WAKE up

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RESEARCH HIGHLIGHTS

AWAKE accelerator upgrade gets a head start

AWAKE has become the first facility to pause operations for CERN's third long shutdown (LS3). While most of CERN's accelerator complex will enter LS3 in mid-2026, AWAKE ended operations on 1 June 2025 to begin a series of significant improvements.

In its initial 2016 – 2018 run, AWAKE became the first experiment in the world to demonstrate that electrons could be accelerated to multi-GeV energy levels in a wakefield driven by protons, rather than electrons or a laser. The first phase of its second run, which began in 2021 and ended on 1 June this year, showed how proton bunches drive and maintain high-amplitude wakefields over the entire 10-metre-long plasma medium. Project leader Edda Gschwendtner explained, "when the proton beam enters the plasma it starts to self-modulate, meaning it produces small bunches that resonantly drive strong wakefields".

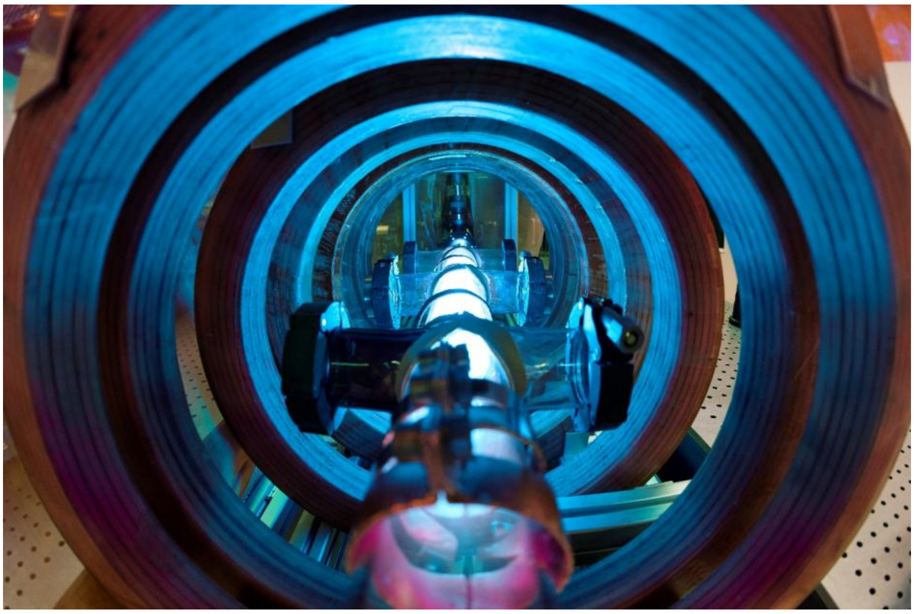
Researchers now want to show that the quality of the electron beam can be controlled while the electrons are accelerated to a high energy and that this process is scalable. To facilitate this, AWAKE needs to be upgraded, including through the installation of a new electron beam system and an additional plasma source. The first plasma source will act as the self-modulator of the proton beam and the second will accelerate externally injected electrons in the proton-driven plasma wakefields to 4-10 GeV over 10 metres.

Increasing the size of AWAKE to incorporate these changes is challenging as it is located upstream of a chamber previously used by the CERN Neutrinos to Gran Sasso (CNGS) experiment. CNGS involved directing an SPS proton beam onto a graphite target to produce a neutrino beam that was sent towards the Gran Sasso laboratory in Italy.

This process made the target and its shielding material highly radioactive, so their dismantling and removal requires dedicated protection measures. The complex process is now under way to make room for the expanded AWAKE experiment, and a new building to store the dismantled CNGS material has already been constructed.

To spread the demands on CERN's workforce, the dismantling and removal process is scheduled to be largely completed before other experiments enter LS3 in July 2026. The improved version of AWAKE will then be constructed before the start of the SPS proton run in 2029, when tests of the new set-up will commence. AWAKE's goal, to accelerate particles to far higher energies over a far shorter distance, will then be one step closer to realisation.

(Original article by Emma Hattersley, taken from https://home.cern/news/news/accelerators/awake-accelerator-upgrade-gets-head-start)



The AWAKE helicon plasma cell prototype as a candidate for scalable plasma sources. (Image: CERN)

FUNDAMENTALS

Generation and Acceleration of Isolated- Attosecond Electron Bunch via Phase-Compressed Injection

Zhang, Liang-Qi; Si, Mei-Yu; Yu, Tong-Pu; Bi, Yuan-Jie; Huang, Yong-Sheng
ULTRAFAST SCIENCE 5, 0101 (JUN 2025)
https://doi.org/10.34133/ultrafastscience.0101

We propose a novel scheme for generating and accelerating simultaneously a dozen-GeV isolated attosecond electron bunch via phase-compressed injection in a radiative-wakefield-breaking process from an electron beam-driven hollow-channel plasma target. During the beam-target interaction, transverse oscillations of plasma electrons are induced, and subsequently, a radiative wakefield is generated. Meanwhile, a large number of plasma electrons of close to the speed of light are injected transversely toward the center of the hollow channel from the position of the transverse electric field of radiative wakefield, forming an isolated attosecond electron bunch due to the phase compression in the radiative-wakefield-breaking process. The injected attosecond electron bunch is then located just in the acceleration phase of the longitudinal electric field of the radiative wakefield and is importantly accelerated to high energies by the radiative wakefield. It is demonstrated theoretically and numerically that this scheme can efficiently generate an isolated attosecond electron bunch with a charge of more than 2 nC, a peak energy up to 13 GeV of more than 2 times that of the driving electron beam, a peak divergence angle of less than 5 mrad, a duration of 276 as, and an energy conversion efficiency of 36.7% as well as a high stability as compared with the laser-beam drive case. Such an isolated attosecond electron bunch in the range of GeV would provide critical applications in ultrafast physics and high-energy physics.

Study of nonlinear theory refinements for small plasma bubbles

Yan, Jiayang; Jain, Arohi; Zhang, Xuan; Vafaei-Najafabadi, Navid
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH SECTION A-ACCELERATORS; SPECTROMETERS DETECTORS AND ASSOCIATED EQUIPMENT 1079, 170602 (OCT 2025)
https://doi.org/10.1016/j.nima.2025.170602

Beam-driven plasma wakefield accelerators (PWFAs) have demonstrated exceptionally high acceleration gradients, reaching GV/m in the nonlinear blowout regime. While the well-established nonlinear theory provides accurate approximations for bubble structure, wake potential, and the longitudinal electric field near the bubble center, it is primarily suited for large plasma bubbles. However, this approximation becomes less accurate for small-radius bubbles ($k_p R_b < 4$, where k_p is the plasma wavenumber and Rb is the maximum plasma bubble radius). This proceeding presents a modified model tailored for small-radius plasma bubbles, informed by simulation studies. The proposed corrections are compared with Particle-In-Cell (PIC) simulations, focusing on bubbles with $k_p R_b < 4$. The refined model is further applied to calculate witness beam profiles that enabling complete beam loading in small bubbles.

PLASMA TECHNOLOGY & DIAGNOSTICS

Exploration of helicon plasmas for wakefield accelerators at the Madison AWAKE prototype

Granetzny, Marcel; Elward, Barret; Zepp, Michael; Loughan, Maxwell; Schmitz, Oliver
PHYSICS OF PLASMAS 32(9), 093507 (SEP 2025)
https://doi.org/10.1063/5.0267516

Plasma wakefield accelerators have the potential to revolutionize particle physics by providing collision energies orders of magnitude beyond current technology. Crucially, these accelerators require a high-density, highly homogeneous, scalable plasma source. The Madison AWAKE Prototype (MAP) is a new plasma development platform that has been built as part of CERN's beam-driven wakefield accelerator project AWAKE. MAP uses a dual helicon antenna setup with up to 20 kW of RF power to create plasmas in a highly uniform 47 mT magnetic field. The project is supported by a range of diagnostics that allow non-invasive measurements of plasma density, ion and neutral flows, and temperatures, and a 3D finite element model that can calculate helicon wavefield and power deposition patterns. In this paper, we present an in-depth overview of MAP's design and construction principles and main physics results. We show that the plasma discharge direction is set by the combination of antenna helicity and field direction and linked to the well-known preference for right-handed helicon modes. We find that the plasma density depends dramatically on the relative directions of plasma and neutral flows and can reach densities of 6×10^{19} m^{-3} at RF power levels as low as 2 kW. A detailed measurement of the ionization source rate distribution reveals that most of the plasma is fueled radially by recycling at the wall, a finding with strong implications for optimizing plasma homogeneity. Finally, we describe how helicon antennas can be engineered to optimize power coupling for a given target density. Together, these findings pave the way toward the practical use of helicon plasmas in wakefield accelerators. (c) 2025 Author(s).

Implementation of light diagnostics for wakefields at AWAKE

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

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

High-precision alpha spectroscopy using sCVD diamond detectors

Divya; Melbinger, Julian; Griesmayer, Erich; Weiss, Christina; Hainz, Dieter
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH SECTION A-ACCELERATORS SPECTROMETERS DETECTORS AND ASSOCIATED EQUIPMENT 1080, 170664 (NOV 2025)
https://doi.org/10.1016/j.nima.2025.170664

Single-crystal chemical vapor deposition (sCVD) diamond detectors are known for their high radiation tolerance and excellent performance at elevated temperatures. sCVD diamond sensors are promising candidates for particle spectroscopy in harsh radiation environments. In this study, we present the energy resolution of sCVD diamond detector. Alpha spectroscopy, a reliable technique for detector calibration is performed. The measurements were conducted in a vacuum environment using an ^{241}Am alpha-particle source and CIVIDEC's high-resolution data acquisition system, ROSY (R) AX106. Geant4 simulations were performed to study the factors contributing to the energy resolution of sCVD diamond detectors.

Fully plasma-based electron injector for a linear collider or XFEL

Dalichaouch, T. N.; Xu, X. L.; Li, F.; Tsung, F. S.; Mori, W. B.
PHYSICAL REVIEW RESEARCH 7(2), 023118 (MAY 2025)
https://doi.org/10.1103/PhysRevResearch.7.023118

We demonstrate through high-fidelity particle-in-cell (PIC) simulations a simple approach for efficiently generating 20+ GeV electron beams with the necessary charge, energy spread, and emittance for use as an injector in a future linear collider or a next generation XFEL. A high quality injected bunch is generated by self-focusing an unmatched electron driver in a nonlinear plasma wakefield. Over pump depletion distances, the drive beam dynamics and self-loading effects lead to high energy, low-energy spread output beams. For plasma densities of 10^{18} cm^{-3}, PIC simulation results indicate that self-injected beams with 0.52 nC charge can be accelerated to 20 GeV with projected core energy spreads of < 1%, normalized slice emittances of 110 nm, peak normalized brightness of >10^{19} A/m^2/rad^2, and transfer efficiencies of >44%.

Three-dimensional beam size compression for external injection of plasma wakefield acceleration

Shi, Xueyan; Ma, Ande; Li, Dazhang; Wang, Yiwei; Xu, Haisheng
RADIATION DETECTION TECHNOLOGY AND METHODS (JUL 2025)
https://doi.org/10.1007/s41605-025-00584-y

Plasma acceleration is a novel acceleration principle characterized by a high acceleration gradient. This area has garnered extensive research interest from major accelerator laboratories worldwide because of its potential to increase accelerator energy and reduce accelerator size. Currently, using existing conventional accelerators as external injectors for plasma-based accelerators is a promising direction that has attracted notable interest from the research community. However, a critical challenge is matching the three-dimensional beam sizes produced by conventional radio-frequency (RF) accelerators to the plasma accelerating structures. This alignment is crucial for utilizing existing non-state-of-the-art accelerators in plasma-based acceleration research. For instance, the BEPCII linac generates beams with transverse sizes approximately one millimeter and longitudinal sizes around ten picoseconds, while plasma accelerating structures are typically on the order of hundreds of micrometers. Addressing this mismatch is essential for advancing plasma acceleration research. In our recent work at BEPCII, we tackled the challenge of transporting both electron and positron beams from an RF linac into the plasma.

We adopted an innovative design concept that decouples longitudinal and transverse beam size compression, implementing them in separate stages. For transverse beam size compression, we utilized a global optimization method that balances the nominal beta functions with chromatic aberrations at the interaction point and provides self-compensation for chromatic aberrations along the beamline.

By using this approach, we developed a beam transport line for BEPCII that achieves a tenfold compression of the three-dimensional beam sizes produced by the conventional accelerator.

This paper presents our design concept and the resulting transport line design, demonstrating its effectiveness in addressing the beam size matching challenge for plasma acceleration.

BEAMLINES & APPLICATIONS

The positron arm of a plasma-based linear collider

Joshi, Chandrashekhar; Mori, Warren B.; Hogan, Mark J.
NATURE PHYSICS 21(6), 885-894 (JUN 2025)
https://doi.org/10.1038/s41567-025-02910-z

Plasma-based acceleration of electrons has produced high-energy beams at high accelerating gradients with a narrow energy spread and high efficiency both in experiments and simulations. It is now being considered as a complementary approach to the use of radiofrequency cavities in next-generation lepton accelerators. However, compared with electrons, plasma-based positron acceleration is at the present time much less advanced. Although high-gradient positron acceleration in a plasma has been achieved, we are one to three orders of magnitude away from delivering the high-quality positron beams needed for a future high-energy linear collider. Here we review the status of plasma-based acceleration of electrons and positrons and discuss the prospects for substantial progress towards developing the positron arm of a plasma-based electron-positron linear collider in the next decade.

Biological applications at the AQUA beamline of the EuPRAXIA@SPARC_LAB free electron laser

Santis, Emiliano De; Andre, Tomas; Alleva, Stefania; Bean, Richard; Ferrario, Massimo; Marcelli, Augusto; Minicozzi, Velia; Principi, Emiliano; Timneanu, Nicusor; Caleman, Carl; Stellato, Francesco
EUROPEAN BIOPHYSICS JOURNAL (JUL 2025)
https://doi.org/10.1007/s00249-025-01778-4

The EuPRAXIA project is a European initiative aimed at developing groundbreaking, ultra-compact accelerator research infrastructures based on novel plasma acceleration concepts. The EuPRAXIA@SPARC_LAB facility, located in the Italian National Institute for Nuclear Physics-Frascati National Laboratory, will be the first operating Free Electron Laser facility of EuPRAXIA, based on an accelerator module driven by an electron bunch driver. The Free Electron Laser will produce ultra-short photon pulses in the soft X-ray region. The photons will be delivered to an endstation, called AQUA, to perform a wide range of experiments in atomic and molecular physics, chemistry, and life sciences for both academic and industrial users. Thanks to its wavelength, which falls within the so-called 'water window', AQUA will be particularly well-suited for coherent imaging and ion spectroscopy measurements on biological samples at room temperature in a fully hydrated environment. This unique capability opens up innovative experimental schemes for studying biological systems in states that closely resemble their physiological conditions. This paper presents numerical simulations of coherent diffraction imaging and Coulomb explosion imaging experiments, anticipating future studies at AQUA on biological samples.

THEORY & SIMULATION

Ten-moment fluid modeling of the Weibel instability

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JOURNAL OF PLASMA PHYSICS 91(2), E66 (APR 2025)
https://doi.org/10.1017/S0022377825000303

We investigate the one-dimensional non-relativistic Weibel instability through the capture of anisotropic pressure tensor dynamics using an implicit 10-moment fluid model that employs the electromagnetic Darwin approximation. The results obtained from the 10-moment model are compared with an implicit particle-in-cell simulation. The linear growth rates obtained from the numerical simulations are in good agreement with the theoretical fluid and kinetic dispersion relations. The fluid dispersion relations are derived using Maxwell's equations and the Darwin approximation. We also show that the magnetohydrodynamic approximation can be used to model the Weibel instability if one accounts for an anisotropic pressure tensor and unsteady terms in the generalised Ohm's law. In addition, we develop a preliminary theory for the saturation magnetic field strength of the Weibel instability, showing good agreement with the numerical results.

A particle-based field ionization algorithm in quasi-static PIC codes

Tang, Rong; An, Weiming; Wang, Jianzhao; Meng, Weiyu; Wang, Hainan; Zhong, Jiayong; Zhao, Yujian; Li, Fei; Su, Qianqian; Hildebrand, Lance; Dalichaouch, Thamine N.; Decyk, Viktor K.; Mori, Warren B.
PLASMA PHYSICS AND CONTROLLED FUSION 67(7), 075001 (JUL 2025)
https://doi.org/10.1088/1361-6587/ade3ff

Particle-in-cell (PIC) simulation code, especially the quasi-static PIC code, has been an indispensable tool to the development of the plasma wake field accelerator (PWFA). Such an advanced accelerator scheme uses a drive particle beam or a laser pulse to generate wake fields inside a plasma for accelerating another particle beam. The acceleration gradient can be 10 GeV m^{-1} or higher in the PWFA, which makes it a promising candidate as the main acceleration method in the future high energy electron-positron colliders or x-ray free electron laser facilities. In the plasma wake field acceleration, the plasma can be generated by ionizing the neutral gas with the Coulomb field around the particle beam or the electric field of the laser pulse. Therefore, the field ionization process plays a key role in the plasma wake field acceleration experiments. The 3D PIC code QuickPIC, which is based on the quasi-static approximation, has been widely used for efficiently modeling the PWFA problems including the field ionization process. However, the current field ionization algorithm in QuickPIC cannot simulate mobile ions. In this work, we developed a particle-based ionization method in order to track the motion of ions that generated during the ionization process. We also implement the new algorithm in another quasi-static PIC code QPAD, which additionally applied the azimuthal Fourier decomposition method compared with QuickPIC. The comparison of simulation results between the old and new algorithm and between QuickPIC and QPAD are presented. The comparison shows that for the plasma wake field acceleration simulation without the plasma ion motion, the particle-based method works as well as the old algorithm in both codes of QuickPIC and QPAD. When including the mobile ions in the field ionized plasma, QuickPIC and QPAD with the particle-based method show a well agreement with each other.

Neural-network-based longitudinal electric field prediction in nonlinear plasma wakefield accelerators

Wang, Xiaoning; Zeng, Ming; Li, Dazhang; An, Weiming; Lu, Wei
PLASMA PHYSICS AND CONTROLLED FUSION 67(5), 055038 (MAY 2025)
https://doi.org/10.1088/1361-6587/add052

Plasma wakefield acceleration holds remarkable promise for future advanced accelerators. The design and optimization of plasma-based accelerators typically require particle-in-cell simulations, which can be computationally intensive and time consuming. In this study, we train a neural network model to obtain the on-axis longitudinal electric field distribution directly without conducting particle-in-cell simulations for designing a two-bunch plasma wakefield acceleration stage. By combining the neural network model with an advanced algorithm for achieving the minimal energy spread, the optimal normalized charge per unit length of a trailing beam leading to the optimal beam-loading can be quickly identified. This approach can reduce computation time from around 7.6 min in the case of using particle-in-cell simulations to under 0.1 s. Moreover, the longitudinal electric field distribution under the optimal beam-loading can be visually observed. Utilizing this model with the beam current profile also enables the direct extraction of design parameters under the optimal beam-loading, including the maximum decelerating electric field within the drive beam, the average accelerating electric field within the trailing beam and the transformer ratio. This model has the potential to significantly improve the efficiency of designing and optimizing the beam-driven plasma wakefield accelerators.

Toward intelligent control of MeV electrons and protons from kHz repetition rate ultra-intense laser interactions

Tamminga, Nathaniel; Feister, Scott; Frische, Kyle D.; Desai, Ronak; Snyder, Joseph; Felice, John J.; Smith, Joseph R.; Orban, Chris; Chowdhury, Enam A.; Dexter, Michael L.; Patnaik, Anil K.
APL MACHINE LEARNING 3(2), 026115 (JUN2025)
https://doi.org/10.1063/5.0253529

Ultra-intense laser-matter interactions are often difficult to predict from first principles because of the complexity of plasma processes and the many degrees of freedom relating to the laser and target parameters. An important approach to controlling and optimizing ultra-intense laser interactions involves gathering large datasets and using these data to train statistical and machine learning models. In this paper, we describe experimental efforts to accelerate electrons and protons to ~ MeV energies with this goal in mind. These experiments involve a 1 kHz repetition rate ultra-intense laser system with ~ 10 mJ per shot, a peak intensity near 5 x 10^{18} W/cm^2, and a "liquid leaf" target. Improvements to the data acquisition capabilities of this laser system greatly aided this investigation. Generally, we find that the trained models were very effective in controlling the numbers of MeV electrons ejected. The models were less successful at shifting the energy range of ejected electrons. Simultaneous control of the numbers of ~ MeV electrons and the energy range will be the subject of future experimentation using this platform.

***WAKE up* is a collection of publicly available abstracts from published papers that are relevant to the AWAKE project.**

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