THE EuPRAXIA FILES

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Foreword

Dr Ralph Aßmann
EuPRAXIA Coordinator

Welcome to the fourth issue of *The EuPRAXIA Files*. The publication rate of EuPRAXIA is gaining momentum. As you will see in this newsletter, six new articles have been published by participants of the EuPRAXIA collaboration in the last four months, including a Nature Communications and a PRL. The first collaboration week of EuPRAXIA, recently held at DESY, showed the excellent progress made in all the work packages towards the realization of a 5 GeV plasma accelerator with industrial beam quality.

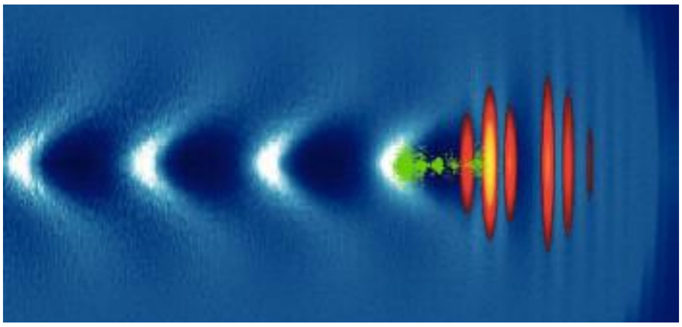
The abstracts reproduced here report the latest advances on injection schemes, laser sources and plasma structures, as well as novel diagnositics and applications. Experimental and theoretical results showing the generation of high quality electron beams, with high stability, narrow energy spread, high current, and high repetition rate, demonstrate that the goals of EuPRAXIA are within reach.

Research Highlights

Laser wakefield acceleration at high repetition rate

A group from the University of Paris-Saclay led by Jerome Faure has made a significant step towards the development of a practical and reliable laser wakefield accelerator.

The researchers used single-cycle laser pulses to drive high-quality MeV relativistic electron beams, producing not only extremely short electron pulses but also at a high repetition rate. The new system is also based on commercially available laser technology.



Simulation of the electron density (blue), the laser intensity (red) and the relativistic electrons (green). (Image: D. Guenot *et al.*, NPG)

According to Faure, their own laser system occupied two optical tables but there are already compact laser systems with the same characteristics which could reduce this size to a half.

The laser pulses had an energy of 2.1 millijoule and a duration of 3.4 femtoseconds. Such ultrashort pulses have inherently a large spectral bandwidth which results in considerable dispersion effects. The researchers introduced a positive chirp in the pulse in order to compensate for the plasma dispersion and reach higher intensities. This increased the amplitude of the plasma waves and thus the energy as well as the number of electrons per pulse.

The laser beam was focused to an intensity of about 3×10^{18} W/cm^2 on a continuously flowing stream of nitrogen with a diameter of 100 micrometers. The spatial divergence of the generated electron beams was about 45 millirad and the pointing stability of the beam was high, with measured fluctuations of only a few millirad. The charge per pulse, depended on the electron density and could be varied with the distance between the focus of the laser and the gas nozzle. Measurements yielded values between 0.5 and 1 picocoulomb. The spectral distribution of the electrons had a width of about 3 MeV, assuming a peak of 5 MeV.

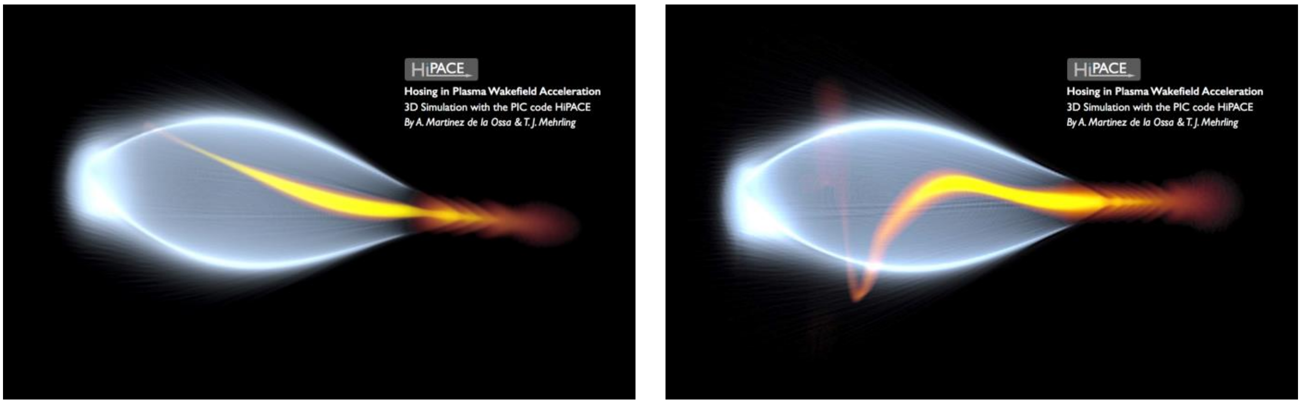
Although the 5 MeV electrons achieved by Faure and colleagues are far from the 5 GeV target of EuPRAXIA, extending laser-plasma acceleration to higher repetition rates would be extremely useful for applications requiring lower electron energy.

Journal reference:
D. Guenot *et al.*, "Relativistic electron beams driven by kHz single-cycle light pulses", Nat. Photonics 11(5), 293-296 (2017)
http://doi.org/10.1038/nphoton.2017.46

Mitigation of the Hose Instability in Plasma-Wakefield Accelerators

A team composed of EuPRAXIA members from IST (Instituto Superior Técnico) in Portugal and DESY in Germany has recently proposed a solution for a long-standing challenge for plasma based accelerators, initially posed in the early 90s. According to the previous scientific perception, plasma accelerators driven by relativistic and intense electron bunches are intrinsically unstable owing to a process known as the hose instability. This instability amplifies small transverse asymmetries of the setup until the beam breaks up. As a result, the hose instability inhibits the acceleration of particles to the energy frontier in plasma wakefield accelerators. By considering a generalised theoretical model, the EuPRAXIA team has now unraveled mechanisms which can intrinsically mitigate and damp the hose instability. The theoretical model, recently published in Physical Review Letters has successfully been compared to full scale three-dimensional simulations, and provides the first theoretical evidence for why hosing was never observed in experiments so far. The numerical simulations were performed on a local high-performance computer at IST (cluster accelerates) and on JUQUEEN, a supercomputer of the highest performance class in Jülich, Germany.

Journal reference:
T. J. Mehrling, R. A. Fonseca, A. Martínez de la Ossa, J. Vieira, "Mitigation of the Hose Instability in Plasma-Wakefield Accelerators", Phys. Rev. Lett. 8, 174801 (2017)
http://doi.org/10.1103/physrevlett.118.174801



Hosing in Plasma Wakefield Acceleration. 3D Simulation with the PIC code HiPACE by A. Martínez de la Ossa and T. J. Mehrling

Electron injection for high-quality wakefield accelerated beams

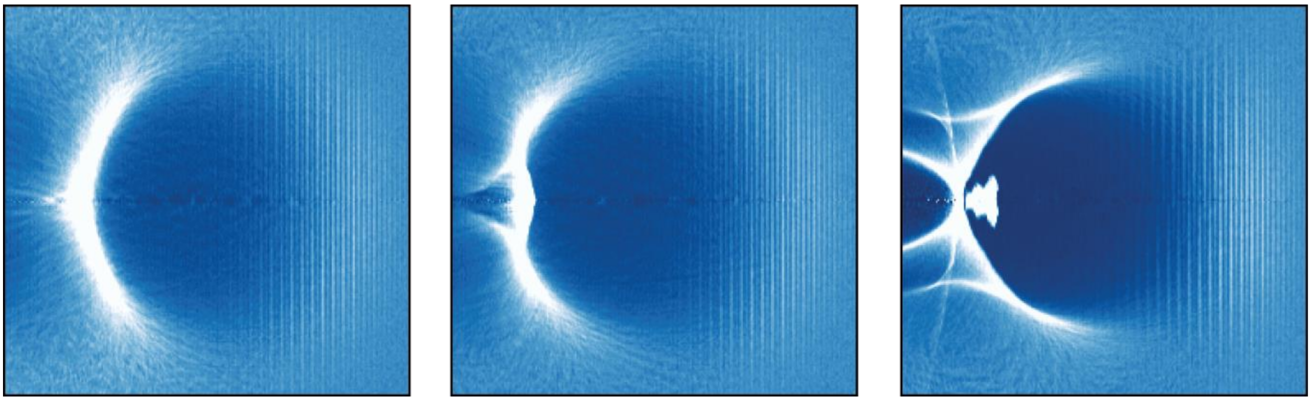
In the field of plasma acceleration, investigating how electron beams can be injected in a plasma wave is of critical importance, because the method used for this purpose strongly determines the final quality of the accelerated beams.

Thus, the laser wakefield acceleration community has always been very active in devising and demonstrating various injection techniques to obtain progressively improved beam qualities.

In a recent paper, Francesco Massimo and colleagues from Laboratoire d'Optique Appliquée (LOA) have presented a theoretical and numerical study on an injection scheme called density transition injection or shock-front injection.

This easy-to-implement scheme has already demonstrated experimentally to produce high quality electron beams. Electron injection is triggered by a sharp density transition (often called shock-front) created in a gas jet through a blade. As the laser passes the shock-front density peak, the wakefield electron cavity behind the laser pulse is enlarged, trapping some of the electrons from the density transition.

The investigation performed by LOA focuses on the beam quality dependence on the density transition characteristics and on the physical mechanisms involved in this injection technique. The beam qualities envisaged in this study make the shock-front injection an appealing option for the EuPRAXIA injector.



PIC simulation of the density transition injection process shown with snapshots of the electron density at time t = 0, t = 63 fs, and t = 1032 fs.

Journal reference:
F. Massimo *et al.*, “Numerical studies of density transition injection in laser wakefield acceleration”, Plasma Phys. Contr. Fusion 59, 085004 (2017)
http://doi.org/10.1088/1361-6587/aa717d

Research Papers

Single-stage plasma-based correlated energy spread compensation for ultrahigh 6D brightness electron beams

Manahan, G. G.; Habib, A. F.; Scherkl, P.; Delinikolas, P.; Beaton, A.; Knetsch, A.; Karger, O.; Wittig, G.; Heinemann, T.; Sheng, Z. M.; Cary, J. R.; Bruhwiler, D. L.; Rosenzweig, J. B.; Hidding, B.
NATURE COMMUNICATIONS 8, 15705 (JUN 2017)
http://doi.org/10.1038/ncomms15705

Plasma photocathode wakefield acceleration combines energy gains of tens of $GeVm^{-1}$ with generation of ultralow emittance electron bunches, and opens a path towards 5D-brightness orders of magnitude larger than state-of-the-art. This holds great promise for compact accelerator building blocks and advanced light sources. However, an intrinsic by-product of the enormous electric field gradients inherent to plasma accelerators is substantial correlated energy spread-an obstacle for key applications such as free-electron-lasers. Here we show that by releasing an additional tailored escort electron beam at a later phase of the acceleration, when the witness bunch is relativistically stable, the plasma wave can be locally overloaded without compromising the witness bunch normalized emittance. This reverses the effective accelerating gradient, and counter-rotates the accumulated negative longitudinal phase space chirp of the witness bunch. Thereby, the energy spread is reduced by an order of magnitude, thus enabling the production of ultrahigh 6D-brightness beams.

Relativistic electron beams driven by kHz single-cycle light pulses

Guenot, D.; Gustas, D.; Vernier, A.; Beaurepaire, B.; Boehle, F.; Bocoum, M.; Lozano, M.; Jullien, A.; Lopez-Martens, R.; Lifschitz, A.; Faure, J.
NATURE PHOTONICS 11(5), 293-296 (MAY 2017)
http://doi.org/10.1038/nphoton.2017.46

Laser-plasma acceleration is an emerging technique for accelerating electrons to high energies over very short distances. The accelerated electron bunches have femtosecond duration, making them particularly relevant for applications such as ultrafast imaging or femtosecond X-ray generation. Current laser-plasma accelerators deliver 100 MeV to GeV electrons using Joule-class laser systems that are relatively large in scale and have low repetition rates, with a few shots per second at best. Nevertheless, extending laser-plasma acceleration to higher repetition rates would be extremely useful for applications requiring lower electron energy. Here, we use single-cycle laser pulses to drive high-quality MeV relativistic electron beams, thereby enabling kHz operation and dramatic downsizing of the laser system. Numerical simulations indicate that the electron bunches are only ~ 1 fs long. We anticipate that the advent of these kHz femtosecond relativistic electron sources will pave the way to applications with wide impact, such as ultrafast electron diffraction in materials with an unprecedented sub-10 fs resolution.

Mitigation of the Hose Instability in Plasma-Wakefield Accelerators

Mehrling, T. J.; Fonseca, R. A.; de la Ossa, A. Martinez; Vieira, J.
PHYSICAL REVIEW LETTERS 8(17), 174801 (APR 2017)
http://doi.org/10.1103/physrevlett.118.174801

Current models predict the hose instability to crucially limit the applicability of plasma-wakefield accelerators. By developing an analytical model which incorporates the evolution of the hose instability over long propagation distances, this work demonstrates that the inherent drive-beam energy loss, along with an initial beam-energy spread, detunes the betatron oscillations of beam electrons and thereby mitigates the instability. It is also shown that tapered plasma profiles can strongly reduce initial hosing seeds. Hence, we demonstrate that the propagation of a drive beam can be stabilized over long propagation distances, paving the way for the acceleration of high-quality electron beams in plasma-wakefield accelerators. We find excellent agreement between our models and particle-in-cell simulations.

Observation of Betatron X-Ray Radiation in a Self-Modulated Laser Wakefield Accelerator Driven with Picosecond Laser Pulses

Albert, F.; Lemos, N.; Shaw, J. L.; Pollock, B. B.; Goyon, C.; Schumaker, W.; Saunders, A. M.; Marsh, K. A.; Pak, A.; Ralph, J. E.; Martins, J. L.; Amorim, L. D.; Falcone, R. W.; Glenzer, S. H.; Moody, J. D.; Joshi, C.
PHYSICAL REVIEW LETTERS 118(13), 134801 (MAR 2017)
http://doi.org/10.1103/physrevlett.118.134801

We investigate a new regime for betatron x-ray emission that utilizes kilojoule-class picosecond lasers to drive wakes in plasmas. When such laser pulses with intensities of $\sim 5 \times 10^{18}$ W/cm^2 are focused into plasmas with electron densities of $\sim 1 \times 10^{19}$ cm^{-3}, they undergo self-modulation and channeling, which accelerates electrons up to 200 MeV energies and causes those electrons to emit x rays. The measured x-ray spectra are fit with a synchrotron spectrum with a critical energy of 10-20 keV, and 2D particle-in-cell simulations were used to model the acceleration and radiation of the electrons in our experimental conditions.

Role of Direct Laser Acceleration of Electrons in a Laser Wakefield Accelerator with Ionization Injection

Shaw, J. L.; Lemos, N.; Amorim, L. D.; Vafaei-Najafabadi, N.; Marsh, K. A.; Tsung, F. S.; Mori, W. B.; Joshi, C.
PHYSICAL REVIEW LETTERS 118(6), 064801 (FEB 2017)
http://doi.org/10.1103/physrevlett.118.064801

We show the first experimental demonstration that electrons being accelerated in a laser wakefield accelerator operating in the forced or blowout regimes gain significant energy from both the direct laser acceleration (DLA) and the laser wakefield acceleration mechanisms. Supporting full-scale 3D particle-in-cell simulations elucidate the role of the DLA of electrons in a laser wakefield accelerator when ionization injection of electrons is employed. An explanation is given for how electrons can maintain the DLA resonance condition in a laser wakefield accelerator despite the evolving properties of both the drive laser and the electrons. The produced electron beams exhibit characteristic features that are indicative of DLA as an additional acceleration mechanism.

Generation of Ramped Current Profiles in Relativistic Electron Beams Using Wakefields in Dielectric Structures

Andonian, G.; Barber, S.; O'Shea, F. H.; Fedurin, M.; Kusche, K.; Swinson, C.; Rosenzweig, J. B.
PHYSICAL REVIEW LETTERS 118(5), 054802 (FEB 2017)
http://doi.org/10.1103/physrevlett.118.054802

Temporal pulse tailoring of charged-particle beams is essential to optimize efficiency in collinear wakefield acceleration schemes. In this Letter, we demonstrate a novel phase space manipulation method that employs a beam wakefield interaction in a dielectric structure, followed by bunch compression in a permanent magnet chicane, to longitudinally tailor the pulse shape of an electron beam. This compact, passive, approach was used to generate a nearly linearly ramped current profile in a relativistic electron beam experiment carried out at the Brookhaven National Laboratory Accelerator Test Facility. Here, we report on these experimental results including beam and wakefield diagnostics and pulse profile reconstruction techniques.

Three electron beams from a laser-plasma wakefield accelerator and the energy apportioning question

Yang, X.; Brunetti, E.; Gil, D. Reboredo; Welsh, G. H.; Li, F. Y.; Cipiccia, S.; Ersfeld, B.; Grant, D. W.; Grant, P. A.; Islam, M. R.; Tooley, M. P.; Vieux, G.; Wiggins, S. M.; Sheng, Z. M.; Jaroszynski, D. A.
SCIENTIFIC REPORTS 7, 43910 (MAR 2017)
http://doi.org/10.1038/srep43910

Laser-wakefield accelerators are compact devices capable of delivering ultra-short electron bunches with pC-level charge and MeV-GeV energy by exploiting the ultra-high electric fields arising from the interaction of intense laser pulses with plasma. We show experimentally and through numerical simulations that a high-energy electron beam is produced simultaneously with two stable lower-energy beams that are ejected in oblique and counter-propagating directions, typically carrying off 5-10% of the initial laser energy. A MeV, 10s nC oblique beam is ejected in a 30 degrees-60 degrees hollow cone, which is filled with more energetic electrons determined by the injection dynamics. A nC-level, 100s keV backward-directed beam is mainly produced at the leading edge of the plasma column. We discuss the apportioning of absorbed laser energy amongst the three beams. Knowledge of the distribution of laser energy and electron beam charge, which determine the overall efficiency, is important for various applications of laser-wakefield accelerators, including the development of staged high-energy accelerators.

Numerical studies of density transition injection in laser wakefield acceleration

F. Massimo, A. F. Lifschitz, C. Thaury, and V. Malka
PLASMA PHYSICS AND CONTROLLED FUSION 59, 085004 (JUN 2017)
http://doi.org/10.1088/1361-6587/aa717d

The quality of laser wakefield accelerated electrons beams is strongly determined by the physical mechanism exploited to inject electrons in the wakefield. One of the techniques used to improve the beam quality is the density transition injection, where the electron trapping occurs as the laser pulse passes a sharp density transition created in the plasma. Although this technique has been widely demonstrated experimentally, the literature lacks theoretical and numerical studies on the effects of all the transition parameters. We thus report and discuss the results of a series of particle in cell (PIC) simulations where the density transition height and downramp length are systematically varied, to show how the electron beam parameters and the injection mechanism are affected by the density transition parameters.

Influence of strong magnetic fields on laser pulse propagation in underdense plasma

Wilson, T. C.; Li, F. Y.; Weikum, M.; Sheng, Z. M.
PLASMA PHYSICS AND CONTROLLED FUSION 59(6), 065002 (JUN 2017)
http://doi.org/10.1088/1361-6587/aa6941

We examine the interaction between intense laser pulses and strongly magnetised plasmas in the weakly relativistic regime. An expression for the electron Lorentz factor coupling both relativistic and cyclotron motion nonlinearities is derived for static magnetic fields along the laser propagation axis. This is applied to predict modifications to the refractive index, critical density, group velocity dispersion and power threshold for relativistic self-focusing. It is found that electron quiver response is enhanced under right circularly-polarised light, decreasing the power threshold for various instabilities, while a dampening effect occurs under left circularly-polarised light, increasing the power thresholds. Derived theoretical predictions are tested by one-and three-dimensional particle-in-cell simulations.

Quasi-monoenergetic electron beams from a few-terawatt laser driven plasma acceleration using a nitrogen gas jet

Rao, B. S.; Moorti, A.; Chakera, J. A.; Naik, P. A.; Gupta, P. D.
PLASMA PHYSICS AND CONTROLLED FUSION 59(6), 065006 (JUN 2017)
http://doi.org/10.1088/1361-6587/aa69f3

An experimental investigation on the laser plasma acceleration of electrons has been carried out using 3 TW, 45 fs duration titanium sapphire laser pulse interaction with a nitrogen gas jet at an intensity of 2 x 10^{18} Wcm^{-2}. We have observed the stable generation of a well collimated electron beam with divergence and pointing variation ~ 10 mrad from nitrogen gas jet plasma at an optimum plasma density around 3 x 10^{19} cm^{-3}. The energy spectrum of the electron beam was quasi-monoenergetic with an average peak energy and a charge around 25 MeV and 30 pC respectively. The results will be useful for better understanding and control of ionization injection and the laser wakefield acceleration (LWFA) of electrons in high-Z gases and also towards the development of practical LWFA for various applications including injectors for high energy accelerators.

Measurements of ionization states in warm dense aluminum with betatron radiation

Mo, M. Z.; Chen, Z.; Fourmaux, S.; Saraf, A.; Kerr, S.; Otani, K.; Masoud, R.; Kieffer, J. -C.; Tsui, Y.; Ng, A.; Fedosejevs, R.
PHYSICAL REVIEW E 95(5), 053208 (MAY 2017)
http://doi.org/10.1103/physreve.95.053208

Time-resolved measurements of the ionization states of warm dense aluminum via K-shell absorption spectroscopy are demonstrated using betatron radiation generated from laser wakefield acceleration as a probe. The warm dense aluminum is generated by irradiating a free-standing nanofoil with a femtosecond optical laser pulse and was heated to an electron temperature of ~ 20-25 eV at a close-to-solid mass density. Absorption dips in the transmitted x-ray spectrum due to the Al^{4+} and Al^{5+} ions are clearly seen during the experiments. The measured absorption spectra are compared to simulations with various ionization potential depression models, including the commonly used Stewart-Pyatt model and an alternative modified Ecker-Kroll model. The observed absorption spectra are in approximate agreement with these models, though indicating a slightly higher state of ionization and closer agreement for simulations with the modified Ecker-Kroll model.

Production of high-angular-momentum electron beams in laser-plasma interactions

Ju, L. B.; Zhou, C. T.; Huang, T. W.; Jiang, K.; Zhang, H.; Wu, S. Z.; Qiao, B.; Ruan, S. C.
PHYSICAL REVIEW E 95(5), 053205 (MAY 2017)
http://doi.org/10.1103/physreve.95.053205

It was shown that in the interactions of ultra-intense circularly polarized laser pulse with the near-critical plasmas, the angular momentum can be transferred efficiently from the laser beam to electrons through the resonance acceleration process. The transferred angular momentum increases almost linearly with the acceleration time t_a when the electrons are resonantly accelerated by the laser field. In addition, it is shown analytically that the averaged angular momentum of electrons is proportional to the laser amplitude a_L, and the total angular momentum of the accelerated electron beam is proportional to the square of the laser amplitude a_L^2 for a fixed parameter of $n_e/(n_c\, a_L)$. These results are verified by three-dimensional particle-in-cell simulations. This regime provides an efficient and compact alternative for the production of high angular momentum electron beams, which may have many potential applications in condensed-matter spectroscopy, new electron microscopes, and bright x-ray vortex generation.

Large-charge quasimonoenergetic electron beams produced by off-axis colliding laser pulses in underdense plasma

Deng, Z. G.; Zhang, Z. M.; Zhang, B.; He, S. K.; Teng, J.; Hong, W.; Dong, K. G.; Wu, Y. C.; Zhu, B.; Gu, Y. Q.
PHYSICAL REVIEW E 95(2), 023206 (FEB 2017)
http://doi.org/10.1103/physreve.95.023206

Electrons can be efficiently injected into a plasma wave by colliding two counterpropagating laser pulses in a laser wakefield acceleration. However, the generation of a high-quality electron beam with a large charge is difficult in the traditional on-axis colliding scheme due to the growth of the electron beam duration coming from the increase of the beam charge. To solve this problem, we propose an off-axis colliding scheme, in which the collision point is away from the axis of the driver pulse. We show that the electrons injected from the off-axis region are highly concentered on the tail of the bubble even for a large trapped charge, thus feeling almost the same accelerating field. As a result, quasimonoenergetic electron beams with a large charge can be produced. The validity of this scheme is confirmed by both the particle-in-cell simulations and the Hamiltonian model. Furthermore, it is shown that a Laguerre-Gauss (LG) laser can be adopted as the injection pulse to realize the off-axis colliding injection in three dimensions symmetrically, which may be useful in simplifying the technical layout of the real experiment setup.

Enhancing the electron acceleration by a circularly polarized laser interaction with a cone-target with an external longitudinal magnetic field

Gong, J. X.; Cao, L. H.; Pan, K. Q.; Xiao, C. Z.; Wu, D.; He, X. T.
PHYSICS OF PLASMAS 24(3), 033103 (MAR 2017)
http://doi.org/10.1063/1.4977526

The propagation of left-hand (LH-) and right-hand (RH-) circularly polarized (CP) lasers and the accompanying generation of fast electrons in a magnetized cone-target with pre-formed plasmas are investigated. In this work, the strength of external magnetic field is comparable to that of the incident laser. Theoretical analyses indicate that the cut-off density of LH-CP laser is larger than that without an external magnetic field. When the external magnetic field normalized by the laser magnetic field is larger than the relativistic factor, the RH-CP laser will keep on propagating till the laser energy is depleted. The theoretical predictions are confirmed by two-dimensional particle-in-cell simulations. Simulation results show that in the presence of external longitudinal magnetic field, the energies and yields of fast electrons are greatly enhanced for RH-CP laser. Besides, the coupling efficiency of laser energy to energetic electrons for RH-CP laser is much higher than that for LH-CP laser and without external magnetic field. Furthermore, detailed simulation results perform an enhancement of the incident laser absorption with increasing external magnetic field. Published by AIP Publishing.

Simulation study of a passive plasma beam dump using varying plasma density

Hanahoe, Kieran; Xia, Guoxing; Islam, Mohammad; Li, Yangmei; Mete-Apsimon, Oznur; Hidding, Bernhard; Smith, Jonathan
PHYSICS OF PLASMAS 24(2), 023120 (FEB 2017)
http://doi.org/10.1063/1.4977449

A plasma beam dump uses the collective oscillations of plasma electrons to absorb the kinetic energy of a particle beam. In this paper, a modified passive plasma beam dump scheme is proposed using either a gradient or stepped plasma profile to maintain a higher decelerating gradient compared with a uniform plasma. The improvement is a result of the plasma wavelength change preventing the re-acceleration of low energy particles. Particle-in-cell simulation results show that both stepped and gradient plasma profiles can achieve improved energy loss compared with a uniform plasma for an electron bunch of parameters routinely achieved in laser wakefield acceleration. *Published by AIP Publishing.*

Generation of 20 kA electron beam from a laser wakefield accelerator

Li, Y. F.; Li, D. Z.; Huang, K.; Tao, M. Z.; Li, M. H.; Zhao, J. R.; Ma, Y.; Guo, X.; Wang, J. G.; Chen, M.; Hafz, N.; Zhang, J.; Chen, L. M.
PHYSICS OF PLASMAS 24(2), 023108 (FEB 2017)
http://doi.org/10.1063/1.4975613

We present the experimentally generated electron bunch from laser-wakefield acceleration (LWFA) with a charge of 620 pC and a maximum energy up to 0.6 GeV by irradiating 80 TW laser pulses at a 3mm Helium gas jet. The charge of injected electrons is much larger than the normal scaling laws of LWFA in bubble regime. We also got a quasi-monoenergetic electron beam with energy peaked at 249MeV and a charge of 68 pC with the similar laser conditions but lower plasma density. As confirmed by 2D particle-in-cell simulations, the boosted bunch charge is due to the continuous injection caused by the self-steepening and self-compression of a laser pulse. During the nonlinear evolution of the laser pulse, the bubble structure broadens and stretches, leading to a longer dephasing length and larger beam charge. *Published by AIP Publishing.*

Generation and evolution of magnetic field in the relativistic plasma following q-nonextensive distribution

Lin, Fu-Jun; Chen, Zong-Hua; Li, Xiao-Qing; Liao, Jing-Jing; Zhu, Yun
PHYSICS OF PLASMAS 24(2), 022120 (FEB 2017)
http://doi.org/10.1063/1.4976981

A GigaGauss quasi-steady magnetic field can be generated in astrophysical plasmas and laser-produced plasmas with high-frequency electromagnetic radiation through wave-wave and wave-particle interactions. A set of governing equations for this field are obtained in the plasma consisting of ultra-relativistic electrons following q-nonextensive distribution. The numerical results show that the initial field is unstable and can collapse to generate various spatially intermittent magnetic flux tubes. It can also be found that the behavior of the magnetic field is greatly dependent on the nonextensive index q, which may be helpful in understanding the magnetic turbulence. *Published by AIP Publishing.*

Wakefield evolution and electron acceleration in interaction of frequency-chirped laser pulse with inhomogeneous plasma

Rezaei-Pandari, M.; Niknam, A. R.; Massudi, R.; Jahangiri, F.; Hassaninejad, H.; Khorashadizadeh, S. M.
PHYSICS OF PLASMAS 24(2), 023112 (FEB 2017)
http://doi.org/10.1063/1.4976127

The nonlinear interaction of an ultra-short intense frequency-chirped laser pulse with an underdense plasma is studied. The effects of plasma inhomogeneity and laser parameters such as chirp, pulse duration, and intensity on plasma density and wakefield evolutions, and electron acceleration are examined. It is found that a properly chirped laser pulse could induce a stronger laser wakefield in an inhomogeneous plasma and result in higher electron acceleration energy. It is also shown that the wakefield amplitude is enhanced by increasing the slope of density in the inhomogeneous plasma.

External injection and acceleration of electron bunch in front of the plasma wakefield produced by a periodic chirped laser pulse

Eslami, Esmaeil; Afhami, Saeedeh
PHYSICS OF PLASMAS 24(1), 013110 (JAN 2017)
http://doi.org/10.1063/1.4973662

Herein, we present the analytical results on the behavior of the electron bunch injected in front of the plasma wakefield produced by a chirped laser pulse. In particular, a periodic chirped pulse may produce an ultra-relativistic electron bunch with a relatively small energy spread. The electrons are trapped near the region of the first accelerating maximum of the wakefield and are compressed in both the longitudinal and transverse directions (betatron oscillation). Our results are in good agreement with the one-dimensional results recently published. *Published by AIP Publishing.*

Trapping and acceleration of hollow electron and positron bunch in a quasi-linear donut wakefield

Firouzjaei, Ali Shekari; Shokri, Babak
PHYSICS OF PLASMAS 24(1), 013107 (JAN 2017)
http://doi.org/10.1063/1.4973598

We study the acceleration and trapping of both negative and positive charged particles in the quasi-linear donut wake (created by a Laguerre Gauss laser pulse). The motion of test charged particles is studied in a two-dimensional wakefield. Once the charged particles are completely trapped in the wakefield, the dynamics will be determined. It is shown that for definite parameters of the problem, a positron bunch could be trapped and accelerated and also well compressed in the first-half bucket of the donut wake. The results also show the possibility of trapping and acceleration of a hollow electron bunch with modified longitudinal and transverse properties. It is proved that electrons could be trapped just as a hollow bunch in the quasi-linear donut wake. *Published by AIP Publishing.*

Generation of Ramped Current Profiles in Relativistic Electron Beams Using Wakefields in Dielectric Structures

Andonian, G.; Barber, S.; O'Shea, F. H.; Fedurin, M.; Kusche, K.; Swinson, C.; Rosenzweig, J. B.
PHYSICAL REVIEW ACCELERATORS AND BEAMS 20(2), 054802 (FEB 2017)
http://doi.org/10.1103/physrevlett.118.054802

Temporal pulse tailoring of charged-particle beams is essential to optimize efficiency in collinear wakefield acceleration schemes. In this Letter, we demonstrate a novel phase space manipulation method that employs a beam wakefield interaction in a dielectric structure, followed by bunch compression in a permanent magnet chicane, to longitudinally tailor the pulse shape of an electron beam. This compact, passive, approach was used to generate a nearly linearly ramped current profile in a relativistic electron beam experiment carried out at the Brookhaven National Laboratory Accelerator Test Facility. Here, we report on these experimental results including beam and wakefield diagnostics and pulse profile reconstruction techniques.

GHz modulation detection using a streak camera: Suitability of streak cameras in the AWAKE experiment

Rieger, K.; Caldwell, A.; Reimann, O.; Muggli, P.
REVIEW OF SCIENTIFIC INSTRUMENTS 88(2), 025110 (FEB 2017)
http://doi.org/10.1063/1.4975380

Using frequency mixing, a modulated light pulse of ns duration is created. We show that, with a ps-resolution streak camera that is usually used for single short pulse measurements, we can detect via an FFT detection approach up to 450 GHz modulation in a pulse in a single measurement. This work is performed in the context of the AWAKE plasma wakefield experiment where modulation frequencies in the range of 80-280 GHz are expected.

The two-screen measurement setup to indirectly measure proton beam self modulation in AWAKE

Turner, M.; Biskup, B.; Burger, S.; Gschwendtner, E.; Mazzoni, S.; Petrenko, A.
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH SECTION A 854, 100-106 (MAY 2017)
http://doi.org/10.1016/j.nima.2017.02.064

The goal of the first phase of the AWAKE experiment at CERN is to measure the self -modulation of the σ_z = 12 cm long SPS proton bunch into microbunches after traversing 10 m of plasma with a plasma density of n_{pe} = 7 x 10^{14} electrons/cm^3. The two screen measurement setup is a proton beam diagnostic that can indirectly prove the successful development of the self -modulation of the proton beam by imaging protons that got defocused by the transverse plasma wakefields after passing through the plasma, at two locations downstream the end of the plasma. This article describes the design and realization of the two screen measurement setup integrated in the AWAKE experiment. We discuss the performance and background response of the system based on measurements performed with an unmodulated Gaussian SPS proton bunch during the AWAKE beam commissioning in September and October 2016. We show that the system is fully commissioned and adapted to eventually image the full profile of a self-modulated SPS proton bunch in a single shot measurement during the first phase of the AWAKE experiment.

Proton acceleration in a slow wakefield

Isaacs, Joshua; Sprangle, Phillip
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We propose and analyze a mechanism to accelerate protons in a low-phase-velocity wakefield. The wakefield is shock-excited by the interaction of two counter-propagating laser pulses in a plasma density gradient. The laser pulses consist of a forward-propagating short pulse (less than a plasma period) and a counter-propagating long pulse. The beating of these pulses generates a slow forward-propagating wakefield that can trap and accelerate protons. The trapping and acceleration is accomplished by appropriately tapering both the plasma density and the amplitude of the backward-propagating pulse. An example is presented in which the trapping and accelerating wakefield has a phase velocity varying from $V_{ph} \simeq 0$ to $\simeq 0.15\ c$ ($\sim$ 10 MeV proton energy) over a distance of $\sim$ 1 cm. The required laser intensities, pulse durations, pulse energies, and plasma densities are relatively modest. Instabilities such as the Raman instability are mitigated because of the large plasma density gradients. Numerical solutions of the wakefield equation and simulations using turboWAVE are carried out to support our model. *Published by AIP Publishing.*

Proton driven plasma wakefield generation in a parabolic plasma channel

Golian, Y.; Dorranian, D.
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An analytical model for the interaction of charged particle beams and plasma for a wakefield generation in a parabolic plasma channel is presented. In the suggested model, the plasma density profile has a minimum value on the propagation axis. A Gaussian proton beam is employed to excite the plasma wakefield in the channel. While previous works investigated on the simulation results and on the perturbation techniques in case of laser wakefield accelerations for a parabolic channel, we have carried out an analytical model and solved the accelerating field equation for proton beam in a parabolic plasma channel. The solution is expressed by Whittaker (hypergeometric) functions. Effects of plasma channel radius, proton bunch parameters and plasma parameters on the accelerating processes of proton driven plasma wakefield acceleration are studied. Results show that the higher accelerating fields could be generated in the PWFA scheme with modest reductions in the bunch size. Also, the modest increment in plasma channel radius is needed to obtain maximum accelerating gradient. In addition, the simulations of longitudinal and total radial wakefield in parabolic plasma channel are presented using LCODE. It is observed that the longitudinal wakefield generated by the bunch decreases with the distance behind the bunch while total radial wakefield increases with the distance behind the bunch.

Online plasma diagnostics of a laser-produced plasma

Gao, Kai; Hafz, Nasr A. M.; Li, Song; Mirzaie, Mohammad; Li, Guangyu; Ain, Quratul
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In this study, we report a laser interferometry experiment for the online-diagnosing of a laser-produced plasma. The laser pulses generating the plasma are ultra-fast (30 femtoseconds), ultra-intense (tens of Terawatt) and are focused on a helium gas jet to generate relativistic electron beams via the laser wakefield acceleration (LWFA) mechanism. A probe laser beam (λ = 800 nm) which is split-off the main beam is used to cross the plasma at the time of arrival of the main pulse, allowing online plasma density diagnostics. The interferometer setup is based on the NoMarski method in which we used a Fresnel bi-prism where the probe beam interferes with itself after crossing the plasma medium. A high-dynamic range CCD camera is used to record the interference patterns. Based upon the Abel inversion technique, we obtained a 3D density distribution of the plasma density.

Transition from coherent to incoherent acceleration of nonthermal relativistic electron induced by an intense light pulse

Liu, Y. L.; Kuramitsu, Y.; Moritaka, T.; Chen, S. H.
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Nonthermal acceleration of relativistic electrons due to the wakefield induced by an intense light pulse is investigated. The spectra of the cosmic rays are well represented by power-law. Wakefield acceleration has been considered as a candidate for the origins of cosmic rays. The wakefield can be excited by an intense laser pulse as large-amplitude precursor waves in collisionless shocks in the universe. National Central University (NCU) 100-TW laser facility in Taiwan is able to provide high-repetition rate and short intense laser. To experimentally study the wakefield acceleration for the spectrum of the cosmic rays, particle-in-cell simulations are performed to calculate the energy distribution functions of electrons in fixed laser conditions with various plasma densities. The transitions of wakefields from coherent to inherent are observed as the plasma density increases. The distribution functions indicate that the smooth nonthermal power-law spectra with an index of -2 appear when the incoherent wakefields are excited. In contrast, the mono-peak appear in the spectra when the coherent wakefields are excited. The incoherent wakefields yielding the power-law spectra imply the stochastic accelerating of electrons. To explain the universal nonthermal power-law spectra with an index of -2, we described and extended the stochastic acceleration model based on Fokker-Planck equation by assuming the transition rate as an exponential function.

Controlling the numerical Cerenkov instability in PIC simulations using a customized finite difference Maxwell solver and a local FFT based current correction

Li, Fei; Yu, Peicheng; Xu, Xinlu; Fiuza, Frederico; Decyk, Viktor K.; Dalichaouch, Thamine; Davidson, Asher; Tableman, Adam; An, Weiming; Tsung, Frank S.; Fonseca, Ricardo A.; Lu, Wei; Mori, Warren B.
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In this paper we present a customized finite-difference-time-domain (FDTD) Maxwell solver for the particle-in-cell (PIC) algorithm. The solver is customized to effectively eliminate the numerical Cerenkov instability (NCI) which arises when a plasma (neutral or non-neutral) relativistically drifts on a grid when using the PIC algorithm. We control the EM dispersion curve in the direction of the plasma drift of a FDTD Maxwell solver by using a customized higher order finite difference operator for the spatial derivative along the direction of the drift (1 direction). We show that this eliminates the main NCI modes with moderate $|k_1|$, while keeps additional main NCI modes well outside the range of physical interest with higher $|k_1|$. These main NCI modes can be easily filtered out along with first spatial aliasing NCI modes which are also at the edge of the fundamental Brillouin zone. The customized solver has the possible advantage of improved parallel scalability because it can be easily partitioned along $\hat{\imath}$ which typically has many more cells than other directions for the problems of interest. We show that FFTs can be performed locally to current on each partition to filter out the main and first spatial aliasing NCI modes, and to correct the current so that it satisfies the continuity

equation for the customized spatial derivative. This ensures that Gauss' Law is satisfied. We present simulation examples of one relativistically drifting plasma, of two colliding relativistically drifting plasmas, and of nonlinear laser wakefield acceleration (LWFA) in a Lorentz boosted frame that show no evidence of the NCI can be observed when using this customized Maxwell solver together with its NCI elimination scheme.

Imaging Laser wake fields by Thomson Scattering a Co-Propagating Pulse

Liu, Hong-Jie; Gu, Yu-Qiu; Li, Gang; Lu, Feng; Cui, Bo; Dai, Zeng-Hai; Ma, Yan-Yun; Zhou, Wei-Min; Cao, Lei-Feng; Zhang, Bao-Han
CHINESE PHYSICS LETTERS 34(1), 015202 (JAN 2017)
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Thomson scattering imaging (TSI) is proposed and experimentally demonstrated to observe the fine structure of the laser wake field. By Thomson scattering a co-propagating laser pulse, we obtain clear images indicating that the wake field is like an acaleph swimming behind the pump laser. The wavelength of the wake field observed at different electron densities agrees well with the theory. Since no mathematics transformation is involved, TSI could be potentially used as an online monitor for future 'tabletop' plasma accelerators.

Pulse chirping effect on controlling the transverse cavity oscillations in nonlinear bubble regime

Vosoughian, H.; Riazi, Z.; Afarideh, H.; Sarri, G.
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The propagation of an intense laser pulse in an under-dense plasma induces a plasma wake that is suitable for the acceleration of electrons to relativistic energies. For an ultra-intense laser pulse which has a longitudinal size shorter than the plasma wavelength, λ_p, instead of a periodic plasma wave, a cavity free from cold plasma electrons, called a bubble, is formed behind the laser pulse. An intense charge separation electric field inside the moving bubble can capture the electrons at the base of the bubble and accelerate them with a narrow energy spread. In the nonlinear bubble regime, due to localized depletion at the front of the pulse during its propagation through the plasma, the phase shift between carrier waves and pulse envelope plays an important role in plasma response. The carrier-envelope phase (CEP) breaks down the symmetric transverse ponderomotive force of the laser pulse that makes the bubble structure unstable. Our studies using a series of two-dimensional (2D) particle-in-cell (PIC) simulations show that the frequency-chirped laser pulses are more effective in controlling the pulse depletion rate and consequently the effect of the CEP in the bubble regime. The results indicate that the utilization of a positively chirped laser pulse leads to an increase in rate of erosion of the leading edge of the pulse that rapidly results in the formation of a steep intensity gradient at the front of the pulse. A more unstable bubble structure, the self-injections in different positions, and high dark current are the results of using a positively chirped laser pulse. For a negatively chirped laser pulse, the pulse depletion process is compensated during the propagation of the pulse in plasma in such a way that results in a more stable bubble shape and therefore, a localized electron bunch is produced during the acceleration process. As a result, by the proper choice of chirping, one can tune the number of self-injected electrons, the size of accelerated bunch and its energy spectrum to the values required for practical applications.

Laser acceleration

Tajima, T.; Nakajima, K.; Mourou, G.
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The fundamental idea of Laser Wakefield Acceleration (LWFA) is reviewed. An ultrafast intense laser pulse drives coherent wakefield with a relativistic amplitude robustly supported by the plasma. While the large amplitude of wakefields involves collective resonant oscillations of the eigenmode of the entire plasma electrons, the wake phase velocity $\sim c$ and ultrafastness of the laser pulse introduce the wake stability and rigidity. A large number of worldwide experiments show a rapid progress of this concept realization toward both the high-energy accelerator prospect and broad applications. The strong interest in this has been spurring and stimulating novel laser technologies, including the Chirped Pulse Amplification, the Thin Film Compression, the Coherent Amplification Network, and the Relativistic Mirror Compression. These in turn have created a conglomerate of novel science and technology with LWFA to form a new genre of high field science with many parameters of merit in this field increasing exponentially lately. This science has triggered a number of worldwide research centers and initiatives. Associated physics of ion acceleration, X-ray generation, and astrophysical processes of ultrahigh energy cosmic rays are reviewed. Applications such as X-ray free electron laser, cancer therapy, and radioisotope production etc. are considered. A new avenue of LWFA using nanomaterials is also emerging.

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