THE EuPRAXIA FILES

ISSUE 1 – May 2016

Foreword

Dr Ralph Aßmann
EuPRAXIA Coordinator

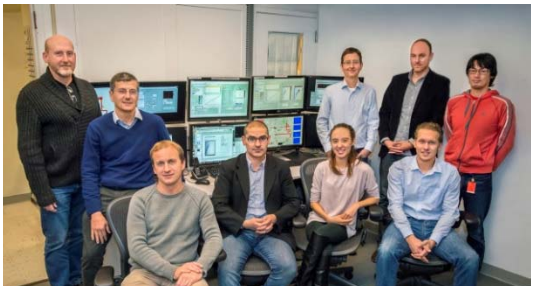
Novel accelerators have seen strong advances not only in achievable beam energy but also in beam quality. This success story is still developing, as you can see from the publications that we collect in this first edition of "The EuPRAXIA Files". As many of you are aware, the Horizon2020 Design Study EuPRAXIA aims at a conceptual design for a European plasma accelerator with usable beams. Instead of another newsletter we will regularly provide you with summaries of recent publications, letting the science speak for itself. EuPRAXIA has meanwhile had an excellent project start and is gearing up to a workshop in Pisa at the end of June, organized together with the European Network for Novel Accelerators EuroNNAc2 and EuCARD2. For further news on EuPRAXIA please visit our website or read regular updates in "Accelerating news". We wish you some inspirational science readings in this edition of "The EuPRAXIA Files", prepared by the EuPRAXIA outreach team in Liverpool with Ricardo Torres as lead editor.

Research Highlights

Berkeley Lab Scientists Create the First-ever, 2-stage Laser-plasma Accelerator Powered by Independent Laser Pulses

Researchers from the Lawrence Berkeley National Laboratory in the US have made an important breakthrough in the development of ultra-compact high-energy plasma-based accelerators.

In a paper recently published in Nature, they demonstrate for the first time the technique of staging, or sequencing multiple plasma accelerators independently powered. Staging is critical for high-energy physics applications of laser-plasma accelerators, as it enables to achieve higher beam energies, while maintaining accelerating gradients orders of magnitude above conventional technology.



Members of the BELLA Center staging experiment team, from left, are Eric Esarey, Wim Leemans, Jeroen van Tilborg, Carlo Benedetti, Kelly Swanson, Anthony Gonsalves, Joost Daniels, Sven Steinke, and Kei Nakamura. Not pictured are Cameron Geddes, Carl Schroeder, Nicholas Matlis, and Brian Shaw. (Photo credit: Roy Kaltschmidt/Berkeley Lab)

In these experiments, electrons from one laser-plasma accelerator were transported into a second laser-plasma accelerator, powered by a second laser pulse, and accelerated. What was particularly novel about this experiment is that a plasma-based lens was employed to transport the beam between stages and a plasma mirror was used to couple in the second laser pulse. These plasma-based components allowed the system to remain extremely compact.

With this result, one can envision scaling to beam energies of interest for high-energy physics applications in a compact footprint. However, these results are a first step toward that vision—experiments at higher beam energy, with higher efficiency and improved beam quality, will need to be performed to further develop plasma-based technology for next-generation colliders.

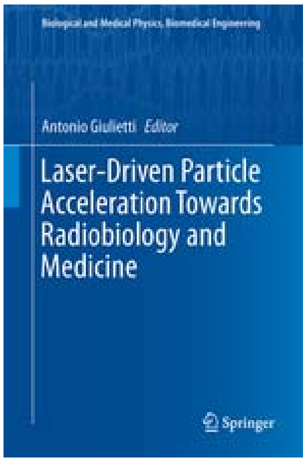
Read more at: http://newscenter.lbl.gov/2016/02/01/2-stage-laser-plasma-accelerator/

New books

Laser-Driven Particle Acceleration Towards Radiobiology and Medicine

Antonio Giulietti (Ed.)

Springer (2016)
doi: 10.1007/978-3-319-31563-8



This book deals with the new method of laser-driven acceleration for application to radiation biophysics and medicine. It provides multidisciplinary contributions from world leading scientist in order to assess the state of the art of innovative tools for radiation biology research and medical applications of ionizing radiation. The book contains insightful contributions on highly topical aspects of spatio-temporal radiation biophysics, evolving over several orders of magnitude, typically from femtosecond and sub-micrometer scales. Particular attention is devoted to the emerging technology of laser-driven particle accelerators and their application to spatio-temporal radiation biology and medical physics, customization of non-conventional and selective radiotherapy and optimized radioprotection protocols.

Research Papers

Multistage coupling of independent laser-plasma accelerators

S. Steinke, J. van Tilborg, C. Benedetti, C. G. R. Geddes, C. B. Schroeder, J. Daniels, K. K. Swanson, A. J. Gonsalves, K. Nakamura, N. H. Matlis, B. H. Shaw, E. Esarey & W. P. Leemans

NATURE 530, 190–193 (FEB 2016)
doi:10.1038/nature16525

Laser-plasma accelerators (LPAs) are capable of accelerating charged particles to very high energies in very compact structures. In theory, therefore, they offer advantages over conventional, large-scale particle accelerators. However, the energy gain in a single-stage LPA can be limited by laser diffraction, dephasing, electron-beam loading and laser-energy depletion. The problem of laser diffraction can be addressed by using laser-pulse guiding and preformed plasma waveguides to maintain the required laser intensity over distances of many Rayleigh lengths; dephasing can be mitigated by longitudinal tailoring of the plasma density; and beam loading can be controlled by proper shaping of the electron beam. To increase the beam energy further, it is necessary to tackle the problem of the depletion of laser energy, by sequencing the accelerator into stages, each powered by a separate laser pulse. Here, we present results from an experiment that demonstrates such staging. Two LPA stages were coupled over a short distance (as is needed to preserve the average acceleration gradient) by a plasma mirror. Stable electron beams from a first LPA were focused to a twenty-micrometre radius—by a discharge capillary-based active plasma lens—into a second LPA, such that the beams interacted with the wakefield excited by a separate laser. Staged acceleration by the wakefield of the second stage is detected via an energy gain of 100 megaelectronvolts for a subset of the electron beam. Changing the arrival time of the electron beam with respect to the second-stage laser pulse allowed us to reconstruct the temporal wakefield structure and to determine the plasma density. Our results indicate that the fundamental limitation to energy gain presented by laser depletion can be overcome by using staged acceleration, suggesting a way of reaching the electron energies required for collider applications.

Amplification and generation of ultra-intense twisted laser pulses via stimulated Raman scattering

Vieira J., Trines R. M. G. M., Alves E. P., Fonseca R. A., Mendonca J. T., Bingham R., Norreys P., Silva L. O.
NATURE COMMUNICATIONS 7, 10371 (JAN 2016)
doi:10.1038/ncomms10371

Twisted Laguerre-Gaussian lasers with orbital angular momentum and characterized by doughnut-shaped intensity profiles provide a transformative set of tools and research directions in a growing range of fields and applications from super-resolution microcopy and ultra-fast optical communications to quantum computing and astrophysics. The impact of twisted light is widening as recent numerical calculations provided solutions to long-standing challenges in plasma-based acceleration by allowing for high-gradient positron acceleration. The production of ultra-high-intensity twisted laser pulses could then also have a broad influence on relativistic laser-matter interactions. Here we show theoretically and with ab initio three-dimensional particle-in-cell simulations that stimulated Raman backscattering can generate and amplify twisted lasers to petawatt intensities in plasmas. This work may open new research directions in nonlinear optics and high-energy-density science compact plasma- based accelerators and light sources.

Vacuum laser acceleration of relativistic electrons using plasma mirror injectors

Thevenet M., Leblanc A., Kahaly S., Vincenti H., Vernier A., Quere F., Faure J.
NATURE PHYSICS 12, 355-360 (APR 2016)
doi:10.1038/NPHYS3597

Accelerating particles to relativistic energies over very short distances using lasers has been a long-standing goal in physics. Among the various schemes proposed for electrons, vacuum laser acceleration has attracted considerable interest and has been extensively studied theoretically because of its appealing simplicity: electrons interact with an intense laser field in vacuum and can be continuously accelerated, provided they remain at a given phase of the field until they escape the laser beam. But demonstrating this effect experimentally has proved extremely challenging, as it imposes stringent requirements on the conditions of injection of electrons in the laser field. Here, we solve this long-standing experimental problem by using a plasma mirror to inject electrons in an ultraintense laser field, and obtain clear evidence of vacuum laser acceleration. With the advent of petawatt lasers, this scheme could provide a competitive source of very high charge (nC) and ultrashort relativistic electron beams.

Nonthermal Electron Energization from Magnetic Reconnection in Laser-Driven Plasmas

Totorica, Samuel R.; Abel, Tom; Fiuza, Frederico
PHYSICAL REVIEW LETTERS 116, 095003 (MAR 2016)
doi:10.1103/PhysRevLett.116.095003

The possibility of studying nonthermal electron energization in laser-driven plasma experiments of magnetic reconnection is studied using two- and three-dimensional particle-in-cell simulations. It is demonstrated that nonthermal electrons with energies more than an order of magnitude larger than the initial thermal energy

can be produced in plasma conditions currently accessible in the laboratory. Electrons are accelerated by the reconnection electric field, being injected at varied distances from the X points, and in some cases trapped in plasmoids, before escaping the finite-sized system. Trapped electrons can be further energized by the electric field arising from the motion of the plasmoid. This acceleration gives rise to a nonthermal electron component that resembles a power-law spectrum, containing up to similar to 8% of the initial energy of the interacting electrons and similar to 24% of the initial magnetic energy. Estimates of the maximum electron energy and of the plasma conditions required to observe suprathermal electron acceleration are provided, paving the way for a new platform for the experimental study of particle acceleration induced by reconnection.

Microengineering Laser Plasma Interactions at Relativistic Intensities

Jiang S., Ji L. L., Audesirk H., George K. M., Snyder J., Krygier A., Poole P., Willis C., Daskalova R., Chowdhury E., Lewis N. S., Schumacher D. W., Pukhov A., Freeman R. R., Akli K. U.

PHYSICAL REVIEW LETTERS 116, 085002 (FEB 2016)
doi:10.1103/PhysRevLett.116.085002

We report on the first successful proof-of-principle experiment to manipulate laser-matter interactions on microscales using highly ordered Si microwire arrays. The interaction of a high-contrast short-pulse laser with a flat target via periodic Si microwires yields a substantial enhancement in both the total and cutoff energies of the produced electron beam. The self-generated electric and magnetic fields behave as an electromagnetic lens that confines and guides electrons between the microwires as they acquire relativistic energies via direct laser acceleration.

Role of momentum and velocity for radiating electrons

Capdessus Remi, Noble Adam, McKenna Paul, Jaroszynski Dino A.

PHYSICAL REVIEW D 93, 045034 (FEB 2016)
doi:10.1103/PhysRevD.93.045034

Radiation reaction remains one of the most fascinating open questions in electrodynamics. The development of multi-petawatt laser facilities capable of reaching extreme intensities has lent this topic a new urgency and it is now more important than ever to properly understand it. Two models of radiation reaction due to Landau and Lifshitz and due to Sokolov have gained prominence but there has been little work exploring the relation between the two. We show that in the Sokolov theory electromagnetic fields induce a Lorentz transformation between momentum and velocity which eliminates some of the counterintuitive results of Landau-Lifshitz. In particular the Lorentz boost in a constant electric field causes the particle to lose electrostatic potential energy more rapidly than it otherwise would explaining the longstanding mystery of how an electron can radiate while experiencing no radiation reaction force. These ideas are illustrated in examples of relevance to astrophysics and laser-particle interactions where radiation reaction effects are particularly prominent.

Resonant interaction between laser and electrons undergoing betatron oscillations in the bubble regime

Curcio, Alessandro; Giulietti, Danilo; Dattoli, Giuseppe; Ferrario, Massimo
JOURNAL OF PLASMA PHYSICS 81, 495810513 (OCT 2015)
doi:10.1017/S0022377815000926

The betatron radiation in the bubble regime is studied in the presence of resonant interaction between the accelerated electrons and the driver laser pulse tail. The calculations refer to experimental parameters available at the FLAME laser facility at the National Laboratories of Frascati (LNF) and represent the radiation spectra and spatial distributions to be expected in forthcoming experiments.

Measurement of the angle temperature and flux of fast electrons emitted from intense laser-solid interactions

Rusby D. R., Wilson L. A., Gray R. J., Dance R. J., Butler N. M. H., MacLellan D. A., Scott G. G., Bagnoud V., Zielbauer B., McKenna P., Neely D.
JOURNAL OF PLASMA PHYSICS 81, 475810505 (OCT 2015)
doi:10.1017/S0022377815000835

High-intensity laser-solid interactions generate relativistic electrons as well as high-energy (multi-MeV) ions and x-rays. The directionality spectra and total number of electrons that escape a target-foil is dependent on the absorption transport and rear-side sheath conditions. Measuring the electrons escaping the target will aid in improving our understanding of these absorption processes and the rear-surface sheath fields that retard the escaping electrons and accelerate ions via the target normal sheath acceleration (TNSA) mechanism. A comprehensive Geant4 study was performed to help analyse measurements made with a wrap-around diagnostic that surrounds the target and uses differential filtering with a FUJI-film image plate detector. The contribution of secondary sources such as x-rays and protons to the measured signal have been taken into account to aid in the retrieval of the electron signal. Angular and spectral data from a high-intensity laser-solid interaction are presented and accompanied by simulations. The total number of emitted electrons has been measured as 2.6 x 10(13) with an estimated total energy of 12 ± 1 J from a 100 mu m Cu target with 140 J of incident laser energy during a 4 x 10(20) W cm(-2) interaction.

Acceleration of on-axis and ring-shaped electron beams in wakefields driven by Laguerre-Gaussian pulses

Zhang, Guo-Bo; Chen, Min; Luo, Ji; Zeng, Ming; Yuan, Tao; Yu, Ji-Ye; Ma, Yan-Yun; Yu, Tong-Pu; Yu, Lu-Le; Weng, Su-Ming; Sheng, Zheng-Ming
JOURNAL OF APPLIED PHYSICS 119, 103101 (MAR 2016)
doi:10.1063/1.4943419

The acceleration of electron beams with multiple transverse structures in wakefields driven by Laguerre-Gaussian pulses has been studied through three-dimensional (3D) particle-in-cell simulations. Under different laser-plasma conditions, the wakefield shows different transverse structures. In general cases, the wakefield shows a donut-like structure and it accelerates the ring-shaped hollow electron beam. When a lower plasma density or a smaller laser spot size is used, besides the donut-like wakefield, a central bell-like wakefield can also be excited. The wake sets in the center of the donut-like wake. In this case, both a central

on-axis electron beam and a ring-shaped electron beam are simultaneously accelerated. Further, reducing the plasma density or laser spot size leads to an on-axis electron beam acceleration only. The research is beneficial for some potential applications requiring special pulse beam structures, such as positron acceleration and collimation.

Parametric study of transport beam lines for electron beams accelerated by laser-plasma interaction

Sciscio M., Lancia L., Migliorati M., Mostacci A., Palumbo L., Papaphilippou Y., Antici P.
JOURNAL OF APPLIED PHYSICS 119, 094905 (MAR 2016)
doi:10.1063/1.4942626

In the last decade, laser-plasma acceleration of high-energy electrons has attracted strong attention in different fields. Electrons with maximum energies in the GeV range can be laser-accelerated within a few cm using multi-hundreds terawatt (TW) lasers, yielding to very high beam currents at the source (electron bunches with up to tens-hundreds of pC in a few fs). While initially the challenge was to increase the maximum achievable electron energy, today strong effort is put in the control and usability of these laser-generated beams that still lack of some features in order to be used for applications where currently conventional, radio-frequency (RF) based, electron beam lines represent the most common and efficient solution. Several improvements have been suggested for this purpose, some of them acting directly on the plasma source, some using beam shaping tools located downstream. Concerning the latter, several studies have suggested the use of conventional accelerator magnetic devices (such as quadrupoles and solenoids) as an easy implementable solution when the laser-plasma accelerated beam requires optimization. In this paper, we report on a parametric study related to the transport of electron beams accelerated by laser-plasma interaction, using conventional accelerator elements and tools. We focus on both, high energy electron beams in the GeV range, as produced on petawatt (PW) class laser systems, and on lower energy electron beams in the hundreds of MeV range, as nowadays routinely obtained on commercially available multi-hundred TW laser systems. For both scenarios, our study allows understanding what are the crucial parameters that enable laser-plasma accelerators to compete with conventional ones and allow for a beam transport. We show that suitable working points require a tradeoff-combination between low beam divergence and narrow energy spread.

Demonstration of a high repetition rate capillary discharge waveguide

Gonsalves A. J., Liu F., Bobrova N. A., Sasorov P. V., Pieronek C., Daniels J., Antipov S., Butler J. E., Bulanov S. S., Waldron W. L., Mittelberger D. E., Leemans W. P.
JOURNAL OF APPLIED PHYSICS 119, 033302 (JAN 2016)
doi:10.1063/1.4940121

A hydrogen-filled capillary discharge waveguide operating at kHz repetition rates is presented for parameters relevant to laser plasma acceleration (LPA). The discharge current pulse was optimized for erosion mitigation with laser guiding experiments and MHD simulation. Heat flow simulations and measurements showed modest temperature rise at the capillary wall due to the average heat load at kHz repetition rates with water-cooled capillaries which is promising for applications of LPAs such as high average power radiation sources.

Dynamics and density distributions in a capillary-discharge waveguide with an embedded supersonic jet

Matlis N. H., Gonsalves A. J., Steinke S., van Tilborg J., Matlis E. H., Shaw B., Mittelberger D. E., Geddes C. G. R., Leemans W. P.

JOURNAL OF APPLIED PHYSICS 118, 204506 (NOV 2015)
doi:10.1063/1.4935631

We present an analysis of the gas dynamics and density distributions within a capillary-discharge waveguide with an embedded supersonic jet. This device provides a target for a laser plasma accelerator which uses longitudinal structuring of the gas-density profile to enable control of electron trapping and acceleration. The functionality of the device depends sensitively on the details of the density profile which are determined by the interaction between the pulsed gas in the jet and the continuously-flowing gas in the capillary. These dynamics are captured by spatially resolving recombination light from several emission lines of the plasma as a function of the delay between the jet and the discharge. We provide a phenomenological description of the gas dynamics as well as a quantitative evaluation of the density evolution. In particular we show that the pressure difference between the jet and the capillary defines three regimes of operation with qualitatively different longitudinal density profiles and show that jet timing provides a sensitive method for tuning between these regimes. (C) 2015 AIP Publishing LLC.

Proton acceleration enhanced by a plasma jet in expanding foils undergoing relativistic transparency

Powell H. W., King M., Gray R. J., MacLellan D. A., Gonzalez-Izquierdo B., Stockhausen L. C., Hicks G., Dover N. P., Rusby D. R., Carroll D. C., Padda H., Torres R., Kar S., Clarke R. J., Musgrave I. O., Najmudin Z., Borghesi M., Neely D., McKenna P.

NEW JOURNAL OF PHYSICS 17, 103033 (OCT 2015)
doi:10.1088/1367-2630/17/10/103033

Ion acceleration driven by the interaction of an ultraintense (2x10(20) Wcm(-2)) laser pulse with an ultrathin (<= 40 nm) foil target is experimentally and numerically investigated. Protons accelerated by sheath fields and via laser radiation pressure are angularly separated and identified based on their directionality and signature features (e.g. transverse instabilities) in the measured spatial-intensity distribution. A low divergence high energy proton component is also detected when the heated target electrons expand and the target becomes relativistically transparent during the interaction. 2D and 3D particle-in-cell simulations indicate that under these conditions a plasma jet is formed at the target rear supported by a self-generated azimuthal magnetic field which extends into the expanded layer of sheath-accelerated protons. Electrons trapped within this jet are directly accelerated to super-thermal energies by the portion of the laser pulse transmitted through the target. The resulting streaming of the electrons into the ion layers enhances the energy of protons in the vicinity of the jet. Through the addition of a controlled prepulse the maximum energy of these protons is demonstrated experimentally and numerically to be sensitive to the picosecond rising edge profile of the laser pulse.

Generation of high quality electron beams from a quasi-phase-stable cascaded laser wakefield accelerator with density-tailored plasma segments

Zhang Zhijun, Liu Jiansheng, Wang Wentao, Li Wentao, Yu Changhai, Tian Ye, Qi Rong, Wang Cheng, Qin Zhiyong, Fang Ming, Liu Jiaqi, Nakajima Kazuhisa, Li Ruxin, Xu Zhizhan
NEW JOURNAL OF PHYSICS 17, 103011 (OCT 2015)
doi:10.1088/1367-2630/17/10/103011

By controlling electron injection into the second period of the laser-driven wakefield in a downward density ramp a high-quality low-energy electron beam can be accelerated in a short segment of high-density plasma. After a second downward density ramp followed by a low-density plasma plateau the pre-accelerated electron beam can be seeded into the first period of the laser-driven wakefield for cascaded acceleration at an optimized phase. A monoenergetic electron beam with peak energy of similar to 1.2 GeV can be generated from plasma with a length of 12 mm and density of 9 x 10(17) cm(-3) driven by a laser pulse with peak power of 77 TW. By modifying the acceleration stage comprising several density-ascending plasma segments the peak energy of the quasi-monoenergetic electron beam can be efficiently increased by about 50% via a quasi-phase-stable multiple-cascade acceleration scheme.

Near-threshold electron injection in the laser-plasma wakefield accelerator leading to femtosecond bunches

Islam M. R., Brunetti E., Shanks R. P., Ersfeld B., Issac R. C., Cipiccia S., Anania M. P., Welsh G. H., Wiggins S. M., Noble A., Cairns R. A., Raj G., Jaroszynski D. A.
NEW JOURNAL OF PHYSICS 17, 093033 (SEP 2015)
doi:10.1088/1367-2630/17/9/093033

The laser-plasma wakefield accelerator is a compact source of high brightness ultra-short duration electron bunches. Self-injection occurs when electrons from the background plasma gain sufficient momentum at the back of the bubble-shaped accelerating structure to experience sustained acceleration. The shortest duration and highest brightness electron bunches result from self-injection close to the threshold for injection. Here we show that in this case injection is due to the localized charge density build-up in the sheath crossing region at the rear of the bubble which has the effect of increasing the accelerating potential to above a critical value. Bunch duration is determined by the dwell time above this critical value which explains why single or multiple ultra-short electron bunches with little dark current are formed in the first bubble. We confirm experimentally using coherent optical transition radiation measurements that single or multiple bunches with femtosecond duration and peak currents of several kiloAmpere and femtosecond intervals between bunches emerge from the accelerator.

Incoherent synchrotron emission of laser-driven plasma edge

Serebryakov D. A., Nerush E. N., Kostyukov I. Yu.
PHYSICS OF PLASMAS 22, 123119 (DEC 2015)
doi:10.1063/1.4938206

When a relativistically intense linearly polarized laser pulse is incident on an overdense plasma a dense electron layer is formed on the plasma edge which relativistic motion results in high harmonic generation ion acceleration and incoherent synchrotron emission of gamma-photons. Here we present a self-consistent

analytical model that describes the edge motion and apply it to the problem of incoherent synchrotron emission by ultrarelativistic plasma electrons. The model takes into account both coherent radiation reaction from high harmonics and incoherent radiation reaction in the Landau-Lifshitz form. The analytical results are in agreement with 3D particle-in-cell simulations in a certain parameter region that corresponds to the relativistic electronic spring interaction regime. (C) 2015 AIP Publishing LLC.

Laser-driven electron acceleration in an inhomogeneous plasma channel

Zhang Rong, Cheng Li-Hong, Xue Ju-Kui

PHYSICS OF PLASMAS 22, 123109 (DEC 2015)
doi:10.1063/1.4937367

We study the laser-driven electron acceleration in a transversely inhomogeneous plasma channel. We find that in inhomogeneous plasma channel the developing of instability for electron acceleration and the electron energy gain can be controlled by adjusting the laser polarization angle and inhomogeneity of plasma channel. That is we can short the accelerating length and enhance the energy gain in inhomogeneous plasma channel by adjusting the laser polarization angle and inhomogeneity of the plasma channel. (C) 2015 AIP Publishing LLC.

An application of laser-plasma acceleration: towards a free-electron laser amplification

Couprie M. E., Labat M., Evain C., Marteau F., Briquez F., Khojoyan M., Benabderrahmane C., Chapuis L., Hubert N., Bourassin-Bouchet C., El Ajjouri M., Bouvet F., Dietrich Y., Valleau M., Sharma G., Yang W., Marcouille O., Veteran J., Berteaud P., El Ajjouri T., Cassinari L., Thaury C., Lambert G., Andriyash I., Malka V., Davoine X., Tordeux M. A., Miron C., Zerbib D., Tavakoli K., Marlats J. L., Tilmont M., Rommeluere P., Duval J. P., N'Guyen M. H., Rouqier A., Vanderbergue M., Herbeaux C., Sebdouai M., Lestrade A., Leclercq N., Dennetiere D., Thomasset M., Polack F., Bielawski S., Szwaj C., Loulergue A.

PLASMA PHYSICS AND CONTROLLED FUSION 58, 034020 (MAR 2016)
doi:10.1088/0741-3335/58/3/034020

The laser-plasma accelerator (LPA) presently provides electron beams with a typical current of a few kA a bunch length of a few fs energy in the few hundred MeV to several GeV range a divergence of typically 1 mrad an energy spread of the order of 1% and a normalized emittance of the order of pi.mm. mrad. One of the first applications could be to use these beams for the production of radiation: undulator emission has been observed but the rather large energy spread (1%) and divergence (1 mrad) prevent straightforward free-electron laser (FEL) amplification. An adequate beam manipulation through the transport to the undulator is then required. The key concept proposed here relies on an innovative electron beam longitudinal and transverse manipulation in the transport towards an undulator: a 'demixing' chicane sorts the electrons according to their energy and reduces the spread from 1% to one slice of a few parts per thousand and the effective transverse size is maintained constant along the undulator (supermatching) by a proper synchronization of the electron beam focusing with the progress of the optical wave. A test experiment for the demonstration of FEL amplification with an LPA is under preparation. Electron beam transport follows different steps with strong focusing with permanent magnet quadrupoles of variable strength a demixing chicane with conventional dipoles and a second set of quadrupoles for further focusing in the undulator. The FEL simulations and the progress of the preparation of the experiment are presented.

An all-optical Compton source for single-exposure x-ray imaging

Dopp A., Guillaume E., Thaury C., Gautier J., Andriyash I., Lifschitz A., Malka V., Rousse A., Phuoc K. Ta

PLASMA PHYSICS AND CONTROLLED FUSION 58, 034005 (MAR 2016)
doi:10.1088/0741-3335/58/3/034005

All-optical Compton sources are innovative compact devices to produce high energy femtosecond x-rays. Here we present results on a single-pulse scheme that uses a plasma mirror to reflect the drive beam of a laser plasma accelerator and to make it collide with the highly-relativistic electrons in its wake. The accelerator is operated in the self-injection regime producing quasi-monoenergetic electron beams of around 150 MeV peak energy. Scattering with the intense femtosecond laser pulse leads to the emission of a collimated high energy photon beam. Using continuum-attenuation filters we measure significant signal content beyond 100 keV and with simulations we estimate a peak photon energy of around 500 keV. The source divergence is about 13 mrad and the pointing stability is 7 mrad. We demonstrate that the photon yield from the source is sufficiently high to illuminate a centimeter-size sample placed 90 centimeters behind the source thus obtaining radiographs in a single shot.

Controlled generation of comb-like electron beams in plasma channels for polychromatic inverse Thomson gamma-ray sources

Kalmykov S. Y., Davoine X., Ghebregziabher I., Lehe R., Lifschitz A. F., Shadwick B. A.

PLASMA PHYSICS AND CONTROLLED FUSION 58, 034006 (MAR 2016)
doi:10.1088/0741-3335/58/3/034006

Propagating a relativistically intense negatively chirped laser pulse (the bandwidth > 150 nm) in a plasma channel makes it possible to generate background-free comb-like electron beams-sequences of synchronized bunches with a low phase-space volume and controlled energy spacing. The tail of the pulse confined in the accelerator cavity (an electron density 'bubble') experiences periodic focusing while the head which is the most intense portion of the pulse steadily self-guides. Oscillations of the cavity size cause periodic injection of electrons from the ambient plasma creating an electron energy comb with the number of components their mean energy and energy spacing dependent on the channel radius and pulse length. These customizable electron beams enable the design of a tunable all-optical source of pulsed polychromatic gamma-rays using the mechanism of inverse Thomson scattering with up to similar to 10(-5) conversion efficiency from the drive pulse in the electron accelerator to the gamma-ray beam. Such a source may radiate similar to 10(7) quasi-monochromatic photons per shot into a microsteradian-scale cone. The photon energy is distributed among several distinct bands each having sub-30% energy spread with a highest energy of 12.5 MeV.

Self-modulated laser wakefield accelerators as x-ray sources

Lemos N., Martins J. L., Tsung F. S., Shaw J. L., Marsh K. A., Albert F., Pollock B. B., Joshi C.

PLASMA PHYSICS AND CONTROLLED FUSION 58, 034018 (MAR 2016)
doi:10.1088/0741-3335/58/3/034018

The development of a directional small-divergence and short-duration picosecond x-ray probe beam with an energy greater than 50 keV is desirable for high energy density science experiments. We therefore explore through particle-in-cell (PIC) computer simulations the possibility of using x-rays radiated by betatron-like

motion of electrons from a self-modulated laser wakefield accelerator as a possible candidate to meet this need. Two OSIRD PIC simulations with mobile ions are presented one with a normalized vector potential a(0) = 1.5 and the other with an a(0) = 3. We find that in both cases direct laser acceleration (DLA) is an important additional acceleration mechanism in addition to the longitudinal electric field of the plasma wave. Together these mechanisms produce electrons with a continuous energy spectrum with a maximum energy of 300 MeV for a0 = 3 case and 180 MeV in the a(0) = 1.5 case. Forward-directed x-ray radiation with a photon energy up to 100 keV was calculated for the a(0) = 3 case and up to 12 keV for the a(0) = 1.5 case. The x-ray spectrum can be fitted with a sum of two synchrotron spectra with critical photon energies of 13 and 45 keV for the a(0) of 3 and critical photon energies of 0.3 and 1.4 keV for a(0) of 1.5 in the plane of polarization of the laser. The full width at half maximum divergence angle of the x-rays was 62 x 1.9 mrad for a(0) = 3 and 77 x 3.8 mrad for a(0) = 1.5.

Low-energy-spread laser wakefield acceleration using ionization injection with a tightly focused laser in a mismatched plasma channel

Li F., Zhang C. J., Wan Y., Wu Y. P., Xu X. L., Hua J. F., Pai C. H., Lu W., Gu Y. Q., Mori W. B., Joshi C.
PLASMA PHYSICS AND CONTROLLED FUSION 58, 034004 (MAR 2016)
doi:10.1088/0741-3335/58/3/034004

An improved ionization injection scheme for laser wakefield acceleration using a tightly focused laser pulse with intensity near the ionization threshold to trigger the injection in a mismatched plasma channel has been proposed and examined via 3D particle-in-cell (PIC) simulations. In this scheme the key to achieving a very low energy spread is shortening the injection distance through the fast diffraction of the tightly focused laser. Furthermore the oscillation of the laser envelope in the mismatched plasma channel can induce multiple low-energy-spread injections with an even distribution in both space and energy. The envelope oscillation can also significantly enhance the energy gain of the injected beams compared to the standard non-evolving wake scenario due to the rephasing between the electron beam and the laser wake. A theoretical model has been derived to precisely predict the injection distance the ionization degree of injection atoms/ions the electron yield as well as the ionized charge for given laser-plasma parameters and such expressions can be directly utilized for optimizing the quality of the injected beam. Through 3D PIC simulations we show that an injection distance as short as tens of microns can be achieved which leads to ultrashort fs few pC electron bunches with a narrow absolute energy spread around 2 MeV (rms). Simulations also show that the initial absolute energy spread remains nearly constant during the subsequent acceleration due to the very short bunch length and this indicates that further acceleration of the electron bunches up to the GeV level may lead to an electron beam with an energy spread well below 0.5%. Such low-energy-spread electron beams may have potential applications for future coherent light sources driven by laser-plasma accelerators.

Laser acceleration in argon clusters and gas media

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We experimentally investigated the generation of high-energy electron beams from laser-driven wakefield acceleration in argon gas jets by using tens of terawatt 30 fs ultrafast laser pulses that were focused to a relatively large-spot size unmatched with the laser-plasma parameters. In this interaction and depending on the Ar gas jet density we could distinguish two different regimes for electron acceleration in the argon medium. In the high-density argon gas jet where argon clusters are formed upon interaction with the laser electron beams having as high a charge as 3nC are generated. However the energy spectra of those electron beams were continuous. On the other hand high-quality quasi-mono-energetic electron beams with a modest charge of tens of pC are observed at much lower argon gas jet densities. The generation of such a high-quality electron beam is attributed to the ionization injection mechanism in which the electron injection takes place over only a few hundred micrometers of the laser-plasma interaction length leading to the generation of high-quality electron beams.

Efficient laser production of energetic neutral beams

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Laser-driven ion acceleration by intense ultra-short laser pulse has received increasing attention in recent years and the availability of much compact and versatile ions sources motivates the study of laser-driven sources of energetic neutral atoms. We demonstrate the production of a neutral and directional beam of hydrogen and carbon atoms up to 200 keV per nucleon with a peak flow of 2.7 x 10(13) atom s(-1). Laser accelerated ions are neutralized in a pulsed supersonic argon jet with tunable density between 1.5 x 10(17) cm(-3) and 6 x 10(18) cm(-3). The neutralization efficiency has been measured by a time-of-flight detector for different argon densities. An optimum is found for which complete neutralization occurs. The neutralization rate can be explained only at high areal densities (> 1 x 10(17) cm(-2)) by single electron charge transfer processes. These results suggest a new perspective for the study of neutral production by laser and open discussion of neutralization at a lower density.

Extending laser plasma accelerators into the mid-IR spectral domain with a next-generation ultra-fast CO_2 laser

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Expanding the scope of relativistic plasma research to wavelengths longer than the lambda/approximate to 0.8-1.1 µm range covered by conventional mode-locked solid-state lasers would offer attractive opportunities due to the quadratic scaling of the ponderomotive electron energy and critical plasma density with lambda. Answering this quest a next-generation mid-IR laser project is being advanced at the BNL ATF as a part of the user facility upgrade. We discuss the technical approach to this conceptually new 100 TW 100 fs lambda = 9-11 µm CO_2 laser BESTIA (Brookhaven Experimental Supra-Terawatt Infrared at ATF) that encompasses several innovations applied for the first time to molecular gas lasers. BESTIA will enable new regimes of laser plasma accelerators. One example is shock-wave ion acceleration (SWA) from gas jets. We review ongoing efforts to achieve stable monoenergetic proton acceleration by dynamically shaping the plasma density profile from a hydrogen gas target with laser-produced blast waves. At its full power 100 TW

BESTIA promises to achieve proton beams at an energy exceeding 200 MeV. In addition to ion acceleration in over-critical plasma the ultra-intense mid-IR BESTIA will open up new opportunities in driving wakefields in tenuous plasmas expanding the landscape of laser wakefield accelerator (LWFA) studies into the unexplored long-wavelength spectral domain. Simple wavelength scaling suggests that a 100 TW CO_2 laser beam will be capable of efficiently generating plasma 'bubbles' a thousand times greater in volume compared with a near-IR solid state laser of an equivalent power. Combined with a femtosecond electron linac available at the ATF this wavelength scaling will facilitate the study of external seeding and staging of LWFAs.

Estimation of direct laser acceleration in laser wakefield accelerators using particle-in-cell simulations

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Many current laser wakefield acceleration (LWFA) experiments are carried out in a regime where the laser pulse length is on the order of or longer than the wake wavelength and where ionization injection is employed to inject electrons into the wake. In these experiments the electrons can gain a significant amount of energy from the direct laser acceleration (DLA) mechanism as well as the usual LWFA mechanism. Particle-in-cell (PIC) codes are frequently used to discern the relative contribution of these two mechanisms. However if the longitudinal resolution used in the PIC simulations is inadequate it can produce numerical heating that can overestimate the transverse motion which is important in determining the energy gain due to DLA. We have therefore carried out a systematic study of this LWFA regime by varying the longitudinal resolution of PIC simulations and then examining the energy gain characteristics of both the highest-energy electrons and the bulk electrons. By calculating the contribution of DLA to the final energies of the electrons produced from the LWFA we find that even at the highest longitudinal resolutions DLA contributes a significant portion of the energy gained by the highest-energy electrons and also contributes to accelerating the bulk of the charge in the electron beam produced by the LWFA.

Matching strategies for a plasma booster

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This paper presents a theoretical study of a matching strategy for the laser-plasma wakefield accelerator where the injected electron beam is produced by an external source. The matching is achieved after an initial focusing using conventional beam optics combining a linear tapering of plasma density and the increasing non linearity of the plasma wake due to the focusing of the laser driver. Both effects contribute in increasing the focusing strength from an initial relatively low value to the considerably higher value present in the flat top plasma profile where acceleration takes place. The same procedure is exploited to match the beam from plasma to vacuum once acceleration has occurred. Beam loading plays a crucial role both at the very beginning and end of the whole process. In the last stage two more effects take place: a partial emittance compensation reducing emittance value by a sizable amount and a reduction of the energy spread due to the relevant beam loading operating when the laser is defocused.

Laser wakefield and direct acceleration with ionization injection

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PLASMA PHYSICS AND CONTROLLED FUSION 58, 034011 (MAR 2016)
doi:10.1088/0741-3335/58/3/034011

We demonstrate using particle-in-cell simulations that electrons can be injected into a hybrid laser wakefield and direct laser accelerator via ionization injection. We propose an accelerator and injector scenario that utilizes two laser pulses. The first (pump) pulse produces the plasma 'bubble' by expelling the plasma electrons generated by its leading edge from the low-Z component of the gas mixture and then injects electrons into the bubble by ionizing the high-Z component. The second time-delayed laser pulse resonantly interacts with these injected electrons undergoing betatron oscillations inside the bubble. We show that the electrons ionized off-axis and on-axis but off the peak ionization phase possess sufficient transverse energy to undergo efficient direct laser acceleration (DLA). When combined with their acceleration by the bubble's longitudinal plasma wake DLA can double the total energy gain and produce a monoenergetic beam.

Laser-driven x-ray and neutron source development for industrial applications of plasma accelerators

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PLASMA PHYSICS AND CONTROLLED FUSION 58, 014039 (JAN 2016)
doi:10.1088/0741-3335/58/1/014039

Pulsed beams of energetic x-rays and neutrons from intense laser interactions with solid foils are promising for applications where bright small emission area sources capable of multi-modal delivery are ideal. Possible end users of laser-driven multi-modal sources are those requiring advanced non-destructive inspection techniques in industry sectors of high value commerce such as aerospace nuclear and advanced manufacturing. We report on experimental work that demonstrates multi-modal operation of high power laser-solid interactions for neutron and x-ray beam generation. Measurements and Monte Carlo radiation transport simulations show that neutron yield is increased by a factor similar to 2 when a 1 mm copper foil is placed behind a 2 mm lithium foil compared to using a 2 cm block of lithium only. We explore x-ray generation with a 10 picosecond drive pulse in order to tailor the spectral content for radiography with medium density alloy metals. The impact of using >1 ps pulse duration on laser-accelerated electron beam generation and transport is discussed alongside the optimisation of subsequent bremsstrahlung emission in thin high atomic number target foils. X-ray spectra are deconvolved from spectrometer measurements and simulation data generated using the GEANT4 Monte Carlo code. We also demonstrate the unique capability of laser-driven x-rays in being able to deliver single pulse high spatial resolution projection imaging of thick metallic objects. Active detector radiographic imaging of industrially relevant sample objects with a 10 ps drive pulse is presented for the first time demonstrating that features of 200 mu m size are resolved when projected at high magnification.

Load management strategy for Particle-In-Cell simulations in high energy particle acceleration

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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH SECTION A – ACCELERATORS SPECTROMETERS DETECTORS AND ASSOCIATED EQUIPMENT (APR 2016)

doi:10.1016/j.nima.2016.03.112i

In the wake of the intense effort made for the experimental CILEX project, numerical simulation campaigns have been carried out in order to finalize the design of the facility and to identify optimal laser and plasma parameters. These simulations bring, of course, important insight into the fundamental physics at play. As a by-product, they also characterize the quality of our theoretical and numerical models. In this paper, we compare the results given by different codes and point out algorithmic limitations both in terms of physical accuracy and computational performances. These limitations are illustrated in the context of electron laser wakefield acceleration (LWFA). The main limitation we identify in state-of-the-art Particle-In-Cell (PIC) codes is computational load imbalance. We propose an innovative algorithm to deal with this specific issue as well as milestones towards a modern, accurate high-performance PIC code for high-energy particle acceleration.

Quadrupole lens-free multiple-profile diagnostics for emittance measurement of laser wakefield accelerated electron beams

Krus M., Lastovicka T., Levato T.

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH SECTION A – ACCELERATORS SPECTROMETERS DETECTORS AND ASSOCIATED EQUIPMENT 810, 32-36 (FEB 2016)

doi:10.1016/j.nima.2015.11.116

A quadrupole lens-free diagnostic is a simple single shot method which can be used to measure the electron beam transverse emittance. LANEX screens are used as profile monitors due to the high yield of visible photons which can be easily detected by standard camera sensors. This type of minimally destructive diagnostics is particularly suitable for electron beams accelerated by the laser wakefield mechanism where the basic parameters of such beams fluctuate shot-to-shot mainly during the beam optimizing process. It allows to simultaneously measure the beam divergence position profile pointing and charge. The numerical study of the diagnostics performance and applicability range is presented and its limits are discussed. The influence of the LANEX screen multiple Coulomb scattering is studied by means of GEANT4; the unfolding procedure for multiple scattering contribution is presented.

Electron acceleration by a bichromatic chirped laser pulse in underdense plasmas

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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH SECTION B – BEAM INTERACTIONS WITH MATERIALS AND ATOMS 369, 50-54 (FEB 2016)

doi:10.1016/j.nimb.2015.10.013

A theoretical study of laser and plasma based electron acceleration is presented. An effective model has been used in which the presence of an underdense plasma has been taken account via its index of refraction n(m). In the confines of this model the basic phenomena can be studied by numerically solving the classical relativistic equations of motion. The key idea of this paper is the application of chirped bichromatic laser fields. We investigated the advantages and disadvantages of mixing the second harmonic to the original lambda = 800 nm wavelength pulse. We performed calculations both for plane wave and Gaussian pulses.

High-energy-density electron beam from interaction of two successive laser pulses with subcritical-density plasma

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PHYSICAL REVIEW SPECIAL TOPICS-ACCELERATORS AND BEAMS 19, 021301 (FEB 2016)
doi:10.1103/PhysRevAccelBeams.19.021301

It is shown by particle-in-cell simulations that a narrow electron beam with high energy and charge density can be generated in a subcritical-density plasma by two consecutive laser pulses. Although the first laser pulse dissipates rapidly the second pulse can propagate for a long distance in the thin wake channel created by the first pulse and can further accelerate the preaccelerated electrons therein. Given that the second pulse also self-focuses the resulting electron beam has a narrow waist and high charge and energy densities. Such beams are useful for enhancing the target-back space-charge field in target normal sheath acceleration of ions and bremsstrahlung sources among others.

Hot spots and dark current in advanced plasma wakefield accelerators

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PHYSICAL REVIEW SPECIAL TOPICS – ACCELERATORS AND BEAMS 19, 011303 (JAN 2016)
doi:10.1103/PhysRevAccelBeams.19.011303

Dark current can spoil witness bunch beam quality and acceleration efficiency in particle beam-driven plasma wakefield accelerators. In advanced schemes hot spots generated by the drive beam or the wakefield can release electrons from higher ionization threshold levels in the plasma media. These electrons may be trapped inside the plasma wake and will then accumulate dark current which is generally detrimental for a clear and unspoiled plasma acceleration process. Strategies for generating clean and robust dark current free plasma wake cavities are devised and analyzed and crucial aspects for experimental realization of such optimized scenarios are discussed.

Investigation on target normal sheath acceleration through measurements of ions energy distribution

Tudisco S., Altana C., Lanzalone G., Muoio A., Cirrone G. A. P., Mascali D., Schillaci F., Brandi F., Cristoforetti G., Ferrara P., Fulgentini L., Koester P., Labate L., Palla D., Gizzi L. A.

REVIEW OF SCIENTIFIC INSTRUMENTS 87, 02A909 (FEB 2016)
doi:10.1063/1.4934691

An experimental campaign aiming at investigating the ion acceleration mechanisms through laser-matter interaction in femtosecond domain has been carried out at the Intense Laser Irradiation Laboratory facility with a laser intensity of up to 2 x 10(19) W/cm(2). A Thomson parabola spectrometer was used to obtain the spectra of the ions of the different species accelerated. Here we show the energy spectra of light-ions and

we discuss their dependence on structural characteristics of the target and the role of surface and target bulk in the acceleration process.

The Effect of Ion Motion on Laser-Driven Plasma Wake in Capillary

Zhou Suyun, Chen Hui, Li Yanfang
PLASMA SCIENCE & TECHNOLOGY 18 (JAN 2016)
doi:10.1088/1009-0630/18/1/15

The effect of ion motion in capillary-guided laser-driven plasma wake is investigated through rebuilding a two-dimensional analytical model. It is shown that laser pulse with the same power can excite more intense wakefield in the capillary of a smaller radius. When laser intensity exceeds a critical value the effect of ion motion reducing the wakefield rises which becomes significant with a decrease of capillary radius. This phenomenon can be attributed to plasma ions in smaller capillary obtaining more energy from the plasma wake. The dependence of the difference value between maximal scalar potential of wake for two cases of ion rest and ion motion on the radius of the capillary is discussed.

Enhancement of laser-driven betatron radiation

Li Minghua, Chen Liming, Li Dazhang, Yan Wenchao, Huang Kai, Ma Yong, Sheng Zhengming, Zhang Jie
OPTICAL ENGINEERING 54, 127105 (DEC 2015)
doi:10.1117/1.OE.54.12.127105

Betatron radiation from the transverse oscillation of laser-wakefield accelerated electrons is very promising for a wide range of applications. Currently the main limitation of this radiation source is the x-ray photon yield. We present our recent progress in achieving higher photon flux using a clustering gas target instead of the normal gas jet leading to a 10-fold enhancement. Moreover we observed monoenergetic electron beams and bright x-rays simultaneously an occurrence which is considered contradictory and succeeded in using the betatron radiation as a probe in the evolution of bubble dynamics. These breakthroughs are of great significance for pushing the use of betatron radiation source toward new applications.

Effect of halo on the stability of electron bunches in laser wakefield acceleration

Nakanii N., Hosokai T., Iwasa K., Pathak N. C., Masuda S., Zhidkov A. G., Nakahara H., Takeguchi N., Mizuta Y., Otsuka T. P., Sueda K., Nakamura H., Kodama R.
EPL 113, 34002 (FEB 2016)
doi:10.1209/0295-5075/113/34002

The stability of short electron bunches formed and accelerated by laser wakefield in gas jets strongly depends on parameters of pre-plasma due to poor pulse focus-ability. Instabilities provoked by light energy remained out of focus spots (halo) usually 30-50% are shown to result in broad and spotted transverse distributions of electrons in uniform gas jets radiated by highcontrast laser pulses. Shaped pre-plasma may drastically improve pulse focus-ability with stable well-pointed and well-collimated electron bunches.

An analytic approach for density gradient injection in laser wake field acceleration

Wang Tong, Wang Xiao-Fang

ACTA PHYSICA SINICA 65, 044102 (FEB 2016)
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In laser wake field acceleration it is relatively easy to achieve and control electron injection by adopting a plasma density gradient. This scheme of plasma density gradient injection has been studied in recent years both theoretically and experimentally but thus far theoretical studies have been done mostly by particle-in-cell simulations. In this paper the density gradient injection and acceleration of electrons are studied with a newly developed analytic approach. The energy threshold for electron injection versus plasma density gradient scale length is given. It is shown that in the plasma density gradient region the energy threshold of electron injection becomes lower at later times after the driving laser pulse or when the gradient becomes sharper. Evolution of plasma wave's phase velocity and motion of the background electrons in the plasma den sity gradient are worked out in the linear plasma wave regime i.e. the normalized laser intensity is a(0) similar to 1. The energy the location and the timing of the injected electrons are obtained. Separatrices of test electrons in the gradient region are obtained by Hamiltonian theory. The influence of injection timing in the density gradient region on the succeeding acceleration in the homogeneous plasma density region is also discussed. It is indicated that whether the injected electrons may be accelerated efficiently or not in the homogeneous region depends on both the energy of the electrons and the phase of the plasma wave at the gradient-to-homogeneous turning point. The analytic results are confirmed by particle-in-cell simulations.

The EuPRAXIA Files

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