

1

2 The FLASHForward Facility at DESY

3 A. Aschikhin¹, C. Behrens¹, S. Bohlen¹, J. Dale¹, N. Delbos², L. di Lucchio¹,
4 E. Elsen¹, J.-H. Erbe¹, M. Felber¹, B. Foster^{3,4,*}, L. Goldberg¹, J. Grebenyuk¹,
5 J.-N. Gruse¹, B. Hidding^{3,5}, Zhanghu Hu¹, S. Karstensen¹, A. Knetsch³, O. Kononenko¹,
6 V. Libov¹, K. Ludwig¹, A. R. Maier², A. Martinez de la Ossa³,
7 T. Mehrling¹, C. A. J. Palmer¹, F. Pannek¹, L. Schaper¹, H. Schlarb¹, B. Schmidt¹,
8 S. Schreiber¹, J.-P. Schwinkendorf¹, H. Steel^{1,6}, M. Streeter¹, G. Tauscher¹, V. Wacker¹,
9 S. Weichert¹, S. Wunderlich¹, J. Zemella¹, J. Osterhoff¹

10

11 ¹ Deutsches Elektronen-Synchrotron (DESY), Notkestrasse 85, 22607 Hamburg, Germany

12 ² Center for Free-Electron Laser Science & Department of Physics, University of Hamburg,
13 Luruper Chaussee 149, 22761 Hamburg, Germany

14 ³ Department of Physics, University of Hamburg, Luruper Chaussee 149, 22761 Hamburg,
15 Germany

16 ⁴ also at DESY and University of Oxford, UK

17 ⁵ also at University of Strathclyde, UK

18 ⁶ also at University of Sydney, Australia

19 * Corresponding author: brian.foster@desy.de, Gruppe FLA, DESY, Notkestrasse 85, 22607
20 Hamburg, Germany. Tel: +494089983201

21

22 Abstract

23 The FLASHForward project at DESY is a pioneering plasma-wakefield acceleration experiment that
24 aims to produce, in a few centimetres of ionised hydrogen, beams with energy of order GeV that are
25 of quality sufficient to be used in a free-electron laser. The plasma is created by ionising a gas in a gas
26 cell with a multi-TW laser system. The plasma wave will be driven by high-current-density electron
27 beams from the FLASH linear accelerator. The laser system can also be used to provide optical
28 diagnostics of the plasma and electron beams due to the <30 fs synchronisation between the laser
29 and the driving electron beam. The project will explore both external and internal witness-beam
30 injection techniques. The operation parameters of the experiment are discussed, as well as the
31 scientific program.

32 1. Introduction

33 Interest in plasma wakefield-based particle acceleration techniques has greatly increased over the
34 last decade, leading to substantial progress. Development has been such that most major large-scale
35 particle-accelerator laboratories, such as BNL [1], CERN [2], DESY [3], LBNL [4], SLAC [5], have
36 initiated or are successfully running their own research programs. In a plasma accelerator, a plasma
37 wave is driven by either a co-propagating high-current-density particle beam [6,7] (PWFA, Plasma
38 Wakefield Acceleration) or an intense laser pulse [8] (LWFA, Laser Wakefield Acceleration). The
39 charge-density perturbation, established in the wake of the driver, results in strong electric fields
40 from of the order of 10 GV/m up to hundreds of GV/m [9], depending on plasma and driver
41 properties. These fields may be utilised to accelerate a trailing charged-particle beam (the witness

42 bunch) to energies of order GeV over centimetre distances, thus promising a dramatic
43 miniaturisation of particle acceleration modules when compared to standard radio-frequency
44 technology. It is also possible to generate the witness beam by trapping plasma electrons into the
45 accelerating phase of the wakefields. In this case, the witness-beam bunch length is a fraction of the
46 plasma wavelength, λ_p , which itself is typically on the order of 10 to 100 μm , so that these beams
47 intrinsically have bunch durations of a few femtoseconds. These properties make wakefield
48 accelerators particularly attractive for photon-science applications in addition to interest in their use
49 as compact accelerators for high-energy physics.

50 Due to the widespread availability and affordability of the laser systems required for laser-driven
51 wakefield accelerators, the vast majority of experiments to date have utilized this approach to
52 plasma wake generation. In contrast, beam-driven plasma wakefield accelerators have not yet
53 received the same degree of investigation, largely due to the limited availability of particle
54 accelerators with the requisite properties. Owing to the scarcity of research infrastructure, PWFAs
55 trail behind LWFA in their developmental progress, and hence, in demonstrated beam quality and
56 applicability. Nevertheless, PWFAs possess a number of fundamental advantages over LWFA: PWFA
57 drivers propagate through plasma at close to the speed of light, c , naturally yielding a plasma-wave
58 phase velocity much higher than in LWFA, where laser pulses propagate at their group velocity,
59 $v_g < c$. Limiting effects such as overtaking and de-phasing of accelerated particles [10] are therefore
60 mitigated [11]. In addition, strong transverse focusing fields in the plasma prevent driver expansion,
61 allowing much longer acceleration lengths than possible in LWFA, with distances of order one metre
62 already achieved [12]. The increased wake phase velocity also reduces unwanted self-injection of
63 plasma electrons into the wakefield, therefore mitigating dark current (current due to un-wanted
64 trapping), at the expense of making trapping of witness bunches more difficult. Furthermore,
65 particle-beam drivers may provide greater parameter stability than high-intensity laser drivers,
66 where observed shot-to-shot variations in the energy spectra of generated electron beams have
67 been attributed in large part to fluctuations in the properties of the driving laser pulse in
68 combination with nonlinear laser-pulse propagation effects in the plasma [13]. Another significant
69 advantage of PWFAs over LWFA for high-average-power applications is of a technical nature:
70 particle beams for plasma wake excitation can be generated with Megawatt powers with efficiencies
71 on the 10% level [14]. In contrast, state-of-the-art high-intensity laser systems deliver output powers
72 of ~ 100 W with 0.1%-level wall-plug efficiency.

73 The FLASH accelerator at DESY [15] fulfills all critical technical requirements to support the delivery
74 of suitable PWFA driver beams, and as such may be utilised to support many highly relevant studies
75 in the field. The FLASHForward (Future ORiented Wakefield Accelerator Research and Development
76 at FLASH) collaboration aims to construct a new electron beamline in the FLASH 2 tunnel, to
77 demonstrate the potential of PWFAs for the production of high-quality electron beams that will
78 support free-electron-laser (FEL) operation as a first step towards applications in high-energy physics.

79 In Section 2, the scientific goals for the FLASHForward project are outlined, with reference to specific
80 milestones and the motivations behind each. Following this, Section 3 describes the technical design
81 of FLASHForward, including the beamline extension to FLASH, and the adjoining laser and
82 preparation laboratory. Important aspects of the PWFA process that will be demonstrated and
83 developed, all crucial precursors to plasma accelerator application in high energy physics, are
84 discussed in Section 4, before the current progress and future milestones of the project are outlined
85 in Section 5.

86 2. Scientific Goals

87 The FLASHForward project has developed a broad scientific program to investigate a number of
88 crucial issues that must be overcome, prior to plasma-wakefield acceleration becoming a fully
89 realistic future acceleration technique. Studies planned will address virtually all aspects of the PWFA
90 process: from optimisation of driving-beam parameters to novel methods for witness-bunch
91 generation, from plasma cell design and plasma shaping for greater stability to methods for
92 improved release and capture of accelerated beams. Once sufficient experience with these
93 techniques has been gained and after careful characterisation of the accelerated electron beams,
94 FLASHForward aims for the first time to demonstrate gain from a wakefield-driven free-electron
95 laser. In addition, the lessons learned in the process will be important for future staging of multiple
96 reproducible plasma accelerators, potentially allowing energy boosting to the scales at the frontier of
97 modern particle-physics research.

98 The specific scientific goals of FLASHForward are three-fold:

- 99 • Characterisation of externally injected electron beams from FLASH at an energy of around
100 1.25 GeV and their controlled release from a wakefield accelerator with energies > 1.6 GeV.
101 Accordingly, the capabilities and performance of the FLASHForward beamline, from
102 extraction at FLASH 2 to post-acceleration diagnostics, will be validated, and comparisons
103 made with the results of extensive plasma cell [16] and beamline simulations performed to
104 date [17].
- 105 • Exploration of novel in-plasma beam-generation techniques, to provide > 1.6 GeV energy,
106 < 100 nm transverse normalised emittance, ~ 1 fs duration, and > 1 kA electron bunches. A
107 number of such techniques, some proposed by members of the FLASHForward collaboration
108 [18, 19, 20, 21], can be implemented at FLASHForward to evaluate their effectiveness, as well
109 as validating 3D particle-in-cell (PIC) simulations.
- 110 • Assessment of the potential of such beams for free-electron laser gain at wavelengths on the
111 few-nanometre scale. That is, starting with a FLASH beam intended for FEL generation,
112 boosting its energy via plasma acceleration and preserving its quality to observe subsequent
113 FEL gain. Preservation of beam quality during acceleration, extraction from the plasma
114 module, and transport to interaction or diagnostics regions is challenging [22]. It must be
115 achieved as a prerequisite for staging of multiple plasma accelerators.

116 3. FLASHForward Technical Design

117 The FLASHForward facility is designed to fulfill the scientific goals outlined in the previous
118 section. It utilises the enabling features of the FLASH facility to exploit innovative concepts in
119 plasma wakefield acceleration that make it unique in a number of aspects:

- 120 • FLASH provides world-leading possibilities for the synchronisation of electron beams with
121 lasers on the few-10 fs level [23]. This is vital for laser-triggered witness-injection (“Trojan
122 Horse”) techniques [19,20,24], which promise the generation of beams with very high
123 brightness. This is important both for photon science and for high-energy physics
124 applications, since it could provide low emittance without the necessity for damping rings.
125 The demonstrated synchronisation accuracy is significantly better than at other existing
126 facilities.

- 127 • FLASH is capable of producing beams with a double-bunch structure at the photocathode
128 and, owing to the superconducting technology of the RF cavities, of accelerating and
129 transporting them to the plasma cell without severe degradation from wakefield effects. The
130 first bunch acts as a driver of the plasma wave while the trailing bunch forms a witness
131 beam. The driver beam produced from the photo gun and transported to the plasma target
132 has excellent beam properties, e.g. a $\sim 2 \mu\text{m}$ normalised projected emittance in both
133 transverse planes. This is a necessary requirement to achieve high-quality witness beams in
134 such external injection techniques and, thus, essential for a careful study of the physics of
135 staging. The excellent beam quality may be preserved when entering and exiting the plasma
136 by deploying a novel windowless hydrogen target design that does not deteriorate beam
137 quality by multiple scattering.
- 138 • The facility allows novel techniques to be used to shape the longitudinal phase-space of the
139 driver beam, and by so doing, optimising the PWFA process. Shaping can be performed by
140 usage of a third-harmonic RF cavity in combination with the FLASH bunch compressors to
141 generate, e.g., triangular current profiles to give optimised transformer ratios [25]. In
142 addition, FLASHForward features a variable R56 extraction dogleg plus collimator, allowing
143 for post-compression of the FLASH beam to achieve multi-kiloamp currents for driving
144 various internal injection techniques, some of which have been formulated [18][19][20][21]
145 by members of the FLASHForward team and of the Helmholtz Virtual Institute (VI) for
146 Plasma-wave Acceleration [26], but not yet tested.
- 147 • An aspect particularly important for high-average-power applications is the ability of FLASH
148 to generate beams at MHz repetition rates owing to its superconducting cavities. This will
149 allow the stability of the plasma-acceleration process at μs time delay between two
150 acceleration events to be tested, a crucial study for the future of PWFA in applications
151 requiring high average power, such as high-energy physics.

152 Furthermore, the plasma cells recently developed by members of the FLASHForward
153 collaboration and the VI (see Sections 3.1 and 4.2) will allow increasingly tunable plasma density
154 profiles, improving controllability of the injection, acceleration, and release phases of PWFA.

155

156 **3.1. FLASHForward Beamline**

157 The FLASH accelerator possesses a number of features that make it an ideal source for the
158 FLASHForward beamline. In particular, the deliverable features of the plasma-wake driver beam
159 include:

- 160 - A beam of sufficient quality to drive an FEL (1.25 GeV energy, $\sim 0.1\%$ energy spread, $\sim 2 \mu\text{m}$
161 transverse normalised emittance) with 2.5 kA peak current
162 - Current profiles with variable length (10 to 500 fs) and flexible shapes (e.g. triangular [25])
163 - Laser-to-beam synchronisation of $< 30 \text{ fs rms}$ [23]
164 - 10 Hz inter-bunch-train repetition rate, providing drive-bunch trains of up to 2 bunches with
165 $1 \mu\text{s}$ intra-bunch-train spacing

166

167 **Figure 1–The FLASH accelerator complex including the new FLASH 2 buildings and the areas**
168 **occupied by the FLASHForward beamline and infrastructure (shaded in red)**

169 Following extraction from FLASH (*Figure 1*), the FLASHForward beamline, built within the FLASH 2
170 tunnel, consists conceptually of five sectors (*Figure 2*); beam extraction, beam matching and
171 focusing, plasma cell, beam diagnostics, and the undulator section; in addition laser beams are
172 transported into the facility.

173

174 **Figure 2 – Configuration of the FLASHForward beamline with its main components, the electron**
175 **beam extraction, beam matching and focusing, laser beamline, the central plasma interaction**
176 **chamber, the beam diagnostics section, and the undulator section with photon diagnostics.**

177 The extraction section is designed to achieve two goals: extraction of electron bunches from the
178 FLASH 2 beamline, and forming the longitudinal current profile of the extracted beams by means of
179 variable temporal compression. The FLASHForward and FLASH 2 beamlines operate simultaneously,
180 with bunches separated spatially by two kicker magnets manufactured by the Budker Institute,
181 Novosibirsk (each 25 cm long, with 8 winding turns and a 40 mm gap), which in combination provide
182 an 8° kick at 1.6 GeV maximum energy. Each magnet’s half-sine pulser (built by the DESY Machine
183 Injection group) has design parameters of 2.24 kHz frequency, temporal jitter < 100 ns, B-field jitter
184 of 10^{-4} , and will allow the magnetic field (coupled to the electron beam inside a ceramic chamber)
185 to switch polarity within 111.5 μ s rise time. The resultant trajectory change is compensated by a set
186 of dipole magnets ($1\times-0.8^\circ$ and $2\times-3.6^\circ$), giving a total transverse separation from the FLASH 2
187 beamline of 4 m. Inside this achromatic beam translation system, optics are chosen such that beam
188 dispersion is closed up to second order, with $R_{16}, R_{166} \approx 0$ m (transverse displacement) and
189 $R_{26}, R_{266} \approx 0$ (transverse angular displacement). High peak currents are achieved via temporal
190 compression of the beam, possible by tuning the transport R_{56} between -5 and 4 mm, and optimising
191 the RF-phase parameter. The beam energy distribution and current profile (*Fig. 3*) can be further
192 improved by cutting the long tails, including the trailing small current bump. As the energy is
193 correlated with the transverse offset in the dispersive section of the extraction beamline, it can be
194 cut transversely with a collimator system, and since the beam is also energy-time correlated
195 (chirped), the tails in the current profile are thus cut. The R_{12} and R_{22} values are tailored such that
196 jitter specifications are fulfilled with $\frac{\Delta B}{B} \approx 10^{-4}$ kicker fluctuations.

197

198 **Figure 3 – Simulated example electron beams through the FLASHForward beam line at the**
199 **entrance of the plasma target for charges of 500 pC and R_{56} at its maximum (a,b), and 250 pC and**
200 **R_{56} at zero (c,d).The (a) and (c) panels show the longitudinal phase-space of the beams together**
201 **with their projection on the p_z axis. The (b) and (d) panels show the current profile of the beam**
202 **(solid line), the slice energy spread (squares), and the slice normalised emittance in the horizontal**
203 **(downwards triangles) and vertical (upwards triangles) planes. Units are as indicated in the panels.**

204 Once parallel with the FLASH 2 beamline, the FLASHForward beam enters the focusing section. At its
205 end the beam is spatially compressed to a transverse spot size of ~ 7 μ m rms with minimal position
206 (< 10 μ m) and angle (< 0.5 mrad) jitter onto the plasma target in the interaction chamber. Also
207 contained in the focusing section are three differential pumping stations to compensate for vacuum

208 degradation caused by the gas loading of the plasma cell, in order to maintain the required
209 10^{-9} mbar at the beginning of the extraction section.

210 The central interaction chamber (Fig. 4) is the heart of the beamline, housing the interaction point of
211 the ionising laser beam, electron beam, and plasma cell. It also contains various scintillator screens,
212 transition-radiation screens, wires and knife edges for use in the profiling and alignment of electron
213 and laser beams. The central interaction chamber consists of a patented double vacuum-chamber
214 design with one vacuum chamber on top of the other [27]. The experimental apparatus is mounted
215 inside the upper vacuum chamber that adheres to the FLASH UHV cleanliness and vacuum
216 requirements¹. Hydrogen gas is used as the target in the plasma cell. The lower, less clean and higher
217 pressure, vacuum chamber houses a hexapod positioning system to admit free translational and
218 rotational control of the target, with its movement transferred to the experimental platform in the
219 upper chamber by a bellows system. The side ports of the chamber provide entry points for
220 additional laser pulses for probing or particle-injection experiments.

221

222 **Figure 4 – The FLASHForward central interaction chamber, which houses the PWFA cell. Side ports**
223 **admit plasma gas lines, laser pulse inputs and cables to control a 6-DOF positioning system while**
224 **alignment cameras operate via view ports.**

225 The beam capture and diagnostics section (*Figure 5*) starts downstream of the interaction point, and
226 is equipped to analyse the laser and driver/witness electrons following their interaction with the
227 plasma. The post-plasma beamline is designed to transport and characterise electrons of up to
228 2.5 GeV. The initial section (beam capturing) consists of several quadrupole magnets focusing the
229 divergent witness beam. After the quadrupoles, a dipole magnet acts as a broadband energy
230 spectrometer. Several metres of drift space following the dipole are needed to reduce the size of the
231 witness beam. A collimator is located at the point at which the beam is sufficiently small. It
232 suppresses the drive beam while the witness beam passes through unaffected. The emittance-
233 measurement section consists of another quadrupole magnet and a profiling screen. Finally, a high-
234 resolution spectrometer precisely determines the energy distribution of the witness beam. Various
235 diagnostics are located along the beamline, such as longitudinal profile measurement using transition
236 radiation and diagnostics of the ionisation laser. In addition, this part of the beamline includes
237 photon diagnostics to investigate the transmitted high-intensity laser radiation and the X-rays
238 created inside the plasma by betatron radiation and by inverse Compton scattering of the laser off
239 the electron beam. After passing through this beamline, the beam may be manipulated further to
240 demonstrate lasing in the undulator.

241

242 **Figure 5 – Post-plasma beamline layout: BPM stands for beam position monitors, BLM is the beam**
243 **loss monitor while XQA/TQA denote electromagnetic quadrupoles.**

244 **3.2. Laser and Preparation Laboratories**

¹ DESY technical specification No.: Vacuum 005/2008.

245 The FLASHForward facility features a high-intensity laser system, utilised for purposes including the
246 creation of the PWFA plasma medium, and as a diagnostic tool via direct interaction with the FLASH
247 electron beam. This 25 TW – 10 Hz titanium-sapphire CPA laser system was built by Amplitude
248 Technologies, France, and in testing has provided peak power of 26.0 TW, pulse durations of 24.5 fs
249 (FWHM), pulse energy (after vacuum compression) of 633 mJ, and 1.25% RMS Energy stability (over
250 3 minutes). A secondary output of 3.5 mJ is compressed to 25 fs, allowing for an independent probe
251 beam. This beam can be coupled into a gas-filled hollow-core fiber to create spectral broadening via
252 self-phase modulation and further compression down to ~5 fs with a chirped mirror compressor [28].

253 The timing instrumentation should achieve sub-30 fs synchronisation between laser pulses and the
254 electron driver, critical for diagnostics and laser-triggered injection schemes. This is realised via a
255 pulsed optical reference signal (rather than electronic RF signals) distributed throughout the FLASH
256 facility, derived from the repetition rate of a femtosecond mode-locked laser oscillator [23], locked
257 to the optical reference clock using feedback from a two-colour optical cross-correlator. A single-
258 colour optical cross-correlator is used to measure changes in the round-trip time of the reference
259 signal's fibre-optic network to a precision better than 10 fs [29], thus allowing compensation for the
260 effects of environmental fluctuations via an adjustable optical delay. In addition, the relevant
261 experimental areas are environmentally stabilised to an accuracy in temperature of 0.1 K and in
262 humidity of 1%, thereby maintaining synchronisation jitter of laser pulses to the FLASH electron
263 beam below a few 10 fs rms.

264 The BOND (Beam Optimisation and Novel Diagnostics) laboratory (*Figure 6*) is designed to allow
265 focusing of test beams from the high-intensity laser inside the BOND experimental chamber (*Figure 6*
266 *(B)*). This chamber includes a 651 mm focal-length parabola to give laser focal intensity of 7.5×10^{18}
267 W cm^{-2} , corresponding to a normalized vector potential (a_0) of 1.9, from which the beam is able to
268 drive an LWFA cell setup in the quasi non-linear wakefield regime for plasma densities of $5 - 15 \times 10^{18}$
269 cm^{-3} . The setup, contained in the ionisation test chamber (*Figure 6 (C)*), is used to mimic the
270 ionisation and shaping of plasma targets in the central FLASHForward interaction chamber,
271 permitting development and acceptance tests of equipment prior to installation in the FLASHForward
272 beamline. The BOND laboratory is surrounded by metre-thick concrete shielding walls to provide
273 protection against ionising radiation.

274

275 **Figure 6 – Laser and preparation laboratories for FLASHForward, consisting of laser lab, and BOND**
276 **lab with 1 metre thickness concrete wall for shielding. (A) Laser output to FLASHForward beamline,**
277 **(B) BOND experimental chamber (C) Ionisation test chamber.**

278 4. Science Program

279 The FLASHForward beamline and adjoining laser and preparation laboratories allow continued study
280 of a number of crucial aspects of the PWFA process that complement the ongoing numerical and
281 theoretical work of the FLASHForward collaboration. These include (but are not limited to) novel in-
282 plasma witness-bunch generation techniques, engineering and development of plasma-cell targets,
283 and optimisation of the shape of the drive beam.

284 4.1. Witness-Bunch Generation

285 The method by which the witness bunch is injected dictates the emergent beam properties, including
286 minimum transverse emittance, energy spread, and peak current [30] and is a limiting aspect of
287 PWFA’s effectiveness in accelerating such a bunch. The two broad approaches to injection, witness-
288 bunch creation by either internal trapping of background plasma or ionised electrons or introduction
289 of a pre-accelerated electron bunch, and different methods to achieve them, will be investigated in
290 detail at FLASHForward.

291

292 **Figure 7 – Charge densities of driving beam (red-blue palette), plasma electrons (black-white) and**
293 **helium electrons (yellow-red), from 3D Particle-In-Cell (PIC) simulations of different internal**
294 **witness-bunch generation techniques with the code OSIRIS [31,32,33]. a) Density down-ramp**
295 **injection [34,35,30], b) Laser-induced ionisation injection [19,20,24], c) Beam-induced ionisation**
296 **injection [18], d) Wakefield-induced ionisation injection [21]. The red curves at the bottom of each**
297 **sub-figure indicate the shape of the axial longitudinal electric field.**

298 With sufficient control of wake-driver peak current and local plasma parameters, FLASHForward’s
299 technical capabilities allow access to a number of novel in-plasma beam-generation techniques
300 (*Figure 7*):

- 301 - Density down-ramp injection (DDI), previously demonstrated in LWFA [30], requires plasma
302 cells with adaptable plasma density profiles, which will be available at FLASHForward. Results
303 of 3D OSIRIS PIC simulations (assuming the expected FLASHForward experimental conditions)
304 have been promising, demonstrating narrow energy bandwidth (0.5% uncorrelated energy
305 spread), high-current (0.7 kA), electron beams with small (0.2 μm) transverse normalised
306 emittance [36]. The density down-ramp slope is found to strongly influence injected beam
307 parameters, with less steep profiles inducing smaller charge and shorter bunches with larger
308 transverse normalised emittance, making DDI an attractive injection method for PWFA owing
309 to its tunability;
- 310 - Laser-induced ionisation injection (“Trojan Horse” injection) [19,20,24], which requires $I_B \gtrsim 5$
311 kA and a synchronised injection laser, used to release electrons from a second medium with
312 higher ionisation threshold than the background plasma; the second medium is provided by
313 a narrow high-density He / H gas jet at the entrance to the plasma cell;
- 314 - Beam-induced ionisation injection [18], which utilises radial electric fields of the driver to
315 trigger ionisation, requires still higher beam currents ($I_B \gtrsim 7.5$ kA), as well as a secondary
316 medium with higher ionisation threshold. Three-dimensional PIC Simulations with OSIRIS
317 using realistic parameters for FLASHForward have yielded promising results with
318 uncorrelated energy spread $\leq 1\%$, 3 kA peak currents, and $\sim 1 \mu\text{m}$ normalised emittance
319 [19];
- 320 - Wakefield-induced ionisation injection [21] uses only the wakefields to trigger ionisation and
321 trapping of plasma electrons, and requires beam currents $I_B \gtrsim 10$ kA. Simulations assuming
322 anticipated FLASHForward experimental conditions are promising, giving witness bunch
323 parameters of ~ 2.5 GeV energy, uncorrelated energy spread $< 1\%$, 5 kA peak currents, and \sim
324 $0.3 \mu\text{m}$ transverse normalised emittance (*Figure 8*) [37]. This strategy for the injection is
325 thought to provide improved control and stability over the accelerated bunches, as it is less
326 sensitive to fluctuations in the driver’s microstructure and does not rely on additional
327 devices, such as lasers, for the injection.

328
329
330
331
332

It should be noted that the thresholds given above on the current of beam drivers to permit trapping in ionization-based techniques may be substantially reduced if assisted by density down-ramps that reduce the phase velocity of the plasma wake, as demonstrated by three-dimensional VSim [38] PIC simulations for the laser-induced ionisation injection case [20].

333
334
335
336
337
338

Figure 8 – Witness electron bunch injected in the plasma wake by means of wakefield-induced ionisation injection, after ~14 mm of acceleration in plasma. (a) Longitudinal phase-space of the beam together with its projection on the p_z axis. (b) Current profile of the beam (solid line), slice energy spread (squares), and slice normalized emittance in the horizontal plane (dots). Units are as indicated in the panels.

339
340
341
342
343
344
345
346
347
348
349
350
351
352

Furthermore, methods for external witness-bunch generation have been simulated and tested at the FLASH facility. These methods offer the possibility of studying staging of plasma cells and may in addition allow for a higher degree of control over the witness-beam parameters. One such technique is generation of a pair of picosecond-separated bunches (a driver and a witness) at the FLASH photocathode, then transport through the accelerator within the same RF bucket (the same period of the RF accelerating fields). The two bunches are provided by a pulse split-and-delay system, which splits the initial laser beam using a polariser, where an adjustment in polarisation angle allows control of the relative intensity of the two beams. The separated beams are directed through optical paths of adjustable length, before being re-combined, yielding two pulses of nearly identical spatial characteristics (shape, transverse size, length) with variable charge and a variable delay between them, ready to pass through the accelerator. The plasma wavelength provides the driving constraint for this procedure; the initial laser pulse delay must be set such that post-acceleration compressed bunches have a spatial separation less than this wavelength, as required for wakefield acceleration in the same wake bucket.

353
354
355
356
357
358
359
360

In 2014 this process was tested at FLASH, with the aim of creating bunches of approximately equal intensity and initial photocathode separation of 20 mm (corresponding to ~ 65 ps delay). The pulse stacker operated effectively, generating the two bunches to within < 10 ps of the desired delay, and demonstrating production of double electron bunches at the gun without complications. Both bunches were then successfully transported through the accelerator in the same RF bucket; measurements using the existing FLASH transverse deflecting structure (TDS) showed two stably compressed and distinguishable resultant bunches, with 100 μm post-compression separation, and final energies of approximately 700 MeV and $\pm 1\%$ spread [17].

361 **4.2. Plasma-Target Development**

362
363
364
365
366
367
368
369

Precise and reliable tailoring of plasma-density profiles is identified as one of the critical points in achieving stable and reproducible conditions in plasma wakefield accelerators. At DESY, multiple input / output plasma cells have been designed, simulated in OpenFOAM [39] and fabricated via a combination of classical milling procedures on sapphire with femtosecond laser machining [16]. These cells are windowless (to reduce emittance growth), allow transverse laser probing (for characterisation of plasma densities and acceleration processes), and are compatible with plasma creation by ionisation laser, electric discharge, or electric fields from beams. Simulations demonstrate their capability to generate consistent electron densities along the beam's acceleration

370 path, whilst maintaining a high-density He / H jet across the cell's entrance (as required for laser
371 induced (Trojan horse), Beam- and Wakefield-induced ionisation injection). These results are
372 supported by the results of transverse Raman spectroscopy on prototype cells [16].

373 Whilst PWFA accelerated beams have, in general, small emittances, durations and transverse
374 dimensions, this comes at the cost of a highly divergent beam upon exit from the plasma cell.
375 Therefore, in order to stage multiple plasma acceleration cells, methods for overcoming the
376 challenges of capture and transport of accelerated beams [22], whilst preserving their emittance,
377 must be developed. One approach is a tailored plasma-density profile in the plasma-to-vacuum
378 transition region subsequent to acceleration [40], necessitating testing and development of
379 specialised plasma targets allowing the requisite level of control. Simulations using OpenFOAM have
380 aided in the design of cells modified for this purpose, currently under construction, validating their
381 capacity to form an adiabatic release region post acceleration. Simulations of the release region
382 (*Figure 9*) demonstrate the merit of this approach, where increased plasma-density transition lengths
383 yield marked reductions in emittance growth during beam extraction [40].

384 *Figure 9 – Simulated plasma-density profile (top), divergence (middle), and r.m.s. phase-space*
385 *emittance (bottom) for a tailored density profile, a typical capillary gas-target outlet, and a density*
386 *cut profile. The vertical dot-dashed line shows the location where plasma density has fallen to a*
387 *negligible value. A substantial reduction in divergence and emittance is evident when a tailored*
388 *plasma density profile (solid line) is used.*

389 **4.3. Driving beam-shape optimisation**

390 The limit for possible energy gain of a single electron accelerated by PWFA is given by the
391 transformer ratio, which for a finite-length bunch with symmetric longitudinal charge distribution in
392 the linear wakefield regime, can be proven to never exceed two [41,42]. Alternate approaches are
393 thus desired, such as the use of triangular-shaped beams in the linear regime [43] and in the
394 nonlinear regime [44]. FLASHForward aims to boost FLASH electrons to ~ 2 GeV (necessitating
395 transformer ratios ~ 2 , near the maximum for driving beams with Gaussian profiles), and by
396 optimisation of the driving-beam parameters, boost particle energies to > 4 GeV, demonstrating
397 transformer ratios substantially exceeding two. PIC simulations [37,45] predict that high-current
398 drivers with symmetric profiles can generate transformer ratios ~ 3 when operating in a strong
399 blowout regime and triangular-shaped beams can reach even ~ 5 . Tuning the current profile of the
400 driving beam is possible in the extraction section of the beamline by means of a variable R_{56} . To this
401 end, the question of which current profile should be selected to maximise the transformer ratio [46]
402 will be the subject of future FLASHForward studies.

403

404 **5. Current Status and Future Milestones**

405 The FLASHForward project is separated into two phases, with each phase being divided into
406 conceptual design phase, technical design phase, fabrication / procurement / installation phase, and
407 the experimental campaign. At the present time phase 1 conceptual design of all beamline sections is
408 completed, and technical design is well advanced, with installation of FLASHForward beamline
409 components foreseen to finish in Q4 2016.

410 Phase 1 of the FLASHForward project will include construction and utilisation of most of the
411 beamline (see *Figure 1* for the extent of Phase 1 design), as well as realisation of the first two science
412 goals outlined in Section 2. The installation period for the first phase began in Q2 2015, with
413 commissioning to take place in Q1 2017. The first-round PWFA studies will then commence in Q2
414 2017 and continue for around 24 months, until the facility goes offline for installation of the Phase 2
415 beamline extension.

416 Significant scientific milestones for phase 1 include:

- 417 • Demonstration of density-down-ramp injection for PWFA – Q3/2017
- 418 • Demonstration of ionisation-based injection – Q4/2017
- 419 • Realisation of transformer ratios >2 , exceeding the theoretical limit for Gaussian beams,
420 using triangularly shaped driver beams – Q1/2018
- 421 • External witness-bunch injection and acceleration – Q3/2018
- 422 • Demonstration of laser-assisted ionisation injection for PWFA – Q1/2019

423 Simulation, fabrication, and testing of phase-2 apparatus will take place concurrently with the first-
424 phase experimental schedule, leading up to the beamline being taken temporarily offline in 2019 for
425 installation of the phase-2 extension (*Figure 1*). This includes commissioning of the extended
426 beamline before PWFA & FEL experimental studies resume. These phase-2 studies will address the
427 third scientific goal outlined in Section 2, FEL gain at few-nm wavelengths, and are scheduled to
428 conclude in 2021.

429 6. Conclusions

430 The FLASHForward experiment promises to allow study of a range of techniques for, and aspects of,
431 plasma-based acceleration. The FLASHForward beamline extends the existing FLASH accelerator
432 facility, which has unique characteristics to provide driving beams ideal for PWFA investigations.
433 Following extraction into the FLASH-2 tunnel, the FLASHForward beamline manipulates incoming
434 FLASH beams, allowing optimisation of driving-bunch parameters and access to a number of novel
435 witness-bunch injection methods. A central interaction chamber houses a highly adjustable plasma
436 acceleration cell, capable of providing tailored plasma-density profiles, as required for proposed
437 techniques for combatting the tendency of the PWFA process to produce strongly diverging
438 emergent beams. The subsequent beam capture and diagnostics section will aid in analysis of these
439 methods, and for the second round of FLASHForward experimental study, will be extended to
440 demonstrate FEL gain at few-nm wavelengths. With the conceptual design complete, and technical
441 design well under way, FLASHForward is on-schedule for installation and to become fully operational
442 in the first half of 2017.

7. Acknowledgements

We thank the management and technical support groups of the DESY Accelerator Division for their support; in particular we acknowledge the assistance of B. Faatz. We thank the OSIRIS consortium (IST/UCLA) for access to the OSIRIS code. Furthermore, we acknowledge the grant of computing time by the Jülich Supercomputing Centre on JUQUEEN under Project No. HHH23 and the use of the High-Performance Cluster (IT-HPC) at DESY. This work was funded by the Alexander von Humboldt Foundation through the award of a Humboldt Professorship to B. Foster, the Helmholtz Virtual Institute VH-VI-503 and the ARD program.

References

- [1] Accelerator Test Facility, <http://www.bnl.gov/atf>, Brookhaven National Laboratory, 2015, Accessed: 02/28/2015.
- [2] Advanced Wakefield Experiment, <http://awake.web.cern.ch/awake>, CERN, 2013, Accessed: 02/28/2015.
- [3] Laboratory for Laser- and beam-driven plasma acceleration, <http://laola.desy.de>, Deutsches Elektronen-Synchrotron, 2015, Accessed: 02/28/2015.
- [4] Berkeley Lab Laser Accelerator, <http://loasis.lbl.gov>, University of California, 2014, Accessed: 02/28/2015.
- [5] FACET and Test Beam Facilities, <http://facet.slac.stanford.edu>, SLAC National Accelerator Laboratory, 2015.
- [6] V. I. Veksler, Coherent Principle Of Acceleration Of Charged Particles. Proceedings of the CERN Symposium on High-Energy Accelerators and Pion Physics, (1956) 80–83, URL <http://inspirehep.net/record/921325?ln=en>.
- [7] P. Chen et al., Acceleration of electrons by the interaction of a bunched electron beam with a plasma. Phys. Rev. Lett. 54 (1985) 693–696.
- [8] T. Tajima and J. Dawson, Laser electron accelerator, Phys. Rev. Lett. 43 (1979) 267.
- [9] A. Modena et al., Electron acceleration from the breaking of relativistic plasma waves. Nature, 377 (1995) 606–608.
- [10] E. Esarey et al., Nonlinear Pump Depletion and Electron Dephasing in Laser Wakefield Accelerators. Advanced Accelerator Concepts: Eleventh Advanced Accelerator Concepts Workshop held 21-26 June, 2004 in Stony Brook, New York. Ed. Vitaly Yakimenko. AIP Conference Proceedings, Melville, NY: American Institute of Physics, 737 (2004) 578-584.
- [11] A. Seryi et al., A concept of plasma wake field acceleration linear collider (PWFA-LC), No. SLAC-PUB-13766 (2009), <http://www-public.slac.stanford.edu/sciDoc/docMeta.aspx?slacPubNumber=SLAC-PUB-13766> .
- [12] I. Blumenfeld et al., Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator, Nature, 445 (2007) 741-744. URL <http://dx.doi.org/10.1038/nature05538> .

- [13] P. Walker et al., Investigation of GeV-scale electron acceleration in a gas-filled capillary discharge waveguide, *New Journal of Physics* 15 (2013) 045024.
- [14] E. Adli et al., Design of a TeV Beam Driven Plasma Wakefield Linear Collider, *Proc. IPAC13*, (2013), Ed. Zhimin Dai, C. Petit-Jean-Genaz, V.R.W. Schaa, Chuang Zhang, <http://accelconf.web.cern.ch/AccelConf/IPAC2013/papers/tupme020.pdf>.
- [15] K. Tiedtke et al., The soft x-ray free-electron laser FLASH at DESY: beamlines, diagnostics and end-stations, *New Journal of Physics* 11 (2009) 023029.
- [16] L. Schaper et al., Longitudinal gas-density profilometry for plasma-wakefield acceleration targets, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 740 (2014) 208-211.
- [17] C.M. Entrena Utrilla, Generation and transport of double-bunch electron beams in the FLASH beamline MSc Thesis, University of Hamburg, Internal Report DESY-2014-03169 (2014) (unpublished) <https://bib-pubdb1.desy.de/record/171126/files/DESY-2014-03169.pdf> .
- [18] A. Martinez de la Ossa et al., High-quality electron beams from field-induced ionization injection in the strong blow-out regime of beam-driven plasma accelerators, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 740 (2014) 231-235.
- [19] B. Hidding et al., Ultracold Electron Bunch Generation via Plasma Photocathode Emission and Acceleration in a Beam-Driven Plasma Blowout . *Phys. Rev. Lett.* 108 (2012) 035001.
- [20] A. Knetsch et al., Downramp-assisted underdense photocathode electron bunch generation in plasma wakefield accelerators, arXiv preprint arXiv:1412.4844, (2014).
- [21] A. Martinez de la Ossa et al., High-Quality Electron Beams from Beam-Driven Plasma Accelerators by Wakefield-Induced Ionization Injection, *Phys. Rev. Lett.* 111 (2013) 245003.
- [22] T. Mehrling et al., Transverse emittance growth in staged laser-wakefield acceleration, *Physical Review Special Topics - Accelerators and Beams* 15 (2012) 111303.
- [23] S. Schulz et al., Femtosecond all-optical synchronization of an X-ray free-electron laser, *Nat Commun*, 6 (2015), <http://dx.doi.org/10.1038/ncomms6938> .
- [24] Y. Xi et al., Hybrid modeling of relativistic underdense plasma photocathode injectors, *Physical Review Special Topics - Accelerators and Beams* 16 (2013) 031303.
- [25] P. Piot et al., Generation and Characterization of Electron Bunches with Ramped Current Profiles in a Dual-Frequency Superconducting Linear Accelerator, *Phys. Rev. Lett.* 108 (2012) 034801.
- [26] Helmholtz VI for PWFA, <https://vi-pwfa.desy.de/>, Deutsches Elektronen-Synchrotron, (2015).
- [27] J. Dale, K. Ludwig, L. Schaper, and J. Osterhoff, "Vorrichtung mit beweglicher Aufnahme für Vakuumkammern", Deutsche Patentanmeldung Nr. 10 2014 116 476.8, filing date November 11, 2014.

- [28] M. Nisoli et al., Generation of high energy 10 fs pulses by a new pulse compression technique. *Applied Physics Letters* 68 (1996) 2793-2795.
- [29] J. Kim et al., Long-term femtosecond timing link stabilization using a single-crystal balanced cross correlator, *Opt. Lett.* 32 (2007) 1044-1046.
- [30] C.G.R. Geddes et al., Plasma-Density-Gradient Injection of Low Absolute-Momentum-Spread Electron Bunches, *Phys. Rev. Lett.* 100 (2008) 215004.
- [31] R. A. Fonseca et al. OSIRIS: A three-dimensional, fully relativistic particle in cell code for modelling plasma based accelerators. In P. Sloot, A. Hoekstra, C. Tan, and J. Dongarra, editors, *Computational Science - ICCS 2002*, volume 2331 of *Lecture Notes in Computer Science*, pages 342–351. Springer Berlin Heidelberg, 2002. ISBN 978-3-540-43594-5.
- [32] R.A. Fonseca et al. One-to-one direct modelling of experiments and astrophysical scenarios: pushing the envelope on kinetic plasma simulations. *Plasma Physics and Controlled Fusion* 50 (2008) 124034.
- [33] R.A. Fonseca et al., Exploiting multi-scale parallelism for large scale numerical modelling of laser wakefield accelerators. *Plasma Physics and Controlled Fusion* 55 (2013) 124011.
- [34] S. Bulanov et al., Particle injection into the wave acceleration phase due to nonlinear wake wave breaking, *Phys. Rev. E* 58 (1998) 5257–5260.
- [35] H. Suk et al., Plasma electron trapping and acceleration in a plasma wake field using a density transition. *Phys. Rev. Lett.* 86 (2001) 1011–1014.
- [36] J. Grebenyuk et al., Beam-driven plasma-based acceleration of electrons with density down-ramp injection at FLASHForward, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 740 (2014) 246-249.
- [37] A. Martinez de la Ossa et al., Wakefield-Induced ionization injection in beam-driven plasma accelerators, *Phys. Plasmas* 22 (2015) 093107.
- [38] C. Nieter and J. R. Cary, VORPAL: a versatile plasma simulation code. *J. Comput. Phys.* 196 (2004) 448.
- [39] OpenFoam Foundation, <http://www.openfoam.com/>.
- [40] T. Mehrling, Theoretical and numerical studies on the transport of transverse beam quality in plasma-based accelerators. PhD Thesis, University of Hamburg, Internal Report DESY-2014-04069 (2014) (unpublished), <http://bib-pubdb1.desy.de/record/191881/files/PUBDB-2014-04069.pdf> .
- [41] K. L. F. Bane et al., Wake fields and wake field acceleration. *AIP Conference Proceedings* 127 (1985) 875–928. URL <http://dx.doi.org/10.1063/1.35182>.
- [42] P. Chen et al., Energy transfer in the plasma wake-field accelerator. *Phys. Rev. Lett.* 56 (1986) 1252–1255. URL <http://link.aps.org/doi/10.1103/PhysRevLett.56.1252>.

[43] T. Katsouleas, Physical mechanisms in the plasma wake-field accelerator. Phys. Rev. A 33 (1986) 2056–2064. URL <http://link.aps.org/doi/10.1103/PhysRevA.33.2056>.

[44] K.V. Lotov, Efficient operating mode of the plasma wakefield accelerator. Physics of Plasmas 12 (2005) 053105. URL <http://dx.doi.org/10.1063/1.1889444>.

[45] R.J. England et al., A high transformer ratio plasma wakefield accelerator scheme for FACET. Proc. PAC2011 (2011) , Ed. T. Roser and V. Litvinenko, URL <http://accelconf.web.cern.ch/AccelConf/PAC2011/papers/mop088.pdf> .

[46] I. Blumenfeld et al., Scaling of the longitudinal electric field and transformer ratio in a nonlinear plasma wakefield accelerator, Physical Review Special Topics - Accelerators and Beams 13 (2010) 111301.