Laser-Plasma Accelerator Workshop 2019

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MedILS

Book of Abstracts

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Presence and future of X-ray scattering techniques for the understanding of ultra-short pulse laser matter interactions

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The development of next generation laser plasma sources for novel applications in various fields ranging from astro-physics, fusion research to particle acceleration and tumor therapy requires methods to study the plasma dynamics and heating on short spatial (few nanometers) and temporal scales (few femtoseconds). Free electron lasers are identified as a potential new tool to achieve this goal for various plasma properties since they combine short bunches, high photon numbers with small bandwidth and high penetration power even through several microns of solid density plasmas.
We give an overview over recent advances in theory and experiments for transferring established scattering techniques into the short-pulse laser domain. Besides the future potentials of the small angle scattering technique we will focus on the possible impact of resonant scattering on the understanding and advancement of laser-based particle sources. The simultaneous measurement of structure and opacity with a single method, with nanometer and femtosecond resolution would enable a level of understanding both in plasma physics as well as transient, non-equilibrium atomic physics that could help developing better predictive simulation capabilities as well as new solutions to defiances towards optimized laser particle source

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Determining impact of LWFA injection schemes on electron bunch profiles and peak currents based on broadband, spectral CTR diagnostics at single shot

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Laser-wakefield accelerators (LWFA) feature electron bunch durations on a fs-scale. Precise knowledge of the longitudinal profile of such ultra-short electron bunches is essential for the design of future compact X-ray light sources. Resolution limits, as well as the limited reproducibility of electron bunches, pose big challenges for LWFA beam diagnostics.

Spectral measurements of broadband transition radiation from LWFA electron bunches passing through a metal foil are especially promising for analyzing ultrashort longitudinal bunch characteristics ranging from of tens of fs down to sub-fs.

Our broadband, single-shot spectrometer combines the TR spectrum in UV/VIS (200-1000nm), NIR (0.9-1.7µm) and mid-IR (1.6-12µm). A complete characterization and calibration of the spectrometer has been done with regard to wavelengths, relative spectral sensitivities and absolute photometric sensitivity. Our spectrometer is able to characterize electron bunches with charges as low as 1 pC and resolve time-scales from 0.7 to 40 fs. In addition, complementary data on the transverse bunch profile is provided by simultaneously imaging the CTR in the far- and near-field.

We present recent experimental results of different LWFA injection mechanisms, such as self-truncated ionization-injection and self-injection. By analyzing the transition radiation spectra and reconstructing electron bunch profiles including error analysis, we determine electron bunch profiles and peak currents of the respective injection regimes. In addition to bunch durations and peak currents, we discuss sub-fs beam micro-structures and systematic experimental scans of the nitrogen doping concentration for ionization-induced injection.

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Laser-driven ion acceleration at CALA

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We investigate acceleration of ion bunches during relativistically intense laser pulse interactions with plasmas. Relying on coherent acceleration, such laser-driven ion sources feature ion bunch characteristics that can be complementary to those typical of conventional (Wideroe-type) accelerators. Particularly novel intrinsic features include (ultra)short bunch duration, high bunch density, low emittance and synchronism with other parallel laser-driven particle and photon sources. The main acceleration concepts based on recent studies with various target (plasma) types; including ultrathin foils [1] and levitated micro targets [2] will be reviewed. We now aim to realize viable sources for applications in fields of radiation physics, chemistry, biology and medicine in the context of the Centre for Advanced Laser Applications (CALA). CALA will feature the Advanced Titanium-Sapphire Laser ATLAS3000, a chirped pulse amplification system that delivers driving laser pulses of 20fs duration and peak power up to 3 petawatts. Advancing from investigative parameter studies towards an integrated laser-driven ion accelerator system (ILDIAS) represents a remarkable technological challenge. Experiences and advances in target technology (i.e. targetry), ion beam guidance and instrumentation will be reported. Among the numerous potential applications of laser-driven particle acceleration [3], ion-bunch induced ultrasound waves in water is highlighted as a fascinating example at the interface of tailored detection methodology and physics at high local and instantaneous energy density.

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3. Bolton, P.R., K. Parodi, and J. Schreiber, Applications of Laser-driven Particle Acceleration. 2018: CRC Press, Taylor & Francis Group.

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Multipurpose bremsstrahlung calorimeters for ultra-intense laser-plasma interactions

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New probes are continuously investigated to explore the physics of laser-plasma interactions. Charged particle detection systems and optical probing are well established techniques. The investigation of the bremsstrahlung generated in laser plasma remains, however, a relatively uncommon method to study these interactions.

In this talk we will present the developments in gamma calorimetry developed at HZDR. Currently, sampling calorimeters based on image plates as well as CCD cameras have been developed. The technique has been used to study bremsstrahlung generated with solid targets, by laser-wakefield accelerated (LWFA) electrons through a radiator and inverse Compton scattered X-rays, as well as calibrated radioactive X-Ray sources (Co60 and Cs137).

We will show how spectra with different functional parametrization can be reconstructed from the dose deposited in the detector. The energy range covered by such a detector is shown to be from a few hundred keV (from inverse Compton X-rays and standard radiation sources) with a Gaussian-like shape, through a few MeV (from solid target bremsstrahlung) up to tens of MeV (generated by LWFA electrons through a radiator).

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Small angle x-ray scattering probing ultrashort pulse high-intensity laser-solid interactions

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The development of second-generation short-pulse laser-driven radiation sources requires a mature understanding of relativistic laser-plasma processes such as plasma oscillations, heating and transport of relativistic electrons as well as the development of plasma instabilities. These dynamic effects occurring on nanometer scales are very difficult to access experimentally during their existence of a few tens of femtoseconds, which often poses a problem of identifying, understanding, modeling and optimizing them.
With Small Angle X-ray Scattering (SAXS) at the LCLS femtosecond x-ray free electron laser facility we were able to measure the non-linear dynamics in the relativistic intensity regime using the MEC short pulse laser [Kluge et al., Phys. Rev. X 8, 031068 (2018)]. We report on the plasma expansion dynamics observed with this technique giving us a unique insight into the fast surface dynamics. Based on those results we designed a follow-up experiment with significantly higher pump intensity, improved targetry and particle diagnostics. This provides unprecedented capabilities by combining a full suite of particle and radiation diagnostics with SAXS and resonant scattering, providing access to a simultaneous measurement of multi-layer correlations in transmission geometry, ionization states and hence plasma temperature.

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Few-Cycle Microscopy of Stimulated Raman Side Scattering in a Laser Wakefield Accelerator

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In 2018 the first Laser Wakefield Acceleration campaign took place at the Helmholtz-Institute Jena with the JETi-200 laser-system. When travelling through the plasma and exciting a plasma wave, the pump pulse can get scattered at plasma structures depending on the pump pulse's evolution inside the plasma, the pump pulse‘s chirp and the plasma electron‘s density.
This (stimulated) Raman Side Scattering was investigated using Few-Cycle Microscopy on a micrometre scale.
First results and a preliminary analysis of the observed side scattering will be presented.

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Quantitative reconstruction of wakefield electron density distribution

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Few-cycle shadowgraphy is a common tool to qualitatively investigate the longitudinal and transverse structure of laser generated wakefields. However the measured intensity distribution provides hardly any information about the wake amplitude since the wakefield itself is a pure phase object and the measured intensity distribution is a function of the imaging plane. Commonly this plane is not precisely known due to the pointing jitter of the driver laser. One possible approach to investigate the phase object constituted by the electron distribution inside the wake is to image multiple planes around the wakefield. From these multiple intensity distributions it is possible to reconstruct the phase that defines the propagation between the imaged planes and therefore represents the original phase object.
We report on the successful reconstruction of the wakefield phase and subsequent extraction of the plasma refractive index. From that the electron density along the wakefield axis is calculated.
We experimentally observe wakefields in He-gasjets driven by a 100TW-class laser. The gas density is in the range of $5 \cdot 10^{18} cm^{-3}$. Assuming radial symmetry we find linear plasma wakes with a modulation depth comparable to that expected from theory and simulations.

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Algorithmic ultrafast imaging

Authors: Robin Wang[1]; Muhammad Kasim[1]; James Holloway[1]; Alexander Picksley[1]; Ramy Aboushelbaya[1]; Marko Mayr[1]; Alexander Savin[1]; Benjamin Spier[1]; Peter Norreys[1]

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A single-shot hyperspectral camera has been built and a single-shot ultrafast videography protocol has been developed. The camera is capable of retrieving three dimensions of information (two spatial dimensions along with a time or spectral dimension) from a two-dimensional signal of a conventional CCD camera. The third dimension is retrieved using a combination of compressed sensing along with the spatial and spectral modulation of an incoming signal.

Time resolution using the camera is achieved by passing a chirped probe pulse through a temporally interesting event. The compressed sensing algorithm then reconstructs a hyperspectral datacube, where slices of the datacube that are lower frequency (redder) will correspond to an earlier point in time while higher frequency slices (more blue) correspond to a later point in time. We expect to capture a video at tens of trillions frames per second.

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Few-cycle shadowgraphy of plasma wave trains

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Few-cycle microscopy diagnostic [1] combining femtosecond time resolution and micrometer spatial resolution allows for direct observation of laser-driven plasma waves. By comparing the period of the wave train and the independently measured in-situ plasma density, we find that existing 1D models [2, 3] tend to overestimate the contribution of laser intensity to the non-linear plasma wave lengthening. Quasi-3D particle-in-cell simulations reproducing our observations suggest that transverse intensity gradient plays an important role in the wave train formation. Furthermore, we show experimental evidence on plasma waves driven by electron bunches generated from a laser wakefield accelerator, paving the way towards research of plasma wakefield acceleration at laser facilities [4].

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Excitation of beam driven plasma waves in a hybrid LPWFA

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Recent progress in laser wakefield acceleration (LWFA) has demonstrated the generation of high peak current electron beams with improved shot to shot stability [1]. Using high-current electron beams from a LWFA as drivers of a beam-driven plasma wakefield accelerator (PWFA) has been proposed as a beam energy and brightness transformer [2], aiming to fulfill the demanding quality requirements for applications such as FELs. It has been demonstrated experimentaly that electron beams from LWFA can actually drive plasma wakefields by themselves [3]. In order to further study the generation of plasma waves in the PWFA stage a sub-10 fs probe pulse was deployed and installed at HZDR. We observed beam driven plasma waves at different plasma densities, showing the capability of the LWFA beam to drive plasma wakefields in the self-ionizing regime. Furthermore we observed a correlation between the energy loss of the driver beam and the shape of the plasma wave. This enables us to find an optimum parameter set towards the experimental demonstration of the hybrid LPWFA.

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Optical measurements of nanosecond-scale plasma channel evolution excited by beam-driven plasma wakes at FACET

Authors: Rafal Zgadzaj[1]; Michael Downer[1]; Mark Hogan[None]; Vadim Khudyakov[2]; Konstantin Lotov[2]; Thales Silva[3]; Alexander Sosedkin[2]; Jorge Vieira[3]; Vitaly Yakimenko[4]

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The energy density deposited in a highly nonlinear "blowout" regime wake reaches that of the rest energy density of plasma electrons [1]. This energy relaxes through a complex redistribution between e.g. accelerated electrons, undirected hot electrons, ion-channel formation, ionization and excitation of surrounding gas and radiation over ns or longer time scales. These relaxation dynamics ultimately govern the repetition rate of plasma accelerators. Although simulations have predicted that strongly nonlinear electron wakes can spawn "ion wakes" of unique structure and dynamics [1-3], experiments have not yet explored this long-term evolution. Here, we present ps-time-resolved optical shadowgraphic measurements of cylindrically symmetric ion channels that emerge from broken plasma wakes generated in singly self-ionized lithium (Li) plasma (n_e=8 10¹⁶ cm⁻³) of meter length, by SLAC's 20 *GeV*, 2 *nC* electron bunches (σ_x=σ_y=30 *μm*, σ_z=50 *μm*). Results show that the plasma column remains peaked on axis and grows continuously in radius from <10 *μm* at time delay Δt<10 *ps* after passage of the drive bunch to several hundred μm at Δt=1.5ns. Measurements at longer Δt show that a strongly refracting plasma column persists at microsecond delays. Simulations using the fully relativistic particle-in-cell code OSIRIS [4] and the quasi-static LCODE [5] model the evolving plasma column out to Δt~1.4 *ns*, and yield an evolving density profile consistent with measurements.
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Off-harmonic optical probe diagnostic for high intensity laser interaction with hydrogen targets

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The development of high-intensity short-pulse lasers in the Petawatt regime offers the possibility to design new compact accelerator schemes by utilizing high-density targets for the generation of high energy ion beams. The optimization of the acceleration process demands comprehensive diagnostic of the plasma dynamics involved, for example via spatially and temporally resolved optical probing. Experimental results can then be compared to numerical particle-in-cell simulations, which is particularly sensible in the case of cryogenic hydrogen jet targets [1]. However, strong plasma self-emission and conversion of the plasma's drive laser wavelength into its harmonics often masks the interaction region and interferes with the data analysis. Recently, the development of a stand-alone and synchronized probe laser system for off-harmonic probing at the DRACO laser operated at the Helmholtz-Zentrum Dresden–Rossendorf showed promising performance [2].
Here, we present an updated stand-alone probe laser system applying a compact CPA system based on a synchronized fs mode-locked oscillator operating at 1030 nm, far off the plasma's drive laser wavelength of 800 nm. A chirped volume Bragg grating is used as a hybrid stretcher and compressor unit [3]. The system delivers 160 fs pulses with a maximum energy of 0.9 mJ. By deploying the probe laser pulses in laser-proton acceleration experiments with renewable cryogenic hydrogen jet targets, the plasma self-emission could be significantly suppressed while studying the temporal

evolution of the expanding plasma jet. Hence, for varied drive laser contrast parameters, by the use of a plasma mirror, the on target contrast was measured and correlated to the temporal drive laser profile.

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Single-shot movies of evolving GeV laser-plasma accelerators by multiplexed Faraday rotation

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To optimize and control GeV-level laser plasma acceleration (LPA), it is important to visualize transient LPA structures in a single shot. In this set of LPA experiments using the Texas Petawatt (~120fs, ~120J) in a plasma of He of density ne < 5 × 1017 cm−3, electrons to (~0.6)GeV were produced in (300pC) bunches. The low repetition-rate and slight fluctuations of the laser motivates capturing the dynamics of bubble structures at multiple points along their path in a single shot. For single snapshots, the Faraday effect has been used1,2, where the magnetic field of the accelerated electrons preferentially magnetizes the relatively dense plasma of the surrounding bubble wall, which in turn rotates the polarization of a probe beam moving transverse to the LPA drive pulse1. Coupled with polarization and imaging optics on the probe beam, the plasma density can be visualized.

Here, we describe and show results from a multiplexed Faraday rotation diagnostic. Our Faraday rotation diagnostic uses multiple non-overlapping transverse probe beams of 1cm diameter, each timed to propagate transversely through the bubble at different positions in its path. Together the probes extended over a field of view of 2.7cm. To acquire this wide horizontal field of view while resolving features vertically, we multiplexed the probes through an anamorphic imaging system to de-magnify the horizontal dimension (30µm resolution) while magnifying the vertical dimension (9µm resolution with 300µm depth of field).

The results demonstrate the feasibility of this single-shot diagnostic for capturing GeV-class LPA structures in tenuous plasma. By exploiting the ~3 kilo-Tesla magnetic fields of this high-charge, high-energy electron bunch to magnetize the bubble's dense walls, we were able to image the plasma bubble structure via Faraday rotation of the transverse probe beams despite low plasma density. The bubble evolution involved its birth, initial rapid evolution, and eventual stabilization. These stages resulted from a "mismatched" focusing geometry, which prompted initial bubble size oscillations and self-injection of up to nCs of electrons from surrounding plasma into the bubble.

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Beam diagnostics for high brightness beams at FACET-II

Authors: Douglas Storey[1]; Mark Hogan[None]; Brendan O'Shea[None]; Claudio Emma[None]; Vitaly Yakimenko[None]

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When it comes online later this fall, FACET-II will begin delivering 10 GeV beams with up to 300 kA peak current and bunch lengths less than 1 µm for a broad range of experiments in advanced accelerator R&D and other novel research directions. Such extreme beam intensities will make diagnostics particularly challenging for FACET-II. Key to the plasma wakefield experimental program is the ability to determine emittance preservation of bunches with their energy doubled by plasma wakefield acceleration. Single shot emittance measurements will be performed using the so-called butterfly emittance measurement which exploits the chromatic focusing of the beam spot size with energy in the spectrometer beamline to extract the emittance with sub mm-mrad accuracy. In order to fully diagnose the parameters of the incoming beams on a shot by shot basis in a nondestructive manner requires the development of novel non-intercepting diagnostics such as edge radiation monitors and a machine learning driven virtual diagnostic of the electron beam phase space. We will discuss these and other diagnostics techniques relevant to high brightness beams at FACET-II.

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Transverse electron probing of interactions of long CO_2 laser pulse with plasma at ATF

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Laser wakefield accelerators (LWFAs) can sustain accelerating gradients that greatly surpass those of conventional accelerators. Long (∼ps) and intense (>TW) laser pulses have been employed in LWFAs to generate bright, hard x-rays which are of interest for imaging and diagnosing warm-dense matter. The CO_2 laser at the ATF facility of the Brookhaven National Laboratory is a unique source,

which can generate >2 ps-long, multi-TW laser pulses in the mid-IR (9-10 μm) regime. At a plasma density of $\sim 2 \times 10^{17}$ cm^{-3}, this laser pulse encompasses hundreds of plasma skin depths, creating three interaction regions with distinct characteristics: laser self-modulation, transverse laser disruption and laser self-channeling. In this talk, numerical results will be presented to show the main properties of this interaction. An electron beam travelling transversely with respect to the direction of laser propagation is used to probe the fields in the three interaction regions. These simulation results as well as the preparations for future experiments will be discussed. The simulations were done using the Particle in Cell code OSIRIS [R.A.Fonseca et al., LNCS (2331) 342, 2002].

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Impact of ultrafast laser generated Weibel magnetic fields on propagation dynamics of relativistic electron bunches

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During laser solid target interactions, the onset of Weibel instability can generate super strong magnetic field structures (up to several kT) on the surface and within the bulk of the solid targets. Weibel magnetic fields can be used to understand several physical events in astrophysics [1] as well as impact laser driven inertial confinement fusion process [2] and gamma-ray generation experiments [3].
Here we report on the measurements of integrated Weibel magnetic fields at femtosecond time scale by using relativistic electron bunches from laser wakefield accelerators (LWFA) to probe the Weibel instability driven by the interaction between ultrashort (30 fs) intense ($I_0 > 10^{18} W/cm^2$) laser pulses and thin solid targets.
Experiments on hybrid Plasma Wakefield Acceleration, in which LWFA-generated electron beams are used to drive wakefield in another plasma target [4], demonstrated that the impact of such a strong magnetic field on a relativistic electron bunch can cause significant beam quality degradation, which complicates its further transportation and utilisation. We will present experimental and simulation results showing integrated B-field of few $kT \cdot m$ generated at the surface and in the bulk of the solid target within a depth of a few microns. The results show that the Weibel instability at femtosecond time scale can be explored with a convenient and simple method based on laser wakefield acceleration.

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Working group:

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Wakefields in a Cluster Plasma

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We report the first observation of large amplitude Langmuir waves in a plasma of nanometer-scale clusters. The shape of these wakefields is captured by a single-shot frequency-domain holography diagnostic at an oblique angle of incidence. The wavefronts are observed to curve backwards, in contrast to the forwards curvature of wakefields in uniform plasma. The first wakefield period is longer than those trailing it. The features of the data are well described by a fully relativistic two-dimensional particle-in-cell simulation.

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Carrier-Envelope-Phase and Dispersion in Laser-Plasma Acceleration Driven by Single-Cycle Laser Pulses

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We will review our recent research activities on high-repetition rate laser-wakefield acceleration. In a recent series of experiments, we have used millijoule near-single-cycle laser pulses of 3.5 fs duration at kHz repetition rate to accelerate electrons to 5 MeV energies [1]. The single-cycle laser pulses were able to excite nonlinear plasma wakefields and accelerate electrons to MeV energies in few tens of microns only. We will discuss the various acceleration mechanisms that allowed us to accelerate high beam-loads of tens of picoCoulomb per pulse at a kHz repetition rate [2].
Using near-sincle cycle laser pulses has allowed us to enter a new regime of laser plasma acceleration where carrier-envelope phase (CEP) and group velocity dispersion effects (GVD) become important. We will show the first clear experimental evidence of CEP effects on electron injection

and acceleration [3]. We will also show unique results where we compare the physics of laser-plasma interaction using laser pulses with different spectral widths (i.e. different Fourier Transform limits). These results outline the fact that for extremely short pulses < 4-fs, dispersion effects complicate the interaction and might become detrimental to electron acceleration in certain cases.
Finally, we will discuss the perspectives of this research, in particular the potential of the electron source for probing condensed matter systems on ultrafast time scales.

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[2] D. Gustas et al., "High-charge relativistic electron bunches from a kHz laser-plasma accelerator"; Phys. Rev. Acc. & Beams 21, 013401 (2018)
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The characteristics of Very High Energy Electron Beam in Laser Wakefield Accelerator for Cancer Therapy

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A laser wakefield accelerator(LWFA)[1], which can be used to accelerate electrons by interaction between high-intensity laser pulse and plasmas, has the advantage to miniaturize the system size as it can obtain in a narrow region compared with conventional systems. The characteristics of the Very High Energy Electron(VHEE) beam in LWFA has attracted much interest because of its potential application such as ultrashort x-ray source, betatron radiation, and medical applications. In particula, many researchers have recently studied the efficiency of VHEE-based cancer treatment systems for the treatment of deep-sated tumors[2]. This result has reported that this system can minimizes damage to normal cells and efficiently remove cancer cells.
In Korea Electrotechnology Research Institute (KERI), we have studied the development of a compact cancer treatment system by 20 TW ultra-short high power laser based LWFA system[3]. In this study, electron beams with energy of 70 and 90 MeV were obtained by ionization injection from mixed gas, helium gas containing 10 % nitrogen, and the charge were 25, 18 nC, respectively. Three-dimensional Percent Dose Distribution(PDD) of electron beam was measured by tough phantom composed of Gafchromic films. The measured PDD shows the size-preserving shape of the electron beam, known as pencil-like beam, at high energy. For comparison with experimental results, "PDD" according to depth of penetration of electron beam was calculated using GEANT4 code. The experimental results and the calculated results were in good agreement. Significantly, because of the electron beam energy spread, the PDD at relatively shallow depths, such as neat the entrance port is similar to the result of low energy beam and to the penetration results at high energy at a deep penetration depth close to the exit port. The dose per electron beam charge was obtained to be 7 cGy/nC.

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Working group:

Laser-driven electron acceleration

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Effects of Beam Loading in LWFAs

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We report on the generation of quasi-monoenergetic electron beams with up to 1.2nC charge, 18 pC/MeV spectral charge density and 1mrad rms divergence using shock-front injection in a 100-TW-class laser wakefield accelerator. These high charge densities result in significant beam loading which affects both the final energy and the spectral shape of the electron beam. We confirm and explain the observed influences using quasi-3D paricle-in-cell simulations. Modifying the shock-front or applying additional colliding pulse injection enables us to create two separate electron bunches serving as driver and witness to study beamloading effects on the trailing electron bunch [1].

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Working group:

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Laser wakefield acceleration research at Center for Relativistic Laser Science

Authors: Hyung Taek Kim[1]; J. H. Shin[2]; C. Aniculaesei[2]; B. S. Rao[2]; V. B. Pathak[2]; M. H. Cho[2]; C. Hojbota[3]; S. K. Lee[3]; J. H. Sung[3]; H. W. Lee[2]; J. W. Yoon[3]; C. H. Nam[1]

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Laser wakefield acceleration (LWFA) is a candidate to build next generation of electron accelerators due to its huge acceleration field in a plasma medium. Progresses of intense laser technologies contributed to developments of multi-GeV [1,2] and high repetition-rate electron beams [3] by LWFA. Recently, we accomplished upgrading one of our PW beamlines to 4 PW peak power [4] and started applying it to LWFA experiments. In addition to multi-PW lasers, we installed a 5-Hz 100-TW laser and a 1-kHz sub-TW laser to examine novel LWFA schemes and develop high-repetition-rate electron beams. In this presentation, we will briefly summarize the current status of LWFA research at Center for Relativistic Laser Science (CoReLS); LWFA with multi-PW laser pulse, nanoparticle-assisted LWFA, and control of LWFA by elliptically shaped laser focus.

Reference
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The bubble regime of LWFA driven by the non-Gaussian beam

Authors: Dominika Maslarova[1]; Vojtech Horny[1]; Miroslav Krus[1]; Jan Psikal[2]

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The non-linear bubble regime of laser-wakefield acceleration (LWFA) is studied for a laser beam with a spatial super-Gaussian profile. Contrarily to the Gaussian beam, the intensity profile of the super-Gaussian beam is flat over almost all the covered area, which alters the bubble shape in a different way. Moreover, diffraction rings are induced during the formation of the super-Gaussian beam. These properties affect the values of wakefield and the whole acceleration process directly. In order to address this issue, the process is investigated for standard parameters feasible with current sub-100 TW laser systems by means of numerical particle-in-cell simulations. It is shown that an additional electron injection can occur due to the evolution of the laser beam. As a consequence, parameters of the electron bunch vary from the ones generated by a Gaussian beam.

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Laser -driven particle acceleration at high repetition rate

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Experiments were conducted using a high:repetition rate (500 Hz) Ti:sapphire laser to measure the scaling of laser wakefield acceleration at low energy (< 20 mJ) and high repetition rate. Electron spectra were measured and the effect of feedback control of the laser pulse phase front and the laser temporal phase were investigated. The development of liquid targets for high rep rate ion and neutron generation will also be described.

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First demonstration of a hybrid laser-electron-beam driven plasma wakefield accelerator

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Co-authors: T. Heinemann [2]; S. Schoebel ; J. P. Couperus Cabadağ [3]; O. Kononenko [4]; Y.-Y. Chang [1]; M. Bussmann [5]; S. Corde [4]; A. Debus [1]; H. Ding [6]; A. Döpp [7]; M. F. Gilljohann [7]; B. Hidding [8]; S. Karsch [7]; A. Köhler [9]; R. Pausch [1]; O. Zarini [9]; U. Schramm [9]; A. Martinez de la Ossa [10]; A. Irman [1]

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Plasma based electron acceleration is widely considered as a promising concept for a compact electron accelerator with broad range of future applications from high energy particle colliders to photon science. These accelerators can be powered by either ultra-intense laser beams (LWFA) or relativistic high-current particle beams (PWFA).
Here, we report on a novel approach to combine both schemes in a truly compact experimental setup. In our "LWFA + PWFA" hybrid accelerator, the electron beam generated by a LWFA stage drives a subsequent PWFA stage where a witness beam is trapped and accelerated. This strategy aims to combine the unique features of both plasma acceleration techniques, the LWFA stage provides with a compact source of high-current electron beams required as PWFA drivers, while the PWFA stage acts as an energy and brightness transformer for the LWFA output[1].
In this work, we show the first experimental evidence of accelerating a distinct witness bunch in a LWFA-driven PWFA (LPWFA) within only about one millimeter acceleration distance. In the self-ionizing case, we observe witness energies of around 50 MeV. By utilizing a counter-propagating pre-ionization laser, the interaction with the plasma becomes stronger, increasing the final energies to around 120 MeV. Thus, yielding a field gradient of (46±11) GeV/m which is comparable to what has been shown at large scale facilities[2].

References:

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Working group:

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Energy absorption, photon-photon scattering and channelling with ultra-intense laser pulses

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I will present an overview the research being undertaken in my group at the Clarendon Laboratory, University of Oxford and with colleagues at the Rutherford Appleton Laboratory. We are particularly interested in exploring how laser energy is absorbed in the laser-QED regime for the 10 PW laser pulses that will shortly be available with the ELI facilities. We have found that there is a regime change in the dependence of fast electron energy on incident laser energy that coincides with the onset of pair production via the Breit-Wheeler process. This prediction is numerically verified via an extensive campaign of QED-inclusive particle-in-cell simulations. The dramatic nature of the power law shift leads to the conclusion that this process is a candidate for an unambiguous signature that future experiments on multi-petawatt laser facilities have truly entered the QED regime [https://arxiv.org/abs/1901.08017]. We have also investigated the effect of orbital angular momentum on photon-photon scattering in vacuum and found that the generated beam also carries a unique orbital angular momentum signature, thereby greatly improving the signal to noise ratio This forms the basis for a future high-power laser experiment utilizing quantum optics techniques to filter the generated photons based on their orbital angular momentum states. [https://arxiv.org/abs/1902.05928]. Finally, I will review hole-boring and channelling simulations and experiments confirming that it is possible to overcome the hosing and filamentation instabilities to generate a straight channel in the coronal plasma of a fusion pellet. This provides a new route to augment the heating of the central hot spot for inertial fusion targets and allows the original fast ignition concept to be explored in detail.

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Beam quality optimization in a beam loaded nanocoulomb-class laser wakefield accelerator

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Here we report on optimization of both energy spread and beam divergence in a laser wakefield accelerator (LWFA) operating in the beam loading regime. The self-truncated ionization injection scheme is employed, enabling a precise control over the amount of injected electrons with charges

up to 0.5 nC (FWHM) at a quasi-monoenergetic peak.
By employing the optimal beam loading condition, the accelerating gradient is flattened and we eliminate additional energy spread contribution from the acceleration process^{1,2}. This point of minimized finite energy spread is used to limit the betatron oscillations of bunch electrons, leading to a decrease of the normalized beam divergence. Meanwhile, an ultrafast single-shot electron beam diagnostic based on Coherent Transition Radiation reveals ~10 femtosecond bunch lengths yielding peak currents of over 10 kA. Such peak currents are one to two orders of magnitude larger than those found in conventional RF accelerators. Control of the energy spread and beam divergence of LWFA beams with the beam loading condition together with the scaling to high peak currents paves the road for driving secondary superradiant lights sources.

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1. J.P. Couperus, et.al., "Demonstration of a beam loaded nanocoulomb-class laser wakefield accelerator", Nature Communication, 8, 487 (2017)
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Controlling the Self-Injection Threshold in Laser Wakefield Accelerators

Authors: Stephan Kuschel[1]; Matthew Schwab[2]; Mark Yeung[3]; Dominik Hollatz[4]; Andreas Seidel[4]; Wolfgang Ziegler[4]; Alexander Sävert[5]; Malte Kaluza[4]; Matt Zepf[5]

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Controlling the parameters of a laser plasma accelerated electron beam is a topic of intense research with a particular focus placed on controlling the injection phase of electrons into the accelerating structure from the background plasma. An essential prerequisite for high-quality beams is dark-current free acceleration (i.e., no electrons accelerated beyond those deliberately injected). We show that small-scale density ripples in the background plasma are sufficient to cause the uncontrolled (self-)injection of electrons. Such ripples can be as short as 50µm and can therefore not be resolved by standard interferometry. Background free injection with substantially improved beam characteristics (divergence and pointing) is demonstrated in a gas cell designed for a controlled gas flow. The results are supported by an analytical theory as well as 3D particle in cell simulations.

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Status of CALA and overview about LMU's LWFA-related activities

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We will give an overview of the latest commissioning status of the ATLAS-3000 laser system at CALA, before reviewing the main results from the laser-wakefield related campaigns with the predecessor 100-TW system. Quasi-monoenergetic shock-front accelerated electron bunches with energies up to 300 MeV and charge figures of >250 pC were routinely produced. The scaling of their spectral shape with injected charge shows clear signs of beamloading, and control over the injected charge could be achieved by modifying the laser field strength at the injection point. Shock-front injection was combined with beatwave-injection, which produced two independently energy-adjustable electron bunches, and the effect of beam-loading of the first bunch on the energy of the second bunch was observed. The high-charge LWFA bunches were used to drive plasma waves in a secondary plasma, and first experiments towards hybrid acceleration were performed. Single or multiple bunches were also used to generate Thomson-scattered photons employed in multi-color imaging experiments. Moreover, betatron radiation was used for fast tomography of a bone sample.

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Superluminal laser plasma acceleration

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Subluminal and superluminal light pulses have attracted a considerable attention in the past decades opening perspectives in telecommunications, optical storage, and fundamental physics. Usually achieved in matter, superluminal propagation has also been demonstrated in vacuum with quasi-Bessel beams or Spatio-Temporal Couplings (STCs). While in the first case the propagation was diffraction-free, but with hardly controllable pulse velocities and limited to moderate intensities, in

the second a high tunability was achieved, yet with significantly lengthened pulse durations. Here, we report on a new concept that extends these approaches to relativistic intensities and ultra-short pulses by mixing STCs and quasi-Bessel beams to control independently the light velocity and intensity. When used to drive a Laser-Plasma Accelerator (LPA), this concept leads to a new regime, dephasing-free, where the electron beam energy gain increases by more than one order of magnitude.

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Traveling-Wave Electron Acceleration - Energy-efficient Laser-plasma acceleration beyond the dephasing and depletion limits

Author: Alexander Debus[1]

Co-authors: Richard Pausch [1]; Axel Huebl [1]; Klaus Steiniger [1]; René Widera [1]; Thomas Cowan [1]; Ulrich Schramm [1]; Michael Bussmann [1]

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We present Traveling-Wave Electron Acceleration (TWEAC), a novel compact electron accelerator scheme based on laser-plasma acceleration. While laser-plasma accelerators provide multi-GeV electron beams today, the acceleration to higher energies is limited. The sub-luminal group-velocity of plasma waves let electrons outrun the accelerating field.

In order to control the speed of the accelerating plasma cavity, TWEAC utilizes two pulse-front tilted laser pulses whose propagation directions enclose a configurable angle. The accelerating cavity is created along their overlap region in the plasma and can move at the vacuum speed of light. The oblique laser geometry enables to constantly cycle different laser beam sections through the interaction region, hence providing quasi-stationary conditions of the wakefield driver. Supported by 3D particle-in-cell simulations using PIConGPU, we show that TWEAC offers constant acceleration without a dephasing electron beam while avoiding usual laser pump depletion within the interaction region. This opens the way for electron energies beyond 10 GeV, possibly towards TeV class electron beams, without the need for multiple laser-accelerator stages. For lower GeV-scale electron energies, TWEAC at high plasma densities and 10TW-class laser systems could enable compact accelerators at kHz-repetition rates.

After analyzing stability of acceleration and possible limits of the scheme, we present energy scaling laws for both laser as well as electrons and detail experimental design considerations. By comparing the energy efficiency of various TWEAC designs to LWFA, we find using simulations that for low-angle TWEAC setups, it is possible to accelerate high-charge bunches with laser to electron beam energy efficiencies close to 50%, which exceeds energy efficiencies typically attained with LWFA.

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Electron beam dynamics in the laser-plasma accelerator

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The capture and acceleration of short electron bunches externally injected into wakefields generated by an intense femtosecond laser pulse in the plasma channel are studied. The injection of low-energy bunches is analyzed, which allows to obtain a substantial longitudinal bunch compression, and also to obtain the bunch energy gain to the GeV range with a small energy spread at an acceleration length of about 10 centimetres. The influence of the beam loading to the final energy and the energy spread of the accelerated electrons is investigated.
A model for numerical simulation of the acceleration of polarized electrons has been elaborated. The effect of synchrotron radiation on the dynamics of energy gain and spin precession of a polarized electron beam is investigated in the process of acceleration at the self-consistent description of the nonlinear dynamics of a laser pulse and the generated accelerating and focusing plasma wake fields. It is shown that synchrotron radiation hardly affects the energy gain and polarization of the electrons, which are accelerated in fields characteristic of the moderately nonlinear mode of laser-plasma acceleration up to an energy of 4 TeV.
The methods of preserving the electron beam quality during acceleration and transportation of particles between stages was investigated. An analytical model of the dynamics of electron beam emittance has been elaborated. Matching the beam with an initial focusing force prevents the growth of the emittance during acceleration. The scheme with a smooth exit from the accelerating stage provides a quasiadiabatic change in the emittance and polarization of the beam.

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Few-cycle laser wakefield acceleration on solid targets with controlled plasma scale length

Authors: Neil Zaim[1]; Frederik Böhle[1]; Maïmouna Bocoum[1]; Aline Vernier[1]; Stefan Haessler[None]; Xavier Davoine[2]; Laurent Videau[2]; Rodrigo Lopez-Martens[1]; Jerome Faure[1]

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We study both experimentally and numerically the emission of energetic electrons during the reflection of a relativistic few-cycle laser pulse (1.4×10^{19} W/cm^2, 3.5 fs) on an overdense plasma. Two distinct acceleration regimes are identified (see Fig. 1), for which the electron ejection mechanisms are radically different. On the one hand, when the plasma-vacuum interface is sharp ("plasma mirror" regime), an attosecond electron bunch is emitted from the plasma at each laser optical cycle. These electrons can then be efficiently accelerated in vacuum by the reflected laser field. On the other hand, when the plasma scale length is larger (a few wavelengths), a different regime is identified in which electrons are accelerated by a laser wakefield in the near-critical density part of the plasma. Because of the resonant condition for plasma wave formation at such high densities, these electrons are only detected when the laser pulse duration is lower than 10 fs. This laser wakefield acceleration regime is characterized by a peculiar geometry where the plasma waves are rotated by the density gradient and the electrons are not emitted in the same direction as the driving laser pulse.

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Ballistic Injection and acceleration of positrons in bubble regime

Author: Zhiyi Xu[1]

Co-authors: Chaofan Xiao [2]; Haiyang Lu [1]

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A novel approach for positron injection and acceleration in laser driven plasma wakefield is proposed. A three-staged theoretical model is developed and confirmed through simulations. The proposal using two co-axis propagating beams, a Laguerre-Gaussian beam and a Gaussian beam, to drive wakefields in a preformed plasma volume filled with both electrons and positrons. The bremsstrahlung force is utilized to provide the transverse momenta for positron injection and those positrons can be trapped by the focusing field and then accelerated. The simulation shows that a relatively high-charged, quasi-monoenergetic positrons beams can be achieved. The positrons can be accelerated to more than 200 MeV within 2mm, which is similar to the acceleration of electrons in the same scenario.

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A novel scheme in the plasma beam dump

Authors: Guoxing Xia[1]; Oscar Jakobsson[1]; Alexandre Bonatto[1]; Yangmei Li[1]; Roger Pizzato Nunes[None]; Yuan Zhao[1]; Toshiki Tajima[2]

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Plasma beam dump has been recently proposed to absorb the kinetic energy of the spent beam from particle accelerators. In this presentation a passive beam dump with multiple stage plasma cells are investigated. In this new scheme, the stepped plasma densities are required after the first stage so as to maintain a high decelerating gradient compared to a uniform plasma. Particle-in-cell simulation results show that more than 90% of beam energy can be absorbed in this scheme.

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Plasma eyepiece for petawatt laser wakefield accelerators

Author: Ming Zeng[1]

Co-authors: Alberto Martinez de la Ossa [1]; Kristjan Poder [1]; Jens Osterhoff [1]

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Focusing petawatt-level laser beams to a variety of spot sizes for different applications is expensive in cost, labor and space. In this talk, we present a plasma lens, similar to an adjustable eyepiece in a telescope, to flexibly resize the laser beam by utilizing the laser self-focusing effect. Using a fixed conventional focusing system to focus the laser a short distance in front of the plasma, one can adjust the effective laser beam waist within a certain range, as if a variety of focusing systems were used. Such a setup is a powerful tool for laser wakefield accelerator experiments in state-of-art petawatt laser projects and allows for scanning focal spot parameters.

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Effect of the Laser Transverse Profile in a Capillary for Laser-Plasma Acceleration With External Injection

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The ESCULAP project aims at studying the capture and acceleration of relativistic electron bunches in a laser plasma wave. A configuration has been proposed where the interaction between the electron bunch and the plasma wave starts few Rayleigh lengths before the laser focal plane. In that configuration, a 100fs 10MeV electron bunch can be compressed up to ~ 4fs during the laser focusing. Then, to accelerate the electrons over large distances, in order to get energies up to several hundreds of MeV, the laser has to be guided over several cm. We have studied guiding by a hollow dielectric capillary. For such guiding, it is well known that the transverse profile of the laser intensity has a strong influence on the fluctuation of the longitudinal and transverse plasma field during the laser propagation. We analyzed in details the effect of these fluctuations on the electron bunch acceleration. Our results show that, even in the best match conditions, the usually used Gaussian transverse profile is not an optimum one, mainly because of the diffraction of the edges of the laser at the entrance of the capillary. We demonstrate that by reducing this diffraction through the use of a flattened Gaussian laser profile, an efficient acceleration of the electron bunch can be obtained over ten centimeters of capillary guiding.

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Axiparabola : a long focal depth mirror for plasma channeling

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In Laser-Plasma Accelerators (LPA), an ultra-short laser pulse is focused in a plasma to generate a plasma wave. The electromagnetic fields amplitude generated by this plasma wave are 3 orders of magnitudes higher than those created in classical accelerators. However, for reaching higher energies, the electron beam has to experience these fields on large distances. This remains an issue in LPA due mainly to three phenomenons : pump depletion, laser diffraction and electron dephasing.

We propose a new optical method that could overcome these limits, it is called axiparabola. This optical element will be used to create a plasma channel, which will act as a waveguide for the laser beam. It was inspired by an already existing optical element called axicon. It produces a long focal line by refracting the rays on a different focal position according to their impinging location on the incident surface of the axicon. The axiparabola exploits the same concept, but it uses a reflective component instead of a refractive one. The shape of the plasma channel created can also be controlled by means of a deformable mirror. Indeed, the addition of optical aberrations permits to produce a focal line with different intensity distributions. This technique can be applied to improve the guiding efficiency.

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Electron beam acceleration to 8 GeV with laser-assisted capillary discharge waveguides

Author: kei nakamura[1]

Co-authors: Anthony Gonsalves [2]; Joost Daniels [2]; Carlo Benedetti [2]; Chris Pieronek [2]; Tim de Raadt [2]; Sven Steinke [2]; Jian-hui Bin [2]; Stepan Bulanov [2]; Jeroen van Tilborg [2]; Cameron Geddes [2]; Carl Schroeder [2]; Csaba Toth [2]; Eric Esarey [2]; Kelly Swanson [2]; Liona Fan-Chiang [2]; Wim Leemans [2]

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The BELLA petawatt (PW) laser facility at Lawrence Berkeley National Laboratory is pursuing development of 10-GeV-class laser plasma accelerators. In this presentation, we show recent progress toward this goal: guiding of 0.85 PW peak power laser pulses over 200 mm in plasma channels and electron acceleration up to 8 GeV. This was achieved by increasing the focusing strength of a capillary discharge waveguide using an independent laser for inverse bremsstrahlung heating of the plasma. Details of the laser guiding structure and properties of the input / output laser pulses as well as electron beams will be discussed.

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Generation of super-ponderomotive electrons in interaction of relativistic laser pulses with long scale near critical plasmas.

Author: Olga N Rosmej[1]

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Experiments were performed to study electron acceleration by intense sub-picosecond laser pulses propagating in sub-mm long plasmas of near critical electron density (NCD). Production of hydrodynamically stable NCD-plasmas remains an important issue for such type of experiments. For these purposes we used low density CHO-foam layers of 300-500 μm thickness. In foams, the NCD-plasma was produced by a mechanism of a super-sonic ionization when a well-defined separate ns-pulse was sent onto the foam-target forerunning the relativistic main pulse. The effect of the relativistic laser pulse channeling and creation of quasi-static azimuthal magnetic and radial electric fields that keeps electrons in the channel ensured effective coupling of the laser energy into energetic electrons. Application of sub-mm thick low density foam layers provided substantial increase of the electron acceleration path in a NCD-plasma compared to the case of freely expanding plasmas created in the interaction of the ns-laser pulse with solid foils. Performed experiments on the electron heating by a 100J, 750 fs short laser pulse of 2-5×1019 W/cm2 intensity demonstrated that the effective temperature of supra-thermal electrons increased from 1.5-2 MeV, in the case of the relativistic laser interaction with a metallic foil at high laser contrast, up to 13 MeV for the laser shots onto the pre-ionized foam. The observed tendency towards the strong increase of the mean electron energy and the number of ultra-relativistic laser-accelerated electrons is reinforced by the results of gamma-yield measurements that showed a 1000-fold increase of the measured doses. The experiment was supported by the 3D-PIC and FLUKA simulations made for used laser parameters and geometry of the experimental set-up. Both measurements and simulations show high directionality of the acceleration process, since the strongest increase in the electron energy, charge and corresponding gamma-yield was observed close to the direction of the laser pulse propagation. The charge of super-ponderomotive electrons with E > 30 MeV reaches a very high value of 80nC.

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Generation of high energy electrons in moderately intense laser matter interaction with mass-limited targets

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Generation of high energy electrons using laser plasma interactions have been of immense interest over the past few decades, owing to their application in various fields like ion acceleration and fast ignition for ICF. Till date relativistic electrons (> 1 MeV) are mostly obtained at intensities of 10^{18} W/cm^2 and above. Such high intensities are generally achieved by using either high power lasers or specialized optics designed to reduce the focal spot size [1-6]. Both these procedures are financially cumbersome and are often limited by the number of shots that can be delivered at a stretch. The need for reducing the laser intensity and delivering high repetition rate system is therefore crucial for viable commercial applications. The other approach has been towards the use of structured targets especially mas-limited targets. Owing to their lack of a cold electron bath mass-limited targets are known to generate hotter electrons compared to bulk targets [7-9].

In addition, generation of high energy electrons has also been approached using target structure modification [6,8-9]. Structural modifications in nano or microscale dimensions result in local field enhancements leading to enhanced charged particle acceleration. However, these techniques too, are constrained by target quality and cannot be implemented for kHz systems. Deriving from these

preliminary ideas of mass-limited targets and target structure modification, we demonstrate a novel technique for generation of high energy electrons at kHz repetition rate using laser driven dynamic structure formation. We use a controlled pre-pulse to generate hydro-dynamically induced micro-structures on a 15 um Methanol droplet. The generation of these dynamic structures being laser driven ensures a 100% reproducibility at each target laser interaction.

On arrival of the main pulse of intensity 4×10^16 W/cm^2 the generated structures lead to confinement and enhancement of the laser field resulting in generation of electrons with energy as high as 6MeV and associated Bremsstrahlung at 100 times lower incident intensity than used in other contemporary experiments. The measured electron and X-ray spectrum are observed to be comprised of two distinct temperature regimes one ranging from 200 keV - 1MeV and other from 1 MeV - 6 MeV having temperatures about 200 keV and 1MeV respectively. These electrons and X-rays seem to have beam like characteristics, where the yield and directionality can be controlled by modulating the laser parameters. The measurement of the electron angular distribution reveals that the electrons confined in the laser polarization plane and are emitted mostly at ± 50° with respect to the laser backward direction, showing a highly direction beam of high energy electrons.

Building on this, we explore the prospect of kHz rate X-ray and electron imaging, in particular for medical imaging applications. We demonstrate proof of principle experiments showing high resolution <20 um imaging using both X-rays and electrons of biological and metallic samples revealing the possibility of a table-top high resolution, kHz rate electron and X-ray sources obtained at a moderate laser intensity of 10^16 W/cm^2.

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A novel method for measuring ultra-low emittance electron beams using structured light fields

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Co-authors: Christian Rödel [2]; Matt Zepf [2]

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Schemes for generating ultra-low emittance beams have been developed in the last years with applications, for example, in high-energy physics and free-electron laser science. Current methods for the characterization of low emittance beams such as pepperpot measurements or quadrupole scans are limit to about $e_n \approx 0.2\pi\ mm\ mrad$. Here we propose a novel method for the characterization of ultra-low emittance beams using structured light fields. In this scheme, two laser pulses are focused under an angle creating a grating-like intensity pattern. When the electron beam interacts with the structured light field, the phase space of the electron beam becomes modulated. By measuring the electron beam profile in the far-field, this method allows the characterization of ultra-low emittance beams. 2D PIC simulations are performed using a parameter range of $e_n = [0.01, 1]\ \pi$ $mm\ mrad$. We discuss several application scenarios for the characterization of ultra-low emittance beams.

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Influence of proton bunch parameters on a proton-driven plasma wakefield acceleration experiment

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AWAKE is a proton-driven plasma wakefield experiment under way at CERN that recently demonstrated the successful acceleration of injected electrons [1]. Underpinning the experiment is the fact that the long proton bunches (~6-12 cm) used to drive the wakefields undergo a self-modulation process, which in practice corresponds to a seeded instability [2]. The resulting train of microbunches (with lengths of the order of the plasma wavelength) is able to excite the wakefields resonantly.
In this work we use particle-in-cell (PIC) simulations to study the effects of small shot-to-shot fluctuations of the initial proton bunch parameters on the amplitude and phase of the wakefields resulting from a seeded self-modulation (SSM) process [3]. We demonstrate that the effects on the wakefield properties are small after saturation of the SSM. In particular, the phase variations correspond to much less than a quarter wakefield period, making deterministic injection of electrons (or positrons) into the accelerating and focusing phase of the wakefields in principle possible. We further use the wakefields from the simulations and a simple test electron model to estimate the same effects on the maximum final energies of electrons injected along the plasma, which are also found to be below the initial variations of $\pm5\%$. Lastly, we discuss the optimal injection conditions for electrons that lead to the most energy gain.

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A permanent magnet system for multi 100 MeV electron positron pair detection on QED experiments at Astra Gemini

Author: Dominik Hollatz[1]

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We present the development and experimental testing of a permanent magnet system to detect electron positron pairs on high intensity laser experiments at Astra Gemini. These experiments where designed to measure fundamental QED phenomena, like the Linear Breit-Wheeler effect as an example for e^+e^--pair production from quantum vacuum, or strong field effects like the Nonlinear Breit-Wheeler effect, measured on laser γ-beam collisions or as part of QED cascade processes, triggered by radiation reaction photons.

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Does Laser Polarization Matter in Laser Wakefield Acceleration?

Authors: Daniel Seipt[1]; Yong Ma[2]; Nick F. Baier[3]; Sahel Hakimi[2]; Amina E. Hussein[2]; Jesus Hinojosa[2]; Anatoly Maksimchuk[2]; John Nees[4]; Karl Krushelnick[2]; Alexander G. R. Thomas[2]; Franklin Dollar[3]

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Laser-wakefield acceleration experiments performed at the Hercules laser show a lowering of the self-injection threshold by circular polarized laser pulses, similar to the threshold lowering in wakfields driven in a warm plasma. In addition to the lower injection threshold, a significantly higher charge was observed for CP compared to LP for a wide range of parameters. We performed particle-in-cell simulations that support the observed experimental findings and indicate at different injection paths for CP laser pulses, which allows electrons to easier fulfill the injection condition.

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Transport of a laser plasma accelerated electron beam on COXINEL

Author: Driss Oumbarek Espinos[1]

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Laser Plasma Acceleration (LPA) enables to generate up to several GeV electron beam with short bunch length and high peak current within centimeters scale. However, the generated beam quality (energy spread, divergence) is not sufficient for numerous applications. In view of a Free Electron Laser application, the energy spread has to be adapted to reach the required small slice value while the beam divergence has to be controlled to avoid chromatic effects and emittance growth with strong focusing elements. We report here on the magnet based COXINEL line designed to transport an LPA electron beam from the source to the undulator, the different effects that can appear and the solutions. The beam is focused by a variable gradient quadrupole close to the source into a magnetic chicane for energy selection, followed by a set of four electro-magnet quadrupoles for proper focusing inside a cryo-ready undulator. Through gradient and position adjustment of the first triplet of quadrupoles the beam pointing and focusing can be compensated during experiment, then the chicane and the slit inside it can also be adjusted to optimize the energy selection and the steerers and electromagnetic quadrupoles are optimized to well align the electron beam with the undulator. The critical effects of the residual multipolar terms of the variable gradient quadrupoles are analyzed and effectively mitigated and the laser shot-to-shot induced electron beam variations are compensated thanks to the translation capacity of the variable quadrupoles. The experiments and the modeling are presented and they show good agreement and proper and robust transport has been experimentally achieved.

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LWFA in mismatched regime

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It is generally believed [1] that the matched laser profile provides the optimal regime of electron acceleration. The laser spot size and the pulse duration evolve a little during laser propagation when the laser intensity, the plasma density and the laser profile are matched. The scaling laws predicted the electron energy as a function of the laser-plasma parameters have been formulated for the matched bubble regime [1,2]. However it has been shown in the recent experiments and numerical simulations [3,4] that the energy of the electrons accelerated in the mismatch regime can exceed the energy predicted by these scaling laws. The mismatch regime remains largely unexplored but looks attractive to increase the energy of the accelerated electrons.
We present recent experimental data on LWFA in the mismatch regime. Up to 20 J, 60fs laser pulses are focused with f/40 focusing system on the input of a gas cell. The laser intensity in the 40 um focal spot is enough to exceed the self-injection threshold. The extracted experimental dependencies are supported by full-scale PIC modeling of LWFA acceleration and by numerical simulation of gas distribution inside the gas cell. The accuracy of spectra reconstruction affected by not perfect pointing stability of the accelerated electron beam are discussed. The electron spectra with cut-off energies beyond 1 GeV and beyond of the predictions of the similarity theory of the bubble regime are demonstrated.

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An experimental study of transverse and longitudinal wakefields driven by a self-modulating proton bunch

Authors: Marlene Turner[1]; The AWAKE Collaboration[None]

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The Advanced Wakefield Experiment (AWAKE) recently demonstrated that: 1) a 400 GeV/c proton bunch (with a bunch length 30-100 times longer than the plasma electron wavelength) self-modulates over 10m of plasma; 2) externally injected ~20 MeV electrons can be accelerated to GeV energies in the resonantly excited wakefield. In this contribution, we show the results of an AWAKE experimental study: we measured the integrated amplitude of the longitudinal and transverse wakefields for different laser seed positions (the laser pulse is overlapped with the proton bunch to seed the self-modulation process) and electron delays (distance between the laser pulse and the externally injected electrons). By changing those parameters we change the initial seed level, the number of protons that contribute to driving the wakefields (and thus the growth rate of the self-modulation process) as well as the amplitude of the driven wakefields. We show that the accelerated electron energy and the transverse proton bunch distribution agree with the trends observed in numerical simulations as well as the expectations from simple considerations.

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CO2-laser-driven laser-wakefield acceleration experiments at Brookhaven's Accelerator Test Facility

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The advent of chirped-pulse-amplified CO₂ lasers [1] has yielded picosecond, long-wavelength infrared (λ=10 *μm*) laser pulses of terawatt (TW) peak power suitable for driving laser wakefield accelerators (LWFAs) with high ponderomotive force (~Iλ²) in low-density (10¹⁶ cm⁻³ < n_e <10¹⁸ cm⁻³) plasma [2]. Such pulses can drive *GeV* plasma accelerating structures large enough (λ_p up to hundreds of *μm*) to enable precise injection of <1%-energy-spread lepton bunches from external linacs and detailed 4D imaging of wake density [3] and field [4] profiles via optical [3] and electron [4] probing. The **AE-71** project at Brookhaven's Accelerator Test Facility (ATF) is devoted to exploring these opportunities. We report time/space-resolved optical measurements of the electron density structure of self-modulated wakes driven by CO₂ laser pulses (4 *ps*, 0.5 *J*, focus w₀ ≈ 25 *μm*) [5] in fully self-ionized hydrogen (0.4< n_e <3 10¹⁸ cm⁻³) with new experimental and simulation results. Wake amplitude and dynamics were observed by monitoring collective Thomson scattering (CTS) of a co-propagating 532 *nm*, 4 *ps*, electronically synchronized probe pulse (jitter ~200 *fs*). First- and second-order CTS sidebands, at Δω=±ω_p, ±2ω_p from the center probe frequency, were observed as a function of pump-probe time delay Δt, plasma density n_e, drive laser peak power P, and focus position within the gas jet. SPACE [6] and OSIRIS [7] simulations explain key observations, including unexpected spectral splitting of sidebands at Δt≈0, wake lifetimes of ~10 *ps*, and dependence of wake amplitude on n_e and P.
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Working group:

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Ion dynamics for beam-driven wakefield acceleration on initially neutral gases

Authors: Thales Silva[1]; Jorge Vieira[1]; Mark Hogan[None]; Vitaly Yakimenko[2]; Konstantin Lotov[3]; Vadim Khudyakov[3]; Alexander Sosedkin[3]; Rafal Zgadzaj[4]; Michael Downer[4]

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Because the proof of principle of operation of plasma-based accelerators is firmly established, much effort is currently been put in demonstrating the generation of relativistic electron bunches with the required quality for various scientific and technological applications. In addition to high-quality beams, several applications also demand very high repetition rates. Here, the long-term plasma dynamics can have a dramatic role in determining beam quality. Understanding the self-consistent interaction between relativistic plasma electrons and the background plasma ions is critical to understand the long-term plasma dynamics, but many open questions still remain.

In this work, we perform particle-in-cell simulations with the code OSIRIS modeling plasma wakefield acceleration experiments done at SLAC-FACET. A beam driver with an energy of 20GeV is used to ionize and drive wakefields in an initially neutral Lithium column. We focus on both the beam dynamics as it passes through the oven and explain and model the ion and electron dynamics for

time delays smaller than 200ps, where we show that the Lithium column dynamics is dominated by their initial interaction with the wakefields excited by the driver. We find good agreement between experimental data and simulations at this time scale before impact ionization becomes relevant. We also compare our results with a similar setup where the plasma is pre-ionized, pointing out the main differences and its possible effects on the long-time plasma dynamics.

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Stable positron acceleration in self-generated hollow channels

Authors: Thales Silva[1]; Jorge Vieira[1]

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Hollow plasma channels are promising candidates for the acceleration of electron and positron beams, as the transverse forces are nearly vanishing inside the hollow channel, as long as the accelerated bunches are perfectly cylindrically symmetric and injected on the axis of the hollow channel structure. Furthermore, the accelerating fields can also be nearly constant provided that the accelerated bunch current profile is appropriately tailored. These features make it fundamentally possible to preserve beam quality during the acceleration [1]. In realistic situations, however, small asymmetries in the beam profile or small misalignments between the beam and the hollow channel axis will seed the growth of the beam breakup instability, thus stopping the acceleration prematurely and degrading beam quality substantially. These beam breakup instabilities are a severe limitation on the use of hollow channels for particle acceleration [2].

Several schemes were recently proposed to stabilize hollow channel acceleration. For example, Pukhov et al. investigated electron acceleration in hollow channels with a plasma filament on axis and simulation results showed a stable acceleration in meter-long hollow channels [3]. Amorim et al. studied hollow channels self-generated by a tightly focused positron beam and found regions of accelerating and focusing fields for positrons [4].

Here, we investigate a new mechanism for stabilization of positron acceleration in hollow channels. Using theory and particle-in-cell simulations with the code OSIRIS [5], we show that the ion motion associated with the wakefield ponderomotive force can form a hollow plasma channel self-consistently. The hollow plasma channel can then be excited by a second particle beam that drives a nonlinear plasma wave with positron focusing and accelerating fields. We investigate the possibility of high-quality acceleration in this scheme.

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Working group:

Laser-driven electron acceleration

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Multi Spectral Coherent Transition Radiation Imaging and Interferometry of Laser Wakefield Accelerated Electron Bunches

Authors: Maxwell LaBerge[None]; Alex Lumpkin[1]; Omid Zarini[2]; Andrea Hannasch[3]; Rafal Zgadzaj[4]; Alexander Debus[5]; Brant Bowers[3]; Jurjen Couperus Cabadağ[6]; Alexander Köhler[2]; Ulrich Schramm[2]; arie irman[2]; Michael Downer[4]

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The low transverse emittance of electron bunches from laser wakefield accelerators (LWFAs) makes these advanced accelerators attractive for compact FELs and colliders. Single-shot, direct, non-intercepting diagnostics of this emittance outside the LWFA are, however, needed. Here we present single-shot coherent transition radiation (CTR) imaging and interferometry data from electron bunches only ~1mm after emerging from a 300 MeV LWFA. We combine near field (NF) and far field (FF) interferometric imaging of CTR emitted from a foil placed directly after our gas jet and a laser-rejection foil. We also employ a multi-octave CTR spectrometer to diagnose the longitudinal structure of the beam (see presentation by A. Debus). The NF system directly images the foil with high resolution for each of several narrow visible bandwidths. Through point spread function (PSF) analysis, the transverse profile of the beam component responsible for each CTR wavelength is deduced from this measurement. We find typical transverse rms radii $2 \leq \sigma$ perp ≤ 3 μm. The FF system collects transition radiation from the same foil and from a foil ~2 cm downstream. The sum of this radiation is then focused onto a camera with a narrow bandpass filter. This double foil Wartski interferometer [1] diagnoses divergence of the portion of the bunch that is micro-bunched at each observed wavelength. We find typical rms divergence $\sigma_\theta \approx 0.5$ mrad, several times smaller than the ensemble divergence ($\sigma_\theta \approx 2.5$ mrad) measured at a downstream electron spectrometer screen. From beam size and divergence, we determine emittance at the first foil location on a single shot for the fraction of the beam that is coherent at the selected bandwidth. Since our CTR imaging/interferometry system measures multiple 10 nm bandwidth spectral regions simultaneously on each shot, and our CTR spectrometer measures spectra over > 5 octave bandwidth, the potential exists to reconstruct a 3D charge distribution at the foil. We will present data and analysis on bunch size and divergence from a combination of FF and NF imaging systems as well as bunch substructure revealed by these diagnostics.

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Working group:

Laser-driven electron acceleration

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Optical field ionized gases as a platform for investigating kinetic plasma instabilities

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Kinetic plasma instabilities such as two-stream [1], filamentation [2] and Weibel [3] instabilities arising from anisotropic electron velocity distributions (EVDs) involve in many scenarios, for instance,

electron beam transport in plasmas [4-5], collisionless shocks [6], laser-created colliding plasmas [7-8] and instability mediated gamma ray flashes [9]. These instabilities have been extensively investigated in theory and simulations yet there have been only a handful direct laboratory verifications of these instabilities due to the lack of a suitable platform that would allow initialization of known EVDs. Here we demonstrate a relatively simple laboratory platform that utilizes optical field ionized plasmas which have anisotropic EVDs for studying kinetic plasma instabilities. We show that when high-density plasmas (1018-1019 cm-3) are formed by sequentially ionizing both helium electrons using a circularly polarized (CP) laser, the streaming and filamentation instabilities grow and saturate in ~one ps and decay as a result of collisionless phase space diffusion and particle trapping. Thereafter a Weibel instability starts to grow in the plasma. The polarization dependent frequency and growth rates of these kinetic instabilities, measured using Thomson scattering of a probe laser, agree well with the kinetic theory and simulations.

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Working group:

Laser-driven electron acceleration

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Initial benchmark experimental results using high contrast high intensity CAEP-PW laser

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Invention and application of chirped pulse amplification technique in short pulse laser has been leading to unprecedented ultra high laser peak power[1]. After more than three decade development, a few petawatt class lasers, whose pulse durations vary from a few femtoseconds to several picoseconds, have been built up around the world[2]. The focused laser intensity goes beyond 1021W/cm2. The ultra-intense and ultra-short pulse laser has wide applications, such as high energy ion acceleration, laser wakefield acceleration, ultra fast x-rays, and fast ignition. The first multi hundred terawatt laser (SILEX-I) started operating in Laser Fusion Research Center, CAEP in 2004[3]. This first high peak power laser facility was followed by an even larger scale laser facility "Xingguang-Ⅲ", which is capable to output three synchronized laser pulses of femtosecond, picosecond, and nanosecond pulse durations[14]. In 2016, the third ultra-high power laser "CAEP-PW", of 4.9 petawatt and 18 femtosecond duration, was commissioned. The laser contrast of "CAEP-PW" reaches higher level thanks to the employment of the complete OPCPA technique. The contrast ratio is better than 1010 20 ps before the main pulse[5]. After the setup of target area of CAEP-PW, the first experimental investigation started in June, 2017. The main results are reported in this presentation.
The basic experiments focused on the characterization of laser foil target interaction. A comprehensive diagnostics were fielded around the targets. A set of experimental data, including spatial

resolved x-ray emission, the image of the coherent transition radiation, the harmonic spectra in reflective direction, the energy spectra and beam profile of accelerated ions, hot electron spectra, and transmitted laser energy fraction and distribution, were collected. From the complete data set, the on-target laser spot size, intensity, and prepulse level were estimated. It's confirmed that the laser intensity reached 5×1020W/cm2 with a 5.8 μm focus (FWHM) and 30 femtosecond pulse duration. The high contrast laser guaranteed that laser transmission did not occur through the CH foil of thickness larger than 50 nm. When S-polarized laser was obliquely impinged on the 50 nm thick CH foil, the protons energy up to 40 MeV were observed in the laser direction, which was about two times higher than that in the target normal direction.
Key words: Multi petawatt, femtosecond laser, OPCPA, ion acceleration, laser plasmas interaction

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Working group:

Laser-driven ion acceleration

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Highly charged heavy ion acceleration from a high temperature solid heated by J-KAREN laser system

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Co-authors: Nicholas Dover [2]; Masayasu Hata [3]; Hironao Sakaki [2]; Kotaro Kondo [2]; Takumi Miyatara [2]; Hiromitsu Kiriyama [2]; James Koga [2]; Natsumi Iwata [3]; Alkhimova Mariya [4]; Alexander Pirozhkov [2]; Anatory Faenov [3]; Tatiana Pikuz [3]; Akito Sagisaka [2]; Yukinobu Watanabe [5]; Masaki Kando [2]; Kiminori Kondo [2]; Yasuhiko Sentoku [3]

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The interaction of relativistically intense short pulse (~few tens of fs) laser pulse with solid material generates quasi-static electric fields with strengths of > TV/m are produced within a short distance of less than μm [1]. Thanks to the very strong field gradient, the field can accelerate ions beyond MeV within a micron. Unlike the acceleration of low-Z ions, acceleration of the high-Z ion is more complicated because charge state distribution should be controlled for pursuing higher acceleration efficiency or for manipulating a spectral shape of the ions. However, all the proposed laser-driven acceleration mechanisms, including the most investigated and easy to implement mechanism, Target Normal Sheath Acceleration (TNSA) [2], are far from being fully understood in the sense of ionization mechanisms. To address this issue, we investigate the ionization mechanisms in HED plasma produced by a laser pulse of peak intensity ~5×10^{21} Wcm^{-2} interacting with a silver 500 nm target by using J-KAREN laser system KPSI, QST [3]. Even the J-KAREN laser is high contrast laser system the pulses show not completely ideal (Gaussian-like) temporal shape. The existence of the rising edge is an inherent feature of high power laser systems based on highly non-linear processes and eliminating this rising edge is challenging, even when applying pulse cleaning techniques such as plasma mirrors and/or a plasma shutter. The rising edge interacts with target in advance to the main pulse and can prematurely expand the target resulting in reduction of proton cutoff energies. This is a serious barrier for not only proton acceleration, however we found this temporal shape can be a beneficial effect on heavy ion acceleration from the bulk of the target. In the experiment we observed that silver ions with a charge state of ~ +40 are accelerated up to ~15 MeV/u with the particle number of $(2\pm1)\times10^{6}$ ion/shot within an energy range of 10-15 MeV/u. With the help of hydrodynamic, particle-in-cell (PIC) simulations and analytical estimates, we find out that the ions in the contaminant layer pre-expands and effectively detaches from the target, still keeping the target material intact, so that the bulk ions are exposed to stronger sheath fields and accelerated to higher energies. The highly charged energetic silver ions are generated via electron collisions in the hot (~6 keV electron temperature) solid plasma. The reported heavy ion acceleration mechanism is in unexplored physical regime, which has been generated for the first time via interaction with a laser with an ultra-high intensity using the state-of-the-art laser system J-KAREN.

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Working group:

Laser-driven ion acceleration

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Achieving highest proton intensities with a laser-driven ion beamline

Authors: Diana Jahn[None]; Dennis Schumacher[1]; Christian Brabetz[1]; Johannes Ding[2]; Rene Leonhardt[2]; Florian Kroll[3]; Florian-Emanuel Brack[4]; Ulrich Schramm[5]; Abel Blazevic[1]; Markus Roth[2]

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In the past two decades, the generation of intense ion beams based on laser-driven sources became an extensively investigated and promising field. The LIGHT collaboration (Laser Ion Generation, Handling and Transport) combines a laser-driven proton/ion source with conventional accelerator technology.

In this context, a laser-driven multi-MeV ion beamline was realized at the GSI Helmholtzzentrum für Schwerionenforschung. The local petawatt laser system PHELIX drives the TNSA source resulting

in an exponentially decaying spectrum with protons up to an energy of 28 MeV. The laser accelerated protons are captured and collimated at a chosen energy using a pulsed high-field solenoid.
Afterwards, the collimated proton bunch is injected into a conventional RF cavity and rotated in longitudinal phase-space. Through this rotation, shaping the bunch in energy or time is possible. We achieved monoenergetic proton bunches at a central energy of 8 MeV with an energy spread less than 3% or pulse durations below 500 ps. In a second target chamber, 6 m away from the TNSA target, an additional solenoid is used for final focusing creating a focal spot of 1.1 mm x 1.2 mm (FWHM).

In this talk, the complete beamline with its focusing capabilities at the interaction point will be discussed. The final parameters reachable at the target point will be presented for planning of future applications.

Working group:

Laser-driven ion acceleration

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Laser-driven Ion Acceleration and Applications at the Extreme Light Infrastructure (ELI)

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Recently the ELIMAIA (ELI Multidisciplinary Applications of laser-Ion Acceleration) beamline has been installed at ELI-Beamlines in the Czech Republic. The main goal of ELIMAIA is to offer short ion bunches accelerated by lasers with high repetition rate to users from different fields (physics, biology, material science, medicine, chemistry, archaeology) and, at the same time, to demonstrate that this source can be delivered through innovative and compact approaches. In fact, ELIMAIA will provide stable, fully characterized and tunable particle beams accelerated by PW-class lasers and will offer them to a broad community of users for multidisciplinary applied research, as well as fundamental science investigations.
An international scientific network, called ELIMED (ELI MEDical applications), particularly interested in future applications of laser-driven ions for hadrontherapy, has already been established. In such a perspective ELIMAIA will enable to use laser-driven proton/ion beams for medical research thanks to the reliability and accuracy of its particle beam transport and dose monitoring devices.
The current status of commissioning of the ELIMAIA beamline, along with experimental results on innovative targetry and diagnostics for laser-driven particle acceleration will be presented and discussed, including preliminary tests carried out during the ramp up phase of the HAPLS (L3), PW-class, 10 Hz laser system at ELI-beamlines.

Working group:

Theory and computation

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Applications of carbon nanotube foams as near-critical-density targets for laser-driven ion acceleration and X-ray/Gamma-ray generation

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Carbon nanotubes are allotropes of carbon with a cylindrical nanostructure. When they randomly bond with each other by van der Waals forces, so-called carbon nanotube foam (CNF) is formed. The average density of CNFs lies in the range of a few mg/cm^3 to tens of mg/cm^3. If fully ionized, such a thin foam can turn to a plasma slab with critical density. Here we report the recent progress on the fabrication and the applications of CNF as near-critical-density targets for laser-driven ion acceleration and X-ray/Gamma-ray generation. Our recent experimental results show that highly energetic carbon ions can be obtained by shooting a CNF-coated ultrathin solid foil with PW laser pulses. Ions in the solid foil undergo a cascaded accelerations process if the density of CNF is lower than 3 mg/cm^2. Our simulation study also reveals that such double-layer targets can be employed to efficiently generate bright X-ray/Gamma-ray pulses with currently available PW lasers in a very simple way. Preliminary experimental results using a 100 TW laser will be presented.

Working group:

Laser-driven ion acceleration

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The role of nanoscale dimensionality in the ultrafast recovery of materials excited by picosecond bursts of laser-driven ions

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Working group:

Laser-driven ion acceleration

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Multi-Species dynamics in the radiation pressure acceleration of ions from ultra-thin foils

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As the community prepares for the next generation of laser facilities coming online in the near future, attention will shift towards advanced mechanisms such as the radiation pressure acceleration (RPA) which has been predicted to be the dominant ion acceleration mechanism at intensities >10^{22}W/cm2 [1]. Recent studies have shown that current facilities can also enter this regime by irradiating ultra-thin foils with circularly polarised (CP) pulses at intensities [2], I ~6x10^{20}W/cm2 on target with the use of double plasma mirrors for contrast enhancement [2]. The use of CP light helps to reduce electron heating thus mitigating relativistic transparency and allowing the target to remain opaque and efficiently accelerated by RPA in the Light Sail mode.
The work presented here will focus on a recent campaign on the GEMINI laser system at the Rutherford Appleton laboratory which has advanced the results reported in [2], by improving the efficiency of the bulk species (Carbon) acceleration and demonstrating the existence of an optimal thickness for Light Sail acceleration. Additionally, the data highlight the importance of multispecies dynamics during the acceleration with clear evidence for a different acceleration mechanism for Carbon ions and protons ions.
Ultra-thin (2-100nm) amorphous carbon foils were irradiated at normal incidence with an f/2 parabola by a high contrast 40fs laser pulse with ~6J on target, producing an intensity of ~5x10^{20}W/cm2. The data shows a clear difference between the effects of linearly polarized and CP light on the ion energies with CP generating significantly higher carbon energies for thinner targets, with an optimum thickness of 15nm.
For this type of target, experimental data shows the acceleration of C6+ up to 33MeV/n (400MeV) while the corresponding proton energies are less than 18MeV. 2D PIC simulations (carried out with the EPOCH code) suggest that this may be associated to a non-negligible laser pedestal on the sub 6ps timescale (within the reflection window of the plasma mirror). Protons, with the higher q/m ratio, will expand much faster than C6+ beyond the short Rayleigh range associated with the f/2 parabola before the peak of the pulse arrives. The remaining plasma will remain an over-dense, sub-wavelength scale, carbon-electron plasma that can still be efficiently accelerated by RPA.

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Working group:

Laser-driven ion acceleration

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Observing Dynamics of Electron Solvation in H2O During Ultrafast Pulsed-ion Radiolysis

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Understanding the effects of ion interactions in condensed matter has been a focus of research for decades. While many of these studies focus on the longer term effects such as cell death or material

integrity, typically this is performed using relatively long (>100 ps) proton pulses from radiofrequency accelerators in conjunction with chemical scavenging techniques [1]. As protons traverse a material, they generate tracks of ionisation that evolve rapidly on femtosecond timescales. Recently, measurements of few-picosecond pulses of laser driven protons have been performed via observation of transient opacity induced in SiO2 with sub-picosecond resolution [2]. Here we present results showing a dramatic difference in the solvation time of electrons generated due to the interaction of relativistic electrons/X-rays and protons in liquid water. The solvation time of these electrons increases from <10 ps for fast electrons and X-rays to >190 ps for the protons. The role of ionisation tracks and subsequent formation of nanoscale cavities in water on the extended recovery time is discussed.

Working group:

Laser-driven ion acceleration

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Towards the 100-MeV proton mark at the PHELIX facility

Authors: Vincent Bagnoud[None]; Johannes Hornung[1]; Annika Kleinschmidt[2]; Victor Schanz[2]; Yannik Zobus[2]; Berhnard Zielbauer[2]; Jonas B. Ohland[2]; Udo Eisenbarth[2]

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Nowadays' research on laser-driven proton acceleration is focusing on the interaction of relativistic-intensity laser pulses with sub-micrometer targets. With such targets, a variety of acceleration mechanisms can be studied, from the robust TNSA to more advanced schemes that predict better performances in particle energy and beam parameters. The ideal conditions for this type of studies are thin targets and sub-picosecond-long laser pulses with relativistic intensities as high as possible, where the target condition (pre-ionization, pre-expansion) at the time of the interaction plays a fundamental role.
For this reason, a series of experimental campaigns using PHELIX to determine the scaling of proton generation with various parameters like laser energy, laser intensity, or laser temporal contrast have been conducted. In the meantime, the PHELIX laser facility is being improved constantly. For instance, the on-target intensity has been increased by nearly one order of magnitude over the last five years, reaching maximum on-target intensities at about 5×10^{20} W/cm^2 for 200 J pulses.
Our findings show that the temporal contrast of the laser plays a predominant role in efficiently coupling the laser energy into particles. Even at these high intensities, the ASE pedestal of the PHELIX laser pulse is low enough to avoid the buildup of a nanosecond pre-plasma thanks to the front end based on ultrafast parametric amplification. However, the ionization threshold is reached during the rising slope of the pulse, about 100 ps before the maximum of the intensity, which we have identified as the limiting factor for shooting ultra-thin foils. For these PHELIX parameters, record-high maximum proton energies above 90 MeV have been observed with targets about 1 micrometer thick.
In this talk, we will present the most recent results of the last experiments conducted at PHELIX in 2018, putting an emphasis on the characterization of the target state at the very time of the interaction with advanced optical methods. We will also review the current bottlenecks that we are working on, to improve these results even more.

Working group:

Laser-driven ion acceleration

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Estimation of the preplasma scale length via time-resolved spectroscopy of back-reflected light

Authors: Johannes Hornung[1]; Annika Kleinschmidt[2]; Mingyuan Shi[3]; Marc Günther[4]; Yannik Zobus[2]; Matt Zepf[3]; Vincent Bagnoud[None]

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Many of the underlying mechanisms for laser-driven ion acceleration exploit the interaction of an ultra-intense laser pulse with sub-micrometer thin foils. These mechanisms rely on well-defined plasma conditions at the time of the maximum laser intensity. These conditions, especially the preplasma scale length, are extremely hard to measure and remain mostly not known, which prevents a detailed study and an efficient use of these acceleration mechanisms.

During this interaction, a part of the laser pulse is reflected back at the critical plasma density and carries important information about the interaction process itself. The spectrum is modulated due to effects such as relativistic self-phase-modulation and is additionally Doppler-shifted by the moving critical density occurring during hole boring or plasma expansion. The interplay between these effects is intimately related to the plasma density gradient in the vicinity of the reflection point, as a shallow plasma gradient will favor hole boring, leading to a red Doppler-shift or instance, whereas a steep plasma gradient will impose a strong electron-pressure, counteracting the laser pressure.

To study these effects and corresponding time scales, a diagnostic for back-reflected light based on frequency resolved optical gating (FROG) has been commissioned at the PHELIX facility at GSI Helmholtzzentrum für Schwerionenforschung GmbH, where intensities above 10^{20} W/cm² and pulses with ultra-low temporal pedestal are available. We have conducted measurements for different plasma conditions: at first with the standard temporal profile of the laser pulse, then with a double plasma mirror setup that dramatically steepens the pulse. A supplementary characterization of the target state was made by measuring the transmitted pulse, showing that the plasma mirror enables 50- nm thick targets to remain opaque throughout the interaction.

As a support to the experimental data, we have performed 1D and 2D simulations using the particle-in-cell code EPOCH, with parameters as close as possible to the experiment, including a pre-expanded target. We varied the scale length of the plasma and monitored its effect on the spectrum of the back-reflected pulse. With decreasing scale-length around or below 1 µm, a transition from a red shifted spectrum to a blue shifted one at even higher gradients is visible, as observed experimentally.

We believe that this method can deliver some estimates on the preplasma expansion on a sub-micrometer scale, a spatial range which can be hardy covered by other experimental methods like shadowgraphy or interferometry (though more complex Frequency Domain Interferometry can access similar ranges). This result is of particular interest for the understanding of experiments aiming at laser-driven ion acceleration, which mostly rely on unexpended foils to maximize the acceleration process.

Working group:

Laser-driven ion acceleration

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Probing the energy loss of TNSA ions in plasma with the LIGHT beam line

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Investigating the energy loss of ions in plasma is a long standing research topic of the plasma physics group at GSI. In particular at low particle velocity, which corresponds to the maximum of the stopping power, the theoretical descriptions based on perturbative approaches fail and models show a discrepancy. This lack of understanding is particularly critical and could be a reason for the issues met with ignition at NIF. One reason therefore could be that the alpha-heating was overestimated due to disregard of coupling effects in the compressed plasma leading to lower stopping powers.
In the parameter region accessible at GSI, the known perturbative stopping-power models are expected to be inaccurate due to the strong beam-plasma coupling. Significant discrepancies have been reported between the different theoretical approaches, reaching 30% in our configuration.
First experiments using ions from the GSI UNILAC accelerator with a pulse length of 5-7 ns to probe a laser generated fully ionized carbon plasma showed energy-loss values significantly smaller than predicted by 1st order perturbation theory. To improve the quality of these measurements shorter ion pulses would be preferable. Therefore, we intend to perform energy loss measurements with laser accelerated ions, shaped with the LIGHT (Laser Ion Generation, Handling and Transport) beam line set up at GSI.
The talk will cover the efforts to create mono-energetic ($\Delta E < 5\%$) laser accelerated C-ion pulses with a pulse length of below 1.5 ns for probing a laser generated plasma 6 m away from the TNSA target.

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Laser-Ion-Acceleration using Water Droplets and Optical Probing

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We present results from a laser-driven proton acceleration experiment performed at the JETI 40 laser system in Jena, Germany. Here, we investigated the influence of the position of water micro-droplets relative to the laser's focus along the polarization axis on the maximum kinetic energy of accelerated protons, either for a steep plasma gradient or an additional pre-plasma. The first case was realized by frequency doubling the laser pulses of the JETI 40 which drastically increases the temporal intensity contrast while for the latter case an additional pre-pulse was introduced. The highest proton energies were achieved when the droplets were irradiated under grazing incidence without a pre-plasma. Two-dimensional Particle-in-Cell simulations show that in this case hot electrons were confined near the droplets' surface due to self-generated electromagnetic fields. This confinement of electrons enhances the electric field responsible for proton acceleration. The laser-plasma interaction was observed and controlled using the few-cycle optical probe of the JETI 40 system.

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Spatial and spectral filtering of laser-accelerated proton beams for radiobiology applications

Author: Marco Cavallone[1]

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Laser-accelerated protons have a great potential for innovative experiments in radiation biology and chemistry due to the ultra-high dose rate (109 Gy/s) delivered in nanosecond time scale. However, the broad angular divergence around the propagation axis makes them not optimal for applications with stringent requirements on dose homogeneity and total flux at the target. The simplest solution often adopted to increase the homogeneity over a surface is to spread the beam with a flat filter. Such method implies a considerable loss in the total flux over the surface, which is a critical aspect with laser-accelerated proton beams because of the limited charge per bunch available. We demonstrated the use of a Genetic Algorithm assisted approach to design a filter optimally matching the beam parameters. The algorithm can be set to increase the dose homogeneity on an in- vitro biological target while keeping at the same time an acceptable value of average dose per shot. Among different studied configurations we found that a filter placed inside the quadrupole transport system is more efficient than a filter placed after it, allowing a better trade-off between dose homogeneity and average dose at the target. This is explained by the fact that such a filter flattens the beam profile not only through scattering but also by taking advantage of the quadrupole chromaticity to intermingle the proton trajectories. The numerical application to the real case of 7.5 MeV TNSA-driven proton beam will be explained[1]. The presented method allows the production of a laser-driven proton beam fully compatible with radiation biology applications using existing laser sources. Our approach can be further extended to improve spectrum or effective LET homogeneity for thicker targets irradiation.

1. L. Pommarel et al. (2017) https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.20.032801

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Properties of ion beams driven by a high-energy ultra-intense laser at the conditions relevant for ion fast ignition

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Laser-driven ion fast ignition (IFI) of fusion targets requires ultra-intense ion beams with parameters whose approximate values are estimated to be as follows (e. g. [1]): the mean ion energy ~10 − 50 MeV/nucleon, the beam intensity ~10^20
W/cm2, the beam fluence ~1 GJ/cm2, the ion pulse duration ~1 - 10 ps, and a total beam energy of ~10 − 20 kJ. To achieve these parameters, an effective ion acceleration scheme and a 100 kJ class picosecond laser driver is necessary. In this contribution, detailed properties of carbon ion beams driven by a 100-kJ, 1-ps laser is numerically investigated, and the possibility of attaining the ion beam parameters required for IFI through the use of an ultraviolet (0.25 um) or infrared (1.05 um) laser beam is discussed. The numerical simulations were performed for realistic, relevant for IFI parameters of the laser pulse and the carbon target using multi-dimensional (2D3V) particle-in-cell PICDOM code, which includes, in particular, the dynamic ionisation of the target and radiation losses due to synchrotron radiation. It was found that for relatively thin targets (LT < 10 um) and a laser beam diameter dL < 20 um, both the radiation pressure acceleration (RPA) mechanism and the sheath acceleration (SA) mechanism significantly affects the ion beam characteristics, and that the ion beam parameters such as the beam intensity, density and fluence are rather far from what is required, independent of the laser wavelength. In the case of thicker targets (LT ~20 − 40 um), the RPA in the hole-boring regime is a dominant mechanism of ion acceleration, and for dL ~10 um and a small distance from the target (x < LT) the ion beam parameters are close to or higher than what is required, both for the UV and IR laser beam. However, the angular divergence of the ion beam driven by the IR laser is smaller than that for the UV laser and, as a result, a decrease in the ion beam intensity and fluence with an increase in the distance from the target is slower for the IR laser-driven ion beam, which is essential for the application of the beam to the ignition of a real fusion target. Factors limiting the possibility of achieving ion beam parameters suitable for IFI will be discussed, along with possible ways to improve the ion beam parameters to better fit them to IFI requirements.
[1] J.C. Fernandez, B.J. Albright, F.N. Beg, M.E. Foord, B.M. Hegelich, J.J. Honrubia, M. Roth, R.B. Stephens, and L. Yin, Nucl. Fusion 54, 054006 (2014).

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A compact pulsed high-field beamline for radiobiological studies with laser-driven protons

Author: Florian Kroll[1]

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Laser-driven ion sources exhibit unique beam properties that open up application opportunities but also pose challenges. Especially the large source divergence (~ 20° half angle) as well as the broad energy bandwidth (100%) of laser-accelerated ion bunches limit their applicability. Yet, temporal structure (~ps bunch durations) and intensity (10^{13} ions per bunch) have roused interest for these novel sources among multiple scientific communities, ranging from warm dense matter research, over cultural heritage to medicine and biology.

We present a versatile pulsed high-field magnet technology platform that is tailored to spectrally and spatially shape laser-driven ion beams while conserving their favorable qualities. The presentation will focus on the development, characterization and experimental proof-of-principle of a tunable pulsed beamline prototype suited to provide homogeneous dose distributions to radiobiological

samples, such as zebra fish embryos, tumor spheroids and small in vivo tumors, e.g. in mice. The beamline consists of two pulsed high-field solenoids (B ≤ 20 T). It has been implemented at the Dresden laser acceleration source (Draco). Using the PW beam of Draco we investigated the feasibility of worldwide first controlled volumetric in vivo tumor irradiations in a dedicated mouse model with laser-accelerated protons. The study shows the reliable generation of homogeneous dose distributions laterally and in depth. Practical issues, like magnet repetition rate and beam optical quality, will be critically discussed in the light of new experimental findings and technological developments toward a high-repetition-rate, high-field beamline for in vivo radiobiology studies.

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Nearcritical carbon foam targets for laser driven ion acceleration

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In this contribution, we present the result of an investigation of foam-based targets for laser-driven ion acceleration. The study was performed in collaboration between the Laser-Particle Acceleration group at Helmholtz-Zentrum Dresden-Rossendorf (HZDR) and the Nanolab group at Politecnico di Milano.

Foam targets used in this experiment are composed of μm-thick solid foils with ultra-low density carbon coating (thickness ~ 4-16 μm, density ~ 0.01 g/cm^3). Foam production and characterization were performed by the Nanolab group using specially developed techniques [1]. Further characterization of the foam density, composition and nanostructure was performed at HZDR. Previous experiments demonstrated an enhancement of ion acceleration performances for foam targets, with a significant increase in the energy and number of accelerated protons with respect to uncoated metal foils in a wide range of laser intensities (5x10^16 – 4x10^20/cm2). This enhancement was attributed to the increased absorption of laser energy in the near-critical plasma produced by the laser-foam interaction, even though a significant role was played by the foam nanostructure, as shown by PIC-simulations [2].

Here, we present the results of an experimental campaign performed at DRACO 150 TW (HZDR) aimed at achieving a better understanding of the absorption physics and role of foam nanostructure. The effect of laser illumination in the region surrounding the interaction site and neighbouring targets was also investigated in this campaign, as the mechanical properties of cluster assembled foams highlights target damage due to the heat wave and debris produced in laser-matter interaction and laser reflections from the target holder.

[1] Zani, A., et al. "Ultra-low density carbon foams produced by pulsed laser deposition." Carbon 56 (2013): 358-365.

Prencipe, I., et al. "Energy dispersive x-ray spectroscopy for nanostructured thin film density evaluation." Science and Technology of Advanced Materials 16.2 (2015): 025007.
[2] Passoni, M., et al. "Energetic ions at moderate laser intensities using foam-based multi-layered targets." Plasma Physics and Controlled Fusion 56.4 (2014): 045001.
Prencipe, I., et al. "Development of foam-based layered targets for laser-driven ion beam production." Plasma Physics and Controlled Fusion 58.3 (2016): 034019.
Passoni, M., et al. "Toward high-energy laser-driven ion beams: Nanostructured double-layer targets." Physical Review Accelerators and Beams 19.6 (2016): 061301.

Working group:

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Recombination of Protons Accelerated by a High Intensity High Contrast Laser

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The interaction of short intense pulses with solid targets is known for the acceleration of ions by the target normal sheath acceleration mechanism. After the ions are accelerated they are assumed to drift in space towards the detector. During this time, the temperature of the plasma is understood to be significantly high such that recombination is prevented and all the ions that are accelerated are assume to retain their charge state till detection. Experiments carried out to study the recombination of accelerated protons from a solid target show a 200 times higher than expected neutral atoms and can contribute to nearly 80% of the accelerated ions at 10 keV which then falls rapidly at higher energies. Neither charge transfer with the background gas nor electron ion recombination in the plasma is sufficient to explain the spectral form of the neutral atoms obtained. We have developed a model where the ions co-propagate with a dense bunch of electrons resulting in spectrally-similar characteristics of fast neutral atoms detected. The model presented here provides insights about the closely linked dynamics of ion acceleration which results in the further release of electrons from the target as the ions are accelerated. These electrons released then co-propagate with the ion bunch allowing electron-ion recombination to take place and resulting in the formation of fast neutral atoms. To further understand the neutralization process, we have also carried out novel experiments to probe the distance after which the ions are converted into fast neutral atoms. The study of neutralization along with the model presented here provides insights into the strongly coupled dynamics of electrons and ions taking place long after the ions are accelerated.

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Fingerprinting Multi-Species Effects in PW-Class Laser-Ion Acceleration

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Co-authors: Martin Rehwald [1]; Lieselotte Obst-Huebl [1]; Tim Ziegler [1]; Marco Garten [1]; René Widera [1]; Karl Zeil [1]; Thomas E. Cowan [1]; Michael Bussmann [1]; Ulrich Schramm [1]; Thomas Kluge [1]

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Spectral signatures of laser-accelerated ion beams are frequently used to characterize underlying acceleration mechanisms. Yet regularly, more than just one ion species are accelerated in experiments, e.g. from hydro-carbon contamination layers, multiple charge states or mixed materials. Such presence of multiple ion species (q/m) in the accelerating field leads to characteristic modulations in observed proton spectra due to electro-static repulsion during co-propagation. Resulting typical spectral modulations from these effects are presented with an analytical model for PW-class laser-ion acceleration. We improve previous predictions with explicit multi-species interaction for arbitrary mixtures, enabling us to connect important ensemble properties of laser-accelerated electrons with spectral signatures of accelerated ions. We support our new model with extensive particle-in-cell simulations and propose an experimental implementation with a novel cryogenic target, allowing systematic verification of our predictions in an environment without the strong influence of hardly controllable processes such as ionization dynamics.

Working group:

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Laser-proton acceleration from a cryogenic hydrogen jet

Authors: M. Rehwald[1]; C. Bernert[2]; T. Cowan[2]; C. Curry[3]; L. Gaus[2]; M. Gauthier[3]; S. Glenzer[3]; S. Goede[4]; J. B. Kim[3]; T. Kluge[2]; S. D. Kraft[2]; L. Obst-Huebl[2]; H.-P. Schlenviogt[2]; C. Schoenwaelder[3]; U. Schramm[2]; F. Treffert[3]; T. Ziegler[2]; K. Zeil[2]

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Demanding applications like radiation therapy of cancer have pushed the development of laser proton accelerators and defined necessary proton beam properties as well as levels of control and stability.
The presentation will give an overview of the recent experiments for laser driven proton acceleration employing a cryogenic target system which is capable of producing a renewable and debris free jet target. The micrometer sized pure hydrogen jet is characterized by a low plasma density of 30 times the critical density at 800 nm and was irradiated at the Petawatt (PW) amplifier stage of the high power laser source DRACO at the HZDR. The Ti:sapphire system delivers laser pulses with energies of up to 23 J and pulse durations of 30 fs on target.
In this talk we present substantially improvements of the target system leading to an increase in stability of the accelerated protons as well as the long-term operations. Evaluation of different target geometries e.g. cylindrical with a diameter of 5µm and planar with up to 4x20 µm² demonstrating the capabilities in terms of size and shape of available hydrogen jets.
We report on the laser contrast dependencies of the proton beam properties by introducing artificial prepulses and describe their influence on the target shape at the interaction time by using a synchronized optical probe beam.
Furthermore different ion diagnostics reveal mono-species proton acceleration in the laser incidence plane from the jet target, reaching foil-like proton cut-off energies in target normal direction.

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Measurements of fast electrons and protons in TNSA experiments

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Thin aluminium foils irradiated by ultraintense femtosecond-long laser pulses have been extensively used in the last two decades for MeV-range proton beam generation. In the early stage of the interaction, a dense cloud of electrons is directly accelerated by the laser, pass through the target and ionize its rear surface. Here, an extremely high quasi-static electric field (of the order of TV/m) is established and it is responsible for ion and proton acceleration.
At SPARC_LAB, the high power ultrashort laser FLAME is currently employed in this research field. In this work, we report about measurements made on fast electrons and accelerated protons by means of two on-line tools, an Electro Optic Sampling diagnostic and a diamond-based Time-Of-Flight detector, respectively. In such a way, we could study the correlations existing between the two beams.

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Modification of proton spectra using optical shaping of over-dense gas jets

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Over-dense gas targets are attractive for ion acceleration since they can provide debris free, high repetition sources of pure ion beams. The spatial profile of gas targets are typically not well suited for laser-plasma energy coupling, however, this can be improved by the addition of an optical prepulse which launches a blast-wave into the plasma. This technique has previously been shown to form short scale-length features in plasmas suitable for a 10.6 µm laser [Tresca PRL 115(9) 2015, Dover JPP 82(1) 2016].
We report on an experiment at the Vulcan Petawatt laser (lambda;$_L$=1.053 µm) where we used optical-shaping of an initially critically dense ($n = 1.7\,n_c$) gas jet. Without optical shaping, no forward-propagating protons were detected, however, a thermal spectrum was detected transverse to the laser propagation direction with a high energy bunch at 11 MeV. Only with optical shaping were forward going protons detected. These protons had a low energy of 1.7 MeV but were bunched with a 14% energy spread. However, damage to the nozzle tip during the laser-plasma interaction, limited shot-rate and reproducibility.

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A feasibility study of zebrafish embryo irradiation with laser accelerated protons

Authors: Thomas Rösch[1]; Jörg Schreiber[2]

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We present the technological advancements of recent years at the laser-driven ion acceleration experiment at the ATLAS 300 laser in Garching near Munich that enabled a first application oriented experiment. Improvements were made in target positioning, proton transport and diagnostics as well as in specimen handling and their capabilities explored by performing an irradiation experiment with the zebrafish embryo model. Results of this first living vertebrate organism irradiation at a laser-driven source show evaluable partial body changes in the very small (<1mm) animals corresponding to the effects of photon doses of up to 15 Gy. Hence, we could demonstrate that a biologically relevant amount of dose could be delivered within a reasonable amount of time (1-2 min). Further, the asymmetry of the malformations proves the inhomogeneous dose deposition due to the focused proton bunch. The outcomes of this proof-of-principle experiment show both the appropriateness of current capabilities and the required improvements of our laser-driven proton source for in-vivo biological experiments.

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Investigation on near-critical targets for enhanced laser-driven ion acceleration

Authors: Andrea Pazzaglia[1]; Alessandro Maffini[1]; Luca Fedeli[1]; Arianna Formenti[1]; Francesco Mirani[1]; David Dellasega[1]; Valeria Russo[1]; Margherita Zavelani-Rossi[1]; Matteo Passoni[1]

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Target Normal Sheath Acceleration (TNSA) is arguably the most robust and well known laser-driven ion acceleration scheme, nevertheless it has one main issue, namely the low efficiency of laser conversion into energetic ions. In order to overcome this limit, one possibility is to use a double-layer target with a near-critical coating [1]. Nevertheless, the electron critical density for the widely used Ti:Sapphire lasers corresponds to a mass density of approximately 6 mg/cm^3, which is intermediate between solid and gas densities and thus very challenging to obtain.
An extremely low density material, called "Carbon foam", has been developed at the Micro and Nanostructured Materials Laboratory (Nanolab) at Politecnico di Milano, exploiting the Pulsed Laser Deposition technique (PLD). By virtue of the foam fractal structure, the material can reach a high void fraction and a density down to few mg/cm^3 [2] and the material can thus be suitably exploited as a near-critical coating. In addition, thanks to PLD features, the foam can be deposited directly onto any kind of substrates (metal/plastic, down to 100 nm) to form a double-layer target. It has been experimentally proven, in different ultra-intense laser facilities, that a foam-based target can be suitably exploited to increase maximum energy and number of laser accelerated ions [3].
Nevertheless, to fully exploit the potential of this kind of target, a deep investigation through a multidisciplinary approach is required. In particular, the ongoing research at Nanolab deals with both the experimental optimization of the target and with the theoretical analysis of the laser-target interaction, carried out with the help of Particle-In-Cell simulations.
In this contribution we present the progresses that we have achieved in these fields. In particular, we developed a technique for the production of substrate of the double-layer target, based on the High-Power Impulse Magnetron Sputtering (HiPIMS), which enables the fine tunability of the substrate thickness and composition. Moreover, we have thoroughly investigated the growth dynamics of the near-critical coating, namely the C foam, which is largely unexplored [4]. We exploited the new insights on the physical process to achieve a better control of the foam properties, as the density and homogeneity. This has been possible also thanks to an improvement of the density measurement technique based on Energy Dispersive X-rays Spectroscopy (EDS) [5].
On the other hand, we used this knowledge to model the near-critical fractal material and to perform PIC simulations of the laser interaction with a realistic foam structure [6]. In addition, we carried out a large simulation parametric scan in order to determine the optimal target parameters and to reveal the physical mechanism underlying the ion energy enhancement.
We finally present the experimental achievements in the enhanced laser-driven ion acceleration with foam-based targets. Thanks to the promising results, we believe that this kind of target could be exploited in the near future for some interesting application, such as ion beam analysis [7] or neutron generation.

[1] Sgattoni, A., et al. "Laser ion acceleration using a solid target coupled with a low-density layer." Physical Review E 85.3 (2012): 036405.
[2] Zani, A., et al. "Ultra-low density carbon foams produced by pulsed laser deposition." Carbon 56 (2013): 358-365.
[3] Passoni, M., et al. "Energetic ions at moderate laser intensities using foam-based multi-layered targets." Plasma Physics and Controlled Fusion 56.4 (2014): 045001.
Prencipe, I., et al. "Development of foam-based layered targets for laser-driven ion beam production." Plasma Physics and Controlled Fusion 58.3 (2016): 034019.
Passoni, M., et al. "Toward high-energy laser-driven ion beams: Nanostructured double-layer targets." Physical Review Accelerators and Beams 19.6 (2016): 061301.
[4] Maffini A., et al. "On the growth dynamics of pulsed laser deposited nanofoams" submitted to Physical Review Materials
[5] Pazzaglia A., et al. "Reference-free evaluation of thin films mass thickness and composition through energy dispersive x-ray spectroscopy." arXiv preprint arXiv:1901.03616 (2019).
[6] Fedeli, L., et al. "Ultra-intense laser interaction with nanostructured near-critical plasmas." Scientific reports 8.1 (2018): 3834.
[7] Passoni M., et a.. "Superintense Laser-driven Ion Beam Analysis." arXiv preprint arXiv:1903.01725 (2019).

Working group:

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Ion acceleration from ultra-thin foil targets with on-shot monitored temporal contrast

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Co-authors: Constantin Bernert [1]; Florian-Emanuel Brack [2]; Stephan Kraft [1]; Florian Kroll [3]; Josefine Metzkes-Ng [1]; Lieselotte Obst-Huebl [1]; Martin Rehwald [1]; Hans-Peter Schlenvoigt [4]; Karl Zeil [1]; Ulrich Schramm [5]

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Laser-driven ion acceleration promises to provide a compact solution for demanding applications like particle therapy, proton radiography or inertial confinement research. Controlling the particle beam parameters to achieve these goals is currently pushing the frontier of laser driven particle accelerators.

The performance of the plasma acceleration is strongly dependent on the complex pre-plasma formation process at the target front surface which is determined by the temporal intensity contrast. Particularly low-density targets require an enhanced temporal contrast to remain overcritical until the main pulse arrives. Plasma mirror setups have proven to significantly improve the temporal contrast by reducing pre-pulse intensity and steepening the rising edge of the main laser pulse, enabling the investigation of laser proton acceleration and proton energy scaling using ultra-thin targets.

We present new experimental results on the interaction of the DRACO Petawatt ultra-short pulse laser [1] with ultra-thin foil targets. Efficient and on-demand contrast cleaning established through a re-collimating plasma mirror setup facilitated thickness scans from the µm range down to several tens of nm. The combination of a complex set of diagnostics, consisting of proton detectors in target normal, laser forward and laser backward axis, laser pulse transmission and reflection diagnostics as well as detection of front surface electrons, delivered concrete indicators for the acceleration conditions. Furthermore, tremendous progress has been achieved by successfully implementing a novel laser contrast diagnostic by means of self-referenced spectral interferometry with extended time excursion (SRSI-ETE) [2], allowing to characterize the temporal contrast in the experimental area on a single-shot base with unprecedented dynamic and temporal range.

[1] Schramm, Ulrich, et al. "First results with the novel petawatt laser acceleration facility in Dresden." Journal of Physics: Conference Series. Vol. 874. No. 1. IOP Publishing, 2017.

[2] Oksenhendler, Thomas, et al. "High dynamic, high resolution and wide range single shot temporal pulse contrast measurement." Optics express 25.11 (2017): 12588-12600

Working group:

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Tunable Metallic Nanocrystal Generation using Laser-Driven Proton Irradiation

Authors: Marianna Barberio[1]; Simone Giusepponi[2]; Simon Vallières[1]; Massimiliano Sciscio[1]; Massimo Celino[2]; Patrizio Antici[1]

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Laser-driven proton acceleration, as produced during the interaction of a high-intensity (I>1x10^18 W/cm^2), short pulse (<1 ps) laser with a solid target, is a prosperous field of endeavor for manifold applications in different domains, including astrophysics, biomedicine and materials science. These emerging applications benefit from the unique features of the laser-accelerated particles such as short duration, intense flux and energy versatility, which allow obtaining unprecedented temperature and pressure conditions. In this paper we show that laser-driven protons are perfectly suited for producing, in a single sub-ns laser shot, gold nanocrystals with tunable diameter ranging from tens to hundreds of nm and very high precision. Our method relies on the intense and very quick proton energy deposition, which induces in a bulk material an explosive boiling and produces nanocrystals that aggregate in a plasma plume composed by atoms detached from the proton-irradiated surface. The properties of the obtained particles depend on the deposited proton energy and on the duration of the thermodynamical process. Suitably controlling the irradiated dose allows fabricating nanocrystals of a specific size with low polydispersity that can easily be isolated in order to obtain a monodisperse nanocrystal solution. Molecular Dynamics simulations confirm our experimental results.

Working group:

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A high repetition rate target assembly for laser-plasma proton acceleration.

Author: Lucía Martín Blanco[1]

[1] *Universidad de Santiago de Compostela*

A high repetition rate target assembly for laser-plasma acceleration has been built at the Laser Laboratory for Acceleration and Applications (L2A2) of the University of Santiago de Compostela. The target consists on two linear stages combined with a rotational one to ensure the focusing and refreshment of the target material shot-by-shot. A multi-target wheel alow us to install different target materials that could accomodate few hundreds of shots at 10 Hz.

A feed-back loop procedure has been design to ensure the accurate shot-by-shot positioning of the target at focus. Focus position is determined by using the Speckle technique. Then, an accurate laser-position sensor is used to map the surface of the target wheel. The movement of the target assembly shot-by-shot is then programmed according to the target surface map. This procedure provides a target positioning at focus with an accuracy below 5 µm.

This target assembly has been used with the compact 45 TW laser of 1.2 J, 10 Hz, 25 fs and a contrast 1012 @ 20 ps at L2A2. First proton pulses were produced and their energy spectra measured with a time-of-flight detector, providing an average maximum energy above 1 MeV. Although, the maximum proton energy will be optimized in future, the most relevant feature is the stability of the proton source. Over several tens of shots the proton spectra are very stable, both in the cut-off energy and temperature. The observed differences are below 3%. The stability of the source is achieved thanks to the positioning system, which avoids the displacements introduced by the wobbling of the target.

This stable, compact, high energy source of protons could be used to produce on demand radioisotopes which could open the study of imaging techniques with short lifetime which are difficult to study with conventional cyclotrons.

Working group:

Laser-driven ion acceleration

Plenary session / 54

Megagauss magnetic fields in intense laser-solid interactions

Author: Gourab Chatterjee[1]

[1] *Max Planck Institute for the Structure and Dynamics of Matter*

Despite piquing interest in the intense laser-plasma community during the past several decades, monitoring the spatio-temporal evolution of megagauss magnetic fields continues to provide a window to the dynamics of hot electron transport, pivotal to ion acceleration schemes. Besides, these magnetic fields mirror the plethora of electromagnetic waves and instabilities, coupled with the disparate behaviours of electrons and ions, and thereby serve as a table-top platform for scaled laboratory replications of diverse astrophysical scenarios. Some recent results in this context [1-2] will be discussed, along with a brief description of our ongoing efforts [3,4] towards novel laser architectures involving sub-mJ-level, $\sim$100 fs optical parametric chirped pulse amplifiers (OPCPAs) in the mid-infrared (>5 μm) for potential applications in efficient high-harmonic generation and hard X-ray plasma sources.

[1] G. Chatterjee et al., Nature Commun. 8, 15970 (2017)
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Working group:

Invited plenary talk

Plenary session / 138

Recent developments of the Betatron source at LOA

Author: Kim TA PHUOC[1]

[1] *LOA*

Recent progress on generation and application of the Betatron source at LOA will be shown.

We will first present the production of Betatron radiation using ionization injection. We observed that both the signal and beam profile fluctuations are significantly reduced on this regime. In addition, radiation becomes polarized with a polarization that follows the laser polarization.

In this regime, the used the Betatron source to perform a femtosecond x-ray absorption experiment. We measured the transmittance of a copper sample brought to warm dense matter condition. The ultrafast dynamic of the electron temperature is inferred from the measurements.

We will then present recent results on the production of Betatron radiation in density tailored plasmas. We show that density tailoring can be used to control electrons orbits. We show that the Betatron source efficiency can be significantly improved for appropriate density profiles.

Working group:

Invited plenary talk

Plenary session / 139

X-rays from Laser Wakefield Accelerators

Author: Alec Thomas[None]

Recent progress in laser wakefield acceleration has led to the emergence of a new generation of electron and X-ray sources that may have considerable benefits for a range of scientific, medical and industrial applications. Betatron oscillations of electrons in the strong transverse fields of a laser wakefield accelerator provide X-ray radiation pulses that have a sub-micron source size, are of femtosecond duration, high brightness and have intrinsic synchronisation with the laser source. In this talk, I will review the physics of X-ray production in plasma wakefields and describe experiments in laser wakefield acceleration, energetic photon generation and its use in imaging for additive manufacturing, using the laser systems HERCULES at the University of Michigan and Gemini at the Rutherford Appleton Laboratory.

Working group:

Invited plenary talk

Plenary session / 135

Laser-driven proton beam profiles in ultra-high fields

Author: Lieselotte Obst-Huebl[1]

[1] *Helmholtz-Zentrum Dresden-Rossendorf*

Extreme field gradients intrinsic to relativistic laser-interactions with thin solid targets enable compact multi-MeV proton accelerators with unique bunch characteristics. Protons are accelerated in TV/m fields that are established within the micrometer-scale vicinity of the high-power laser focus. This initial acceleration phase is followed by ballistic proton bunch propagation with negligible space-charge effects over millimeters to hundreds of centimeters to the particle detector or a proton target at a dedicated irradiation site. The detected proton emission distribution can be influenced by the spatio-temporal intensity distribution in the laser focus, electron transport through the target, potential plasma instabilities, as well as local and global target geometry and surface properties.

Substantially extending this picture, our recent results show a critical influence of the milimeter scale vacuum environment on the accelerated proton bunch, where residual gas molecules are ionized by the remnant laser light that is not absorbed into the target plasma but reflected or transmitted. In an experiment with µm-sized hydrogen jet targets, this effect lead to the counter-intuitive observation of laser near-field feature imprints in the detected proton beam profiles. Our results show that the remnant laser pulse induces a quasi-static deflecting field map in the ionized residual background gas that serves as a memorizing medium and allows for asynchronous information transfer to the naturally delayed proton bunch. Occurring under typical experimental laser, target and vacuum conditions, all-optical imprinting needs to be taken into account for sensible interpretation of modulated proton beam profiles.

Working group:

Invited plenary talk

Plenary session / 137

High-Performance Modeling of Laser-Plasma Acceleration Physics

Author: Jean-Luc Vay[1]

[1] *Lawrence Berkeley National Laboratory*

Turning the current experimental laser-plasma accelerator state-of-the-art from a promising technology into mainstream scientific tools depends critically on high-performance, high-fidelity modeling of complex processes that develop over a wide range of space and time scales. While computer simulation tools are already essential to laser-plasma accelerator research, modeling of some of the complex and detailed three-dimensional physics is still a challenge. There is thus very active research and efforts going into the development of better algorithms and codes that utilize the latest computer architectures to their fullest. We will review the challenges, a selection of the proposed solutions and their application to the modeling of laser-driven electron, positron or ion acceleration, as well as plasma mirrors.

Working group:

Invited plenary talk

Plenary session / 140

Particle acceleration using laser-controlled relativistic plasma-mirrors

Authors: L Chopineau[1]; A Leblanc[1]; G Blaclard[1]; A Denoeud[1]; A Borot[1]; M Thévenet[1]; Jean-Luc Vay[2]; G Bonnaud[1]; Philippe MARTIN[3]; H Vincenti[1]; Fabien Quéré[1]

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[3] *LIDYL Saclay*

Plasma mirrors are produced at the surface of solid targets ionized by intense femtosecond laser pulses [1]. Due to their solid-like density, such plasmas specularly reflect these pulses. The main differences with an ordinary mirror is that the critical surface oscillates between +c and −c at each optical cycle and the coupling with the incident beam occurs within a thin layer, that can be easily tuned [2], at the interface between plasma and vacuum.
In the first part of this talk, we will present two experimental methods allowing for a complete determination of ultra-high-intensity laser electric fields on the whole pupil (TERMITE) and at focus (INSIGHT) [3,4]. We will see that full spatial and temporal metrology of such lasers can hardly be overemphasized to understand the XUV or particle beam properties and can give insights on the generation process itself as well.
In a second part, several examples of laser-produced sources will be presented as a clear evidence of vacuum laser acceleration of electrons to relativistic energies [5].
Finally, we will report briefly the first comprehensive experimental and numerical study of the laser-plasma coupling mechanisms as a function of the plasma interface steepness [6]. Our results reveal a clear transition from a temporally-periodic Brunel mechanism to a chaotic dynamics associated to stochastic heating. By revealing the key signatures of these two distinct regimes on experimental observables, we provide an important landmark for the interpretation of future experiments.

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[6] L. Chopineau et al, Phys. Rev. X 9, 011050 – Published 21 (March 2019)

Working group:

Invited plenary talk

Plenary session / 134

Controlling the dynamics of a laser-driven plasma wakefield accelerator.

Author: Matthew Streeter[1]

[1] *Imperial College London*

The structure of a laser plasma wakefield accelerator is intricately linked to the energy distribution of the driving laser pulse. During propagation, the spatial and temporal variations in the plasma refractive index causes modifications to the laser spectrum and spatial-temporal profile. This results in non-linear evolution of the laser pulse, which in turn affects the properties of the plasma accelerator. In this talk, I will explore how the laser pulse develops during the plasma accelerator and how this can be controlled. Through this control, it is then possible to optimise injection and acceleration in laser wakefield accelerators, thereby achieving improved electron beam properties.

Working group:

Invited plenary talk

Plenary session / 127

X-ray radiation sources based on laser-wakefield accelerators driven by structured pulses

Authors: Joana Luís Martins[1]; Jorge Vieira[2]; Julien Ferri[None]; Tünde Fülöp[3]

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[2] *Instituto Superior Técnico*

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J.L. Martins, J. Vieira, J. Ferri and T. Fülöp

Recent experiments on the production of lasers with Laguerre-Gaussian modes and their interaction with matter have produced high-intensity laser beams with non-zero angular momentum (e.g. [1]). These developments pave the way for exploring laser-wakefield accelerators with structured laser drivers, which provide the access to new acceleration regimes. Recent theory and simulations, for example, have shown that structured lasers can control the topology of the plasma wave towards the generation of vortex electron bunches with orbital angular momentum [2]. Despite these advances, the radiation emission from structured laser-plasma accelerators remains largely unexplored.

In this work, we study X-ray radiation generation from electron bunches accelerated in laser-wakefields driven by lasers with orbital angular momentum. In particular, we explore the use of multiple lasers

with Laguerre-Gaussian modes to drive multiple rotating wakefields [3]. The radius and angular rotation velocity provide new knobs to control key features of the radiation such as its spectral intensity.

Through detailed three-dimensional simulations we explore the transverse dynamics of electrons in the rotating bubbles and the radiation produced by them. We show that this setup allows for greater tunability of the oscillation amplitude of the injected electrons, which is not limited to the radius of the bubble as in typical laser-wakefield accelerators [3]. The detailed properties of the radiation, including its divergence and spectrum are explored in different scenarios with both rotating and non-rotating composite lasers [3].

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Working group:

Invited plenary talk

Plenary session / 141

Mastering the spectral properties of the COXINEL undulator radiation driven by a laser plasma accelerator

Author: Eléonore Roussel[1]

[1] *PhLAM-CNRS, Lille University*

We report here on first observations of spontaneous undulator radiation after a 10-m long transport line using a Laser-plasma acceleration (LPA). The line verses to manipulate the singular properties of the produced electron beams (as energy spread, divergence) before being used for lightsource applications. The COXINEL* transport beam line transport and focus a LPA beam in a 2-m long in-vacuum low gap (down to 4.5 mm) undulator.
The angulo-spectral undulator radiation distribution is characterized using an imaging UV spectrometer.

Besides the wavelength tuneability with the gap variation, we show that the radiation pattern signature provides an insight of the electron beam quality and of the transport. The radiation pattern signature is illustrated in the case of the dependence with the energy spread (modified by introducing a slit in a magnetic chicane). These observations pave the way towards LPA based Free Electron Laser.

- COXINEL: ERC Advanced Grant 340015

Working group:

Invited plenary talk

Plenary session / 113

Diagnostics for plasma-based electron accelerators

Author: Mike Downer[1]

[1] *The University of Texas at Austin*

Plasma-based accelerators that impart energy gain as high as several GeV to electrons or positrons within a few centimeters have engendered a new class of diagnostic techniques very different from those used in connection with conventional radio-frequency (rf) accelerators. The need for new diagnostics stems from the micrometer scale and transient, dynamic structure of plasma accelerators, which contrasts with the meter scale and static structure of conventional accelerators. Because of this micrometer source size, plasma-accelerated electron bunches can emerge with smaller normalized transverse emittance (εn < 0.1 mm mrad) and shorter duration (τb ~ 1 fs) than bunches from rf linacs. I will review single-shot diagnostics that determine such small εn and τb noninvasively and with high resolution from wide-bandwidth spectral measurement of electromagnetic radiation the electrons emit: εn from x rays emitted as electrons interact with transverse internal fields of the plasma accelerator or with external optical fields or undulators; τb from THz to optical coherent transition radiation emitted upon traversing interfaces. The duration of ~1 fs bunches can also be measured by sampling individual cycles of a copropagating optical pulse or by measuring the associated magnetic field using a transverse probe pulse. Because of their luminal velocity and micrometer size, the evolving structure of plasma accelerators, the key determinant of accelerator performance, is exceptionally challenging to visualize in the laboratory. Thus I will also review a new generation of laboratory diagnostics that yield snapshots, or even movies, of laser- and particle-beam-generated plasma accelerator structures based on their phase modulation or deflection of femtosecond electromagnetic or electron probe pulses. Spatiotemporal resolution limits of these imaging techniques are discussed, along with insight into plasma-based acceleration physics that has emerged from analyzing the images and comparing them to simulated plasma structures. An in-depth written version of the material presented was recently published [1].

[1] M. C. Downer, R. Zgadzaj, A. Debus, U. Schramm, and M. C. Kaluza, "Diagnostics for plasma-based electron accelerators," Rev. Mod. Phys. 90, 035002 (2018).

Working group:

Invited plenary talk

Plenary session / 111

Laser-driven ion acceleration: High-energy protons from ultra-thin foils

Author: Paul McKenna[1]

[1] *University of Strathclyde*

There is intense international interest in the development of high power laser-driven ion sources due to the unique properties of the ion beam and the potential to make these sources compact for applications. This has motivated research into new ion acceleration mechanisms to increase the maximum energies achieved and to control the spectral and divergence properties of the ion beam. In this plenary talk, I will set the scene for the latest high-profile developments in the field of laser-driven ion acceleration. I will go on to present my group's latest results on ion acceleration from ultrathin foil targets. I will show experimental and numerical results on the interaction of linearly polarized, picosecond-duration, ultra-intense laser pulse interactions with ultrathin foils, in which proton energies near to 100 MeV are achieved [1]. A coupled programme of simulations shows that this occurs via a hybrid scheme involving both radiation pressure and sheath acceleration, and that the acceleration field is boosted by the onset of relativistic self-induced transparency in the expanding foil. Results showing the onset of instabilities in proton acceleration from ultrathin foils [2] will also be presented.

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Working group:

Invited plenary talk

Plenary session / 114

Towards accelerator-quality beams of high energy protons guided by laser driven helical coils

Author: Hamad Ahmed[1]

[1] *Queen's University Belfast*

Laser driven ion beams provide a promising alternative to conventional accelerators as, in addition to the compactness and possible cost-effectiveness, they exhibit remarkable properties such as high particle flux, short pulse duration and laminarity [1]. However, some of the inherent shortcomings of ion beams driven by target normal sheath acceleration (TNSA) mechanism, such as large divergence and broad energy spectra, have limited so far end-user applications [1]. The helical coil targets recently developed by our group [2] provide, in this context, a miniature and versatile setup for effective control of the spectral and angular properties of the proton beams, with potential for delivering high energy beams of near accelerator quality, and added scope for implementing the scheme in multiple stages.
By harnessing the intense EM pulse generated from a laser-irradiated target [3], the helical coil (HC) produces a large electric field structure (> 1GV/m), which can be tuned to travel synchronously with the protons in transit through the coil. [2]. By employing these targets on PW-class laser systems, such as the Vulcan Petawatt, CLF (UK) and Titan, LLNL (USA), collimated and quasi-monoenergetic proton beams containing >108 particles at ~ 45 MeV were obtained by simultaneous focusing and post acceleration of ~30 MeV protons. Particle tracing simulations reproducing the experimental data, suggest an accelerating gradient of ~ 2 GeV/m within the miniature, linear accelerating module. Further optimization of the coil's accelerating and collimating effects were studied systematically by varying its dimensions (radius, pitch and length) at a given laser condition. Simulations and modelling suggest the use of coils with variable pitch for sustained post-acceleration over an extended length to overcome de-phasing between the accelerated particles and the moving accelerating structure. The viability of staging coils in succession will also be discussed based upon preliminary data and simulations.

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Working group:

Invited plenary talk

Plenary session / 31

Flying Focus and its application to Laser-Plasma Accelerators

Author: Jessica Shaw[1]

Co-authors: John Palastro [2]; David Turnbull [2]; Seung-Whan Bahk [2]; Ildar Begishev [2]; Robert Boni [2]; Jake Bromage [2]; Sara Bucht [2]; Andrew Davies [2]; Russell Follett [2]; Philip Franke [2]; Daniel Haberberger [2]; Joseph Katz [2]; Terrance Kessler [2]; Avram Milder [2]; Dustin Froula [2]

[1] *LLE*

[2] *Laboratory for Laser Energetics, University of Rochester*

A chromatic focusing system combined with chirped laser pulses was used to create a "flying focus" [1]. This advanced focusing scheme provides unprecedented spatiotemporal control over the laser focal volume by enabling a small-diameter laser focus to propagate over 100 times its Rayleigh length. Furthermore, the flying focus decouples the speed at which the peak intensity propagates from the group velocity of the laser pulse, allowing the laser focus to co- or counter-propagate along its axis at any velocity. Experiments have demonstrated a nearly constant intensity over 4.5 mm while the velocity of the focus ranged from subluminal (0.01c) to superluminal (15c). When increasing the laser intensity above the ionization threshold of the background gas, an ionization wave was measured to track the ionization threshold intensity isosurface as it propagated and ionization waves of arbitrary velocity were demonstrated [2,3]. Subluminal and superluminal ionization fronts were produced over the entire 4.5 mm, both forward- and backward-propagating relative to the ionizing laser. All backward and all superluminal cases mitigated the issue of ionization-induced refraction, which typically challenges the formation of long, contiguous plasma channels. The properties of the flying focus provide the opportunity to overcome dephasing in laser-plasma accelerators, but theory predicts that the overall acceleration length will remain the same. Flying focus also presents a path around current fundamental limitations in laser-plasma amplifiers [4], photon accelerators, ion accelerators, THz generation, and high-order frequency conversion.

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Working group:

Invited plenary talk

Plenary session / 133

New approaches to high energy physics with lasers for radiation-nuclear applications

Author: Valery Bychenkov[1]

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Laser-driven charged particle acceleration mechanisms with relativistically intense pulses of ultra-short duration are reviewed for innovative low-density targets either of near critical or near relativistically critical densities. These targets being optimized over thickness and density for given laser intensity with 3D PIC simulations allow generate electrons with maximum total charge and protons with maximum energy. Applications of the generated high-energy electron and proton beams to nuclear and radiation sources are discussed.

We have extended recently published results of so-called SASL (synchronized acceleration by slow light) simulations to other relevant schemes of laser-plasma interaction for proton acceleration involving manipulation of laser polarization and parameters of low-density targets which are available in practice. In all cases, the main idea is to capture the protons from a target front side in the laser

pulse ponderomotive electric field sheath and keep them synchronized with the latter due to specific nonlinear propagation and laser-target design. We have performed optimization study for given laser pulse energy to find the target which may produce protons with maximum possible energy. The 3D PIC simulations performed have also demonstrated effective acceleration of electrons from low-density targets (inhomogeneous preplasma at the front of solid-dense foil and homogeneous near-critical plasma) in terms of the increased electron yield. It has been shown that homogeneous planar target with the density somewhat lower than a critical density is best suited for maximum total charge of high-energy electrons. This density, which is higher than a standard gas density for wakefield acceleration provides formation of laser field filled bubble, where electrons are stochastically accelerated in complicated firlds: longitudinal plasma field, focusing electrostatic field and laser field. The electron charge per shot with energies in excess of 100 MeV reaches multi-nC level for current femtosecond lasers, that is not available for standard wakefield-based accelerators with relatively low gas density as well as for electron acceleration from planar solid targets with step-like density profile.

Our findings constitute an important approach to laser-based radiation and radioactive sources for enhanced multi-keV x-ray betatron source, deep gamma-radiography of dense samples, neutron generation, positrons and mesons production. This approach is demonstrated on some examples for multi-TW and 1 PW lasers.

This work was supported by the Russian Science Foundation (Grant No. 17-12-01283).

Working group:

Invited plenary talk

Plenary session / 132

Inverse Compton X/γ Source Based on Laser-Wake Field Accelerator

Authors: Wenchao Yan[1]; Uddhab Chaulagain[None]; Tae Moon Jeong[None]; Yanjun Gu[None]; Jaroslav Nejdl[None]; Stefan Weber[None]; Sergei. V. Bulanov[None]; Georg Korn[None]

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A new generation of accelerator-based hard X/γ-ray sources driven exclusively by laser light will be discussed. One ultrahigh intense CPA laser pulses will be split into two pulse: first used to accelerate electrons by laser-driven plasma wake-field to hundreds-MeV, and second, to collide on the electron for the generation of X/γ-rays by inverse Compton scattering (ICS).

Such all-laser-driven X/γ source have recently been demonstrated to be energetic, tunable, narrow/broad in bandwidth, short pulsed and well collimated. Simulation show orbital angular momentum can also be added onto these sources. Such characteristics, especially from a compact source, are highly advantageous for numerous advanced X-ray applications. Moreover, preliminary plan of laser wake-field accelerator and radiation source in ELI-beamlines will be presented.

Working group:

Invited plenary talk

Plenary session / 9

Recent studies on plasma channel based new laser wakefield staging scheme and radiation source at SJTU

Authors: Min Chen[1]; Zheng-Ming Sheng[1]; Su-Ming Weng[1]; Jie Zhang[1]

[1] *Shanghai Jiao Tong University*

Recent studies on laser wakefield acceleration at SJTU will be introduced. Especially two new schemes based on plasma channel will be discussed in detail.
Multistage coupling of laser-wakefield accelerators with independent driving laser pulses is essential to overcome laser energy depletion for high energy applications such as the TeV level electron-positron collider. Currently a staging scheme is achieved by feeding a second laser pulse via a plasma mirror and by controlling the electron beam focusing via active plasma lenses. Here a more compact and efficient scheme is proposed to realize simultaneous coupling of the electron beam and the laser pulse to the second stage with plasma channels. A special designed bending channel is used to guide a fresh laser into a following straight channel, while the electron beam always propagates in the straight channel. Benefiting from the shorter coupling distance and continuous guiding of the electron beam in plasma, its transverse dispersion is suppressed. With moderate laser parameters, our particle-in-cell simulations demonstrate that the electron beam from the previous acceleration stage can be efficiently injected into the following stage for further acceleration, where the re-injection ratio, stability, and beam quality can be kept at a high level.
At the same time, based on plasma channel, we propose a new scheme of controlled X-ray radiation. The laser centroid motion in a plasma channel can be well controlled by tuning the channel depth and width. Wakefield behind the driver laser makes similar transverse oscillation, which makes the electrons inside the wake structure do transverse betatron motion and radiate. Three-dimensional PIC simulation and VDSR radiation calculation codes are used to study plasma channel based Helical plasma undulator radiation. It shows both the radiation spectrum and polarization can be well controlled.

Working group:

Invited plenary talk

Plenary session / 131

Plasma acceleration - what were we thinking in those early days and where are we headed?

Author: Chandrashekhar Joshi[1]

[1] *UCLA*

The concept of particle acceleration using collective field generated by charge separation of ions and electrons in a plasma, predated the now famous Tajima and Dawson paper. The many avatars of this concept had had a modest success, until Dawson proposed using a relativistic plasma wave to accelerate electrons. The initial response to this paper was either total disbelief or skepticism. It was in this climate that the UCLA - Laser-Plasma Group (later came to be known as the UCLA-Plasma Accelerators Group), started the first experimental program to demonstrate the most audacious prediction of this idea- that plasma waves could support 1 GeV/cm accelerating gradients. I will discuss what we were thinking in those early days and how a supportive high-energy physics community and funding agency were patient and instrumental in conclusive demonstration of acceleration of externally injected electrons by a relativistic plasma wave. Thereafter the plasma acceleration field rapidly spread worldwide as CPA lasers became commonplace. These lasers and GeV class charged particle beams provided by SLAC enabled rapid progress of the field that included high gradient acceleration of both electrons and positrons, acceleration of narrow energy spread beams containing a significant charge and high efficiency of energy extraction from wakes. At the same time some near term applications have emerged from the directional X-ray beams, tunable IR pulses, 100s of MeV class electron beams and intense THz pulses that can be generated using these wakes. As for the

ultimate goal of building a plasma-based linear collider many basic problems still remain providing an opportunity for young scientists to make their mark on the field.

Working group:

Invited plenary talk

Plenary session / 110

Relativistic nanophotonics

Authors: Laszlo Veisz[1]; Daniel Cardenas[2]; Tobias Ostermayr[3]; Laura Di Lucchio[4]; Luisa Hofmann[2]; Matthias Kling[3]; Jörg Schreiber[3]; Paul Gibbon[4]

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[3] *Ludwig-Maximilian-Universität München, Germany*

[4] *Forschungszentrum Jülich GmbH, Germany*

Laser-driven electron acceleration in gas media [1] provides extreme accelerating fields around 100 GV/m, however, using vacuum should offer even multi-TV/m values. These fields are much beyond that of conventional RF devices. Furthermore, the electron bunches have durations in the few-femtosecond regime, which is also much shorter than from conventional facilities.
A novel approach for the acceleration, that we termed relativistic nanophotonics, utilizes solid density nanoplasmas irradiated with sub-5-fs ultra-relativistic laser pulses [2]. The target emits electrons in intensity- and target size-dependent directions. The electrons are in the 5-10 MeV energy range and possess a clear dependence in propagation direction also on the waveform of the laser (carrier-envelope phase). An average experimental accelerating field beyond 1 TV/m is evaluated. Numerical investigations [3] indicate a two-step process behind the interaction. First a nanophotonics step emits electron pulses and accelerates them to a certain energy, while a second vacuum laser acceleration step further accelerates them and determines their final propagation direction. The simulations predict isolated electron pulses with a duration of about 300 attosecond and a peak accelerating field up to 10 TV/m.
These results form the basis of high-energy micro- to nanoaccelerators, record-breaking accelerating electric fields strengths, and isolated attosecond electron bunches. These accelerators are unique candidates as a source of energetic X-ray radiation with attosecond pulse duration.

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Working group:

Invited plenary talk

Plenary session / 42

External injection acceleration with ~100% capture efficiency

Authors: Jianfei Hua[1]; Yingpeng Wu[1]; Yingchao Du[1]; Zheng Zhou[1]; Chih-Hao Pai[2]; Wei Lu[1]; Warren Mori[3]; Joshi Chan[3]

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Staging acceleration of plasma accelerators is a critical requirement for compact colliders. The achivements have been made based on two different staging accelerartion schemes (from a LWFA to another LWFA [1] or from a Linac to a PWFA [2]) in recent years, however, the capure efficiency is very low (few percent or even lower). Here we present the first successful demonstration of external injection from a linear accelerator into a laser wakefield accelerator and the subsequent acceleration with ~100% capture efficiency. Stable 31-MeV, 20-fC electron beams from a conventional radio-frequency accelerator were velocity bunched to the duration of ~15fs (r.m.s.) and then external injected into the linear wakefield excited by a 10TW, 42 fs laser. Nearly all the electrons are mono-energetically accelerated and the maximum energy gain reaches 1.8 MeV in a 6-mm long plasma. High capture efficiency of external injection acceleration has also been systematically validated by 3D PIC simulations. This result paves the way toward the development of a high efficiency high energy particle accelerator.

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Working group:

Laser-driven electron acceleration

Plenary session / 143

Hybrid acceleration: Studying PWFAs with LWFAs

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Plasma wakefield acceleration (PWFA) is a novel acceleration technique with promising prospects for both particle colliders and light sources. However, PWFA research has so far been limited to a few large-scale accelerator facilities worldwide. We present first results on plasma wakefield excitation and acceleration using electron beams generated with the Ti:sapphire lasers ATLAS (LMU, Munich) and DRACO (HZDR, Dresden).

Because of their ultrashort duration and high charge density, the laser-accelerated electron bunches are suitable to drive plasma waves at electron densities in the order of 10^{18} to 10^{19} cm^{-3}. We have

capture the beam-induced plasma dynamics with femtosecond resolution using few-cycle optical probing, clearly showing the generation of a plasma wave by the electron beam. In addition to the plasma wave itself, we observe a distinctive transverse ion motion in its trail. This previously unobserved phenomenon can be explained by the ponderomotive force of the plasma wave acting on the ions, resulting in a modulation of the plasma density over many picoseconds [1].

We also present first results on the witness bunch acceleration. The witness is either injected into a subsequent wakefield period during shock-front injection or into the bubble during the density downramp at the exit of the laser wakefield stage. In both cases electron acceleration of the order of tens of MeV is observed.

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Proton Bunch Self-Modulation and Electron Acceleration in AWAKE

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Large energy gain by a witness bunch in a single plasma wakefields stage requires a driver carrying a large amount of energy. Proton bunches produced in large synchrotrons (SPS or LHC at CERN) carry tens to hundreds of kilojoules, but are long, typically 6-12cm. The self-modulation (SM) of the bunch in the plasma [1] transforms the continuous bunch in a train of bunches shorter than, and separated by the wakefields period. The train then resonantly drives the wakefields to large amplitude (~GV/m). This is the scheme adopted by the AWAKE experiment [2] to accelerate electrons.
We will introduce the experiment, and present experimental results that show the occurrence of the SM process [3] its growth both along the bunch and along the plasma [4] its seeding with two methods, the robustness of the process against variations of the incoming bunch parameters and the observation, under some condition of the hosing instability. Results also show that these wakefields are suitable to accelerate electrons. Externally injected, ~19MeV electrons gained energy to ~2GeV [5].
We will briefly briefly outline plans and possible application of this acceleration scheme to high-energy physics.

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Terahertz Pulse Generation by Laser Plasma Wakefield Accelerator

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In the past 10 years, the generation of terahertz (THz) radiation by ultrashort laser pulses has become an active field of research due to many promising applications in medicine, security, telecommunication and spectroscopy [1]. In gas, two-color near infrared laser pulses with moderate pump intensities and temporally asymmetric profile trigger transverse currents through photoionization [2]. This conversion mechanism, issued from "photocurrents", has been proved to prevail up to sub-relativistic intensities [3]. Here, we explore two-color plasmas beyond the relativistic threshold. Under such conditions we numerically demonstrate that the classical THz generation mechanism is dominated by the coherent transition radiation (CTR) of wakefield-accelerated electrons going across the plasma/vacuum interface [4]. Particle-in-cell (PIC) simulations performed display good agreement with the CTR theory [5] over a wide range of laser-plasma parameters.

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Using laser plasma accelerator for simultaneous X-ray absorption and 2-photon Light Induced Fluorescence imaging of a car engine spray.

Authors: Diego Guenot[1]; Edouard Berrocal[1]; Kristoffer Svendsen[1]; Jonas Björklund Svensson[1]; Martin Hansson[2]; Isabel Gallardo Gonzalez[1]; Henrik Ekerfelt[1]; Anders Persson[1]; Olle Lundh[1]

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High-pressure sprays are widely used in various field of industry such as combustion or rocket engines and paint applications. However, quantitative imaging of atomizing sprays is particularly challenging due to the presence of a variety of irregular liquid structures such as ligaments, liquid blobs, droplets, liquid sheets and a possible liquid core. This is why the only measurements of the liquid mass have been obtained using X-ray radiography on synchrotron, thus limiting the number of studies. We report here the first radiography of a fuel-port injection spray using betatron X-rays emitted from a laser plasma accelerator (see attached file).
For this experiment, we used the High Intensity Laser system at Lund University that provides on

target 800mJ, 38fs laser pulses. It was focused down to 12µm focal spot onto a gas jet (99% He, 1% N2) flowing from a 1mm supersonic nozzle. The betatron radiation emitted had a critical energy of 2.3keV and propagated outside of the vacuum chamber where an X-ray camera recorded the shadow of the spray.
The spray flowed from a commercially available port fuel injection system used in small diesel engines with 4.6 bars of backing pressure. The liquid consisted either of water and 0.1% of fluorescein either of a mixture of water and 10% of an X-ray contrast agent (KI).
We have found that we reached a liquid mass sensitivity of 60µm in a single shot for pure water and 30µm for water with KI, i.e. about two times better than the latest synchrotron measurement. Moreover, this sensitivity was achieved while observing a four times larger field of view.

In parallel to that, a small fraction of the laser pulse (approx. 10mJ) was send directly on the spray and focused with a cylindrical lens where it induced fluorescence via a 2 photon process (2p-LIF) in a dye (fluorescein) added to the liquid. The 2p-LIF images provides a great level of details on the size and shape of the liquid structures, optically sectioned by the light sheet, while the integrated liquid mass is extracted from the X-ray radiography.
This is making the two imaging techniques highly complementary for the characterization of spray systems as well as for further understanding the physics related to liquid atomization. We believe that this new application will greatly benefit industry and hydrodynamic simulation.

Attached image: Images of the liquid jet recorded with X-ray (top) and fluorescence (bottom) taken simultaneously 350µs after the beginning of the injection. On the right is a shadowgraph of the same jet taken at for a different event. The red rectangle represents the Light sheet use for two photon LIF.

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Picosecond x-ray driver for isochoric heating in LWFA pump-probe experiments

Author: Cary Colgan[None]

Isochoric heating is a necessary step in generating warm-dense matter (WDM) conditions from near solid-density targets. The volumetric heating of the sample must be rapid to limit expansion, and reach temperatures of 10's of eVs for relevant applications to the Jovian interior and ICF capsule implosions. Here, the viability of x-ray heating from a picosecond, laser-driven thin-foil Ge target was assessed. M-L band emission from the Ge produced a dense x-ray field in the 1 - 2 keV range that was characterised using crystal spectroscopy and pinhole imaging. This reproducible, laser-driven isochoric heater can be naturally synchronised to betatron radiation produced using laser wakefield acceleration (LWFA), enabling pump-probe experiments into the equation of state and transport properties of the transient WDM conditions.

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An Innovative Beam Cooling Technique using a Laser-Plasma Undulator

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Beam cooling is a crucial step for the luminosity delivery system in a linear collider or an accelerator based light source to achieve ultra low beam emittance required for high luminosity and high brightness, respectively. Damping rings equipped with wiggler magnets and accelerating cavities were previously proposed for systematic reduction of horizontal phase space area through radiation reaction whilst compensating for longitudinal momentum loss. In this paper, the concept of plasma undulator and its effective model analogous to a magnetic wiggler as well as its relation to damping properties were recapitulated. EPOCH simulations for the laser propagation optimisation are presented; formation of an order of magnitude larger undulator field compared to conventional wigglers is demonstrated. In conclusion, an existing conventional damping ring design was reviewed to explore the indications of an upgrade to plasma technology.

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1 MeV Thomson backscatter x-ray source from a 250 MeV laser-plasma accelerator and plasma mirror

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Thomson backscatter (TBS) of near-IR (hνL ~ 1eV) laser pulses from laser-plasma-accelerated (LPA) electron bunches (200 < γe < 4000) provides a compact source of bright, tunable, ultrashort x-rays (0.1 < 4γe2hνL < 100 MeV) for radiography and nuclear science [1]. Inserting a plasma mirror (PM) near the LPA exit to retro-reflect spent LPA drive pulses onto trailing electron bunches [2] is an exceptionally compact, inexpensive, simple way to convert even the smallest LPAs into robust TBS sources, but raises as-yet-unanswered questions about x-ray beam quality: Is the spent LPA pulse spectrum (and thus TBS) severely broadened by its interaction with LPA and PM? Do pre-pulses pre-expand the PM surface, degrading its reflectivity, and TBS efficiency? Do LPA electrons generate broadband bremsstrahlung in the PM that pollutes narrowband TBS? Can the spectrum of MeV x-rays from a PM-based LPA-TBS source be characterized with compactness, simplicity and frugality matching those of the source, without resorting to bulky pair-production spectrometers? Here, through systematic experiments using 6 J, 800nm, 25fs pulses from HZDR's DRACO laser facility to drive a 250 MeV (10% spread), 500pC LPA in a nitrogen-doped He gas jet [3], we answer these questions. Our main findings are: spent drive pulses broaden, but contribute less to x-ray spectral broadening than electron energy spread; the PM remains highly reflective even near the LPA exit,

where drive pulse amplitude reaches a0~3; background bremstrahlung becomes negligible compared to TBS with thin (~25μm) low-Z PMs; we reconstruct accurate single-shot x-ray spectra near 1 MeV by recording and analyzing particle cascades that x-rays generate in an inexpensive calorimetric stack consisting of ~20 image plates or scintillators separated by converters. Reconstructed x-ray spectra reveal both TBS and bremsstrahlung, and track centroid shifts accompanying changes in γe and spectral broadening accompanying nonlinear TBS.

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Double Optical Gating of XUV pulses in Relativistic Laser-Plasma Interactions

Author: Mark Yeung[1]

Co-authors: Paul Matthew Gilmore [1]; Brendan Dromey [1]

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Attosecond extreme-ultraviolet (XUV) pulses from laser-matter interactions have provided a unique tool for controlling and measuring electronic dynamics on the atomic scale [1]. Currently these pulses are typically generated via high harmonic generation (HHG) in gases where the highest pulse energies are limited to the microjoule range due to phase-matching effects and ground-state depletion. HHG from relativistic interactions with plasma surfaces has the potential to surpass these limitations by employing significantly higher intensities. A key challenge for the application of these pulses is the need to isolate individual attosecond pulses from the pulse train that is responsible for the emitted radiation appearing as harmonics rather than as a continuous spectrum. For normal incidence interactions it has previously been shown that manipulating the polarization of the laser pulse so that it switches from circular to linear to circular again can restrict the attosecond emission to only the linear period, thus gating the mechanism [2]. For this process to be efficient, however, the initial laser pulse must already only consist of a few cycles which is a major challenge for lasers with enough power to drive such a relativistic process. Here we present simulations that show how this restriction can be softened by combining this polarization effect with two-color fields where the addition of the 2nd harmonic of the laser switches the attosecond pulse emission rate from twice per cycle to once per cycle as well as increasing the intensity of the resulting isolated attosecond pulse. This Double Optical Gating technique has previously been employed for HHG in gases [3] but our simulations demonstrate its applicability to relativistic harmonics which will permit much higher attosecond pulse energies suitable for intense attosecond pump-probe studies.

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Creation of Electron-Positron Pairs in Photon-Photon Collisions Driven by 10-PW Laser Pulses

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A novel approach is proposed to demonstrate the two-photon Breit-Wheeler process by using collimated and wide-bandwidth γ-ray pulses driven by 10-PW lasers. Theoretical calculations suggest that more than 3.2×10^8 electron-positron pairs with a divergence angle of 7° can be created per shot, and the signal-to-noise ratio is higher than 10^3. The positron signal, which is roughly 100 times higher than the detection limit, can be measured by using the existing spectrometers. This approach, which could demonstrate the e−e+ pair creation process from two photons, would provide important tests for two-photon physics and other fundamental physical theories.

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Laser-plasma X-Ray microfocus source for high resolution imaging applications

Authors: Lucía Martín[1]; Camilo Ruiz[2]; José Benlliure[1]; Dolores Cortina[1]; Juan José Llerena[1]; David González[1]; Juan Peña[1]

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Development of novel X-ray sources has a significant impact on the society due to its applications on very different fields such as medicine, biology, chemistry, industry. Laser-plasma X-ray sources provides a new route to high brightness and small source size somewhere in the middle of low cost microfocus X-rays and large-scale synchrotron facilities. We explore one application of this new type of sources with emphasis on the stability of the source at high repetition rate and the advantage over similar conventional sources.
The laser-plasma X-ray source, currently installed at the Laser Laboratory for Acceleration and Applications (L2A2) of the University of Santiago de Compostela (USC), is produced by 1mJ, 35 fs, 1kHz pulses centered at 800 nm wavelength on thick metallic targets. The X-ray spectra of this source are characterized by the K peaks of the target material and a Bremsstrahlung continuum up to several tens of keV. The L2A2 x-ray source has been optimized and stabilized for operation in air conditions and for imaging applications. The stability of the source is achieved by optimizing the positioning system of the metallic target which refresh and keep the surface within the 8 μm of the Rayleigh length.
The micrometric size of the source enables higher imaging resolutions and, makes this source suitable for phase contrast imaging. The high-resolution imaging system is composed by the laser-plasma X-ray source and a large area CMOS sensor with a plastic scintillator (RadEye 2). We present some imaging applications like high resolution absorption imaging, phase contrast imaging and 3D tomographic reconstruction of biological and non-biological samples.

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X-ray sources using a kJ-class laser driven plasma accelerator

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X-ray photon beams in the keV to MeV energy range are essential to study high energy density (HED) matter and to improve the understanding of inertial confinement fusion and astrophysical systems. HED experiments produce highly transient matter under extreme states of temperatures and pressures and it is essential to develop light sources that are: in the hard x-ray energy range (0.01-1 MeV), directional, high-yield, low-divergence, and short-duration (ps and sub-ps). In this work we show that by using a laser plasma accelerator (LPA) driven by a kJ-ps class laser it is possible to generate a broadband (0.01-1 MeV) hard x-ray source that satisfies the previous requirements. A series of experiments were conducted on the Titan laser at Lawrence Livermore National Laboratory where a >10 nC electron beam in the 10-400 MeV energy range was generated through LPA. The electrons generate x-rays via their betatron motion (few-30 keV) and hard x-rays rays through inverse Compton scattering (10-300 keV) and/or Bremsstrahlung (up to 100 MeV). Due to its unique characteristics this source can be an important tool on large-scale laser HED facilities opening up the prospect for many applications.

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Numerical simulations of Betatron Radiation from wakeless plasma channel

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Plasma accelerators provide unique opportunities for the generation of high quality, short-pulse electrons beams which are an ideal basis for high quality radiation generation. This provides an exciting way forward to the generation of very high brightness X-ray betatron radiation from an ultra-bright, plasma-injected beam in a plasma. In this contribution, we present initial results from studies into the generation of betatron radiation in the keV to MeV range.

The state-of-the-art PIC simulation codes EPOCH and QuickPIC were used to simulate single/double bunch beam dynamics in a plasma channel with different plasma and beam parameters. The results were then analyzed in terms of the number of photons generated and variations in the betatron radiation spectrum in a narrow and wide plasma channel. An optimization of the drive and trailing bunch under matched and mismatched oscillations in a plasma channel was then done to deduce the beam parameters and phase space properties. Finally, the results obtained in both codes are compared against each other for benchmarking purposes.

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Investigation of photon and positron emission in laser collision with relativistic electrons

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Co-authors: Yangmei Li [2]; Guoxing Xia [1]

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In the regime of Quantum Electricdynamics (QED), relativistic electrons collide with an ultra-intense laser pulse can generate high-energy gamma-rays by nonlinear Compton scattering. All-optical nonlinear Compton scattering regime have been analysed by using different laser-plasma acceleration schemes in past decades. However, since the process involves electron acceleration, non-linear Compton scattering and radiation reaction, et al, the effect of key parameters on nonlinear Compton scattering and B-W process are difficult to describe. We analysed the ideal relativistic electron bunch colliding with an ultra-intense laser in different incident angles, shapes of laser pulses, laser intensities and electron bunch lengths. Simulation results show that the spectra of emitted photons and positron are similar for different parameters, which is due to the broad spectra of electrons after collision with laser field. However, the yields of photon and positron vary for different cases. With the increase of the incident angle, the yields decrease dramatically when it is greater than 20 degree. The delayed location of laser peak field can increase the number of photons and positron generated. The laser intensity, which dominates the photon emissions, can increase the yields of photons and positron when using a higher intensity laser to interact with electron bunch. By tuning the length of electron bunch, while keeping the electron charge constant, we find that both the electron density and bunch length are important to photons emission.

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Relativistic Laser Plasma Interactions at Short Wave Infrared Wavelengths

Author: Franklin Dollar[1]

Co-authors: Karl Krushelnick [2]; Alexander G. R. Thomas [2]; John Nees [3]; Nick Beier [1]; Jinpu Lin [4]; Tam Nguyen [1]

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Recent advances in laser technology have enabled the generation of relativistic laser pulses at wavelengths above the near infrared for the first time. We present a series of experiments which examine laser solid plasma interactions and applications utilizing a normalized vector potential of near unity

at wavelengths of 1300 and 2100 nm. We present results which highlight the unique benefits of experiments in this wavelength regime, including comparisons with particle-in-cell simulations.

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Characterizing high energy bremsstrahlung emission from laser plasma experiments at moderately relativistic intensity

Authors: Alejandro Laso Garcia[1]; Andreas Wagner[1]; Baoqiang Zhu[2]; Chris Armstrong[3]; David Neely[3]; Dean Rusby[3]; Deepak Kumar Batheja[4]; Huija Liu[2]; Jianqiang Zhu[2]; Lei Ren[2]; Mingying Sun[2]; Neng Hua[2]; Ning Kang[2]; Ondrej Klimo[4]; Paul McKenna[5]; Stefan Weber[4]; Sushil Singh[6]; Thomas Cowan[1]; Vladimir Tikhonchuk[4]; Yan Zhang[2]

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Abstract

Many applications of laser matter interaction at relativistic intensities, for e.g., ion acceleration, fast ignition, X-ray and neutron radiography, depend crucially on the laser absorption into hot electrons. Measurement of bremsstrahlung spectra generated by these hot electrons inside the target provides information on the electron energy distribution and their transport inside the target.

In this poster, we present results from a recently conducted experimental campaign using the 9 th beam of the SG-II Upgrade laser facility in Shanghai Institute of Optics and Fine Mechanics (SIOM). The p-polarized laser delivered approximately 300 J on target with a pulse duration of about 1 ps and focused intensity of about 7x10 18 W/cm 2 . Tantalum targets of various thickness from 100 um to 3 mm were shot during the experiment. Bremsstrahlung emission was measured using scintillator stack detectors [1] and forward Compton scattering high energy X-ray spectrometer [2]. In situ measurement of reflected laser energy in the specular direction was done using a scattering plate. The measurements characterize laser absorption into hot electrons, and the subsequent generation of high energy X-rays.

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Applications of tunable Thomson sources

Author: Sabine Schindler[1]

Co-authors: Andreas Döpp [2]; Hao Ding [2]; Max F. Gilljohann [1]; Johannes Götzfried [3]; Stefan Karsch

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We report results on all-optical Thomson scattering within a laser wakefield accelerator. We show that the pulse collision can be detected using transverse shadowgraphy, facilitating alignment and permitting accurate determination of the scattering position. As the electron beam energy is evolving inside the accelerator, the emitted spectrum changes with the scattering position. Such a configuration could be employed as accelerator diagnostic as well as reliable setup to generate X-rays with tunable energy. Furthermore we report results on multi-energy X-ray imaging using a single beam setup with a plasma mirror and tunable shock-front injected electrons.

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Numerical studies on polarized betatron radiation from laser wakefield accelerators

Author: Tim Hager[None]

Co-authors: Andreas Döpp [1]; Stefan Karsch

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We investigate the generation of polarized betatron radiation in laser wakefield accelerators. Due to the isotropic fields of the wakefield cavity, betatron oscillations usually have no preferential direction and hence, the resulting betatron radiation is unpolarized. However, interaction with the laser pulse can induce oscillations along the laser's polarization axis. We use particle-in-cell simulations to study two different interaction regimes, namely electron-laser interactions during the injection phase [1] and late acceleration phase [2,3], regarding their potential to generate highly polarized femtosecond X-rays.

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Hard X-ray Sources from Laser-driven Relativistic Electrons at ELI Beamlines

Authors: Stefan Karatodorov[1]; Uddhab Chaulagain[1]; Marcel Lamač[1]; Jakub Vančura[1]; Karel Boháček[1]; Martin Albrecht[1]; Wenchao Yan[1]; Yanjun Gu[1]; Michaela Kozlová[2]; Tae Moon Jeong[1]; Kim Ta-Phuoc[3]; Stefan Weber[1]; Jaroslav Nejdl[1]

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We report the status of the LWFA driven X-ray sources at ELI beamlines facility. Gammatron beamline, that covers the X-ray energies from 1-100 keV in betatron scheme, and up to a few MeV in Compton scheme will be implemented in the Experimental hall E2. A state-of-the-art Ti:Sa diode-pumped HAPLS laser system (L3 laser) generating laser pulse of less than 30 fs, with energies of up to 30 Joule and with repetition frequency of 1-10 Hz would be used as a driving laser for these X-ray sources. The *Betatron* source will be broadband while *Compton* source would be quasi monoenergetic or broadband. These sources are characterized with a low divergence (< 20 mrad), small source size (few µm), short pulse duration (a few fs) and photon flux up to1010 photons per pulse. The Gammatron beamline will open new horizons in ultrafast X-ray science.

Experimental hall E3 (Plasma Physics Platform) houses a separate betatron source with similar properties to the one in E2. It will be an excellent source for probing various types of laser-generated plasmas and warm dense matter or other high-energy density physics phenomena.

Besides the presentation of the two X-ray sources we will also introduce a new optical probing method with increased interferometric sensitivity for characterization of low-density gas jets. This method was employed for characterization of a low-density argon gas jet at various backing pressures and the results were compared to commonly used Mach-Zehnder interferometer setup using a 405 nm laser.

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Towards an all-optical Thomson source for X-ray flourescence imaging

Authors: Kristjan Poder[1]; Simon Bohlen[1]; Theresa Staufer[2]; Martin Meisel[2]; Theresa Bruemmer[1]; Florian Gruener[2]; Jens Osterhoff[1]

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Laser wakefield accelerators can provide a very compact source of electron beams, which when combined with intense laser pulses result in a versatile X-ray source. Of particular interest for medical imaging are X-rays in the 50-100 keV energy range, high enough energy to penetrate through human-sized objects. Such beams also form the basis of an all optical Thomson source for X-ray Fluorescence Imaging (XFI) of (functionalized) gold-nanoparticles (F. Grüner et al., Sci. Rep. **8**, 16561 (2018)). Experimental progress towards realising such a source for XFI with gold nanoparticles is presented, with simulation studies of using an active plasma lens to restrict the radiation spectrum detailed.

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Gamma-ray radiation in beam-plasma interaction as a diagnostics for emittance growth in PWFA and for beam filamentation instabilities

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Low-emittance ultra-relativistic electron beams delivered for next generation of plasma wakefield acceleration (PWFA) experiments are expected to produce very high wakefields over very large distances when going through a plasma. Assessing electron beam dynamics under such fields will be of key importance to achieve the next milestones of the PWFA concept. Here we report on the use of the betatron X-ray and gamma-ray radiation emitted by the electron bunches under these fields to assess the electron beam dynamics and emittance evolution. We will present simulation results showing how the betatron radiation emitted by a relativistic electron beam is correlated to its emittance growth when propagating through the plasma in the highly non-linear regime. Gamma-ray radiation can also be a powerful tool in a related context: the growth of electromagnetic filamentation instabilities during beam-plasma interaction, with plasma densities ranging from gas density to solid density. We will present simulation results showing how very large electromagnetic fields produced during the electron beam filamentation instability can cause the production of bright gamma rays, which in turn can be used to assess the onset and evolution of the instability.

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The control of laser wakefield accelerated electron beams and betatron X-ray radiation using arrays of multiple gas jets

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The stability of Laser Plasma Wakefield Accelerated (LWFA) electron beams and the efficiency of betatron X-ray sources can be controlled using staged gas targets. Implementation of ionization-assisted [1] and density down-ramp [2] electron injection allows to change the energy and charge of accelerated electron beams. The double-jet betatron source with a low-density LWFA region and a high-density plasma radiator region produces photons of higher energy and has better efficiency relative to a single-jet gas target source [3].
In this report, we present the results of LWFA and X-ray generation using monolithic gas jet microarrays at the 40 TW 30 fs at the Lund Laser Centre. The density profiles of gas jets, ejected by micronozzles, were simulated using OpenFOAM compressible steady-flow solver [4]. The propagation of the laser beam and the acceleration of electrons were modelled using spectral FBPIC (Fourier–Bessel Particle-In-Cell) algorithm [5]. The results of the distribution of electron velocities were post-processed to estimate the photon energy of betatron radiation. Low-density gas targets of cylindrical de Laval and slit-shaped nozzles with the dimensions of 0.5 – 2.25 mm were used for electron acceleration. Single and an array of four cylindrical nozzles with the diameter of 200 - 800 µm, producing high-density gas regions at the output, were implemented for the density triggered injection and X-ray plasma radiator. The micronozzles were manufactured from fused silica using hybrid nanosecond laser rear-side processing and femtosecond laser-assisted selective etching technique [6]. The acceleration of electron beams of the energy of 30 -180 MeV and charge of 20 – 600 pC with different energy distribution and formation of double and triple electron beams using the gas jet arrays of pure helium and mixture of 1% nitrogen and helium were demonstrated. The energy of betatron X-ray radiation was 1.5 – 4.5 keV with 2·107 - 1·108 photons per shot. The implementation of the four-jet gas array of 200 µm diameter as the second gas target region resulted in the increase of betatron photon energy by a factor of 1.5 -2. The generated X-ray radiation was used for the transmission imaging of small-scale biological objects and polymer foils with micrometric resolution.

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Generation of tunable relativistic, single-cycle infrared pulses from a tailored plasma structure

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During the past decade, the development of intense few-cycle mid-infrared (mid-IR, λ<5 μm) laser sources has made significant progress, which has opened many opportunities for infrared nonlinear optics, high-harmonic generation and pump-probe experiments in the "molecular fingerprint" region. However, even longer carrier wavelength (~10 μm) are needed in many applications. It is one of the current challenges to generate high-energy, ultra-short long-wavelength IR pulses (LWIR), beyond the capability of existing methods including optical parametric amplifiers, high pressure carbon-dioxide lasers, difference frequency generation, and four-wave mixing, etc. In this work, we propose a new scheme that utilizes asymmetric self-phase modulation in a tailored plasma density structure to generate multi-millijoule energy, single-cycle LWIR pulses tunable in the spectral range of 5-14 μm. We experimentally demonstrate this novel scheme for the first time. An intense single-cycle IR pulse with a central wavelength of 9.4 μm and energy of 3.4 mJ is generated using a ~580 mJ, 36 fs, 810 nm drive laser. Furthermore, the tunability of the IR wavelength in the range of 3-19 μm is also demonstrated through simple adjustment of the plasma structure.

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High Field QED Experiments with Lasers Progress and Challenges

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The combination of GeV electron beams and ultra-intense lasers provides a perfect basis for experiments testing high intensity QED effects from vacuum pair production to determining the equation of motion of an electron in an intense laser field including strong radiation reaction.
Initial experiments (for example [1,2]) have shown significant promise and highlighted the remaining challenges. First experiments have shown that significant radiation reaction effects are observable and have demonstrated that our detection equipment is capabal of measureing vacuum pair creation against the strong gamma and pair background present in LPAs.
The experiments performed to date and the developments underlying future successful experiments are discussed.

[1] K. Poder al., Experimental Signatures of the Quantum Nature of Radiation Reaction in the Field of an Ultraintense Laser, PHYSICAL REVIEW X, Vol: 8 (2018)

[2] J.M.Cole et al., 2018, Experimental Evidence of Radiation Reaction in the Collision of a High-Intensity Laser Pulse with a Laser-Wakefield Accelerated Electron Beam, PHYSICAL REVIEW X, Vol: 8 (2018)

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Analytical Model for Beam Dynamics in Plasma Density Ramps

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A plasma-based accelerator operating in the blowout regime exerts a strong, transverse focusing force on the electron beam being accelerated. If the beam divergence is not matched to the focusing force, the beam will undergo chromatic emittance growth. A ramped plasma density profile at the entrance to the plasma source can focus the beam down to the matched size, limiting emittance growth during acceleration. When the beam exits the plasma source, the focusing force disappears and the beam rapidly diverges. The divergence can be controlled by using a ramped plasma density profile at the exit of the plasma. We present an analytic theory describing the transverse beam dynamics within the ramps. Our theory can be used to predict the emittance growth within a given ramp or to predict the ramp lengths required for coupling a given beam into and out of an accelerator with negligible computational cost.

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First fully kinetic full 3D AWAKE baseline scenario simulation

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Co-authors: Hartmut Ruhl ; Karl-Ulrich Bamberg

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The "Advanced Proton Driven Plasma Wakefield Acceleration Experiment" (AWAKE) aims to enable lepton acceleration via proton-driven wakefields. It comprises extensive numerical studies as well as experiments at the CERN laboratory.

The baseline scenario has a simulation domain of 0.81 cm in the x, 0.42 cm in the y, and 10 m in the z direction. The smallest scale in this domain is the plasma wavelength, which is about 1.25 mm and needs to be resolved. This makes the computational requirements of this experiment very intense.

Previous numerical studies were performed using reduced models, most prominently the axisymmetric approximation, which reduces the number of dimensions by one, resulting in a two dimensional problem. While this helps with reducing the computational demand, several important effects can not be accurately reproduced when using these approximations, most notably the hosing instability and the complex process of witness beam trapping in the emerging wakefield.

We present results for the first three dimensional simulation of this baseline scenario with a full model. The simulations took 22 Mch on the SuperMUC system and required substantial optimization efforts, including a host of inline evaluations, dynamic load balancing and a dynamic simulation domain.

After analyzing the files from the simulation, which have a total size of tens of TBs, we were able to obtain several important results. The simulation reproduces the self-modulation instability of the proton beam and does not show significant hosing. The accelerating gradient as well as the witness beam acceleration conform to the previous results using reduced models. From plotting specific witness beam trajectories we were able to deduce several important observations regarding the nature of the trapping process.

We will present the details of the simulation as well as figures showing its results and our subsequent observations.

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Simulations of long-term wakefield evolution in a radially bounded plasma

Authors: Konstantin Lotov[1]; Michael Downer[2]; Mark Hogan[3]; Vadim Khudyakov[1]; Thales Silva[4]; Alexander Sosedkin[1]; Jorge Vieira[4]; Vitaly Yakimenko[3]; Rafal Zgadzaj[2]

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In plasma wakefield accelerators, intense laser or particle beams drive strong Langmuir waves with the energy density as high as the rest energy of plasma electrons. A large fraction of this energy remains in the plasma after passage of the accelerated beam and causes rapid expansion of the plasma column boundary. The energy initially stored in coherent electron oscillations first transforms into incoherent motion of plasma electrons with multi-keV velocities and, later, into radial motion of plasma ions. The resulting stream of fast ions escapes the initial plasma channel, penetrates the surrounding neutral gas and creates some "seed" plasma there through impact ionization. Once new ions appear at a given location, more electrons come there and further ionize the gas causing near-exponential growth of the plasma density. The energy needed for gas ionization is small compared to the initial wave energy, so the plasma boundary expands with nearly constant velocity corresponding to the velocity of the fast ion front, with the plasma amount growing proportionally. Numerical simulations that include the described effects show quantitative agreement with results of ps-time-resolved optical shadowgraphy that measured evolving plasma density profile at FACET.

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Efficient 3D envelope modelisation for two-stage laser wakefield acceleration experiments

Authors: Francesco Massimo[1]; Arnaud Beck[1]; Julien Derouillat[2]; Mathieu Lobet[2]; Mickael Grech[3]; Frédéric Pérez[3]; Imen Zemzemi[1]; Arnd Specka[1]

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Three dimensional Particle in Cell simulations of Laser Wakefield Acceleration require a considerable amount of resources but are necessary to have realistic predictions and to design future experiments. The planned experiments for the CILEX facility also include two stages of plasma acceleration, for a total plasma length of the order of centimiters. In this context, where traditional 3D simulations would be infeasible, we present the results of the application of a recently developed explicit 3D envelope method. This model describes the laser pulse ant its self-consistent interaction with the

plasma without the need to resolve its high frequency oscillations, considerably reducing the computation time. The implementation of this envelope model in the code Smilei will be described, as well as the results of benchmark simulations against standard simulations and its applications for the design of two stage CILEX experiments.

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Simulations of laser-driven ion acceleration using the quasi-cylindrical PIC code CALDER-CIRC and application to the PETAL facility

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Target normal sheath acceleration (TNSA) of ions from laser-irradiated solid foils is a well-known, robust and widely used method. Numerical simulation of this process using PIC codes is, however, very challenging. Indeed, very small space and time steps are required to resolve the plasma skin depth and plasma period at the solid densities considered, while large spatiotemporal domains are needed to capture the full scales of ion acceleration. In addition, the hot electrons' transverse expansion, which strongly affects the dynamics and spatial distribution of the accelerating sheath field, can only be correctly described in a 3D geometry. In particular, such electron dilution is underestimated in 2D geometry, leading to significant overestimation of the final ion energy. Despite this limitation, 2D PIC simulations often appear to be the only reasonable option due to the excessive computational cost of 3D simulations.
As an alternative, we investigate here the benefit of using the quasi-cylindrical PIC code CALDER-CIRC [1] to describe TNSA over experimentally relevant scales. This code employs a field decomposition into a few Fourier modes along the poloidal angle, thus enabling reduced 3D simulations at a computational cost close to that of 2D Cartesian simulations. This method, originally developed for laser wakefield acceleration, remains valid if the plasma fields retain a quasi-cylindrical symmetry. To illustrate both its potential and limitations, we will compare simulations of a typical TNSA setup carried out using CALDER-CIRC and the 2D and 3D Cartesian versions of CALDER.
Moreover, we will report on a CALDER-CIRC simulation of TNSA under conditions relevant to the PW PETAL laser (~450 J energy, ~600 fs pulse duration, ~50 µm focal spot). The effect of the laser prepulse on the relativistic laser interaction and the acceleration processes will be analyzed.

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Mitigation of beam transverse deflections induced by the beam-hollow plasma channel misalignment

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Co-authors: Guoxing Xia [2]; Yuan Zhao [2]; Oznur Apsimon [3]

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Hollow plasma has been introduced into the proton-driven plasma wakefield accelerator to overcome the issue of beam quality degradation caused by the nonlinear transverse wakefields varying in radius and in time in uniform plasma. It has been demonstrated that the electrons can be accelerated to the energy frontier with a well-preserved beam quality in a long hollow plasma channel. However, this scheme requires the driver bunch in perfect alignment with the hollow channel, otherwise asymmetric and possibly strong transverse wakefields come into play, which could significantly deflect the beam and deteriorate the beam quality. In this paper, we examine these detrimental effects from theoretical and numerical aspects. We demonstrate that the proton driver is less sensitive to the misalignment due to the strong focusing field formed within the hollow channel. However, the induced transverse fields cause significant particle loss of the witness beam. Fortunately, by adopting a near-hollow plasma channel which maintains a small number of ions within the channel, we create a deep potential well to confine the witness beam. Eventually, the beam quality is well conserved.

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Acceleration rate increase due to plasma ion motion

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Theoretical and computer simulation models of plasma wakefield acceleration often do not take into account the ion motion, considering ions immobile due to the large mass. This approximation is inapplicable in the cases of intense or long drivers, or a large distance between the driver and the witness. In such cases, the ions can move so that the disturbance of the ion density makes significant changes to the field map at the witness location. Accounting for this factor usually leads to a lower amplitude of the electric field in the wake and rapid damping of plasma oscillations.

There are, however, conditions in which ion motion leads to an increase in the amplitude of the accelerating field on the axis. This occurs in a weakly nonlinear wakefield due to the redistribution of its energy over the plasma cross section. The effect can be identified by visualizing the energy flow in the wave. Under certain conditions, an increase in the longitudinal field, as compared with the immobile ions case, can reach 20%.

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Beam quality preservation by loading of a preceding electron beam in proton driven plasma wakefield acceleration

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Proton-driven plasma wakefield acceleration has been demonstrated in simulations to be capable of accelerating electrons to the energy frontier in a single plasma stage. However, the achieved beam quality especially the normalized emittance is still far from applications. This is because the transverse plasma wakefield acting on the witness electron bunch is nonlinear to the radius, and it varies along the bunch and in time as well, regardless of whether the operation regime is nonlinear or not. In addition, the longitudinal electric field is nonuniform along the radius, which causes the energy spread to increase during the acceleration. In this paper, we propose to load another electron bunch ahead of the witness bunch. This preceding electron bunch completely expels the plasma electrons away from the witness bunch and sustains a local plasma electron free "bubble" within the accelerating structure. In the "bubble", the witness bunch sees a radially linear focusing and a transversely uniform accelerating field, which preserves the normalized emittance and maintains low energy spread of the witness beam. Studies show that for the preceding electron beam, the initial energy needed is only ~550 MeV for a 1 TeV proton driver. Also it is initially placed close to the zero-field region, so it doesn't extract much energy from the wakefield. Interestingly, all the obtained energy will eventually contribute to the wake excitation in the later stage. At the end of the accelerating stage, the witness bunch reaches the energy frontier with high beam quality.

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A three-dimensional ponderomotive guiding center solver in Osiris

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Particle-in-cell (PIC) simulations play a major role to the development of laser-wakefield acceleration (LWFA). Although PIC simulations provide quantitative predictions, that can be directly compared with experimental results, they are also very computationally intensive. Full scale 3d PIC simulations of LWFA are challenging due to the large-scale disparity between the laser wavelength λ_0, which is in μm-range, and the acceleration distance, which can exceed the m-range. Since the work of Gordon et al. [1], the ponderomotive guiding center (PGC) solver is a promising candidate to bridge the scale disparity. By advancing the laser envelope rather than the fields of a laser pulse a speedup of

$\sim (\lambda_p/\lambda_0)^2$ can be achieved where λ_p is the plasma skin depth. Here, we discuss our implementation of a PGC solver [2] into OSIRIS [3] which includes cylindrical, 3d cartesian coordinates and full ionization support. The discussion includes 3d parametric studies for beam properties for downramp injection cases and the usage of external magnetic quadrupoles for shaping beams in LWFA cases. We also present ionization seeding of a self-modulation instability for the full 10 m experimental realization of the AWAKE experiment [4].

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RaDiO-Radiation Diagnostic for Osiris: an efficient radiation processing tool for particle-in-cell simulations

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Radiation processes in plasmas are extremely relevant for a number of fields, ranging from astrophysics to small scale microscopy. These processes are usually associated with the motion of a large number of electrons, under the action of intense electric and magnetic self-consistent fields and require numerical descriptions in order to be explored. Particle-In-Cell (PIC) codes like OSIRIS are able to accurately describe the motion of the individual particles but they cannot be employed to capture radiation emission at wavelengths much smaller than the grid size because of the large computational requirements.
To circumvent this issue, here, we present RaDiO - Radiation Diagnostic for Osiris - which is fully integrated into OSIRIS and is capable of capturing the spatiotemporal properties of the radiation emitted by tens of millions of charged particles. RaDiO has built-in spatial and temporal coherence and uses a sophisticated radiation deposition algorithm that allows for radiation to be deposited in a grid with much higher resolution than the PIC simulation grid.
This tool recovers the theoretical spectra for well-known scenarios of radiation emission, and has been thoroughly tested and benchmarked for typical trajectories associated with synchrotron radiation in the undulator and wiggler regimes.
In addition, we show that our algorithm strongly reduces the computational requirements associated with radiation simulations in three-dimensions, allowing for an accurate description of physical processes up to very high frequencies in 3D. As an illustration, we will explore the spatiotemporal betatron radiation profile in plasma based acceleration.

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Directionality control of electron-positron pairs produced in laser-electron collisions

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State-of-the-art Petawatt laser facilities [1] routinely generate multi-GeV electron beams [2,3] by laser wakefield acceleration and are envisioned to study fundamental QED processes in near future [4]. Laser pulses with intensities over 1022 W/cm2 can be used to investigate nonlinear QED effects by colliding against counter-propagating high energy electron beams [5,6], and produce copious amounts of high energy photons and electron-positron pairs. These sources will be of great importance in their applications in broad areas of physics, as well as for understanding QED in strong background fields.
In this work, we examine the directionality of positrons and electrons produced from the pair creation process during laser-electron collisions. We numerically investigate the pair creation processes in collisions where a laser pulse with intensity I > 1022 W/cm2 scatters off a multi-GeV electron beam. The simulations are performed using the 3D particle-in-cell code EPOCH [7]. We observed that the pulse shape, intensity, and polarization have effects on the phase-space distributions of pairs produced from Breit-Wheeler and Trident processes [8]. We noticed that a significant number of pairs is expelled from the center of the laser pulse, following the polarization direction. Additionally, a small number of particles reverse the direction of its longitudinal momentum, propagating in the opposite direction of the incident electron beam. The results obtained in this work can provide crucial information on planning and detection of electron-positron pairs in collision experiments performed at multi-petawatt laser facilities.

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Modeling the Temporal Evolution of a Laser-Ionized Plasma Source

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Characterizing the plasma density profile in a plasma accelerator is important for predicting the beam dynamics and the electric field gradients produced in the plasma wake structure. In this poster, we present a two fluid model for the time evolution of the plasma and neutral gas density profiles for a laser ionized plasma filament. Our model includes the effects of hydrodynamic expansion and recombination. We compare our model with experimental measurements of a laser ionized Ar and He plasma that is $\sim .5\,mm$ wide and $\sim 100\,cm$ long with densities $10^{15-17}cm^{-3}$.

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DLA of electrons in plasma channels using extremely intense lasers

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Plasma channels represent a well-suited environment for laser-based particle acceleration. The reasons for this are twofold. On one hand, the laser can be self-guided within the channel, which allows for long propagation distances. On the other hand, the channel can affect the particles directly. For example, self-generated electromagnetic fields can assist direct laser acceleration within the channel and allow energy gain beyond the vacuum acceleration limit [1,2]. As fluctuations of the longitudinal electric field affect the dephasing between the electrons and the laser, it becomes possible to generate “superponderomotive” electrons [3]. Laser pulses of extreme intensities ($I > 10^{22}\ \mathrm{W/cm^2}$) are about to become available in the laboratory. The prepulse of such a laser can induce a plasma expansion that generates a low- density channel in near-critical gas jets. Here we present a study of channel formation and subsequent direct laser acceleration of electrons within the pre-formed plasma channel [4]. We show that the radiation reaction is important for the global plasma dynamics and affects the electron acceleration in several ways. It first interferes with the motion of the return current on the channel walls, which changes the dynamics of the channel-splitting. In addition, it reduces the radial expelling efficiency of the transverse ponderomotive force, leading to radiative trapping of particles near the channel axis. The radiation reaction also changes the onset of parametric resonance, which allows more particles to achieve the resonant condition [5]. The combination of these effects is favourable for obtaining multi-GeV electron beams with a total charge higher than 1 nC.
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Working group:

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Multi-dimensional evolutions of transverse instability in the "light sail" ion acceleration

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Acceleration of the ultrathin plasma foils by the laser radiation pressure promises a compact alternative of conventional accelerator delivering energetic ions. It was shown, that a major showstopper of this scheme is a strong transverse instability, which develops the surface ripples often attributed to the Rayleigh-Taylor-like (RT) mechanism triggered by the laser pressure. However, simulations indicate that the developing perturbations have a specific spectral structure, that cannot be consistently explained by the RT mechanism. Here we develop a three-dimensional (3D) theory of this instability, which shows that its linear stage is mainly driven by the strong electron-ion coupling, while the RT contribution is actually weak. The model provides instability spectral structure and growth rate, that agree well with large scale 3D particle-in-cell simulations. Numerical modelling shows, that the target is destroyed during the nonlinear instability phase by the induced plasma heating, which also triggers the merging of small filaments. Possible paths to instability mitigation are discussed.

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Quasistatic and PIC simulations of electron self-trapping by the wake of low power laser pulse

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Laser plasma wakefield acceleration is a promising development path for acceleration technologies. Studying this phenomenon relies heavily on numerical simulations. Generic PIC simulations provide the most detailed description of laser-plasma interaction, but they are computationally demanding. Simplyfing the model, e.g., with quasistatic approximation, yields significant performance gains at the cost of not accounting for some physical processes, such as plasma electron self-trapping. However, the simulations of high energetic part of plasma electrons with full equation of the motion in quasistatic code allow one to obtain reasonable data about electron self-trapping. With both quasistatic and PIC codes available, parametric scans could be carried out with fast code, leaving only the most important points to be verified in detail with PIC code. We have used modified quasistatic code LCODE and PIC code WARP to study low power laser pulse interaction with plasma. Both codes give similar results. The focusing of laser pulse into plasma leads to modification of self-focusing laser-plasma instability and higher wake amplitude. The beam formation can be initiated by this processes. The beam parameters dependence on plasma profile has also been studied. The reported study was funded by RFBR and Government of the Novosibirsk region according to the research project No. 17-41-543162.

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Modeling hybrid plasma accelerator experiments with PIConGPU

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Utilizing laser-wakefield accelerated (LWFA) electrons to drive a plasma-wakefield accelerator (PWFA) holds great promise for realizing centimeter-scale electron accelerators providing ultra-high brightness beams. Recent experiments at HZDR could demonstrate for the first time such an electron acceleration in a nonlinear PWFA plasma wakefield. For driving this compact hybrid accelerator setup, high-charge electron bunches from LWFA self-truncated ionization injection were used.

In this talk, we present recent results of the accompanying simulation campaign performed with the 3D3V particle-in-cell code PIConGPU. These simulations model the geometry, density distributions, laser modes, and gas dopings as determined in the experiments. The simulation conditions resemble the experiment to a very high degree and thus provide good comparability between experiment and simulation. Additionally, the wealth of information provided by the in-situ data analysis of PIConGPU provides insight into the plasma dynamics, otherwise inaccessible in experiments.

From an algorithmic and computational perspective, we modeled the hybrid accelerator from start to end in a single simulation scenario. We discuss the associated challenges in maintaining numerical stability and experimental comparability of these long-duration simulations.

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