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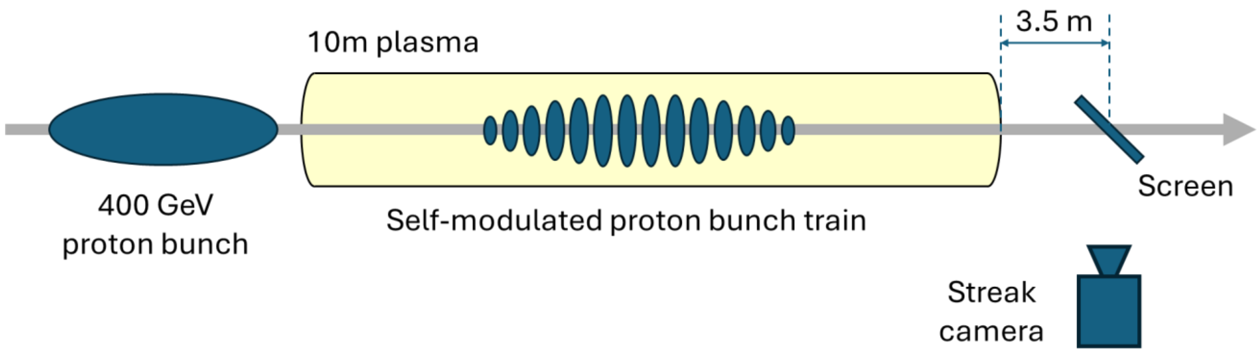
CONTENTS

RESEARCH HIGHLIGHTS

Observation of Ion Motion in Plasma Wakefield Accelerators

A recent study led by Marlene Turner and a team of researchers from the international AWAKE collaborations has provided new insights into the behaviour of ions within plasma wakefield accelerators. Their findings, published in Physical Review Letters, reveal that ion motion in these accelerators inversely correlates with the plasma ion mass. This motion manifests as a "bunch tail," occurring when sufficient ion movement suppresses wakefields.

Plasma wakefield accelerators utilize plasma electrons oscillating collectively in a background of positively charged plasma ions to generate accelerating structures. While these accelerators can achieve gradients much higher than traditional radio-frequency cavities, they often assume plasma ions are immobile and uniformly distributed. However, this study challenges that assumption by demonstrating that ion motion, driven by the ponderomotive force of wakefields, significantly impacts accelerator performance.



Schematic of the experimental setup.

The researchers observed that the ion motion effect depends on the plasma ion mass, appearing first with lighter ions. They also found that increasing the amplitude of wakefields, achieved by varying the drive bunch charge, enhances this effect. These observations align with theoretical predictions and simulations, suggesting that ion motion can influence the efficiency and stability of plasma-based acceleration processes.

Understanding these dynamics is crucial for advancing plasma wakefield acceleration technology, which holds promise for compact and efficient particle accelerators in various applications.

More information:

M. Turner *et al.*, "Experimental Observation of the Motion of Ions in a Resonantly Driven Plasma Wakefield Accelerator", Phys. Rev. Lett. 134, 155001 (2025)
https://doi.org/10.1103/PhysRevLett.134.155001

FUNDAMENTALS

Optical Imaging of Laser-Driven Fast Electron Weibel-like Filamentation in Overcritical Density Plasma

Dover, N. P.; Tresca, O.; Cook, N.; Ettlinger, O. C.; Kingham, R. J.; Maharjan, C.; Polyanskiy, M. N.; Shkolnikov, P.; Pogorelsky, I.; Najmudin, Z.
PHYSICAL REVIEW LETTERS 134(2), 025102 (JAN 2025)
https://doi.org/10.1103/PhysRevLett.134.025102

We report on the measurement of filamented transport of laser-generated fast electron beams in near-critical density plasma. A relativistic intensity long-wave-infrared laser irradiated a hydrodynamically shaped helium gas flow at an electron density $n_e \simeq 10^{25}$ m^{-3}, generating a large flux of fast electrons that propagated beyond the critical surface. The beam-to-background electron density ratio was sufficiently high to drive growth of Weibel-like filamentation, which was measured by optical probing to extend up to 800 µm with radii 10 µm. Particle-in-cell simulations reproduce the main features of the filamentation generation, suggesting that collisionless processes are dominant in these interactions. Expansion of the filaments after formation infers a fast electron heated plasma temperature 400 eV in the overcritical density plasma.

Experimental Observation of the Motion of Ions in a Resonantly Driven Plasma Wakefield Accelerator

Turner, M.; Walter, E.; Amoedo, C.; Torrado, N.; Lopes, N.; Sublet, A.; Bergamaschi, M.; Pucek, J.; Mezger, J. et al. (AWAKE Collaboration)
PHYSICAL REVIEW LETTERS 134, 155001 (APR 2025)
https://doi.org/10.1103/PhysRevLett.134.155001

We show experimentally that an effect of motion of ions, observed in a plasma-based accelerator, depends inversely on the plasma ion mass. The effect appears within a single wakefield event and manifests itself as a bunch tail, occurring only when sufficient motion of ions suppresses wakefields. Wakefields are driven resonantly by multiple bunches, and simulation results indicate that the ponderomotive force causes the motion of ions. In this case, the effect is also expected to depend on the amplitude of the wakefields, experimentally confirmed through variations in the drive bunch charge.

Development of self-modulation as a function of plasma length

Clairembaud, Arthur; Turner, Marlene; Muggli, Patric
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH SECTION A-ACCELERATORS SPECTROMETERS DETECTORS AND ASSOCIATED EQUIPMENT 1073, 170265 (APR 2025)
https://doi.org/10.1016/j.nima.2025.170265

We use numerical simulations to determine whether the saturation length of the self-modulation (SM) instability of along proton bunch in plasma could be determined by measuring the radius of the bunch halo SM produces. Results show that defocused protons acquire their maximum transverse momentum and exit the wakefields at a distance approximately equal to the saturation length of the wakefields. This suggests that measuring the radius of the halo as a function of plasma length in the AWAKE experiment would yield a very good estimate for the saturation length of SM.

Effect of frequency-chirped ionization laser on accelerated electron beam characteristics in plasma wakefield acceleration

Singh, Jagnishan; Kumar, Sandeep; Kant, Niti; Rajput, Jyoti
EUROPEAN PHYSICAL JOURNAL PLUS 140(2), 135 (FEB 2025)
https://doi.org/10.1140/epjp/s13360-025-06061-1

Trojan Horse underdense photocathode plasma wakefield acceleration is an effective technique for generating ultralow-emittance electron bunches. In this study, we investigate the impact of frequency chirp in the ionization laser on the properties of the accelerated electron bunches using two-dimensional (2D) particle-in-cell (PIC) simulations. It is found that the total charge of the high-energy electrons produced in the acceleration process depends strongly on the magnitude and the sign of frequency chirp in ionization laser. For an un-chirped ionization laser, an electron bunch gets a maximum acceleration of up to 400 MeV with bunch current $I_p \sim 0.27$kA. However, the use of a negative-chirped ionization laser shows lower energy gain, i.e., 200 MeV with an enhanced bunch current $I_p \sim 5$kA, with normalized emittance $\varepsilon_n \sim 0.78$ µm in 7.5-mm-long plasma channel. Such high current electron bunches will be useful for compact hard X-ray free-electron laser (FEL) sources.

CONTROL & OPTIMIZATION

Active energy compression of a laser-plasma electron beam

Winkler, P.; Trunk, M.; Huebner, L.; de la Ossa, A. Martinez; Jalas, S.; Kirchen, M.; Agapov, I.; Antipov, S. A.; Brinkmann, R.; Eichner, T.; Pousa, A. Ferran; Huelsenbusch, T.; Palmer, G.; Schnepp, M.; Schubert, K.; Thevenet, M.; Walker, P. A.; Werle, C.; Leemans, W. P.; Maier, A. R.
NATURE (APR 2025)
https://doi.org/10.1038/s41586-025-08772-y

Radio-frequency (RF) accelerators providing high-quality relativistic electron beams are an important resource enabling many areas of science, as well as industrial and medical applications. Two decades ago, laser-plasma accelerators that support orders of magnitude higher electric fields than those provided by modern RF cavities produced quasi-monoenergetic electron beams for the first time. Since then, high-brightness electron beams at gigaelectronvolt (GeV) beam energy and competitive beam properties have been demonstrated from only centimetre-long plasmas, a substantial advantage over the hundreds of metres required by RF-cavity-based accelerators. However, despite the considerable progress, the comparably large energy spread and the fluctuation (jitter) in beam energy still effectively prevent laser-plasma accelerators from driving real-world applications. Here we report the generation of a laser-plasma electron beam using active energy compression, resulting in a performance so far only associated with modern RF-based accelerators. Using a magnetic chicane, the electron bunch is first stretched longitudinally to imprint an energy correlation, which is then removed with an active RF cavity. The resulting energy spread and energy jitter are reduced by more than an order of magnitude to below the permille level, meeting the acceptance criteria of a modern synchrotron, thereby opening the path to a compact storage ring injector and other applications.

Acceleration rate enhancement by negative plasma density gradient in multi-bunch driven plasma wakefield accelerator

Okhotnikov, N. V.; Lotov, K. V.
PHYSICS OF PLASMAS 32(3), 033102 (MAR 2025)
https://doi.org/10.1063/5.0249127

In a plasma wakefield accelerator driven by a train of short particle bunches, it is possible to locally increase the acceleration rate by slightly decreasing the plasma density and introducing its small negative gradient. There is a regime in which changing the density affects only the relative phasing of the driver bunches and the wave, keeping the wave phase behind the driver stable. With this technique, it is possible to increase the energy gain of the accelerated witness bunch in a plasma section of limited length.

Energy boosting and scaling of self-guided hybrid laser-plasma wakefield acceleration in a single uniform plasma

Chang, Xinyuan; Zeng, Ming; Wang, Jia; Li, Dazhang
NEW JOURNAL OF PHYSICS 27(2), 023021 (FEB 2025)
https://doi.org/10.1088/1367-2630/adb2b9

In laser-driven plasma wakefield acceleration (LWFA), laser pump depletion and electron dephasing are the major constraints of the electron energy gain. Hybrid laser-PWFA, which uses the laser-accelerated electron beam to drive a beam-driven plasma wakefield in separated stages, has been proposed to increase the beam brightness. However, the overall electron energy gain in hybrid acceleration is even lower than single-stage laser acceleration. In this paper, we report the observation of the energy boosting effect of the hybrid acceleration in single uniform plasmas through a series of particle-in-cell simulations. The self-injected electron beam from the laser-driven wakefield automatically moves forward to drive the beam-driven wakefield after laser depletion. The electrons at the beam tail are then accelerated by the beam-driven plasma wakefield, and the energy gain is at least doubled compared to previous single-stage experiments with the same laser energy. We also propose the scaling of the electron energy gain and the acceleration distance with the laser energy. For example, with a 9.1 J energy laser pulse and a 3.5 cm long plasma of $1.6\text{x}10^{18}$ cm^{-3} density, one can produce a quasi-monoenergetic electron beam at 3.5 GeV energy with 23 pC charge.

Wakefield regeneration in a plasma accelerator

Farmer, J. P.; Della Porta, G. Zevi
PHYSICAL REVIEW RESEARCH 7(1), L012055 (MAR 2025)
https://doi.org/10.1103/PhysRevResearch.7.L012055

Plasma wakefields offer high acceleration gradients, orders of magnitude larger than conventional RF accelerators. However, the achievable luminosity remains relatively low, typically limited by the repetition rate and the charge accelerated per shot. In this work, we show that a train of drive bunches can be harnessed to accelerate multiple witness bunches in a single shot. We demonstrate that periodically loading the wakefields removes the limit on the energy transfer from the drive beam to the plasma, which allows the luminosity to be increased. Proof-of-concept simulations for the AWAKE scheme are carried out to demonstrate the technique, achieving a doubling of the accelerated charge while exploiting only a fraction of the drive train.

TECHNOLOGY

DIAGNOSTICS

Reconstruction of beam parameters and betatron radiation spectra measured with a Compton spectrometer

Yadav, M.; Oruganti, M. H.; Naranjo, B.; Zhang, S.; Andonian, G.; Zhuang, Y.; Apsimon, O.; Welsch, C. P.; Rosenzweig, J. B.
PHYSICAL REVIEW ACCELERATORS AND BEAMS 28(4), 042802 (APR 2025)
https://doi.org/10.1103/PhysRevAccelBeams.28.042802

The photon flux resulting from high-energy electron beam interactions with high-field systems, such as those found in the upcoming FACET-II experiments at the SLAC National Accelerator Laboratory, yields deep insight into the electron beam's underlying dynamics during the interaction. However, extracting this information is an intricate process. To demonstrate how to approach this challenge using modern methods, this paper utilizes simulated data that models plasma wakefield acceleration-derived betatron radiation in experiments to determine reliable methods of reconstructing key beam and beam-plasma interaction properties. For betatron radiation measurements, translating the observed 200 keV to 30 MeV photon double-differential energy-angle spectra obtained from an advanced Compton spectrometer requires testing multiple methods to optimize the pipeline from its response to incident electron beam information. The paper compares maximum likelihood estimation and machine learning to refine the translation of photon spectra into precise electron beam metrics, such as spot size, energy, and emittance, enhancing the understanding of beam behavior within these dense, high-field environments. We also introduce machine learning and the expected maximization algorithm to reconstruct the primary photon spectrum, employing a multilayer neural network for regression analysis of the energy and angle spectra. With appropriate modifications, the advanced methods reproduce relevant incident beam parameters with high accuracy, even for beam sizes in the <10 µm range. This capacity is critical to understanding intense beam propagation and its optimization in plasma.

Design and experimental verification of a bunch length monitor based on coherent Cherenkov diffraction radiation

Davut, C.; Xia, G.; Apsimon, O.; Mcgunigal, J.; Karataev, P.; Lefevre, T.; Mazzoni, S.; Senes, E.
PHYSICAL REVIEW ACCELERATORS AND BEAMS 28(2), 013193 (FEB 2025)
https://doi.org/10.1103/PhysRevResearch.7.013193

This paper presents the design and experimental commissioning of a noninvasive electron bunch length monitor based on the detection of coherent Cherenkov diffraction radiation (ChDR). The measurement technique effectively eliminates the influence of bunch-by-bunch charge fluctuations, as each detector measures the signal from the same bunch while mitigating the impact of bunch position jitter on the measurements, providing a potential real-time diagnostic tool with significant operational advantages. The sensitivity of the measurements to both bunch length and longitudinal bunch profile was experimentally demonstrated, with results validated against invasive radio frequency deflector measurements at the CLEAR electron test facility at CERN. The ChDR bunch length monitor can be applied to accelerators operating with ultrashort bunches.

Implementation of light diagnostics for wakefields at AWAKE

Mezger, J.; Bergamaschi, M.; Ranc, L.; Sublet, A.; Pucek, J.; Turner, M.; Clairembaud, A.; Muggli, P.
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH SECTION A-ACCELERATORS SPECTROMETERS DETECTORS AND ASSOCIATED EQUIPMENT 1075, 170426 (JUN 2025)
https://doi.org/10.1016/j.nima.2025.170426

We describe the implementation of light diagnostics for studying the self-modulation instability of a long relativistic proton bunch in a 10 m-long plasma. The wakefields driven by the proton bunch dissipate their energy in the surrounding plasma. The amount of light emitted as atomic line radiation is related to the amount of energy dissipated in the plasma. We describe the setup and calibration of the light diagnostics, configured for a discharge plasma source and a vapor plasma source. For both sources, we analyze measurements of the light from the plasma only (no proton bunch). We show that with the vapor plasma source, the light signal is proportional to the energy deposited in the vapor/plasma by the ionizing laser pulse. We use this dependency to obtain the parameters of an imposed plasma density step. This dependency also forms the basis for ongoing studies, focused on investigating the wakefield evolution along the plasma.

Transient chirp reconstruction of an ultrafast electron beam via a tightly focused chirped laser pulse

Zhang, Zhijun; Zhou, Shiyi; Liu, Jiansheng
OPTICS LETTERS 50(6), 2025-2028 (MAR 2025)
https://doi.org/10.1364/OL.552063

Controlling particle beam phase space is essential for producing high-quality, ultrashort electron beams (e-beams) in plasma-based accelerators. Diagnosing the rapidly evolving transient energy chirp during early acceleration remains challenging. We propose what we believe to be a novel method using tightly focused and chirped laser pulses to reconstruct the chirp profile. By analyzing conditions for enhancing divergence modulation and leveraging intrinsic phase correlations in phase space, precise chirp reconstruction is achieved. Additionally, temporal delay between the laser and e-beam is determined via Fourier analysis of the divergence modulation. This method enables attosecond-level precision laser streaking for relativistic ultrashort e-beams, offering a powerful tool for ultrafast electron dynamics diagnosis. (c) 2025 Optica Publishing Group.

PLASMA TARGETS

Femtosecond laser-induced plasma filaments for beam-driven plasma wakefield acceleration

Galletti, M.; Crincoli, L.; Pompili, R.; Verra, L.; Villa, F.; Demitra, R.; Biagioni, A.; Zigler, A.; Ferrario, M.
PHYSICAL REVIEW E 111(2), 025202 (FEB 2025)
https://doi.org/10.1103/PhysRevE.111.025202

We describe the generation of plasma filaments for application in plasma-based particle accelerators. The complete characterization of a plasma filament generated by a low-energy self-guided femtosecond laser pulse is studied experimentally and theoretically in a low-pressure nitrogen gas environment. For this

purpose, we adopted a spectroscopic methodology to measure the plasma density and electron temperature. In addition to this, we also employed a side-imaging technique to retrieve the plasma column sizes (length and diameter). The measurements show the stable generation of a 4-cm-long plasma filament with 300 µm diameter. The peak plasma density and temperature are ne 10^{16} cm^{-3} and T_e 1.3 eV, respectively, with a decay time of approximately 8 ns. We show that the experimental results are in agreement with numerical simulations in terms of filament size and density decay time.

Advanced ceramic plasma discharge capillaries for high repetition rate operation

Crincoli, Lucio; Demitra, Romain; Lollo, Valerio; Pellegrini, Donato; Pitti, Marco; Pronti, Lucilla; Romani, Martina; Ferrario, Massimo; Biagioni, Angelo
SCIENTIFIC REPORTS 15(1), 12456 (APR 2025)
https://doi.org/10.1038/s41598-025-96882-y

In view of future applications of plasma-based particle accelerators, within the fields of high-energy physics and new light sources, the capability of plasma sources to operate at high repetition rates is crucial. In particular for gas-filled plasma discharge capillaries, which allow direct control over plasma properties, a key aspect is the longevity of the material, subject to erosion due to the heat flux delivered by high voltage plasma discharges. In this regard, we present an innovative design of discharge capillaries based on the use of different ceramic materials, which can sustain high voltage plasma discharges at high repetition rate and, moreover, be easily machined for the complex geometries required for plasma-based accelerators. Experimental campaigns are carried out at 10-150 Hz, assessing the longevity of ceramic capillaries by means of different diagnostic techniques. In addition, numerical simulations are performed to analyze the heat transfer within the whole plasma source. Results from experimental and numerical analysis highlight the capability of ceramic capillaries to preserve plasma properties and the integrity of the source during long-term plasma discharge operation at high repetition rate. In particular, we demonstrated the suitability of the proposed solution for the operative range of 100-400 Hz, foreseen for EuPRAXIA@SPARC_LAB project.

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

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

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

Parametric study of voltage in plasma-discharge capillary systems: a benchmarking of experimental and simulation data

Arjmand, S.; Amato, A.; Catalano, R.; Manna, C.; Mascali, D.; Mauro, G. S.; Oliva, D.; Pappalardo, A. D.; Pidatella, A.; Suarez, J.; Vinciguerra, F.; Cirrone, G. A. P.
JOURNAL OF INSTRUMENTATION 20(3), C03035 (MAR 2025)
https://doi.org/10.1088/1748-0221/20/03/C03035

We explore the use of gas-filled plasma-discharge capillaries for laser wakefield acceleration (LWFA) by employing a hybrid system that integrates an external high-voltage source to driven an electrical discharge, generate plasma within the capillary channel before to the main laser pulse. The process enhances plasma formation, boosts operational efficiency, and maintains laser intensity over multiple Rayleigh lengths, enabling high-energy electron acceleration. The electrical discharge creates a stable, uniform plasma environment, improving beam charge, energy stability, and reducing energy spread. This uniform plasma ensures better laser coupling and mitigates instabilities, leading to improved beam quality. This method supports efficient acceleration and the production of very-highenergy electron (VHEE) pencil beams (250 MeV) in a compact, cost-effective system designed for radiobiological studies at the future I-LUCE (INFN-Laser indUCEd Radiation Production) facility at the Istituto Nazionale di Fisica Nucleare-Laboratori Nazionali del Sud (INFN-LNS) in Catania, Italy. The system aims to generate high-energy electron beams tailored for VHEE and FLASH radiotherapy (FLASH-RT) applications. In this paper, we present simulations of capillaries performed using COMSOL Multiphysics software, where plasma density is obtained as a function of the applied voltage. We analyze plasma behavior under varying voltage and compare the results with experimental data, demonstrating the model's accuracy in predicting plasma characteristics and its potential to optimize discharge conditions.

Advanced plasma target from pre-ionized low-density foam for effective and robust direct laser acceleration of electrons

Rosmej, Olga N.; Gyrdymov, Mikhail; Andreev, Nikolay E.; Tavana, Parysatis; Popov, Vyacheslav; Borisenko, Nataliya G.; Gromov, Alexandr I.; Gus'kov, Sergey Yu.; Yakhin, Rafael; Vegunova, Galina A.; Bukharskii, Nikolai; Korneev, Philipp; Cikhardt, Jakub; Zaehter, Sero; Busch, Sebastian; Jacoby, Joachim; Pimenov, Vladimir G.; Spielmann, Christian; Pukhov, Alexander
HIGH POWER LASER SCIENCE AND ENGINEERING 13, e3 (FEB 2025)
https://doi.org/10.1017/hpl.2024.85

Low-density polymer foams pre-ionized by a well-controlled nanosecond pulse are excellent plasma targets to trigger direct laser acceleration (DLA) of electrons by sub-picosecond relativistic laser pulses. In this work, the influence of the nanosecond pulse on the DLA process is investigated. The density profile of plasma generated after irradiating foam with a nanosecond pulse was simulated with a two-dimensional hydrodynamic code, which takes into account the high aspect ratio of interaction and the microstructure of polymer foams. The obtained plasma density profile was used as input to the three-dimensional particle-in-cell code to simulate energy, angular distributions and charge carried by the directional fraction of DLA electrons. The modelling shows good agreement with the experiment and in general a weak dependence of the electron spectra on the plasma profiles, which contain a density up-ramp and a region of near-critical electron density. This explains the high DLA stability in pre-ionized foams, which is important for applications.

ELECTRON BEAM INJECTORS

Verification of electron beam alignment and optics for external off-axis injection in AWAKE Run 2b

van Gils, Nikita Z.; Turner, Marlene; Bencini, Vittorio; Bergamaschi, Michele; Ranc, Lucas; Pakuza, Collette; Pannell, Fern; Della Porta, Giovanni Zevi; Velotti, Francesco; Gerbershagen, Alexander; Gschwendtner, Edda
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH SECTION A-ACCELERATORS SPECTROMETERS DETECTORS AND ASSOCIATED EQUIPMENT 1072, 170204 (MAR 2025)
https://doi.org/10.1016/j.nima.2025.170204

The Advanced Wakefield Experiment (AWAKE) has the long term goal to accelerate electrons to particle physics relevant energies using self-modulated proton bunches as drivers in plasma. AWAKE is currently in its Run 2b (2023-2025), where the goal is to stabilise the wakefield amplitude after the saturation of the self-modulation process by introducing a plasma density step. To optimise witness electron injection, retractable YAG screens have been installed inside the vapour source. These screens enable, for the first time, direct measurements of electron bunch sizes at the injection location and estimates of the spatial overlap with the wakefields. This manuscript presents an overview of the upgraded experimental setup and measurements of the transverse distribution of the electron bunches, crucial for improved control over the injection process. Additionally, results show agreement between simulated and measured transverse bunch sizes and positions, and the influence of various factors (e.g., plasma density, electron bunch charge, and witness bunch timing) on the electron charge overlapping with the wakefields. Furthermore, alignment challenges as well as potential solutions are discussed.

Simulation study of high-quality electron beam injector for external injection of laser plasma wakefield acceleration

Liu, Lanxin; Zhong, Jianhua; Guan, Jiabao; Dai, Zeyi; Xia, Guoxing; Wang, Jike; Nie, Yuancun

NUCLEAR ENGINEERING AND TECHNOLOGY 57(7), 103531 (JUL 2025)
https://doi.org/10.1016/j.net.2025.103531

The laser wakefield acceleration (LWFA) with external injection requires high-quality, ultra-short electron bunches, which can be produced by using a photocathode injector based on the room-temperature RF electron gun. In this paper, the physics design of such a photocathode injector system is discussed for two operating modes: low charge (10 pC) and high charge (50 pC). The front end of the injector was optimized by combining the beam dynamics simulation software ASTRA with the multi-objective genetic algorithm NSGA-II. The downstream section was simulated using CSRtrack and ASTRA to optimize the magnetic chicane and match the Twiss parameters. A slit collimator was inserted in the middle of the chicane to filter part of the electrons, and hence shorten the bunch length and reduce the relative energy spread. The obtained beam parameters meet the requirements for an external injection of the LWFA, where the electrons can be further accelerated from 100 MeV to 1.5 GeV. Such a photocathode injector combined with the LWFA has the potential to be applied in the accumulation injection of a 1.5 GeV storage ring at Wuhan Advanced Light Source.

BEAM TRANSPORT

Development of a nonlinear plasma lens for achromatic beam transport

Drobniak, P.; Adli, E.; Anderson, H. Bergravf; Dyson, A.; Mewes, S. M.; Sjobak, K. N.; Thevenet, M.; Lindstrom, C. A.

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH SECTION A-ACCELERATORS SPECTROMETERS DETECTORS AND ASSOCIATED EQUIPMENT 1072, 170223 (MAR 2025)
https://doi.org/10.1016/j.nima.2025.170223

We introduce the new idea of a nonlinear active plasma lens, as part of a larger transport lattice for achromatic electron beam transport. The proposed implementation uses an external dipole magnet acting on a plasma and is motivated by 1D-hydrodynamic simulations. The manufactured design is presented, including its undergoing experimental characterisation on the CLEAR beam-line at CERN.

BEAMLINES & APPLICATIONS

Coherent frequency combs from electrons colliding with a laser pulse

Quin, Michael J.; Di Piazza, Antonino; Tamburini, Matteo
PLASMA PHYSICS AND CONTROLLED FUSION 67(5), 055008 (MAY 2025)
https://doi.org/10.1088/1361-6587/adc59c

Highly coherent and powerful light sources capable of generating soft x-ray frequency combs are essential for high precision measurements and rigorous tests of fundamental physics. In this work, we derive the analytical conditions required for the emission of coherent radiation from an electron beam colliding with a laser pulse, modeled as a plane wave. These conditions are applied in a series of numerical simulations, where we show that a soft x-ray frequency comb can be produced if the electrons are regularly-spaced and sufficiently monoenergetic. High quality beams of this kind may be produced in the near future from laser-plasma interactions or linear accelerators. Furthermore, we highlight the advantageous role of employing few-cycle laser pulses in relaxing the stringent monoenergeticity requirements for coherent emission. The conditions derived here can also be used to optimize coherent emission in other frequency ranges, such as the terahertz domain.

Generation of narrow-band low frequency radiation via laser-generated electron bunches and resonant cavities

Robinson, A. P. L.
PLASMA PHYSICS AND CONTROLLED FUSION 67(4), 045026 (APR 2025)
https://doi.org/10.1088/1361-6587/adbd74

It is shown that the single transit of a laser-generated electron bunch can generate strong, narrow-band radiation in a resonant cavity. This is shown numerically for an electron bunch relevant to those produced by laser wakefield acceleration. The bunch can also transit through two adjacent cavities and generate radiation in both. The phase relation between the radiation in the two cavities is well defined implying that coherent combination of radiation from multiple cavities is theoretically achievable.

Vacuum-plasma transition effect on positron acceleration in the bubble regime plasma wakefield accelerators

Wang, Jia; Zeng, Ming; Li, Dazhang; Gao, Jie
PHYSICAL REVIEW ACCELERATORS AND BEAMS 28(3), 031301 (MAR 2025)
https://doi.org/10.1103/PhysRevAccelBeams.28.031301

In recent years, the field of positron acceleration in plasma wakefield accelerators has witnessed rapid theoretical advancements, and several effective schemes have been proposed. In these studies, longitudinally uniform plasma is taken into account, with the positron beam located at the start of the second wakefield bubble. The electron filament near the positron beam provides Coulomb attraction force for the guiding of the positron beam. However, the influence of vacuum-plasma transition on positron beams has not been considered yet, where wakefield bubble is larger than that in the density plateau region, and the positron beam is in the defocusing region. In this paper, we study the evolution of positron beam size in the vacuum-plasma transition region and find out that the transition is detrimental to low-energy positron beams. Wide drive beams with relatively large transverse sizes are proposed as a possible solution to this difficulty.

Very High-Energy Electron Therapy Toward Clinical Implementation

Panaino, Costanza Maria Vittoria; Piccinini, Simona; Andreassi, Maria Grazia; Bandini, Gabriele; Borghini, Andrea; Borgia, Marzia; Di Naro, Angelo; Labate, Luca Umberto; Maggiulli, Eleonora; Portaluri, Maurizio Giovanni Agostino; Gizzi, Leonida Antonio
CANCERS 17(2), 181 (JAN 2025)
https://doi.org/10.3390/cancers17020181

The use of very high energy electron (VHEE) beams, with energies between 50 and 400 MeV, has drawn considerable interest in radiotherapy due to their deep tissue penetration, sharp beam edges, and low sensitivity to tissue density. VHEE beams can be precisely steered with magnetic components, positioning VHEE therapy as a cost-effective option between photon and proton therapies. However, the clinical implementation of VHEE therapy (VHEET) requires advances in several areas: developing compact, stable, and efficient accelerators; creating sophisticated treatment planning software; and establishing clinically validated protocols. In addition, the perspective of VHEE to access ultra-high dose-rate regime presents a promising avenue for the practical integration of FLASH radiotherapy of deep tumors and metastases with VHEET (FLASH-VHEET), enhancing normal tissue sparing while maintaining the inherent dosimetric advantages of VHEET. However, FLASH-VHEET systems require validation of time-dependent dose parameters, thus introducing additional technological challenges. Here, we discuss recent progress in VHEET research, focusing on both conventional and FLASH modalities, and covering key aspects including dosimetric properties, radioprotection, accelerator technology, beam focusing, radiobiological effects, and clinical outcomes. Furthermore, we comprehensively analyze initial VHEET in silico studies on coverage across various tumor sites.

THEORY & SIMULATION

Computational methods for focused arbitrary laser fields in plasma simulations

Charbonnet, K. J.; Nelson, E. C.; Reutershan, T.; Barty, C. P. J.
PHYSICS OF PLASMAS 32(4), 043901 (APR 2025)
https://doi.org/10.1063/5.0250718

An open-source code, arbitrary laser fields for particle-in-cell (ALFP), is provided to enable the use of accurately focused arbitrary beam structures in particle-in-cell (PIC) simulations, and is used to demonstrate the utility of space-time coupled beams for ion acceleration. ALFP provides significant flexibility for simulating focused beams with complex space, time, and polarization couplings in PIC simulations. This facilitates exploration of laser-matter interactions beyond the standard Gaussian laser pulse interaction. Additionally, polychromatic focusing effects that are often left out of analytic formulations are included. ALFP is first verified against theory, both directly with its computed output field and with 3D PIC simulations. Then ALFP is used to simulate space-time coupled beams in laser-matter interaction 2D PIC simulations, revealing improvements in ion collimation. (c) 2025 Author(s).

Control of instability in a Vlasov-Poisson system through an external electric field

Einkemmer, Lukas; Li, Qin; Mouhot, Clement; Yue, Yukun
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Plasma instabilities are a major concern in plasma science, for applications ranging from particle accelerators to nuclear fusion reactors. In this work, we consider the possibility of controlling such instabilities by adding

an external electric field to the Vlasov-Poisson equations. Our approach to determining the external electric field is derived from a linear analysis that examines the revised dispersion relation. Allowing the external electric field to depend on time and space, we show that it is possible to completely suppress the plasma instabilities when the equilibrium distribution and the perturbation are known, with one particular choice of external field turning the system back to free-streaming. Numerical simulations of the nonlinear two-stream and bump-on-tail instabilities verify our theory and demonstrate the effectiveness of the few choices of external electric field that we derive.

Declustering of macroparticles in long-term simulations of plasma wakefield acceleration

Kargapolov, I. Yu.; Okhotnikov, N. V.; Shalimova, I. A.; Sosedkin, A. P.; Lotov, K. V.
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A recently developed three-dimensional version of the quasistatic code LCODE has a novel feature that enables high-accuracy simulations of the long-term evolution of waves in plasma wakefield accelerators. Equations of plasma particle motion are modified to suppress clustering and numerical heating of macroparticles, which otherwise occur because the Debye length is not resolved by the numerical grid. The previously observed effects of premature wake chaotization and wavebreaking disappear with the modified equations. C2025 Author(s).

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