# Annual report

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| Funding Programme: | **Virtual Institutes** |
| Project ID No.: | VH-VI-503 |
| Project title: | Plasma wakefield acceleration of highly relativistic electrons with FLASH |
| Project spokesperson | Prof. Dr. Brian Foster |
| Principal Helmholtz centre: | DESY |
| Further Helmholtz centres participating: | |
| Participating universities and other partners: | University of Hamburg, Germany<br>Max Planck Institute for Particle Physics, Munich, Germany<br>John Adams Institute for Accelerator Science, University of Oxford, Royal Holloway University of London, Imperial College London, UK<br>Stanford Linear Accelerator National Laboratory, Stanford, CA. USA<br>Lawrence Berkeley National Laboratory, Berkeley, CA. USA<br>CERN, Geneva, Switzerland<br>Frascati National Laboratory, Frascati, Italy<br>University of Lisbon, Lisbon, Portugal<br>Strathcylde University, Glasgow, UK<br>Griffith University, Brisbane, Australia |
| Report period (total funding period) | 01.01.2018 – 01.10.2018 |

## Activity report

a) Progress within the work plan delineated in the application

The FLASHForward facility was brought into operation as defined in the project proposal. Progress is reported in terms of the four working groups

**WG1**

The numerical simulations necessary to study PWFA processes require extremely large computational resources, requiring time on the highest performance supercomputers worldwide. This high CPU requirement effectively precluded conducting parameter scans with the particle-in-cell (PIC) codes that were in use when the VI was first proposed. In order to solve this issue, a collaboration of scientists from DESY and LBNL developed a reduced-model simulation code, HiPACE, which is less widely applicable than general PIC codes, but still captures the physics essential for PWFA. HiPACE allows for a speed-up in computation time by more than two orders of magnitude for standard FLASHForward plasma-acceleration schemes. This simulation tool allowed controlled injection techniques and the subsequent acceleration of the injected particles to multi-GeV energies to be simulated for the first time with extensive parameter scans. In the course of the VI, HiPACE was developed to include for example a new field solver and particle pusher which is capable of dealing with hosing dynamics (see below) with high physical fidelity at numerical noise levels significantly below those of typical finite-difference- time-domain codes, whose artificial numerical fluctuations may seed beam hosing and alter its growth dynamics, in particular for long propagation distances in the plasma.

The VI explored the realisation of several novel injection strategies in FLASHForward, such as density-down-ramp injection, beam-induced, laser-induced and wakefield-induced ionization injection. Each of these methods has various advantages, disadvantages and requirements. Particle-in-cell simulations showed that all of these injection techniques can be successfully operated at FLASHForward based on ideal driver-beam models. The simulation framework was extended to deal with realistic beam distributions as provided by particle-tracking codes, making full start-to-end simulations possible. Realistic distributions are often asymmetric with respect to the propagation axis, in particular in those regions in which most of the charge is located, owing to coherent synchrotron radiation effects in the FLASH bunch compressors. Simulations with realistic beams showed an impact of these asymmetries leading to transverse oscillations or hosing in the wakefield structure. These oscillations would be significant enough to hamper the acceleration and transport of the witness bunches. This led to years of development and study of this instability within the VI and to the production of several publications. The eventual conclusion of the simulations was that this was in principle a very important effect but that the instability could be mitigated in several different ways, for example increasing the emittance and widening the spot size of the FLASHForward drive beams at the plasma entrance, or using tapered plasma profiles.

A comprehensive study of the density down-ramp injection mechanism in beam-driven plasma accelerators has been published. The observed effect that shorter ramps lead to witness beams of higher charge and current, lower energy-spread and lower emittance is explained therein. It contains novel insights regarding the optimisation of the electron-injection process in density transitions in PWFAs with experimental parameters close to FLASHForward. Using the PIC code OSIRIS, witness electron beams of ~140 pC charge, with an emittance of ~200 nm, uncorrelated energy spread of ~0.3% and an approximately flat-top current profile of ~1.0 kA were generated.

**WG2**

This working group developed, installed, commissioned and is operating the FLASHForward beam line to transport and diagnose plasma-accelerated electron beams. It was necessary to consider factors such as damage by the high-power laser beam downstream of the plasma target, which required careful design of screen-based electron diagnostics as well as laser. The design of special diagnostics such the broadband transition-radiation spectrometer and betatron-radiation detectors were carefully studied. Care was necessary to ensure shielding of the FLASH driver beams, generation of tuneable FLASH double bunches and the mitigation of head-to-tail correlations induced by coherent synchrotron radiation that may seed the hosing instability. The FLASHForward beamline was integrated into the overall machine control system as an independent beamline, allowing independent control of the beam properties.

The lattice supports the inclusion of a high-field gradient (in excess of 1000 T/m) plasma lens close to the plasma cell. Such a lens, pioneered by the LBNL group in the VI, reduces chromatic emittance growth at FLASHForward by an order of magnitude compared to conventional focusing elements. Combined with the controlled beam release from plasma to vacuum (plasma-density tailoring), emittance can be conserved.

Detailed studies for beam orbit control have been performed. The current design, containing four cavity beam-position monitors, allows measurements of position, pointing and charge of the beams exiting the plasma. Provision was made for the addition of a transverse-deflecting structure (TDS), as a collaboration between CERN, PSI and DESY. The TDS allows longitudinal phase-space and slice emittance measurements to be carried out in Phase I of FLASHForward. This required extension of the post-plasma section of the beam line design, adding some space for the TDS and additional quadrupoles to meet the beam-optics requirements.

The production of double bunches to act as driver and witness bunches for PWFA was extensively studied. A double-laser-pulse method gave good transmission of both the drive and witness bunches from the RF through the beam line. A working point was found where the drive bunch was compressed to around 700A and separated by around 1 ps from the witness. Alternatively, double-bunches can be produced with a scraper in the dispersive section of FLASHForward. The thickness of the scraper was determined using simulations. The scraper method has been used in experiments to date. The beam line has now been fully commissioned and is in routine use for experimental activities.

**WG3**

As remarked earlier, the optimal exploitation of FLASHForward, with its remarkable spatial and temporal precision, is critically dependent on the development of a range of new and high-performance diagnostic devices. Many diagnostics have been considered, including Raman scattering, measurement of Stark broadening of spectral lines, Smith-Purcell radiation, etc. The most promising have been developed further.

There has also been considerable work on the development of plasma sources. The gas system had to be modified to cope with the stringent requirements imposed by the vacuum group for gas sources interacting with the accelerator vacuum. The table on which the plasma cell rests underwent considerable optimization and development and now behaves very satisfactory, Plasmas can be obtained and characterised reliably.

The focussing geometry originally implemented in the ionisation test-beam line using transmissive optics degraded the beam properties. A new setup incorporating the same reflective focussing geometry as implemented in the FLASHForward beamline was implemented in the spring of 2018. This setup allows phase-objects to be introduced into the laser beam and thus generate, for example, ring-shaped modes allowing hollow-core plasma channels to be produced, which are of great interest for example in investigating schemes for positron acceleration.

**WG4**

The main focus of Working Group 4 is to establish a viable scheme to generate FEL gain from plasma-accelerated electron bunches. Although this is a comparatively long-term goal of the FLASHForward project, the impact of this working group on the rest of the project has been considerable. In particular, numerical simulations have been conducted that show the potential performance of PWFA beams in a FLASH-like undulator section. The input beams were taken from plasma simulations in which the accelerated bunch was internally injected from the background plasma, resulting in a spatially compact electron distribution. This work showed the importance of electron bunch length and mitigation of gain degradation caused by undulator slippage.

VI collaborators from LBNL have developed several analytical expressions that help to estimate the viability of plasma-accelerated electron beams for generating measurable FEL gain in a FLASH TTF undulator section. This work provided a convenient way to assess the quality of simulated PWFA beams. Furthermore, it has directed the focus to electron-bunch slice parameters, i.e. the local current, emittance and energy spread. The relevant length of this slice is twice the slippage length during the propagation over one gain length of the undulator. Diagnostics of these parameters in the experiments will be highly challenging, but could be of critical importance in demonstrating that FEL-quality electron beams can be produced.

Energetic photon beams generated via betatron radiation and Thomson scattering can be produced in the FLASHForward test and preparation laboratory. This photon source was the first produced by the core FLASHForward team and was extremely useful in testing experiments and diagnostics. The laser setup was improved to allow operation at the10 Hz design rate.

The PIC simulations work allowed a programme of work to be carried out in the following areas, using a basic FODO setup for the undulator section:

- Establish the capability to model the transport of beams from the plasma section to the undulator with the final FLASHForward beamline design by simulation with Elegant;
- Provide a code based on Ming Xie for a quick evaluation of beams. This could be used as a rapid way to quantify the results of PIC simulations;
- Develop Genesis 1.3 simulations for a full evaluation of the simulated beams. A 1D simulation provided relatively quick checks of promising beams., while the 3D code was used for more rigorous checks. Non-linear beam transport effects were introduced into the 3D simulations for beams that were particularly interesting.

The beam-optics lattice designed by WG2 for the X-band TDS has been modified to be more adaptable to a beamline with undulator sections. However, further studies and additional modifications are foreseen. Additionally, the expected SASE signal is estimated to be initially on a nJ-level. Therefore, options for photon diagnostics such as microchannel plate detectors are planned to be developed in collaboration with the photon-diagnostics group at FLASH.

b) Milestones achieved

The major milestone of the VI is the installation and commissioning of the FLASHForward beamline. The project has now completed the initial installation phase and has commissioned the beamline. Significant science results are now being produced and e.g. an article has been published in Physics Review Letters. (R. D'Arcy et al, Phys. Rev. Lett. 122, 034801 (2019))

c) Compliance with financial plan and schedule

The revised schedule and financial plan, taking account of previous delays due to the delay in DESY technical resources, has been adhered to.

d) Publications, talks, prizes, etc.

**Peer-reviewed publications:**

1. G. Loisch, et al.,"Observation of High Transformer Ratio Plasma Wakefield Acceleration", Physical Review Letters 121, 064801 (2018)

2. M.J.V.Streeter et al., "Temporal Feedback Control of High-Intensity Laser Pulses to Optimize Ultrafast Heating of Atomic Clusters", Appl Phys Lett 112, 244101 (2018)

3. P.Niknejadi et al., “Status of the Transverse Diagnostics at FLASHForward”, J Phys Conf Ser 1067, 042010 (2018)

4. M.Gross et al., “Characterization of Self-Modulated Electron Bunches in an Argon Plasma”, J Phys Conf Ser 1067, 042012 (2018)

5. V.Libov et al., “FLASHForward X-2 - Towards Beam Quality Preservation in a Plasma Booster”, Nucl Instrum & Methods Phys Res A 909, 80 (2018)

6. C.A.Lindstrøm et al., “Overview of the CLEAR Plasma Lens Experiment”, Nucl Instrum & Methods Phys Res A 909, 379 (2018)

7. A.Aschikhin et al., “Analytical Model for the Uncorrelated Emittance Evolution of Externally Injected Beams in Plasma-Based Accelerators”, Nucl Instrum & Methods Phys Res A 909, 414 (2018)

8. T.J.Mehrling et al., “Accurate Modeling of the Hose Instability in Plasma Wakefield Accelerators”, Phys Plasmas 25, 056703 (2018)

9. J.-H.Röckemann et al., “Direct Measurement of Focusing Fields in Active Plasma Lenses”, Phys Rev Accel Beams 21, 122801 (2018)

10. M.Gross et al., “Observation of the Self-Modulation Instability via Time-Resolved Measurements”, Phys Rev Lett 120, 144802 (2018)

11. A.Martinez de la Ossa et al., “Intrinsic Stabilization of the Drive Beam in Plasma-Wakefield Accelerators”, Phys Rev Lett 121, 064803 (2018)

12. C.A.Lindstrøm et al., “Emittance Preservation in an Aberration-Free Active Plasma Lens”, Phys Rev Lett 121, 194801 (2018)

13. T.Kurz et al., “Calibration and Cross-Laboratory Implementation of Scintillating Screens for Electron Bunch Charge Determination”, Rev Sci Instrum 89, 093303 (2018)

**Conference presentations and invited talks:**

1. Heinemann, T. et al., “A hybrid laser-to-beam-driven plasma wakefield accelerator” Advanced Accelerator Concepts Workshop 2018, AAC 2018, Breckenridge, USA, 12 Aug 2018 - 17 Aug 2018

2. Libov, V., “Origins and mitigation strategies of beam centroid offsets”, ALEGRO 2018, Oxford, UK, 26 Mar 2018 - 29 Mar 2018

3. Zeng, M. ; Martinez de la Ossa, A. ; Osterhoff, J., “Plasma Lens for Relativistic Lasers in Laser Wakefield Accelerators”, 18th Advanced Accelerator Concepts Workshop, AAC 2018, Denver, America, 12 Aug 2018 - 17 Aug 2018

4. Christie, F. et al., “PolariX TDS - Applications at DESY”, High Gradient Workshop 2018, HG2018, Shanghai, SINAP, China, 4 Jun 2018 - 8 Jun 2018

5. Karstensen, S. et al., “FLASHForward: DOOCS CONTROL System for a Beam-Driven Plasma-Wakefield Acceleration Experiment”, 9th International Particle Accelerator Conference, IPAC'18, Vancouver, Canada, 29 Apr 2018 - 4 May 2018

6. Poder, K. et al., ”Development of a laser-wakefield Thomson source for medical imaging”, Hamburg Alliance New Beams and Accelerators, Hamburg, Germany, 5 Sep 2018 - 7 Sep 2018