CONTENTS

FUNDAMENTALS

Emittance preservation in a plasma-wakefield accelerator

Lindstrom, C. A.; Beinortaite, J.; Svensson, J. Bjoerklund; Boulton, L.; Chappell, J.; Diederichs, S.; Foster, B.; Garland, J. M.; Caminal, P. Gonzalez; Loisch, G.; Pena, F.; Schroeder, S.; Thevenet, M.; Wesch, S.; Wing, M.; Wood, J. C.; D'Arcy, R.; Osterhoff, J.

NATURE COMMUNICATIONS 15(1), 6097 (JUL 2024)
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Radio-frequency particle accelerators are engines of discovery, powering high-energy physics and photon science, but are also large and expensive due to their limited accelerating fields. Plasma-wakefield accelerators (PWFAs) provide orders-of-magnitude stronger fields in the charge-density wave behind a particle bunch travelling in a plasma, promising particle accelerators of greatly reduced size and cost. However, PWFAs can easily degrade the beam quality of the bunches they accelerate. Emittance, which determines how tightly beams can be focused, is a critical beam quality in for instance colliders and free-electron lasers, but is particularly prone to degradation. We demonstrate, for the first time, emittance preservation in a high-gradient and high-efficiency PWFA while simultaneously preserving charge and energy spread. This establishes that PWFAs can accelerate without degradation-an essential step toward energy boosters in photon science and multistage facilities for compact high-energy particle colliders. High beam quality is key for particle-accelerator applications in high-energy physics and photon science. Here, authors demonstrate gigavolt-per meter acceleration of electron bunches in a plasma-wakefield accelerator with no degradation of emittance, while also preserving charge and energy spread.

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

Verra, L.; Galletti, M.; Pompili, R.; Biagioni, A.; Carillo, M.; Cianchi, A.; Crincoli, L.; Curcio, A.; Demurtas, F.; Di Pirro, G.; Lollo, V.; Parise, G.; Pellegrini, D.; Romeo, S.; Silvi, G. J.; Villa, F.; Ferrario, M.
PHYSICAL REVIEW LETTERS 133(3), 035001 (JUL 2024)
https://doi.org/10.1103/PhysRevLett.133.035001

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Zepp, M.; Granetzny, M.; Schmitz, O.

PHYSICS OF PLASMAS 31(7), 070704 (JUL 2024)

https://doi.org/10.1063/5.0211109

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

Energy stabilization of high-charge bunches from laser plasma accelerators

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

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

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

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

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

On the energy spectrum evolution of electrons undergoing radiation cooling

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

Radiative cooling of electron beams interacting with counter-propagating electromagnetic waves is analyzed, taking into account the quantum modification of the radiation friction force. Central attention is paid to the evolution of the energy spectrum of electrons accelerated by the laser wake field acceleration mechanism.

As an electron beam loses energy to radiation, the mean energy decreases and the form of the energy distribution also changes due to quantum-mechanical spectral broadening.

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

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

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

Diagnostics

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

Laberge, Maxwell; Bowers, Brant; Chang, Yen-Yu; Cabadag, Jurjen Couperus; Debus, Alexander; Hannasch, Andrea; Pausch, Richard; Schoebel, Susanne; Tiebel, Jessica; Ufer, Patrick; Willmann, Anna; Zarini, Omid; Zgadzaj, Rafal; Lumpkin, Alex H.; Schramm, Ulrich; Irman, Arie; Downer, M. C.
NATURE PHOTONICS 18(9) (SEP 2024)
https://doi.org/10.1038/s41566-024-01475-2

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

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

Ma, Y.; Cardarelli, J. A.; Campbell, P. T.; Fourmaux, S.; Fitzgarrald, R.; Balcazar, M. D.; Antoine, A. F.; Beier, N. F.; Qian, Q.; Hussein, A. E.; Kettle, B.; Klein, S. R.; Krushelnick, K.; Li, Y. F.; Mangles, S. P. D.; Sarri, G.; Seipt, D.; V. Senthilkumaran, V.; Streeter, M. J. V.; Willingale, L.; Thomas, A. G. R.
PHYSICAL REVIEW LETTERS 132(22), 225001 (MAY 2024)
https://doi.org/10.1103/PhysRevLett.132.225001

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

Selective electron beam sensing through coherent Cherenkov diffraction radiation

Senes, E.; Krupa, M.; Mazzoni, S.; Lasocha, K.; Lefevre, T.; Shloegelhofer, A.; Wendt, M.; Davut, C.; Karataev, P.; Pakuza, C.; Spear, B.
PHYSICAL REVIEW RESEARCH 6(2), 023278 (JUN 2024)
https://doi.org/10.1103/PhysRevResearch.6.023278

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

Advanced Diagnostics of Electrons Escaping from Laser-Produced Plasma

Krasa, Josef; Krupka, Michal; Agarwal, Shubham; Nassisi, Vincenzo; Singh, Sushil
PLASMA 7(2), 366-385 (JUN 2024)
https://doi.org/10.3390/plasma7020021

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

Plasma structures

Resonant excitation of plasma waves in a plasma channel

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

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

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

Zhao, Yujian; Hildebrand, Lance; An, Weiming; Xu, Xinlu; Li, Fei; Dalichaouch, Thamine N.; Su, Qianqian; Joshi, Chan; Mori, Warren B.
PHYSICS OF PLASMAS 31(6), 063106 (JUN 2024)
https://doi.org/10.1063/5.0206378

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

Instabilities

Filamentation of a relativistic proton bunch in plasma

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

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

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

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

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

BEAMLINES & APPLICATIONS

Guiding of Charged Particle Beams in Curved Plasma-Discharge Capillaries

Pompili, R.; Anania, M. P.; Biagioni, A.; Carillo, M.; Chiadroni, E.; Cianchi, A.; Costa, G.; Curcio, A.; Crincoli, L.; Del Dotto, A.; Del Giorno, M.; Demurtas, F.; Frazzitta, A.; Galletti, M.; Giribono, A.; Lollo, V.; Opromolla, M.; Parise, G.; Pellegrini, D.; Di Pirro, G.; Romeo, S.; Rossi, A. R.; Silvi, G. J.; Verra, L.; Villa, F.; Zigler, A.; Ferrario, M.
PHYSICAL REVIEW LETTERS 132(21), 215001 (MAY 2024)
https://doi.org/10.1103/PhysRevLett.132.215001

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

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

Pompili, R.; Anania, M. P.; Biagioni, A.; Carillo, M.; Chiadroni, E.; Cianchi, A.; Costa, G.; Curcio, A.; Crincoli, L.; Del Dotto, A.; Del Giorno, M.; Demurtas, F.; Galletti, M.; Giribono, A.; Lollo, V.; Opromolla, M.; Parise, G.; Pellegrini, D.; Di Pirro, G.; Romeo, S.; Silvi, G. J.; Verra, L.; Villa, F.; Zigler, A.; Ferrario, M.
PHYSICAL REVIEW E 109(5), 055202 (MAY 2024)
https://doi.org/10.1103/PhysRevE.109.055202

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

Plasma-based particle sources

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

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

X rays

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

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

REVIEWS OF MODERN PLASMA PHYSICS 8(1), 24 (JUN 2024)
https://doi.org/10.1007/s41614-024-00158-3

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

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

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

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The long proton beams present at CERN have the potential to evolve into a train of microbunches through the self-modulation instability process. The resonant wakefield generated by a periodic train of proton microbunches can establish a high acceleration field within the plasma, facilitating electron acceleration. This paper investigates the impact of plasma density on resonant wakefield excitation, thus influencing the acceleration of a witness electron bunch and its corresponding betatron radiation within the wakefield. Various scenarios involving different plasma densities are explored through particle-in-cell simulations. The peak wakefield in each scenario is calculated by considering a long pre-modulated proton driver with a fixed peak current. Subsequently, the study delves into the witness beam acceleration in the peak wakefield and

its radiation emission. Elevated plasma density increases both the number of microbunches and the accelerating gradient of each microbunch, consequently resulting in heightened resonant wakefield. Nevertheless, the scaling is disrupted by the saturation of the resonant wakefield due to the nonlinearities. The simulation results reveal that at high plasma densities, an intense and broadband radiation spectrum extending into the domain of the hard x-rays and gamma rays is generated. Furthermore, in such instances, the energy gain of the witness beam is significantly enhanced. The impact of wakefield on the witness energy gain and the corresponding radiation spectrum is clearly evident at elevated densities. (c) 2024 Author(s).

Free Electron Lasers

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

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

FACILITIES

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

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

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

Storey, D.; Zhang, C.; Claveria, P. San Miguel; Cao, G. J.; Adli, E.; Alsberg, L.; Ariniello, R.; Clarke, C.; Corde, S.; Dalichaouch, T. N.; Doss, C. E.; Ekerfelt, H.; Emma, C.; Gerstmayr, E.; Gessner, S.; Gilljohann, M.; Hast, C.; Knetsch, A.; Lee, V.; Litos, M.; Loney, R.; Marsh, K. A.; Matheron, A.; Mori, W. B.; Nie, Z.; O'Shea, B.; Parker, M.; White, G.; Yocky, G.; Zakharova, V.; Hogan, M. J.; Joshi, C.
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Plasma wakefield acceleration provides ultrahigh acceleration gradients of tens of GeV/m, providing a novel path toward efficient, compact, TeV-scale linear colliders, and high brightness free electron lasers. Critical to the success of these applications is demonstrating simultaneously high gradient acceleration, high energy transfer efficiency, and preservation of emittance, charge, and energy spread. Experiments at the FACET-II National User Facility at SLAC National Accelerator Laboratory aim to achieve all of these milestones in a single-stage plasma wakefield accelerator, providing a 10 GeV energy gain in a < 1 m plasma with high energy transfer efficiency. Such a demonstration depends critically on diagnostics able to measure emittance with mm mrad accuracy, energy spectra to determine both percent level energy spread, and broadband energy gain and loss, incoming longitudinal phase space, and matching dynamics. This paper discusses the experimental setup at FACET-II, including the incoming beam parameters from the FACET-II linac, plasma sources, and diagnostics developed to meet this challenge. Initial progress on the generation of beam ionized wakes in meter-scale hydrogen gas is discussed as well as commissioning of the plasma sources and diagnostics.

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

Zhang, Chaojie; Storey, Doug; Claveria, Pablo San Miguel; Nie, Zan; Marsh, Ken A.; Mori, Warren B.; Adli, Erik; An, Weiming; Ariniello, Robert; Cao, Gevy J.; Clark, Christine; Corde, Sebastien; Dalichaouch, Thamine; Doss, Christopher E.; Emma, Claudio; Ekerfelt, Henrik; Gerstmayr, Elias; Gessner, Spencer; Hansel, Claire; Knetsch, Alexander; Lee, Valentina; Li, Fei; Litos, Mike; OShea, Brendan; White, Glen; Yocky, Gerry; Zakharova, Viktoriia; Hogan, Mark; Joshi, Chan
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This study documents several correlations observed during the first run of the plasma wakefield acceleration experiment E300 conducted at FACET-II, using a single drive electron bunch. The established correlations include those between the measured maximum energy loss of the drive electron beam and the integrated betatron X-ray signal, the calculated total beam energy deposited in the plasma and the integrated X-ray signal, among three visible light emission measuring cameras and between the visible plasma light and X-ray signal. The integrated X-ray signal correlates almost linearly with both the maximum energy loss of the drive beam and the energy deposited into the plasma, demonstrating its usability as a measure of energy transfer from the drive beam to the plasma. Visible plasma light is found to be a useful indicator of the presence of a wake at three locations that overall are two metres apart. Despite the complex dynamics and vastly different time scales, the X-ray radiation from the drive bunch and visible light emission from the plasma may prove to be effective non-invasive diagnostics for monitoring the energy transfer from the beam to the plasma in future high-repetition-rate experiments.

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

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

Experimental capabilities of the LMJ-PETAL facility

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

INSTRUMENTATION

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

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

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

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

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