THE EuPRAXIA FILES

ISSUE 8 – March 2023

FOREWORD

The recent start of the EuPRAXIA Preparatory Phase, the EuPRAXIA Doctoral Networks, and the EuPRAXIA Advanced Photon Sources has given a new vigour to the plans for the construction of a new European research infrastructure based on novel acceleration concepts and laser technology. Following this renewed impulse, we have decided to restart the distribution of **The EuPRAXIA Files**, a quarterly newsletter for the partners and friends of EuPRAXIA.

The EuPRAXIA Files is a collection of publicly available abstracts of published articles that are relevant to the EuPRAXIA project. Putting together the latest research in plasma accelerators, the aim is to facilitate the work of the many researchers involved in EuPRAXIA and to highlight the scientific outcomes of the various projects supporting the inititative. We hope you find it useful.

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RESEARCH HIGHLIGHTS

Attosecond-Angstrom free-electron-laser towards the cold beam limit

An international team of scientists led by University of Strathclyde had a conceptual breakthrough in Plasma Wakefield Accelerator (PWFA) driven hard X-ray free-electron lasers (X-FELs).

The results, published in NATURE COMMUNICATIONS, show with high-fidelity start-to-end simulations, that a PWFA equipped with an advanced electron injection method called plasma photocathode (aka “Trojan Horse”) can produce electron beams 100,000 times brighter than state-of-the-art.

Then, the tens to hundreds of gigavolt-per-meters accelerating electric field in PWFA allows one to realize the accelerator on cm-scale compared to km-scales of traditional accelerators.

The study continues with how to extract, transport, isolate and inject the ultra-high brightness electron beams from plasma photocathode PWFA into an undulator without charge and quality loss.

Finally, focused into an undulator, the ultrahigh quality electron beam produces powerful coherent photon pulses at the **Angstrom** wavelength on the fly, with pulse durations in the **attosecond** regime.

In addition to extreme quality of the electron and resulting photon pulses, the entire system may have a spatial footprint of only few tens of meters, in contrast to state-of-the-art, km-size X-FEL machines. The scientists believe that the three milestones achieved in the study could be a gateway to next-generation ultra-compact hard X-FELs. Such a plasma photocathode PWFA brightness and energy booster stage can be implemented into already existing or future X-FEL facilities or the emerging Hybrid LWFA2PWFA platform.

Full article:

A. F. Habib et al., "Attosecond-Angstrom free-electron-laser towards the cold beam limit", NATURE COMMUNICATIONS 14, 1054 (2023)

Artistic representation of the PWFA X-FEL. Credits: University of Strathclyde / Science Communication Lab

Free-electron lasing with compact beam-driven plasma wakefield accelerator

The SPARC_LAB research team at the Frascati National Laboratory has recently demonstrated that the plasma-based acceleration technique allows to obtain an **high-quality particle beam**, comparable to the beams produced in traditional accelerators.

The results of this study have been published on Nature and pave the way to the **realization of compact and portable particle accelerators,** to be used not only in the research context but also in the medical and industrial sectors.

The possibility to accelerate electron beams to ultra-relativistic velocities over short distances by using plasma-based technology holds the potential for a **revolution in the field of particle accelerators**.

Despite the high acceleration gradients produced in a plasma (up to three orders of magnitude higher than the conventional machines based on RF technology), their use has been limited due to the low quality of the beam produced. The study reported on Nature carried out at SPARC_LAB showed that, for the first time, it is possible to use a high quality beam accelerated by a plasma wave to generate coherent radiation in a Free Electron Laser (FEL) in the infrared range.

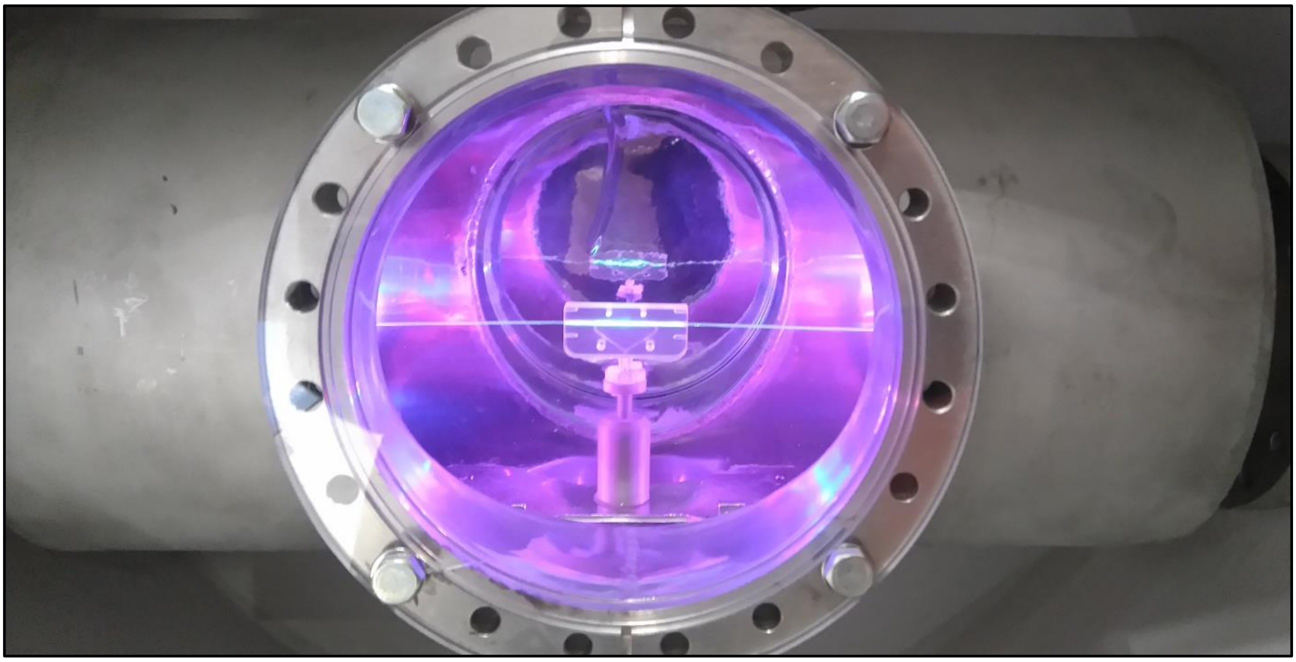
The results was obtained injecting two electron bunches (few tens of microns sized) in the plasma contained in a 3 cm long capillary. Firstly it is necessary to create the plasma by ionizing hydrogen gas with a high voltage discharge. Then, the two electron bunches are injected. The first bunch (driver) serves to excite the plasma accelerating waves that are exploited by the second bunch (witness) that is accelerated. The high quality of the witness at the entrance of the plasma is preserved along the acceleration process and, in addition to the high current, is capable of driving a free-electron laser (FEL) by generating coherent light pulses. The experiment conducted at SPARC_LAB allowed the light pulses to reach the energy of 30 nJ.

“The plasma acceleration technique will allow to realize accelerators in small places, limiting the production costs of the hosting infrastructures and making this technology more accessible and available also for medical applications in equipped hospitals, and especially in underground facilities as the ones necessary for accelerators in High Energy physics”, says Riccardo Pompili, Principal Investigator of the experiment carried out at SPARC_LAB.

“This result has not only a great scientific relevance per se, but it represents also a milestone towards the realization of the are project EUPRAXIA, that yearns for the construction of the first research infrastructure addressed to users, based on plasma acceleration”, explains Massimo Ferrario, responsible of the EUPRAXIA@SPARC_LAB project, financed also by a contribution of the Italian Minister of Research and University (MUR) and recently included in the ESFRI roadmap, the strategic forum for research infrastructures.

Full article:

R. Pompili et al. “Free-electron lasing with compact beam-driven plasma wakefield accelerator”, NATURE 605(7911), 659 (2022)



BEAMLINES & APPLICATIONS

Free-electron lasing with compact beam-driven plasma wakefield accelerator

Pompili, R.; Alesini, D.; Anania, M. P.; Arjmand, S.; Behtouei, M.; Bellaveglia, M.; Biagioni, A.; Buonomo, B.; Cardelli, F.; Carpanese, M.; Chiadroni, E.; Cianchi, A.; Costa, G.; Del Dotto, A.; Del Giorno, M.; Dipace, F.; Doria, A.; Filippi, F.; Galletti, M.; Giannessi, L.; Giribono, A.; Iovine, P.; Lollo, V; Mostacci, A.; Nguyen, F.; Opromolla, M.; Di Palma, E.; Pellegrino, L.; Petralia, A.; Petrillo, V; Piersanti, L.; Di Pirro, G.; Romeo, S.; Rossi, A. R.; Scifo, J.; Selce, A.; Shpakov, V; Stella, A.; Vaccarezza, C.; Villa, F.; Zigler, A.; Ferrario, M.

NATURE 605(7911), 659 (2022)
https://doi.org/10.1038/s41586-022-04589-1

The possibility to accelerate electron beams to ultra-relativistic velocities over short distances by using plasma-based technology holds the potential for a revolution in the field of particle accelerators. The compact nature of plasma-based accelerators would allow the realization of table-top machines capable of driving a free-electron laser (FEL), a formidable tool to investigate matter at the sub-atomic level by generating coherent light pulses with sub-angstrom wavelengths and sub-femtosecond durations. So far, however, the high-energy electron beams required to operate FELs had to be obtained through the use of conventional large-size radio-frequency (RF) accelerators, bound to a sizeable footprint as a result of their limited accelerating fields. Here we report the experimental evidence of FEL lasing by a compact (3-cm) particle-beam-driven plasma accelerator. The accelerated beams are completely characterized in the six-dimensional phase space and have high quality, comparable with state-of-the-art accelerators. This allowed the observation of narrow-band amplified radiation in the infrared range with typical exponential growth of its intensity over six consecutive undulators. This proof-of-principle experiment represents a fundamental milestone in the use of plasma-based accelerators, contributing to the development of next-generation compact facilities for user-oriented applications.

Attosecond-Angstrom free-electron-laser towards the cold beam limit

Habib, A. F.; Manahan, G. G.; Scherkl, P.; Heinemann, T.; Sutherland, A.; Altuiri, R.; Alotaibi, B. M.; Litos, M.; Cary, J.; Raubenheimer, T.; Hemsing, E.; Hogan, M. J.; Rosenzweig, J. B.; Williams, P. H.; McNeil, B. W. J.; Hidding B.

NATURE COMMUNICATIONS 14, 1054 (2023)
https://doi.org/10.1038/s41467-023-36592-z

Electron beam quality is paramount for X-ray pulse production in free- electron-lasers (FELs). State-of-the-art linear accelerators (linacs) can deliver multi-GeV electron beams with sufficient quality for hard X-ray-FELs, albeit requiring km-scale setups, whereas plasma-based accelerators can produce multi-GeV electron beams on metre-scale distances, and begin to reach beam qualities sufficient for EUV FELs. Here we show, that electron beams from plasma photocathodes many orders of magnitude brighter than state-of-the- art can be generated in plasma wakefield accelerators (PWFAs), and then extracted, captured, transported and injected into undulators without sig- nificant quality loss. These ultrabright, sub-femtosecond electron beams can drive hard X-FELs near the cold beam limit to generate coherent X-ray pulses of attosecond-Angstrom class, reaching saturation after only 10 metres of undulator. This plasma-X-FEL opens pathways for advanced photon science capabilities, such as unperturbed observation of electronic motion inside atoms at their natural time and length scale, and towards higher photon energies.

Generation of ultrahigh-brightness pre-bunched beams from a plasma cathode for X-ray free-electron lasers

Xu, Xinlu; Li, Fei; Tsung, Frank S.; Miller, Kyle; Yakimenko, Vitaly; Hogan, Mark J.; Joshi, Chan; Mori, Warren B.
NATURE COMMUNICATIONS 13(1), 3364 (2022)
https://doi.org/10.1038/s41467-022-30806-6

The longitudinal coherence of X-ray free-electron lasers (XFELs) in the self-amplified spontaneous emission regime could be substantially improved if the high brightness electron beam could be pre-bunched on the radiated wavelength-scale. Here, we show that it is indeed possible to realize such current modulated electron beam at angstrom scale by exciting a nonlinear wake across a periodically modulated plasma-density downramp/plasma cathode. The density modulation turns on and off the injection of electrons in the wake while downramp provides a unique longitudinal mapping between the electrons' initial injection positions and their final trapped positions inside the wake. The combined use of a downramp and periodic modulation of micrometers is shown to be able to produces a train of high peak current (17 kA) electron bunches with a modulation wavelength of 10's of angstroms - orders of magnitude shorter than the plasma density modulation. The peak brightness of the nano-bunched beam can be O(10^{21} A/m^2/rad^2) orders of magnitude higher than current XFEL beams. Such prebunched, high brightness electron beams hold the promise for compact and lower cost XEFLs that can produce nanometer radiation with hundreds of GW power in a 10s of centimeter long undulator.; Laser-produced plasma can be used for acceleration and tuning of particle beams. Here the authors discuss the generation of a bunched electron beam using simulations and its application to X-ray free-electron laser.

Compact all-optical precision-tunable narrowband hard Compton X-ray source

Bruemmer, T.; Bohlen, S.; Gruener, F.; Osterhoff, J.; Poder, K.
SCIENTIFIC REPORTS 12(1), 16017 (2022)
https://doi.org/10.1038/s41598-022-20283-8

Readily available bright X-ray beams with narrow bandwidth and tunable energy promise to unlock novel developments in a wide range of applications. Among emerging alternatives to large-scale and costly present-day radiation sources which severely restrict the availability of such beams, compact laser-plasma-accelerator-driven inverse Compton scattering sources show great potential. However, these sources are currently limited to tens of percent bandwidths, unacceptably large for many applications. Here, we show conceptually that using active plasma lenses to tailor the electron bunch-photon interaction, tunable X-ray and gamma beams with percent-level bandwidths can be produced. The central X-ray energy is tunable by varying the focusing strength of the lens, without changing electron bunch properties, allowing for precision-tuning the X-ray beam energy. This method is a key development towards laser-plasma-accelerator-driven narrowband, precision tunable femtosecond photon sources, enabling a paradigm shift and proliferation of compact X-ray applications.

Positron acceleration via laser-augmented blowouts in two-column plasma structures

Reichwein, Lars; Pukhov, Alexander; Golovanov, Anton; Kostyukov, Igor Yu
PHYSICAL REVIEW E 105(5), 055207 (2022)
https://doi.org/10.1103/PhysRevE.105.055207

We propose a setup for positron acceleration consisting of an electron driver and a laser pulse creating a twofold plasma column structure. The resulting wakefield is capable of accelerating positron bunches over long distances even when the evolution of the driver is considered. The scheme is studied by means of particle-in-cell simulations. Further, the analytical expression for the accelerating and focusing fields are obtained, showing the equilibrium lines along which the witness bunch is accelerated.

High efficiency uniform positron beam loading in a hollow channel plasma wakefield accelerator

Zhou, Shiyu; Hua, Jianfei; Lu, Wei; An, Weiming; Su, Qianqian; Mori, Warren B.; Joshi, Chan
PHYSICAL REVIEW ACCELERATORS AND BEAMS 25(9), 091303 (2022)
https://doi.org/10.1103/PhysRevAccelBeams.25.091303

We propose a novel positron beam loading regime in a hollow plasma channel that can efficiently accelerate e^+ beam with a high gradient and narrow energy spread. In this regime, the e^+ beam coincides with the drive e^- beam in time and space and their net current distribution determines the plasma wakefields. By precisely shaping the beam current profile and loading phase according to explicit expressions, three-dimensional particle-in-cell (PIC) simulations show that the acceleration for e^+ beam of ~nC charge with ~GV/m gradient, less than or ~0.5% induced energy spread, and ~50% energy transfer efficiency can be achieved simultaneously. Besides, only tailoring the current profile of the more tunable e^- beam instead of the e^+ beam is enough to obtain such favorable results. A theoretical analysis considering both linear and nonlinear plasma responses in hollow plasma channels is proposed to quantify the beam loading effects. This theory agrees very well with the simulation results and verifies the robustness of this beam loading regime over a wide range of parameters.

Observation of tunable parametric x-ray radiation emitted by laser-plasma electron beams interacting with crystalline structures

Curcio, A.; Ehret, M.; Perez-Hernandez, J. A.; Gatti, G.
PHYSICAL REVIEW ACCELERATORS AND BEAMS 25(6), 063403 (2022)
https://doi.org/10.1103/PhysRevAccelBeams.25.063403

Parametric x-ray radiation (PXR) is the quantum process analogue to Laue diffraction where a pseudophoton is scattered out of a crystalline structure as a radiation photon. In this work, PXR emitted by electron beams generated in a compact laser-plasma accelerator and interacting afterward with a Si 220 crystal is observed in single-shot operations. The combination of laser wakefield acceleration and PXR is an efficient and table-top way to obtain monochromatic, pulsed, ultrashort, and stable emission of high-energy photons: to our knowledge such a complete set of performance parameters is new. Unlike other relevant radiation mechanisms, such as betatron radiation or incoherent bremsstrahlung, PXR is insensitive to the beam energy spread. With a long crystal, we demonstrate the stability of the PXR bandwidth toward shot-to-shot variations of the beam energy and divergence.

Trapping and acceleration of spin-polarized positrons from gamma photon splitting in wakefields

Liu, Wei-Yuan; Xue, Kun; Wan, Feng; Chen, Min; Li, Jian-Xing; Liu, Feng; Weng, Su-Ming; Sheng, Zheng-Ming; Zhang, Jie
PHYSICAL REVIEW RESEARCH 4(2), L022028 (2022)
https://doi.org/10.1103/PhysRevResearch.4.L022028

Energetic spin-polarized positrons are very useful for forefront research such as $e^- e^+$ collider physics, but it is still quite challenging to generate such sources. Here, we propose an efficient scheme of trapping and accelerating polarized positrons in plasma wakefields. By developing a fully spin-resolved Monte Carlo method, we find that in the nonlinear Breit-Wheeler pair production the polarization of intermediate gamma photons significantly affects the pair spin polarization, and ignoring this effect would result in an overestimation of the pair yield and polarization degree. In particular, seed electrons colliding with a bichromatic laser create polarized gamma photons which split into $e^- e^+$ pairs via the nonlinear Breit-Wheeler process with an average (partial) positron polarization above 30% (70%). Over 70% of positrons are then trapped and accelerated in the recovered wakefields driven by a hollow electron beam, obtaining an energy gain of 3.5 GeV/cm with slight depolarization. Our method provides the potential for constructing compact polarized positron sources for future applications and may also attract broad interest in strong-field physics, high-energy physics, and particle physics.

Positron driven high-field terahertz waves via dielectric wakefield interaction

Majernik, N.; Andonian, G.; Williams, B.; O'Shea, B. D.; Hoang, P. D.; Clarke, C.; Hogan, M. J.; Yakimenko, V; Rosenzweig, J. B.

PHYSICAL REVIEW RESEARCH 4(2), 023065 (2022)

https://doi.org/10.1103/PhysRevResearch.4.023065

Advanced acceleration methods based on wakefields generated by high-energy electron bunches passing through dielectric-based structures have demonstrated > GV/m fields, paving the first steps on a path to applications such as future compact linear colliders. For a collider scenario, it is desirable that, in contrast with plasmas, wakefields in dielectrics do not behave differently for positron and electron bunches. In this article, we present measurements of large amplitude fields excited by positron bunches with collider-relevant parameters (energy 20 GeV and 0.7 x 10^{10} particles per bunch) in a 0.4 THz, cylindrically symmetric dielectric structure. Interferometric measurements of emitted coherent Cerenkov radiation permit spectral characterization of the positron-generated wakefields, which are compared to those excited by electron bunches. Statistical equivalence tests are incorporated to show the charge-sign invariance of the induced wakefield spectra. Transverse effects on positron beams resulting from off-axis excitation are examined and found to be consistent with the known linear response of the DWA system. The results are supported by numerical simulations and demonstrate high-gradient wakefield excitation in dielectrics for positron beams.

Brilliant circularly polarized gamma-ray sources via single-shot laser plasma interaction

Wang, Yu; Ababekri, Mamutjan; Wan, Feng; Zhao, Qian; Lv, Chong; Ren, Xue-Guang; Xu, Zhong-Feng; Zhao, Yong-Tao; Li, Jian-Xing

OPTICS LETTERS 47(13), 3355-3358 (2022)

https://doi.org/10.1364/OL.462612

Circularly polarized (CP) gamma-ray sources are versatile for broad applications in nuclear physics, high-energy physics, and astrophysics. The laser-plasma based particle accelerators provide accessibility for much higher flux gamma-ray sources than conventional approaches, in which, however, the circular polarization properties of the emitted gamma-photons are usually neglected. In this Letter, we show that brilliant CP gamma-ray beams can be generated via the combination of laser plasma wakefield acceleration and plasma mirror techniques. In a weakly nonlinear Compton scattering scheme with moderate laser intensities, the helicity of the driving laser can be transferred to the emitted.-photons, and their average polarization degree can reach ~61% (20%) with a peak brilliance of greater than or ~10^{21} photons/(s . mm^2 . $mrad^2$. 0.1% BW) around 1 MeV (100 MeV). Moreover, our proposed method is easily feasible and robust with respect to the laser and plasma parameters. (C) 2022 Optica Publishing Group

Plasma-based positron sources at EuPRAXIA

Sarri, Gianluca; Calvin, Luke; Streeter, Matthew
PLASMA PHYSICS AND CONTROLLED FUSION 64(4), 044001 (2022)
https://doi.org/10.1088/1361-6587/ac4e6a

Plasma-based positron sources are attracting significant attention from the research community, thanks to their rather unique characteristics, which include broad energy tuneability and ultra-short duration, obtainable in a compact and relatively inexpensive setup. Here, we show a detailed numerical study of the positron beam characteristics obtainable at the dedicated user target areas proposed for the EuPRAXIA facility, the first plasma-based particle accelerator to be built as a user facility for applications. It will be shown that MeV-scale positron beams with unique properties for industrial and material science applications can be produced, alongside with GeV-scale positron beams suitable for fundamental science and accelerator physics.

Low-initial-energy muon acceleration in beam-driven plasma wakefield using a plasma density down-ramp

Jiang, You-Ge; Wang, Xiao-Nan; Lan, Xiao-Fei; Huang, Yong-Sheng
PHYSICS OF PLASMAS 29(10), 103110 (2022)
https://doi.org/10.1063/5.0107458

The muon plays a key role in the field of particle physics and applied physics. To build the neutrino factories or muon colliders, high-quality muon sources are needed. At present, we can only get the low-flux cosmic-ray muons and low-energy accelerator-generated muons. The key issue about accelerating a low-initial-energy muon beam in the plasma wakefield driven by an electron beam is the phase matching between muons and a wakefield. A plasma density down-ramp is considered as an effective method for accelerating a low-initial-energy muon beam, and the decreasing phase velocity at the back edge of the wakefield can lower the muon trapped energy threshold. A 100 MeV muon beam can be accelerated to 6.21 GeV in the plasma wakefield based on a negative plasma density gradient. The trapping and accelerating process can be controlled by adjusting the parameters of the density down-ramp. Published under an exclusive license by AIP Publishing.

Performance Study on a Soft X-ray Betatron Radiation Source Realized in the Self-Injection Regime of Laser-Plasma Wakefield Acceleration

Curcio, Alessandro; Cianchi, Alessandro; Costa, Gemma; Demurtas, Francesco; Ehret, Michael; Ferrario, Massimo; Galletti, Mario; Giulietti, Danilo; Antonio Perez-Hernandez, Jose; Gatti, Giancarlo
APPLIED SCIENCES-BASEL 12(23), 12471 (2022)
https://doi.org/10.3390/app122312471

We present an analysis of the performance of a broadband secondary radiation source based on a high-gradient laser-plasma wakefield electron accelerator. In more detail, we report studies of compact and ultra-short X-ray generation via betatron oscillations in plasma channels. For the specific working point examined in this paper, determined by the needs of other experiments ongoing at the facility, at ~0.02 Hz operation rate, we have found $\lesssim 10^6$ photons emitted per shot (with a fluctuation of 50%) in the soft X-rays, corresponding to a critical energy of ~0.8 keV (with a fluctuation of 40%). The source will be implemented for experiments in time-domain spectroscopy, e.g., biological specimens, and for other applications oriented to medical physics.

On possibility of low-emittance high-energy muon source based on plasma wakefield acceleration

Shiltsev, V

JOURNAL OF INSTRUMENTATION 17(5), T05010 (2022)
https://doi.org/10.1088/1748-0221/17/05/T05010

Plasma wakefield acceleration (PWA) channels are characterized by very high accelerating gradients and very strong focusing fields. We propose to employ these properties for effective production of low emittance high energy muon beams, consider muon beam dynamics in the PWFA cell and analyze various options and potential of the PWA-based muon sources.

ELI Gammatron Beamline: A Dawn of Ultrafast Hard X-ray Science

Chaulagain, U.; Lamac, M.; Raclavsky, M.; Khakurel, K. P.; Rao, Kavya H. H.; Ta-Phuoc, K.; Bulanov, S. V.; Nejdl, J.

PHOTONICS 9(11), 853 (2022)
https://doi.org/10.3390/photonics9110853

The realization of compact X-ray sources is one of the most intriguing applications of laser-plasma based electron acceleration. These sources based on the oscillation of short micron-sized bunches of relativistic electrons provide femtosecond X-ray pulses that are collimated, bright, and partially coherent. The state-of-the-art laser plasma X-ray sources can provide photon flux of over 10^{11} photons/shot. The photon flux can further be enhanced with the availability of high repetition rate, high-power lasers, providing capacities complementary to the large scale facilities such as synchrotrons and X-ray free-electron lasers. Even though the optimization of such sources has been underway for the last two decades, their applications in material and biological sciences are still emerging, which entail the necessity of a user-oriented X-ray beamlines. Based on this concept, a high-power-laser-based user-oriented X-ray source is being developed at ELI Beamlines. This article reports on the ELI Gammatron beamline and presents an overview of the research accessible with the ultrashort hard X-ray pulses at the ELI Gammatron beamline.

Experimental Study on Positronium Detection under Millimeter Waves Generated from Plasma Wakefield Acceleration

Min, Sun-Hong; Park, Chawon; Lee, Kyo Chul; Lee, Yong Jin; Sattorov, Matlabjon; Kim, Seonmyeong; Hong, Dongpyo; Park, Gun-Sik

ELECTRONICS 11(19), 3178 (2022)
https://doi.org/10.3390/electronics11193178

Positronium (Ps) is an unstable system created by the temporary combination of electrons and negative electrons, and Ps generation technology under resonance conditions at millimeter waves is emerging as a new research topic. In general, Ps can be observed when an unstable separate state remains after electron and positron pair annihilation, as in positron emission tomography (PET). However, in this study, a plasma wakefield accelerator based on vacuum electronics devices (VEDs) was designed in the ponderomotive force generating electrons and positrons simultaneously using annular relativistic electron beams. It can induce Cherenkov radiation from beam-wave interaction by using dielectric materials. According to the size of dielectric materials, the frequency of oscillation is approximately 203 GHz at the range of millimeter waves. At this time, the output power is about 10^9 watts-levels. Meanwhile, modes of millimeter waves polarized by a three-stepped axicon lens are used to apply the photoconversion technology. Thus, it is possible to confirm light emission in the form of a light-converted Bessel beam.

Prompt acceleration of a μ^+ beam in a toroidal wakefield driven by a shaped steep-rising-front Laguerre-Gaussian laser pulse

Wang, Xiaonan; Lan, Xiaofei; Huang, Yongsheng; Jiang, Youge; Zhang, Chunlei; Zhang, Hao; Yu, Tongpu
PLASMA SCIENCE & TECHNOLOGY 24(5), 055502 (2022)
https://doi.org/10.1088/2058-6272/ac58eb

Recent experimental data for anomalous magnetic moments strongly indicates the existence of new physics beyond the Standard Model. Energetic μ^+ bunches are relevant to μ^+ rare decay, spin rotation, resonance and relaxation (μSR) technology, future muon colliders, and neutrino factories. In this paper, we propose prompt μ^+ acceleration in a nonlinear toroidal wakefield driven by a shaped steep-rising-front Laguerre-Gaussian (LG) laser pulse. An analytical model is described, which shows that a μ^+ beam can be focused by an electron cylinder at the centerline of a toroidal bubble and accelerated by the front part of the longitudinal wakefield. A shaped LG laser with a short rise time can push plasma electrons, generating a higher-density electron sheath at the front of the bubble, which can enhance the acceleration field. The acceleration field driven by the shaped steep-rising-front LG laser pulse is about four times greater than that driven by a normal LG laser pulse. Our simulation results show that a 300 MeV μ^+ bunch can be accelerated to 2 GeV and its transverse size is focused from an initial value of $w_0 = 5$ μm to $w = 2$ μm in the toroidal bubble driven by the shaped steep-rising-front LG laser pulse with a normalized amplitude of a = 22.

Micro-size picosecond-duration fast neutron source driven by a laser-plasma wakefield electron accelerator

Li, Yaojun; Feng, Jie; Wang, Wenzhao; Tan, Junhao; Ge, Xulei; Liu, Feng; Yan, Wenchao; Zhang, Guoqiang; Fu, Changbo; Chen, Liming
HIGH POWER LASER SCIENCE AND ENGINEERING 10, e33 (2022)
https://doi.org/10.1017/hpl.2022.27

A pulsed fast neutron source is critical for applications of fast neutron resonance radiography and fast neutron absorption spectroscopy. However, due to the large transversal source size (of the order of mm) and long pulse duration (of the order of ns) of traditional pulsed fast neutron sources, it is difficult to realize high-contrast neutron imaging with high spatial resolution and a fine absorption spectrum. Here, we experimentally present a micro-size ultra-short pulsed neutron source by a table-top laser-plasma wakefield electron accelerator driving a photofission reaction in a thin metal converter. A fast neutron source with source size of approximately 500 μm and duration of approximately 36 ps has been driven by a tens of MeV, collimated, micro-size electron beam via a hundred TW laser facility. This micro-size ultra-short pulsed neutron source has the potential to improve the energy resolution of a fast neutron absorption spectrum dozens of times to, for example, approximately 100 eV at 1.65 MeV, which could be of benefit for high-quality fast neutron imaging and deep understanding of the theoretical model of neutron physics.

FACILITIES

Design and operation of transfer lines for plasma wakefield accelerators using numerical optimizers

Ramjiawan, R.; Doebert, S.; Farmer, J.; Gschwendtner, E.; Velotti, F. M.; Verra, L.; Della Porta, G. Zevi; Bencini, V; Burrows, P. N.
PHYSICAL REVIEW ACCELERATORS AND BEAMS 25(10), 101602 (2022)
https://doi.org/10.1103/PhysRevAccelBeams.25.101602

The Advanced Wakefield (AWAKE) Experiment is a proof-of-principle experiment demonstrating the acceleration of electron beams via proton-driven plasma wakefield acceleration. AWAKE Run 2 aims to build on the results of Run 1 by achieving higher energies with an improved beam quality. As part of the upgrade to Run 2, the existing proton and electron beamlines will be adapted and a second plasma cell and new 150-MeV electron beamline will be added. The specification for this new 150-MeV beamline will be challenging as it will be required to inject electron bunches with micron-level beam size and stability into the second plasma cell while being subject to tight spatial constraints. In this paper, we describe the techniques used (e.g., numerical optimizers and genetic algorithms) to produce the design of this electron line. We present a comparison of the methods used in this paper with other optimization algorithms commonly used within accelerator physics. Operational techniques are also studied including steering and alignment methods utilizing numerical optimizers and beam measurement techniques employing neural networks. We compare the performance of algorithms for online optimization and beam-based alignment in terms of their efficiency and effectiveness.

Start-to-end simulations of plasma-wakefield acceleration using the MAX IV Linear Accelerator

Svensson, J. Bjoerklund; Andersson, J.; Ferri, J.; Charles, T. K.; Ekerfelt, H.; Mansten, E.; Thorin, S.; Lundh, O.
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH SECTION A-ACCELERATORS; SPECTROMETERS DETECTORS AND ASSOCIATED EQUIPMENT 1033, 166591 (2022)
https://doi.org/10.1016/j.nima.2022.166591

Plasma-wakefield acceleration (PWFA) relies on the interaction between intense particle bunches and plasma for reaching higher accelerating gradients than what is possible with conventional radio-frequency technology. Using ultra-relativistic beam drivers allows for long acceleration lengths and have potential applications such as energy booster stages for synchrotron light sources or linear colliders and generating ultra-high-brightness beams from the background plasma. In this article, we present start-to-end simulations of the MAX IV Linear Accelerator as part of our investigations into the feasibility of using the linac for a PWFA experiment. We find that PWFA appears to be a viable application for the linac. A part of this conclusion is based on our finding that the general properties of the bunch compressor type employed in the MAX IV linac are well-suited for efficient generation of PWFA-optimized bunch current profiles, both for single-and double-bunch beams.

Characterisation and optimisation of targets for plasma wakefield acceleration at SPARC_LAB

Costa, G.; Anania, M. P.; Arjmand, S.; Biagioni, A.; Del Franco, M.; Del Giorno, M.; Galletti, M.; Ferrario, M.; Pellegrini, D.; Pompili, R.; Romeo, S.; Rossi, A. R.; Zigler, A.; Cianchi, A.

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One of the most important features of plasma-based accelerators is their compactness because plasma modules can have dimensions of the order of mm cm^{-1}, providing very high-accelerating fields up to hundreds of GV m^{-1}. The main challenge regarding this type of acceleration lies in controlling and characterising the plasma itself, which then determines its synchronisation with the particle beam to be accelerated in an external injection stage in the laser wakefield acceleration (LWFA) scheme. This issue has a major influence on the quality of the accelerated bunches. In this work, a complete characterisation and optimisation of plasma targets available at the SPARC_LAB laboratories is presented. Two plasma-based devices are considered: supersonic nozzles for experiments adopting the self-injection scheme of laser wakefield acceleration and plasma capillary discharge for both particle and laser-driven experiments. In the second case, a wide range of plasma channels, gas injection geometries and discharge voltages were extensively investigated as well as studies of the plasma plumes exiting the channels, to control the plasma density ramps. Plasma density measurements were carried out for all the different designed plasma channels using interferometric methods in the case of gas jets, spectroscopic methods in the case of capillaries.

Facilities in Asia for future accelerator development

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We introduce and review available and active research facilities that involve novel acceleration concepts in Asia. Most of the facilities equip with high-peak-power (> 10 TW) lasers with tens of femtosecond duration for laser wakefield acceleration. The activities in Asia are growing and several problems on the realization of high energy frontier accelerators would be accessed through the existing facilities.

Towards a PWFA linear collider – opportunities and challenges

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JOURNAL OF INSTRUMENTATION 17(5), T05006 (2022)
https://doi.org/10.1088/1748-0221/17/05/T05006

I discuss some key opportunities and challenges of a PWFA collider, and outline some objectives which I consider important to be able to assess the machine performance, assuming that numerous technical challenges can be solved. The highlighted topics are purely the choices of this author. Several other articles in this issue are relevant for a collider design, and discuss challenges for different sub-systems of a collider, including the articles on the beam delivery system, drive-beam generation, and emittance preservation. A more complete overview of agreed challenges and objectives can be found in international research roadmaps. Here, we highlight in particular the option of a PWFA gamma gamma collider.

US advanced and novel accelerator beam test facilities

Clarke, C.; Esarey, E.; Geddes, C.; Hofstaetter, G.; Hogan, M. J.; Nagaitsev, S.; Palmer, M.; Piot, P.; Power, J.; Schroeder, C.; Umstadter, D.; Vafaei-Najafabadi, N.; Valishev, A.; Willingale, L.; Yakimenko, V
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https://doi.org/10.1088/1748-0221/17/05/T05009

Demonstrating the viability of Advanced Accelerator Concepts (AAC) relies on experimental validation. Over the last three decades, the U.S. has maintained a portfolio of advanced and novel accelerator test facilities to support research critical to AAC. The facilities have enabled pioneering developments in a wide variety of beam and accelerator physics, including plasma-wakefield and structure-wakefield acceleration. This paper provides an overview of the current portfolio of U.S. facilities possessing charged particle drive beams with high energies, on the order of tens of joules per pulse, or drive lasers with high peak powers, on the order of a petawatt, and are actively conducting AAC research.

Roadmap for Structure-based Wakefield Accelerator (SWFA) R&D and its challenges in beam dynamics

Jing, C.; Ha, G.
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The combination of advantages in positron acceleration over plasma-based accelerators and high gradient over conventional accelerators puts the structure-based wakefield accelerator (SWFA) in a unique spot on the road to a multi-TeV linear collider. As a result of the significant advancements that have been made throughout the past several decades, the SWFA related research continues gaining special attention from the accelerator community. In this article, we will present a survey of the research on SWFAs, with a particular focus on the challenges in beam dynamics, and lay out a roadmap toward its ultimate goal of delivering a mature linear collider design.

Emittance preservation in advanced accelerators

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JOURNAL OF INSTRUMENTATION 17(5) (2022)
https://doi.org/10.1088/1748-0221/17/05/P05016

Emittance is a beam quality that is vital for many future applications of advanced accelerators, such as compact free-electron lasers and linear colliders. In this paper, we review the challenges of preserving the transverse emittance during acceleration, both inside and outside accelerator stages. Sources of emittance growth range from space charge and instabilities caused by transverse wakefields, which can occur in any advanced accelerator scheme regardless of medium or driver type, to sources more specific to plasma accelerators, such as mismatching, misalignment, ion motion, Coulomb scattering, chromaticity between stages, and more.

European facilities for advanced accelerators development

Muggli, P.; Ferrario, M.; Osterhoff, J.; Cros, B.
JOURNAL OF INSTRUMENTATION 17(5), T05008 (2022)
https://doi.org/10.1088/1748-0221/17/05/T05008

Research on the application of advanced and novel accelerator schemes to high-energy physics requires facilities capable of producing multi-GeV particle beams. We briefly review the challenges faced by advanced accelerators in reaching collider-relevant parameters and give a concise description of relevant European facilities and large scale installations, either in operation or in a state of advanced design, with their main goals. We also emphasize contributions from smaller, mostly university groups or laboratories. These facilities and groups advance the field considerably and address some of the challenges arising in the translation of advanced accelerator concepts to a future high-energy physics machine. We highlight the fact that there is in addition the strong need for a dedicated European facility with a scientific and R&D program specific to the research questions exclusive to a plasma-based e^-e^+ linear collider.

Beam dynamics challenges in linear colliders based on laser-plasma accelerators

Schroeder, C. B.; Benedetti, C.; Bulanov, S. S.; Terzani, D.; Esarey, E.; Geddes, C. G. R.
JOURNAL OF INSTRUMENTATION 17(5), P05011 (2022)
https://doi.org/10.1088/1748-0221/17/05/P05011

In this paper we discuss design considerations and beam dynamics challenges associated with laser-driven plasma-based accelerators as applied to multi-TeV-scale linear colliders. Plasma accelerators provide ultra-high gradients and ultra-short bunches, offering the potential for compact linacs and reduced power requirements. We show that stable, efficient acceleration with beam quality preservation is possible in the nonlinear bubble regime of laser-plasma accelerators using beam shaping. Ion motion, naturally occuring for dense beams (i.e., low emittance and high energy) severely damps transverse beam instabilities. Coulomb scattering by the background ions is considered and it is shown that the strong focusing in the plasma strongly suppresses scattering-induced emittance growth. Betatron radiation emission from the transverse motion of the beam in the plasma will result in beam power loss and energy spread growth; however for sub-100 nm emittances, the beam power loss and energy spread growth will be sub-percent for multi-TeV-class plasma linacs.

The AWAKE Run 2 Programme and Beyond

Gschwendtner, Edda et al.
SYMMETRY-BASEL 14(8), 1680 (2022)
https://doi.org/10.3390/sym14081680

Plasma wakefield acceleration is a promising technology to reduce the size of particle accelerators. The use of high energy protons to drive wakefields in plasma has been demonstrated during Run 1 of the AWAKE programme at CERN. Protons of energy 400 GeV drove wakefields that accelerated electrons to 2 GeV in under 10 m of plasma. The AWAKE collaboration is now embarking on Run 2 with the main aims to demonstrate stable accelerating gradients of 0.5-1 GV/m, preserve emittance of the electron bunches during acceleration and develop plasma sources scalable to 100s of metres and beyond. By the end of Run 2, the AWAKE scheme should be able to provide electron beams for particle physics experiments and several possible experiments have already been evaluated. This article summarises the programme of AWAKE Run 2 and how it will be achieved as well as the possible application of the AWAKE scheme to novel particle physics experiments.

FUNDAMENTS

Recovery time of a plasma-wakefield accelerator

D'Arcy, R.; Chappell, J.; Beinortaite, J.; Diederichs, S.; Boyle, G.; Foster, B.; Garland, M. J.; Caminal, P. Gonzalez; Lindstrom, C. A.; Loisch, G.; Schreiber, S.; Schroeder, S.; Shalloo, R. J.; Thevenet, M.; Wesch, S.; Wing, M.; Osterhoff, J.
NATURE 603(7899), 58 (2022)
https://doi.org/10.1038/s41586-021-04348-8

The interaction of intense particle bunches with plasma can give rise to plasma wakes capable of sustaining gigavolt-per-metre electric fields, which are orders of magnitude higher than provided by state-of-the-art radio-frequency technology. Plasma wakefields can, therefore, strongly accelerate charged particles and offer the opportunity to reach higher particle energies with smaller and hence more widely available accelerator facilities. However, the luminosity and brilliance demands of high-energy physics and photon science require particle bunches to be accelerated at repetition rates of thousands or even millions per second, which are orders of magnitude higher than demonstrated with plasma-wakefield technology. Here we investigate the upper limit on repetition rates of beam-driven plasma accelerators by measuring the time it takes for the plasma to recover to its initial state after perturbation by a wakefield. The many-nanosecond-level recovery time measured establishes the in-principle attainability of megahertz rates of acceleration in plasmas. The experimental signatures of the perturbation are well described by simulations of a temporally evolving parabolic ion channel, transferring energy from the collapsing wake to the surrounding media. This result establishes that plasma-wakefield modules could be developed as feasible high-repetition-rate energy boosters at current and future particle-physics and photon-science facilities.

Direct observation of relativistic broken plasma waves

Wan, Yang; Seemann, Omri; Tata, Sheroy; Andriyash, Igor A.; Smartsev, Slava; Kroupp, Eyal; Malka, Victor
NATURE PHYSICS 18(10), 1186 (2022)
https://doi.org/10.1038/s41567-022-01717-6

Plasma waves contribute to many fundamental phenomena, including astrophysics, thermonuclear fusions and particle accelerations. Such waves can develop in numerous ways, from classic Langmuir oscillations carried by electron thermal motions, to the waves excited by an external force and travelling with a drivers. In plasma-based particle accelerators, a strong laser or relativistic particle beam launches plasma waves with field amplitude that follows the driver strength up to the wavebreaking limits, which is the maximum wave amplitude that a plasma can sustain. In this limit, plasma electrons gain sufficient energy from the wave to outrun it and to get trapped inside the wave buckets. Theory and numerical simulations predict multi-dimensional wavebreaking, which is crucial in the electron self-injection process that determines the accelerator performances. Here we present a real-time experimental visualization of the laser-driven nonlinear relativistic plasma waves by probing them with a femtosecond high-energy electron bunch from another laser-plasma accelerator coupled to the same laser system. This single-shot electron deflectometry allows us to characterize nonlinear plasma wakefield with femtosecond temporal and micrometre spatial resolutions revealing features of the plasma waves at the breaking point.

Ultrabright Electron Bunch Injection in a Plasma Wakefield Driven by a Superluminal Flying Focus Electron Beam

Li, F.; Dalichaouch, T. N.; Pierce, J. R.; Xu, X.; Tsung, F. S.; Lu, W.; Joshi, C.; Mori, W. B.
PHYSICAL REVIEW LETTERS 128(17), 174803 (2022)
https://doi.org/10.1103/PhysRevLett.128.174803

We propose a new method for self-injection of high-quality electron bunches in the plasma wakefield structure in the blowout regime utilizing a "flying focus" produced by a drive beam with an energy chirp. In a flying focus the speed of the density centroid of the drive bunch can be superluminal or subluminal by utilizing the chromatic dependence of the focusing optics. We first derive the focal velocity and the characteristic length of the focal spot in terms of the focal length and an energy chirp. We then demonstrate using multidimensional particle-in-cell simulations that a wake driven by a superluminally propagating flying focus of an electron beam can generate GeV-level electron bunches with ultralow normalized slice emittance (~30 nm rad), high current (~17 kA), low slice energy spread (~0.1%), and therefore high normalized brightness (> 10^{19} A/m^2 /rad^2) in a plasma of density ~10^{19} cm^{-3}. The injection process is highly controllable and tunable by changing the focal velocity and shaping the drive beam current. Near-term experiments at FACET II where the capabilities to generate tens of kA, < 10 fs drivers are planned, could potentially produce beams with brightness near 10^{20} A/m^2/rad^2.

Transient Relativistic Plasma Grating to Tailor High-Power Laser Fields, Wakefield Plasma Waves, and Electron Injection

Chen, Qiang; Maslarova, Dominika; Wang, Junzhi; Lee, Shao Xian; Horny, Vojtech; Umstadter, Donald
PHYSICAL REVIEW LETTERS 128(16), 164801 (2022)
https://doi.org/10.1103/PhysRevLett.128.164801

We show the first experiment of a transverse laser interference for electron injection into the laser plasma accelerators. Simulations show such an injection is different from previous methods, as electrons are trapped into later acceleration buckets other than the leading ones. With optimal plasma tapering, the dephasing limit of such unprecedented electron beams could be potentially increased by an order of magnitude. In simulations, the interference drives a relativistic plasma grating, which triggers the splitting of relativistic-intensity laser pulses and wakefield. Consequently, spatially dual electron beams are accelerated, as also confirmed by the experiment.

In Situ Measurement of Electron Energy Evolution in a Laser-Plasma Accelerator

Bohlen, S.; Bruemmer, T.; Gruener, F.; Lindstrom, C. A.; Meisel, M.; Staufer, T.; Streeter, M. J. V.; Veale, M. C.; Wood, J. C.; D'Arey, R.; Poder, K.; Osterhoff, J.
PHYSICAL REVIEW LETTERS 129(24), 244801 (2022)
https://doi.org/10.1103/PhysRevLett.129.244801

We report on a novel, noninvasive method applying Thomson scattering to measure the evolution of the electron beam energy inside a laser-plasma accelerator with high spatial resolution. The determination of the local electron energy enabled the in-situ detection of the acting acceleration fields without altering the final beam state. In this Letter we demonstrate that the accelerating fields evolve from (265 +/- 119) GV/m to (9 +/- 4) GV/m in a plasma density ramp. The presented data show excellent agreement with particle-in -cell simulations. This method provides new possibilities for detecting the dynamics of plasma-based accelerators and their optimization.

Stable and High-Quality Electron Beams from Staged Laser and Plasma Wakefield Accelerators

Foerster, F. M.; Doepp, A.; Haberstroh, F.; Grafenstein, K., V; Campbell, D.; Chang, Y-Y; Corde, S.; Cabadag, J. P. Couperus; Debus, A.; Gilljohann, M. F.; Habib, A. F.; Heinemann, T.; Hidding, B.; Irman, A.; Irshad, F.; Knetsch, A.; Kononenko, O.; de la Ossa, A. Martinez; Nutter, A.; Pausch, R.; Schilling, G.; Schletter, A.; Schoebel, S.; Schramm, U.; Travac, E.; Ufer, P.; Karsch, S.
PHYSICAL REVIEW X 12(4), 041016 (2022)
https://doi.org/10.1103/PhysRevX.12.041016

We present experimental results on a plasma wakefield accelerator (PWFA) driven by high-current electron beams from a laser wakefield accelerator (LWFA). In this staged setup stable and high-quality (low-divergence and low energy spread) electron beams are generated at an optically generated hydro-dynamic shock in the PWFA. The energy stability of the beams produced by that arrangement in the PWFA stage is comparable to both single-stage laser accelerators and plasma wakefield accelerators driven by conventional accelerators. Simulations support that the intrinsic insensitivity of PWFAs to driver energy fluctuations can be exploited to overcome stability limitations of state-of-the-art laser wakefield accelerators when adding a PWFA stage. Furthermore, we demonstrate the generation of electron bunches with energy spread and divergence superior to single-stage LWFAs, resulting in bunches with dense phase space and an angular-spectral charge density beyond the initial drive beam parameters. These results unambiguously show that staged LWFA-PWFA can help to tailor the electron-beam quality for certain applications and to reduce the influence of fluctuating laser drivers on the electron-beam stability. This encourages further development of this new class of staged wakefield acceleration as a viable scheme toward compact, high-quality electron beam sources.

Multi-GeV Electron Bunches from an All-Optical Laser Wakefield Accelerator

Miao, B.; Shrock, J. E.; Feder, L.; Hollinger, R. C.; Morrison, J.; Nedbailo, R.; Picksley, A.; Song, H.; Wang, S.; Rocca, J. J.; Milchberg, H. M.
PHYSICAL REVIEW X 12(3), 031038 (2022)
https://doi.org/10.1103/PhysRevX.12.031038

We present the first demonstration of multi-GeV laser wakefield acceleration in a fully optically formed plasma waveguide, with an acceleration gradient as high as 25 GeV/m. The guide was formed via self-waveguiding of <15 J, 45 fs (< ~300 TW) pulses over 20 cm in a low-density hydrogen gas jet, with accelerated electron bunches driven up to 5 GeV in quasimonoenergetic peaks of relative energy width as narrow as ~15%, with divergence down to ~1 mrad and charge up to tens of picocoulombs. Energy gain is inversely correlated with on-axis waveguide density in the range N_{e0} = (1.3-3.2) x 10^{17} cm^{-3}. We find that shot-to-shot stability of bunch spectra and charge are strongly dependent on the pointing of the injected laser pulse and gas jet uniformity. We also observe evidence of pump depletion-induced dephasing, a consequence of the long optical guiding distance.

Bragg scattering induced laser deflection and electron injection in x-ray laser driven wakefield acceleration in crystals

An, Xiangyan; Chen, Min; Weng, Suming; Sheng, Zhengming; Zhang, Jie
PHYSICAL REVIEW ACCELERATORS AND BEAMS 25(11), L042034 (2022)
https://doi.org/10.1103/PhysRevResearch.4.L042034

Propagation of intense ultrashort x-ray laser pulse in a metal crystal and its effects on x-ray laser-driven wakefield acceleration are theoretically and numerically investigated with particle-in-cell simulations, where

the bound electron effects are included. New features of laser pulse dissipation due to Bragg scattering have been observed and analyzed. The beat wave generated by the drive laser and scattered laser results in plasma density modulation and subsequent drive laser deflection. Continuous electron injection into the wakefields is also found due to the beat wave. These new features of laser propagation, wake generation, and electron injection provide effective controls on x-ray laser driven wakefield acceleration, where an acceleration gradient as high as 0.75 TV/cm is numerically demonstrated.

Characterization of laser wakefield acceleration efficiency with octave spanning near-IR spectrum measurements

Streeter, M. J. V.; Ma, Y.; Kettle, B.; Dann, S. J. D.; Gerstmayr, E.; Albert, F.; Bourgeois, N.; Cipiccia, S.; Cole, J. M.; Gonzalez, I. Gallardo; Hussein, A. E.; Jaroszynski, D. A.; Falk, K.; Krushelnick, K.; Lemos, N.; Lopes, N. C.; Lumsdon, C.; Lundh, O.; Mangles, S. P. D.; Najmudin, Z.; Rajeev, P. P.; Sandberg, R.; Shahzad, M.; Smid, M.; Spesyvtsev, R.; Symes, D. R.; Vieux, G.; Thomas, A. G. R.

PHYSICAL REVIEW ACCELERATORS AND BEAMS 25(10), 101302 (2022)
https://doi.org/10.1103/PhysRevAccelBeams.25.101302

We report on experimental measurements of energy transfer efficiencies in a GeV-class laser wakefield accelerator. Both the transfer of energy from the laser to the plasma wakefield and from the plasma to the accelerated electron beam was diagnosed by simultaneous measurement of the deceleration of laser photons and the acceleration of electrons as a function of plasma length. The extraction efficiency, which we define as the ratio of the energy gained by the electron beam to the energy lost by the self-guided laser mode, was maximized at 19 +/- 3% by tuning the plasma density and length. The additional information provided by the octave-spanning laser spectrum measurement allows for independent optimization of the plasma efficiency terms, which is required for the key goal of improving the overall efficiency of laser wakefield accelerators.

Mechanisms to control laser-plasma coupling in laser wakefield electron acceleration

Dickson, L. T.; Underwood, C. I. D.; Filippi, F.; Shalloo, R. J.; Svensson, J. Bjorklund; Guenot, D.; Svendsen, K.; Moulanier, I; Dufrenoy, S. Dobosz; Murphy, C. D.; Lopes, N. C.; Rajeev, P. P.; Najmudin, Z.; Cantono, G.; Persson, A.; Lundh, O.; Maynard, G.; Streeter, M. J., V; Cros, B.

PHYSICAL REVIEW ACCELERATORS AND BEAMS 25(10), 101301 (2022)
https://doi.org/10.1103/PhysRevAccelBeams.25.101301

Experimental results, supported by precise modeling, demonstrate optimization of a plasma-based injector with intermediate laser pulse energy (<1 J), corresponding to a normalized vector potential a_0 = 2.15, using ionization injection in a tailored plasma density profile. An increase in electron bunch quality and energy is achieved experimentally with the extension of the density downramp at the plasma exit. Optimization of the focal position of the laser pulse in the tailored plasma density profile is shown to efficiently reduce electron bunch angular deviation, leading to a better alignment of the electron bunch with the laser axis. Single peak electron spectra are produced in a previously unexplored regime by combining an early focal position and adaptive optic control of the laser wavefront by optimizing the symmetry of the prefocal laser energy distribution. Experimental results have been validated through particle-in-cell simulations using realistic laser energy, phase distribution, and temporal envelope, allowing for accurate predictions of difficult to model parameters, such as total charge and spatial properties of the electron bunches, opening the way for more accurate modeling for the design of plasma-based accelerators.

Observation of transverse injection and enhanced beam quality in laser wakefield acceleration of isolated electron bunches using an optimized plasma waveguide

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PHYSICAL REVIEW ACCELERATORS AND BEAMS 25(6), 065210 (2022)
https://doi.org/10.1103/PhysRevE.105.065210

The laser wakefield acceleration of monoenergetic multi-GeV electron beams in the bubble regime is investigated via particle-in-cell simulations considering laser guiding of sub-petawatt pulses by an optimized plasma waveguide. The density profile of the plasma has a transverse transition from a low value for the laser guiding central channel to an optimal higher value for the surrounding plasma. Multidimensional particle-in-cell simulations in the nonlinear bubble regime show that when the spot size of the Gaussian laser pulse is matched to the diameter of the low-density laser-guiding plasma channel, electron self-injection can be transversely provided from the surrounding high-density plasma mitigating the need for a minimum electron density of the low-density channel to trigger the self-injection. Accordingly, the pump depletion and electron dephasing lengths can be increased by reducing the electron density of the axial channel, and the electron bunch can be accelerated to considerably longer distances. As a result, the energy gain of the trapped electrons, injected from the surrounding high-density region, can be efficiently enhanced. Under such conditions, a completely localized electron bunch with considerably decreased energy spread (<2%) and enhanced peak energy (~2.5 GeV) is accelerated over a length of ~6 mm by a sub-petawatt laser pulse (~86 TW).

Plasma photonic spatiotemporal synchronization of relativistic electron and laser beams

Scherkl, P.; Knetsch, A.; Heinemann, T.; Sutherland, A.; Habib, A. F.; Karger, O. S.; Ullmann, D.; Beaton, A.; Manahan, G. G.; Xi, Y.; Deng, A.; Litos, M. D.; O'Shea, B. D.; Green, S. Z.; Clarke, C., I; Andonian, G.; Assmann, R.; Bruhwiler, D. L.; Smith, J.; Cary, J. R.; Hogan, M. J.; Yakimenko, V; Rosenzweig, J. B.; Hidding, B.
PHYSICAL REVIEW ACCELERATORS AND BEAMS 25(5), 052803 (2022)
https://doi.org/10.1103/PhysRevAccelBeams.25.052803

We present an ultracompact plasma-based method to measure spatial and temporal concurrence of intense electron and laser beams nonintrusively at their interaction point. The electron beam couples with a laser-generated seed plasma in dependence of spatiotemporal overlap, which triggers additional plasma production and manifests as enhanced plasma afterglow. This optical observable is exploited to measure beam concurrence with ~4 μm spatial and ~26.7 fs temporal accuracy, supported by auxiliary diagnostics. The afterglow interaction fingerprint is highly sensitive and enables ultraversatile femtosecond-micrometer beam metrology.

Nanoparticle-insertion scheme to decouple electron injection from laser evolution in laser wakefield acceleration

Xu, Jiancai; Bae, Leejin; Ezzat, Mohamed; Kim, Hyung Taek; Yang, Jeong Moon; Lee, Sang Hwa; Yoon, Jin Woo; Sung, Jae Hee; Lee, Seong Ku; Ji, Liangliang; Shen, Baifei; Nam, Chang Hee
SCIENTIFIC REPORTS 12(1), 11128 (2022)
https://doi.org/10.1038/s41598-022-15125-6

A localized nanoparticle insertion scheme is developed to decouple electron injection from laser evolution in laser wakefield acceleration. Here we report the experimental realization of a controllable electron injection by the nanoparticle insertion method into a plasma medium, where the injection position is localized within the short range of 100 μm. Nanoparticles were generated by the laser ablation process of a copper blade target using a 3-ns 532-nm laser pulse with fluence above 100 J/cm^2. The produced electron bunches with a beam charge above 300 pC and divergence of around 12 mrad show the injection probability over 90% after optimizing the ablation laser energy and the temporal delay between the ablation and the main laser pulses. Since this nanoparticle insertion method can avoid the disturbing effects of electron injection process on laser evolution, the stable high-charge injection method can provide a suitable electron injector for multi-GeV electron sources from low-density plasmas.

Control of electron beam polarization in the bubble regime of laser-wakefield acceleration

Fan, H. C.; Liu, X. Y.; Li, X. F.; Qu, J. F.; Yu, Q.; Kong, Q.; Weng, S. M.; Chen, M.; Buscher, M.; Gibbon, P.; Kawata, S.; Sheng, Z. M.

NEW JOURNAL OF PHYSICS 24(8), 083047 (2022)

https://doi.org/10.1088/1367-2630/ac8951

Electron beam polarization in the bubble regime of the interaction between a high-intensity laser and a longitudinally pre-polarized plasma is investigated by means of the Thomas-Bargmann-Michel-Telegdi equation. Using a test-particle model, the dependence of the accelerated electron polarization on the bubble geometry is analysed in detail. Tracking the polarization dynamics of individual electrons reveals that although the spin direction changes during both the self-injection process and acceleration phase, the former has the biggest impact. For nearly spherical bubbles, the polarization of electron beam persists after capture and acceleration in the bubble. By contrast, for aspherical bubble shapes, the electron beam becomes rapidly depolarized, and the net polarization direction can even reverse in the case of a oblate spheroidal bubble. These findings are confirmed via particle-in-cell simulations.

Effect of driver charge on wakefield characteristics in a plasma accelerator probed by femtosecond shadowgraphy

Schoebel, Susanne; Pausch, Richard; Chang, Yen-Yu; Corde, Sebastien; Cabadag, Jurjen Couperus; Debus, Alexander; Ding, Hao; Doepp, Andreas; Foerster, F. Moritz; Gilljohann, Max; Haberstroh, Florian; Heinemann, Thomas; Hidding, Bernhard; Karsch, Stefan; Koehler, Alexander; Kononenko, Olena; Kurz, Thomas; Nutter, Alastair; Steiniger, Klaus; Ufer, Patrick; de la Ossa, Alberto Martinez; Schramm, Ulrich; Irman, Arie

NEW JOURNAL OF PHYSICS 24(8), 083034 (2022)

https://doi.org/10.1088/1367-2630/ac87c9

We report on experimental investigations of plasma wave structures in a plasma wakefield acceleration (PWFA) stage which is driven by electron beams from a preceding laser plasma accelerator. Femtosecond optical probing is utilized to allow for direct visualization of the plasma dynamics inside the target. We compare two regimes in which the driver propagates either through an initially neutral gas, or a preformed plasma. In the first case, plasma waves are observed that quickly damp after a few oscillations and are located within a narrow plasma channel ionized by the driver, having about the same transverse size as the plasma wakefield cavities. In contrast, for the latter robust cavities are recorded sustained over many periods. Furthermore, here an elongation of the first cavity is measured, which becomes stronger with increasing driver beam charge. Since the cavity length is linked to the maximum accelerating field strength, this elongation implies an increased field strength. This observation is supported by 3D particle-in-cell simulations performed with PIConGPU. This work can be extended for the investigation of driver depletion by probing at different propagation distances inside the plasma, which is essential for the development of high energy efficiency PWFAs.

Parametric study of high-energy ring-shaped electron beams from a laser wakefield accelerator

Maitrallain, A.; Brunetti, E.; Streeter, M. J., V; Kettle, B.; Spesyvtsev, R.; Vieux, G.; Shahzad, M.; Ersfeld, B.; Yoffe, S. R.; Kornaszewski, A.; Finlay, O.; Ma, Y.; Albert, F.; Bourgeois, N.; Dann, S. J. D.; Lemos, N.; Cipiccia, S.; Cole, J. M.; Gonzalez, I. G.; Willingale, L.; Higginbotham, A.; Hussein, A. E.; Smid, M.; Falk, K.; Krushelnick, K.; Lopes, N. C.; Gerstmayr, E.; Lumsdon, C.; Lundh, O.; Mangles, S. P. D.; Najmudin, Z.; Rajeev, P. P.; Symes, D. R.; Thomas, A. G. R.; Jaroszynski, D. A.

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https://doi.org/10.1088/1367-2630/ac3efd

Laser wakefield accelerators commonly produce on-axis, low-divergence, high-energy electron beams. However, a high charge, annular shaped beam can be trapped outside the bubble and accelerated to high energies. Here we present a parametric study on the production of low-energy-spread, ultra-relativistic electron ring beams in a two-stage gas cell. Ring-shaped beams with energies higher than 750 MeV are observed simultaneously with on axis, continuously injected electrons. Often multiple ring shaped beams with different energies are produced and parametric studies to control the generation and properties of these structures were conducted. Particle tracking and particle-in-cell simulations are used to determine properties of these beams and investigate how they are formed and trapped outside the bubble by the wake produced by on-axis injected electrons. These unusual femtosecond duration, high-charge, high-energy, ring electron beams may find use in beam driven plasma wakefield accelerators and radiation sources.

Evolution of equilibrium particle beams in plasma under external wakefields

Baistrukov, M. A.; Lotov, K., V

PLASMA PHYSICS AND CONTROLLED FUSION 64(7), 075003 (2022)
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A beam of ultrarelativistic charged particles in a plasma can reach equilibrium with its own radial wakefield and then propagate with little change in shape. If some co-moving perturbation appears ahead of the beam, it may or may not destroy the beam with its wakefield, depending on the phase and amplitude of the wakefield. We numerically study which perturbations can destroy a single short bunch or a train of many short bunches at the parameters of interest for plasma wakefield acceleration in an axisymmetric configuration, and how fast. We find that there are particularly dangerous wakefield phases in which the beam can be destroyed by perturbations of very low amplitude. We also find that perturbations with an amplitude larger than the wakefield of a single bunch in the train are always destructive.

Improving a high-power laser-based relativistic electron source: the role of laser pulse contrast and gas jet density profile

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PLASMA PHYSICS AND CONTROLLED FUSION 64(4), 044007 (2022)
https://doi.org/10.1088/1361-6587/ac4b06

A relativistic electron source based on high power laser interaction with gas jet targets has been developed at the Institute of Plasma Physics and Lasers of the Hellenic Mediterranean University. Initial measurements were conducted using the 'Zeus' 45 TW laser with peak intensities in the range of 10^{18}-10^{19} W cm^{-2} interacting with a He pulsed gas jet having a 0.8 mm diameter nozzle. A significant improvement of the electron signal was measured after using an absorber to improve the laser pulse contrast from 10^{-10} to 10^{-11}. A high stability quasi-mono-energetic electron beam of about 50 MeV was achieved and measured using a magnetic spectrometer for pulsed gas jet backing pressure of 12 bar. Supplementary studies using a 3 mm diameter nozzle for backing pressures in the range of 35-40 bar showed electron beam production with energies spread in the range from 50 to 150 MeV. The pulsed jet density profile was determined using interferometric techniques. Particle-in-cell simulations, at the above experimentally determined conditions, support our experimental findings.

Ion dynamics driven by a strongly nonlinear plasma wake

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PLASMA PHYSICS AND CONTROLLED FUSION 64(4), 045003 (2022)
https://doi.org/10.1088/1361-6587/ac4523

In plasma wakefield accelerators, the wave excited in the plasma eventually breaks and leaves behind slowly changing fields and currents that perturb the ion density background. We study this process numerically using the example of a Facility for Advanced aCcelerator Experimental Tests (FACET) experiment where the wave is excited by an electron bunch in the bubble regime in a radially bounded plasma. Four physical effects underlie the dynamics of ions: (1) attraction of ions toward the axis by the fields of the driver and the wave, resulting in formation of a density peak, (2) generation of ion-acoustic solitons following the decay of the density peak, (3) positive plasma charging after wave breaking, leading to acceleration of some ions in the radial direction, and (4) plasma pinching by the current generated during the wave-breaking. The interplay of these effects results in the formation of various radial density profiles, which are difficult to produce in any other way.

Scissor-cross ionization injection in laser wakefield accelerators

Wang, Jia; Zeng, Ming; Wang, Xiaoning; Li, Dazhang; Gao, Jie

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We propose to use a frequency-doubled pulse colliding with the driving pulse at an acute angle to trigger ionization injection in a laser wakefield accelerator. This scheme effectively reduces the duration of the injection; thus, high injection quality is obtained. Three-dimensional particle-in-cell simulations show that electron beams with energy of ~500 MeV, a charge of ~40 pC, energy spread of ~1% and normalized emittance of a few millimeter milliradian can be produced by ~100 TW laser pulses. By adjusting the angle between the two pulses, the intensity of the trigger pulse and the gas doping ratio, the charge and energy spread of the electron beam can be controlled.

Laser wakefield acceleration of 10-MeV-scale electrons driven by 1-TW multi-cycle laser pulses in a sub-millimeter nitrogen gas cell

Lai, P. -W.; Liu, K. -N.; Tran, D. K.; Chou, S. -W.; Chu, H. -H.; Chen, S. -H.; Wang, J.; Lin, M. -W.

PHYSICS OF PLASMAS 30(1), 010703 (2023)
https://doi.org/10.1063/5.0131155

By focusing conventional 1-TW 40-fs laser pulses into a dense 450 -μm-long nitrogen gas cell, we demonstrate the feasibility of routinely generating electron beams from laser wakefield acceleration (LWFA) with primary energies scaling up to 10 MeV and a high charge in excess of 50 pC. When electron beams are generated with a charge of ≈30 pC and a beam divergence of ≈40 mrad from the nitrogen cell having a peak atom density of 7.6×10^{18} cm^{-3}, increasing the density inside the cell by 25%, controlled by tuning the backing pressure of fed nitrogen gas, can induce defocusing of the pump pulse that leads to a twofold increase in the output charge but with a trade-off in beam divergence. Therefore, this LWFA scheme has two preferred regimes for acquiring electron beams with either lower divergence or higher beam charge depending on a slight variation of the gas/plasma density inside the cell. Our results identify the high potential for implementing sub millimeter nitrogen gas cells in the future development of high-repetition-rate LWFA driven by sub-TW or few-TW laser pulses.

Meter-scale plasma waveguides for multi-GeV laser wakefield acceleration

Shrock, J. E.; Miao, B.; Feder, L.; Milchberg, H. M.

PHYSICS OF PLASMAS 29(7), 073101 (2022)
https://doi.org/10.1063/5.0097214

We present results from two new techniques for the generation of meter-scale, low density ~10^{17} cm^{-3} on axis) plasma waveguides, the "two-Bessel" technique, and the "self-waveguiding" technique. Plasma waveguides of this density and length range are needed for demonstration of a ~10 GeV laser wakefield accelerator module, key for future staging for a ~TeV lepton collider. Both techniques require the use of high quality ultrashort pulse Bessel beams to efficiently and uniformly ionize hydrogen gas in meter-scale supersonic gas jets via optical field ionization. We review these two techniques, describe our meter-scale gas jets, and present a new method for correction of optical aberrations in Bessel beams. Finally, we briefly present results from recent experiments employing one of our techniques, demonstrating quasi-monoenergetic acceleration of ~5 GeV electron bunches in 20 cm long, low density plasma waveguides.

Stable electron beam propagation in a plasma column

Diederichs, S.; Benedetti, C.; Esarey, E.; Thevenet, M.; Osterhoff, J.; Schroeder, C. B.

PHYSICS OF PLASMAS 29(4), 043101 (2022)
https://doi.org/10.1063/5.0087807

The stability of plasma-based accelerators against transverse misalignments and asymmetries of the drive beam is crucial for their applicability. Without stabilizing mechanisms, even small initial offsets of the drive beam centroid can couple coherently to the plasma wake, grow, and ultimately lead to emittance degradation or beam loss for a trailing witness beam. In this work, we demonstrate the intrinsic stability of a beam propagating in a plasma column. This result is relevant in the context of plasma-based positron acceleration, where a wakefield suitable for the transport and acceleration of a positron witness beam is generated in a plasma column by means of an electron drive beam. The stable propagation of the drive beam is a necessary condition for the experimental implementation of this scheme. The differences and similarities of stabilizing mechanisms in a plasma column compared to a homogeneous plasma are identified via theory and particle-in-cell simulations. Experimental tolerances are given, demonstrating the experimental feasibility of the scheme.

Acceleration of an Electron Bunch with a Non-Gaussian Transverse Profile in Proton-Driven Plasma Wakefield

Liang, Linbo; Xia, Guoxing; Pukhov, Alexander; Farmer, John Patrick

APPLIED SCIENCES-BASEL 12(21), 10919 (2022)
https://doi.org/10.3390/app122110919

Beam-driven plasma wakefield accelerators typically use the external injection to ensure controllable beam quality at injection. However, the externally injected witness bunch may exhibit a non-Gaussian transverse density distribution. Using particle-in-cell simulations, we show that the common beam quality factors, such as the normalized RMS emittance and beam radius, do not strongly depend on the initial transverse shapes of the witness beam. Nonetheless, a beam with a highly-peaked transverse spatial profile can achieve a higher fraction of the total beam charge in the core. The same effect can be seen when the witness beam's transverse momentum profile has a peaked non-Gaussian distribution. In addition, we find that an initially non-axisymmetric beam becomes symmetric due to the interaction with the plasma wakefield.

Limiting effects in drive bunch beam dynamics in beam-driven accelerators: instability and collective effects

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JOURNAL OF INSTRUMENTATION 17(5), P05013 (2022)

https://doi.org/10.1088/1748-0221/17/05/P05013

In a collinear beam-driven wakefield accelerator, a bunch of charged particles is accelerated by a strong electric field that is generated in a medium by a preceding high-charge drive bunch. Multiple beam-driven acceleration concepts have been proposed and demonstrated in proof-of-principle experiments. In some concepts, the medium is plasma where very strong electric fields are created due to the motion of ions and electrons with respect to each other. In other configurations, the medium is a slow-wave electromagnetic structure made of dielectric and/or metal, and high gradients are achieved due to the very short duration of the electromagnetic pulse excited in the structure by the drive bunch. Because of the high charge, and consequently long length of the drive bunch, wakefields excited by the leading particles of the drive bunch affect the trailing particles in the same bunch and result in beam-driven instabilities obstructing the drive bunch's stable propagation and extended interactions with the witness bunch, ultimately terminating the energy transfer process. This paper presents an overview of the drive-bunch beam dynamics in beam-driven structure- and plasma-based accelerators with a focus on beam instabilities that limit stable propagation of the drive bunch, such as the beam break-up instability and transverse defocusing and deflection in cases of cylindrical and planar structures and plasma waveguides. Possible mitigation techniques are discussed.

Review of Quality Optimization of Electron Beam Based on Laser Wakefield Acceleration

Jiang, Kangnan; Wang, Wentao; Feng, Ke; Li, Ruxin

PHOTONICS 9(8), 511 (2022)

https://doi.org/10.3390/photonics9080511

Compared with state-of-the-art radio frequency accelerators, the gradient of laser wakefield accelerators is 3-4 orders of magnitude higher. This is of great significance in the development of miniaturized particle accelerators and radiation sources. Higher requirements have been proposed for the quality of electron beams, owing to the increasing application requirements of tabletop radiation sources, specifically with the rapid development of free-electron laser devices. This review briefly examines the electron beam quality optimization scheme based on laser wakefield acceleration and presents some representative studies. In addition, manipulation of the electron beam phase space by means of injection, plasma profile distribution, and laser evolution is described. This review of studies is beneficial for further promoting the application of laser wakefield accelerators.

Wakefield Acceleration in a Jet from a Neutrino-driven Accretion Flow around a Black Hole

Kato, Yoshiaki; Ebisuzaki, Toshikazu; Tajima, Toshiki
ASTROPHYSICAL JOURNAL 929(1), 42 (2022)
https://doi.org/10.3847/1538-4357/ac56e3

We have investigated electromagnetic (EM) wave pulses in a jet from a neutrino-driven accretion flow (NDAF) around a black hole (BH). NDAFs are massive accretion disks whose accretion rates $\dot{M} \approx 0.01$–$10\ M_{\odot}\ s^{-1}$ for stellar-mass BHs. Such an extreme accretion may produce a collimated relativistic outflow like a magnetically driven jet in active galactic nuclei and microquasars. When we consider strong toroidal magnetic field stranded in the inner region of an NDAF disk and magnetic impulses on the jet, we find that they lead to the emanation of high-energy emissions for gamma-ray bursts, as well as high-energy cosmic rays. When Alfvenic wave pulses are generated by episodic immense accretions, they propagate along the large-scale structured magnetic field in the jet. Once the Alfvenic wave pulses reach nearly the speed of light in the underdense condition, they turn into EM wave pulses, which produce plasma wakes behind them. These wakefields exert a collective accelerating force synchronous to the motion of particles. As a result, the wakefield acceleration premises various observational signatures, such as pulsating bursts of high-energy gamma rays from accelerated electrons, pulses of neutrinos from accelerated protons, and protons with maximum energies beyond 10^{20} eV.

Experimental study on capillary discharge for laser plasma wake acceleration

Zhu Xin-Zhe; Li Bo-Yuan; Liu Feng; Li Jian-Long; Bi Ze-Wu; Lu Lin; Yuan Xiao-Hui; Yan Wen-Chao; Chen Min; Chen Li-Ming; Sheng Zheng-Ming; Zhang Jie
ACTA PHYSICA SINICA 71(9), 095202 (2022)
https://doi.org/10.7498/aps.71.20212435

Preformed plasma channels play important roles in many applications, such as laser wakefield acceleration, plasma lens, and so on. Laser pulses can be well guided when the radial density distribution of the plasma channel has a parabolic profile and it is matched with the laser focus. Discharging a gas-filled capillary is a possible way to form such plasma channels. In this work, we report the capillary discharging and laser guiding experiments performed in the Laboratory for Laser Plasmas at Shanghai Jiao Tong University. The plasma density distributions in the Helium-filled discharged capillary are measured by using the spectral broadening method. In a capillary with a length of 3 cm and a diameter of 300 μm, the plasma density profile is observed to be uniformly distributed along the axial direction and have a parabolic profile along the radial direction. Parameters for plasma channel generation are scanned. The deepest channel depth obtained is 28 μm, which is close to the focal spot radius of the laser used in the experiment. Laser guidance in the plasma channel is also studied. The results show that the laser can maintain its focus and continuously propagate when the channel depth matches the focal spot, indicating that the well guiding of the laser pulse by the preformed plasma channel is obtained. These studies may serve as the ground work for the future studies, such as staged laser wakefield acceleration and phase-locked wakefield acceleration.

Characteristics of short electron bunch in the quasi-linear donut wake acceleration

Firouzjaei, Ali Shekari; Sobhani, Hassan
WAVES IN RANDOM AND COMPLEX MEDIA (JAN 2023)
https://doi.org/10.1080/17455030.2023.2168087

The trapping and acceleration of an externally injected electron bunch into a donut-like wakefield driven by an intense Laguerre-Gaussian (LG) laser pulse in the plasma are studied. The results because of the doughnut shape profile of the LG laser pulse and low divergence propagating can be used in applications such as accelerating a hollow electron bunch. For the high-energy acceleration in the donut wake, while keeping the emittance conserved and making the Relative Energy Spread (RES) a few percent, the suitable initial bunch parameters are investigated. Careful optimization of the test electron bunch parameters allows one to obtain a minimum suitable RES and a stable emittance of the accelerated bunch in the donut wakefield.

Coupled effect of spatio-temporal variation of Laguerre-Gaussian laser pulse on electron acceleration in magneto-plasma

Kad, Proxy; Singh, Arvinder

WAVES IN RANDOM AND COMPLEX MEDIA (SEP 2022)

https://doi.org/10.1080/17455030.2022.2121011

In this work, the acceleration of electrons via incidence of a Laguerre-Gaussian laser pulse in a plasma medium with relativistic non-linearity in the presence of a uniform external magnetic field along the direction of propagation has been presented. The moment theory approach has been used to obtain the two non-linear second-order differential equations, which have been further solved numerically to determine the variation in the radial and temporal width of the laser pulse in the plasma medium. The propagation of the laser pulse in the plasma medium excites the electron plasma wave, which acts as a wakefield for electron acceleration. The effect of radial and temporal variation on electron acceleration has also been investigated. Furthermore, the spatio-temporal variation and energy gain have been studied for different Laguerre modes of lasers, their intensities, and plasma densities.

Controlled acceleration of GeV electron beams in an all-optical plasma waveguide

Oubrerie, Kosta; Leblanc, Adrien; Kononenko, Olena; Lahaye, Ronan; Andriyash, Igor A.; Gautier, Julien; Goddet, Jean-Philippe; Martelli, Lorenzo; Tafzi, Amar; Ta Phuoc, Kim; Smartsev, Slava; Thaury, Cedric

LIGHT-SCIENCE & APPLICATIONS 11(1), 180 (2022)

https://doi.org/10.1038/s41377-022-00862-0

Laser-plasma accelerators (LPAs) produce electric fields of the order of 100 GV m^{-1}, more than 1000 times larger than those produced by radio-frequency accelerators. These uniquely strong fields make LPAs a promising path to generate electron beams beyond the TeV, an important goal in high-energy physics. Yet, large electric fields are of little benefit if they are not maintained over a long distance. It is therefore of the utmost importance to guide the ultra-intense laser pulse that drives the accelerator. Reaching very high energies is equally useless if the properties of the electron beam change completely from shot to shot, due to the intrinsic lack of stability of the injection process. State-of-the-art laser-plasma accelerators can already address guiding and control challenges separately by tweaking the plasma structures. However, the production of beams that are simultaneously high quality and high energy has yet to be demonstrated. This paper presents a novel experiment, coupling laser-plasma waveguides and controlled injection techniques, facilitating the reliable and efficient acceleration of high-quality electron beams up to 1.1 GeV, from a 50 TW-class laser.

INSTRUMENTATION

Direct spectral measurements of midinfrared radiation from a laser wakefield accelerator

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PHYSICAL REVIEW A 106(6), 063505 (2022)
https://doi.org/10.1103/PhysRevA.106.063505

The formation of plasma waves during laser wakefield acceleration (LWFA) produces time-dependent frequency shifts in the driving laser pulse, extending its spectral content to the infrared. We present direct spectral measurements of multi-mJ infrared pulses from an LWFA. Experimental beam profile measurements and three-dimensional particle-in-cell simulations suggest high focusability of these pulses. Particle-in-cell simulations demonstrate that the measurement of side-scattered infrared radiation may serve as a diagnostic of plasma waves and the efficiency of spectral broadening during LWFA.

Excitation of the W-band Structure of Cavities by the Charged Particle Train

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PHYSICS OF PARTICLES AND NUCLEI LETTERS 19(4), 384-388 (2022)
https://doi.org/10.1134/S1547477122040069

The development of the millimeter wavelength structure of cavities is underway at the Budker Institute of Nuclear Physics. The initial interest in such structures is caused by the possibility of obtaining a higher accelerating gradient due to the breakdown limit increase at a higher operating frequency domain. The W-band structures can also be used for charged particle bunch production for experiments with plasma wakefield acceleration. An analysis of cavity structure excitation by the single bunch was given in our previous studies, as well as a comparison of it with excitation simulations. This paper presents an analysis of the structure excitation by the train of charged particle bunches taking into account the train parameters and the individual detuning of the cavity frequency relative to the bunch repetition rate.

LASER DRIVERS

A model for pumping optimization in edge-pumped disk amplifiers

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OPTICS & LASER TECHNOLOGY 156, 108524 (2022)
https://doi.org/10.1016/j.optlastec.2022.108524

A model for the calculation of the pump energy coupling to a disk amplifier is presented. The disk is considered to be pumped on its edge by diode bars. A composite geometry, namely a disk with a doped (pump absorbing) inner region surrounded by an undoped region is considered. The model allows the overall pump energy coupling as well as the absorption 3D map to be obtained for different geometric diode bars arrangements on an N-sided polygon. A set of fundamental conditions for the maximization of the total energy coupled to the active region is laid out first. Using the model, we then show that once these conditions are fulfilled, the precise diode bars arrangement and focusing can be tuned to get the desired energy absorption spatial distribution, while preserving the highest overall energy coupling to the doped region. The most interesting case of a cylindrically symmetric, radially uniform absorption profile is discussed, providing some general hints on achieving such a condition.

High-brightness 1.4 kW 780 nm QCW laser pump module with low-loss coupling into 1 mm fiber up to 50 % duty cycle

Hübner, M.; Wilkens, M.; Eppich, B.; Basler, P.S.; Maaßdorf, A.; Martin, D.; Knigge, A.; Ginolas, A.; Kreutzmann, S.; Crump, P.

PROC. OF SPIE, VOL. 11983, HIGH-POWER DIODE LASER TECHNOLOGY XX, PHOTONICS WEST, SAN FRANCISCO, USA, JAN 22-27, 1198309 (2022)
https://doi.org/10.1117/12.2608625

The performance characteristics of two stack modules (emitting near 780 nm) each consisting of 24 wide-aperture (1200 µm) diode laser chips is presented and the results are discussed. The stack modules are constructed using diode lasers from two different epitaxial design iterations. Compared to the first iteration, the second iteration was optimized for higher conversion efficiency and optical in-pulse power (lower losses), without compromising the beam characteristics. The stack modules make use of an established (field-proven) FBH design that utilizes innovative edge-cooling of both sides of the diode stack with large-channel (micro-channel free), water-cooled, thermally-expansion-matched heatsinks. We investigate here their performance up to high duty cycles and results for pulse width up to 10 ms at high duty cycle (50 %) operation is presented. Test of the completed modules show that the iteration 2 (power-optimized) chips deliver about 15 % more optical power without compromising the beam propagation ratio. Specifically, the stack module with first iteration chips delivers approx. 1.4 kW whereas the stack module with the optimized chips delivers approx. 1.6 kW. For the stack module that uses the first chip iteration a fiber coupling to a 1 mm core fiber was demonstrated with approx. 90 % coupling efficiency and loss channels are discussed. Finally, very high duty cycle operation (50 %) is demonstrated for the first time, using an iteration 1 stack module.

Power and brightness scaling of GaAs-based diode lasers and modules for direct and pump applications

Wilkens, M.; Hübner, M.; Crump, P.

2022 IEEE RESEARCH AND APPLICATIONS OF PHOTONICS IN DEFENSE CONFERENCE (RAPID), MIRAMAR BEACH, FL, USA, PP. 1-2 (2022)
https://doi.org/10.1109/RAPID54472.2022.9911575

We present an overview of recent developments of brilliant high-power diode lasers and diode laser systems as direct or pump sources, containing high duty cycle and CW systems, ranging from 665 nm for alexandrite, via 780 nm for thulium to 970 nm for Yb:YAG.

Axiparabola: a new tool for high-intensity optics

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JOURNAL OF OPTICS 24(4), 045503 (2022)
https://doi.org/10.1088/2040-8986/ac57d2

An axiparabola is a reflective aspherical optics that focuses a light beam into an extended focal line. The light intensity and group velocity profiles along the focus are adjustable through the proper design. The on-axis light velocity can be controlled, for instance, by adding spatio-temporal couplings via chromatic optics on the incoming beam. Therefore the energy deposition along the axis can be either subluminal or superluminal as required in various applications. This article first explores how the axiparabola design defines its properties in the geometric optics approximation. Then the obtained description is considered in numerical simulations for two cases of interest for laser-plasma acceleration. We show that the axiparabola can be used either to generate a plasma waveguide to overcome diffraction or for driving a dephasingless wakefield accelerator.

Comparative study of ultrashort single-pulse and multi-pulse driven laser wakefield acceleration

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LASER PHYSICS LETTERS 20(2), 026001(2023)
https://doi.org/10.1088/1612-202X/aca978

Laser wakefield acceleration (LWFA) is a promising technique to build compact and powerful particle accelerators. In such accelerators, the electric fields required to accelerate charged particles are sustained by electron density modulations in the plasma. The plasma wave modulating the electron density may be excited by an intense laser pulse. However, propagation of intense laser pulse in plasma is subject to various instabilities which result in significant losses of laser energy, reducing the efficiency of wakefield generation. Using a train of lower intensity pulses instead of a single higher intensity pulse appears to be a more efficient scheme for LWFA. Here we have studied this alternative scheme by applying an ultra-short femtosecond Gaussian laser beam consisting pulse train of a various number of pulses in different cases to underdense plasma. The plasma density modulation and strength of the resulting wakefield have been compared in various cases of multi-pulse and single-pulse lasers, for the same amount of input energies. Here we demonstrate that applying multi-laser pulses of optimally selected lower intensities and proper spacing leads to stronger wakefield generation and more efficient electron acceleration compared to the case of a single pulse of higher energy.

Guiding of Laguerre-Gaussian pulses in high-order plasma channels

Yu, L.; Zhao, H. M.; Cao, Q.; Zhu, X. Z.; Li, J. L.; Li, B. Y.; Liu, F.; Chen, M.; Sheng, Z. M.
PLASMA PHYSICS AND CONTROLLED FUSION 64(7), 075009 (2022)
https://doi.org/10.1088/1361-6587/ac734f

In laser wakefield accelerators, guiding of drive laser pulses in preformed plasma channels plays a key role to overcome laser diffraction for effective acceleration. Different from guiding schemes studied previously, where a Gaussian laser pulse and a parabolic plasma channel were investigated, here we investigate the guiding of Laguerre-Gaussian (LG) pulses in plasma channels. Analytical studies and three-dimensional particle-in-cell simulations show that the matched conditions still exist for high order laser pulses and high order plasma channels. For usual Gaussian and high order LG pulses, the second order parabolic channel gives the best guiding. Although the laser pulse can also be guided in even higher order channels, its envelope deforms during propagation. For laser pulses with combined multi-LG modes, determined by their azimuthal orbit angular momenta, there is axisymmetric or non-axisymmetric evolution for the transverse laser intensity profile. The preformed plasma channel can guide the combined pulses but the transverse intensity profile of the laser pulses always evolves.

Controlling the characteristics of injected and accelerated electron bunch in corrugated plasma channel by temporally asymmetric laser pulses

Sedaghat, M.; Amouye Foumani, A.; Niknam, A. R.
SCIENTIFIC REPORTS 12(1), 8115 (2022)
https://doi.org/10.1038/s41598-022-11955-6

In laser-driven plasma wakefield accelerators, the accelerating electric field is orders of magnitude stronger than in conventional radio-frequency particle accelerators, but the dephasing between the ultrarelativistic electron bunch and the wakefield traveling at the group velocity of the laser pulse puts a limit on the energy gain. Quasi-phase-matching, enabled by corrugated plasma channels, is a technique for overcoming the dephasing limitation. The attainable energy and the final properties of accelerated electron beams are of utmost importance in laser wakefield acceleration (LWFA). In this work, using two-dimensional particle-in-cell simulations, the effect of the driving pulse duration on the performance of quasi-phase-matched laser wakefield acceleration (QPM-LWFA) is investigated. It is observed that for a pulse duration around half the plasma period, the maximum energy gain of the beam electrons finds its peak value. However, the results show that for a pulse of that duration the collimation of the bunch is much worse, compared to the case where the pulse duration is twice as long. Furthermore, the dynamics of the laser pulse and the evolution of the quality of the externally-injected electron bunch are studied for a symmetric pulse with sine-squared temporal profile, a positive skew pulse (i.e., one with sharp rise and slow fall), and a negative skew pulse (i.e., one with a slow rise and sharp fall). The results indicate that for a laser pulse with an appropriate pulse length compared with the plasma wavelength, the wakefield amplitude can be greatly enhanced by using a positive skew pulse, which leads to higher energy gain. Initially, this results from the stronger ponderomotive force associated with a fast rise time. Later, due to the distinct evolution of the three pulses with different initial profiles, the wakefield excited by the positive skew pulse becomes even stronger. In our simulations, the maximum energy gain for the asymmetric laser pulse with a fast rise time is almost two times larger than for the temporally symmetric laser pulse. Nevertheless, stronger focusing and defocusing fields are generated as well if a positive skew pulse is applied, which degrade the collimation of the bunch. These results should be taken into account in the design of miniature particle accelerators based on QPM-LWFA.

Particle acceleration by twisted laser beams

Mendonca, J. T.; Vieira, J.; Willim, C.; Fedele, R.

FRONTIERS IN PHYSICS 10, 995379 (2022)

https://doi.org/10.3389/fphy.2022.995379

We consider particle acceleration in plasmas, using twisted laser beams, or beams with orbital angular momentum. We discuss different acceleration processes using two LG laser modes, which include donut wakefield, beat-wave and self-torque acceleration, and compare the respective properties. We show that a self-torque configuration is able to produce azimuthal acceleration and can therefore be considered as an alternative method to produce helical electron beams.

Direct laser acceleration of electrons from a plasma mirror by an intense few-cycle Laguerre-Gaussian laser and its dependence on the carrier-envelope phase

Pae, Ki Hong; Kim, Chul Min; Pathak, Vishwa Bandhu; Ryu, Chang-Mo; Nam, Chang Hee

PLASMA PHYSICS AND CONTROLLED FUSION 64(5), 055013 (2022)

https://doi.org/10.1088/1361-6587/ac5a0a

A direct acceleration scheme to generate high-energy, high-charge electron beams with an intense few-cycle Laguerre-Gaussian (LG) laser pulse was investigated using three-dimensional particle-in-cell simulations. In this scheme, an intense LG laser pulse was irradiated onto a solid density plasma slab. When the laser pulse is reflected, electrons on the target front surface are injected into the longitudinal electric field of the laser and accelerated further. We found that the carrier-envelope phase (CEP) of the few-cycle laser pulse plays a key role in the electron injection and acceleration process. Using a three-cycle LG laser pulse with $a_0 = 2$ and an appropriate CEP, an about 60 pC electron beam could be obtained at a maximum energy of 16 MeV. In comparison, when a laser pulse with mismatched CEP was used, a total of 4 pC electron beam with a maximum energy of 3.5 MeV was obtained. Linear scaling of electron energy to the laser strength was shown up to $a_0 = 100$ at which a quasi-monoenergetic electron beam of 850 MeV energy with a charge equal to 600 pC could be obtained. These results demonstrate that high-energy electron beams can be stably generated through direct laser acceleration using a CEP-controlled intense few-cycle LG laser pulse.

Propagation of axiparabola-focused laser pulses in uniform plasmas

Geng, Pan-Fei; Chen, Min; Zhu, Xin-Zhe; Liu, Wei-Yuan; Sheng, Zheng-Ming; Zhang, Jie

PHYSICS OF PLASMAS 29(11), 112301 (2022)
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An axiparabola-based flying focus laser possesses a long focal depth, a small focal spot, and a controllable group velocity. It has been proposed for wide applications, such as phase-locked laser wakefield acceleration and photon acceleration. We numerically study the propagation of axiparabola-focused laser pulses in plasmas and find that such lasers can propagate stably over long distances in plasmas at low intensity. When the laser intensity increases to the relativistic intensity, they no longer propagate stably. Pulse front deformation and fracture appear due to the formation of plasma density modulations. We propose three schemes to mitigate the unstable propagation of axiparabola-focused lasers: (i) adding a radially dependent pulse front delay, (ii) placing the plasma away from the beginning of the focal line, and (iii) using an axiparabola mirror with a negative focal line. All these methods are relatively easy to implement. Our studies can provide guidance for applications of axiparabola-focused lasers. Published under an exclusive license by AIP Publishing.

Carrier-envelope phase controlled dynamics of relativistic electron beams in a laser-wakefield accelerator

Rovige, Lucas; Monzac, Josephine; Huijts, Julius; Andriyash, Igor A.; Vernier, Aline; Kaur, Jaismeen; Ouille, Marie; Cheng, Zhao; Tomkus, Vidmantas; Girdauskas, Valdas; Raciukaitis, Gediminas; Dudutis, Juozas; Stankevic, Valdemar; Gecys, Paulius; Lopez-Martens, Rodrigo; Faure, Jerome

EUROPEAN PHYSICAL JOURNAL-SPECIAL TOPICS (OCT 2022)
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In laser-wakefield acceleration, an ultra-intense laser pulse is focused into an underdense plasma to accelerate electrons to relativistic velocities. In most cases, the pulses consist of multiple optical cycles and the interaction is well described in the framework of the ponderomotive force where only the envelope of the laser has to be considered. But when using single-cycle pulses, the ponderomotive approximation breaks down, and the actual waveform of the laser has to be taken into account. In this paper, we use near-single-cycle laser pulses to drive a laser-wakefield accelerator. We observe variations of the electron beam pointing on the order of 10 mrad in the polarization direction, as well as 30% variations of the beam charge, locked to the value of the controlled laser carrier-envelope phase, in both nitrogen and helium plasma. Those findings are explained through particle-in-cell simulations indicating that low-emittance, ultrashort electron bunches are periodically injected off-axis by the transversally oscillating bubble associated with the slipping carrier-envelope phase.

Electron acceleration and spatio-temporal variation of Laguerre-Gaussian laser pulse in relativistic plasma

Kad, Proxy; Singh, Arvinder

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https://doi.org/10.1140/epjp/s13360-022-03054-2

In this paper, the investigation of spatial and temporal dynamics of high power Laguerre-Gaussian laser pulse propagating inside the plasma medium has been presented. The effect of relativistic nonlinearity has been taken into account. The variation in the mass of the relativistic moving electrons introduces perturbation in the dielectric function and results in the generation of the electron plasma wave. This excited electron

plasma wave with a high field acts as a wakefield that accelerates the electrons along with it. The variation in the spatial and temporal width of the Laguerre-Gaussian laser pulse has been studied by using the method of moments approach. The solution for the spatial and temporal width parameters of the laser pulse has been obtained numerically by solving two nonlinear coupled differential equations. The electric field of the generated electron plasma wave is then used to calculate the energy gained by the electrons. The spatio-temporal dynamics and energy gain have been studied for different modes of the Laguerre-Gaussian laser pulse. From the investigation, it has been observed that the (0, 2) mode of the Laguerre-Gaussian laser pulse is more suitable for higher energy gain.

Study of two cross focused Bessel-Gaussian laser beams on electron acceleration in relativistic regime

Kad, Proxy; Choudhary, Rishi; Bhatia, Aman; Walia, Keshav; Singh, Arvinder

OPTIK 271, 170117 (2022)

https://doi.org/10.1016/j.ijleo.2022.170117

In the present work, self-focusing of two cross-focused Bessel-Gaussian lasers having difference in their frequencies equal to plasma frequency has been examined. The variation in the mass of plasma electrons, due to the occurrence of relativistic effects by laser-plasma interaction has been taken into consideration. Two second-order nonlinear coupled differential equations governing the spatial variation of laser profile have been obtained by using the moment theory approach and are numerically solved. The propagation of coupled beam inside the plasma medium excites the wakefield, which is responsible for electron acceleration. The coupled effect of spatial variation of both beams on the acceleration of plasma electrons has been studied. Effects of the different transverse extent of coupled laser beam intensities and plasma densities on electron acceleration have been investigated and are found to be very useful for electron acceleration.

Electron beam acceleration using colliding pulses injection in parabolic plasma channel

Phadte, D.; Upadhyay, A.; Prasad, Y. B. S. R.

OPTIK 265, 169402 (2022)

https://doi.org/10.1016/j.ijleo.2022.169402

Optical injection of electrons in laser wakefield accelerator scheme has been shown using the PIC simulation of colliding pulse injection method. Parameter scans like laser polarization, colliding angle, delay and injector pulse intensity have been carried out, to get the optimum values for the injection. To guide the laser pulse over many Rayleigh lengths a parabolic plasma channel is used. For a 45 fs laser pulse of intensity 9×10^{18} W/cm^2 focused to spot size of 6 μm inside a plasma of density 4.0×10^{18} cm^{-3}, a highly mono-energetic electron beam with 2.1 pC charge at 337 MeV was obtained.

Laser wakefield and direct laser acceleration of electron by chirped laser pulses

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Chirped laser pulses are investigated theoretically for laser wakefield (LW) and direct laser (DL) acceleration of electrons in the plasma-bubble regime. Chirping of laser pulse with a suitable frequency allows a better trapping of electron in bubble regime which enforces a strong betatron resonance inside the plasma bubble. Linear and non-linear effects of frequency chirp determine electron acceleration, de-phasing, beam quality in terms of energy spread and high energy from the direct laser field and its plasma wake in bubble regime. Gaussian chirped laser pulse exhibit high energy to the electrons compared with linear and other non-linear chirped pulses in plasmabubble regime. The investigation with chirped laser pulse opens new dimension to hybrid LW-DL acceleration mechanism in bubble regime.

THEORY & SIMULATION

Accurate electron beam phase-space theory for ionization-injection schemes driven by laser pulses

Tomassini, P.; Massimo, F.; Labate, L.; Gizzi, L. A.

HIGH POWER LASER SCIENCE AND ENGINEERING 10, E15 (2022)

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After the introduction of the ionization-injection scheme in laser wake field acceleration and of related high-quality electron beam generation methods, such as two-color and resonant multi-pulse ionization injection (ReMPI), the theory of thermal emittance has been used to predict the beam normalized emittance obtainable with those schemes. We recast and extend such a theory, including both higher order terms in the polynomial laser field expansion and non-polynomial corrections due to the onset of saturation effects on a single cycle. Also, a very accurate model for predicting the cycle-averaged distribution of the extracted electrons, including saturation and multi-process events, is proposed and tested. We show that our theory is very accurate for the selected processes of $Kr^{8+\rightarrow 10+}$ and $Ar^{8+\rightarrow 10+}$, resulting in a maximum error below 1%, even in a deep-saturation regime. The accurate prediction of the beam phase-space can be implemented, for example, in laser-envelope or hybrid particle-in-cell (PIC)/fluid codes, to correctly mimic the cycle-averaged momentum distribution without the need for resolving the intra-cycle dynamics. We introduce further spatial averaging, obtaining expressions for the whole-beam emittance fitting with simulations in a saturated regime, too. Finally, a PIC simulation for a laser wakefield acceleration injector in the ReMPI configuration is discussed.

Spatiotemporal dynamics of ultrarelativistic beam-plasma instabilities

Claveria, P. San Miguel; Davoine, X.; Peterson, J. R.; Gilljohann, M.; Andriyash, I; Ariniello, R.; Clarke, C.; Ekerfelt, H.; Emma, C.; Faure, J.; Gessner, S.; Hogan, M. J.; Joshi, C.; Keitel, C. H.; Knetsch, A.; Kononenko, O.; Litos, M.; Mankovska, Y.; Marsh, K.; Matheron, A.; Nie, Z.; O'Shea, B.; Storey, D.; Vafaei-Najafabadi, N.; Wu, Y.; Xu, X.; Yan, J.; Zhang, C.; Tamburini, M.; Fiuza, F.; Gremillet, L.; Corde, S.

PHYSICAL REVIEW RESEARCH 4(2), 023085 (2022)

https://doi.org/10.1103/PhysRevResearch.4.023085

An electron or electron-positron beam streaming through a plasma is notoriously prone to microinstabilities. For a dilute ultrarelativistic infinite beam, the dominant instability is a mixed mode between longitudinal two-stream and transverse filamentation modes, with a phase velocity oblique to the beam velocity. A spatiotemporal theory describing the linear growth of this oblique mixed instability is proposed which predicts that spatiotemporal effects generally prevail for finite-length beams, leading to a significantly slower instability evolution than in the usually assumed purely temporal regime. These results are accurately supported by particle-in-cell (PIC) simulations. Furthermore, we show that the self-focusing dynamics caused by the plasma wakefields driven by finite-width beams can compete with the oblique instability. Analyzed through PIC simulations, the interplay of these two processes in realistic systems bears important implications for upcoming accelerator experiments on ultrarelativistic beam-plasma interactions.

Machine learning-based direct solver for one-to-many problems on temporal shaping of relativistic electron beams

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FRONTIERS OF PHYSICS 17(6), 64601 (2022)
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To control the temporal profile of a relativistic electron beam to meet requirements of various advanced scientific applications like free-electron-laser and plasma wakefield acceleration, a widely-used technique is to manipulate the dispersion terms which turns out to be one-to-many problems. Due to their intrinsic one-to-many property, current popular stochastic optimization approaches on temporal shaping may face the problems of long computing time or sometimes suggesting only one solution. Here we propose a real-time solver for one-to-many problems of temporal shaping, with the aid of a semi-supervised machine learning method, the conditional generative adversarial network (CGAN). We demonstrate that the CGAN solver can learn the one-to-many dynamics and is able to accurately and quickly predict the required dispersion terms for different custom temporal profiles. This machine learning-based solver is expected to have the potential for wide applications to one-to-many problems m other scientific fields.

The optimal beam-loading in two-bunch nonlinear plasma wakefield accelerators

Wang, Xiaoning; Gao, Jie; Su, Qianqian; Wang, Jia; Li, Dazhang; Zeng, Ming; Lu, Wei; Mori, Warren B.; Joshi, Chan; An, Weiming
PLASMA PHYSICS AND CONTROLLED FUSION 64(6), 065007 (2022)
https://doi.org/10.1088/1361-6587/ac6a10

Due to the highly nonlinear nature of the beam-loading, it is currently not possible to analytically determine the beam parameters needed in a two-bunch plasma wakefield accelerator for maintaining a low energy spread. Therefore in this paper, by using the Broyden-Fletcher-Goldfarb-Shanno algorithm for the parameter scanning with the code QuickPIC and the polynomial regression together with k-fold cross-validation method, we obtain two fitting formulas for calculating the parameters of tri-Gaussian electron beams when minimizing the energy spread based on the beam-loading effect in a nonlinear plasma wakefield accelerator. One formula allows the optimization of the normalized charge per unit length of a trailing beam to achieve the minimal energy spread, i.e. the optimal beam-loading. The other one directly gives the transformer ratio when the trailing beam achieves the optimal beam-loading. A simple scaling law for charges of drive beams and trailing beams is obtained from the fitting formula, which indicates that the optimal beam-loading is always achieved for a given charge ratio of the two beams when the length and separation of two beams and the plasma density are fixed. The formulas can also help obtain the optimal plasma densities for the maximum accelerated charge and the maximum acceleration efficiency under the optimal beam-loading respectively. These two fitting formulas will significantly enhance the efficiency for designing and optimizing a two-bunch plasma wakefield acceleration stage.

Excitation and enhancement of wakefield by beating of two laser beams in a preformed plasma channel: An analytical study

Arefnia, M.; Ghorbanalilu, M.; Niknam, A. R.
PHYSICS OF PLASMAS 29(7), 072305 (2022)
https://doi.org/10.1063/5.0096499

We investigate analytically the nonlinear interaction of two beating laser beams with plasma by considering electron density inhomogeneity in the axial and radial directions. We apply the fluid model coupled with

Maxwell equations to obtain a nonlinear equation for studying the plasma wave. We solve this nonlinear equation using the hypergeometric and Airy functions and present the damping and outgoing wave solutions. Our results show that the longitudinal and transverse wakefields generated in the preformed density-ramped plasma channel are much stronger than the inhomogeneous plasma with density-ramped profile. Published under an exclusive license by AIP Publishing.

Lattice Boltzmann simulations of plasma wakefield acceleration

Parise, G.; Cianchi, A.; Del Dotto, A.; Guglietta, F.; Rossi, A. R.; Sbragaglia, M.
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https://doi.org/10.1063/5.0085192

We explore a novel simulation route for Plasma Wakefield Acceleration (PWFA) by using the computational method known as the Lattice Boltzmann Method (LBM). LBM is based on a discretization of the continuum kinetic theory while assuring the convergence toward hydrodynamics for coarse-grained fields (i.e., density, velocity, etc.). LBM is an established numerical analysis tool in computational fluid dynamics, able to efficiently bridge between kinetic theory and hydrodynamics, but its application in the context of PWFA has never been investigated so far. This paper takes a step forward to fill this gap. Results of LBM simulations for PWFA are discussed and compared with those of a code (Architect) implementing a Cold Fluid (CF) model for the plasma. In the hydrodynamic framework, we discuss the importance of regularization effects related to diffusion properties intrinsic of the LBM, allowing to go beyond the CF approximations. Issues on computational efficiency are also addressed. Published under an exclusive license by AIP Publishing.

A hybrid nodal-staggered pseudo-spectral electromagnetic particle-in-cell method with finite-order centering

Zoni, Edoardo; Lehe, Remi; Shapoval, Olga; Belkin, Daniel; Zaim, Neil; Fedeli, Luca; Vincenti, Henri; Vay, Jean-Luc
COMPUTER PHYSICS COMMUNICATIONS 279, 108457 (2022)
https://doi.org/10.1016/j.cpc.2022.108457

Electromagnetic particle-in-cell (PIC) codes are widely used to perform computer simulations of a variety of physical systems, including fusion plasmas, astrophysical plasmas, plasma wakefield particle accelerators, and secondary photon sources driven by ultra-intense lasers. In a PIC code, Maxwell's equations are solved on a grid with a numerical method of choice. This article focuses on pseudo-spectral analytical time-domain (PSATD) algorithms and presents a novel hybrid PSATD PIC scheme that combines the respective advantages of standard nodal and staggered methods. The novelty of the hybrid scheme consists in using finite-order centering of grid quantities between nodal and staggered grids, in order to combine the solution of Maxwell's equations on a staggered grid with the deposition of charges and currents and the gathering of electromagnetic forces on a nodal grid. The correctness and performance of the novel hybrid scheme are assessed by means of numerical tests that employ different classes of PSATD equations in a variety of physical scenarios, ranging from the modeling of electron-positron pair creation in vacuum to the simulation of laser-driven and particle beam-driven plasma wakefield acceleration. It is shown that the novel hybrid scheme offers significant numerical and computational advantages, compared to purely nodal or staggered methods, for all the test cases presented. (C) 2022 The Authors. Published by Elsevier B.V.

HiPACE plus plus : A portable, 3D quasi-static particle-in-cell code

Diederichs, S.; Benedetti, C.; Huebl, A.; Lehe, R.; Myers, A.; Sinn, A.; Vay, J. -l.; Zhang, W.; Thevenet, M.
COMPUTER PHYSICS COMMUNICATIONS 278, 108421 (2022)
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Modeling plasma accelerators is a computationally challenging task and the quasi-static particle-in-cell algorithm is a method of choice in a wide range of situations. In this work, we present the first performance-portable, quasi-static, three-dimensional particle-in-cell code HiPACE++. By decomposing all the computation of a 3D domain in successive 2D transverse operations and choosing appropriate memory management, HiPACE++ demonstrates orders-of-magnitude speedups on modern scientific GPUs over CPU-only implementations. The 2D transverse operations are performed on a single GPU, avoiding time-consuming communications. The longitudinal parallelization is done through temporal domain decomposition, enabling near-optimal strong scaling from 1 to 512 GPUs. HiPACE++ is a modular, open-source code enabling efficient modeling of plasma accelerators from laptops to state-of-the-art supercomputers. (C) 2022 The Author(s). Published by Elsevier B.V.

Integrating a ponderomotive guiding center algorithm into a quasi-static particle-in-cell code based on azimuthal mode decomposition

Li, Fei; An, Weiming; Tsung, Frank S.; Decyk, Viktor K.; Mori, Warren B.
JOURNAL OF COMPUTATIONAL PHYSICS 470, 111599 (2022)
https://doi.org/10.1016/j.jcp.2022.111599

High fidelity modeling of plasma based acceleration (PBA) requires the use of three dimensional, fully nonlinear, and kinetic descriptions based on the particle-in-cell (PIC) method. In PBA an intense particle beam or laser (driver) propagates through a tenuous plasma whereby it excites a plasma wave wake. Three-dimensional PIC algorithms based on the quasi-static approximation (QSA) have been successfully applied to efficiently model the interaction between relativistic charged particle beams and plasma. In a QSA PIC algorithm, the plasma response to a charged particle beam or laser driver is calculated based on forces from the driver and self-consistent forces from the QSA form of Maxwell's equations. These fields are then used to advance the charged particle beam or laser forward by a large time step. Since the time step is not limited by the regular Courant-Friedrichs-Lewy (CFL) condition that constrains a standard 3D fully electromagnetic PIC code, a 3D QSA PIC code can achieve orders of magnitude speedup in performance. Recently, a new hybrid QSA PIC algorithm that combines another speedup technique known as an azimuthal Fourier decomposition has been proposed and implemented. This hybrid algorithm decomposes the electromagnetic fields, charge and current density into azimuthal harmonics and only the Fourier coefficients need to be updated, which can reduce the algorithmic complexity of a 3D code to that of a 2D code. Modeling the laser-plasma interaction in a full 3D electromagnetic PIC algorithm is very computationally expensive due the enormous disparity of physical scales to be resolved. In the QSA the laser is modeled using the ponderomotive guiding center (PGC) approach. We describe how to implement a PGC algorithm compatible for the QSA PIC algorithms based on the azimuthal mode expansion. This algorithm permits time steps orders of magnitude larger than the cell size and it can be asynchronously parallelized. Details on how this is implemented into the QSA PIC code that utilizes an azimuthal mode expansion, QPAD, are also described. Benchmarks and comparisons between a fully 3D explicit PIC code (OSIRIS), as well as a few examples related to laser wakefield acceleration, are presented. (C) 2022 Elsevier Inc. All rights reserved.

Numerical dispersion free in longitudinal axis for particle-in-cell simulation

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JOURNAL OF COMPUTATIONAL PHYSICS 462, 111221 (2022)
https://doi.org/10.1016/j.jcp.2022.111221

We introduce a new scheme for a field solver for particle-in-cell simulations; it uses P- and S-polarized variables in the modified Maxwell equations to eliminate numerical dispersion along the longitudinal axis. By obtaining numerical stability of the dispersion relation, the scheme has two major advantages of simulating the exact laser group velocity and the exact electron beam propagation. Those advantages are important for simulations of laser wakefield acceleration in a low-density plasma, and of the propagation of an electron beam that has low emittance. The scheme is implemented in multi-dimensional Cartesian and cylindrical coordinates following Fourier decomposition of the azimuthal direction. Results of both calculations compare well with results of three-dimensional simulations. (C) 2022 The Author(s). Published by Elsevier Inc.

Vlasov description of the beam response to noise in the presence of wakefields in high-energy synchrotrons: beam transfer function, diffusion, and loss of Landau damping

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Noise can have severe impacts on particle beams in high-energy synchrotrons. In particular, it has recently been discovered that noise combined with wakefields can cause a diffusion that leads to a loss of Landau damping after a latency. Such instabilities have been observed in the Large Hadron Collider. This paper, therefore, studies the beam response to noise in the presence of wakefields, within the framework of the Vlasov equation. First, a wakefield beam eigenmode transfer function (MTF) is derived, quantifying the amplitude of a wakefield eigenmode when excited by noise. Then, the MTFs of all the wakefield eigenmodes are combined to derive the beam transfer function (BTF) including the impact of wakefields. It is found to agree excellently with multi-particle tracking simulations. Finally, the MTFs are also used to derive the single-particle diffusion driven by the wakefield eigenmodes. This new Vlasov-based theory for the diffusion driven by noise-excited wakefields is found to be superior to an existing theory by comparing to multi-particle tracking simulations. Through sophisticated simulations that self-consistently model the evolution of the distribution and the stability diagram, the diffusion is found to lead to a loss of Landau damping after a latency. The most important technique to extend the latency and thereby mitigate these instabilities is to operate the synchrotron with a stability margin in detuning strength relative to the amount of detuning required to barely stabilize the beam with its initial distribution.

Kinetic theory of longitudinal stability analysis of a non-laminar electron beam in self-consistent plasma wake field excitation

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PHYSICA SCRIPTA 97(6), 065602 (2022)
https://doi.org/10.1088/1402-4896/ac698c

We carry out a stability analysis of a relativistic nonlaminar electron beam which is experiencing the self-consistent plasma wake field excitation. This is done in overdense regime (i.e. plasma density much greater than beam density) in a cold plasma. We adopt the self-consistent kinetic model for the plasma wake field excitation, that is based on the pair of Vlasov-Poisson-type equations. The latter governs the phase-space spatiotemporal evolution of the beam and its linearized form leads to a Landau-type approach to the beam stability analysis. Thereby, the analysis, performed for the case of a Gaussian electron beam distribution, shows the existence of the unstable modes for both cold and warm beams, respectively.

High-order corrections to the radiation-free dynamics of an electron in the strongly radiation-dominated regime

Samsonov, A. S.; Nerush, E. N.; Kostyukov, I. Yu.

MATTER AND RADIATION AT EXTREMES 8(1), 014402 (2023)
https://doi.org/10.1063/5.0117504

A system of reduced equations is proposed for electron motion in the strongly radiation-dominated regime for an arbitrary electromagnetic field configuration. The approach developed here is used to analyze various scenarios of electron dynamics in this regime: motion in rotating electric and magnetic fields and longitudinal acceleration in a plane wave and in a plasma wakefield. The results obtained show that this approach is able to describe features of electron dynamics that are essential in certain scenarios, but cannot be captured in the framework of the original radiation-free approximation [Samsonov et al., Phys. Rev. A 98, 053858 (2018) and A. Gonoskov and M. Marklund, Phys. Plasmas 25, 093109 (2018)]. The results are verified by numerical integration of the nonreduced equations of motion with account taken of radiation reaction in both semiclassical and fully quantum cases. (c) 2022 Author(s).

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