Final Report Form

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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 Max Planck Institute for Particle Physics, Munich, Germany John Adams Institute for Accelerator Science, University of Oxford, Royal Holloway University of London, Imperial College London, UK Stanford Linear Accelerator National Laboratory, Stanford, CA. USA Lawrence Berkeley National Laboratory, Berkeley, CA. USA CERN, Geneva, Switzerland Frascati National Laboratory, Frascati, Italy University of Lisbon, Lisbon, Portugal Strathcylde University, Glasgow, UK Griffith University, Brisbane, Australia
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1. Summary

The FLASHForward project was conceived at a time of great excitement and rapid progress within the field of plasma wakefield acceleration. Its aim of the Virtual Institute was to create a facility to complement and rival the premiere world facility for beam-driven plasma wakefield acceleration (PWFA), FACET, at the SLAC National Accelerator Laboratory, USA. The specific goals were to do world-leading experiments and research to further our knowledge of the basic physics of PWFA and how to employ it to produce applications across a broad range of science, from particle physics to the determination of molecular structures using photon beams. While the applications of the FLASHForward beamline are just getting under way on the completion of the VI, it is clear that these aspirations have been largely met and that future prospects for the facility are bright.

At the time of the VI proposal, there was only one flexible facility in the world where PWFA experiments could be carried out, viz. FACET. Basic breakthroughs had recently been demonstrated, such as the production of quasi-monoenergetic electron beams with GeV-scale energies as well as the first demonstration of a laser-driven soft X-ray undulator source. However, the characteristics of the beams available at FACET, a conventional “warm” accelerator, limited the type of experiments that could be undertaken. These limitations inspired the VI proposal; that the proposal was well founded is evinced by the subsequent proposal for the FACET-II facility at SLAC, with similar capabilities as FLASHForward but still relying on “warm” accelerator technology. This FACET-II facility, which also has the unique ability to accelerate positron beams, will become available for researchers around 2020. Thus, at the end of the VI, FLASHForward is indeed a unique facility in the world.

The FLASHForward experimental programme is just beginning. Progress with constructing the facility was slower than initially hoped due to the unavailability of specialised and limited resources at DESY due to contention with the construction of the European X-ray Free Electron laser (XFEL). The future of the facility for the next few years looks very bright. An extensive set of experiments proposed by the DESY group led by J. Osterhoff is underway and a call for proposals from other collaborators has gone out. A successor of the VI will be inaugurated at a Collaboration Meeting to be held at DESY in December, 2018. A Scientific Advisory Committee has been set up and the collaboration itself will be set up at the same time. The applications of the techniques to be investigated at FLASHForward are extremely broad. Ultimately, it is hoped to demonstrate lasing via a wiggler from the PWFA-produced beams, opening up exciting possibilities for high-quality photon beams. The application of these techniques to major particle-physics projects, such as the Chinese electron-positron collider, CepC, is already being seriously considered. The diagnostic techniques being developed at FLASHForward will have wide applications across accelerator science in general as well as for PFWA in particular.

2. Work and results report

a) Starting point:

The limitations of conventional radiofrequency cavities in terms of the achievable sustainable gradient to a few tens of MV/m have long been evident. Equally, since the pioneering insights of Tajima and Dawson, the potential of plasmas to produce several orders-of-magnitude higher gradient has been widely accepted. However, to produce beams of a quality that could be used in applications, e.g. for particle physics or to drive a free-electron laser, was extremely difficult. Although there was a great deal of activity across the world in the field of laser-driven plasma wakefield acceleration (LWFA), there were only a few laboratories in the world who had a programme to investigate PWFA. DESY, with its great expertise in superconducting cavities and facility construction, was an ideal place to push to the next level in PWFA investigations. In particular, the upgrade of the superconducting user facility, FLASH, to install an extra beamline gave a unique opportunity to exploit the excellent beam parameters and the exquisite timing available from the FLASH accelerator. A scheme to add an addition beamline that could utilise some of the bunches produced by the FLASH-II parasitically was evolved by the proponents of the VI and accepted by the DESY Directorate.

A range of problems were unsolved and presented themselves to the proponents of the VI at the time of the proposal. These included the feedback from the structure of the produced wakefields on the quality of the beams produced from plasma acceleration. The wakefield structure can be probed with the short 1 GeV electron bunches available at FLASH. The staging of multiple plasma acceleration steps is essential for applications in particle physics; the timing resolution available at FLASH would make the interpretation of results much easier than other facilities. The development of suitable plasma cells is necessary to utilise FLASHForward optimally. All of these developments need to be carried out in the context of and informed by sophisticated Monte Carlo simulations of the basic physics processes. The development of such programmes is a major goal of the VI. The unprecedented timing accuracy of the beams from FLASH means that it is necessary to develop a new generation of diagnostics capable of utilising the precision this opened up. The final goal that could only be achieved if all the other goals are attained is the generation of X-ray photons by a beam, accelerated to roughly 2 GeV inside a plasma cell, by passing it through an undulator. Lasing can only be achieved if the generating beams are of very high quality in terms of their size, divergence, and energy bandwidth. The operation of such an FEL would give dramatic evidence for the ability to produce excellent beam quality from PWFA as well as opening up the possibility of exciting applications for photon-science experiments.

b) Progress of the work carried out

The VH-VI-503 contract was signed by Deutsches Elektronen-Synchrotron (DESY), the University of Hamburg (UHH), Max-Planck-Institute for Physics (MPP), and John Adams Institute (JAI). Partner institutions from the United States: Lawrence Berkeley National Laboratory (LBNL) and SLAC National Accelerator Laboratory (SLAC), were not allowed to sign MoUs because of changes in regulations by the US Department of Energy. They did however play an important part and were full collaborators in the VI.

The project was fully implemented as planned. However, it was significantly delayed compared to the original specifications. In any project at the cutting edge of technology, some delays are inevitable and were taken into account in the planning process. In particular, the start date of the VI was delayed by six months after a detailed re-evaluation of the schedule. However, the major delay to the VI project was due to external factors. DESY is a major laboratory with very wide-ranging technical infrastructure groups across the whole range of particle physics, accelerator physics and photon science from materials to molecular biology. The very broad range of the laboratory can put strain on a few key groups, for example those related to vacuum engineering, magnets, etc. The start of the VI project coincided with the ongoing very large commitment of the laboratory to the European XFEL project. Delays in this project and the concomitant requirement for technical groups caused knock-on delays to the VI. Although the DESY Directorate was very supportive of the FLASHForward project, the requirements of the XFEL had priority. This meant that parts of the project that needed effort from the specialist technical groups were delayed until the relevant XFEL activities were completed. The effect on the schedule of this lack of specialist technical effort is difficult to evaluate in detail, but probably led to a delay of around a year.

Other delays to the project include the failure of a contracted company to deliver ceramic chambers required inside the two pulsed dipoles in the FLASHForward extraction area, requiring the construction of temporary solutions to avoid further schedule delay.

Despite these external delays, generally speaking the construction of the FLASHForward beamline otherwise went to plan and adhered to the original work plan. Because of the delays in the project caused by the XFEL delay, the construction period was extended. This caused some problems with retaining essential people but since the great majority of the scientific and technical staff were either long-term DESY employees or employed with matching funds, in particular from the Alexander von Humboldt Professorship of B. Foster, this did not impact on the time profile of the VI funding. This was however extended to September of 2018 in order to cope with the parental leave of the one of the staff employed on the VI funding. Otherwise the project was completed on budget.

The original technical specification of the FLASHForward beamline as defined in the VI proposal was adhered to. Some minor details have been adapted as experience was gained. For the initial testing phase, the plasma was ionised inside the cell by means of a high-voltage discharge rather than using the high-power laser. The laser laboratory infrastructure including the laser vacuum system, laser wakefield-acceleration test laboratory and the laser itself were mostly completed by the end of 2015. The 25 TW peak-power laser was commissioned in December 2015 and fulfilled all its specifications:

Performances	Specified value	Test performed during OSAT 2
Pulse Duration	<25 fs	<25 fs
Output Energy	>600 mJ	611 mJ
Energy stability (3 min)	<2% RMS	0.65% RMS
Peak power	>24 TW	>24 TW
Beam pointing stability	<20 µrad RMS	3.27 µrad RMS
Temporal intensity contrast	10^{-3} @ 1 ps	2.10^{-4}
	10^{-5} @ 5 ps	2.10^{-7}
	10^{-7} @ 20 ps	4.10^{-9}
	≤10^{-9} @ 300 ps	2.10^{-9}
	≤10^{-9} (replica)	$9.7.10^{-10}$
Strehl ratio	≥0.7	0.85

The laser laboratory and associated experiments started full operation in 2016. Laser ionisation of the plasma is also possible. The initial experiments that have been carried out, described in more detail in the following section, demonstrate that the general characteristics of the beamline fulfil the design criteria.

c) Description of the results

The first official VI collaboration meeting took place at DESY on September 30th, 2013. It was decided that scientific working groups should be formed that focus the competences of each centre onto the major aspects of the project. These working groups (WGs) were jointly coordinated by a Hamburg scientist and a member of a collaborating institute:

- WG 1: plasma simulations
- WG 2: plasma-cell technologies
- WG 3: beam instrumentation and transport
- WG 4: photon generation

Results are presented in terms of these working groups.

WG1

The numerical simulations necessary to study PWFA processes require extremely large computational resources, requiring time on the highest performance supercomputers worldwide. For example, in 2016 the VI was awarded 17.7 MCPUh on the supercomputer JUQUEEN, Jülich, Germany. Furthermore, the VI received the excellence award of the John von Neumann-Institute for Computing, recognizing the best scientific proposal of the JUQUEEN computing cycle from May 2016 to April 2017.

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 FACET facility, now closed down, was an accelerator test facility dedicated mostly to PWFA at SLAC. The E-210 particle injection experiment was studied there by a collaboration including scientists from the VI in 2014 as a preparation for FLASH experiments. E-210 produced important results toward realization of the so-called “Trojan Horse” scheme to inject a witness beam into the PWFA cavity.

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. A comparative review of these methods took place in spring 2016 to determine priorities for further study of these concepts in both theory and experiment at FLASHForward. A committee of international experts in the field from within the VI helped to rank and prioritize the different proposed injection techniques for generation of witness beams. The ranking was based on the quality of the expected bunch parameters, expected jitter sensitivity, and the complexity of implementation under realistic experimental conditions at FLASHForward. As a result, density down-ramp injection methods received highest priority.

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.

In conclusion, there is no doubt that the general simulation environment relating to PWFA has been very significantly improved by the work carried out within the VI. This has had significant ramifications in the international PWFA community.

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.

At the end of August 2017, first tests with beam were initiated. On August 31st, 2017, at 2am first beam was seen on the scintillating screen station in the compression section of FLASHForward. Subsequently, the beam diagnostic group of DESY (MDI) assisted in the commissioning of the beam position monitors, screen stations, and the charge monitors by performing beam-based studies. More advanced beam studies, such as orbit response measurements, took place in parallel to FLASH operation during the following weeks. On November 9th, dedicated beam time within the framework of the FLASH Accelerator Research and Development (ARD) programme commenced. More advanced optics studies were carried out, including simultaneous on-crest operation (uncompressed beams) at FLASHForward and off- crest operation (longitudinally compressed beams) at FLASH1, which greatly enhances the flexibility and parameter space for simultaneous experiments. 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.

In preparation for experimentation at FLASHForward, plasma lenses were characterised at the MaMi microtron accelerator in Mainz in November 2016, using an electron beam of 855 MeV. One of the goals was to evaluate the magnetic field quality of active plasma lenses, important for beam quality preservation. This and further experimental campaigns resulted in a paper on the measured gradients, non-linearities and resulting emittance degradation that has been accepted for publication. In parallel, plasma-lens experiments were carried out at the CLEAR facility at CERN led by collaborators from the University of Oslo.

Several preparatory experiments were carried out in the laser preparation laboratory adjacent to the FLASHForward beamline. These included obtaining the calibration data for electron-density determination via Stark broadening, a collaborative experiment on characterisation of a specific density-down-ramp target type together with a group from the LUX experiment, and the investigation of the electron-density profile inside active plasma lenses. Electron beams generated via laser-wakefield acceleration were used extensively to test e-beam diagnostics and calibrate a cavity-based charge monitor.

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.

d) Outlook on future work, sustainability:

There is no doubt that the VI has been an enormous success. Without the VI, the beamline itself could not have been completed and FLASHForward would not have been possible. Unusually for a VI, the majority of the funds awarded were used to fund the construction of the beamline, since other funding sources were mostly employed to hire the required postdocs and other associated staff; in particular the funds from the Alexander von Humboldt Professorship of Prof. B. Foster were used in this way. In terms of the networking between partners, this has also been a remarkable success story. There have been very close connections between all of the partners in the VI, both those able to sign the required MoU and those who associated with the VI in a more informal way. This had very little effect on the effective functioning of the VI, although it did increase the effort needed from the DESY administration since DESY was required to hold the travel funds required to fund VI collaborator trips to VI meetings. There is no doubt that the existence of the VI greatly strengthened the interactions between the constituent groups. Since these represent many of the strongest and most renowned groups in the field, this has had a significantly positive effect on the development of the PWFA technique internationally.

The networking activity of the VI has been vital. It reinforced already existing links between the member institutions as well as forging new ones. In addition to travel to and funding of collaboration meetings, working visits between collaborators were financed through VI funds. The collaboration in the working groups was excellent and facilitated by extensive use of teleconferencing.

The success of the VI can also be gauged by the fact that a successor organisation is being founded, the “FLASHForward International Partnership for Science” (FIPS). This will be formalised at the first collaboration meeting to be held in DESY in December 2018. There has been a call for proposals for future running at FLASHForward. The parasitic nature of the facility precludes its being run as a user facility, as was the case for FACET. Nevertheless, it is intended that within the constraints of available beam time and the requirements for the current programme of experiments, time will be available for external groups to carry out excellent experiments. Proposals will be prioritised by the Scientific Advisory Committee (SAC). This has substantial overlap with the SAC of the VI, but has a new chair, Professor Stefan Karsch, following the retirement of Dr Ilan ben Zvi. The SAC has been a source of enormous help to the SI with advice and evaluation. Following one of the SAC’s recommendations, Prof. B. Foster will continue as the Spokesperson of the new organisation, FIPS. It is envisaged that many of the organs of the VI, such as the Collaboration Council, will be perpetuated in FIPS.

The operation of FLASHForward will be supported from within the DESY base budget, but we are actively seeking for additional funds to support collaborative visits to use the facility and for other collaborative work. Although there is a small amount of money available inside DESY to fund collaborative visits, it would be advantageous, particularly for exploratory experiments and the development of new ideas, to obtain additional funds. Such applications are ongoing.

e) Potential for application:

The major application of the work of the VI is in the potential for compact free-electron lasers. The very high gradients obtainable in plasma wakefield accelerators make it seem feasible to shrink the footprint a facility such as FLASH substantially, making a free-electron laser facility a possibility for many small research facilities, such as a large research university. While the FLASHForward work mostly involves beam-driven acceleration, much of what is learnt can be applied to other methods of plasma acceleration. Indeed, considerable facilities for laser-driven plasma acceleration (LWFA) are available in the FLASHForward complex. The commercial importance of such developments, given the interest in structural determination using high-energy photons, is immense.

Other applications derive from the work inside the collaboration on diagnostic techniques. Many of these techniques are directly applicable to a wide variety of situations both in accelerator physics and in cognate fields such as particle, nuclear and plasma physics. It is expected that some of the developments in diagnostics will lead to patentable ideas and to the possibility of producing commercial devices. The development of plasma lenses could have significant impact on areas of accelerator physics where very high magnetic fields are required and where space is at a premium. The work carried out within the VI on simulations has direct applicability to a variety of plasma applications, from astrophysical plasmas in the distant universe to energy generation through plasma ignition in Tokomaks. Exchange of ideas and techniques among researchers interested in these areas has already impacted on the work of the VI.

Two patents have been granted arising from the work of the VI:

M. J. V. Streeter and J. Osterhoff, “Device and method for characterizing an ultrashort laser through spectral phase analysis by coordinate encoded dispersion”, European patent application EP 14 190 069.6-1556 (2016)

J. Dale, K. Ludwig, L. Schaper and J. Osterhoff, “Vorrichtung mit beweglicher Aufnahme für Vakuumkammern”, Deutsche Patentanmeldung Nr. 10 2014 116 476.8 (2014)

3. Qualification of junior researchers:

The arrangements for career progression and well-being of junior researchers were necessarily in the hands of the individual institutes of the VI. We report here on those in place for the majority of graduate students and junior researchers working in the VI, who were based in Hamburg. All graduate students working at DESY and University of Hamburg were members of the PIER Helmholtz graduate school. This is collaboration which aims to promote top-level education, research and innovation. PIER focuses on the following research fields: Particle and Astroparticle Physics, Nanosciences, Photon Science and Infection and Structural Biology. Additional interdisciplinary areas include

Theory of Physics (Wolfgang Pauli Centre) and Accelerator Research (Voss-Wideröe-Centre). It provides travel grants, competitive seed-corn funds, language courses, etc. It provides a training programme that encompasses three pillars: 1) Qualification; 2) Interdisciplinarity; 3) Support:

1) In the study programme, doctoral students acquire:

- Professional skills in their main research field
- Interdisciplinary knowledge in the context of the PIER research fields
- Key skills such as communication, staff management and planning

2) Interdisciplinary events in the PIER research fields provide participants with the basis for lively scientific discourse. The spectrum of events ranges from cross-curricular doctoral seminars that the participants organise themselves to interdisciplinary lecture weeks.

3) Optimal scientific support is crucial for enabling doctoral candidates to complete their dissertations quickly and successfully. Extracurricular services concerning career planning and social networking also help participants successfully complete their dissertations and embark smoothly on their careers. At the beginning of their collaboration, the supervisors and the doctoral candidate sign the PIER Helmholtz Graduate School supervision agreement, which specifies good practice such as a work plan, regular meetings etc.

New postdoctoral researchers are also fully integrated into both the VI and the Hamburg research environment. An annual discussion between the junior researcher takes places, in which progress is assessed, problems are discussed, solutions to alleviate them agreed, further training needs discussed etc. Close interaction with other group members is assured by weekly group seminars, research and progress meetings etc.

Numbers of theses in areas covered by the VI in its lifetime

University of Hamburg:

PhD: 7

Goldberg, L.,"Spectroscopic Electron Density Determination of Plasma Targets for Plasma Wakefield Acceleration" (Examined 2018, currently under correction)

Hass, E., "Longitudinal Electron Bunch Shape Reconstruction from Form Factor Modulus based on Spectrally Resolved Measurements of Coherent Transition Radiation" (2018)

Kononenko, O. "Controlled injection into a Laser-driven wakefield accelerator" (2018)

Knetsch, A., "Acceleration of laser-injected electron beams in an electron-beam driven plasma wakefield accelerator" (2018)

Wunderlich, S, "Development and Commissioning of a Double-Prism Spectrometer for the Diagnosis of Femtosecond Electron Bunches" (2016)

Mehrling, T., "Theoretical and numerical studies on the transport of transverse beam quality in plasma-based accelerators" (2014)

Schulz, S. "Implementation of the Laser-Based Femtosecond Precision Synchronization System at FLASH" (2014)

Masters : 13

Meisel, M. “Emittance Measurement of Electron Beams from Laser Wakefield Acceleration using an Active Plasma Lens” (2018)

Quast, M., “Hollow Core Plasma Channel Generation” (2018)

Weichert, S, “Spectral Broadening of 25 fs Laser Pulses via Self-Phase Modulation in a Neon filled Hollow Core Fibre” (2017).

Bohlen, S., “Detection of Inverse Compton Scattering in Plasma Wakefield Experiments” (2016)

Borissenko, D., “Designing and Commissioning of a Setup for Timing-Jitter Measurements Using Electro-Optic Temporal Decoding” (2016)

Gruse, J.-N., “Calibration of laser diagnostics for laser plasma-wakefield acceleration” (2016)

Olgun, H., “Aufbau und Charakterisierung eines Gas Targets zur Demonstration der kontrollierten Injektion durch negativen Dichtegradient”, (2015)

Aschikhin, A., “sparc - ein Programm zur Analyse von Strahlungsphänomenen in von Particle-in-Cell-Codes simulierten Plasma-Wakefield-Beschleunigungsszenarien” (2014)

Entrena, C.,“Erzeugung und Transport von Doppelpaket-Elektronenstrahlen im FLASH Linearbeschleuniger” (2014)

Goldberg, L., “Laser-Based Discharge Ignition for Capillary Waveguides” (2013)

Bachelor: 1

Pannek, F., “A study on the feasibility of a plasma wakefield acceleration based FEL at the FLASHForward facility, DESY” (2015)

John Adams Institute:

Christopher Thornton: "Experimental Aspects of Plasma Wakefields Driven in Linear Regime”, University of Oxford (2018)

Muhammad Kasim: "Quantitative optical probing of plasma accelerators”, University of Oxford (2017)

Kristjan Poder: "Characterisation of self-guided laser wakefield accelerators to multi-GeV energies", Imperial College London (2016)

Oliver Pike: "Particle Interactions in High Temperature Plasmas”, Imperial College London (2016)

4. List of publications

Peer-reviewed publications:

1. A. Martinez de la Ossa, J. Grebenyuk, T. Mehrling, L. Schaper, J. Osterhoff, “High-Quality Electron Beams from Beam-Driven Plasma Accelerators by Wakefield-Induced Ionization Injection”, Physical Review Letters 111, 245003 (2013)

2. Robson, R. E., Mehrling, T., Osterhoff, J., “Phase-Space Moment-Equation Model of Highly Relativistic Electron-Beams in Plasma-Wakefield Accelerators”, Annals of Physics 356, 306 – 319 (2015). [10.1016/j.aop.2015.03.004]

3. Martinez de la Ossa, A., Mehrling, T.J., Schaper, L., Streeter, M.J.V., Osterhoff, J., “Wakefield-induced ionization injection in beam-driven plasma accelerators”, Physics of Plasmas 22 (9), 093107 (2015). [10.1063/1.4929921]

4. A. Aschikin et al.; “The FLASHForward facility at DESY”, Nuclear instruments & methods in physics research / A 806, 175-183 (2016)

5. Caldwell, A. et al., “Path to AWAKE: Evolution of the concept”, Nuclear instruments & methods in physics research / A 829, 3 - 16 (2016) [10.1016/j.nima.2015.12.050]

6. Dorda, U. ; et al.; „SINBAD—The accelerator R&D facility under construction at DESY”, Nuclear instruments & methods in physics research / A 829, 233-236 (2016) [10.1016/j.nima.2016.01.067]

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Conference presentations and invited talks:

1. Mehrling T., et al., “Development of the Quasi-Static Particle-In-Cell Code HiPACE”, at Physics in Intense Fields 2013, Hamburg, Germany, July 9 – 11, 2013

2. Dale, J. et al., “FLASHForward – Beam-Driven Wakefield Acceleration at FLASH”, Laser and Plasma Accelerator Workshop 2013, Goa, India, September 2 – 6, 2013

3. Kleinwächter,T. et al., “Specialised Gas Targets for Controlled Injection of Electrons into Laser-Driven Wakefields”, Laser and Plasma Accelerator Workshop 2013, Goa, India, September 2 – 6, 2013

4. Palmer, C. A. J. et al., “Transition Radiation as a Single-Shot Diagnostic of Laser-Plasma-Accelerated Electron Bunches”, Laser and Plasma Accelerator Workshop 2013, Goa, India, September 2 – 6, 2013

5. Osterhoff J., et al., “High Quality Electron Beams from Beam-Driven Plasma Wakefield Accelerators”, invited at the 3rd International Conference Frontiers in Diagnostic Technologies, Frascati, Italy, November 25 – 27, 2013

6. Osterhoff, J., “New Concepts for Energy Frontier Colliders - Plasma Wakefield Acceleration” 20th Particle & Nuclei International Conference, PANIC 2014, Hamburg, Germany, 25 Aug 2014

7. Osterhoff, J. “FLASHForward into the Future”, Institutsseminar, Jena, Helmholtz Institut Jena, Germany, 14 Jan 2015

8. Kononenko, O., et al., “Controlled injection of plasma electrons into a laser-driven wakefield using a variable length gas target”, European Advanced Accelerator Conference, EAAC, Isola Elba, Italy, 14 Sep 2015 - 18 Sep 2015.

9. Schwinkendorf, J.-P., et al.,, “Betatron Radiation Diagnostic for FLASHForward”, Laser Plasma Acceleration Workshop 2015, LPAW 2015, Guadeloupe, France, 10 May 2015.

10. Schaper L. et al., “Beam driven plasma wakefield acceleration at FLASHForward”, Laser Plasma Acceleration Workshop 2015, LPAW 2015, Guadeloupe, France, 10 May 2015.

11. Goldberg, L., et al., “Electron Density Determination via Broadening and Shift of Spectral Lines” Laser Plasma Acceleration Workshop 2015, LPAW 2015, Guadeloupe, France, 10 May 2015.

12. Martinez de la Ossa, A., Mehrling, T., Schaper, L., Osterhoff, J., “Wakefield Injection in the Beam-driven Plasma Wake Field Accelerator”, Laser Plasma Acceleration Workshop 2015, LPAW 2015, Guadeloupe, France, 10 May 2015.

13. Osterhoff, J., Najmudin, Z., Faure, J., “Case Studies on Plasma Wakefield Accelerator Design”, CAS-CERN Accelerator School: Plasma Wake Acceleration, Geneva, Switzerland, 23 Nov 2014 - 29 Nov 2014
CERN Accelerator School Yellow Report CERN-2016-001, 301-308 (2016)
[http://dx.doi.org/10.5170/CERN-2016-001.301]

14. Osterhoff, J., “The Wave of the Future - Plasma wakefield acceleration at DESY, in the Helmholtz Association, and in Germany”, IAEA Technical Meeting on Advanced Accelerator Technology, Athens, Greece, 13 Jun 2016 - 17 Jun 2016

15. Osterhoff, J., “Beam Diagnostics Challenges in Plasma Wakefield Acceleration”, International Beam Instrumentation Conference, Barcelona, Spain, 11 Sep 2016 - 15 Sep 2016

16. Osterhoff, J., “Novel Acceleration Technologies - Miniature machines for the future of photon science and particle physics”, Helmholtz Alliance “Physics at the Terascale” 10th Annual Meeting, Hamburg, Germany, 21 Nov 2016 - 23 Nov 2016

17. Osterhoff, J., “Plasma Wakefield Acceleration - An introduction to laser- and beam-driven concepts”, The 7th Asian Summer School and Symposium on Laser-Plasma Acceleration and Radiation, Shanghai, China, 17 Jul 2016 - 23 Jul 2016

18. Osterhoff, J., “DESY surft die Plasmawelle - Minibeschleuniger für die Zukunft der Photonen- und Teilchenphysik”, DESY Öffentlicher Abendvortrag, Hamburg, Germany, 26 Sep 2016

19. Osterhoff, J., “The Wave of the Future - Prospects for Plasma-Wave Acceleration in Particle Physics and Photon Science”, Seminar for the Vereniging Voor Natuurkunde, Gent, Belgium, 21 Mar 2016

20. Osterhoff, J. “FLASHForward into the Future - Challenges and Prospects for Beam-Driven Plasma-Wave Acceleration”, Seminar, Universiteit Gent, Gent, Belgium, 21 Mar 2016

21. Osterhoff, J., "Plasma Wakefield Acceleration - and other novel acceleration techniques” Workshop des Forums Beschleunigerphysik, Darmstadt, Germany, 2017

22. Osterhoff, J., “Plasma Wakefield Acceleration - An introduction to laser- (and beam-) driven concepts”, DESY Summer Student School, Hamburg, DESY, Germany, 23 Aug 2017

23. Osterhoff, J., “FLASHForward▸▸ into the Future - Challenges and Prospects for Plasma-Wave Acceleration”, Physikalisches Kolloquium, Greifswald, University Greifswald, Germany, 20 Jul 2017

24. Osterhoff, J.,” FLASHForward▸▸ into the Future - Challenges and Prospects for Plasma-Wave Acceleration”, SFB 676 Colloquium, Hamburg, University Hamburg, Germany, 25 Jan 2017

25. Osterhoff, J., “FLASHForward▸▸, PITZ, LUX, and ATHENAe- - Plasma-wakefield accelerator research at DESY”, FACET-II Science Workshop, SLAC, USA, 2017

26. Osterhoff, J., “FLASHForward >> - Future-Oriented Wakefield-Accelerator Research and Development at FLASH”, BELLA Seminar, LBNL, USA, 16 Oct 2017

27. Mehrling, T. et al., “Mechanisms for the mitigation of the hose instability in plasma-wakefield accelerators”, 59th Annual Meeting of the APS Division of Plasma Physics, DPP17, Milwaukee, Wisconsin, 23 Oct 2017

28. Mehrling, T. et al., “Mitigation of the Hose Instability in Plasma-Wakefield Accelerators”, 3rd European Advanced Accelerator Concepts Workshop, EAAC 2017, La Biodola, Isola d'Elba, Italy, 24 Sep 2017

29. Mehrling, T. et al., “Stable acceleration of high-quality beams in plasma-based accelerators” Seminar, Cockcroft Institute, Daresbury, UK, England, 6 Feb 2017

30. Osterhoff, J., “OSIRIS usage at DESY - Full start-to-end PWFA simulations for FLASHForward▸▸” OSIRIS Meeting, Los Angeles, USA, 18 Sep 2017

31. Martinez de la Ossa, A. et al., “A laser-to-beam-driven plasma wakefield accelerator” 3rd European Advanced Accelerator Concepts Workshop, EAAC 2017, La Biodola, Isola d'Elba, Italy, 24 Sep 2017 - 30 Sep 2017

32. D’Arcy, R. et al., "FLASHForward P-9: An X-band transverse deflection cavity for femtosecond-scale longitudinal phase space diagnostics”, 3rd European Advanced Accelerator Concepts Workshop, EAAC 2017, La Biodola, Isola d'Elba, Italy, 24 Sep 2017 - 30 Sep 2017

33. Libov, V. ; et al., “FLASHForward X-2: Beam quality preservation in a plasma booster” 3rd European Advanced Accelerator Concepts Workshop, EAAC 2017, La Biodola, Isola d'Elba, Italy, 24 Sep 2017 - 30 Sep 2017

34. Bohlen, S. et al., “Calibration of Charge Diagnostics using Electrons from a Laser Plasma Accelerator”, 3rd European Advanced Accelerator Concepts Workshop, EAAC 2017, La Biodola, Isola d'Elba, Italy, 24 Sep 2017

35. Knetsch, A., “FLASHForward X-1: High-brightness electron beams from a plasma cathode”, *3rd European Advanced Accelerator Concepts Workshop, EAAC 2017, La Biodola, Isola d'Elba, Italy*, 24 Sep 2017 - 30 Sep 2017

36. Aschikhin, A. ; Martinez de la Ossa, A. ; Mehrling, T. ; Osterhoff, J., “Development of a non-numerical model for emittance calculation in external injection scenarios”, 3rd European Advanced Accelerator Concepts Workshop, EAAC 2017, La Biodola, Isola d'Elba, Italy, 24 Sep 2017

37. Tauscher, G. et al., “Theoretical and experimental studies of plasma generation. Tailoring plasmas for wakefield accelerators”, *3rd European Advanced Accelerator Concepts Workshop, EAAC 2017, La Biodola, Isola d'Elba, Italy,* 24 Sep 2017 - 30 Sep 2017

38. Mehrling, T. et al., “High-quality electron beam generation in plasma-based accelerators” Neumann-Institut für Computing - Vortragsveranstaltung des Wissenschaftlichen Rates, Darmstadt, GSI Darmstadt, Germany, 20 Apr 2017

39. Osterhoff, J.,”DESY surft die Plasmawelle - Miniaturmaschinen für die Zukunft der Beschleunigerphysik”, VFFD Hauptversammlung, Hamburg, Germany, 25 Jan 2016

40. Osterhoff, J., “FLASHForward − Status and Plans”, DESY Beschleuniger-Betriebsseminar, Travemünde, Germany, 31 Oct 2016

41. Kononenko, O., “Investigation of advanced electron bunch generation and diagnostics in the BOND laboratory at DESY”, 58th Annual Meeting of the APS Division of Plasma Physics, San Jose, USA, 31 Oct 2016

42. Mehrling, T. ; Martinez de la Ossa, A. ; Fonseca, R. ; Vieira, J., “Mitigation of the hose instability in plasma-wakefield accelerators”, 17th Advanced Accelerator Concepts Workshop, AAC 2016, National Harbor, Maryland, USA, 31 Jul 2016 - 5 Aug 2016

43. Schwinkendorf, J.-P., et al., “FLASHForward - Beam-driven plasma wakefield acceleration at DESY”, 17th Advanced Accelerator Concepts Workshop, AAC 2016, National Harbor, Maryland, USA, 31 Jul 2016 - 5 Aug 2016

44. Schaper, L. et al., "Fragmentation Dynamics of Gases and their Impact on Plasma Wakefield Acceleration”, 17th Advanced Accelerator Concepts Workshop, AAC 2016, National Harbor, USA, 31 Jul 2016 - 5 Aug 2016

45. Goldberg, L. et al., “Electron density determination via broadening and shift of spectral lines”, 17th Advanced Accelerator Concepts Workshop, AAC 2016, National Harbor, Maryland, USA, 31 Jul 2016

46. Aschikhin, A. ; Ossa, A. M. d. l. ; Mehrling, T. ; Osterhoff, J., “Emittance conservation through tailored plasma ramps in PWFA scenarios”, DPG-Frühjahrstagung: Arbeitskreis Beschleunigerphysik, Darmstadt, Germany, 14 Mar 2016

47. Kövener, T. et al., "THz Spectrometer Calibration at FELIX”, DPG-Frühjahrstagung: Arbeitskreis Beschleunigerphysik, Darmstadt, Germany, 14 Mar 2016

48. Tauscher, G. et al., “Theoretical and Experimental Studies on Ionisation Properties for Plasma Accelerators”, DPG-Frühjahrstagung: Arbeitskreis Beschleunigerphysik, Darmstadt, Germany, 14 Mar 2016

49. Bohlen, S. et al., “Detection of Inverse Compton Scattering in Plasma Wakefield Experiments”, DPG-Frühjahrstagung: Arbeitskreis Beschleunigerphysik, Darmstadt, Germany, 14 Mar 2016

50. 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

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

52. 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

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

54. 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

55. 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

5. Public relations:

The main method to report the results of the VI has been the quarterly Newsletters, which are widely distributed within the PWFA community, the VI web site and articles for various publications. These have included the DESY Newsline, which headlined the first evidence for plasma acceleration at FLASHForward as the lead in its second issue of 2018, entitled “Surfing the plasma wave”. A further article “Teilchen mit teilchen beschleunigen” appeared in the January 2018 edition of the DESY Newsline.