ISSUE 1 March 2023

FOREWORD

Welcome to the first issue of ***WAKE up***, the new quarterly newsletter for the partners and friends of AWAKE-UK. ***WAKE up*** is a collection of publicly available abstracts of published articles that are relevant to the AWAKE project. Putting together the latest research in plasma accelerators, the aim is to facilitate the work of the researchers involved in AWAKE-UK and to highlight the scientific outcomes of the project. We hope you find it useful.

CONTENTS

RESEARCH HIGHLIGHTS

Paving the Way for Next-Generation X-Ray Sources

To build powerful but small particle accelerators, one requires both strong accelerating fields and particles in the right place at the right time.

Previously, it was shown that it is possible to inject resting electrons into a plasma structure smaller than the width of a hair travelling at the speed of light. Now, a team of researchers led by Prof Peter Norreys from the University of Oxford, have demonstrated how to switch off this injection process in a controlled manner enabling clean electron beams which may be accelerated over greater distances than previously feasible.

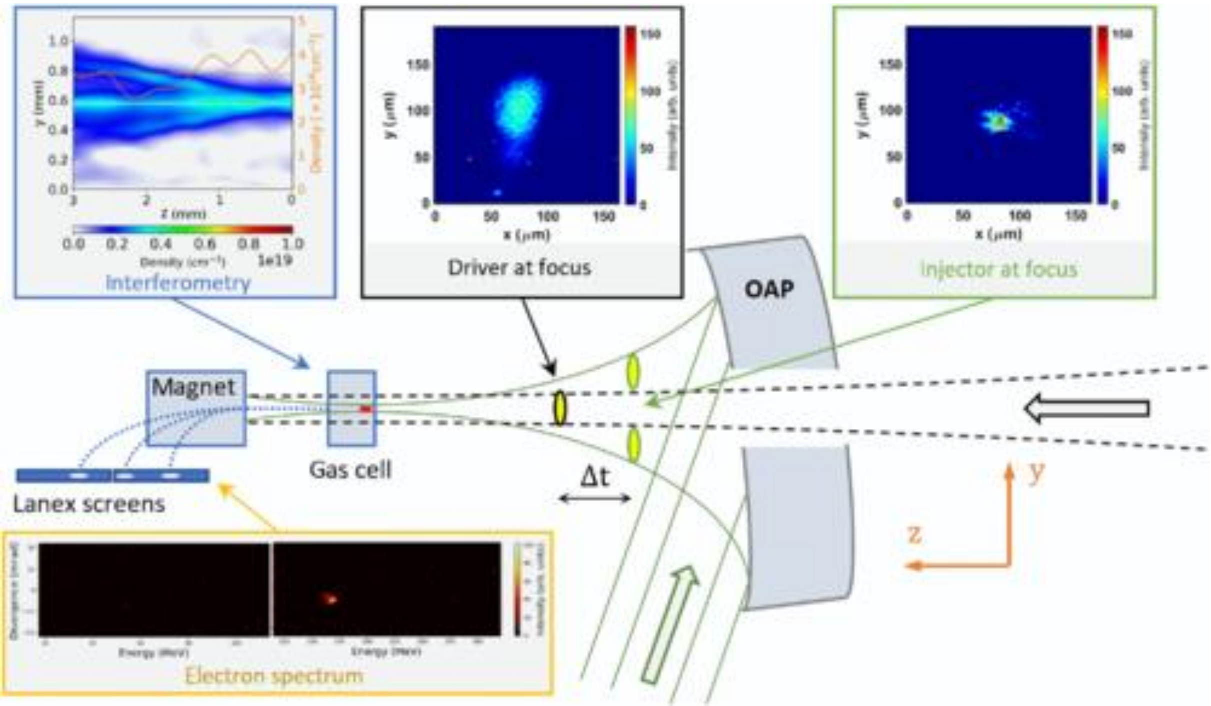
X-Rays have served humanity greatly allowing to penetrate materials and image them – be it in medical, industrial or security applications. Detecting foreign objects in human tissue, micro-cracks in metals or sharp objects in suitcases is part of our everyday lives. However, there is a limitation to the detail that can be achieved, which greatly corresponds to the quality of the X-Rays.

Generating even brighter bursts of high-energy X-Rays in a narrow energy band requires precise control over the acceleration of charged particles which are the source of the radiation. Laser-driven plasma accelerators offer a promising route to unprecedented electric fields, dramatically reducing the cost and footprint of accelerators.

In an article published in Physical Review Letters, Norreys and collaborators show that the particles to be accelerated can be trapped in the accelerating wave in a controlled way. They do this by using two ultra-short co-propagating laser pulses of different diffraction lengths, separating the trapping process from the creation of an accelerating micro-structure. This allows for generating electron bunches with narrow energy spread that can be guided over great distances enabling next-generation accelerators.

Full article:

M.W. von der Leyen et al., "Observation of Monoenergetic Electrons from Two-Pulse Ionization Injection in Quasilinear Laser Wakefields", PHYSICAL REVIEW LETTERS 130, 105002 (2023)



Schematic of the experimental setup in the target chamber. The drive beam path is depicted as a dashed black line. The annular injector beam path is depicted as a green line. Both pulses travel through the gas cell from the right-hand side to the left-hand side. The red area in the gas cell indicates the volume of injection. The blue dashed lines represent possible electron trajectories. (Image reproduced from the original article under Creative Commons Attribution 4.0 International license)

BEAMLINES & APPLICATIONS

Observation of Monoenergetic Electrons from Two-Pulse Ionization Injection in Quasilinear Laser Wakefields

von der Leyen, M. W.; Holloway, J.; Ma, Y.; Campbell, P. T.; Aboushelbaya, R.; Qian, Q.; Antoine, A. F.; Balcazar, M.; Cardarelli, J.; Feng, Q.; Fitzgarrald, R.; Hou, B. X.; Kalinchenko, G.; Latham, J.; Maksimchuk, A. M.; McKelvey, A.; Nees, J.; Ouatu, I.; Paddock, R. W.; Spiers, B.; Thomas, A. G. R.; Timmis, R.; Krushelnick, K.; Norreys, P. A.

PHYSICAL REVIEW LETTERS 130, 105002 (2023)
https://doi.org/10.1103/PhysRevLett.130.105002

The generation of low emittance electron beams from laser-driven wakefields is crucial for the development of compact x-ray sources. Here, we show new results for the injection and acceleration of quasimonoenergetic electron beams in low amplitude wakefields experimentally and using simulations. This is achieved by using two laser pulses decoupling the wakefield generation from the electron trapping via ionization injection. The injection duration, which affects the beam charge and energy spread, is found to be tunable by adjusting the relative pulse delay. By changing the polarization of the injector pulse, reducing the ionization volume, the electron spectra of the accelerated electron bunches are improved.

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

Liu, Wei-Yuan; Xue, Kun; Wan, Feng; Chen, Min; Li, Jian-Xing; Liu, Feng; Weng, Su-Ming; Sheng, Zheng-Ming; Zhang, Jie

PHYSICAL REVIEW RESEARCH 4(2), L022028 (2022)
https://doi.org/10.1103/PhysRevResearch.4.L022028

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

Positron driven high-field terahertz waves via dielectric wakefield interaction

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

PHYSICAL REVIEW RESEARCH 4(2), 023065 (2022)
https://doi.org/10.1103/PhysRevResearch.4.023065

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

Plasma-based positron sources at EuPRAXIA

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

FACILITIES

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

Ramjiawan, R.; Doebert, S.; Farmer, J.; Gschwendtner, E.; Velotti, F. M.; Verra, L.; Della Porta, G. Zevi; Bencini, V; Burrows, P. N.

PHYSICAL REVIEW ACCELERATORS AND BEAMS 25(10), 101602 (2022)
https://doi.org/10.1103/PhysRevAccelBeams.25.101602

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

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

Svensson, J. Bjoerklund; Andersson, J.; Ferri, J.; Charles, T. K.; Ekerfelt, H.; Mansten, E.; Thorin, S.; Lundh, O.

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH SECTION A-ACCELERATORS; SPECTROMETERS DETECTORS AND ASSOCIATED EQUIPMENT 1033, 166591 (2022)
https://doi.org/10.1016/j.nima.2022.166591

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

Characterisation and optimisation of targets for plasma wakefield acceleration at SPARC_LAB

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

PLASMA PHYSICS AND CONTROLLED FUSION 64(4), 044012 (2022)
https://doi.org/10.1088/1361-6587/ac5477

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

Facilities in Asia for future accelerator development

Kando, M.; Hosokai, T.; Kim, K. Y.; Tang, C.
JOURNAL OF INSTRUMENTATION 17(6), T06001 (2022)
https://doi.org/10.1088/1748-0221/17/06/T06001

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

Towards a PWFA linear collider – opportunities and challenges

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

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

US advanced and novel accelerator beam test facilities

Clarke, C.; Esarey, E.; Geddes, C.; Hofstaetter, G.; Hogan, M. J.; Nagaitsev, S.; Palmer, M.; Piot, P.; Power, J.; Schroeder, C.; Umstadter, D.; Vafaei-Najafabadi, N.; Valishev, A.; Willingale, L.; Yakimenko, V
JOURNAL OF INSTRUMENTATION 17(5), T05009 (2022)
https://doi.org/10.1088/1748-0221/17/05/T05009

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

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

Jing, C.; Ha, G.
JOURNAL OF INSTRUMENTATION 17(5), T05007 (2022)
https://doi.org/10.1088/1748-0221/17/05/T05007

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

Emittance preservation in advanced accelerators

Lindstrom, C. A.; Thevenet, M.
JOURNAL OF INSTRUMENTATION 17(5) (2022)
https://doi.org/10.1088/1748-0221/17/05/P05016

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

European facilities for advanced accelerators development

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

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

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

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

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

The AWAKE Run 2 Programme and Beyond

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

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

FUNDAMENTS

Recovery time of a plasma-wakefield accelerator

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

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

Direct observation of relativistic broken plasma waves

Wan, Yang; Seemann, Omri; Tata, Sheroy; Andriyash, Igor A.; Smartsev, Slava; Kroupp, Eyal; Malka, Victor

NATURE PHYSICS 18(10), 1186 (2022)
https://doi.org/10.1038/s41567-022-01717-6

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

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

Li, F.; Dalichaouch, T. N.; Pierce, J. R.; Xu, X.; Tsung, F. S.; Lu, W.; Joshi, C.; Mori, W. B.

PHYSICAL REVIEW LETTERS 128(17), 174803 (2022)
https://doi.org/10.1103/PhysRevLett.128.174803

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

Controlled Growth of the Self-Modulation of a Relativistic Proton Bunch in Plasma

Verra, L. et al. (AWAKE Collaboration)

PHYSICAL REVIEW ACCELERATORS AND BEAMS 25(7), 024802 (2022)
https://doi.org/10.1103/PhysRevLett.129.024802

A long, narrow, relativistic charged particle bunch propagating in plasma is subject to the self -modulation (SM) instability. We show that SM of a proton bunch can be seeded by the wakefields driven by a preceding electron bunch. SM timing reproducibility and control are at the level of a small fraction of the modulation period. With this seeding method, we independently control the amplitude of the seed wakefields with the charge of the electron bunch and the growth rate of SM with the charge of the proton bunch. Seeding leads to larger growth of the wakefields than in the instability case.

Plasma photonic spatiotemporal synchronization of relativistic electron and laser beams

Scherkl, P.; Knetsch, A.; Heinemann, T.; Sutherland, A.; Habib, A. F.; Karger, O. S.; Ullmann, D.; Beaton, A.; Manahan, G. G.; Xi, Y.; Deng, A.; Litos, M. D.; O'Shea, B. D.; Green, S. Z.; Clarke, C., I; Andonian, G.; Assmann, R.; Bruhwiler, D. L.; Smith, J.; Cary, J. R.; Hogan, M. J.; Yakimenko, V; Rosenzweig, J. B.; Hidding, B.

PHYSICAL REVIEW ACCELERATORS AND BEAMS 25(5), 052803 (2022)
https://doi.org/10.1103/PhysRevAccelBeams.25.052803

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

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

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

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

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

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

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

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

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

Evolution of equilibrium particle beams in plasma under external wakefields

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PLASMA PHYSICS AND CONTROLLED FUSION 64(7), 075003 (2022)

https://doi.org/10.1088/1361-6587/ac6ffe

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

Ion dynamics driven by a strongly nonlinear plasma wake

Khudiakov, V. K.; Lotov, K., V; Downer, M. C.

PLASMA PHYSICS AND CONTROLLED FUSION 64(4), 045003 (2022)

https://doi.org/10.1088/1361-6587/ac4523

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

Stable electron beam propagation in a plasma column

Diederichs, S.; Benedetti, C.; Esarey, E.; Thevenet, M.; Osterhoff, J.; Schroeder, C. B.
PHYSICS OF PLASMAS 29(4), 043101 (2022)
https://doi.org/10.1063/5.0087807

The stability of plasma-based accelerators against transverse misalignments and asymmetries of the drive beam is crucial for their applicability. Without stabilizing mechanisms, even small initial offsets of the drive beam centroid can couple coherently to the plasma wake, grow, and ultimately lead to emittance degradation or beam loss for a trailing witness beam. In this work, we demonstrate the intrinsic stability of a beam propagating in a plasma column. This result is relevant in the context of plasma-based positron acceleration, where a wakefield suitable for the transport and acceleration of a positron witness beam is generated in a plasma column by means of an electron drive beam. The stable propagation of the drive beam is a necessary condition for the experimental implementation of this scheme. The differences and similarities of stabilizing mechanisms in a plasma column compared to a homogeneous plasma are identified via theory and particle-in-cell simulations. Experimental tolerances are given, demonstrating the experimental feasibility of the scheme. (C) 2022 Author(s).

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

Liang, Linbo; Xia, Guoxing; Pukhov, Alexander; Farmer, John Patrick
APPLIED SCIENCES-BASEL 12(21), 10919 (2022)
https://doi.org/10.3390/app122110919

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

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

Simakov, E., I; Andonian, G.; Baturin, S. S.; Manwani, P.
JOURNAL OF INSTRUMENTATION 17(5), P05013 (2022)
https://doi.org/10.1088/1748-0221/17/05/P05013

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

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

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

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

INSTRUMENTATION

Cherenkov Radiation in Optical Fibres as a Versatile Machine Protection System in Particle Accelerators

Wolfenden, J.; Alexandrova, A. S.; Jackson, F.; Mathisen, S.; Morris, G.; Pacey, T. H.; Kumar, N.; Yadav, M.; Jones, A.; Welsch, C. P.
Sensors 23(4), 2248 (2023)
https://doi.org/10.3390/s23042248

Machine protection systems in high power particle accelerators are crucial. They can detect, prevent, and respond to events which would otherwise cause damage and significant downtime to accelerator infrastructure. Current systems are often resource heavy and operationally expensive, reacting after an event has begun to cause damage; this leads to facilities only covering certain operational modes and setting lower limits on machine performance. Presented here is a new type of machine protection system based upon optical fibres, which would be complementary to existing systems, elevating existing performance. These fibres are laid along an accelerator beam line in lengths of ∼100 m, providing continuous coverage over this distance. When relativistic particles pass through these fibres, they generate Cherenkov radiation in the optical spectrum. This radiation propagates in both directions along the fibre and can be detected at both ends. A calibration based technique allows the location of the Cherenkov radiation source to be pinpointed to within 0.5 m with a resolution of 1 m. This measurement mechanism, from a single device, has multiple applications within an accelerator facility. These include beam loss location monitoring, RF breakdown prediction, and quench prevention. Detailed here are the application processes and results from measurements, which provide proof of concept for this device for both beam loss monitoring and RF breakdown detection. Furthermore, highlighted are the current challenges for future innovation.

High-resolution, low-latency, bunch-by-bunch feedback system for nanobeam stabilization

Bett, D. R.; Kraljevic, N. Blaskovic; Bromwich, T.; Burrows, P. N.; Christian, G. B.; Perry, C.; Ramjiawan, R.
PHYSICAL REVIEW ACCELERATORS AND BEAMS 25(2), 022801 (2022)
https://doi.org/10.1103/PhysRevAccelBeams.25.022801

We report the design, operation, and performance of a high-resolution, low-latency, bunch-by-bunch feedback system for nanobeam stabilization. The system employs novel, ultralow quality-factor cavity beam position monitors (BPMs), a two-stage analog signal down-mixing system, and a digital signal processing and feedback board incorporating a field-programmable gate array. The field-programmable gate array firmware allows for the real-time integration of up to fifteen samples of the BPM waveforms within a measured latency of 232 ns. We show that this real-time sample integration improves significantly the beam position resolution and, consequently, the feedback performance. The best demonstrated real-time beam position resolution was 19 nm, which, as far as we are aware, is the best real-time resolution achieved in any operating BPM system. The feedback was operated in two complementary modes to stabilize the vertical position of the ultrasmall beam produced at the focal point of the ATF2 beamline at KEK. In single-BPM feedback mode, beam stabilization to 50 ± 5 nm was demonstrated. In two-BPM feedback mode, beam stabilization to 41 ± 4 nm was achieved.

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

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

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

THEORY & SIMULATION

Spatiotemporal dynamics of ultrarelativistic beam-plasma instabilities

Claveria, P. San Miguel; Davoine, X.; Peterson, J. R.; Gilljohann, M.; Andriyash, I; Ariniello, R.; Clarke, C.; Ekerfelt, H.; Emma, C.; Faure, J.; Gessner, S.; Hogan, M. J.; Joshi, C.; Keitel, C. H.; Knetsch, A.; Kononenko, O.; Litos, M.; Mankovska, Y.; Marsh, K.; Matheron, A.; Nie, Z.; O'Shea, B.; Storey, D.; Vafaei-Najafabadi, N.; Wu, Y.; Xu, X.; Yan, J.; Zhang, C.; Tamburini, M.; Fiuza, F.; Gremillet, L.; Corde, S.
PHYSICAL REVIEW RESEARCH 4(2), 023085 (2022)
https://doi.org/10.1103/PhysRevResearch.4.023085

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

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

Wan, Jinyu; Jiao, Yi
FRONTIERS OF PHYSICS 17(6), 64601 (2022)
https://doi.org/10.1007/s11467-022-1205-y

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

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

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

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

Lattice Boltzmann simulations of plasma wakefield acceleration

Parise, G.; Cianchi, A.; Del Dotto, A.; Guglietta, F.; Rossi, A. R.; Sbragaglia, M.

PHYSICS OF PLASMAS 29(4), 043903 (2022)
https://doi.org/10.1063/5.0085192

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

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

Zoni, Edoardo; Lehe, Remi; Shapoval, Olga; Belkin, Daniel; Zaim, Neil; Fedeli, Luca; Vincenti, Henri; Vay, Jean-Luc

COMPUTER PHYSICS COMMUNICATIONS 279, 108457 (2022)
https://doi.org/10.1016/j.cpc.2022.108457

Electromagnetic particle-in-cell (PIC) codes are widely used to perform computer simulations of a variety of physical systems, including fusion plasmas, astrophysical plasmas, plasma wakefield particle accelerators, and secondary photon sources driven by ultra-intense lasers. In a PIC code, Maxwell's equations are solved on a grid with a numerical method of choice. This article focuses on pseudo-spectral analytical time-domain (PSATD) algorithms and presents a novel hybrid PSATD PIC scheme that combines the respective advantages of standard nodal and staggered methods. The novelty of the hybrid scheme consists in using finite-order centering of grid quantities between nodal and staggered grids, in order to combine the solution of

Maxwell's equations on a staggered grid with the deposition of charges and currents and the gathering of electromagnetic forces on a nodal grid. The correctness and performance of the novel hybrid scheme are assessed by means of numerical tests that employ different classes of PSATD equations in a variety of physical scenarios, ranging from the modeling of electron-positron pair creation in vacuum to the simulation of laser-driven and particle beam-driven plasma wakefield acceleration. It is shown that the novel hybrid scheme offers significant numerical and computational advantages, compared to purely nodal or staggered methods, for all the test cases presented. (C) 2022 The Authors. Published by Elsevier B.V.

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

Diederichs, S.; Benedetti, C.; Huebl, A.; Lehe, R.; Myers, A.; Sinn, A.; Vay, J. -l.; Zhang, W.; Thevenet, M.
COMPUTER PHYSICS COMMUNICATIONS 278, 108421 (2022)
https://doi.org/10.1016/j.cpc.2022.108421

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

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

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

High fidelity modeling of plasma based acceleration (PBA) requires the use of three dimensional, fully nonlinear, and kinetic descriptions based on the particle-in-cell (PIC) method. In PBA an intense particle beam or laser (driver) propagates through a tenuous plasma whereby it excites a plasma wave wake. Three-dimensional PIC algorithms based on the quasi-static approximation (QSA) have been successfully applied to efficiently model the interaction between relativistic charged particle beams and plasma. In a QSA PIC algorithm, the plasma response to a charged particle beam or laser driver is calculated based on forces from the driver and self-consistent forces from the QSA form of Maxwell's equations. These fields are then used to advance the charged particle beam or laser forward by a large time step. Since the time step is not limited by the regular Courant-Friedrichs-Lewy (CFL) condition that constrains a standard 3D fully electromagnetic PIC code, a 3D QSA PIC code can achieve orders of magnitude speedup in performance. Recently, a new hybrid QSA PIC algorithm that combines another speedup technique known as an azimuthal Fourier decomposition has been proposed and implemented. This hybrid algorithm decomposes the electromagnetic fields, charge and current density into azimuthal harmonics and only the Fourier coefficients need to be updated, which can reduce the algorithmic complexity of a 3D code to that of a 2D code. Modeling the laser-plasma interaction in a full 3D electromagnetic PIC algorithm is very computationally expensive due the enormous disparity of physical scales to be resolved. In the QSA the laser is modeled using the ponderomotive guiding

center (PGC) approach. We describe how to implement a PGC algorithm compatible for the QSA PIC algorithms based on the azimuthal mode expansion. This algorithm permits time steps orders of magnitude larger than the cell size and it can be asynchronously parallelized. Details on how this is implemented into the QSA PIC code that utilizes an azimuthal mode expansion, QPAD, are also described. Benchmarks and comparisons between a fully 3D explicit PIC code (OSIRIS), as well as a few examples related to laser wakefield acceleration, are presented.

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

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

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

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

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EUROPEAN PHYSICAL JOURNAL PLUS 137(4), 506 (2022)
https://doi.org/10.1140/epjp/s13360-022-02645-3

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

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

Akhter, Tahmina; Fedele, Renato; De Nicola, Sergio; Jovanovic, Dusan; Fiore, Gaetano

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

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

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

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

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

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

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