure and a nonlinearly chirped laser pulse. Three-dimensional high-fidelity simulations show that the nonlinear chirp can effectively mitigate the laser waveform distortion and lengthen the acceleration distance. This, combined with an interstage rephasing process in the stepwise plasma, can triple the beam energy gain compared to that in a uniform plasma for a fixed laser energy, thereby dramatically increasing the efficiency. A dynamic beam loading effect can almost perfectly cancel the energy chirp that arises during the acceleration, leading to the sub-percent energy spread. This scheme is highly scalable and can be applied to petawatt LWFA scenarios. Scaling laws are obtained, which suggest that electron beams with parameters relevant for a Higgs factory could be reached with the proposed high-efficiency, low-energy-spread scheme.

Instabilities

Filamentation of a relativistic proton bunch in plasma

Verra, L. et al. (AWAKE Collaboration)
PHYSICAL REVIEW E 109(5), 055203 (MAY 2024)
https://doi.org/10.1103/PhysRevE.109.055203

We show in experiments that a long, underdense, relativistic proton bunch propagating in plasma undergoes the oblique instability, which we observe as filamentation. We determine a threshold value for the ratio between the bunch transverse size and plasma skin depth for the instability to occur. At the threshold, the outcome of the experiment alternates between filamentation and self-modulation instability (evidenced by longitudinal modulation into microbunches). Time-resolved images of the bunch density distribution reveal that filamentation grows to an observable level late along the bunch, confirming the spatiotemporal nature of the instability. We provide a rough estimate of the amplitude of the magnetic field generated in the plasma by the instability and show that the associated magnetic energy increases with plasma density.

Investigation of laser plasma instabilities driven by 527 nm laser pulses relevant for direct drive inertial confinement fusion

F. Wasser ; Ş. Zähter; M. Rivers; S. Atzeni; F. P. Condamine; G. Cristoforetti; G. Fauvel; N. Fischer; L. A. Gizzi; D. Hoffmann; P. Koester; T. Laštovička; J. F. Myatt; R. L. Singh; M. Sokol; W. Theobald; S. Weber; T. Ditmire; T. Forner; M. Roth
PHYSICS OF PLASMAS 31, 022107 (FEB 2024)
https://doi.org/10.1063/5.0188693

We report on a study of laser plasma instabilities with 527nm laser pulses in an intensity range of 0.5×10^{13} – 1.1×10^{15} Wcm^{-2} and plasma parameters entering a regime that is relevant for direct drive inertial confinement fusion. Using the kilojoule high repetition rate L4n laser at the Extreme Light Infrastructure—Beamlines, more than 1300 shots were collected, and the onset and the growth of stimulated Brioullin scattering (SBS) and stimulated Raman scattering (SRS) were studied with a high confidence level. The measured onset intensities are 0.2×10^{14} Wcm^{-2} for SBS and 1.4×10^{14} Wcm^{-2} for SRS. At the maximum intensity, the total fraction of backscattered energy reaches 2.5% for SBS and 0.1% for SRS. These results are of high relevance for advanced concepts for inertial fusion energy, which rely on the use of 527nm laser light to drive the implosion of the fuel target, and in particular, they can be used as a benchmark for advanced simulations.

BEAMLINES & APPLICATIONS

Guiding of Charged Particle Beams in Curved Plasma-Discharge Capillaries

Pompili, R.; Anania, M. P.; Biagioni, A.; Carillo, M.; Chiadroni, E.; Cianchi, A.; Costa, G.; Curcio, A.; Crincoli, L.; Del Dotto, A.; Del Giorno, M.; Demurtas, F.; Frazzitta, A.; Galletti, M.; Giribono, A.; Lollo, V.; Opromolla, M.; Parise, G.; Pellegrini, D.; Di Pirro, G.; Romeo, S.; Rossi, A. R.; Silvi, G. J.; Verra, L.; Villa, F.; Zigler, A.; Ferrario, M.

PHYSICAL REVIEW LETTERS 132(21), 215001 (MAY 2024)
https://doi.org/10.1103/PhysRevLett.132.215001

We present a new approach that demonstrates the deflection and guiding of relativistic electron beams over curved paths by means of the magnetic field generated in a plasma-discharge capillary. We experimentally prove that the guiding is much less affected by the beam chromatic dispersion with respect to a conventional bending magnet and, with the support of numerical simulations, we show that it can even be made dispersionless by employing larger discharge currents. This proof-of-principle experiment extends the use of plasma-based devices, that revolutionized the field of particle accelerators enabling the generation of GeV beams in few centimeters. Compared to state-of-the-art technology based on conventional bending magnets and quadrupole lenses, these results provide a compact and affordable solution for the development of next-generation tabletop facilities.

Acceleration and focusing of relativistic electron beams in a compact plasma device

Pompili, R.; Anania, M. P.; Biagioni, A.; Carillo, M.; Chiadroni, E.; Cianchi, A.; Costa, G.; Curcio, A.; Crincoli, L.; Del Dotto, A.; Del Giorno, M.; Demurtas, F.; Galletti, M.; Giribono, A.; Lollo, V.; Opromolla, M.; Parise, G.; Pellegrini, D.; Di Pirro, G.; Romeo, S.; Silvi, G. J.; Verra, L.; Villa, F.; Zigler, A.; Ferrario, M.

PHYSICAL REVIEW E 109(5), 055202 (MAY 2024)
https://doi.org/10.1103/PhysRevE.109.055202

Plasma wakefield acceleration represented a breakthrough in the field of particle accelerators by pushing beams to gigaelectronvolt energies within centimeter distances. The large electric fields excited by a driver pulse in the plasma can efficiently accelerate a trailing witness bunch paving the way toward the realization of laboratory-scale applications like free-electron lasers. However, while the accelerator size is tremendously reduced, upstream and downstream of it the beams are still handled with conventional magnetic optics with sizable footprints and rather long focal lengths. Here we show the operation of a compact device that integrates two active-plasma lenses with short focal lengths to assist the plasma accelerator stage. We demonstrate the focusing and energy gain of a witness bunch whose phase space is completely characterized in terms of energy and emittance. These results represent an important step toward the accelerator miniaturization and the development of next-generation table-top machines.

Laser-driven pointed acceleration of electrons with preformed plasma lens

Ivanov, K. A.; Gorlova, D. A.; Tsymbalov, I. N.; Tsygvintsev, I. P.; Shulyapov, S. A.; Volkov, R. V.; Savel'ev, A. B.

PHYSICAL REVIEW ACCELERATORS AND BEAMS 27(5), 051301 (MAY 2024)
https://doi.org/10.1103/PhysRevAccelBeams.27.051301

The simultaneous laser-driven acceleration and angular manipulation of the fast electron beam are experimentally demonstrated. The bunch of multi-MeV energy charged particles is generated during the propagation of the femtosecond laser pulse through the near-critical plasma slab accompanied by plasma channeling. Plasma is formed by the controlled breakdown of a thin-tape target by a powerful nanosecond prepulse. The electron beam pointing approach is based on the refraction of a laser pulse in the presence of a strong radial density gradient in the breakdown of the tape with a small displacement of the femtosecond

laser beam relative to the breakdown symmetry axis. A shift of several micrometers makes it possible to achieve beam deflection by an angle up to 10 degrees with acceptable beam charge and spectrum conservation. This opens up opportunities for in situ applications for scanning objects with an electron beam and the multistage electron beam energy gain in consecutive laser accelerators without bulk magnetic optics for particles. Experimental findings are supported by numerical particle -in -cell calculations of laser -plasma acceleration and hydrodynamic simulations.

Plasma-based particle sources

Fuchs, M.; Andonian, G.; Apsimon, O.; Buescher, M.; Downer, M. C.; Filippetto, D.; Lehrach, A.; Schroeder, C. B.; Shadwick, B. A.; Thomas, A. G. R.; Vafaei-Najafabadi, N.; Xia, G.
JOURNAL OF INSTRUMENTATION 19(1), T01004 (JAN 2024)
https://doi.org/10.1088/1748-0221/19/01/T01004

High-brightness particle beams generated by advanced accelerator concepts have the potential to become an essential part of future accelerator technology. In particular, high-gradient accelerators can generate and rapidly accelerate particle beams to relativistic energies. The rapid acceleration and strong confining fields can minimize irreversible detrimental effects to the beam brightness that occur at low beam energies, such as emittance growth or pulse elongation caused by space charge forces. Due to the high accelerating gradients, these novel accelerators are also significantly more compact than conventional technology. Advanced accelerators can be extremely variable and are capable of generating particle beams with vastly different properties using the same driver and setup with only modest changes to the interaction parameters. So far, efforts have mainly been focused on the generation of electron beams, but there are concepts to extend the sources to generate spin -polarized electron beams or positron beams. The beam parameters of these particle sources are largely determined by the injection and subsequent acceleration processes. Although, over the last decade there has been significant progress, the sources are still lacking a sufficiently high 6-dimensional (D) phase-space density that includes small transverse emittance, small energy spread and high charge, and operation at high repetition rate. This is required for future particle colliders with a sufficiently high luminosity or for more near-term applications, such as enabling the operation of free-electron lasers (FELs) in the X-ray regime. Major research and development efforts are required to address these limitations in order to realize these approaches for a front-end injector for a future collider or next-generation light sources. In particular, this includes methods to control and manipulate the phase-space and spin degrees-of-freedom of ultrashort plasma-based electron bunches with high accuracy, and methods that increase efficiency and repetition rate. These efforts also include the development of high-resolution diagnostics, such as full 6D phase-space measurements, beam polarimetry and high-fidelity simulation tools. A further increase in beam luminosity can be achieve through emittance damping. Emittance cooling via the emission of synchrotron radiation using current technology requires kilometer-scale damping rings. For future colliders, the damping rings might be replaced by a substantially more compact plasma-based approach. Here, plasma wigglers with significantly stronger magnetic fields are used instead of permanent-magnet based wigglers to achieve similar damping performance but over a two orders of magnitude reduced length.

Radiotherapy

First in vitro cell co-culture experiments using laser-induced high-energy electron FLASH irradiation for the development of anti-cancer therapeutic strategies

Orobeti, Stefana; Sima, Livia Elena; Porosnicu, Ioana; Diplasu, Constantin; Giubega, Georgiana; Cojocaru, Gabriel; Ungureanu, Razvan; Dobrea, Cosmin; Serbanescu, Mihai; Mihalcea, Alexandru; Stancu, Elena; Staicu,

Cristina Elena; Jipa, Florin; Bran, Alexandra; Axente, Emanuel; Sandel, Simion; Zamfirescu, Marian; Tiseanu, Ion; Sima, Felix
SCIENTIFIC REPORTS 14(1), 14866 (JUN 2024)
https://doi.org/10.1038/s41598-024-65137-7

Radiation delivery at ultrahigh dose rates (UHDRs) has potential for use as a new anticancer therapeutic strategy. The FLASH effect induced by UHDR irradiation has been shown to maintain antitumour efficacy with a reduction in normal tissue toxicity; however, the FLASH effect has been difficult to demonstrate in vitro. The objective to demonstrate the FLASH effect in vitro is challenging, aiming to reveal a differential response between cancer and normal cells to further identify cell molecular mechanisms. New high-intensity petawatt laser-driven accelerators can deliver very high-energy electrons (VHEEs) at dose rates as high as 10^{13} Gy/s in very short pulses (10^{-13} s). Here, we present the first in vitro experiments carried out on cancer cells and normal non-transformed cells concurrently exposed to laser-plasma accelerated (LPA) electrons. Specifically, melanoma cancer cells and normal melanocyte co-cultures grown on chamber slides were simultaneously irradiated with LPA electrons. A non-uniform dose distribution on the cell cultures was revealed by Gafchromic films placed behind the chamber slide supporting the cells. In parallel experiments, cell co-cultures were exposed to pulsed X-ray irradiation, which served as positive controls for radiation-induced nuclear DNA double-strand breaks. By measuring the impact on discrete areas of the cell monolayers, the greatest proportion of the damaged DNA-containing nuclei was attained by the LPA electrons at a cumulative dose one order of magnitude lower than the dose obtained by pulsed X-ray irradiation. Interestingly, in certain discrete areas, we observed that LPA electron exposure had a different effect on the DNA damage in healthy normal human epidermal melanocyte (NHEM) cells than in A375 melanoma cells; here, the normal cells were less affected by the LPA exposure than cancer cells. This result is the first in vitro demonstration of a differential response of tumour and normal cells exposed to FLASH irradiation and may contribute to the development of new cell culture strategies to explore fundamental understanding of FLASH-induced cell effect.

THz radiation

Millijoule Terahertz Radiation from Laser Wakefields in Nonuniform Plasmas

Wang, Linzheng; Zhang, Zhelin; Chen, Siyu; Chen, Yanping; Hu, Xichen; Zhu, Mingyang; Yan, Wenchao; Xu, Hao; Sun, Lili; Chen, Min; Liu, Feng; Chen, Liming; Zhang, Jie; Sheng, Zhengming
PHYSICAL REVIEW LETTERS 132(16), 165002 (APR 2024)
https://doi.org/10.1103/PhysRevLett.132.165002

We report the experimental measurement of millijoule terahertz (THz) radiation emitted in the backward direction from laser wakefields driven by a femtosecond laser pulse of few joules interacting with a gas target. By utilizing frequency -resolved energy measurement, it is found that the THz spectrum exhibits two peaks located at about 4.5 and 9.0 THz, respectively. In particular, the high frequency component emerges when the drive laser energy exceeds 1.26 J, at which electron acceleration in the forward direction is detected simultaneously. Theoretical analysis and particle -in -cell simulations indicate that the THz radiation is generated via mode conversion from the laser wakefields excited in plasma with an upramp profile, where radiations both at the local electron plasma frequency and its harmonics are produced. Such intense THz sources may find many applications in ultrafast science, e.g., manipulating the transient states of matter.

X rays

Ultrabroad-band x-ray source using a picosecond, laser-driven plasma accelerator

Lemos, N.; King, P. M.; Rusby, D.; Pagano, I.; Sinclair, M.; Marsh, K. A.; Shaw, J. L.; Milder, A. L.; Pak, A.; Pollock, B. B.; Aufderheide, M.; Hartemann, F., V; Wu, S. Q.; Hwang, Y.; Hegelich, B. M.; Moody, J.; Michel, P.; Joshi, C.; Albert, F.

PHYSICAL REVIEW RESEARCH 6(3), L032022 (JUL 2024)

https://doi.org/10.1103/PhysRevResearch.6.L032022

An ultrabroad-band x-ray source, with photon energies from 10 keV to >1 MeV, based on a picosecond laserdriven plasma accelerator, is characterized and used to radiograph high-energy-density-science relevant targets. The measured yield of 10^{12} photons/shot is reaching the necessary photon yields to radiograph, in a single shot, high areal density objects and matter under extreme conditions. By focusing a short laser pulse (120 J, 1 ps) into a gas jet, a <100 mrad electron beam with energies up to 350 MeV and up to 70 nC of charge was produced by a combination of laser self-modulation instability and direct laser acceleration. A foil placed at the exit of the gas jet is used to convert part of the electron beam energy into x rays through inverse bremsstrahlung and/or inverse Compton scattering, generating a bright, broad-band, high-photon-energy beam. This beam is used to radiograph a gold half hohlraum with a high-density sphere inside with relevant characteristics for high-energy-density science and inertial confinement fusion.

Extended X-ray absorption spectroscopy using an ultrashort pulse laboratory-scale laser-plasma accelerator

Kettle, Brendan; Colgan, Cary; Los, Eva E.; Gerstmayr, Elias; Streeter, Matthew J. V.; Albert, Felicie; Astbury, Sam; Baggott, Rory A.; Cavanagh, Niall; Falk, Katerina; Hyde, Timothy I.; Lundh, Olle; Rajeev, P. Pattathil; Riley, Dave; Rose, Steven J.; Sarri, Gianluca; Spindloe, Chris; Svendsen, Kristoffer; Symes, Dan R.; Smid, Michal; Thomas, Alec G. R.; Thornton, Chris; Watt, Robbie; Mangles, Stuart P. D.

COMMUNICATIONS PHYSICS 7(1), 247 (JUL 2024)

https://doi.org/10.1038/s42005-024-01735-1

Laser-driven compact particle accelerators can provide ultrashort pulses of broadband X-rays, well suited for undertaking X-ray absorption spectroscopy measurements on a femtosecond timescale. Here the Extended X-ray Absorption Fine Structure (EXAFS) features of the K-edge of a copper sample have been observed over a 250 eV window in a single shot using a laser wakefield accelerator, providing information on both the electronic and ionic structure simultaneously. This capability will allow the investigation of ultrafast processes, and in particular, probing high-energy-density matter and physics far-from-equilibrium where the sample refresh rate is slow and shot number is limited. For example, states that replicate the tremendous pressures and temperatures of planetary bodies or the conditions inside nuclear fusion reactions. Using high-power lasers to pump these samples also has the advantage of being inherently synchronised to the laser-driven X-ray probe. A perspective on the additional strengths of a laboratory-based ultrafast X-ray absorption source is presented.; Laser-driven X-rays can provide ultrashort pulses of broadband light, well suited for femtosecond timescale absorption spectroscopy. Here the authors measure the extended X-ray absorption features of a copper sample using a laser wakefield accelerator, in a single shot; important for studying samples driven to extreme and non-equilibrium states.

Bright X/γ -ray emission and lepton pair production by strong laser fields: a review

Yu, Tong-Pu; Liu, Ke; Zhao, Jie; Zhu, Xing-Long; Lu, Yu; Cao, Yue; Zhang, Hao; Shao, Fu-Qiu; Sheng, Zheng-Ming

REVIEWS OF MODERN PLASMA PHYSICS 8(1), 24 (JUN 2024)

https://doi.org/10.1007/s41614-024-00158-3

The advent of high-power ultra-short laser pulses opens up new frontiers of relativistic non-linear optics, high energy density physics and laboratory astrophysics. As the laser electric field in the particle rest frame approaches the Schwinger field E_{cr} =1.3 x 10^{18} Vm^{-1}, the laser interaction with matter enters into the quantum electrodynamics (QED) dominated regime, where extremely rich non-linear phenomena take place, such as a violent acceleration of charged particles, copious lepton pair production, and ultra-brilliant X/γ-ray emission. Among them, X/γ-ray emission based on the laser-plasma is generally characterized by large photon flux, high brilliance, small source size, and high photon energy, which can even annihilate into lepton pairs by colliding with photons. Though various schemes have been proposed for bright high-energy photon emission and lepton generation and acceleration, many predictions remain to be confirmed and thoroughly tested in experiments. In this review, we introduce recent advances in bright X/γ-ray radiation and lepton pair generation in the QED regime by the interaction of relativistic intense lasers with various plasma targets. The characteristics of the radiation and secondary particles generated via these schemes are summarized, and the experimental progresses are elaborated.

Source size of x rays from self-modulated laser wakefield accelerators

Pagano, I. M.; Lemos, N.; King, P. M.; Rusby, D.; Sinclair, M.; Aghedo, A.; Khan, S.; Downer, M. C.; Joshi, C.; Albert, F.

PHYSICS OF PLASMAS 31(7), 073110 (JUL 2024)
https://doi.org/10.1063/5.0191435

A comparative study of x-ray sources generated with different mechanisms from self-modulated laser wakefield acceleration (SM-LWFA) electrons was performed to compare the source size or spatial resolution for use in high energy density science applications. We examine the source size of betatron, inverse Compton scattering, and bremsstrahlung radiation with a Fresnel diffraction based formalism and a modified x-ray ray tracing model. We observe the dependence of source size on the radiation generation process, laser parameters, and compare to what is possible in other regimes of LWFA, as well as current methods. This information is significant as we begin to explore the use of light sources driven by SM-LWFA for use as a diagnostic at large-scale laser facilities where blowout regime LWFA is not possible. (c) 2024 Author(s).

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

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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. (c) 2024 Author(s).

Laser polarization control of ionization-injected electron beams and x-ray radiation in laser wakefield accelerators

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PLASMA PHYSICS AND CONTROLLED FUSION 66(8), 085001 (AUG 2024)
https://doi.org/10.1088/1361-6587/ad5379

In this paper, we have studied the influence of laser polarization on the dynamics of the ionization-injected electron beams, and subsequently, the properties of the emitted betatron radiation in laser wakefield accelerators (LWFAs). While ionizing by strong field laser radiation, the generated photo-electrons carry a residual transverse momentum in excess of the ionization potential via the above threshold ionization (ATI) process. This ATI momentum explicitly depends on the polarization state of the ionizing laser and eventually governs the dynamics of the electron beam trapped inside the wake potential. In order to systematically investigate the effect of the laser polarization, here, we have employed complete three-dimensional particle-in-cell simulations in the nonlinear bubble regime of the LWFAs. We focus, in particular, on the effects the laser polarization has on the ionization injection mechanism, and how these features affect the final beam properties, such as beam charge, energy, energy spread, and transverse emittance. We have also found that as the laser polarization gradually changes from linear to circular, the helicity of the electron trajectory, and hence the angular momentum carried by the beam, increases significantly. Studies have been further extended to reveal the effect of laser polarization on the radiation emitted by the accelerated electrons. The far-field radiation spectra have been calculated for the linear and circular polarization states of the laser. It has been shown that the spatial distributions and the polarization properties (Stokes parameters) of the emitted radiation in the above two cases are substantially different. Therefore, our study provides a facile and efficient alternative to regulate the properties of the accelerated electron beams and x-ray radiation in LWFAs, utilizing ionization injection mechanism.

Free Electron Lasers

Prospects for free-electron lasers powered by plasma-wakefield-accelerated beams

Galletti, M.; Assmann, R.; Couprie, M. E.; Ferrario, M.; Giannessi, L.; Irman, A.; Pompili, R.; Wang, W.
NATURE PHOTONICS 18, 780–791 (AUG 2024)
https://doi.org/10.1038/s41566-024-01474-3

Plasma-wakefield-based acceleration technology has the potential to revolutionize the field of particle accelerators. By providing acceleration gradients orders of magnitude larger than conventional radiofrequency particle accelerators, this technology allows accelerators to be reduced to the centimetre length scale. It also provides a new compact approach for driving free-electron lasers, a valuable source of high-brilliance ultrashort coherent radiation within the infrared to X-ray spectral range for the study of subatomic matter, ultrafast dynamics of complex systems and X-ray nonlinear optics, among other applications. Several laboratories around the world are working on the realization of these new light sources, exploring different configurations for the plasma wakefield driver beam, plasma stage design and operational regime. This Review describes the operating principles of plasma accelerators, an overview of recent experimental milestones for plasma-driven free-electron lasers in self-amplified spontaneous emission and seeded configurations, and highlights the remaining major challenges in the field.

Permanent helical micro-undulators for x-ray free electron lasers

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https://doi.org/10.1063/5.0199053

Helical Halbach undulators, formed by four alternately axially and radially magnetized rare-earth helices, produce a stronger field than two planar Halbach undulators with perpendicular polarization. Hybrid undulators of two longitudinally premagnetized rare-earth helices and two initially unmagnetized steel (or vanadium permendur) helices produce an equal or higher field and are easier to implement. We made sure that the required helices with a period of down to 3 mm or even less could be manufactured with high precision using Wire Electric Discharge Machining. According to the simulation results, when using identical electron bunches with moderate initial spreads in energy and angles, the gain in x-ray free electron laser (XFEL) power from replacing planar micro-undulators with the helical micro-undulators under consideration can be significantly greater than predicted by the simplest 1D theory with a cold electron beam. This makes such micro-undulators promising for creating compact XFELs of various types, both based on modern linear accelerators and plasma wakefield accelerators.

FACILITIES

Quantitative elemental analysis of a specimen in air via external beam laser-driven particle-induced x-ray emission with a compact proton source

Martina Salvadori , Fernando Brandi , Luca Labate, Federica Baffigi, Lorenzo Fulgentini, Pietro Galizia, Petra Koester, Daniele Palla, Diletta Sciti, and Leonida A. Gizzi

PHYSICAL REVIEW APPLIED 21, 064020 (JUN 2024)
https://doi.org/10.1103/PhysRevApplied.21.064020

Particle-induced x-ray emission (PIXE) is a well-established ion-beam analysis technique, enabling quantitative measurement of the elemental composition of a sample surface under an ambient atmosphere with an external beam, which significantly simplifies the measurements, and is strictly necessary for those samples that cannot sustain a vacuum environment. Few-MeV electrostatic proton accelerators are used today in PIXE systems. We present here an external beam PIXE methodology based on a compact laser-driven proton accelerator. A 10-TW class ultrashort laser is used to generate a few-MeV proton beam, and a compact transport magnetic beamline is used to collect and transport the proton beam and to prevent unwanted fast electrons from reaching the sample. An x-ray CCD camera in single-photon detection mode is used to retrieve the spectrum of radiation emitted by the samples upon proton irradiation in air. Elemental composition analysis is performed and validated against standard energy-dispersive x-ray spectroscopy, demonstrating quantitative and accurate external beam PIXE analysis with compact laser-driven accelerators.

Shock compression experiments using the DiPOLE 100-X laser on the high energy density instrument at the European x-ray free electron laser: Quantitative structural analysis of liquid Sn

M. G. Gorman et al.

JOURNAL OF APPLIED PHYSICS 135, 165902 (APR 2024)
https://doi.org/10.1063/5.0201702

X-ray free electron laser (XFEL) sources coupled to high-power laser systems offer an avenue to study the structural dynamics of materials at extreme pressures and temperatures. The recent commissioning of the

DiPOLE 100-X laser on the high energy density (HED) instrument at the European XFEL represents the state-of-the-art in combining x-ray diffraction with laser compression, allowing for compressed materials to be probed in unprecedented detail. Here, we report quantitative structural measurements of molten Sn compressed to 85(5) GPa and ∼3500 K. The capabilities of the HED instrument enable liquid density measurements with an uncertainty of ∼1% at conditions which are extremely challenging to reach via static compression methods. We discuss best practices for conducting liquid diffraction dynamic compression experiments and the necessary intensity corrections which allow for accurate quantitative analysis. We also provide a polyimide ablation pressure vs input laser energy for the DiPOLE 100-X drive laser which will serve future users of the HED instrument.

Design of Machine Learning-Based Algorithms for Virtualized Diagnostic on SPARC_LAB Accelerator

Latini, Giulia; Chiadroni, Enrica; Mostacci, Andrea; Martinelli, Valentina; Serenellini, Beatrice; Silvi, Gilles Jacopo; Pioli, Stefano
PHOTONICS 11(6), 516 (JUN 2024)
https://doi.org/10.3390/photonics11060516

Machine learning deals with creating algorithms capable of learning from the provided data. These systems have a wide range of applications and can also be a valuable tool for scientific research, which in recent years has been focused on finding new diagnostic techniques for particle accelerator beams. In this context, SPARC_LAB is a facility located at the Frascati National Laboratories of INFN, where the progress of beam diagnostics is one of the main developments of the entire project. With this in mind, we aim to present the design of two neural networks aimed at predicting the spot size of the electron beam of the plasma-based accelerator at SPARC_LAB, which powers an undulator for the generation of an X-ray free electron laser (XFEL). Data-driven algorithms use two different data preprocessing techniques, namely an autoencoder neural network and PCA. With both approaches, the predicted measurements can be obtained with an acceptable margin of error and most importantly without activating the accelerator, thus saving time, even compared to a simulator that can produce the same result but much more slowly. The goal is to lay the groundwork for creating a digital twin of linac and conducting virtualized diagnostics using an innovative approach.

Wakefield generation in hydrogen and lithium plasmas at FACET-II: Diagnostics and first beam-plasma interaction results

Storey, D.; Zhang, C.; Claveria, P. San Miguel; Cao, G. J.; Adli, E.; Alsberg, L.; Ariniello, R.; Clarke, C.; Corde, S.; Dalichaouch, T. N.; Doss, C. E.; Ekerfelt, H.; Emma, C.; Gerstmayr, E.; Gessner, S.; Gilljohann, M.; Hast, C.; Knetsch, A.; Lee, V.; Litos, M.; Loney, R.; Marsh, K. A.; Matheron, A.; Mori, W. B.; Nie, Z.; O'Shea, B.; Parker, M.; White, G.; Yocky, G.; Zakharova, V.; Hogan, M. J.; Joshi, C.
PHYSICAL REVIEW ACCELERATORS AND BEAMS 27(5), 051302 (MAY 2024)
https://doi.org/10.1103/PhysRevAccelBeams.27.051302

Plasma wakefield acceleration provides ultrahigh acceleration gradients of tens of GeV/m, providing a novel path toward efficient, compact, TeV-scale linear colliders, and high brightness free electron lasers. Critical to the success of these applications is demonstrating simultaneously high gradient acceleration, high energy transfer efficiency, and preservation of emittance, charge, and energy spread. Experiments at the FACET-II National User Facility at SLAC National Accelerator Laboratory aim to achieve all of these milestones in a single-stage plasma wakefield accelerator, providing a 10 GeV energy gain in a < 1 m plasma with high energy transfer efficiency. Such a demonstration depends critically on diagnostics able to measure emittance with mm mrad accuracy, energy spectra to determine both percent level energy spread, and broadband energy gain and loss, incoming longitudinal phase space, and matching dynamics. This paper discusses the experimental setup at FACET-II, including the incoming beam parameters from the FACET-II linac, plasma sources, and diagnostics developed to meet this challenge. Initial progress on the generation of beam ionized wakes in meter-scale hydrogen gas is discussed as well as commissioning of the plasma sources and diagnostics.

Correlations between X-rays, visible light and drive-beam energy loss observed in plasma wakefield acceleration experiments at FACET-II

Zhang, Chaojie; Storey, Doug; Claveria, Pablo San Miguel; Nie, Zan; Marsh, Ken A.; Mori, Warren B.; Adli, Erik; An, Weiming; Ariniello, Robert; Cao, Gevy J.; Clark, Christine; Corde, Sebastien; Dalichaouch, Thamine; Doss, Christopher E.; Emma, Claudio; Ekerfelt, Henrik; Gerstmayr, Elias; Gessner, Spencer; Hansel, Claire; Knetsch, Alexander; Lee, Valentina; Li, Fei; Litos, Mike; OShea, Brendan; White, Glen; Yocky, Gerry; Zakharova, Viktoriia; Hogan, Mark; Joshi, Chan
JOURNAL OF PLASMA PHYSICS 90(4), 965900401 (SEP 2024)
https://doi.org/10.1017/S0022377824000734

This study documents several correlations observed during the first run of the plasma wakefield acceleration experiment E300 conducted at FACET-II, using a single drive electron bunch. The established correlations include those between the measured maximum energy loss of the drive electron beam and the integrated betatron X-ray signal, the calculated total beam energy deposited in the plasma and the integrated X-ray signal, among three visible light emission measuring cameras and between the visible plasma light and X-ray signal. The integrated X-ray signal correlates almost linearly with both the maximum energy loss of the drive beam and the energy deposited into the plasma, demonstrating its usability as a measure of energy transfer from the drive beam to the plasma. Visible plasma light is found to be a useful indicator of the presence of a wake at three locations that overall are two metres apart. Despite the complex dynamics and vastly different time scales, the X-ray radiation from the drive bunch and visible light emission from the plasma may prove to be effective non-invasive diagnostics for monitoring the energy transfer from the beam to the plasma in future high-repetition-rate experiments.

Fundamental physics opportunities with multi-petawatt- and multi-megaJoule-class facilities

Norreys, Peter A.
HIGH ENERGY DENSITY PHYSICS 52, 101129 (SEP 2024)
https://doi.org/10.1016/j.hedp.2024.101129

In this invited paper, I will touch on some highlights from my research career in the Clarendon Laboratory and in the Central Laser Facility, Rutherford Appleton Laboratory, obtained working in partnership with many outstanding international collaborators. These fall under the three broad themes. The first is novel laser-plasma interactions. The second theme is that of extreme field physics using multi-petawatt laser facilities. The third theme is that of inertial fusion studies. All of these studies indicate that an international, dual-use, 20-MJ Inertial Confinement Fusion (ICF)/Inertial Fusion Energy (IFE) facility, with the first 2-MJ at high repetition rate supplying single-shot high energy amplifiers, will open many new exciting avenues for both fundamental physics and high energy density science in the decades ahead.

Experimental capabilities of the LMJ-PETAL facility

Cayzac, W. et al.
HIGH ENERGY DENSITY PHYSICS 52, 101125 (SEP 2024)
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Recent progress in the experimental capabilities of the LMJ-PETAL laser facility is reviewed. Updates on the indirect-drive D_2 implosion experiments and equation-of-state experiments using the LMJ laser are presented, including the commissioning of new plasma diagnostics. Several recent campaigns using the PETAL laser alone are also presented, namely the development of a platform using high-resolution and high-energy X-ray sources for radiography experiments, laser wakefield acceleration studies in the self-modulated regime, and neutron generation using a Target Normal Sheath Accelerated proton beam in a pitcher-catcher configuration.

High-energy laser facility PHELIX at GSI: latest advances and extended capabilities

Major, Zs.; Eisenbarth, U.; Zielbauer, B.; Brabetz, C.; Ohland, J. B.; Zobus, Y.; Roeder, S.; Reemts, D.; Kunzer, S.; Goette, S.; Neidherr, D.; Hornung, J.; Kewes, P.; Schumacher, D.; Beck, D.; Hesselbach, P.; Malki, M.; Neumayer, P.; Weyrich, K.; Tauschwitz, A.; Bagnoud, V.
HIGH POWER LASER SCIENCE AND ENGINEERING 12, e39 (APR 2024)
https://doi.org/10.1017/hpl.2024.17

The high-energy/high-intensity laser facility PHELIX of the GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt, Germany, has been in operation since 2008. Here, we review the current system performance, which is the result of continuous development and further improvement. Through its versatile frontend architecture, PHELIX can be operated in both long- and short-pulse modes, corresponding to ns-pulses with up to 1 kJ pulse energy and sub-ps, 200 J pulses, respectively. In the short-pulse mode, the excellent temporal contrast and the control over the wavefront make PHELIX an ideal driver for secondary sources of high-energy ions, neutrons, electrons and X-rays. The long-pulse mode is mainly used for plasma heating, which can then be probed by the heavy-ion beam of the linear accelerator of GSI. In addition, PHELIX can now be used to generate X-rays for studying exotic states of matter created by heavy-ion heating using the ion beam of the heavy-ion synchrotron of GSI.

Plasma Wakefield Acceleration Driven by XCELS Laser Pulse

Kutergin, D. D.; Lotov, I. K.; Minakov, V. A.; Spitsyn, R. I.; Tuev, P. V.; Lotov, K. V.
PHYSICS OF PARTICLES AND NUCLEI LETTERS 21(3), 316-321 (JUN 2024)
https://doi.org/10.1134/S1547477124700183

A laser pulse from one channel of the Russian eXawatt Center for Extreme Light Studies (XCELS) facility will make it possible to accelerate an electron bunch with a charge of 50 pC to an energy of ~ 100 GeV with an energy spread of 0.7%. This requires a plasma channel of length 70 m, radius 200 μm, and plasma density on the axis of 3×10^{15} cm^{-3}. Numerical optimization of the acceleration process at such scales is computationally expensive, but can be efficiently performed using a quasistatic code by a two-step simulation method, which is described in the paper.

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.

Development, operations, and applications of TW to PW lasers at the BELLA Center for plasma-based particle acceleration studies

Toth, Csaba

Proceedings of SPIE, vol. 12939, High-Power Laser Ablation VIII, Santa Fe NM, Feb 26 – Mar 2, , 129390O (2024)

https://doi.org/10.1117/12.3016319

The BELLA PW Facility's (LBNL, Berkeley CA/USA) recent laser system upgrades provide new capabilities for 1) ultrahigh intensity experiments with solid targets at Interaction Point#2 [iP2]; and 2) staged laser plasma accelerator [LPA] studies at the Second Beamline [2BL]. An overview of the special considerations, planning and implementation processes related to radiation shielding, laser and radiation interlock systems required for the safe and efficient operation of the new BELLA PW beamlines and the conduction of efficient experimental campaigns are reviewed.

INSTRUMENTATION

Design and Test of a Klystron Intra-Pulse Phase Feedback System for Electron Linear Accelerators

Piersanti, Luca; Bellaveglia, Marco; Cardelli, Fabio; Gallo, Alessandro; Magnanimi, Riccardo; Quaglia, Sergio; Scampati, Michele; Scarselletta, Giorgio; Serenellini, Beatrice; Tocci, Simone

PHOTONICS 11(5), 413 (MAY 2024)

https://doi.org/10.3390/photonics11050413

Beam stability and timing jitter in modern linear accelerators are becoming increasingly important. In particular, if a magnetic or radio-frequency (RF) compression regime is employed, the beam time of arrival jitter at the end of the linac can be strictly correlated with the phase noise of the accelerating fields of the RF structure working off-crest. For this reason, since 2008, an RF fast-feedback technique, which acts within each RF pulse, has been successfully employed at LNF-INFN (Laboratori Nazionali di Frascati dell'Istituto Nazionale di Fisica Nucleare) in the SPARC_LAB (Sources for Plasma Accelerators and Radiation Compton with Laser And Beam) facility on S-band (2856 MHz) klystrons powered by pulse-forming network (PFN) modulators, as reported in this paper. However, in order to meet the more stringent requirements of plasma wakefield acceleration schemes, some upgrades to this feedback system have been recently carried out. The first prototype has been experimentally tested on a C-band (5712 MHz) klystron, driven by a solid-state modulator, in order to investigate the possibility for additional improvement resulting from the inherently more stable power source. In this paper, the design, realization and the preliminary measurement results obtained at SPARC_LAB after such upgrades will be reviewed.

Design and Implementation of EPICS on the Laser Accelerator: CLAPA-I Control System Upgrade

Xia, Yadong; Wang, Qiang; Zhao, Jie; Feng, Liwen; Guo, Enshuo; Yang, Tong; Wang, Yifan; Li, Fangnan; Guo, Zhen; He, Qiangyou; Chen, Ke; Lu, Yuanrong; Yan, Xueqing; Lin, Chen

IEEE TRANSACTIONS ON NUCLEAR SCIENCE 71(1), 18-30 (JAN 2024)
https://doi.org/10.1109/TNS.2023.3342191

The Compact Laser Plasma Accelerator (CLAPA-I) is a laser accelerator device comprised of a 200-TW laser system, an optical path transmission system, a target field system, a proton beamline system, an experimental terminal, and a control system, among other components. Its main application is in fundamental research, focusing on areas like the laser plasma acceleration mechanism and ion irradiation applications. This article delves into the upgrade process of the control system for laser accelerators. Initially, building on the foundation of the CLAPA-I system, we developed a distributed control system employing the Experimental Physics and Industrial Control System (EPICS) control architecture, enhanced by programmable logic controller (PLC), LabVIEW, and Python. This integration allowed for a unified equipment interface capable of managing complex logic. Furthermore, this article distinguishes between the operational and control aspects of laser accelerators and their traditional counterparts, offering appropriate solutions. A reasonable and effective electromagnetic shielding scheme was proposed to counter the pronounced magnetic interference encountered during laser-target interactions. This advancement not only boosts the CLAPA-I control system's performance but also broadens the applicability of EPICS in the laser accelerator domain, shedding light on the practical deployment of EPICS-based control systems.

Fabrication and Powering Test of a High-Temperature Superconducting Periodic Quadrupole Driving a Short-Length Transport Line for Laser-Plasma Accelerators

Fatehi, S.; Bernhard, A.; Richter, S. C.; Grau, A.; Eisele, M.; Hornung, F.; Arndt, T.; Mueller, Anke-Susanne

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY 34(3), 4001905 (MAY 2024)
https://doi.org/10.1109/TASC.2024.3351958

Laser-plasma accelerators, have extremely high accelerating gradients and can generate ultra-short electron bunches with micrometer bunch lengths which makes them a prominent candidate to drive the next-generation compact light sources and free-electron lasers (FELs). To fully exploit the advantages of this novel accelerating technology and to compensate for large chromatic effects in the beam transport line, novel compact beam optic elements based on high-temperature superconductor technology are studied. Moreover, the limited mechanical properties of the HTS ceramic-structured superconductors lead to many manufacturing issues during the coil winding process and to ease this difficulty, designing magnets with simple shape coils is of interest. In this article, the magnet design as well as the fabrication and test of a demonstrator of a periodic iron-core miniature HTS quadrupole is discussed. This magnet features simple pancake coils that are capable of providing high field gradients and in the experiments were successfully powered in liquid nitrogen and liquid helium showing no degradation.

THEORY & SIMULATION

A scalar field theory of 1+1-dimensional laser wakefield accelerators

Aleksiejuk, Mark; Burton, David A.

JOURNAL OF PHYSICS A-MATHEMATICAL AND THEORETICAL 57(35), 355701 (SEP 2024)
https://doi.org/10.1088/1751-8121/ad6db0

A relativistic non-linear scalar field theory is developed from a 2+2-dimensional decomposition of the cold plasma field equations, and the theory is used to investigate a 1+1-dimensional description of a laser wakefield accelerator. The relationship between the properties of a compact laser pulse and its wake is explored. Non-linear solutions are sought describing a regular (i.e. unbroken) wake driven by a prescribed rectangular circularly-polarised laser pulse. An upper bound on the dimensionless amplitude a_0 of the laser pulse is determined as a function of the phase speed v of the wake. The asymptotic behaviour of the upper bound on a_0 as $v \to c$ is shown to agree with well-established, but approximate, results obtained using the conventional encoding of the plasma degrees of freedom. Our approach leads to a closed-form expression for the upper bound on a_0 which is exact for all values of the phase speed of the wake, unlike conventional results that are applicable only when v is sufficiently close to c.

Quasi-monoenergetic electron beam from LWFA: analytical approach

Starodubtseva, E. M.; Tsymbalov, I. N.; Gorlova, D. A.; Ivanov, K. A.; Savelev, A. B.
LASER PHYSICS LETTERS 21(7), 075401 (JUL 2024)
https://doi.org/10.1088/1612-202X/ad4eb4

Analytical dependence of the energy spread of electron beam on time and injection duration has been obtained with the 1D model of the quasi-linear laser wakefield electron acceleration, presented as phase portraits of electron energy relative to the plasma wave phase. The method for producing electron beams with variable energy and a lower energy spread compared to a standard bubble-like approach by transferring to a deaccelerating part with another phase trajectory (by reducing the plasma amplitude of a wave) has been developed. The analytically obtained results successfully describe key features of the previously obtained in Tsymbalov et al (2024 arXiv:2403.19828) experimental and numerical (PIC) data.

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www.eupraxia-pp.org

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