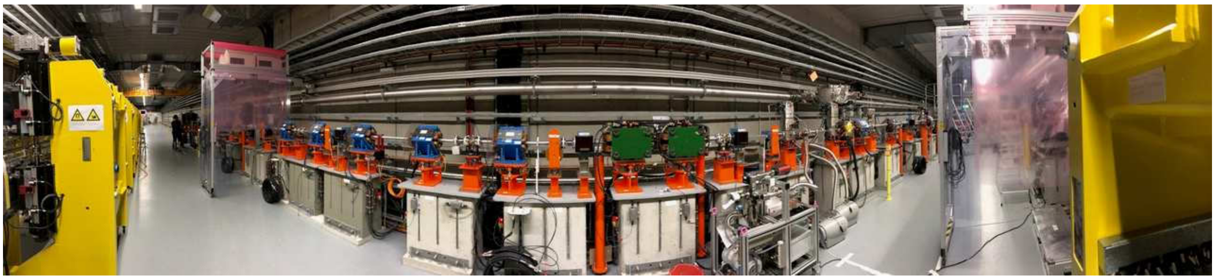
Annual report

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
Report period:	01.01.2017 – 31.12.2017

Activity report

a) Progress within the work plan delineated in the application

The activities within the Virtual Institute in the reporting year have concentrated on the completion of the installation of the FLASHForward beamline. Its ancillary laboratories and equipment are now fully in use. The summer FLASH shutdown saw the major effort to install the FLASHForward beamline (see Fig. 1) up to the point that first beam-driven experiments will be possible after the end of the final beamline



commissioning phase in the spring of 2018.

Fig 1. The FLASHForward beamline at the end of 2017. The green beamline components are dipole magnets that bend the beams from the compression section to the final focussing section.

Details on the installation can be found below in the report of Working Group 2.

The third meeting of the VI Scientific Advisory Committee (SAC) took place on March 23 and 24. The meeting took place remotely by video conference. The report of the SAC was very positive: for example, “A major scientific capability is being developed in FLASHForward”. The SAC was particularly asked about the future direction when the funding for the VI terminates in 2018. It endorsed the current structure as a template for the future and gave a variety of recommendations on the future form that international collaboration at FLASHForward should take. The SAC also gave detailed advice to the four VI Working Groups.

The project has been extensively reviewed by DESY internal committees. FLASHForward underwent the annual review by the DESY project management commission on February 22. This panel focusses on the quality of various aspects of project management at DESY, i.e. budgetary and personnel resources and planning, project controlling, management structures and reporting, risk management and mitigation, and scheduling. The outcome of this review was very positive, with the commission attesting solid project planning and emphasising their belief that the FLASHForward project coordination has adequate measures in place to reduce major scientific, technological, personnel, and financial risks to a minimum. A further review took place on December 6th with similarly positive outcome and recommendations to the DESY Board of Directors for the further development of the project. The DESY Machine Advisory Committee (MAC) was informed about the scientific and technical progress within FLASHForward on November 8th. Along with their many positive statements they highlighted the importance of the fast kicker dipole (for the simultaneous operation of all three FLASH beamlines) and suggested to give highest priority to its rapid installation. In addition, they pointed out the requirement for a fully developed scheme to safely extract and dump FLASH drive beams while maintaining a high-quality witness bunch.

The Annual Meeting of the Helmholtz Virtual Institute took place in conjunction with the European Advanced Accelerator Conference in Elba, Italy. There was once again an excellent attendance, with representatives from CERN, DESY, INFN Frascati, Hamburg University, IST Lisbon, JAI, LBL, and UCLA. The status of the project and activities in the partner institutions were presented and discussed. There was a meeting of the Collaboration Council following the main meeting, where discussions on the shape of the organisation to be put in place when the VI ends in June 2018 were discussed and agreed. The guiding idea is that the leadership and structures should be as far as possible continued over the transition period. The new organisation, “FLASHForward Accelerator Science Partnership” (FASP) will meet for the first time at DESY at a date to be fixed in 2018.

As always in a dynamic project, there have been a number of personnel changes. The core FLASHForward team has been strengthened by the addition of several new positions. At the beginning of April, Richard D’Arcy assumed the position of FLASHForward Scientific Coordinator. Richard will be responsible for the day-to-day operation of the FLASHForward science program and will become the future anchor point for our international collaborations. He will help us to develop a programme for experimental access to the facility for the broader PWFA community, possibly through an open call for proposals. Kristjan Poder from Imperial College London joined us on March 20 as a DESY fellow and immediately took over responsibility for the FLASHForward laser and preparation laboratories. His laser team was strengthened by three new students at the beginning of April and one in November: in April, Martin Meisel (U Hamburg) and Jeyathasan Viswanathan (U Paris Sud) are working on their Masters Theses while Severin Diederichs is working as a graduate research assistant; in November, Arathi Ramesh also joined as a graduate research assistant. In September Zeng Ming joined the group as a postdoctoral fellow working on plasma theory and numerical simulations. In November, Pau Gonzalez started his

PhD on electron beam phase-space diagnostics under the supervision of Richard D'Arcy. Also in November, Peng Kuang obtained an OCPC - Helmholtz Fellowship and will work as a postdoc on transverse electron-beam diagnostics, while Artemis Kontogoula will investigate an upgraded electron beamline design for the reduction of coherent synchrotron radiation (CSR) effects in her Bachelor thesis under the supervision of Slava Libov. Martin Quast successfully completed his Master's Thesis at Hamburg University on "Hollow core plasma channels" at the beginning of 2018, while Timon Mehrling has accepted a postdoc position at Lawrence Berkeley National Laboratory with our collaborator Carl Schroeder. Pardis Niknejadi (DESY) has taken over as one of the VI WG4 co-coordinators.

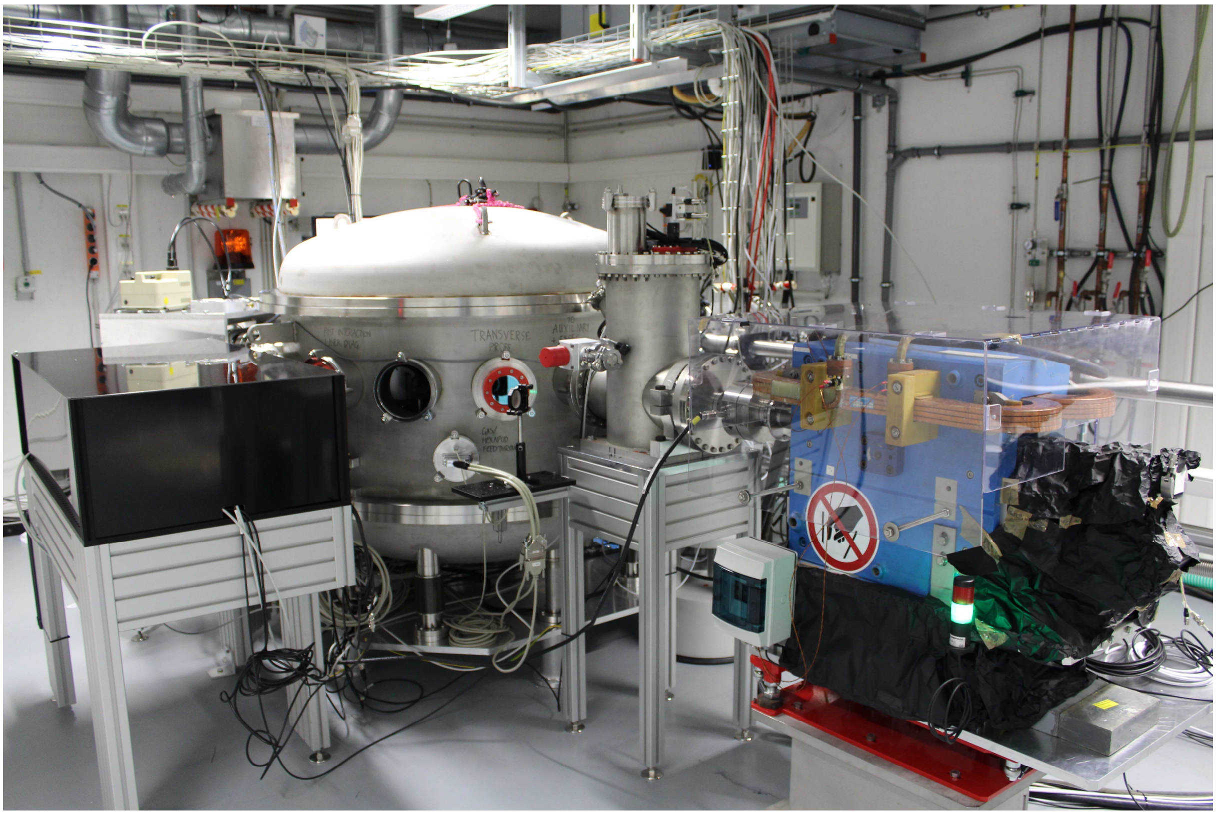


Fig 2. The FLASHForward preparation (BOND) lab.

We are pleased to report on a variety of scientific results. The FLASHForward LWFA team in collaboration with Klaus Flöttmann (DESY Accelerator Division), Heinz Graafsma (DESY Photon Science Division) and Florian Grüner (Hamburg University) successfully applied for support through the DESY Strategy Fund to develop a prototype application of a compact plasma accelerator for medical imaging purposes. Jens Osterhoff (DESY Particle Physics Division) will lead this project as a cross-divisional activity as principal investigator starting in January 2018. The FLASHForward theory and simulation team, led by Alberto Martinez de la Ossa (Hamburg University), successfully applied for computational time on the supercomputer system JuQUEEN in Jülich, Germany. They were granted 14.2 million core hours over the course of the next 11 months, which is actually slightly more hours than was applied for. Another scientific highlight was the very successful experiment at the Mainz Mikrotron (MaMi) at the beginning of May on the characterisation of active plasma lenses. This experiment was a collaboration between DESY, U. Hamburg, U. Mainz, and Lawrence Berkeley Lab. The data from the beam time was presented at the EAAC in September and will be submitted shortly to a journal.

In addition, a number of papers related to FLASHForward were published from authors within our collaboration, as detailed in section d).

Reports from Working Groups

The scientific work and preparation of the Virtual Institute is organized into four working groups.

WG1: Plasma simulations

Coordinators: Alberto Martinez de la Ossa (UHH), Jorge Vieira (IST)

Hosing instability studies.
The work of reference (1) demonstrates that the inherent drive-beam energy loss, along with an initial beam-energy spread, detunes the betatron oscillations of beam electrons and thereby mitigates the hosing instability (see Figure 3). It is also shown that tapered plasma profiles can strongly reduce initial hosing seeds.

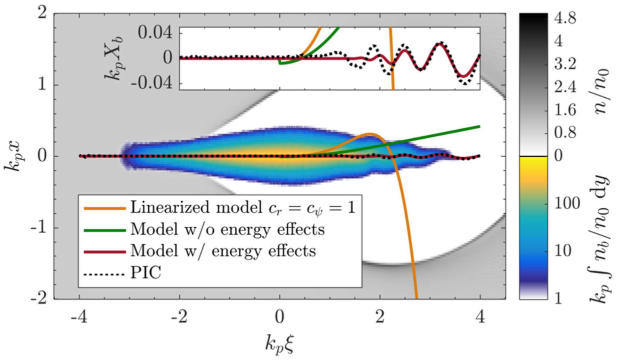


Figure 3. Result from a 3D PIC simulation showing plasma (grey scale) and beam (colour) charge densities after some propagation time. The simulation result (dashed curve) is compared with previous models for the

New studies on the suppression of the hosing instability by means of wider- and higher-emittance drive beams have been conducted using the quasi-static PIC code HiPACE. The simulation analysis reveals that the hosing instability can be suppressed when beams are widened (see Figure 4). When employing wider beams, the focusing plasma wakefields are non-linear and uniform along most of the drive-beam (in contrast to the narrow-beam case in which a perfectly clear plasma blowout with linear and uniform focusing fields is produced). These non-linearities in the focusing field cause a strong decoherence in the betatron motion of the electrons of the beam, which suppresses the centroid oscillation amplitude on a short time scale. However, a clear blowout is still formed behind the drive-beam and the focusing fields are uniform and linear, thereby preserving the quality of the acceleration of the witness beam. A manuscript describing these findings is in an advanced state of preparation and will be submitted soon.

Start-to-end simulations.

Thanks to the latest improvements in the field solver and the particle pusher, HiPACE is now capable of dealing with hosing dynamics with high physical fidelity at noise levels significantly below those of typical finite-difference time-domain codes. This step is of high importance to continue the start-to-end (S2E) simulation studies for beam optimisation in FLASHForward using HiPACE, which promise to greatly improve performance. Thanks to the latest advances in the code, we will be able to

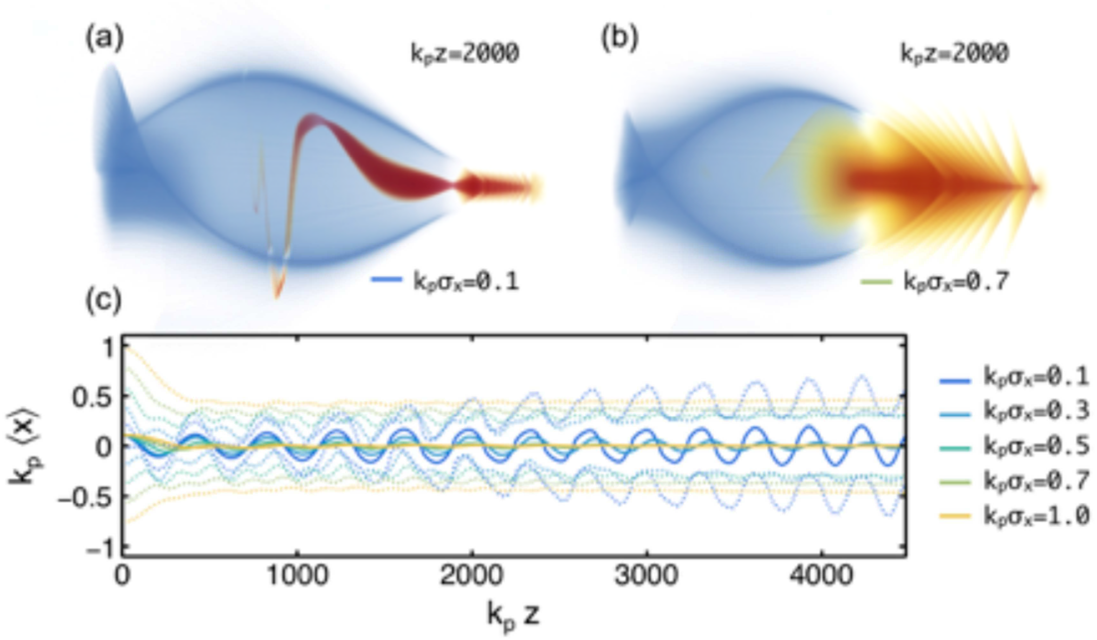


Fig. 4 Results from 3D PIC simulations with HiPACE demonstrating the mitigation of the hosing instability through use of a drive beam with a larger transverse size. In the case of b) the beam is seven times broader than that in a), leading to betatron decoherence and a reduced hosing effect as illustrated in c). The dotted lines in c) correspond to RMS contours.

analyse, efficiently and in full detail, the suppression of the hosing instability observed in S2E simulations with higher emittance driver beams. The aim is to determine the ideal conditions for transverse stability and acceleration performance. Start-to-end simulation studies employing ELEGANT simulated beams from FLASH injected into the plasma acceleration section have been continued, now using wider beams at focus (to suppress hosing) and HiPACE for the plasma simulations. A significant reduction of the centroid oscillations has been observed (see Figure 4c), in qualitative agreement with the results obtained with linearly tilted and Gaussian beams. Further optimisation of the FLASHForward beams is ongoing, with the aim of compensating the centroid offsets caused by CSR effects in the bunch compressors, and therefore further diminishing the hosing seed.

Density-down-ramp injection.

A comprehensive study of the density down-ramp injection mechanism in beam-driven plasma accelerators has recently been published in Physical Review Accelerators and Beams (see ref. (2)). 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, we were able to demonstrate the generation of 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.

WG2: Beam dynamics and instrumentation

Coordinators: Vladyslav Libov (DESY), Ivan Konoplev (JAI)

Activities in WG2 were focused on the beamline installation during the summer shutdown and on the subsequent commissioning phase. A critical issue turned out to be the ceramic chambers, which are to be installed inside the two pulsed dipoles in the FLASHForward extraction area. Unfortunately, the supplier of the chamber had to renege on the commitment to deliver the contracted parts, which made an installation this summer impossible. A temporary solution based on DC dipole magnets and standard metallic chambers was implemented in order to start FLASHForward commissioning on schedule. With the help of the MEA group of DESY, we identified two suitable replacement magnets, type “BZ” which have been recycled from the now defunct HERA collider. The DESY construction group ZM1 completed the interim chamber.

The summer shutdown of FLASH came to an end in August 2017. It resulted in the installation of all vacuum components down to a few meters upstream of the plasma chamber. Therefore, work in WG2 up until the end of 2017 focused on commissioning the newly installed first part of the FLASHForward electron beamline.
Shortly after the shutdown, general commissioning of the beamline started, involving components such as magnet power supplies and polarity tests with a Hall probe. Integration of new components into the FLASH control system (DOOCs) was achieved and tested. In particular, the so-called FLASH3 mode was established - the control system now treats FLASHForward as a third, separate beamline (in addition to FLASH1 and FLASH2) allowing independent control of the beam properties.

At the end of August 2017, first tests with beam were initiated. At 2am on August 31st, first beam was seen on the scintillating screen station in the compression section of FLASHForward. Subsequently, the beam diagnostic group of DESY (MDI) helped us commission 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. During this beam time, we performed more advanced optics studies and introduced the possibility of 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.

Additional activities of this WG that occurred in parallel to beam-based studies included the finalisation of the technical design of the variable mask (scraper) in the dispersive section (to produce driver-witness bunch pairs), and the finalisation of the conceptual design of the post-plasma-beamline extension to accommodate the transverse deflection structure and undulators in the future. Detailed simulations have been performed, including the complete FLASH linac and FLASHForward extraction (using ASTRA and elegant), as well as particle-matter interaction with GEANT4. A scraper length of 20 mm was found to be sufficient to remove all intermediate particles between the driver and the witness bunches at the end of the dispersive section.

WG3: Plasma sources

Coordinators: Lucas Schaper (DESY), Patric Muggli (MPP)

In the first months of 2017, several experimental campaigns, both external and on the DESY site, as well as preparations for the FLASHForward installation in the summer shutdown, were major points on the agenda of WG3. Experiments in the FLASHForward preparation laboratory 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. Moreover, electron-beam generation via laser-wakefield acceleration for testing of e-beam diagnostics is now used on a daily basis and has been used to calibrate a cavity-based charge monitor. Data analysis of the last experiments on active plasma lenses at the Mainz Mikrotron (MaMi) in November proved inconclusive with regard to the emittance evolution of the transported electron beams. A modified experimental setup was implemented at MaMi and a further campaign was conducted in early May. The data has been used in a publication on the measured gradients, non-linearities and resulting emittance degradation which has been prepared and will be submitted soon. In parallel, plasma-lens experiments at the CLEAR facility at CERN led by collaborators from the University of Oslo are now installed and operational. In December, plasma-lens operation was confirmed and first data was taken.

The design of the plasma source for first observation of interaction and wakefield generation of the electron drive beam delivered by FLASH was revised. In particular, the safe transport of the plasma-forming high-voltage pulse to the target while still complying with the accelerator-vacuum standards at FLASH required a design adjustment. This first plasma cell is based on concepts already tested and proven to be successful in experiments on active plasma lenses. Together with some modifications to the experimental chamber, this will allow us to completely preassemble the target under cleanroom conditions and thus minimise the number of process steps inside the target chamber and the time for installation on maintenance days, as well as mitigating the risk of vacuum contamination.

Fragmentation and ionisation dynamics: The current focussing geometry implemented in the ionisation test-beam line using transmissive optics has been shown to degrade beam properties and thus impact plasma generation. A new setup incorporating the same reflective focussing geometry as implemented in the FLASHForward beamline has been designed and will be implemented in the spring of 2018. This setup will also allow 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. The generation of such modes via a phase object has already been tested successfully in the setup described in an earlier newsletter. Results on the formation of hollow-core plasma channels are currently being analysed.

WG4: Photon sources

Coordinators: Pardis Niknejadi (DESY), *Carl Schroeder (LBNL)*

Free Electron Laser (FEL). External injection and density-down-ramp injection will be the first two injection methods studied at FLASHForward. Figures 5a and b show results of a PIC simulation of an externally injected shaped witness beam accelerated to 2 GeV (injected at 1 GeV) with a peak current of approximately 3 kA. Figure 5 shows the calculated gain length for TTF-type undulators, as an example, based on the beam parameters shown in Fig. 4b. Based on these results, an investigation of an FEL beam line with strong focusing has been initiated. A full beam-line design and 3D FEL simulations will be performed. Collaborations with the Universities of Hamburg and Strathclyde have been initiated in order to perform 3D FEL simulations with an un-averaged 3D FEL code: Puffin (Parallel Un-averaged FEL INtegrator).

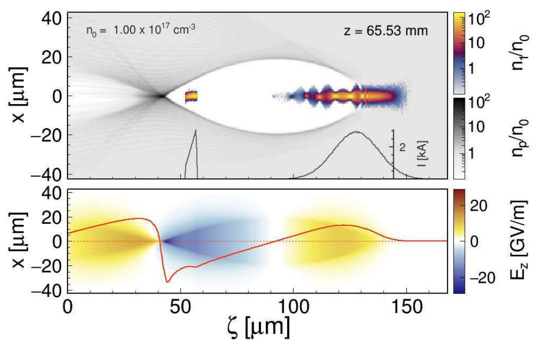


Figure 5a: Drive and witness beam currents and density (top). Accelerating field, E_z; the red curve is the on-axis field (bottom).

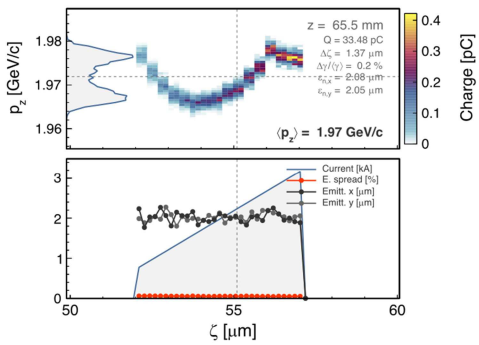


Figure 5b: Longitudinal phase space (top). Witness beam parameters (bottom).

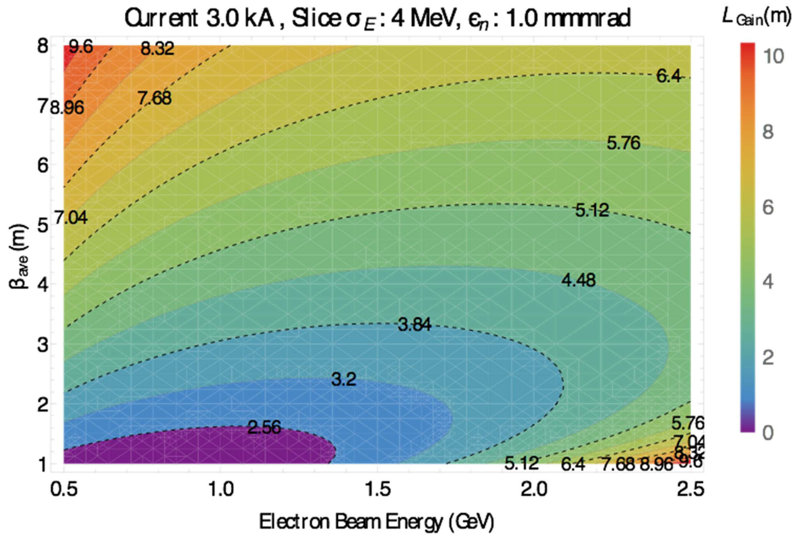


Figure 6: Gain length of the accelerated witness bunch in TTF undulators (evaluated using Ming Xie formalism).

The focus of FEL beamline studies was on the post-plasma beamline for the X-band transverse deflection structure (TDS) that will be compatible or easily adaptable to the 2020+ beamline which will include undulators (possibly of TTF FLASH-type). The major challenges are matching the post-plasma beam into the first undulator section with a minimum waist in the vertical direction, as well as the debunching in the focusing elements between the undulator sections. 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.

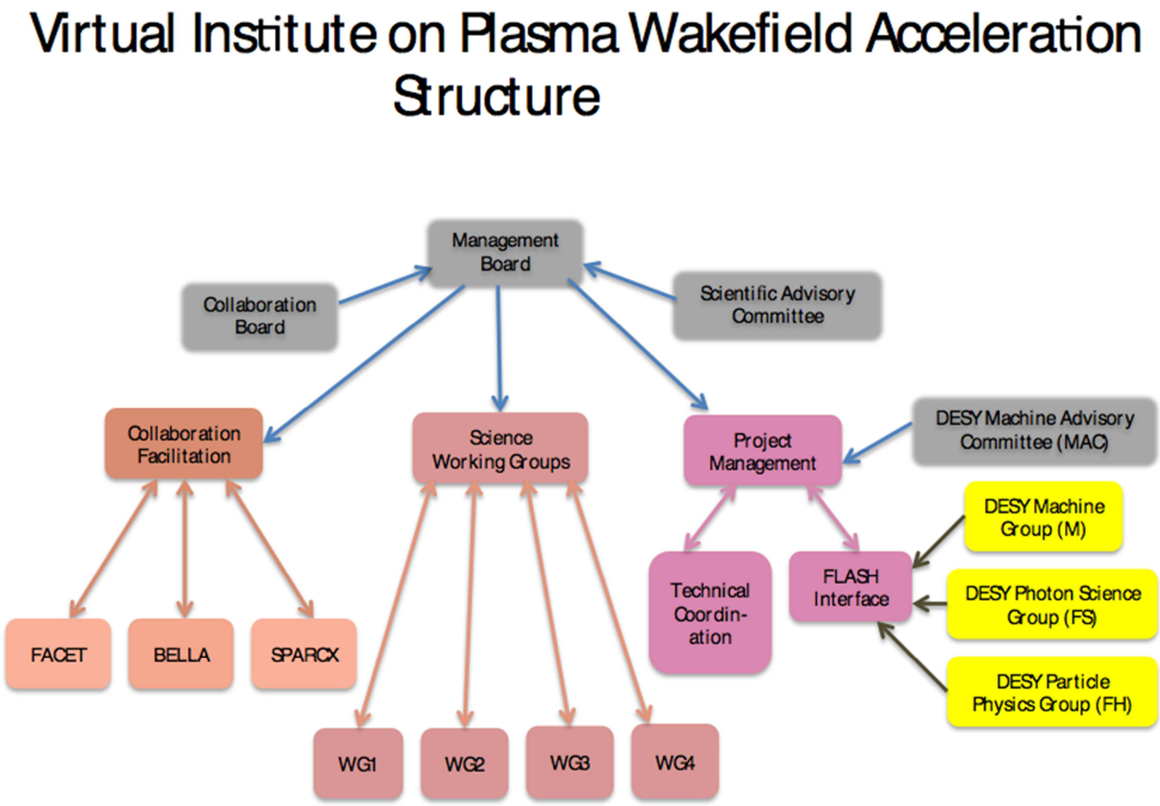
Additionally, the expected SASE signal is estimated to be initially on a nJ-level. Therefore, options for photon diagnostics such as micro-channel plate detectors are being discussed with the photon diagnostics group at FLASH. WG4 is also working closely with WG1 (PIC simulations) and WG2 (Beam Diagnostics) to develop the FEL application.

Inverse Thomson Scattering: Auxiliary photons in the MeV range have been investigated as a diagnostic of the electron beams. Simulation studies have shown that electron properties, such as divergence and electron spectrum, can be reconstructed from the photons generated by inverse Thomson scattering. For such reconstruction, a well-collimated beam is required. Furthermore, it is possible to obtain the transverse properties of the electron bunch from a multi-shot experiment in a 90-degree scattering setup (after removing the divergence). Since there are currently no off-the-shelf spectrometers available for the measurements of the MeV γ-ray spectrum that are required for these diagnostics, a collaboration has been initiated with the ILC group at DESY to design a detector that measures the spectrum by means of detecting and tracking the e+e- pairs produced by the γ-rays using a time-projection chamber.

Betatron radiation: Auxiliary photons in the keV range generated by betatron emission have been investigated as a diagnostic of the electron beams. Two possible diagnostic measurements from the betatron radiation are being investigated. One is a measurement of the beam source size - with the assumption that the plasma boundary is not affecting the electrons - for the purpose of approximating emittance. The second is a beam-tilt measurement. The feasibility and requirements of both methods are being studied. The vacuum window and camera for the betatron measurements have been received and are being tested. In the second half of the year, the focus in the FLASHForward test and preparation laboratory has shifted from testing betatron radiation diagnostics for FLASHForward to using harder X-rays generated from inverse Compton scattering (ICS). The goal is to investigate the usability of ICS photons as a diagnostic of the scattering electron beam. In addition, an upgrade to the LWFA setup to operate at full 10 Hz repetition rate is now running, after the arrival and installation of a new differential pumping system. Meanwhile, analysis of the data from the betatron-radiation experiments is in progress.

VI organisation and collaboration structure

The VI structure is displayed in the following diagram



The Collaboration board in chaired by Professor Andrei Seryi, JAI, and meets annually in conjunction with the Annual Meeting of the VI. This is normally held at the Advanced Accelerator Concepts meetings which alternate between the US and Europe. The final VI Annual Meeting was held on September 24th, 2017, on Elba in advance of the EAAC meeting. It is envisaged that the organisation after the completion of the VI will be very similar.

It has been decided to postpone the final meeting of the VI Scientific Advisory Committee planned for June in order to integrate it in the first Users Meeting of the FLASHForward Accelerator Science Partnership, the successor organisation to the VI. The proposed date for the first Users Meeting is 4 - 6 December, 2018.

b) Milestones achieved

The major milestone of the VI is the installation and commissioning of the FLASHForward beamline. After significant delays relating to the delay in completion of the European XFEL, which absorbed the specialist staff also required for FLASHForward installation, the project has now completed the initial installation phase and begun commissioning of the beamline.

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.

1. T. Mehrling, A. Martinez de la Ossa, R. Fonseca, and J. Vieira, "Mitigation of the Hose Instability in Plasma-Wakefield Accelerators", *Physical Review Letters* 118(17), 174801 (2017)
2. A. Martinez de la Ossa, Z. Hu, M. J. V. Streeter, T. Mehrling, O. Kononenko, B. Sheeran, and J. Osterhoff, "Optimizing density down-ramp injection for beam-driven plasma wakefield accelerators", *Physical Review Accelerators and Beams* 20(9), 091301 (2017)
3. R. E. Robson, T. J. Mehrling, and J. Osterhoff, "Great Moments in Kinetic Theory: 150 Years of Maxwell's (other) Equations", *European Journal of Physics* 38(6), 065103 (2017)
4. R. Brinkmann, N. Delbos, I. Dornmair, M. Kirchen, R. Assmann, C. Behrens, K. Floettmann, J. Grebenyuk, M. Gross, S. Jalas, T. Mehrling, A. Martinez de la Ossa, J. Osterhoff, B. Schmidt, V. Wacker, and A. Maier, "Chirp Mitigation of Plasma-Accelerated Beams by a Modulated Plasma Density", *Physical Review Letters* 118(21), 214801 (2017)