Science and Applications of Plasma-Based Accelerators

767. WE-Heraeus-Seminar

15 - 18 May 2022

HYBRID
at the Physikzentrum Bad Honnef/Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 767. WE-Heraeus-Seminar:

Recent breakthroughs make the prospects for practical plasma-based accelerators more and more encouraging. On the laser plasma acceleration front, the advent of novel laser technologies and the systematic approach to making the laser pulses more reproducible, coupled with the demonstration of the stageability of the acceleration process have led to very promising perspectives. On the beam-driven front, the recent demonstration of a high energy transfer efficiency between the driver and witness bunches and energy bandwidth conservation using electron drivers, and the demonstration that proton-driven plasma wakefield acceleration is an attractive approach for the future have invigorated this research area.

A goal of the workshop is to, on the one hand, review and discuss the applications for which the different plasma-based acceleration schemes can contribute, and, on the other hand, to review the main technological challenges that require solutions for these schemes to become practical. We discuss these aspects separately for the different acceleration schemes we plan to cover in the workshop.

Scientific Organizers:

Prof. Dr. Allen Caldwell	Technische Universität München (TUM), Germany E-mail: caldwell@mpp.mpg.de
Prof. Dr. Wim Leemans	Universität Hamburg, DESY, Germany E-mail: wim.leemans@desy.de
Dr. Jens Osterhoff	Universität Hamburg, DESY, Germany E-mail: jens.osterhoff@desy.de

Introduction

Administrative Organization:

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Registration:

Mojca Peklaj (WE Heraeus Foundation)
at the Physikzentrum, Reception Office
Sunday (17:00 h – 21:00 hrs) and
Monday morning

Program

Program *(CEST)*

Sunday, 15 May 2022

17:00 – 21:00	Registration	
18:00	*BUFFET SUPPER and informal get-together*	

Monday, 16 May 2022

08:00	*BREAKFAST*	
08:45 – 09:00	Organizers	**Welcome and Goals**

Light Source Applications (Convener: Andreas Maier)

09:00 – 09:05	Andreas Maier	**Introduction**
09:05 – 09:35	Agostino Marinelli	**X-Ray Free-Electron Lasers: State of the Art and Opportunities for Advanced Particle Accelerators**
09:35 – 10:05	Félicie Albert	**Laser Plasma Accelerators: Next Generation X-Ray Light Sources**
10:05 – 10:30	**Discussion**	
10:30 – 11:00	*COFFEE / TEA BREAK*	

Particle Physics Applications (Convener: Edda Gschwendtner)

11:00 – 11:05	Edda Gschwendtner	**Introduction**
11:05 – 11:35	Beate Heinemann	**HEP Applications of Plasma Wakefield Accelerators**
11:35 – 12:05	Brian Foster	**Applications of Plasma-Wave Acceleration Techniques to Particle Colliders**
12:05 – 12:30	**Discussion**	
12:30 – 14:00	*LUNCH BREAK*	

Program *(CEST)*

Health and Industrial Applications (Convener: Jörg Schreiber)		
14:00 – 14:05	Jörg Schreiber	**Introduction**
14:05 – 14:35	François Sylla	**Laser Plasma Accelerators to Address the Industrial Inspection Market**
14:35 – 15:05	Ulrich Schramm	**Establishing Laser Accelerated Proton Beam Performance for Dose Controlled Irradiation Studies**
15:05 – 15:30	**Discussion**	
15:30 – 16:00	*COFFEE / TEA BREAK*	

Simulation / Theory (Convener: Jean-Luc Vay)		
16:00 – 16:05	Jean-Luc Vay	**Introduction**
16:05 – 16:35	Maxence Thévenet	**Theoretical Basis and Exascale Simulations**
16:35 – 17:05	Marija Vranić	**Laser-Electron Collisions and Laser-Plasma Interaction in QED Regime (Theory and Simulations)**
17:05 – 17:30	**Discussion**	
18:30	*HERAEUS DINNER* (social event with cold & warm buffet with complimentary drinks)	

Program *(CEST)*

Tuesday, 17 May 2022

08:00	*BREAKFAST*	

Driver Technology (Convener: Jens Limpert)

09:00 – 09:05	Jens Limpert	**Introduction**
09:05 – 09:35	Stefan Karsch	**Ti:Sapphire Lasers as Drivers for Plasma-Based Accelerators**
09:35 – 10:05	Laura Corner	**Laser Technology for LWFA**
10:05 – 10:30	**Discussion**	
10:30 – 11:00	*COFFEE / TEA BREAK*	

Plasma Technology (Convener: Patric Muggli)

11:00 – 11:05	Patric Muggli	**Introduction**
11:05 – 11:35	Brigitte Cros	**Overview of Plasma Technology for Accelerators**
11:35 – 12:05	Howard Milchberg	**Optical Guiding of High Intensity Laser Pulses for Laser Wakefield Acceleration**
12:05 – 12:30	**Discussion**	
12:30 – 14:00	*LUNCH BREAK*	
14:00 – 15:30	**Poster Session Introductions**	
15:30 – 17:30	**Poster Session / COFFEE**	
17:30 – 19:00	*WORKSHOP DINNER AND EXTENDED DISCUSSIONS*	

Program *(CEST)*

Wednesday, 18 May 2022

08:00	*BREAKFAST*	
Plasma Astrophysics (Convener: Frank Jenko)		
09:00 – 09:05	Frank Jenko	**Introduction**
09:05 – 09:35	Frederico Fiuza	**Cosmic-Ray Driven Instabilities**
09:35 – 10:05	Tony Bell	**The Surprising Effectiveness of Cosmic Ray Acceleration**
10:05 – 10:30	**Discussion**	
10:30 – 11:00	*COFFEE / TEA BREAK*	
Diagnostics (Convener: Mike Downer)		
11:00 – 11:05	Mike Downer	**Introduction**
11:05 – 11:35	Malte Kaluza	**High-Resolution Diagnostics for Plasma-Based Accelerators - a Tool for Detailed Insights into the Interaction**
11:35 – 12:05	Enrica Chiadroni	**Electron Beam Diagnostics**
12:05 – 12:30	**Discussion**	
12:30 – 14:00	*LUNCH BREAK*	
Machine Learning in Wakefield Acceleration (Convener: Adi Hanuka)		
14:00 – 14:05	Adi Hanuka	**Introduction**
14:05 – 14:35	Remi Lehe	**Overview of Gaussian Processes and Bayesian Optimization for Plasma-Based Accelerators**
14:35 – 15:05	Alexander Scheinker (online)	**Overview of Adaptive Machine Learning Methods: Towards Virtual 6D Phase Space Diagnostics**
15:05 – 15:30	**Discussion**	

End of Seminar / Departure

Posters

Poster Session - Tuesday, 17 May, 15:30 h

1	Masoud Afshari	**New Insights into the Acceleration of Gold Atoms by High Power Lasers**
2	Carolina Amoedo	**Monitoring Gas Composition Evolution of Discharge Plasma Source with Optical Emission Spectroscopy, for the AWAKE Experiment**
3	Michael Backhouse	**Measurements of the Effect of Density Ramps and Plasma Mirrors on 2GeV Laser Wakefield Accelerated Beams**
4	Chiara Badiali	**Acceleration of Non-Relativistic Muons in Plasma Based Accelerators**
5	Judita Beinortaite	**Signal Subtraction of Consecutive Electron Bunches from a High-Repetition-Rate Plasma-Wakefield Accelerator**
6	Michele Bergamaschi	**Observation of Plasma Light at AWAKE**
7	Jonas Björklund Svensson	**Future Plans for the Beam-Driven Plasma-Wakefield Experiment FLASHForward**
8	Frida Brogren	**Prediction of Beam Energy Using Neural Networks and Beam Position Monitors**
9	Michael Bussmann	**The Digitalization of Advanced Plasma Accelerator Experiments – A Perspective**
10	Richard D'Arcy	**Recovery Time of a Plasma-Wakefield Accelerator**
11	Alexander Debus	**PIConGPU -- High-Fidelity Plasma Simulations on Desktop Computers up to Exascale Compute Systems and a View on its Recent Applications**

Poster Session - Tuesday, 17 May, 15:30 h

12	Severin Diederichs	**Modelling Positron Acceleration with HiPACE++**
13	Mike Downer	**CO 2 Laser-Driven Wakefield Acceleration**
14	Michael Ehret (online)	**Enhancement of Tape Targets at VEGA**
15	Bonaventura Farace	**A Confined Continuous-Flow Plasma Source For High-Average-Power Laser Plasma Acceleration**
16	John Farmer	**Injection Tolerances for AWAKE Run 2c**
17	Moritz Foerster	**Hybrid LWFA-PWFA: A Stability and Beam-Quality Booster for Laser-Generated Electron Beams**
18	Marcel Granetzny	**Computation and Measurement of Helicon Wave Fields and Plasma Parameters in a Wakefield Accelerator Prototype**
19	Cornelia Gustafsson	**Shock-Assisted Ionisation Injection for Very High Energy Electron Radiotherapy**
20	Andrea Hannasch	**Compact Spectroscopy of keV to MeV X-rays from Laser Plasma Electron Accelerators**
21	Arie Irman	**DRACO Laser-Driven Electron source for secondary radiation generation and applications**
22	Faran Irshad	**Multi-Objective Multi-Fidelity Optimization of Laser Wakefield Accelerator**
23	Soeren Jalas	**Bayesian Optimisation of Laser Plasma Accelerators**

Poster Session - Tuesday, 17 May, 15:30 h

24	Advait Kanekar	**Gas-Flow Simulations of a Discharge-Capillary Plasma Source for High-Repetition-Rate Plasma-Wakefield Operation**
25	Manuel Kirchen	**Surrogate Modelling of Laser-Plasma Acceleration**
26	Arpad Lenart	**Advanced Space Radiation Reproduction Using Laser Wakefield Accelerators**
27	Erik Löfquist	**Design and Numerical Investigations of a Phase Locked Few Cycle Laser Accelerator**
28	Antoine Maitrallain	**Parametric Study of High-Energy Ring-Shaped Electron Beams from a Laser Wakefield Accelerator**
29	Conor McAnespie	**High-dose Femtosecond-Scale Gamma-Ray Beams for Radiobiological Applications**
30	Orla McCusker	**Diamond Detectors for Time of Flight Measurements in High Repetition Rate Laser-Plasma Interactions**
31	Mathis Mewes	**Hydrodynamics Simulations of Plasma Accelerator Sources**
32	Pablo Israel Morales Guzman	**PIC Simulations of the Self-Modulation of a Long Proton Bunch using two seeds: an Electron Bunch and a Density Cut**
33	Mariana Moreira	**Control of the Self-Modulation and Long-Bunch Hosing Instabilities with Plasma Frequency Detuning**
34	Tatiana Nechaeva	**Hosing of a Long Relativistic Particle Bunch Induced by an Electron Bunch**

Poster Session - Tuesday, 17 May, 15:30 h

35	Isabella Pagano	**Source Size Analysis of Laser Plasma Acceleration Generated X-Rays**
36	Felipe Peña	**Progress Toward High Overall Energy Efficiency in a Beam-Driven Plasma-Wakefield Accelerator Stage**
37	Christopher Pieronek	**Ionization Injection in a Laser-Heated Capillary Discharge Waveguide**
38	Kristjan Poder	**Polarised Electron Beams from Plasmas**
39	Dennis Proft	**Plasma-Based Accelerator as Possible Replacement of a 26 MeV Linear Accelerator as Pre-Injector for a Synchrotron**
40	Jan Pucek	**Competition Between Electron Seeding and Relativistic Ionization Front Seeding**
41	Alexander Pukhov	**Positron Acceleration via Laser-Augmented Blowouts in Two-Column Plasma Structures**
42	Susanne Schöbel	**Optical Probing of Plasma Waves in a Hybrid LWFA-PWFA Stage**
43	Sarah Schröder	**Stability Studies in a Plasma-Wakefield Accelerator**
44	Rob Shalloo	**Automation and Control of Plasma Accelerators Using Bayesian Optimisation**
45	Xiaofei Shen	**Electron Acceleration by Surface Plasma Wave at Overdense Plasma-Vacuum Interface**
46	Thales Silva	**Two Schemes for Plasma-Based Positron Acceleration: Thin Hollow Channels and Non-Neutral Fireball Beams**

Poster Session - Tuesday, 17 May, 15:30 h

47	Alexander Sinn	**Improving Performance and Numerics of the Quasi-static PIC Code HiPACE++**
48	Michael Switka	**Studies for an LPWA-Based Injector of Polarized Electrons for the ELSA Facility**
49	Davide Terzani	**High-Quality Electron Beams from Two-Color Ionization Injection at BELLA**
50	Nuno Torrado	**Double Pulse Generator for Long Tube Plasma Discharges**
51	Livio Verra	**Electron Bunch Seeding of the Self-Modulation Instability in Plasma**
52	Katinka von Grafenstein	**Laser Wakefield Acceleration to GeV Electron Energies**
53	Nils Weisse	**Spectrally Resolved Wavefront Analysis of the ATLAS 3000 Petawatt Laser**
54	Camilla Willim	**Proton Acceleration with Shaped Lasers and Double-Layer Targets**
55	Anna Willmann	**Surrogate Modelling for Boosting Research of Electron Acceleration Processes**
56	Michael Zepp	**High Time Resolution Particle Balance Measurements in AWAKE Helicon Plasmas**
57	Giovanni Zevi Della Porta	**e4AWAKE – Next Generation Electron Source for the Advanced Wakefield (AWAKE) Proton-Driven Plasma Acceleration Experiment at CERN**

Abstracts of Lectures

(in alphabetical order)

Laser plasma accelerators: next generation x-ray light sources

Félicie Albert

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Bright sources of x-rays, such as synchrotrons and x-ray free electron lasers (XFEL) are transformational tools for many fields of science. They are used for biology, material science, medicine, or industry. Such sources rely on conventional particle accelerators, where electrons are accelerated to gigaelectronvolts (GeV) energies. The accelerating particles are also wiggled in magnetic structures to emit x-ray radiation that is commonly used for molecular crystallography, fluorescence studies, chemical analysis, medical imaging, and many other applications. One of the drawbacks of synchrotrons and XFELs is their size and cost, because electric field gradients are limited to about a few 10s of MeV/M in conventional accelerators.

This presentation will review particle acceleration in laser-driven plasmas as an alternative to generate x-rays, and in particular present some experiments at LaserNetUS facilities, a consortium of 10 high power lasers in America. A plasma is an ionized medium that can sustain electrical fields many orders of magnitude higher than that in conventional radiofrequency accelerator structures. When short, intense laser pulses are focused into a gas, it produces electron plasma waves in which electrons can be trapped and accelerated to GeV energies. This process, laser-wakefield acceleration (LWFA), is analogous to a surfer being propelled by an ocean wave. Betatron x-ray radiation, driven by electrons from laser-wakefield acceleration, has unique properties that are analogous to synchrotron radiation, with a 1000-fold shorter pulse. This source is produced when relativistic electrons oscillate during the LWFA process.

An important use of x-rays from laser plasma accelerators we will discuss is in High Energy Density (HED) science. This field uses large laser and x-ray free electron laser facilities to create in the laboratory extreme conditions of temperatures and pressures that are usually found in the interiors of stars and planets. To diagnose such extreme states of matter, the development of efficient, versatile and fast (sub-picosecond scale) x-ray probes has become essential. In these experiments, x-ray photons can pass through dense material, and absorption of the x-rays can be directly measured, via spectroscopy or imaging, to inform scientists about the temperature and density of the targets being studied.

Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344, supported by the LLNL LDRD program under tracking code 13-LW-076, 16-ERD-024, 16-ERD-041, supported by the DOE Office of Fusion Energy Sciences under SCW 1476 and SCW 1569, and by the DOE Office of Science Early Career Research Program under SCW 1575.

The surprising effectiveness of cosmic ray acceleration

Tony Bell[1,2]

[1]Clarendon Laboratory, University of Oxford, OX1 3PU, UK
[2] Central Laser Facility, Rutherford Appleton Laboratory, OX11 0QX, UK

Cosmic rays are accelerated to a few PeV, and maybe 100PeV, in the Milky Way Galaxy. They are accelerated beyond 100EeV elsewhere. If I did not know better, I would say this could not happen, especially with such high efficiency. In this talk I discuss how acceleration to these energies pushes against the limits of theoretical credibility and how plasma physics occasionally works for us instead of against us.

Electron Beam Diagnostics

E. Chiadroni[1,3], A. Cianchi[2], M. Galletti[2], V. Shpakov[3]

[1]SBAI Sapienza University, Rome, Italy
[2] University of Rome Tor Vergata and INFN-Tor Vergata, Rome, Italy
[3] INFN-LNF, Frascati - Rome, Italy

In any accelerator the diagnostic is mandatory for the success of its operation, even more so for advanced accelerators such those based on plasma, being the efficiency of the acceleration and the quality of plasma-accelerated electron beams strongly dependent on the demanding matching conditions required at the plasma structure. In addition, the electron beam parameters downstream from the plasma accelerating module must be known to transport the beam and match it to any desired application, e.g FEL undulator, additional accelerating module, etc. [1].
Single shot measurements are preferable for plasma-accelerated beams, including normalized transverse emittance, while micrometer and femtosecond scale, for transverse and longitudinal beam size respectively, is requested.
Furthermore, the needed to separate the driver pulse (either laser or electron beam) from the witness accelerated bunch imposes additional constrains for the diagnostics.
A conceptual design of the proposed diagnostics is here presented using state of the art systems and new and under development devices [2].

References

[1] P. A. Walker et al., J. Phys.: Conf. Ser., **874** (1), 012029 (2017).
[2] A. Cianchi et al., Nucl. Instrum. and Meth. in Phys. Res. Section A: Accel., Spectr., Det. and Assoc. Equip., **909**, 350-354 (2018).

Laser technology for LWFA

L. Corner[1,2]

[1]School of Engineering, University of Liverpool, Brownlow Hill, Liverpool L69 3GH, UK
[2] Cockcroft Institute, Keckwick Lane, Daresbury, Warrington WA4 4AD, UK

Current driver technology for laser plasma wakefield acceleration (LWFA) does not operate at the repetition rate or efficiency required for practical machines. In this talk, I will present an overview of the laser parameters ideally needed for future accelerators based on LWFA, and the possible laser technologies, besides standard titanium sapphire systems, which might be able to fulfill these requirements.

Overview of plasma technology for accelerators

<u>B. Cros[1]</u>

[1]*CNRS Université Paris Saclay LPGP, Orsay, France*

Plasma components can be used for several purposes in plasma based accelerators: compact particle sources, accelerating medium (plasma cavity), waveguide (for laser driver), particle beam optical device (plasma lens).

I will introduce the main concepts, and give an overview of parameter range and techniques, highlight the main achievements and current challenges for the development of future accelerators in terms of:

1) Plasmas for laser driven compact sources of electrons (without external guiding, or without discussing guiding effects)
2) Plasmas for beam driven wakefield accelerators
3) Plasmas for beam optics (plasma lens, beam dump).

Cosmic-ray driven instabilities

<u>F. Fiuza[1]</u>

[1]*SLAC National Accelerator Laboratory, Menlo Park, USA*

Cosmic-ray (CR) driven plasma instabilities play a very important role in magnetic field amplification and particle acceleration in astrophysical shocks as well as in CR transport in the interstellar/intergalactic medium. I will focus on magnetic field amplification by CRs in the context of astrophysical shocks, which is an intrinsically multi-scale phenomenon. I will discuss some of the challenges associated with the study of the nonlinear interplay between different CR-driven instabilities as well as new opportunities to probe these processes experimentally, including those based on plasma accelerators.

Applications of Plasma-Wave Acceleration Techniques to Particle Colliders

Brian Foster[1]

[1]*University of Oxford, Oxford, UK & University of Hamburg/DESY, Germany*

Professor Brian Foster, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH.

Plasma-wave acceleration (PWFA) is a very active field of current research. As the techniques mature, they are finding application in a variety of contexts. I will discuss some of the applications in the field of high-energy particle physics, in particular in particle colliders. These will include the use of PWFA as an injector to an electron-positron collider, as a “booster/afterburner” to increase the collision energy of a conventional collider, e.g. the International Linear Collider, and as a “pure” PWFA-based linear collider at multi-TeV energies. All of these applications pose real challenges, which I will partially explore in the talk.

HEP Applications of Plasma Wakefield Accelerators

<u>B. Heinemann</u>

DESY, Hamburg, Germany

Plasma wakefield accelerators are providing a very promising technology for compact accelerators of electrons (and positrons) towards high energies of 5 GeV or beyond. Such beams are of interest to a variety of HEP applications, e.g. to explore QED in very strong fields, for searches for dark sector particles at beam dump experiments and for test beam applications. This talk will discuss the various opportunities that would be of interest for an accelerator with energies of up to 50 GeV.

High-Resolution Diagnostics for Plasma-Based Accelerators – a Tool for Detailed Insights into the Interaction

M. C. Kaluza[1,2]

[1]Institute of Optics and Quantum Electronics, Friedrich-Schiller-University Jena, Germany
[2] Helmholtz-Institute Jena, Germany

Relativistic plasmas generated by high-power laser pulses are a potential candidate for future compact electron accelerators. In a plasma-electron accelerator, the driving laser pulse generates a high-amplitude plasma wave forming the electric field structure (the “wakefield”), which can trap and accelerate electrons to several GeV energies over distances of a few centimeters only. The properties of the generated electron pulses (spectrum, pulse duration, lateral dimensions) strongly depend on the parameters and the evolution of this accelerating structure.
Therefore, a complete understanding of the physical phenomena underlying the acceleration process is mandatory to improve the controllability of the electron pulses, which will determine their potential
applicability in the future. This presentation will give a short introduction to laser wakefield accelerators, discuss transverse optical probing as a diagnostic tool [1, 2, 3] and present experimental results on the characterization and evolution of the electron pulses [4] and of the plasma wave [5, 6].

References

[1] M. B. Schwab *et al.,* Applied Physics Letters **103,** 191118 (2013)
[2] M. C. Downer *et al.,* Reviews of Modern Physics **90,** 035002 (2018)
[3] M. B. Schwab *et al.,* Physical Review Accelerators and Beams **23,** 032801 (2020)
[4] A. Buck *et al.,* Nature Physics **7,** 543 (2011)
[5] A. Sävert *et al.,* Physical Review Letters **115,** 055002 (2015)
[6] E. Siminos *et al.,* Plasma Physics and Controlled Fusion **58,** 065004 (2016)

Ti:Sapphire laser as drivers for laser-plasma accelerators

S. Karsch[1]

[1]*Centre for Advanced Laser Applications, Ludwig-Maximilians-Universität München, Garching, Germany*

Ti:Sapphire lasers are set apart by their favorable combination of high saturation fluence, good thermal conductivity of the laser medium and exceptionally broad bandwidth. Together, this supports energetic (multi-J) pulses with durations of approximately 20 fs and practical repetition rates (Hz to multi-Hz). This made them the first laser systems that allowed statistically significant experiments with ultraintense laser pulses on plasma-based acceleration concepts. I will report on practical experience with Ti:Sapphire lasers as drivers for such experiments, discuss the benefits and limitations of these systems and will give and outlook on possible future developments.

Overview of Gaussian processes and Bayesian optimization for plasma-based accelerators

R. Lehe[1]

[1]Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley CA 94720, USA

In recent years, Bayesian optimization is one of the machine learning techniques that have been successfully applied to plasma-based accelerators. We will introduce the optimization task that Bayesian optimization intends to solve, and describe the theoretical basis of this method. We will illustrate the method based on results from the recent literature on plasma-based accelerators. For more perspective, we will also place Bayesian optimization within the wider set of machine learning techniques, and contrast it with other well-known techniques. In doing so, we will also emphasize the importance of uncertainty quantification in machine learning.

Optical guiding of high intensity laser pulses for laser wakefield acceleration

B. Miao, J. Shrock, L. Feder, and H.M. Milchberg

Dept. of Physics, Dept. of Elect. Eng., and IREAP
University of Maryland, College Park, MD 20742 USA

This presentation will first review the physics and technology of optical guiding of intense laser pulses in plasma, with application to laser-driven plasma wakefield accelerators. The talk will then highlight recent experimental results [1-6] using several of these guiding methods to achieve *multi-GeV* electron acceleration over sub-meter-scale distances.

References

[1] X. Wang et al., Nat. Commun. **4**, 1988 (2013).
[2] W. P. Leemans *et al*, Phys. Rev. Lett. **113**, 245002 (2014).
[3] A. J. Gonsalves *et al*., Phys. Rev. Lett. **122**, 084801 (2019)
[4] B. Miao *et al*., Phys. Rev. Lett. **125**, 074801 (2020).
[5] L. Feder *et al*., Phys. Rev. Res. **2**, 043173 (2020).
[6] B. Miao *et al*., *Multi-GeV electron bunches from an all-optical laser wakefield accelerator*, (2022) https://arxiv.org/abs/2112.03489

Overview of Adaptive Machine Learning Methods: Towards Virtual 6D Phase Space Diagnostics

A. Scheinker

Los Alamos National Laboratory, Los Alamos, USA

Plasma wakefield accelerators (PWFA) can utilize intense, short charged particle bunches to achieve the same energy gain within a single meter which requires kilometers of conventional radiofrequency (RF) cavity-based acceleration. However, PWFA techniques have not yet achieved the same level of beam quality (energy spread, transverse emittance, etc) that is possible with large conventional machines. The PWFA process requires extremely precise control and manipulation of the six dimensional phase space (x,y,z,x',y',E) of intense beams which is governed by complex collective effects which couple all of the dimensions including coherent synchrotron radiation (CSR), space charge, and wakefields. For example, the precise control of extremely short (few fs) high peak current (20 – 200 kA) bunches with few nC of charge is required to generate custom current profiles for machines such as FACET-II. In order to precisely control a beam's phase space, one must be able to see it, and this is a very difficult task for short intense bunches. Machine learning (ML) methods have recently shown great potential for use as virtual beam diagnostics. However, one of the main challenges of ML methods is that they cannot handle time-varying systems or systems with distributions shifts, for which they typically require repeated re-training, which is not feasible for most accelerator applications. In this talk we present an overview of ML-based phase space diagnostics and introduce adaptive ML techniques for time-varying systems and the potential they have shown to be used as virtual 6D phase space diagnostics for time-varying accelerators and their charged particle beams [1,2].

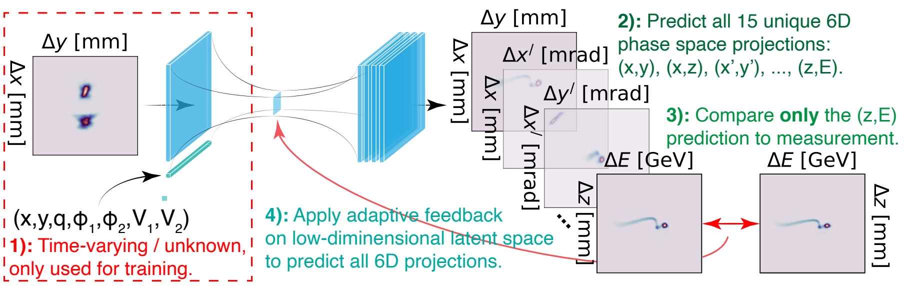

Figure 1: Overview of adaptive ML for 6D phase space diagnostics is shown, utilizing model-independent feedback on the learned low-dimensional representation oft he beam's phase space.

References

[1] A. Scheinker. "Adaptive machine learning for time-varying systems: low dimensional latent space tuning." *Journal of Instrumentation* **16**.10, P10008 (2021).

[2] A. Scheinker, F. Cropp, S. Paiagua, and D. Filippetto. "An adaptive approach to machine learning for compact particle accelerators." *Scientific reports*, ***11***(1), 1-11 (2021).

Establishing Laser Accelerated Proton Beam Performance for Dose Controlled Irradiation Studies

U. Schramm

Helmholtz-Zentrum Dresden-Rossendorf, 01328 Dresden, Germany
Technische Universität Dresden, 01062 Dresden, Germany

The application of laser plasma accelerated proton beams [1] in radiation therapy of cancer has been proposed and discussed almost since the first demonstration of plasma accelerators reaching 10s of MeV energies. It was initially motivated by accelerator compactness and consequently assumed cost efficiency, promising a wider spread of advanced therapy methods. Various and still ongoing in-vitro studies have been performed to investigate the radiobiology of these intense particle bunches, in particular with respect to the exploration of potential dose rate related effects. With the recently reported FLASH effect, a high dose rate effect observed to reduce radiation toxicity in normal tissue, the field has regained significant interest as provision of high single pulse dose rate is inherent to plasma accelerators.

For the translation to in-vivo studies laser accelerated proton beams however not only lacked sufficient energy to penetrate the required volume but often stability and reprodicibility of beam parameters to ensure the provision of a homogeneous dose distribution in a prescribed way. This presentation focuses on the development at the Petawatt laser DRACO at Helmholtz-Center Dresden-Rosendorf and the related reference accelerators in use a spart oft the Dresden Platform that enabled the dose controlled systematic irradiation of tumors in mice [2] with laser accelerated protons. Details on acceleration mechanisms and strategies to increase stability and energy well beyond the 60 MeV range are discussed [3] as well as beam transport by means of a dedicated pulsed solenoid beamline to a secondary target together [4] with online metrology and dosimetry. Dose profiles reached for the first mouse irradiation campaign [2] are reported as well as future perspectives for FLASH related studies.

References:

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Laser Plasma Accelerators to address the industrial inspection market

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SourceLAB, the spinoff of Laboratoire d'Optique Appliquée (LOA), has been marketing over the last ten years reliable and user-friendly scientific instruments, directly inspired by the know-how of leading research groups in laser plasma science.

Recently, a further crucial step towards the dissemination of accelerators based on laser plasma technology has been achieved : the integration of a kHz-rep rate accelerator into a ready-to-use and all-in-one product, the KAIO. This novel technological blocks is pivotal to address the specific needs of the industrial inspection market for new sources of energetic particles.

Theoretical basis and exascale simulations

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Plasma accelerators [1] enable the acceleration of charged particles over short distances due to their many-GeV/m field gradients, making them a compact alternative to conventional technologies. Despite large progress on beam energy and quality over the last decade, significant progress is still required on beam quality and stability to fill the gap between promising concepts and production-ready accelerators. The Particle-in-Cell (PIC) method [2] is a reliable tool to simulate plasma acceleration, and PIC simulations play a major role in understanding, exploring and improving plasma accelerators.

The PIC method provides a full kinetic plasma description, as required for plasma acceleration, without the need to mesh the 6D (position and velocity) phase space of the charged particles forming the plasma. In this method, the electric and magnetic fields are resolved on a 1/2/3D mesh, and the plasma dynamics is represented by an ensemble of macro-particle moving freely in the domain and constantly interacting with the mesh. Production simulations routinely use billions of grid cells and macro-particles, making the use of high-performance computing a necessity. Furthermore, the feasibility of the most challenging simulations depends critically on the numerical schemes.

In this presentation, we will introduce the PIC method and discuss common algorithms and methods, in particular the electromagnetic and quasistatic flavors relevant for plasma acceleration. The use of supercomputers being required for the most challenging simulations, we will discuss high-performance computing with a particular focus on Graphics Processing Units (GPUs), which equip most of the world's top supercomputers.

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Laser-electron collisions and laser-plasma interaction in QED regime (theory and simulations)

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The next generation of lasers will access intensities above 10^{23} W/cm^2. When plasmas or relativistic electron beams interact with these lasers, energy loss due to radiation emission, or quantum effects such as electron-positron pair creation become important for their dynamics. Repeated occurrence of pair creation can induce a so-called “QED cascade”, that generates an exponentially rising number of particles. This allows for creating exotic plasmas that are a mix of electrons, ions, positrons, energetic photons and intense background fields. Extreme laser-plasma interactions can be explored to form optical traps, create&accelerate particles and produce novel radiation sources. I will introduce a QED module coupled with the particle-in-cell framework OSIRIS that allows studying nonlinear plasma dynamics in the transition from the classical to the quantum-dominated regime of interaction. Studies relevant for (near) future experiments will be discussed.

Abstracts of Posters

(in alphabetical order)

New insights into the acceleration of gold atoms by high power lasers

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We present here simulation results of the laser-driven acceleration of gold ions using the EPOCH code [1]. Recently, an experiment reported the acceleration of gold ions up to 7 MeV/u with a remarkable dependency of the charge-state distribution on the target foil thickness and dominant charge states up to z=70 [2]. Previous simulation [3] contrasts this observation and predicted that the dominant charge state is z=51.
Our simulations using the latest version of the EPOCH code 4.18 shows that the collisional ionization is the most important reason for increasing charge states beyond z=51 in the range of z=50-70. Figure1 shows charge states of gold ions due to the interaction of a 4.1×10^{20} W/cm^2 laser pulse, 500 fs pulse duration, with a 100 nm gold foil without (a) and with (b) collisional ionization. First results indicate that collisional ionization alters the forward emitted charge state distribution significantly.

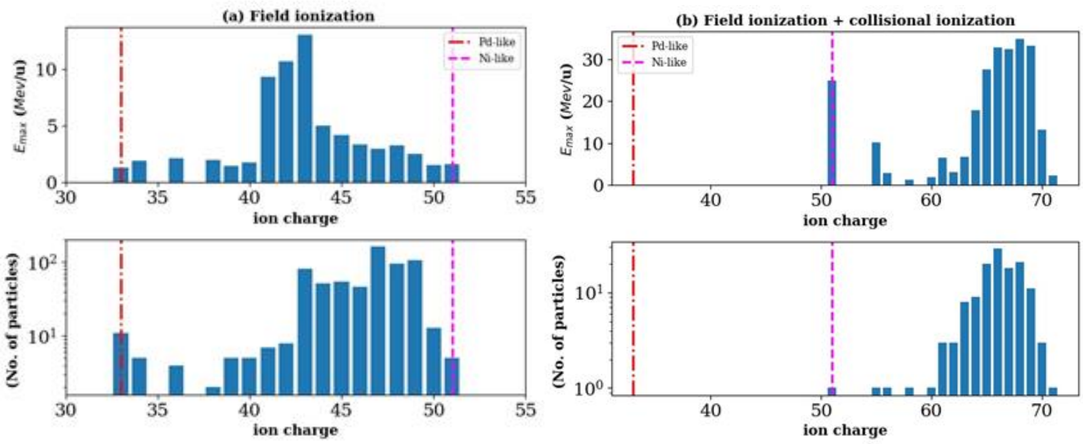

Figure1: Simulation results of charge states of gold ions 2 ps after the interaction of a 4.1×10^{20} W/cm^2 laser pulse with 500 fs pulse duration with a 100 nm gold foil without (a) and with (b) collisional ionization. For both cases field ionization is activated.
Upper row: maximum energy per nucleon as a function of the charge state.
Bottom row: charge state distribution within a forward angular cone of 10°.

We acknowledge support by the Centre for Advanced Laser Applications (CALA), and Super Computer LRZ under application number 24836.

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Monitoring gas composition evolution of Discharge Plasma Source with optical emission spectroscopy, for the AWAKE experiment

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AWAKE (the Advanced WAKefield Experiment) explores plasma wakefield acceleration of electrons, using proton bunches as driver. In order to reach suitable energies for high-energy physics applications, AWAKE needs to extend the acceleration plasma length to 10s of meters. This range is beyond the maximum length of efficient operation for a source based on the presently used principle, namely a laser ionised rubidium vapor plasma source [1]. Therefore, scalable plasma sources, achieving an electron density of 7x10^20 m^−3 with an axial uniformity of 0.2% over 10m [2], need to be developed.
At CERN two types of scalable plasma sources are under study, the helicon plasma source [3] and the Discharge Plasma Source (DPS) [4], the latter being discussed here. DPS is based on a direct current double-pulse arc discharge produced between two electrodes at the extremities of long dielectric tubes, filled with argon at low pressure. The discharge is generated by a first high voltage (up to 120 kV) *ignition* pulse that ignites a low current arc plasma (10 A), followed by a second *heater* pulse that increases the arc current up to 400 A at lower voltage (10 kV), to achieve the high plasma density required by AWAKE.
Optical emission spectroscopy has been chosen to assess the gas composition using fibres to collect the light emitted by the plasma at 6 locations along the tube. This study presents the time-integrated, pulse resolved, gas composition evolution over hundreds of discharges to evaluate the stability and reproducibility over time, in static and dynamic pressure regime. The effect of the first *ignition* pulse on the jitter, duration and resulting gas composition of the second heater pulse will also be shown.

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Measurements of the effect of density ramps and plasma mirrors on 2GeV laser wakefield accelerated beams

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Laser wakefield acceleration promises to revolutionise particle accelerators by using plasmas to support extremely strong electric fields, facilitating the production of GeV electron beams in just centimetres of plasma. However, to reach particle energies far in excess of 10GeV it is likely that multiple acceleration stages are required, and transferring electron beams between these stages is a multifaceted problem. One difficulty lies in extracting and injecting the laser pulses without substantially increasing the length of the system, as doing so would undermine the short interaction length that makes plasma-based accelerators attractive. A solution is to use plasma mirrors to reflect the laser pulses close to focus, allowing the stages to be placed within centimetres of one another. This solves the compactness issue, but since the mirrors must be placed on the beam axis they have the potential to reduce the electron beam quality through a variety of scattering mechanisms. In addition, due to their proximity to the target, these plasma mirrors can physically disrupt the density profile of the accelerating medium, thereby modifying the beam indirectly.

In my poster I will present results that show the effect of two independent plasma mirrors on a 2 GeV laser wakefield accelerated beam. The first of these plasma mirrors, formed on the surface of a tape laid at 45 degrees across the exit of the gas cell target, increased the total beam divergence by 78% when compared to a 1mm diameter exit pinhole. In contrast, the second plasma mirror, placed 8mm after the accelerator exit, was found to reduce the beam divergence by 16%. The interactions between the laser, plasma mirror, wakefield, and electron beam have been investigated using particle-in-cell simulations, using separate simulations for the overdense and underdense plasmas. The results of this analysis are discussed in the context of target design considerations for future multi-stage acceleration experiments.

Acceleration of non-relativistic muons in plasma based accelerators

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Nowadays, very promising plasma-based acceleration techniques, such as Laser Wake Field Acceleration [1] and Plasma Wake Field Acceleration [2] have been intensively studied and tested. Nonetheless, these methods are applicable only to particles whose velocities are close to the speed of light (relativistic particles). Heavier particles, e.g. muons, are thus excluded from the acceleration mechanism because they are usually produced with non-relativistic velocities, even though these particles could particularly benefit from plasma acceleration for the mitigation of decay losses [3].
State-of-the-art techniques to sculpt the spatio-temporal spectrum of electromagnetic wave packets leading to pulses with arbitrary group velocities have been recently developed [4]. These pulses are able to propagate with a subluminal group velocity, making them suitable candidates to drive acceleration wakes for heavier particles.

In this work, we propose a plasma-based acceleration technique for non-relativistic particles. We first investigated the acceleration using an external field with a non-relativistic group velocity analytically and in 2D particle-in-cell simulations using OSIRIS [5]. Subsequently, we investigated the evolution and wakefield properties using optical space-time wave-packet drivers, traveling with group velocities smaller than the speed of light.
We have found that these pulses are able to drive plasma wakes that travel slower than the speed of light. However, they could be prone to plasma instabilities. We discuss the onset and potential mitigation strategies for these instabilities.

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Signal subtraction of consecutive electron bunches from a high-repetition-rate plasma-wakefield accelerator

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Beam-driven plasma-wakefield acceleration is a promising avenue for the future design of compact linear accelerators with applications in high-energy physics and photon science. In order to meet their luminosity and brilliance requirements, at least thousands of bunches must be delivered per second – many orders of magnitude beyond present state-of-the-art plasma-wakefield accelerators, which operate at the Hz-level. As recently explored at FLASHForward, the fundamental limitation for the highest repetition rate is the long-term motion of ions that follows the dissipation of the driven wakefield [1]. The recovery of the plasma is observed in the images of probe bunches, separated from a preceding bunch in increments of 0.77 ns. The properties of the electron bunches are imaged using scintillator screens, the light-output of which lasts for milliseconds. As all bunches arrive well within the scintillation lifetime of the screen of 380 µs, an image processing technique capable of resolving individual bunches is needed. Here we present a technique which uses many shots of the preceding bunch to accurately identify and remove its signal from the overlapped signal of the subsequent bunch pair. With this method the effects of the perturbed plasma on the subsequent bunch pair can be observed with high temporal resolution. This allows high-repetition-rate processes to be studied in greater detail – an essential first step in advancing beam-driven plasma-wakefield acceleration to a level required for meaningful application to high-energy-physics and photon-science facilities of the future.

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Observation of Plasma Light at AWAKE

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The advanced wakefield (AWAKE) experiment at CERN is designed to test the concept of proton-driven plasma wakefield acceleration. Externally injected electrons were succefully accelerated to 2 GeV in the 10 m of plasma by the wakefields induced by the 400 GeV SPS protons [1]. The plasma is obtained fully ionizing a Rb vapor with an intense IR laser. The plasma density is controlled varying the temperature of the Rb vapor and measured with a white light interferometer. At present, the effect of the wakefields is observed looking at time-resolved images of transition radiation light emitted by the proton bunch crossing a screen located after the plasma cell. The energy of the wakefields is stored in the oscillating motion of the plasma electrons, this energy is dissipated by collision. A part of it is eventually emitted as plasma light from recombination of plasma electrons and ions. The observation of the plasma light can then be used as diagnostic for the plasma wakefields. This contribution present the preliminary observations of the plasma light emission at the AWAKE experiment.

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Future plans for the beam-driven plasma-wakefield experiment FLASHForward

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FLASHForward is an experimental facility at DESY dedicated to beam-driven plasma-accelerator research. The X-2 experiment aims to demonstrate high-gradient acceleration with simultaneous beam-quality preservation and high energy-transfer efficiency, both in a compact plasma stage. In parallel with the FLASH2020+ upgrade project of the FLASH linear accelerator - the source of electron beams for FLASHForward - an overhaul of the experimental infrastructure is being carried out. The infrastructural upgrades are motivated by the desire to increase stability, energy gain, and fidelity of transmission. This contribution describes the planned upgrades and their role in achieving the future goals of FLASHForward.

Prediction of beam energy using neural networks and beam position monitors

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Laser-Plasma Acceleration has the capacity to provide compact generation of high-brightness relativistic electron beams [1]. An attractive application is plasma-driven Free-Electron Laser (FEL) [1] which is the incentive behind the LUX beamline. For generation of FEL X-ray radiation optimization and close monitoring of electron beam energy is crucial. However, due to focusing and deflecting inside the undulator and during beam transport, energy measurements are occasionally unreliable. The study shows that a rudimentary energy prediction can be obtained from beam position measurements by utilizing neural networks. The method provides a non-invasive way to monitor energy, decoupled from beam dynamics inside the undulator. Further it exemplifies the use of machine learning for inference of beam properties.

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The digitalization of advanced plasma accelerator experiments – A perspective

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Plasma accelerators have reached a state of maturity that the natural next step is to implement prototypic applications of these unique sources. Towards this goal, understanding, control, versatility and scalability of these sources have to be enhanced.

Critical steps towards these goals are a better theoretical understanding, accurate control of the decisive experimental parameters and optimization of the sources towards specific application goals.

While simulations have for long been drivers towards new regimes of plasma acceleration, experimental capabilities have strongly developed in recent years and are now often on par to simulations when providing high quality data on the acceleration processes. New methods such as machine learning are helping to understand and control nonlinearities in the acceleration process.

Nevertheless, the very nature of plasma acceleration as a nonlinear process happening on atomic length and time scales makes the scalability towards reliable operation challenging, despite recent successes in control of these machines.

In this contribution we give a perspective on existing state of the art digital technologies that can help enhance the reliability of plasma accelerators and what this means for experiments.

Recovery time of a plasma-wakefield accelerator

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Plasma-acceleration schemes may hold the key to both reducing the size and increasing the proliferation of future photon-science and high-energy-physics facilities due to the ultra-high accelerating gradients they can sustain. In order to be at least competitive with conventional accelerator technology, however, the aforementioned applications will likely require the acceleration in plasma of thousands of bunches per second—orders of magnitude higher than the current state of the art. The fundamental limit to high-repetition-rate plasma acceleration is defined by the time it takes for the plasma to recovery to approximately its initial condition after a high-strength wakefield has been driven. First measurements of the recovery time of a plasma-wakefield accelerator were recently made at the beam-driven experimental facility FLASHForward (DESY) [1], indicating an upper limit to the inter-bunch repetition rate at the *O(*10 MHz) level [2]. This contribution will outline the experimentation performed at FLASHForward, the implications the results have for the field, and the next steps on the roadmap towards a practical high-repetition-rate solution.

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Modelling positron acceleration with HiPACE++

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Plasma accelerators sustain extreme field gradients, and potentially enable future compact linear colliders. Although tremendous progress has been achieved in accelerating electron beams in a plasma accelerator, positron acceleration with collider-relevant parameters is challenging. A recently proposed positron acceleration scheme relying on the wake generated by an electron drive beam in a plasma column has demonstrated the acceleration of positron witness beams with low emittance and low energy spread.
Since this scheme relies on cylindrical symmetry, it is possibly prone to transverse instabilities that could lead to drive or witness beam break-up. Modelling these instabilities requires full 3D Particle-in-Cell (PIC) simulations, which can be extremely computationally expensive. By using the novel, open-source, GPU-accelerated, 3D, quasi-static PIC code HiPACE++ we model stability of positron acceleration in a plasma column with unprecedented resolution at a modest cost. We show that both the drive and the witness beams are subject to various damping mechanisms. Therefore, this positron acceleration scheme is inherently stable and enables high-quality plasma-based positron acceleration.

CO_2 laser-driven wakefield acceleration

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Laser-driven plasma accelerators provide tabletop sources of relativistic electron bunches and femtosecond x-ray pulses, but so far only solid-state laser pulses of wavelength ~1 micron have been powerful enough to drive them. Longer-wavelength terawatt lasers can potentially enable more efficient acceleration with longer, more controllable wakes at lower peak power in less dense plasma. Here we report an accelerator in which terawatt chirped-pulse-amplified CO_2 laser pulses of 10-micron wavelength drive plasma wakes via a self-modulation instability [1]. We observe high-amplitude wakes in, and relativistic electron beams from, hydrogen plasma down to 1/300 atmospheric density, driven by pulses with peak power down to 1/2 terawatt, 100x and 10 to 50x lower, respectively, than self-modulated wakes driven by 1-micron laser pulses. Measurements and simulations of wake structure and e-beam properties as conditions change detail the physics of long-wavelength-infrared self-modulated wakefield acceleration. Observations of peaked electron spectra on 50% of shots provide evidence that we are close to generating strongly nonlinear wakes, portending future higher-quality accelerators driven by yet shorter, more powerful pulses [2].

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Enhancement of Tape Targets at VEGA

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We present and compare experimental studies and prospects of high repetition rate (HRR) targetry for the interaction of relativistic laser pulses at intensities of several 10^{20} W/cm^2 with solid density targets. So-called tape targets are rewound in vacuum conditions in order to always expose a new section of undisturbed surface to the laser focus. The requirements for the target are high resistance to ionizing radiation released by laser-matter interaction and immunity to electromagnetic pulses.
Studies consider both high-power 30 fs duration lasers at CLPU (Salamanca, Spain), VEGA-2 with 200 TW and VEGA-3 with 1 PW. The creation of ultra-fast sources of ion beams with large spectra in the MeV-range is one typical application of the interaction of such lasers with matter. Experiments at VEGA 3 show typical proton spectra for the so-called Target Normal Sheath Acceleration mechanism. Ramping up of the intensity with the energy in the laser pulse, beneficial for the maximum energy of accelerated protons, leads to a destruction of the tape target. One observes welding of the tape to the support structure when the heated region approaches the size of later. We present mitigation strategies.
Building upon the study, we pinpoint prospects for a target geometry mitigating EMP and potentially applicable to particle beam collimation.

A Confined Continuous-Flow Plasma Source For High-Average-Power Laser Plasma Acceleration

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High average power, kHz laser plasma acceleration (LPA) is an emerging technique which could supply few MeV, few femtoseconds electron bunches with high average current. Such electron beams can be transformative for many industrial applications, for ultrafast pump-probe studies as well as drivers for secondary sources. Tailoring the plasma profile is an essential part, allowing to control both the injection and the acceleration mechanism. Here a novel plasma source for high repetition rate, 10 MeV electron acceleration is presented, consisting of a steady-state flow capillary. It is able to supply a localized and confined gas region (~100μm) with sharp density gradients, which are a key feature for both coupling the laser into the gas and injecting electrons. Its tunability and the minimized gas load into the vacuum chamber make this new source a promising candidate for high average power LPA.

Injection Tolerances for AWAKE Run 2c

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The AWAKE project at CERN makes use of a proton-driven plasma wakefield to accelerate a witness electron bunch [1]. While Run 1 relied on selective trapping of a long electron bunch, Run 2c will use a short witness bunch to allow better control of the accelerated bunch parameters. This work investigates the tolerances for injection into such a quasilinear wake through simulation. A figure of merit based on a potential high-energy application for AWAKE is developed to provide a single metric for the accelerated bunch, allowing different configurations to be easily compared and providing a quantitative basis for future design decisions. Further, it is shown that the figure of merit naturally gives rise to constraints on the tunability and stability of the initial witness bunch parameters.

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Hybrid LWFA-PWFA: A stability and beam-quality booster for laser-generated electron beams

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Laser-wakefield acceleration (LWFA) has long been investigated as a possible route towards a compact, high-gradient replacement for the current RF-based acceleration technology. Such accelerators recently made huge progress in terms of achievable energy (multi-GeV), charge (up to nC), current (up to 100 kA) and spectral charge density (up to 20pC/MeV). However, due to the sensitive dependence on driver fluctuations and heating by the laser, it remains extremely challenging to generate stable and low emittance electron bunches in LWFA.
In particle driven wakefield acceleration (PWFA) some of these problems can be attributed – so far, such research was only possible on a few large-scale accelerator facilities. In past experiments we showed that high current LWFA-generated electron bunches from 100-TW-class laser facilities [1] are suited as drive beams for PWFA – demonstrating wakefield generation [2] and witness acceleration [3,4].
This contribution summarizes our recent experiments demonstrating the insensitivity of PWFA to fluctuations in driver energy, making the hybrid scheme comparable or possibly even more stable than pure LWFA. Moreover, due to the high energy transfer efficiency and cold injection in our PWFA, the spectro-spatial charge density and the emittance can exceed that of a pure LWFA, giving a real-world performance boost to LWFAs.

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Computation and Measurement of Helicon Wave Fields and Plasma Parameters in a Wakefield Accelerator Prototype

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The Advanced Proton Driven Plasma Wakefield Acceleration Experiment (AWAKE) at CERN is aiming to make wakefield accelerators a reality, just in time for next generation linear collider projects pushing the TeV frontier. To do so a high-density, uniform, scalable and reproducible plasma approaching a density of 10^{21} m^{-3} is needed. Helicon waves are routinely used to create high-density plasmas but they are still an active area of research. This includes questions about the exact ionization mechanism as well as plasma density and uniformity control. Using the COMSOL framework we simulate the RF wavefields from a 3D helicon antenna inside the 2 meter long, high density, magnetized, linear plasma cell which has been built as part of the AWAKE project at the University of Wisconsin - Madison, the *Madison AWAKE Prototype (MAP)*. Plasma density and temperature in MAP are measured by means of a microwave interferometer and RF compensated Langmuir probes. Using a combination of global power and particle balance, helicon dispersion relation analysis and Fourier decomposition of the antenna currents we designed an antenna that successfully ignited a helicon plasma in the projected operating space in MAP. As predicted by the RF simulations, the plasma exhibits a directionality which is antiparallel to the magnetic background field. We are currently working on detailed verification of the simulations by comparing predicted wavefields against measurements with three-axis Mirnov probes in MAP. Once the simulation capability is verified it will be coupled to a simple 1D, or possibly 2D axisymmetric, plasma equilibrium model. This combined model can then guide the design of helicon plasma cells for AWAKE, optimizing them towards high density and high uniformity and for implementation into the accelerator tunnel system at CERN.

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Shock-assisted ionisation injection for very high energy electron radiotherapy

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Very high energetic electrons (50-250 MeV) can potentially be favourable in radiotherapy [1, 2], and when focused, the dose can effectively be deposited at a target area while sparing healthy tissue [3]. Laser-wakefield accelerators [4] can provide the necessary dose and energy, but efficient magnetic transport and focusing also requires narrow divergence and energy spread. Here, we demonstrate the production of 100 MeV electron bunches with a small energy spread using a shock-assisted ionisation injection scheme. The electrons are then focused using an electromagnetic quadrupole triplet in a point-to-point imaging configuration.

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Compact Spectroscopy of keV to MeV X-rays from Laser Plasma Electron Accelerators

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Laser-driven plasma electron accelerators provide tabletop sources of secondary x-rays ranging from few keV betatron, to few-MeV inverse Compton to >100 MeV bremsstrahlung. Spectroscopy of these x-ray sources is often done with multiple spectrometers sensitive to narrow energy ranges, e.g. x-ray sensitive CCDs for 1-30 keV x-rays or Ross pair filters for 5-100 keV x-rays. Compact stack calorimeters are inexpensive alternatives made of interleaved layers of absorbers and image plates that record the energy-depth distributions of the incident x-rays. Thus far, stack calorimeters based on imaging plates and a forward unfolding algorithms have diagnosed betatron, inverse Compton and bremsstrahlung x-rays from a laser wakefield accelerator with characteristic energies spanning over 4 orders of magnitude [1]. By implementing a Bayesian unfolding algorithm, stack calorimeters have also been used to unfold broadband spectra from laser-solid interactions and emissions from ^{137}Cs and ^{60}Co sources [2]. If needed, stack designs can be easily modified to enhance sensitivity and/ or resolution with a narrower spectral range of interest and adapted to high repetition rates by replacing the image plates with scintillators. Here, we present the highest unfolded bremsstrahlung x-ray spectra with average energies >100 MeV as well as narrowband inverse Compton x-rays with peak energies of a few MeV to a few tens of MeV from a GeV class LPA. We also present preliminary data from a scintillator-based stack design that diagnosed bremsstrahlung cut-off energies from few GeV electron bunches, acting as a supporting diagnostic for the maximum accelerated electron energies.

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DRACO Laser-Driven Electron source for secondary radiation generation and applications

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We present stable multi-day operation of DRACO Laser-Driven Electron source, delivering nanocoulomb electron beams at energies up to 0.5 GeV with sub-mrad divergence[1]. Together with the intrinsic ultrashort bunch duration at micrometer beam[2,3,4], their charge densities can readily surpass the typical beams from state-of-the-art linear accelerator machines. While there are still room for improvement, such a beam quality can already open a new horizon in applications and as a driver for secondary radiation generation. A prominent example is to use such beams to power a beam-driven plasma acceleration (PWFA) stage, where high-brightness beam generation is envisioned in a compact hybrid LWFA-PWFA platform. After witness beam acceleration has been demonstrated[5], we show further control on electron injection, by deploying plasma density ramps, and energy tunability with plasma density[6]. We anticipate this result to open the path toward the generation of energetic high-brightness beam for quality-demanding applications such as free-electron lasers.

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Multi-Objective Multi-Fidelity optimization of Laser Wakefield Accelerator

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Beam parameter optimization in accelerators involves multiple, sometimes competing objectives. Condensing these multiple objectives into a single objective unavoidably results in bias towards particular outcomes that do not necessarily represent the best possible outcome for the operator in terms of parameter optimization. A more versatile approach is multi-objective optimization, which establishes the trade-off curve or Pareto front between objectives. Here we present first results on multi-objective Bayesian optimization of a simulated laser-plasma accelerator. Even with the use of Bayesian statistics, performing such optimizations on a multi-dimensional search space may require hundreds or thousands of evaluations. We significantly reduce the computational costs of the optimization by choosing the resolution of the simulations dynamically. Our algorithm translates information gained from fast, low-resolution runs with lower fidelity to high-resolution data, thus requiring few actual evaluations at highest resolution [1]. The techniques established in this paper may be translated to many different use cases, both computational and experimental.

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Bayesian optimisation of laser plasma accelerators

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Generating high-quality laser-plasma accelerated electron beams requires carefully balancing a plethora of physical effects and is therefore challenging — both conceptually and in experiments. Here, we use Bayesian optimization of key laser and plasma parameters to flatten the longitudinal phase space of an ionization-injected electron bunch via optimal beam loading. We first study the concept with particle-in-cell simulations and then demonstrate it in experiments. Starting from an arbitrary set-point the plasma accelerator autonomously tunes the beam energy spread to the sub-percent level at 254 MeV and 4.7 pC/MeV spectral density. Finally, we study a robust regime, which improves the stability of the laser-plasma accelerator and delivers sub-5-percent rms energy spread beams for 90% of all shots.

Gas-flow simulations of a discharge-capillary plasma source for high-repetition-rate plasma-wakefield operation

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Plasma-wakefield accelerators provide acceleration gradients several orders of magnitude higher than conventional accelerators and therefore represent a promising technology for reducing the footprint of future particle accelerators. The luminosity in colliders, as well as the brilliance in free-electron lasers, scales with the repetition rate of the accelerator, and is therefore a crucial performance parameter to consider when developing plasma-based accelerators. A plasma source that delivers consistent plasma properties at megahertz repetition rates will be required to act as an energy booster at pre-existing photon-science facilities. Today's state-of-the-art plasma-source technology operates at the few-Hertz-level with research in the direction of high repetition rate largely unexplored. Optimisation of the gas flow in discharge capillaries is the first step towards achieving repeatable plasma conditions at high repetition rate. In this contribution 3D simulations of computational fluid dynamics in discharge capillaries are presented, revealing a better understanding of the gas flow in existing cell designs and for their future optimisation.

Surrogate modelling of laser-plasma acceleration

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Laser-plasma acceleration (LPA) promises compact sources of high-brightness electron beams for science and industry. However, transforming LPA into a technology to drive real-world applications remains a challenge. Machine learning techniques could prove decisive in further understanding and improving the performance of these machines. Here, we discuss the application of supervised learning to create surrogate models of the LPA process at LUX. Using simulated and experimental data, we train artificial neural networks to predict the electron beam quality as a function of the drive laser properties. Of the many potential applications of such models, we emphasize their use to study the influence of laser fluctuations on the electron beam stability.

Advanced space radiation reproduction using Laser Wakefield Accelerators

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Space radiation with broadband exponential energy spectra can be harmful for satellite instruments. Today, monoenergetic particles beams are utilized for testing the survival of satellites in the harsh radiation environments of space. However, this does not resemble accurately the conditions in space. Laser Wakefield Accelerators (LWFA) on the other hand may be capable of overcoming these limitations with unique applications in space radiation hardness testing [1][2]. We show that LWFA can potentially reproduce broadband exponential space radiation spectra in a cost-efficient table-top setup. The broadband electron beams from LWFA may have a transformative impact on advanced radiation testing and space radiobiology [3] with accurate reproduction of the space radiation environment.

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Design and numerical investigations of a phase locked few cycle laser accelerator

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A new OPCPA laser system for LWFA is currently being designed at the Lund Laser Centre High-Power Laser Facility. Key features compared to the previous Ti:Sapphire based system includes a shorter pulse duration, below 10 fs, and the ability to phase lock the carrier and envelope. The shorter pulse duration will enable the laser to enter the plasma close to the matched condition, while the carrier envelope phase plays a significant role in the acceleration process as the pulse duration approaches the few cycle regime [1]. Presented here is a preliminary system design, along with numerical investigations in FBPIC [2] of the expected performance from this unique electron accelerator.

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

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

High-dose femtosecond-scale gamma-ray beams for radiobiological applications

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In the irradiation of living tissue, the fundamental physical processes involved in radical production typically occur on a timescale of a few femtoseconds. A detailed understanding of these phenomena has thus far been limited by the relatively long duration of the radiation sources employed, extending well beyond the timescales for radical generation and evolution. Here, we propose a femtosecond-scale photon source, based on inverse Compton scattering of laser- plasma accelerated electron beams in the field of a second scattering laser pulse. Detailed numerical modelling indicates that existing laser facilities can provide ultra-short and high-flux MeV-scale photon beams, able to deposit doses tuneable from a fraction of Gy up to a few Gy per pulse, resulting in dose rates exceeding 10^{13} Gy/s. We envisage that such a source will represent a unique tool for time-resolved radiobiological experiments, with the prospect of further advancing radio-therapeutic techniques.

Diamond detectors for Time of Flight measurements in high repetition rate laser-plasma interactions.

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Multi Hz repetition rate laser-target interactions are explored with the use of the Gemini TA2 laser system at the Central Laser Facility, UK. Various types of targets were investigated, which included Kapton tape (12.7um and 50um) as well as a water jet, which provided water sheets of thicknesses within the range of 100nm - 100um. The interaction was optimised with the use of machine learning, which employed Bayesian optimisation based on gaussian process regression methods, allowing for optimisation of many parameters simultaneously. Live feedback from the diagnostics was therefore achieved. Such optimisation is not achievable at low repetition rate experiments of this kind. Two diamond Time of Flight (ToF) detectors were employed, one at the front and rear of the target surface, providing on shot feedback on the ion beam features, such as ion energy and flux. This information was fed into the algorithm for optimisation. ToF results from various optimizations with different target types are presented, as well as general feedback on the use of the diagnostic operating at 1Hz and 5Hz, including computational techniques required for analysis of the high numbers of shots.

Hydrodynamic simulations of plasma accelerator sources

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Understanding the long-term dynamics of plasma sources is critical to improve several aspects of plasma acceleration including discharge control [1], laser guiding [2,3] and repetition rate [4]. Numerical simulations can provide helpful insight into the relevant dynamics, but they can be challenging.

On the one hand, PIC simulations accurately capture the kinetic regime of wakefield acceleration, which occurs on time scales of femtoseconds to picoseconds, but they are impractical on the nanosecond to millisecond time scales covering thousands to billions of plasma periods. On the other hand, Magneto-Hydrodynamics (MHD) simulations can describe such thermalized plasmas, but they still prove to be computationally expensive.

In this work, we propose a quasi-neutral single-fluid plasma model capturing long-term plasma dynamics relevant for plasma accelerators. The model uses two temperatures (for atoms and electrons, respectively) and the plasma composition is tracked via collisional reaction rates rather than relying on Local Thermal Equilibrium. The model is implemented in the multiphysics simulation software COMSOL, which provides an established framework for fluid simulations and allows easy tuning of functionalities for specific use cases.

We will present simulation results capturing the full dynamics of capillary discharge plasmas routinely used at FLASHForward and of hydrodynamic optical-field-ionized plasmas, and show comparisons to measurements.

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PIC Simulations of the Self-Modulation of a Long Proton Bunch using two seeds: an Electron Bunch and a Density Cut

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When a relativistic, long particle bunch propagates in plasma, it can undergo self-modulation (SM) [1]. During SM, the long bunch is transformed into a train of microbunches that resonantly drive wakefields, as demonstrated experimentally [2]. These wakefields can accelerate externally injected particles to high energies [3]. To generate reproducible wakefields, in terms of phase and amplitude, the SM must be seeded [4]. This is a requisite to produce accelerated particles with reproducible properties. For the future of the Advanced Wakefield (AWAKE) Acceleration Experiment it is interesting to study the interaction of an unseeded SM of the bunch front with the seeded SM of the back. This will be measured in the Run 2 of AWAKE [5] by placing inside the proton bunch a co-propagating seed electron bunch. Ahead of both bunches, a laser pulse is used as a relativistic ionizing front (RIF) to create the plasma by ionizing Rb atoms. We explore with particle-in-cell simulations the situation described previously, using parameters similar to the experiment. In simulations, the RIF is replaced by a density cut in the bunch, which always acts as a seed. In particular, we study the conditions under which the electron bunch seeds the wakefields, as well as the effect the wakefields driven by the modulation in the front seeded by the density cut have on the rest of the bunch, starting at position of the seed electron bunch.

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Control of the self-modulation and long-bunch hosing instabilities with plasma frequency detuning

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The success of plasma-based acceleration schemes often relies on the ability to manipulate complex beam-plasma interactions. In one of these concepts – the one explored in the AWAKE experiment [1] – the key interactions are two modes (symmetric and asymmetric) of the transverse two-stream instability called self-modulation and hosing, respectively. The self-modulation instability (SMI) [2,3] can be harnessed to produce high-amplitude wakefields from a very long driver (compared to the plasma skin depth), but the fields tend to decay quickly after the instability has saturated. The hosing instability (HI) [4] is undesirable due to its potential disruption of the bunch, and should therefore be mitigated [5,6].

During their growth, both of these instabilities can be understood as driven harmonic oscillators. Here we show that it is possible to control their growth rates if the plasma oscillation responding to either the beam radius (SMI) or centroid (HI) perturbation is detuned early enough. The detuning can be achieved by varying the background plasma density, as we demonstrate with particle-in-cell simulations. Using plasma density steps [7], we apply this idea to mitigating the HI and optimizing the amplitude decay of the SMI after saturation. This novel approach to controlling the growth of beam-plasma instabilities could have important implications for plasma-based accelerators.

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Hosing of a long relativistic particle bunch induced by an electron bunch

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A long relativistic charged particle bunch propagating through plasma undergoes self-modulation instability. This process can be seeded to yield reproducible outcome by placing ahead and on the axis of the long bunch a short electron bunch that drives initial wakefields. In the experiment, we use a long proton bunch. When the trajectory of the electron bunch is misaligned with respect to that of the proton bunch, the effect of initial wakefields on the proton bunch is not axi-symmetric. This leads to the development of hosing that we observe as proton bunch centroid oscillation in addition to self-modulation. We show that hosing occurs in the plane of the electron bunch misalignment and self-modulation is observed in the perpendicular plane. The phase of self-modulation and that of hosing are reproducible along the bunch. We measure the frequencies of plasma, self-modulation and hosing and show that they are equal within the measurement uncertainty.

Source size analysis of Laser Plasma Acceleration generated X-rays

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One of the main challenges when developing X-ray sources for applications from high intensity laser-driven processes, such as Laser Plasma Acceleration (LPA), is determining the spatial resolution of the X-ray source. We developed an analytical tool based on the Fresnel Diffraction formalism, to determine the X-ray source size of LPA generated X-rays, in several regimes (Self Modulated, Nano-particle enhanced, and Blowout), and at multiple facilities (BELLA, Texas PW, OMEGA-EP, and Jupiter Laser Facility). This analysis will help us understand the properties of these X-ray sources for use in radiography and High Energy Density (HED) science applications. In our analysis, a razor blade was imaged using the respective X-ray sources, and from the diffraction pattern cast onto the detector, we can fit a model diffraction pattern to determine the x-ray source size. This work primarily focuses on Betatron x-rays, Inverse Compton Scattering, and Bremsstrahlung. Due to the different pulse duration and laser parameters available at facilities, it is important to examine various characteristics of LPA, and their impact on the X-ray source when designing an X-ray diagnostic to be used for radiography of HED phenomena, or other application experiments. We will show the distinction between X-ray source sizes generated by different laser and gas target parameters, radiation processes, and facilities.

Progress Toward High Overall Energy Efficiency in a Beam-Driven Plasma-Wakefield Accelerator Stage

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Beam-driven plasma-wakefield acceleration has the potential to reduce the building cost of accelerator facilities, with large accelerating fields that are orders of magnitude greater than radio-frequency cavities. Sustaining strong decelerating fields for the driver and strong accelerating fields for the trailing bunch across long plasma stages will be key to demonstrating high energy efficiency in this scheme. We present preliminary experimental results of driver electrons decelerated to zero energy at the FLASHForward plasma-accelerator facility at DESY.

Ionization injection in a laser-heated capillary discharge waveguide

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Experimental and computational results on guiding of high-power pulses from the BELLA laser in laser-heated capillary discharges are presented. Group-velocity-based measurements of on-axis plasma density, measurements of laser spectral evolution, MHD simulations of channel formation, and PIC simulations of laser guiding are compared. Control of electron bunch injection is demonstrated. These results indicate a path toward high quality bunch production in multi-GeV acceleration stages.

Work supported by the Director, Office of Science, Office of High Energy Physics, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231 as well as by the National Science Foundation under Grant No. PHY-1415596. This research used the resources of the National Energy Research Scientific Computing Center, a DOE Office of Science User Facility.

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Polarised electron beams from plasmas

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Laser Plasma Acceleration (LPA) has seen rapid development over the last decades, with nearly 10 GeV energy gains [1], sustained 30 h operation [2] and recent demonstration of Free-Electron Laser gain [3]. With large improvements making various applications feasible, spin-polarisation of the accelerated beams has become a topic of increased interest. Novel concepts for generating spin-polarised beams have recently been proposed, relying on pre-polarised plasma sources [4], multiphoton ionisation [5] or interaction with ultra-intense laser pulses [6]. The physics of spin alignment and preservation, electron injection and acceleration into the plasma accelerator and the challenges of diagnosing the polarisation of the generated beams will be discussed in this contribution. The design and status of the proof-of-principle LEAP (Laser Electron Acceleration with Polarisation) project at DESY aimed at experimentally demonstrating generation of spin-polarised electron beams from a plasma accelerator is presented.

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Plasma-based Accelerator as Possible Replacement of a 26 MeV Linear Accelerator as Pre-Injector for a Synchrotron

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At the Physics Institute of the University of Bonn the electron stretcher facility delivers electrons with energies from 0.5 up to 3.2 GeV with user-defined rates to hadron physics experiments and a detector test site with internal and external users in a quasi-continuous beam. A 26 MeV linear accelerator and a subsequent booster synchrotron act as a pre-injector for the main storage ring. The linear accelerator delivers electron pulses of up to 16 nC with a repetition rate of 50 Hz.

We will present our current study on the possible use case of a plasma based accelerator in combination with conventional accelerator technology to act as a replacement for the LINAC. This includes a possible setup of an injector beam line at the booster synchrotron as well as plans for an additional test site for evaluation of plasma cell performance.

Competition between electron seeding and relativistic ionization front seeding

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Building a particle accelerator with accelerating gradient orders of magnitude higher than the one reached with RF technology is a challenging task. It was demonstrated that particle bunches propagating in plasma can drive large amplitude electromagnetic fields (called wakefields) that can be used to accelerate particles [1]. We prepare an experiment to uncover competition between wakefields driven by electron and proton bunch. At AWAKE the proton bunch is longer than a plasma period, meaning that the bunch develops and undergoes a process called self-modulation that forms a "train" of microbunches [2]. There are several ways of controlling the self-modulation, including a relativistic ionization front [3], and by including an electron bunch to drive initial wakefields [4]. In our presentation we will outline experimental plans to study the competition between the two controlling mechanisms when both are present.

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Positron acceleration via laser-augmented blowouts in two-column plasma structures

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We propose a setup for positron acceleration consisting of an electron driver and a laser pulse creating a two-fold plasma column structure. The resulting wakefield is capable of accelerating positron bunches over long distances even when evolution of the driver is considered. The scheme is studied by means of particle-in-cell simulations. Further, the analytical expression for the accelerating and focusing fields are obtained, showing the equilibrium lines along which the witness bunch is accelerated.

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Nuclear Security Applications of LPA-based Photon Sources

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Photon sources have been implemented as valuable tools for applications including cargo screening, unknown device characterization, and waste characterization. To date, the photon sources applied to those problems have been almost exclusively bremsstrahlung used for radiographic or tomographic measurements. The potential to leverage narrower energy spread photon beams derived from laser Compton/Thomson scatter (LCS) could dramatically improve the fidelity of many radiographic measurements, could enable radiography of objects with larger areal densities, and increase the applicability of measurements that leverage additional physics such as polarized beams, back-scatter radiography, photofission, and nuclear resonance fluorescence (NRF). The drawback, to date, of LCS sources is that they have required large facilities, which would require the security concern be co-located with at the facility, which is impractical in most cases. However, the prospect of Laser Plasma Accelerator (LPA)-based LCS sources, such as that under development at the Berkeley Laser Lab Accelerator (BELLA) Center, would reduce the footprints of such accelerator systems such that they could be portable, greatly increasing the realm of applicability. This poster will cover the motivations for photon-based security measurements, summarize the physics of the phenomena of interest, and highlight how LCS-based photon beams could improve existing capabilities and enable new types of application-motivated measurements.

Optical Probing of plasma waves in a hybrid LWFA-PWFA stage

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It was recently demonstrated that Laser wakefield accelerated (LWFA) electron beams are suitable to be used as drivers for a particle driven wakefield acceleration (PWFA) stage [1,2]. Integration of the two methods can promote the advantage of smaller and cheaper accelerators for high brightness electron beam generation. In order to optimize the performance, femtosecond optical probing allows for the insight view into the plasma wave dynamics during the propagation of the driver [3]. Pronounced differences in the morphology of beam driven plasma waves were observed when surrounded by either neutral gas or a broad pre-generated plasma channel. Here, we can relate the cavity size to the initial charge of the drive beam. This work can be extended for the investigation of driver depletion by probing at different propagation lengths inside the plasma.

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Stability studies in a plasma-wakefield accelerator

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Beam-driven plasma-wakefield acceleration is a promising technology to significantly reduce the footprint of future linear colliders and free-electron lasers. Such applications place stringent demands on beam quality and stability. Great strides have been made towards the preservation of incoming transverse and longitudinal beam quality. For all meaningful applications, however, shot-to-shot stability is also required in order to facilitate stable continuous operation over many days. Driven by the superconducting linear accelerator of the free-electron laser FLASH, FLASHForward is keenly positioned to identify limiting factors for stability in beam-driven plasma-wakefield accelerators. In this contribution, the state-of-the-art stability at the FLASHForward facility is presented with sources of instability also discussed.

Automation and Control of Plasma Accelerators Using Bayesian Optimisation

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Plasma accelerators promise to revolutionize many areas of accelerator science. However, one of the greatest challenges to their widespread adoption is the difficulty in the control and optimisation of the accelerator outputs due to coupling between input parameters and the dynamic evolution of the accelerating structure. Here, we use machine learning techniques to automate a 100 MeV-scale accelerator, which optimised its outputs by simultaneously varying up to six parameters including the spectral and spatial phase of the laser and the plasma density and length. Most notably, the model built by the algorithm enabled optimisation of the laser evolution that might otherwise have been missed in single-variable scans. Subtle tuning of the laser pulse shape caused an 80% increase in electron beam charge, despite the pulse length changing by just 1% by the standard experimental metrics.

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Electron acceleration by surface plasma wave at overdense plasma-vacuum interface

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When an intense laser pulse hits on an edge of a solid target, a strong surface plasma wave (SPW) can be easily excited and propagate along the plasma-vacuum interface. Significant amounts of electrons peeled off by the laser field are trapped in the SPW and accelerated to superponderomotive energies by the longitudinal field. Our three-dimensional particle-in-cell simulations demonstrate that a high-flux (tens of nC), collimated, superponderomotive electron beam can be obtained by an intense femtosecond laser pulse. Such an electron beam can be further used to proton acceleration and high-flux x-ray generation. The proposed scheme opens a new route for the development of future compact particle and radiation sources.

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Two schemes for plasma-based positron acceleration: thin hollow channels and non-neutral fireball beams

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Positron-based plasma acceleration is exceptionally challenging; due to the discrepancy between the plasma electron and ion masses, the most efficient schemes for electron acceleration are not directly applicable to positrons. Nevertheless, high-energy, high-quality positron beams are half of the requirement if one wishes to design a plasma-based e^-e^+ collider; thus, we must find solutions for this outstanding problem.

Recent advances rely on molding the plasma [1] or the driver beam [2] profile to shape the plasma wave containing positron focusing structures. Here, we propose two new solutions.

The first uses a thin hollow plasma channel with warm electrons [3]; we show how this plasma structure can be self-consistently generated and demonstrate stable, high-quality acceleration over tens of cm.

The second employs spatially overlapped electron and positron beams (also known as a fireball beam) propagating in a uniform plasma; we demonstrate that, under certain conditions, the beams will self-consistently evolve toward a hollow electron beam and focused positron beam. Thus, it replicates established schemes to accelerate positrons [2]. We also discuss the equivalent optical system, replacing the electron with a laser beam.

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Improving Performance and Numerics of the Quasi-static PIC Code HiPACE++

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Particle-In-Cell (PIC) simulations [1] are central to enable progress in plasma accelerators, but they are notoriously computationally expensive. The quasi-static PIC method accelerates simulations by allowing larger time steps, but the highest resolutions still need to fully leverage the compute capabilities of modern HPC systems. As Graphics Processing Units (GPUs) equip a majority of the largest supercomputers (7 of the world's top 10 and 6 of the EU's top 10 machines are GPU-accelerated [2]), it becomes more and more important for codes to exploit their computing power.

HiPACE++ [3] is a GPU-capable (and CPU-capable), open-source, 3D quasi-static PIC code for simulations of plasma acceleration. Performance-portability is achieved on GPU through the portability layer provided by the AMReX library [4], enabling a single-source code to run efficiently on multiple platforms. The code features two field solvers and can model beam-driven and laser-driven wakefield acceleration, ion-motion, ADK field ionization as well as the effects of plasma temperature and collisions.

In this work, we focus on performance-critical aspects of the code:
- An efficient Poisson solver using discrete sine transformations.
- Open boundary conditions for this Poisson solver using a multipole expansion.
- Extending compatibility with ion-motion to both solvers in HiPACE++.

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PIConGPU – High-fidelity plasma simulations on desktop computers up to exascale compute systems and a view on its recent applications

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Abstract

PIConGPU's latest release 0.6.0 in December 2021 brought a number of new features. Among these are an arbitrary-order Maxwell solver, the Higuera-Cary pusher, collisions, and incident field generation via the total field/scattered field technique enhancing its numerical stability and predictive capabilities. Furthermore, there are various technical advances, most notably support of the HIP computational backend allowing to run on AMD GPUs. These advances are mainly driven by our participation in OLCF's Frontier Center for Accelerated Application Readiness providing access to the hardware platform of the Frontier exascale supercomputer scheduled for deployment in 2022. We show performance data and present recent applications of PIConGPU profiting from these developments. To these applications belongs the advanced laser-plasma accelerator scheme Traveling-wave electron acceleration (TWEAC), providing scalability to energies beyond 10 GeV while avoiding staging. We further present simulation campaigns modeling and delivering valuable insight into the micrometer and femtosecond plasma dynamics of existing experimental campaigns.

Studies for an LPWA-based injector of polarized electrons for the ELSA facility

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At the University of Bonn the storage ring ELSA [1] extracts spin-polarized and unpolarized electrons with energies up to 3.2 GeV to hadron physics, novel detector testing and medical irradiation experiments. In a continuous approach for machine modernization we study the feasibility of replacing the current 26 MeV LINAC injector and its electron sources with a laser plasma wakefield accelerator (LPWA) and envision the establishment of a test facility for the development of such novel injector for unpolarized and polarized electrons. For the latter, theoretical calculations for feasibility have been carried out [1] and show promising results.

For this, we discuss a conceptional draft of a potential LWA setup at the existing facility and investigate environmental parameters to determine the suitability for the installation of a plasma generating high power laser system and a subsequent injector beamline to the ELSA synchrotron. In addition, the current hardware for measuring the spin-polarization of stored and extracted high energetic electrons is presented.

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High-quality electron beams from two-color ionization injection at BELLA

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Laser plasma accelerators (LPAs) are strong candidates as future compact particle sources for many applications, ranging from high-energy physics, to medical application, to light sources. In an LPA, ultrashort (< 10 μm) particle beams are accelerated in gradients of the order of 10-100 GV/m, and production of electron beams with normalized emittances below 1 μm has been experimentally demonstrated. For many applications, however, it is crucial to produce high-quality particle beams with normalized emittances ϵ_n<100 nm. The two-colors laser-ionization injection scheme [1] offers a path to produce tunable, ultralow emittance beams using an all-optical two-laser configuration. This scheme makes use of a low frequency (e.g., Ti:Sapphire) laser pulse or a train of pulses to generate a plasma wakefield, and a trailing high frequency beam, that ionizes atoms from a high-Z dopant in the plasma. The delay of the trailing pulse is such that the extracted electrons can be trapped in the plasma bucket. By increasing the difference in frequency between the two laser pulses and for appropriate dopants, it is possible to produce beams with a charge of several tens of pC and an emittance at the ~10 nm level.

We will present a design study based on the BELLA laser to demonstrate this technique using pulses from a Ti:Sapphire laser system to generate the wakefield, and a third harmonic pulse to locally inject electrons into the wake.

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Double pulse generator for long tube plasma discharges

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The AWAKE experiment, running at CERN, requires long plasma cells to perform wakefield particle acceleration experiments [1]. Plasma with suitable characteristics for these experiments is being developed using pulsed Direct Current Gas Discharges. This method rapidly ignites the plasma and further heats it by applying a current between two electrodes immersed in the gas, inside a glass tube. Discharges will be established between electrodes separated by 1 m to 30 m.

To produce the required plasma discharges, a high-power double pulse generator was designed and tested using a 5 m plasma cell setup [2]. The first pulse's objective is to ignite the plasma into a low current arc (10 A). This is obtained with voltages up to 120 kV. The second pulse takes advantage of the low impedance of the ignited plasma, to increase the arc current up to 400 A using a lower voltage pulse (up to 10 kV). The second pulse rises the ionisation fraction of the plasma to the AWAKE required density range [3]. To have a scalable plasma source, able to reach kilometre-long plasmas, tubes can be placed in series with shared electrodes and produce multiple synchronous plasma discharges. A magnetic circuit (composed of common-mode chokes) guarantees the synchronization of discharges and current uniformity across the multiple tubes.

This poster contains a description of the electrical components of the plasma source and the experimental results obtained from the double pulse generator and the current balancing magnetic circuit.

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Electron Bunch Seeding of the Self-Modulation Instability in Plasma

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When a long, narrow, relativistic particle bunch enters a plasma, it undergoes the self-modulation instability [1, 2]. The process can be seeded using a preceding short particle bunch, driving the seed wakefields from which the self-modulation grows [3].

In the AWAKE experiment [4], we use a short 18 MeV electron bunch to seed the self-modulation of a long 400 GeV proton bunch. In this work, we show experimentally that the self-modulation instability can be seeded by a preceding short electron bunch [5]. We prove that the timing of the self-modulation is reproducible from event to event and that it is controlled by the timing of the seed bunch with respect to the proton bunch. We show that the amplitude of the seed wakefields depends on the properties of the seed electron bunch and that the growth rate of the self-modulation depends on those of the proton bunch.

The electron bunch seeding of the self-modulation in plasma is an important milestone on the path towards proton driven plasma wakefield acceleration of electron bunches, with quality and energy suitable for high-energy physics applications [6].

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Laser Wakefield Acceleration to GeV Electron Energies

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For the creation of matter-antimatter pairs from the quantum vacuum via the Breit-Wheeler mechanism [1], energetic γ-rays and an intense laser need to interact with each other. The Breit-Wheeler experiment in the perturbative regime has been accomplished at the Stanford Linear Accelerator Center in 1997 [2] but was never implemented in the non-perturbative regime. At the moment, this experiment is in preparation in a fully laser-driven set-up using Laser Wakefield Acceleration (LWFA) with the ATLAS3000 laser at the Centre for Advanced Laser Applications [3]. In the experiment an initial high energy electron beam will be sent onto a Bremsstrahlung converter to generate γ-rays that are to interact with the intense laser. For this, an electron beam with multi-GeV energies is needed. Since several years LWFA has been improved to reach multi-GeV electron energies [4],[5]. However, building a reliable and stable source with low divergence and low pointing jitter with quasi-monoenergetic bunches over 2 GeV, as is needed for the Breit-Wheeler experiment, still holds challenges. The careful design of gas targets, such as gas jets and gas cells, is essential. These have to provide homogeneous gas densities over a distance of a few centimetres. In preparation for the Breit-Wheeler experiment in Garching, Computational Fluid Dynamic simulations were conducted to design and build centimetre-long gas nozzles. First LWFA results can be shown with electron energies reaching over 1.5 GeV using these nozzles and energies reaching over 2 GeV with a gas cell as target. Moreover, different injection techniques using these nozzles or the gas cell were tested with the goal to obtain quasi-monoenergetic electron bunches in the GeV regime.

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Spectrally Resolved Wavefront Analysis of the ATLAS 3000 Petawatt Laser

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The Center for Advanced Laser Applications in Garching is home to the ATLAS 3000 Petawatt Laser. Peak powers of 2.5 – 3 PW, at a repetition rate of 1 Hz, allow cutting-edge research in the fields of medical physics [1] and accelerator physics [2]. For the first time at the ATLAS 3000, the development and implementation of a new diagnostic device, consisting of a Shack-Hartmann Sensor and a Bandpass-Filter Wheel, enables a spectrally resolved wavefront analysis.

This poster presents the experimental setup of the developed diagnostic, integration in the pre-existing laser chain and network infrastructure, as well as preliminary results regarding spatio-temporal couplings, wavefront aberrations and beam-pointing jitter.

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Proton acceleration with shaped lasers and double-layer targets

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Ultrashort (ps) multi-MeV proton bunches generated during high-intensity laser-plasma interactions attract significant experimental and theoretical efforts due to a wide range of applications such as the modification of material parameters or 'fast ignition' of inertial confinement fusion [1,2]. Plasma-accelerated multi-10-MeV protons are already in use [3], but applications such as proton therapy require an improvement of the proton bunch properties, e.g. collimated bunches with energies in excess of 200 MeV [4]. Double-layer targets can support enhanced proton energies in comparison to single-layer targets due to an improved conversion efficiency from laser to plasma [5] but a reduction in proton bunch divergence has not been reported. Studies, focused on single-layer targets, have demonstrated that a driver with orbital angular momentum (OAM) [6] can lead to a reduction in beam divergence [7].
Here, we study a novel setup by combining both, double-layer targets and lasers with OAM. The self-consistent laser–plasma dynamics is investigated analytically and with three-dimensional particle-in-cell simulations in OSIRIS [8].
The work was devoted to examining the effects of relativistic self-focusing of Gaussian and OAM laser drivers in the near-critical plasma part of the target. The results indicate that the weaker self-focusing of the driver with OAM plays a crucial role in the generation of high-energetic proton bunches with low divergence. We identified a simplified relation between laser intensity and target composition that leads to consistent generation of high-quality proton bunches for a broad range of laser pulse energies under experimentally feasible conditions.

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Surrogate Modelling for Boosting Research of Electron Acceleration Processes

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Recent studies of laser plasma acceleration processes feature increasing requirements to the technical equipment and time consumption in both numerical and experimental research. This rising demand on statistical and mathematical methods for inversion of the system state, comprehension of measurement data and quantification of data stability can only be met by a comprehensive machine learning based surrogate model for Laser-driven Plasma Accelerators (LPA). This surrogate potentially accelerates theoretical comprehension of the system, novel means for design space exploration and promises reliable in-situ analysis of experimental data which leads to novel guidance mechanisms for future LPA experiments. The main aim of our work is to elaborate a surrogate model for electron acceleration processes by virtue of that one could unveil beam dynamics on the scope of collected diagnostic. Recently achieved results on laser-wakefield electron acceleration, demonstrate the capability to learn an approximation of the data-dependent posterior distribution by conditional inventible neural networks. The further derived model is able to describe an electron bunch transformation in the simulated beam transport in terms of phase space particle distribution based on its initial parameters: divergence and size. This step opens a perspective to a potential elaborated model that could use obtained diagnostics for reconstructions at any point in the electron beamline consisting of conventional magnetic elements.

High Time Resolution Particle Balance Measurements in AWAKE Helicon Plasmas

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A moderately high plasma density approaching 10^{21} m^{-3} is needed to achieve proton driven wakefield acceleration of electrons in the GV/m range in plasmas for the Advanced Proton Driven Plasma Wakefield Acceleration Experiment (AWAKE) at CERN. These plasmas must also maintain their high density along the axis to within 0.25% to coherently amplify the wakefield. While it is known that helicon plasmas are capable of reaching sufficient densities at the beginning of a 5 ms pulse, it is not known how uniform such plasmas are, or what mechanisms are behind the formation of the density profiles. Using laser induced fluorescence, it is possible to derive a complete particle balance in helicon plasmas. A new high speed laser induced fluorescence technique is being developed to measure densities and flow velocities with time resolution down to at least 1 ms. This new diagnostic will be capable of providing density and flow velocity measurements for both argon ions and neutrals, and from this data, the particle balance will be derived. This particle balance not only provides the necessary details about the axial density homogeneity, but it also gives insight into the physics of the ion sources that establish this profile. This new information about densities and source rates will indicate if additional fueling is necessary to correct the axial density homogeneity.

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e4AWAKE: Next generation electron source for the Advanced Wakefield (AWAKE) proton-driven plasma acceleration experiment at CERN

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Following the successful demonstration of proton-driven plasma wakefield acceleration in 2018 [1], AWAKE has initiated a research program to produce high-quality and high-energy electron beams [2]. To maximize the chances of success, AWAKE has chosen to use an RF-based source to generate the electrons which are accelerated in the plasma. However, this choice requires a 1-meter vacuum gap which reduces by more than 50% the proton-driven wakefields, and it does not allow to inject an electron bunch-train spaced by the plasma wavelength.

The e4AWAKE project introduces a next-generation electron source based on a high-power laser impinging on a solid target installed directly inside the AWAKE plasma [3]. This source does not require the 1-meter gap, and it potentially allows to inject an electron bunch train to take full advantage of the proton micro-bunch train produced by the self-modulation process. As a result, it would provide the AWAKE scheme with a factor of 2 improvement in accelerating gradient and a factor of 10 or more improvement in luminosity.

The project would proceed as follows: build a standalone version of the next-generation electron source (2024); optimize it for the requirements of proton-driven acceleration (2025-26); integrate it in the design of the future plasma cell of AWAKE, to be installed in 2027; demonstrate its compatibility with proton-driven acceleration during the 2028 run and compare its results with those of the RF-based electron source. Since the target used for the new electron source can be extracted from the beamline, the e4AWAKE project can proceed in parallel with the baseline AWAKE Run 2 plan, complementing its results without affecting its timeline.

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