THE EuPRAXIA FILES

ISSUE 10 – October 2023

FOREWORD

This is the tenth issue of the quarterly newsletter for members and friends of the EuPRAXIA consortium, with abstracts of published articles that are relevant to the EuPRAXIA project. The list is by no means exhaustive and its purpose is to facilitate your research and continue to strengthen the EuPRAXIA community. If you have any suggestion or an article that should be included in the next issue, please send an email to the address at the end of this newsletter.

CONTENTS

RESEARCH HIGHLIGHTS

Coherence and superradiance from a quasi-particle accelerator

A group of international scientists led by researchers from EuPRAXIA partner Instituto Superior Técnico (Laser and Plasma Group, Institute of Plasma and Nuclear Fusion) and including experts from the University of Rochester and University of California Los Angeles in the United States and the Applied Optics Laboratory in France, have discovered something fascinating. If faster-than-light particles exist, they might be the key to creating a new kind of super-bright light source, just as powerful as the most advanced ones we have today, but much smaller.

Instead of focusing on individual particles, the researchers looked at something called "quasi-particles." These quasi-particles are the result of electrons moving together in sync, like waves on a river moving in the opposite direction of the water's flow. The interesting part is that these quasi-particles can travel at any speed, even faster than light, and can withstand intense forces.

According to Jorge Vieira, a professor at the Instituto Superior Técnico, and coordinator of this study, "*these special quasi-particles provide an exciting new way to explore and suggest extremely powerful sources of light that nobody had thought of before.*" This approach is simple enough that it can be tried in dozens or even hundreds of labs around the world, bringing the theoretical concept a step closer to becoming a reality.

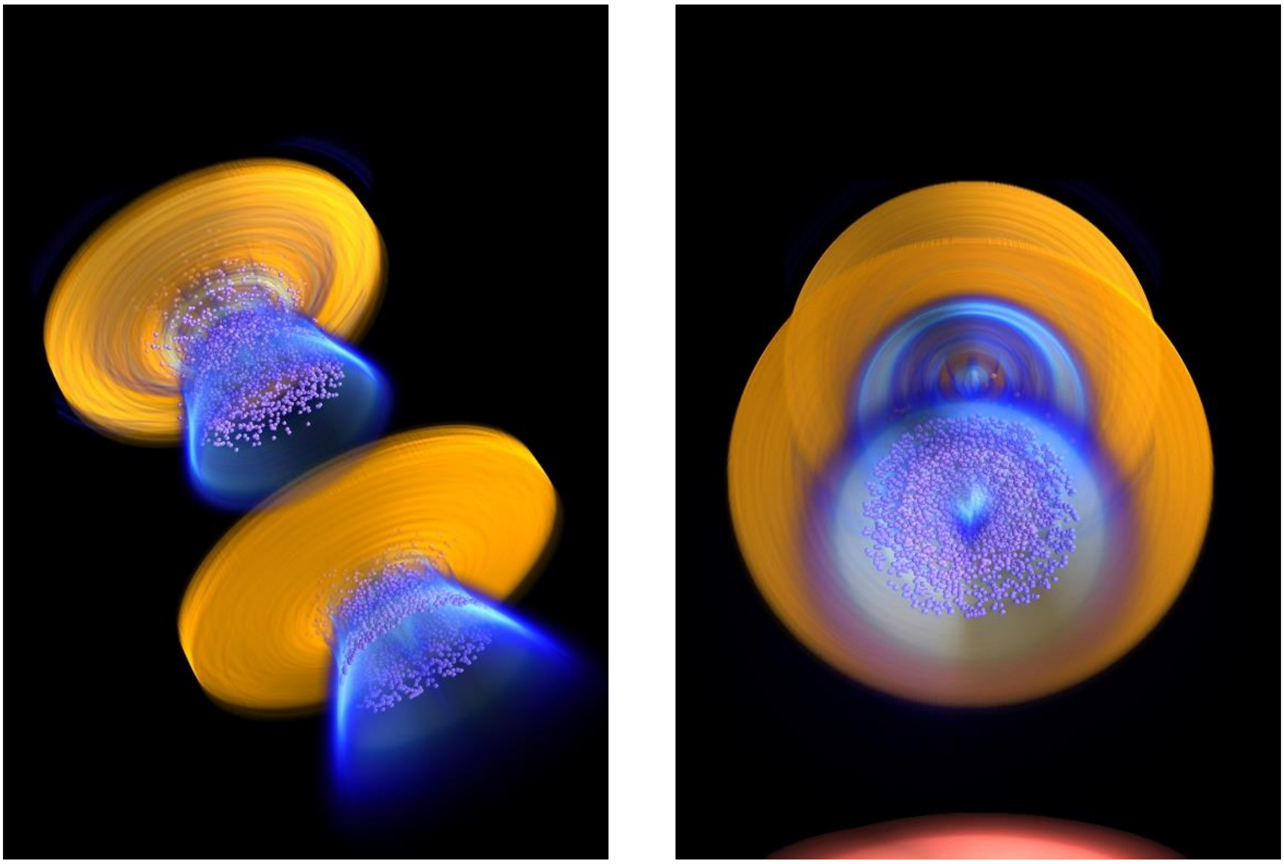
According to Bernardo Malaca, a doctoral student at IST and the study's primary author, "*The flexibility is enormous. Even though each electron is performing relatively simple movements, the total radiation from all* *the electrons can mimic that of a particle moving faster than light or an oscillating particle, even though there isn't a single electron locally that's faster than light or an oscillating electron.*"

The most powerful sources of light are massive, making them impractical for most laboratories, hospitals, and businesses. But with the theory proposed here, quasi-particles could produce incredibly bright light with just a tiny distance to travel.

The researchers explored quasi-particles in plasma waves, using intense laser and electron beams. To study the behavior of these quasi-particles and their light emissions, they ran advanced computer simulations on supercomputers available in Europe through the EuroHPC consortium.

This groundbreaking research has been published in Nature Photonics:

Coherence and superradiance from a plasma-based quasiparticle accelerator
Malaca, B.; Pardal, M.; Ramsey, D.; Pierce, J. R.; Weichman, K.; Andriyash, I. A.; Mori, W. B.; Palastro, J. P.; Fonseca, R. A.; Vieira, J.
NATURE PHOTONICS (2023)
https://doi.org/10.1038/s41566-023-01311-z



Superradiance from quasiparticles. By using adequate plasma density profiles, a laser can drive a superluminal plasma wave (shown in blue). As electrons (represented by spheres) converge onto axis, they emit an electromagnetic Cherenkov-like cone (in yellow). Even though the electrons are themselves subluminal, the synchronization allows them to radiate as a single, voluminous superluminal particle. Credits: B. Malaca / IST (OSIRIS simulation).

FUNDAMENTALS

Three-stage laser wakefield accelerator scheme for sub-Joule few-cycle laser pulses

Lecz, Zsolt; Andreev, Alexander; Papp, Daniel; Kamperidis, Christos; Hafz, Nasr A. M.
PLASMA PHYSICS AND CONTROLLED FUSION 65(10), 105001 (OCT 2023)
https://doi.org/10.1088/1361-6587/aceeb2

Laser-driven electron acceleration in underdense plasma is a promising route towards the realization of reliable sources of relativistic electrons in the 0.1-1 GeV energy range. Generation of such electron bunches at high repetition rates is hindered by the limited energy per pulse, which inevitably results in very short pulse duration and tight focusing. Compressing the laser energy in time and space allows scientists to use higher plasma density to drive wakefieds, which in turn results in enhanced diffraction and dispersion of the broadband laser pulse. These features make difficult to control the acceleration in the plasma wave and to improve the beam quality. Here we propose a mm-long three-stage acceleration scheme, which allows for tunable injection and optimal acceleration of high-quality electron bunches. The full interaction length is modeled by 3D particle-in-cell simulations.

Random scan optimization of a laser-plasma electron injector based on fast particle-in-cell simulation

Drobniak, P. ; Baynard, E.; Bruni, C.; Cassou, K.; Guyot, C.; Kane, G.; Kazamias, S.; Kubytskyi, V.; Lericheux, N.; Lucas, B.; Pittman, M.; Massimo, F.; Beck, A.; Specka, A.; Nghiem, P.; Minenna, D.
PHYSICAL REVIEW ACCELERATORS AND BEAMS 26, 091302 (SEP 2023)
https://doi.org/10.1103/PhysRevAccelBeams.26.091302

The optimization and advanced study of a laser-plasma electron injector are presented based on a truncated ionization injection scheme for high quality beam production. The SMILEI code is used with laser envelope approximation and a low number of particles per cell to reach computation time performances enabling the production of a large number of accelerator configurations. The developed and tested workflow is a possible approach for the production of a large dataset for laser-plasma accelerator optimization. A selection of functions of merit used to grade generated electron beams is discussed. Among the significant number of configurations, two specific working points are presented in detail. All data generated are left open to the scientific community for further study and optimization.

Low energy electron injection for direct laser acceleration

Starodubtseva, E.; Tsymbalov, I.; Gorlova, D.; Ivanov, K.; Savel'ev, A.
PHYSICS OF PLASMAS 30(8), 083105 (AUG 2023)
https://doi.org/10.1063/5.0155196

The feasibility of ionization injection for Direct Laser Acceleration (DLA) of electrons up to hundreds of MeV has been studied analytically. Criteria for effective injection determining a range of background and in-channel plasma parameters, laser intensity, etc., were found using phase portraits of the system deduced from the simplified analytical model. The found optimal trajectory in the phase space corresponds to the electron with low (few eV) initial energy experiencing ~ 10^9 times energy gain. For this to occur, electron density should be a few percent of the critical density, while the in-channel electron density should be ~ 3 times lower. The analytically obtained dependence of the energy gain on the initial electron longitudinal and transverse momenta corresponds well to the results of exact numerical simulations of an electron motion in the plasma channel. To test the theory, a series of PIC simulations were carried out. PIC simulation confirms the model if the plasma channel has appropriate parameters. The developed approach can form the basis for further studies of electron injection in DLA varying plasma and laser parameters as well as initial electron energies.

Neutral particle acceleration by spatially modulated laser pulses

Yan, J. Y.; Wang, W.; Wei, Q.; Wang, P. X.
NEW JOURNAL OF PHYSICS 25(8), 083015 (AUG 2023)
https://doi.org/10.1088/1367-2630/ace472

The velocity gain of neutral particles (atoms, molecules, etc) from laser acceleration is always small. A possible scheme to obtain a high speed neutral particle beam is multistage acceleration. However, according to previous theoretical and experimental studies, generally, lateral acceleration is larger than longitudinal acceleration. These transverse velocities destroy the expected quality of the longitudinally transmitted neutral particle beam. In order to realize multistage accelerations of neutral particle, it is necessary to restrain the beam divergence caused by lateral acceleration. How to optimize and utilize these laterally accelerated neutral particles is worthy of in-depth study. In this paper, we use a multi-mode combined laser pulse and a flattened Gaussian laser pulse to accelerate the neutral atoms. The transverse divergence of the beam is well controlled while the longitudinal acceleration is retained, which provides the possibility for improving the beam quality of neutral particles as well as the corresponding multistage acceleration.

Laser-accelerated electron beams at 1 GeV using optically-induced shock injection

V. Grafenstein, K.; Foerster, F. M.; Haberstroh, F.; Campbell, D.; Irshad, F.; Salgado, F. C.; Schilling, G.; Travac, E.; Weisse, N.; Zepf, M.; Doepp, A.; Karsch, S.
SCIENTIFIC REPORTS 13(1), 11680 (JUL 2023)
https://doi.org/10.1038/s41598-023-38805-3

In recent years, significant progress has been made in laser wakefield acceleration (LWFA), both regarding the increase in electron energy, charge and stability as well as the reduction of bandwidth of electron bunches. Simultaneous optimization of these parameters is, however, still the subject of an ongoing effort in the community to reach sufficient beam quality for next generation's compact accelerators. In this report, we show the design of slit-shaped gas nozzles providing centimeter-long supersonic gas jets that can be used as targets for the acceleration of electrons to the GeV regime. In LWFA experiments at the Centre for Advanced Laser Applications, we show that electron bunches are accelerated to 1GeV using these nozzles. The electron bunches were injected into the laser wakefield via a laser-machined density down-ramp using hydrodynamic optical-field-ionization and subsequent plasma expansion on a ns-timescale. This injection method provides highly controllable quasi-monoenergetic electron beams with high charge around 100pC, low divergence of 0.5mrad, and a relatively small energy spread of around 10% at 1GeV . In contrast to capillaries and gas cells, the scheme allows full plasma access for injection, probing or guiding in order to further improve the energy and quality of LWFA beams.

Relativistic electron bunches accelerated by radially polarized TW lasers from near-critical-density plasmas

Cheng, Zhong-Ming; Wu, Hui-Chun; Deng, Da-Chao; Yu, Ming-Young
PHYSICS OF PLASMAS 30(7), 073105 (JUL 2023)
https://doi.org/10.1063/5.0150260

By three-dimensional particle-in-cell simulation, we study electron acceleration by tightly focusing a few-cycle radially polarized laser onto near-critical-density plasmas. Laser ponderomotive force first pushes electrons into the target, forming a compressed electron layer and leaving behind a charge-separation field. Together with the strong longitudinal electric field of this radially polarized light, the charge-separation field accelerates the electrons backward and injects them into laser fields. The reflected light continuously accelerates these injected electrons by its longitudinal field. Simulations show that a tight quasi-monoenergetic electron bunch at 15 MeV is generated within a few micrometers.

Multi-pico-Coulomb and multi-GeV electron beam generation from LWFA with a cm scale gas cell

Ghotra, Harjit Singh
LASER PHYSICS 33(7), 076005 (JUL 2023)
https://doi.org/10.1088/1555-6611/acd371

Analytical calculations are made for the scaling and design parameters for the generation of a multi-pico Coulomb and multi-GeV electron beam from a laser Wakefield acceleration (LWFA). The numerical values are optimized for electron acceleration from a cm-scale gas cell and self-guided laser plasma in the bubble domain, where the low-density plasma serves as an accelerating medium. A graphical analysis of the matched parameters is presented for 1-10 GeV electron beam energy gain, where the laser pulse is powered between 30 ~ 700 TW with delivery capabilities of 1-100 J pulse energy, 25-150 fs pulse duration, and 15-95 μm spot size operating with $10^{18\text{-}19}$ W cm^{-2} laser intensity at a plasma density ~ 10^{17} cm^{-3}. The result shows the generation of multi-pico-Coulomb and multi-GeV electron beams. These parameters will be helpful for the future LWFA related experiments using cm scale gas cells in the bubble regime.

Tuning curves for a laser-plasma accelerator

Jalas, S.; Kirchen, M.; Braun, C.; Eichner, T.; Gonzalez, J. B.; Huebner, L.; Huelsenbusch, T.; Messner, P.; Palmer, G.; Schnepp, M.; Werle, C.; Winkler, P.; Leemans, W. P.; Maier, A. R.
PHYSICAL REVIEW ACCELERATORS AND BEAMS 26(7), 071302 (JUL 2023)
https://doi.org/10.1103/PhysRevAccelBeams.26.071302

Applications of laser-plasma accelerators (LPA) require independent control of electron beam parameters. However, due to the complex coupling of the many variables governing the laser-plasma interaction, precisely tuning these parameters based on simple scalings is often impossible or at least suboptimal. Here, we apply multiobjective Bayesian optimization to derive optimal tuning curves for LPAs, both in simulations and experiments. For electron energies between 150 and 250 MeV, we demonstrate tuning of the charge over a range of nearly 100 pC, while preserving optimal beam loading conditions with energy spreads below 5%. The derived tuning curves can explain the sometimes counterintuitive interplay between laser and plasma control variables that is necessary to find the best trade-off between competing beam properties.

Bubble structure evolution and electron injection controlled by optical cycles in wakefields

Liu, Song; Zhang, Guo-Bo; Yang, Xiao-Hu; Ma, Yan-Yun; Cui, Ye; Li, Dong-Ao; Zou, De-Bin; Du, Lin-He; Zhao, Zi-Qi; Wang, Wei-Quan; Shao, Fu-Qiu
PHYSICS OF PLASMAS 30(7), 073103 (JUL 2023)
https://doi.org/10.1063/5.0156263

The evolution of bubble structure and electron injection in laser wakefield acceleration with different optical cycles is investigated through three-dimensional particle-in-cell simulations. Under fixed transverse and longitudinal ponderomotive force, the effect of optical cycles on the evolution of bubble structure and electron injection is studied by changing the laser wavelength. For a multi-cycle laser, electron acceleration is dominated by the ponderomotive force that produces symmetrical bubble and continuous injection. As the optical cycles decrease, the dominant effect of the electron acceleration can transition from the ponderomotive force to the carrier wave, and the carrier envelope phase shift can cause transverse oscillation of the bubble and periodic electron injection in the direction of laser polarization. The criterion for the dominant acceleration mechanism and the dependence of transition distance on the optical cycles and pulse width are obtained. The results are beneficial for manipulating electron acceleration and betatron radiation generation.

Plasma-wave generation and acceleration of electrons by a nondiverging beating optical beam

Ponomareva, Evgeniia; Shevchenko, Andriy
PHYSICAL REVIEW ACCELERATORS AND BEAMS 26(6), 061301 (JUN 2023)
https://doi.org/10.1103/PhysRevAccelBeams.26.061301

Plasma waves can be used to create efficient and small-sized electron accelerators. Despite the already demonstrated success in reaching GeV-scale energy gain in the motion of electrons, laser-induced wakefields still suffer from the transverse spreading and the loss of synchronization with the accelerating particles. In this work, to tackle these problems, we propose using a two-wavelength structured laser beam with a designed angular dispersion and adjustable group velocity in free space to efficiently excite a nondiverging plasma wave. This approach allows one to generate an electron bunch with low transverse spread and reach high average acceleration gradients.

The effects of pre-plasma scale length on the relativistic electron beam directionality

Park, Jaebum; Jiang, S.; Divol, L.; Nagel, S. R.; Andrews, D. S.; Hazi, A. U.; Marley, E. V.; Kerr, S.; Shepherd, R.; Williams, G. J.; Baldis, H. A.; Chen, Hui
PHYSICS OF PLASMAS 30(5), 053110 (MAY 2023)
https://doi.org/10.1063/5.0133263

The effects of pre-plasmas on the electron beam directionality was experimentally and numerically investigated. Single material and layered targets made of Ti and/or CH were used to simultaneously measure high-energy (>= 3 MeV) electrons along two directions, pre-pulse energy and pre-plasma density. The electron directionality is quantified by using a new parameter, the electron energy ratio of the total kinetic energies along the two directions. Measurements and radiation-hydrodynamic (RH) simulations show that a large (>= 3.5 μm) plasma scale length at the critical surface enhances electrons along the laser axis, and such pre-plasma conditions could only be achieved with the CH targets. Particle-in-cell simulations were performed on the RH generated pre-plasmas from Ti and CH targets, and the results show that the CH target provided conditions for higher forward momentum gains by electrons. First, the CH target allowed longer distances for electrons to interact with laser. Second, the intense laser pulse modified the critical surface, but the resulting surface differed. The CH target resulted in a smooth surface where a retro-reflection was observed while the Ti target resulted in a rippled surface that scattered the reflected light. As results, the CH electrons gained higher forward momentum via a direct-laser-acceleration in the counter propagating laser fields. The results presented in this article show a way of controlling the high-energy electron directionality.

Demonstration of efficient relativistic electron acceleration by surface plasmonics with sequential target processing using high repetition lasers

Arikawa, Yasunobu; Morace, Alessio; Abe, Yuki; Iwata, Natsumi; Sentoku, Yasuhiko; Yogo, Akifumi; Matsuo, Kazuki; Nakai, Mitsuo; Nagatomo, Hideo; Mima, Kunioki; Nishimura, Hiroaki; Fujioka, Shinsuke; Kodama, Ryosuke; Inoue, Shunsuke; Hashida, Masaki; Sakabe, Shuji; De Luis, Diego; Gatti, Giancarlo; Huault, Marine; Perez-Hernandez, Jose Antonio; Roso, Luis; Volpe, Luca
PHYSICAL REVIEW RESEARCH 5(1), 013062 (JAN 2023)
https://doi.org/10.1103/PhysRevResearch.5.013062

For high repetition ultrahigh-intensity laser system, automatic alignment of structured target is key to achieving consistent particle acceleration and plasma heating. In this work, we demonstrate efficient electron acceleration with two sequential steps of laser processing using a high repetition rate, 30-fs ultrahigh-intensity laser. The first pulse does laser machining and creates a steep cylindrical crater on the surface of a flat stainless -steel target. The crater is formed by the hydrodynamic expansion of the heated surface and by spallation of the inner, deeper material by nonthermal relativistic electrons. The crater shape is well controlled and reproducible with 200 μm width and 350 μm depth. The second pulse irradiates deeply inside the crater and interacts with the crater wall, efficiently accelerating electrons via surface plasmonic, without need for target realignment. The laser absorption efficiency increases from 32.5 to 97.5% by the process.

Generation of THz radiation by wakefield under a wiggler magnetic field: An analytical study

Abedi-Varaki, Mehdi
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH SECTION A-ACCELERATORS SPECTROMETERS DETECTORS AND ASSOCIATED EQUIPMENT 1048, 168010 (MAR 2023)
https://doi.org/10.1016/j.nima.2022.168010

In this article, the generation of terahertz (THz) radiation owing to wakefields produced by Gaussian-like laser pulse propagating throughout magnetized plasma has been investigated analytically under a wiggler magnetic field. Non-linear equations and analytical formulations governing the laser pulse THz radiation generation at a mildly relativistic regime have been derived. Besides, the total electric and magnetic wakefields inside and behind the laser pulse by employing the relativistic equations of motion, Maxwell's equations, and perturbation technique in the attendance of a planar magnetostatic wiggler have been obtained. It is shown that the maximum transverse electric wakefield amplitude has an increasing trend with enchanting the wiggler frequency for inside and behind the laser pulse and the peak of the maximum transverse electric wakefield amplitude behind of laser pulse is higher compared to the inside of laser pulse for different values of the wiggler magnetic field. Furthermore, it is observed that electric wakefield amplitude has a fluctuating behavior inside and behind the laser pulse due to the existence of the planar magnetostatic wiggler. Also, it is shown that by using a wiggler magnetic field and components of perturbed velocities, we can generate THz waves. Moreover, it is found that we can achieve the needed values of the wiggler magnetic field for THz radiation generation for different values of the laser strength parameters. Indeed, we can control the generation of THz radiation throughout magnetized plasma by adjusting the wiggler magnetic field and laser pulse intensity.

Simulation of self-modulated laser wakefield acceleration using few TW in downramp injection and ionization injection regimes

Maldonado, Edison Puig; Samad, Ricardo Elgul; Zuffi, Armando Valter Felicio; Vieira Jr, Nilson Dias
APPLIED OPTICS 62(12), 3202-3207 (APR 2023)
https://doi.org/10.1364/AO.477401

Simulations of transitional self-modulated laser wakefield acceleration driven by laser pulses of a few terawatts are discussed, comparing a downramp-based injection regime with an ionization injection regime. We demonstrate that a configuration using an N_2 gas target and a laser pulse of ~ 75 mJ with ~ 2 TW peak power is a good alternative as a high repetition rate system that produces electrons of many tens of MeV, pC charge, and emittance of the order of 1 mm mrad. (c) 2023 Optica Publishing Group

Electron acceleration by wakefield generated by the propagation of chirped laser pulse in plasma

Singh, Saumya; Mishra, Dinkar; Kumar, Bhupesh; Jha, Pallavi
PHYSICA SCRIPTA 98(7), 075504 (JUL 2023)
https://doi.org/10.1088/1402-4896/acd915

A study of generation of wakefield and particle acceleration via propagation of linearly polarised, chirped, Gaussian laser pulse in preformed plasma channel is presented. Perturbation technique is used to separate slow and fast varying plasma electron velocities and density. Considering the laser pulse length and amplitude to be evolving along the propagation distance, nonlinear fluid equations are used to derive longitudinal electric wakefields at varying propagation distances for chirped as well as unchirped pulses. It has been seen that longitudinal wakefield amplitude generated by positively (negatively) chirped laser pulses is higher (lower) than the amplitude obtained by unchirped laser pulses. The wakefield amplitudes are optimized with respect to the propagation distance. Further, trapping and acceleration of electrons by the generated wakes, is analysed. Comparing the energy of an accelerated test electron using chirped and unchirped laser pulses, it is shown that positively chirped laser pulses are capable of accelerating test electron to maximum energy using minimum injection energy. Hence, highest energy gain can be obtained by propagation of positively chirped laser pulse in plasma.

Progress in hybrid plasma wakefield acceleration

Hidding, B.; Assmann, R.; Bussmann, M.; Campbell, D.; Chang, Y.-Y.; Corde, S.; Couperus Cabadağ, J.; Debus, A.; Döpp, A.; Gilljohann, M.; Götzfried, J.; Foerster, F.M.; Haberstroh, F.; Habib, F.; Heinemann, T.; Hollatz, D.; Irman, A.; Kaluza, M.; Karsch, S.; Kononenko, O.; Knetsch, A.; Kurz, T.; Kuschel, S.; Köhler, A.; Martinez de la Ossa, A.; Nutter, A.; Pausch, R.; Raj, G.; Schramm, U.; Schöbel, S.; Seidel, A.; Steiniger, K.; Ufer, P.; Yeung, M.; Zarini, O.; Zepf, M.
PHOTONICS 10, 99 (JAN 2023)
https://doi.org/10.3390/photonics10020099

Plasma wakefield accelerators can be driven either by intense laser pulses (LWFA) or by intense particle beams (PWFA). A third approach that combines the complementary advantages of both types of plasma wakefield accelerator has been established with increasing success over the last decade and is called hybrid LWFA→PWFA. Essentially, a compact LWFA is exploited to produce an energetic, high-current electron beam as a driver for a subsequent PWFA stage, which, in turn, is exploited for phase-constant, inherently laser-synchronized, quasi-static acceleration over extended acceleration lengths. The sum is greater than its parts: the approach not only provides a compact, cost-effective alternative to linac-driven PWFA for exploitation of PWFA and its advantages for acceleration and high-brightness beam generation, but extends the parameter range accessible for PWFA and, through the added benefit of co-location of inherently synchronized laser pulses, enables high-precision pump/probing, injection, seeding and unique experimental constellations, e.g., for beam coordination and collision experiments. We report on the accelerating progress of the approach achieved in a series of collaborative experiments and discuss future prospects and potential impact.

BEAMLINES & APPLICATIONS

Positron Generation and Acceleration in a Self-Organized Photon Collider Enabled by an Ultraintense Laser Pulse

Sugimoto, K.; He, Y.; Iwata, N.; Yeh, I-l.; Tangtartharakul, K.; Arefiev, A.; Sentoku, Y.
PHYSICAL REVIEW LETTERS 131(6), 065102 (AUG 2023)
https://doi.org/10.1103/PhysRevLett.131.065102

We discovered a simple regime where a near-critical plasma irradiated by a laser of experimentally available intensity can self-organize to produce positrons and accelerate them to ultrarelativistic energies. The laser pulse piles up electrons at its leading edge, producing a strong longitudinal plasma electric field. The field creates a moving gamma-ray collider that generates positrons via the linear Breit-Wheeler process-annihilation of two gamma rays into an electron-positron pair. At the same time, the plasma field, rather than the laser, serves as an accelerator for the positrons. The discovery of positron acceleration was enabled by a first-of-its-kind kinetic simulation that generates pairs via photon-photon collisions. Using available laser intensities of 10^{22} W/cm^2, the discovered regime can generate a GeV positron beam with a divergence angle of around 10°; and a total charge of 0.1 pC. The result paves the way to experimental observation of the linear Breit-Wheeler process and to applications requiring positron beams.

Terahertz-driven positron acceleration assisted by ultra-intense lasers

Zhao, J. I. E.; LI, Qian-ni; Hu, Yan-ting; Zhang, H. A. O.; Cao, Y. U. E.; Sha, R. O. N. G.; Shao, Fu-qiu; Yu, Tong-pu
OPTICS EXPRESS 31(14), 23171-23182 (JUL 2023)
https://doi.org/10.1364/OE.488505

Generation and acceleration of energetic positrons based on laser plasma have attracted intense attention due to their potential applications in medical physics, high energy physics, astrophysics and nuclear physics. However, such compact positron sources face a series of challenges including the beam dispersion, dephasing and unstability. Here, we propose a scheme that couples the all-optical generation of electron-positron pairs and rapid acceleration of copious positrons in the terahertz (THz) field. In the scheme, nanocoulomb-scale electrons are first captured in the wakefield and accelerated to 2.5 GeV. Then these energetic electrons emit strong THz radiation when they go through an aluminum foil. Subsequently, abundant γ photons and positrons are generated during the collision of GeV electron beam and the scattering laser. Due to the strong longitudinal acceleration field and the transvers confining field of the emitted THz wave, the positrons can be efficiently accelerated to 800 MeV, with the peak beam brilliance of 2.26 x 10^{12} s^{-1} mm^{-2} mrad^{-2} eV^{-1}. This can arouse potential research interests from PW-class laser facilities together with a GeV electron beamline.

Laser-driven muon production for material inspection and imaging

Calvin, Luke; Tomassini, Paolo; Doria, Domenico; Martello, Daniele; Deas, Robert M.; Sarri, Gianluca
FRONTIERS IN PHYSICS 11, 1177486 (JUN 2023)
https://doi.org/10.3389/fphy.2023.1177486

We numerically show that laser-wakefield accelerated electron beams obtained using a PetaWatt-scale laser system can produce high-flux sources of relativistic muons that are suitable for radiographic applications. Scalings of muon energy and flux with the properties of the wakefield electron beams are presented. Applying these results to the expected performance of the 10-PW class laser at the Extreme Light

Infrastructure Nuclear Physics (ELI-NP) demonstrates that ultra-high power laser facilities currently in the commissioning phase can generate ultra-relativistic muon beams with more than 10^4 muons per shot reaching the detector plane. Simple magnetic beamlines are shown to be effective in separating the muons from noise, allowing for their detection using, for example, silicon-based detectors. It is shown that a laser facility like the one at ELI-NP can produce high-fidelity and spatially resolved muon radiographs of enclosed strategically sensitive materials in a matter of minutes.

Characteristics of betatron radiation in AWAKE Run 2 experiment

Liang, Linbo; Saberi, Hossein; Xia, Guoxing; Farmer, John Patrick; Pukhov, Alexander
JOURNAL OF PLASMA PHYSICS 89(3), 965890301 (JUN 2023)
https://doi.org/10.1017/S0022377823000491

The oscillating relativistic electrons in the accelerating/focusing wakefields of plasma accelerators emit electromagnetic radiation known as betatron radiation (BR). The proton-driven plasma wakefield acceleration has been demonstrated in the Advanced Wakefield Experiment (AWAKE) at CERN; however, its accompanying radiation emission is less explored compared with those in the laser- and electron beam-driven plasma accelerators. In this paper, a detailed simulation study of BR in the AWAKE is presented. Considering the new set-up of the AWAKE Run 2 (2021-), the radiation emission from both the witness electron beam and the seeding electron beam is investigated using particle-in-cell simulations. The influence of radial size mismatch and misaligned off-axis injection on the witness beam dynamics, as well as the spectral features of the relevant BR are studied. These non-ideal electron injections are likely to occur in experiment. The proton self-modulation stage is also investigated with a close look at the seeding electron beam dynamics and its BR. As a footprint of the emitting particles, BR can provide valuable information about the beam dynamics. Some practical challenges to implement the betatron diagnostic in the AWAKE Run 2 experiment are also addressed.

Generation of attosecond micro bunched beam using ionization injection in laser wakefield acceleration

Deng, Aihua; Li, Xiaowen; Luo, Zhiling; Li, Yan; Zeng, Jiaolong
OPTICS EXPRESS 31(12), 19958-19967 (JUN 2023)
https://doi.org/10.1364/OE.492468

Micro bunched electron beams with periodic longitudinal density modulation at optical wavelengths give rise to coherent light emission. In this paper, we show attosecond micro bunched beam generation and acceleration in laser-plasma wakefield via particle-in-cell simulations. Due to the near-threshold ionization with the drive laser, the electrons with phase-dependent distributions are non-linearly mapped to discrete final phase spaces. Electrons can preserve this initial bunching structure during the acceleration, leading to an attosecond electron bunch train after leaving the plasma with separations of the same time scale. The modulation of the comb-like current density profile is about $2k_0 \sim 3k_0$, where k_0 is the wavenumber of the laser pulse. Such pre-bunched electrons with low relative energy spread may have potential in applications related to future coherent light sources driven by laser-plasma accelerators and broad application prospects in attosecond science and ultrafast dynamical detection.

Focusing and reduction of correlated energy spread of chirped electron beams in passive plasma lens

Pathak, N.; Zhidkov, A.; Espinos, D. Oumbarek; Hosokai, T.
PHYSICS OF PLASMAS 30(6), 063103 (JUN 2023)
https://doi.org/10.1063/5.0145693

All-optical compact plasma focusing and transportation of electron beams, in the passive mode of a plasma lens, is studied via real geometry particle-in-cell simulations for its suitability for the laser wakefield acceleration technique. The focusing of an electron beam by a passive plasma lens is a non-linear and dynamic process, which strongly depends on the space charge induced evacuation of the plasma electrons in the vicinity of the propagating electron beam. Effects of such focusing on the energy spread, divergence, and emittance of laser-driven electron beams are analyzed numerically for different plasma densities. An initially negative chirp in electron beam energy is shown to be instrumental in suppressing the unwanted growth in the relative energy spread of the electron beam during the passive lensing. Usefulness of such a passive plasma element for a single and multi-stage laser wakefield acceleration configuration is demonstrated.

Positron acceleration by terahertz wave and electron beam in plasma channel

Xu, Zhangli; Shen, Baifei; Si, Meiyu; Huang, Yongsheng
NEW JOURNAL OF PHYSICS 25(6), 063013 (JUN 2023)
https://doi.org/10.1088/1367-2630/acdc47

We present a scheme of positron acceleration by intense terahertz (THz) wave together with the driving large-charge electron beam in a plasma channel. The THz wave rapidly evolves into a transversely uniform acceleration field and a weakly focusing/defocusing lateral field in the channel. The THz wave is partially formed with the scheme of coherent transition radiation when the electron beam goes through a metal foil and partially because of the wakefield in the plasma channel. The electron beam continuously supplies energy to the THz wave. Such a field structure offers the feasibility of long-distance positron acceleration while preserving beam quality. By two-dimensional simulations, we demonstrate the acceleration of positrons from initial 1 GeV to 126.8 GeV with a charge of ~ 10 pC over a distance of 1 m. The energy spread of accelerated positrons is 2.2%. This scheme can utilize the electron beam either from laser-driven or conventional accelerators, showing prospects towards high-quality and flexible THz-driven relativistic positron sources of ~ 100 GeV.

A beamline to control longitudinal phase space whilst transporting laser wakefield accelerated electrons to an undulator

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https://doi.org/10.1038/s41598-023-35435-7

Laser wakefield accelerators (LWFAs) can produce high-energy electron bunches in short distances. Successfully coupling these sources with undulators has the potential to form an LWFA-driven free electron laser (FEL), providing high-intensity short-wavelength radiation. Electron bunches produced from LWFAs have a correlated distribution in longitudinal phase space: a chirp. However, both LWFAs and FELs have strict parameter requirements. The bunch chirp created using ideal LWFA parameters may not suit the FEL; for example, a chirp can reduce the high peak current required for free-electron lasing. We, therefore, design a flexible beamline that can accept either positively or negatively chirped LWFA bunches and adjust the chirp during transport to an undulator. We have used the accelerator design program MAD8 to design a beamline in stages, and to track particle bunches. The final beamline design can produce ambidirectional values of longitudinal dispersion (R_{56}): we demonstrate values of + 0.20 mm, 0.00 mm and - 0.22 mm. Positive or negative values of R_{56} apply a shear forward or backward in the longitudinal phase space of the electron bunch, which provides control of the bunch chirp. This chirp control during the bunch transport gives an additional free parameter and marks a new approach to matching future LWFA-driven FELs.

Dose rate assessment of spot-scanning very high energy electrons radiotherapy driven by laser plasma acceleration

Lv, Jianfeng; Zhao, Xingyi; Liu, Jiaxin; Wu, Di; Yang, Gen; Kang, Minglei; Yan, Xueqing
JOURNAL OF APPLIED PHYSICS 133(19), 194901 (MAY 2023)
https://doi.org/10.1063/5.0146117

Laser plasma accelerators (LPA) can produce very high-energy electrons (VHEE) with ultra-short bunch duration, which may facilitate the application of ultra-high dose rate radiotherapy (FLASH-RT) to treat deep-seated tumors. The study aims to evaluate the dose rate delivery by spot-scanning VHEE beams produced by LPA and to discuss the feasibility and beam specifications for FLASH-RT implementation. Various dose rate metrics, including averaged dose rate (ADR), dose-averaged dose rate (DADR), and dose-threshold dose rate (DTDR), are examined in the context of spot-scanning. Theoretical analysis and Monte Carlo simulations are employed to quantify the dose rate distribution for a water phantom and explore the impact of beam parameters. All the beam parameters are based on experimental results. With a lower pulse repetition rate of 5 Hz, ADR can only reach a dose rate in the order of 10^{-1} Gy/s, while attaining the FLASH-RT dose rate of 40 Gy/s necessitates the utilization of high-power lasers with a kilohertz working repetition rate. In contrast to ADR, DADR and DTDR remain independent of the scanning path and can reach the ultra-high dose rate surpassing 10^{14} Gy/s at the phantom surface. Meanwhile, the ultrashort electron bunch can be stretched during scattering within the water, resulting in a dependence of DADR and DTDR on the penetration depth. Both the charge per shot and angular spread are important parameters in dose rate calculations. This investigation offers insights into practical beam parameters for preclinical applications and supplies guidance for designing the LPAs suitable for future spot-scanning VHEE FLASH-RT.

Generation of Large-Bandwidth High-Power X-Ray Free-Electron-Laser Pulses Using a Hollow-Channel Plasma

Peng, Bo; Feng, Chao; Wang, Zhen; Hua, Jianfei; Wu, Yipeng; Deng, Haixiao; Li, Fei; Lu, Wei; Zhao, Zhentang
PHYSICAL REVIEW APPLIED 19(5), 054066 (MAY 2023)
https://doi.org/10.1103/PhysRevApplied.19.054066

Large-bandwidth x-ray free-electron-laser (XFEL) facilities are desirable scientific tools in various fields, such as molecular structural dynamics and spectroscopy diagnosis. Various methods are proposed to broaden the FEL spectra. Here, a method is proposed to generate high-power XFEL radiation of tunable spectral bandwidth using plasma wakefield acceleration. An ultrabroad bandwidth is achieved by chirping the electron beam in a hollow-channel plasma without noticeable slice-beam-quality degradation. A dedicated beamline can match the beams with a large energy chirp in the undulators almost without beam loss. Numerical simulations demonstrate that a relative spectral bandwidth (full width) of up to 24% can be obtained with optimized beam and plasma parameters.

Photonuclear production of nuclear isomers using bremsstrahlung induced by laser-wakefield electrons

Lan, Hao-Yang; Wu, Di; Liu, Jia-Xin; Zhang, Jian-Yao; Lu, Huan-Gang; Lv, Jian-Feng; Wu, Xue-Zhi; Luo, Wen; Yan, Xue-Qing
NUCLEAR SCIENCE AND TECHNIQUES 34(5), 74 (MAY 2023)
https://doi.org/10.1007/s41365-023-01219-x

In this study, we theoretically investigate the feasibility of using laser-wakefield accelerated (LWFA) electrons for the photo-nuclear measurement of nuclear isomers according to the characteristics of the electrons obtained from LWFA experiments conducted at the Compact Laser-Plasma Accelerator (CLAPA) laboratory.

The experiments at the CLAPA show that a stable electron beam with an energy of 78-135 MeV and a charge of 300-600 pC can be obtained. The bremsstrahlung spectra were simulated using Geant4, which suggests that a bremsstrahlung source with a peak intensity of 10^{19} photons/s can be generated. Theoretical calculations of isomer production cross sections from the photonuclear reactions on six target nuclei, ^{197}Au, ^{180}Hf, ^{159}Tb, ^{115}In, ^{103}Rh, and ^{90}Zr, were performed and compared with the available experimental data in EXFOR, which suggest that further experiments are required for a series of photonuclear reaction channels. Flux-averaged cross sections and isomer ratios (IR) resulting from such bremsstrahlung sources are theoretically deduced. The results suggest that IR measurements can be used to constrain nuclear components, such as γ strength function and optical model potential. In addition, the detection of the decay characteristics was evaluated with Geant4 simulations. The use of the LWFA electron beam and its bremsstrahlung for photonuclear studies involving nuclear isomers is anticipated.

New measurements of ^{92}Mo(γ, n) and (γ, 3n) reactions using laser-driven bremsstrahlung γ-ray

Wu, D.; Lan, H. Y.; Zhang, J. Y.; Liu, J. X.; Lu, H. G.; Lv, J. F.; Wu, X. Z.; Zhang, H.; Cai, J.; Xu, X. L.; Geng, Y. X.; Ma, W. J.; Lin, C.; Zhao, Y. Y.; Wang, H. R.; Liu, F. L.; He, C. Y.; Yu, J. Q.; Guo, B.; Wang, N. Y.; Yan, X. Q.
FRONTIERS IN PHYSICS 11, 1178257 (APR 2023)
https://doi.org/10.3389/fphy.2023.1178257

The flux-weighted average cross sections and isomeric ratios of ^{92}Mo(γ, n) ^{91m,g}Mo and ^{92}Mo(γ, 3n)^{89}Mo reactions were measured through activation methods. Laser-driven bremsstrahlung γ -ray were generated by the laser wakefield accelerated quasi-monoenergetic electrons using the 200 TW laser in the Compact Laser Plasma Accelerator laboratory, Peking University. The results showed good agreements with previous works using traditional γ-ray sources, and were compared with TALYS 1.9 calculations. We extended the experimental results of ^{92}Mo photonuclear reactions to higher energies, the experimental discrepancies of ^{92}Mo(γ, n) ^{91m,g}Mo isomeric ratios at high energy region were clarified, and the cross sections of ^{92}Mo(γ, 3n)^{89}Mo reaction were first obtained.

Tail-Wave-Assisted Positron Acceleration in Nonlinear Laser Plasma Wakefields

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PHYSICAL REVIEW APPLIED 19(4), 044048 (APR 2023)
https://doi.org/10.1103/PhysRevApplied.19.044048

Relativistic laser-wakefield acceleration is characterized by an unsurpassed accelerating gradient, which is very suitable for electron acceleration over short distances and could be a promising candidate for next-generation compact accelerators. However, using this technique for positron acceleration remains challenging because positively charged particles are commonly defocused in the accelerating structure of a standard nonlinear wakefield driven by an ultrashort laser pulse. Here we propose and numerically demonstrate a scheme to accelerate an externally injected positron beam in a nonlinear laser wakefield in a regime where a tail wave is formed behind density cusps of the wakefield. This tail wave can provide a focusing force in addition to longitudinal acceleration for the positrons. Three-dimensional particle-in-cell simulations demonstrate that a trapping efficiency of positrons of nearly 100% in the nonlinear wakefield is possible. This scheme may open a simple way to achieve compact positron acceleration of hundreds of MeV at high repetition rates with terawatt-class laser systems without the need for special laser modes and plasma structures.

Collimated gamma beams with high peak flux driven by laser-accelerated electrons

Fan, Lulin; Xu, Tongjun; Li, Shun; Xu, Zhangli; Xu, Jiancai; Zhu, Jianqiang; Shen, Baifei; Ji, Liangliang
HIGH POWER LASER SCIENCE AND ENGINEERING 11, e26 (MAR 2023)
https://doi.org/10.1017/hpl.2023.25

Laser-accelerated electrons are promising in producing gamma-photon beams of high peak flux for the study of nuclear photonics, obtaining copious positrons and exploring photon-photon interaction in vacuum. We report on the experimental generation of brilliant gamma-ray beams with not only high photon yield but also low divergence, based on picosecond laser-accelerated electrons. The 120 J 1 ps laser pulse drives self-modulated wakefield acceleration in a high-density gas jet and generates tens-of-MeV electrons with 26 nC and divergence as small as 1.51 degrees. These collimated electrons produce gamma-ray photons through bremsstrahlung radiation when transversing a high-Z solid target. We design a high-energy-resolution Compton-scattering spectrometer and find that a total photon number of 2.2×10^9 is captured within an acceptance angle of 1.1 degrees for photon energies up to 16 MeV. Comparison between the experimental results and Monte Carlo simulations illustrates that the photon beam inherits the small divergence from electrons, corresponding to a total photon number of 2.2×10^{11} and a divergence of 7.73 degrees.

Laser-driven low energy electron beams for single-shot ultra-fast probing of meso-scale materials and warm dense matter

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SCIENTIFIC REPORTS 13(1), 4252 (MAR 2023)
https://doi.org/10.1038/s41598-023-30995-0

Laser wakefield acceleration has proven to be an excellent source of electrons and X-rays suitable for ultra-fast probing of matter. These novel beams have demonstrated unprecedented spatial and temporal resolution allowing for new discoveries in material science and plasma physics. In particular, the study of dynamic processes such as non-thermal melt and lattice changes on femtosecond time-scales have paved a way to completely new scientific horizons. Here, we demonstrate the first single-shot electron radiography measurement using an femtosecond electron source based on the downramp-density gradient laser-wakefield-acceleration with the use of a compact Ti:sapphire laser. A quasi-monoenergetic electron beam with mean energy of 1.9 +/- 0.4 MeV and charge 77 +/- 47 pC per shot was generated by the laser incident onto a gas target and collimated using a two ring-magnet beam path. High quality electron radiography of solid objects with spatial resolution better than 150 μm was demonstrated. Further developments of this scheme have the potential to obtain single-shot ultrafast electron diffraction from dynamic lattices. This scheme poses a great promise for smaller scale university laboratories and facilities for efficient single-shot probing of warm dense matter, medical imaging and the study of dynamic processes in matter with broad application to inertial confinement fusion and meso-scale materials (mg g/cm^2).

Single-shot electron radiography using a laser-plasma accelerator

Bruhaug, G.; Freeman, M. S.; Rinderknecht, H. G.; Neukirch, L. P.; Wilde, C. H.; Merrill, F. E.; Rygg, J. R.; Wei, M. S.; Collins, G. W.; Shaw, J. L.
SCIENTIFIC REPORTS 13, 2227 (FEB 2023)
https://doi.org/10.1038/s41598-023-29217-4

Contact and projection electron radiography of static targets was demonstrated using a laser-plasma accelerator driven by a kilojoule, picosecond-class laser as a source of relativistic electrons with an average

energy of 20 MeV. Objects with areal densities as high as 7.7 g/cm^2 were probed in materials ranging from plastic to tungsten, and radiographs with resolution as good as 90 μm were produced. The effects of electric fields produced by the laser ablation of the radiography objects were observed and are well described by an analytic expression relating imaging magnification change to electric-field strength.

Temperature effects in plasma-based positron acceleration schemes using electron filaments

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PHYSICS OF PLASMAS 30(7), 073104 (JUL 2023)
https://doi.org/10.1063/5.0155489

Preserving the quality of a positron beam in a plasma-based accelerator, where a wakefield suitable for positron transport and acceleration is generated by means of an electron filament, is challenging. This is due to the nature of the wakefields, characterized by focusing fields that vary nonlinearly in the transverse direction, and by accelerating fields that are non-uniform. These fields also change slice-by-slice along the beam. Maintaining a high beam quality is pivotal for application of positron beams in a plasma-based collider. In this paper, we show that an initial background plasma temperature can help mitigate the positron beam quality degradation in plasma-based accelerators that rely on electron filaments. We show that temperature effects broaden the electron filament and smooth radially both the non-linear transverse and the non-uniform longitudinal wakefields. Using warm plasmas opens up new possibilities to improve beam quality in several plasma-based positron acceleration concepts. VC 2023 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

LASER DRIVERS

Fast laser field reconstruction method based on a Gerchberg–Saxton algorithm with mode decomposition

Moulanier, I.; Dickson, L. T.; Massimo, F.; Maynard, G.; Cros, B.
JOURNAL OF THE OPTICAL SOCIETY OF AMERICA B 40(9), 2450-2461 (AUG 2023)
https://doi.org/10.1364/JOSAB.489884

Knowledge of the electric field of femtosecond, high intensity laser pulses is of paramount importance to study the interaction of this class of lasers with matter. A hybrid method to reconstruct the laser field from fluence measurements in the transverse plane at multiple positions along the propagation axis is presented, combining a Hermite–Gauss mode decomposition (MD) and elements of the Gerchberg–Saxton algorithm (GSA). The proposed GSA-MD takes into account the pointing instabilities of high intensity laser systems by tuning the centers of the HG modes. Furthermore, it quickly builds a field description by progressively increasing the number of modes and thus the accuracy of the field reconstruction. The results of field reconstruction using the GSA-MD are shown to be in excellent agreement with experimental measurements from two different high peak power laser facilities.

Study of particle acceleration by Laguerre-Gaussian ultra intense laser plasma interactions

Culfa, O.; Sagir, S.; Satilmis, I.
PLASMA PHYSICS AND CONTROLLED FUSION 65(8), 085019 (AUG 2023)
https://doi.org/10.1088/1361-6587/acdaf4

In this work, simulations of multi-petawatt lasers in the range of ~ 0.2 PW - ~ 100 PW with varying Laguerre-Gaussian (LG) azimuthal modes as well as linearly polarized (LP) and circularly polarized (CP) laser beams striking near critical density targets were studied by using three-dimensional particle in cell (PIC) codes. Particle acceleration mechanisms have a dependence on laser polarization and it affects the energy gained by the particles. It is known that laser pulses can be polarized helically by applying the LG distribution function to the fundamental Gaussian laser profile. In this study, differently polarized laser beams with varying powers were employed to study laser driven particle acceleration and compares accelerated charged particles' energy spectra and angular distribution. It is seen that LG laser beams can accelerate higher energetic particles due to higher conversion efficiency compared to LP and CP laser beams. It is also seen that LG laser beams can collimate ions with a narrower spread compared to LP and CP beams. Furthermore, ions can have a smaller divergence angle with increasing azimuthal mode index when the laser is LG polarized. We also studied the energy deposition of these particles in a water cell obtained by the PIC codes for different laser parameters by using Geant4 Monte Carlo simulations which suggests that LG laser beam can be useful for the future hadron therapy applications.

Self-focusing of a q-gaussian laser beam under the influence of an exponential plasma density ramp in plasma

Butt, Anees Akber; Kant, Niti; Thakur, Vishal

PHYSICA SCRIPTA 98(4), 045621 (APR 2023)

https://doi.org/10.1088/1402-4896/acc617

The goal of the current manuscript is to investigate how a plasma density ramp affects the ability of a q-Gaussian laser beam (q-GLB) to self-focus in plasma. The laser beam exhibits oscillatory self-focusing and defocusing behaviour with increasing distance of propagation. We used an exponential plasma density ramp to combat this defocusing tendency, allowing the particular laser beam to achieve a minimal spot size and nearly retain it up to several Rayleigh lengths. In addition to that, it has been observed that self-focusing increases with increasing q-values and the laser intensity. However, the lower values of q suggest strong self-focusing. By warily selecting the plasma and laser parameters, the density ramp could play a key role in the self-focusing of q-Gaussian laser. Self-focusing is seen to become stronger as propagation distance increases and the q-parameter affects the behaviour of the beam-width parameter in the plasma as shown.

PLASMA TECHNOLOGY & DIAGNOSTICS

Stability of the modulator in a plasma-modulated plasma accelerator

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PHYSICAL REVIEW E 108(1), 015204 (JUL 2023)

https://doi.org/10.1103/PhysRevE.108.015204

We explore the regime of operation of the modulator stage of a recently proposed laser-plasma accelerator scheme [Phys. Rev. Lett. 127, 184801 (2021)], dubbed the plasma-modulated plasma accelerator (P-MoPA). The P-MoPA scheme offers a potential route to high-repetition-rate, GeV-scale plasma accelerators driven by picosecond-duration laser pulses from, for example, kilohertz thin-disk lasers. The first stage of the P-MoPA scheme is a plasma modulator in which a long, high-energy "drive" pulse is spectrally modulated by copropagating in a plasma channel with the low-amplitude plasma wave driven by a short, low-energy "seed" pulse. The spectrally modulated drive pulse is converted to a train of short pulses, by introducing dispersion, which can resonantly drive a large wakefield in a subsequent accelerator stage with the same on-axis plasma density as the modulator. In this paper we derive the 3D analytic theory for the evolution of the drive pulse in the plasma modulator and show that the spectral modulation is independent of transverse coordinate, which is ideal for compression into a pulse train. We then identify a transverse mode instability (TMI), similar to the TMI observed in optical fiber lasers, which sets limits on the energy of the drive pulse for a given set of laser-plasma parameters. We compare this analytic theory with particle-in-cell (PIC) simulations and find that even higher energy drive pulses can be modulated than those demonstrated in the original proposal.

Generation of a curved plasma channel from a discharged capillary for intense laser guiding

Li, Jian-Long; Li, Bo-Yuan; Zhu, Xin-Zhe; Bi, Ze-Wu; Wen, Xin-Hui; Lu, Lin; Yuan, Xiao-Hui; Liu, Feng; Chen, Min
HIGH POWER LASER SCIENCE AND ENGINEERING 11, e58 (MAY 2023)
https://doi.org/10.1017/hpl.2023.40

Straight plasma channels are widely used to guide relativistic intense laser pulses over several Rayleigh lengths for laser wakefield acceleration. Recently, a curved plasma channel with gradually varied curvature was suggested to guide a fresh intense laser pulse and merge it into a straight channel for staged wakefield acceleration [Phys. Rev. Lett. 120, 154801 (2018)]. In this work, we report the generation of such a curved plasma channel from a discharged capillary. Both longitudinal and transverse density distributions of the plasma inside the channel were diagnosed by analyzing the discharging spectroscopy. Effects of the gas-filling mode, back pressure and discharging voltage on the plasma density distribution inside the specially designed capillary are studied. Experiments show that a longitudinally uniform and transversely parabolic plasma channel with a maximum channel depth of 47.5 & μm and length of 3 cm can be produced, which is temporally stable enough for laser guiding. Using such a plasma channel, a laser pulse with duration of 30 fs has been successfully guided along the channel with the propagation direction bent by 10.4°.

Plasma density profile reconstruction of a gas cell for Ionization Induced Laser Wakefield Acceleration

Filippi, F.; Dickson, L. T.; Backhouse, M.; Forestier-Colleoni, P.; Gustafsson, C.; Cobo, C.; Ballage, C.; Dufrenoy, S. Dobosz; Lofquist, E.; Maynard, G.; Murphy, C. D.; Najmudin, Z.; Panza, F.; Persson, A.; Sciscio, M.; Vasilovici, O.; Lundh, O.; Cros, B.
JOURNAL OF INSTRUMENTATION 18(5), C05013 (MAY 2023)
https://doi.org/10.1088/1748-0221/18/05/C05013

Laser-driven plasma wakefields can provide hundreds of MeV electron beam in mm-range distances potentially shrinking the dimension of the actual particle accelerators. The plasma density plays a fundamental role in the control and stability of the acceleration process, which is a key development for the future electron injector proposed by EuPRAXIA. A gas cell was designed by LPGP and LIDYL teams, with variable length and backing pressure, to confine the gas and tailor the gas density profile before the arrival of the laser. This cell was used during an experimental campaign with the multi TW-class laser at the Lund Laser Centre. Ionization assisted injection in a tailored density profile is used to tune the electron beam properties. During the experiment, we filled the gas cell with hydrogen mixed with different concentration of nitrogen. We also varied the backing pressure of the gas and the geometrical length of the gas cell. We used a transverse probe to acquire shadowgraphic images of the plasma and to measure the plasma electron density. Methods and results of the analysis with comparisons between shadowgraphic and interferometric images will be discussed.

Electron-beam-controlled deflection of near-infrared laser in semiconductor plasma

Sakai, Y.; Williams, O. B.; Fukasawa, A.; Murokh, A.; Kupfer, R.; Kusche, K.; Fedurin, M.; Pogorelsky, I.; Polyanskiy, M.; Babzien, M.; Palmer, M.; Rosenzweig, J. B.
JOURNAL OF APPLIED PHYSICS 133(14), 143102 (APR 2023)
https://doi.org/10.1063/5.0146255

A timing method for experiments on the interaction of a near-infrared laser and an ultra-relativistic electron beam via a semiconductor plasma switch is experimentally validated. As an intermediate medium, a thin Si plate is excited by the energetic, intense electron beam to produce a semiconductor plasma, which in turn deflects counter-colliding laser light having 1 μm wavelength. An electron beam of sub-nC charge sufficiently induces the needed electron number density gradient of 1 x 10^{20} cm^{-3} per tens of μm length at the interaction point. Demonstration during an inverse Compton scattering experiment by a counter-colliding electron beam of 300 pC and 70 MeV with an Nd: YAG laser at a wavelength of 1 μm is reported.

Shot-by-shot stability of the discharge produced plasmas in suitably shaped capillaries

Arjmand, S.; Anania, M. P.; Biagioni, A.; Ferrario, M.; Del Franco, M.; Galletti, M.; Lollo, V.; Pellegrini, D.; Pompili, R.; Zigler, A.
JOURNAL OF INSTRUMENTATION 18(4), C04016 (APR 2023)
https://doi.org/10.1088/1748-0221/18/04/C04016

Compact accelerator machines are capable of producing accelerating gradients in the GV/m scale, which is significantly higher than the MV/m scale of conventional machines. As accelerators are widely used in many fields, such as industrial, research institutes, and medical applications, the development of these machines will undoubtedly have a profound impact on people's daily lives. SPARC_LAB, a test facility at INFN-LNF (Laboratori Nazionali di Frascati), is focused on enhancing particle accelerator research infrastructure using innovative plasma acceleration concepts. Within SPARC_LAB, we utilize plasma-filled capillaries with lengths of up to tens of centimeters. However, the plasma formation process is critical to ensure proper oversight of the plasma properties, which subsequently affects the dynamics of the electron bunch to be accelerated. One of the most critical points that significantly affects the properties of the electron beam passing through the plasma source is the shot-by-shot stability of the plasma density along the longitudinal dimension of the plasma-discharge capillary. Therefore, this paper aims to investigate the shot-by-shot stability of the plasma density during discharge, contributing to further advancements in the field of plasma acceleration.

Fabrication of THz corrugated wakefield structure and its high power test

Kong, H.; Chung, M.; Doran, D. S.; Ha, G.; Kim, S. -H.; Kim, J. -H.; Liu, W.; Lu, X.; Power, J.; Seok, J. -M.; Shin, S.; Shao, J.; Whiteford, C.; Wisniewski, E.
SCIENTIFIC REPORTS 13, 3207 (FEB 2023)
https://doi.org/10.1038/s41598-023-29997-9

We present overall process for developing terahertz (THz) corrugated structure and its beam-based measurement results. 0.2-THz corrugated structures were fabricated by die stamping method as the first step demonstration towards GW THz radiation source and GV/m THz wakefield accelerator. 150-μm thick disks were produced from an OFHC (C10100) foil by stamping. Two types of disks were stacked alternately to form 46 mm structure with ~ 170 corrugations. Custom assembly was designed to provide diffusion bonding with a high precision alignment of disks. The compliance of the fabricated structure have been verified through beam-based wakefield measurement at Argonne Wakefield Accelerator Facility. Both measured longitudinal and transverse wakefield showed good agreement with simulated wakefields. Measured peak gradients, 9.4 MV/m/nC for a long single bunch and 35.4 MV/m/nC for a four bunch trains, showed good agreement with the simulation.

Characteristic diagnosis of supersonic gas jet target for laser wakefield acceleration with high spatial-temporal resolution Nomarski interference system

Liu, Qiushi; Ma, Mingjiang; Zhang, Xiaohua; Lv, Chong; Song, Jianmin; Wang, Zhao; Yang, Guoqing; Yang, Yanlei; Wang, Jiahao; Li, Qinxiang; Zhao, Baozhen
FRONTIERS IN PHYSICS 11, 1203946 (JUL 2023)
https://doi.org/10.3389/fphy.2023.1203946

Gas targets hold distinctive significance and advantages in the field of laser-matter interaction. As a major type of gas targets, supersonic gas target is one of the most commonly used targets for laser wakefield acceleration (LWFA). The temporal-spatial resolution study of it could provide valuable data references for the LWFA experiment. In this work, a Nomarski interference system with high spatial-temporal resolution was set up to diagnose the jet process of supersonic gas jet target. The formation process of supersonic gas jet under different jet durations, different injection positions and different gas back pressures was studied. It is beneficial to determine the more optimized time and position of laser injection into target when conducting LWFA experiments. Therefore, the quality of the obtained electron beam and radiation source can be effectively improved.

Investigating of plasma diagnostics by utilizing spectroscopic measurements of Balmer emission

Arjmand, S.; Anania, M. P.; Biagioni, A.; Ferrario, M.; Del Franco, M.; Galletti, M.; Lollo, V.; Pellegrini, D.; Pompili, R.; Zigler, A.
JOURNAL OF INSTRUMENTATION 18(5), C05007 (MAY 2023)
https://doi.org/10.1088/1748-0221/18/05/C05007

Plasma technology offers revolutionary potential for particle accelerators by enabling the acceleration of electron beams to ultra-relativistic velocities in a small-scale dimension. The compact nature of plasma-based accelerators permits the creation of accelerating gradients on the GV scale. Plasma acceleration structures are created by utilizing either ultra-short laser pulses (Laser Wakefield Acceleration, LWFA) or energetic particle beams (Particle Wakefield Acceleration, PWFA), which need to be tailored to the plasma parameters. However, both methods face the challenge of limited acceleration length, which is currently only a few centimeters. To overcome this challenge, one approach is to generate plasma within a capillary tube, which can extend the acceleration length up to approximately forty centimeters or more. Consequently, it is crucial to characterize the produced plasma in terms of density and geometric structure. Optical emission spectroscopy (EOS) methods can be employed to measure and characterize the plasma electron density by analyzing the emitted plasma light. This paper presents measurements of the plasma electron density distribution for a hydrogen-filled capillary tube using both Balmer alpha (H_α) and Balmer beta (H_β) lines. Comparing the intensities of H_α and H_β emissions enables more precise measurements of the plasma electron density and provides additional information about other plasma properties.

Measurement of electron beam transverse slice emittance using a focused beamline

Jiang, Kangnan; Feng, Ke; Wang, Hao; Yang, Xiaojun; Bai, Peile; Xu, Yi; Leng, Yuxin; Wang, Wentao; Li, Ruxin
HIGH POWER LASER SCIENCE AND ENGINEERING 11, e36 (MAR 2023)
https://doi.org/10.1017/hpl.2023.9

A single-shot measurement of electron emittance was experimentally accomplished using a focused transfer line with a dipole. The betatron phase of electrons based on laser wakefield acceleration (LWFA) is energy dependent owing to the coupling of the longitudinal acceleration field and the transverse focusing (defocusing) field in the bubble. The phase space presents slice information after phase compensation relative to the center energy. Fitting the transverse size of the electron beam at different energy slices in the energy spectrum measured 0.27 mm mrad in the experiment. The diagnosis of slice emittance facilitates local electron quality manipulation, which is important for the development of LWFA-based free electron lasers. The quasi-3D particle-in-cell simulations matched the experimental results and analysis well.

Femtosecond laser-plasma dynamics study by a time-resolved Mach-Zehnder-like interferometer

Zuffi, Armando Valter Felicio; dos Santos, Jhonatha Ricardo; Maldonado, Edison Puig; Vieira Jr, Nilson Dias; Samad, Ricardo Elgul
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Side-view density profiles of a laser-induced plasma were measured by a home-built, time-resolved, Mach-Zehnder-like interferometer. Due to the pump-probe femtosecond resolution of the measurements, the plasma dynamics was observed, along with the pump pulse propagation. The effects of impact ionization and recombination were evidenced during the plasma evolution up to hundreds of picoseconds. This measurement system will integrate our laboratory infrastructure as a key tool for diagnosing gas targets and laser-target interaction in laser wakefield acceleration experiments. (c) 2023 Optica Publishing Group

Real time reconstruction of the fast electron spectrum from high intensity laser plasma interaction using gamma counting technique

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X-ray and gamma fluxes from the high intensity laser-plasma interaction are extremely short, well beyond temporal resolution of any detectors. If laser pulses come repetitively, the single photon counting technique allows to accumulate the photon spectra, however, its relation to the spectrum of the initial fast electron population in plasma is not straightforward. We present efficient and fast approach based on the Geant4 package that significantly reduces computer time needed to re-construct the high energy tail of electron spectrum from experimental data accounting for the pileup effect. Here, we first tabulate gamma spectrum from monoenergetic electron bunches of different energy for a given experimental setup, and then compose the simulated spectrum. To account for the pileups, we derive analytical formula to reverse the data. We also consider errors coming from the approximation of the initial electron spectrum by the sum of monoenergetic impacts, the finite range of the electron spectrum, etc. and give estimates on how to choose modelling parameters to minimize the approximation errors. Finally, we present an example of the experimental data treatment for the case of laser-solid interaction using 50 fs laser pulse with intensity above 10^{18} W/cm^2.

FACILITIES

Design study for a compact, two-stage, laser-plasma-based source of positron beams

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PLASMA PHYSICS AND CONTROLLED FUSION 65(8), 085016 (AUG 2023)
https://doi.org/10.1088/1361-6587/ace3f1

Owing to their large accelerating gradients, plasma-based accelerators have attracted considerable interest as potential drivers for future, compact electron-positron colliders. Despite great progress achieved in plasma-based electron acceleration, positron acceleration still remains a challenging task, with an efficient positron source being the prerequisite for such acceleration. Here a concept for a compact, two-stage plasma-based positron source is discussed. In the first stage the positrons are created by a multi GeV electron beam produced by a laser-plasma accelerator interacting with a solid density foil. In the second stage the positrons are captured and accelerated in a plasma wave driven by either an electron beam or a laser pulse. Three potential configurations of such a source are considered: (i) a single electron beam is used for both the creation of positrons in the foil and for driving the wakefield in the second stage; (ii) a train of two electron beams is used: the positrons produced by the trailing beam in the foil are captured and accelerated in the second stage by the plasma wave generated by the leading beam; and (iii) a single electron beam is used to produce positrons in the foil and an independent laser pulse is coupled to the second stage to drive the plasma wave. These three configurations show different degrees of effectiveness with positron capture efficiency, varying from less than a percent to almost half of all produced positrons.

Linear colliders based on laser-plasma accelerators

Schroeder, C. B.; Albert, F.; Benedetti, C.; Bromage, J.; Bruhwiler, D.; Bulanov, S. S.; Campbell, E. M.; Cook, N. M.; Cros, B.; Downer, M. C.; Esarey, E.; Froula, D. H.; Fuchs, M.; Geddes, C. G. R.; Gessner, S. J.; Gonsalves, A. J.; Hogan, M. J.; Hooker, S. M.; Huebl, A.; Jing, C.; Joshi, C.; Krushelnick, K.; Leemans, W. P.; Lehe, R.; Maier, A. R.; Milchberg, H. M.; Mori, W. B.; Nakamura, K.; Osterhoff, J.; Palastro, J. P.; Palmer, M.; Poder, K.; Power, J. G.; Shadwick, B. A.; Terzani, D.; Thevenet, M.; Thomas, A. G. R.; van Tilborg, j.; Turner, M.; Vafaei-Najafabadi, N.; Vay, J. -l.; Zhou, T.; Zuegel, J.

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https://doi.org/10.1088/1748-0221/18/06/T06001

Laser-plasma accelerators are capable of sustaining accelerating fields of 10-100 GeV/m, 100-1000 times that of conventional technology and the highest fields produced by any of the widely researched advanced accelerator concepts. Laser-plasma accelerators also intrinsically accelerate short particle bunches, several orders of magnitude shorter than that of conventional technology, which leads to reductions in beamstrahlung and, hence, savings in the overall power consumption to reach a desired luminosity. These properties make laser-plasma accelerators a promising accelerator technology for a more compact, less expensive high-energy linear collider providing multi-TeV polarized leptons. In this submission to the Snowmass 2021 Accelerator Frontier, we discuss the motivation for a laser-plasma-accelerator-based linear collider, the status of the field, and potential linear collider concepts up to 15 TeV. We outline the research and development path toward a collider based on laser-plasma accelerator technology, and highlight near-term and mid-term applications of this technology on the collider development path. The required experimental facilities to carry out this research are described. We conclude with community recommendations developed during Snowmass.

Control systems and data management for high-power laser facilities

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HIGH POWER LASER SCIENCE AND ENGINEERING 11, e56 (JUN 2023)
https://doi.org/10.1017/hpl.2023.49

The next generation of high-power lasers enables repetition of experiments at orders of magnitude higher frequency than what was possible using the prior generation. Facilities requiring human intervention between laser repetitions need to adapt in order to keep pace with the new laser technology. A distributed networked control system can enable laboratory-wide automation and feedback control loops. These higher-repetition-rate experiments will create enormous quantities of data. A consistent approach to managing data can increase data accessibility, reduce repetitive data-software development and mitigate poorly organized metadata. An opportunity arises to share knowledge of improvements to control and data infrastructure currently being undertaken. We compare platforms and approaches to state-of-the-art control systems and data management at high-power laser facilities, and we illustrate these topics with case studies from our community.

Principles and applications of x-ray light sources driven by laser wakefield acceleration

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https://doi.org/10.1063/5.0142033

One of the most prominent applications of modern particle accelerators is the generation of radiation. In a synchrotron or an x-ray free electron laser (XFEL), high energy electrons oscillating in periodic magnetic structures emit bright x rays. In spite of their scientific appeal that will remain evident for many decades, one limitation of synchrotrons and XFELs is their typical mile-long size and their cost, which often limits access to the broader scientific community. This tutorial reviews the principles and prospects of using plasmas produced by intense lasers as particle accelerators and x-ray light sources, as well as some of the applications they enable. A plasma is an ionized medium that can sustain electrical fields many orders of magnitude higher than that in conventional radio frequency accelerator structures and can be used to accelerate electrons. When short, intense laser pulses are focused into a gas, it produces electron plasma waves in which electrons can be trapped and accelerated to GeV energies. This process, laser-wakefield acceleration (LWFA), is analogous to a surfer being propelled by an ocean wave. Many radiation sources, from THz to gamma-rays, can be produced by these relativistic electrons. This tutorial reviews several LWFA-driven sources in the keV-MeV photon energy range: betatron radiation, inverse Compton scattering, bremsstrahlung radiation, and undulator/XFEL radiation. X rays from laser plasma accelerators have many emerging applications. They can be used in innovative and flexible x-ray imaging and x-ray absorption spectroscopy configurations, for use in biology, industry, and high-energy density science.

Tango Controls and data pipeline for petawatt laser experiments

Weisse, Nils; Doyle, Leonard; Gebhard, Johannes; Balling, Felix; Schweiger, Florian; Haberstroh, Florian; Geulig, Laura D.; Lin, Jinpu; Irshad, Faran; Esslinger, Jannik; Gerlach, Sonja; Gilljohann, Max; Vaidyanathan, Vignesh; Siebert, Dennis; Muenzer, Andreas; Schilling, Gregor; Schreiber, Joerg; Thirolf, Peter G.; Karsch, Stefan; Doepp, Andreas

HIGH POWER LASER SCIENCE AND ENGINEERING 11, e44 (FEB 2023)
https://doi.org/10.1017/hpl.2023.17

The Centre for Advanced Laser Applications in Garching, Germany, is home to the ATLAS-3000 multi-petawatt laser, dedicated to research on laser particle acceleration and its applications. A control system based on Tango Controls is implemented for both the laser and four experimental areas. The device server approach features high modularity, which, in addition to the hardware control, enables a quick extension of the system and allows for automated data acquisition of the laser parameters and experimental data for each laser shot. In this paper we present an overview of our implementation of the control system, as well as our advances in terms of experimental operation, online supervision and data processing. We also give an outlook on advanced experimental supervision and online data evaluation - where the data can be processed in a pipeline - which is being developed on the basis of this infrastructure.

Design of the proton and electron transfer lines for AWAKE Run 2c

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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH SECTION A-ACCELERATORS; SPECTROMETERS DETECTORS AND ASSOCIATED EQUIPMENT 1049, 168094 (APR 2023)
https://doi.org/10.1016/j.nima.2023.168094

The Advanced Wakefield (AWAKE) Run 1 experiment, which concluded in 2018, achieved electron acceleration to 2 GeV via plasma wakefield acceleration driven by 400 GeV, self-modulated proton bunches extracted from the CERN SPS. The Run 2c phase of the experiment aims to advance these results by demonstrating acceleration up to about 10 GeV while preserving the quality of the accelerated electron beam. For Run 2c, the Run 1 proton transfer line will be reconfigured to shift the first plasma cell 40 m longitudinally and a second plasma cell will be added 1 m downstream of the first. In addition, a new 150 MeV beamline will be required to inject a witness electron beam, with a beam size of several microns, into the second plasma cell to probe the accelerating fields. Proposed adjustments to the proton transfer line and the design of the 150 MeV electron transfer line are detailed in this paper.

THEORY & SIMULATION

Bayesian optimization of laser-plasma accelerators assisted by reduced physical models

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PHYSICAL REVIEW ACCELERATORS AND BEAMS 26(8), 084601 (AUG 2023)
https://doi.org/10.1103/PhysRevAccelBeams.26.084601

Particle-in-cell simulations are among the most essential tools for the modeling and optimization of laser-plasma accelerators, since they reproduce the physics from first principles. However, the high computational cost associated with them can severely limit the scope of parameter and design optimization studies. Here, we show that a multitask Bayesian optimization algorithm can be used to mitigate the need for such high-fidelity simulations by incorporating information from inexpensive evaluations of reduced physical models. In a proof-of-principle study, where a high-fidelity optimization with FBPIC is assisted by reduced-model simulations with Wake-T, the algorithm demonstrates an order-of-magnitude speedup. This opens a path for the cost-effective optimization of laser-plasma accelerators in large parameter spaces, an important step toward fulfilling the high beam quality requirements of future applications.

Accurate simulation of direct laser acceleration in a laser wakefield accelerator

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PHYSICS OF PLASMAS 30(7), 073902 (JUL 2023)
https://doi.org/10.1063/5.0152383

In a laser wakefield accelerator (LWFA), an intense laser pulse excites a plasma wave that traps and accelerates electrons to relativistic energies. When the pulse overlaps the accelerated electrons, it can enhance the energy gain through direct laser acceleration (DLA) by resonantly driving the betatron oscillations of the electrons in the plasma wave. The particle-in-cell (PIC) algorithm, although often the tool of choice to study DLA, contains inherent errors due to numerical dispersion and the time staggering of the electric and magnetic fields. Further, conventional PIC implementations cannot reliably disentangle the fields of the plasma wave and laser pulse, which obscures interpretation of the dominant acceleration mechanism. Here, a customized field solver that reduces errors from both numerical dispersion and time staggering is used in conjunction with a field decomposition into azimuthal modes to perform PIC simulations of DLA in an LWFA. Comparisons with traditional PIC methods, model equations, and experimental data show improved accuracy with the customized solver and convergence with an order-of-magnitude fewer cells. The azimuthal-mode decomposition reveals that the most energetic electrons receive comparable energy from DLA and LWFA.

Six-Dimensional Beam-Envelope Equations: An Ultrafast Computational Approach for Interactive Modeling of Accelerator Structures

Kelisani, M. D.; Barzegar, S.; Craievich, P.; Doebert, S.

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https://doi.org/10.1103/PhysRevApplied.19.054011

The design and implementation of accelerators capable of providing high-quality bunches require precise and efficient online modeling tools. Current comprehensive beam dynamics studies are prohibitively costly and challenging to use for interactive system design. A precise high-speed method for beam dynamics analysis in accelerator components is presented and compared to the results of the conventional particle-in-cell codes. Using powerful mathematical techniques, the suggested method evaluates the temporal evolution of a bunch shape in six-dimensional (6D) phase space along the accelerators. The moment equations that govern the evolution of the bunch envelope in 6D phase space are introduced. The three-dimensional space-charge, external, and emittance forces are calculated to be fully analytically insensitive to different beam envelopes. Substituting the obtained forces into the beam-envelope equations establishes a set of six modified equations describing the beam dynamics using simple algebraic expressions. The whole solution considers the energy spread inherent to an electron beam. The model accuracy is demonstrated by studying beam transport through various components of an accelerator. Applying this analytical approach not only forms a style of physical thinking by indicating the factors that affect the behavior of the charged particle bunches but also has an ultrafast computational speed that is at least 3 orders of magnitude faster than that of particle tracking codes for designing today's linear accelerators. Finally, the model's feasibility is benchmarked for successfully designing a photoinjector for the advanced proton driven plasma wakefield acceleration experiment.

Optimization of transformer ratio and beam loading in a plasma wakefield accelerator with a structure-exploiting algorithm

Su, Q.; Larson, J.; Dalichaouch, T. N.; Li, F.; An, W.; Hildebrand, L.; Zhao, Y.; Decyk, V.; Alves, P.; Wild, S. M.; Mori, W. B.
PHYSICS OF PLASMAS 30(5), 053108 (MAY 2023)
https://doi.org/10.1063/5.0142940

Plasma-based acceleration has emerged as a promising candidate as an accelerator technology for a future linear collider or a next-generation light source. We consider the plasma wakefield accelerator (PWFA) concept where a plasma wave wake is excited by a particle beam and a trailing beam surfs on the wake. For a linear collider, the energy transfer efficiency from the drive beam to the wake and from the wake to the trailing beam must be large, while the emittance and energy spread of the trailing bunch must be preserved. One way to simultaneously achieve this when accelerating electrons is to use longitudinally shaped bunches and nonlinear wakes. In the linear regime, there is an analytical formalism to obtain the optimal shapes. In the nonlinear regime, however, the optimal shape of the driver to maximize the energy transfer efficiency cannot be precisely obtained because currently no theory describes the wake structure and excitation process for all degrees of nonlinearity. In addition, the ion channel radius is not well defined at the front of the wake where the plasma electrons are not fully blown out by the drive beam. We present results using a novel optimization method to effectively determine a current profile for the drive and trailing beam in PWFA that provides low energy spread, low emittance, and high acceleration efficiency. We parameterize the longitudinal beam current profile as a piecewise-linear function and define optimization objectives. For the trailing beam, the algorithm converges quickly to a nearly inverse trapezoidal trailing beam current profile similar to that predicted by the ultrarelativistic limit of the nonlinear wakefield theory. For the drive beam, the beam profile found by the optimization in the nonlinear regime that maximizes the transformer ratio also resembles that predicted by linear theory. The current profiles found from the optimization method provide higher transformer ratios compared with the linear ramp predicted by the relativistic limit of the nonlinear theory.

Transfer learning and multi-fidelity modeling of laser-driven particle acceleration

Djordjevic, B. Z.; Kim, J.; Wilks, S. C.; Ludwig, J.; Myers, C.; Kemp, A. J.; Swanson, K. K.; Zeraouli, G.; Grace, E. S.; Simpson, R. A.; Rusby, D.; Antoine, A. F.; Bremer, P. -t.; Thiagarajan, J.; Anirudh, R.; Williams, G. J.; Ma, T.; Mariscal, D. A.
PHYSICS OF PLASMAS 30(4), 043111 (APR 2023)
https://doi.org/10.1063/5.0139285

Computer models of intense, laser-driven ion acceleration require expensive particle-in-cell simulations that may struggle to capture all the multi-scale, multi-dimensional physics involved at reasonable costs. Explored is an approach to ameliorate this deficiency using a multi-fidelity framework that can incorporate physical trends and phenomena at different levels. As the basis for this study, an ensemble of approximately 8000 1D simulations was generated to buttress separate ensembles of hundreds of higher fidelity 1D and 2D simulations. Using transfer learning with deep neural networks, one can reproduce the results of more complex physics at a much lower cost. The networks trained in this fashion can, in turn, act as surrogate models for the simulations themselves, allowing for quick and efficient exploration of the parameter space of interest. Standard figures-of-merit were used as benchmarks such as the hot electron temperature, peak ion energy, conversion efficiency, and so on. We can rapidly identify and explore under what conditions differing fidelities become an important effect and search for outliers in feature space.

Mitigation of the Onset of Hosing in the Linear Regime through Plasma Frequency Detuning

Moreira, Mariana; Muggli, Patric; Vieira, Jorge
PHYSICAL REVIEW LETTERS 130(11), 115001 (MAR 2023)
https://doi.org/10.1103/PhysRevLett.130.115001

The hosing instability poses a feasibility risk for plasma-based accelerator concepts. We show that the growth rate for beam hosing in the linear regime (which is relevant for concepts that use a long driver) is a function of the centroid perturbation wavelength. We demonstrate how this property can be used to damp centroid oscillations by detuning the plasma response sufficiently early in the development of the instability. We also develop a new theoretical model for the early evolution of hosing. These findings have implications for the general control of an instability's growth rate.

Multi-objective and multi-fidelity Bayesian optimization of laser-plasma acceleration

Irshad, F.; Karsch, S.; Döpp, A.
PHYSICAL REVIEW RESEARCH 5, 013063 (JAN 2023)
https://doi.org/10.1103/PhysRevResearch.5.013063

Beam parameter optimization in accelerators involves multiple, sometimes competing, objectives. Condensing these individual objectives into a single figure of merit unavoidably results in a bias towards particular outcomes, often in an undesired way in the absence of prior knowledge. Finding an optimal objective definition then requires operators to iterate over many possible objective weights and definitions, a process that can take many times longer than the optimization itself. A more versatile approach is multi-objective optimization, which establishes the trade-off curve or Pareto front between objectives. Here we present the first results on multi-objective Bayesian optimization of a simulated laser-plasma accelerator. We find that multi-objective optimization reaches comparable performance to its single-objective counterparts while allowing for instant evaluation of entirely new objectives. This dramatically reduces the time required to find appropriate objective definitions for new problems. Additionally, our multi-objective, multi-fidelity method reduces the time required for an optimization run by an order of magnitude. It does so by dynamically choosing simulation resolution and box size, requiring fewer slow and expensive simulations as it learns about the Pareto-optimal solutions from fast low-resolution runs. The techniques demonstrated in this paper can easily be translated into many different computational and experimental use cases beyond accelerator optimization.

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