ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPGW019

FLASHForward FINDINGS FOR THE EuPRAXIA DESIGN STUDY AND THE NEXT-GENERATION OF COMPACT ACCELERATOR FACILITIES*

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Abstract

FLASHForward, the exploratory FLASH beamline for Future-ORiented Wakefield Accelerator Research and Development, is a European pilot test bed facility for accelerating electron beams to GeV-levels in a few centimeters of ionized gas. The main focus is on the advancement of plasma-based particle acceleration technology through investigation of injection schemes, novel concepts and diagnostics, as well as benchmarking theoretical studies and simulations. Since the plasma wakefield will be driven by the optimal high-current-density electron beams extracted from the FLASH L-band Superconducting RF accelerator, FLASHForward is in a unique position for studying and providing insight for the design study of next-generation light source and high energy physics facilities such as EuPRAXIA. Summary of these findings and their broader impact is discussed here.

ALTERNATIVE E-BEAM DRIVEN PLASMA STRUCTURE FOR EuPRAXIA

The goal of the EuPRAXIA [1–3] project is to produce a conceptual design report for the worldwide first high energy plasma-based accelerator that can provide industrial beam quality and user areas. Over the past two decades, beam-driven plasma wakefield acceleration (PWFA) [4, 5], has emerged as a promising candidate for the next-generation technology of compact, high-gradient particle accelerators. While laser-driven plasma accelerator schemes are currently limited in the achievable average power and repetition rate by the available high-peak-intensity laser technology to less than 1 kW and 10 Hz, respectively, PWFA benefits from the development of average power on the order of MW and MHz repetition rate electron accelerator technology. Moreover, the achieved acceleration gradients of order 10 GV/m [6] outperform those from conventional metallic-structure accelerators by several orders of magnitude and are comparable to gradients realized in laser-driven plasma wakefield acceleration (LWFA) [7].

These considerations led to the establishment of the EuPRAXIA Work Package 9 (WP9) to investigate this alternative drive technology for EuPRAXIA plasma modules. In a primary design report, the core concepts, the basic structure, and the main sub-systems for a 1 GeV accelerator were introduced. The full start-to-end simulations of the beam transport to the free electron laser and 3D simulations of self amplified spontaneous emission (SASE) was also provided.

The next challenging task is to scale these results to reach the envisioned 5 GeV level while maintaining the overall quality (in terms of energy spread and emittance) of the accelerated electron bunches. While PWFAs are especially promising for free electron lasers (FELs) and linear colliders with regards to energy transfer efficiency and repetition rate, they still require high energy and high brightness drive bunches produced by an RF accelerator section in place of the high power laser driver of the LWFA case. Since the aim is to make a compact accelerator, it is essential to be able to accelerate the witness bunch well beyond the energy of the drive bunch. A joint R&D effort at FLASHForward [8, 9] at DESY and SPARC-LAB [10] at INFN has been dedicated to determining the most optimum drive beam and acceleration scheme. Table 1 shows the values for the 1 GeV case from the full start to end simulation studies [11], the 5 GeV case is still under study. The most recent result for the best obtainable witness beam from these studies is summarized in Table 2. Also, current research at FLASHForward on several elements would be of high value to the EuPRAXIA beam driven final design report. The subsequent sections provide a summary of our findings.

SHAPED DRIVE BUNCHES

The ratio of the accelerating field experienced by the witness bunch to the decelerating field of the driver is known as transformer ratio (TR). For symmetric beams the maximum TR is two. The first column in Table 1, summarizes the drive beam requirements for a transformer ratio of 2 and drive and witness bunches of 0.5 GeV for the 1 GeV EuPRAXIA case. The current state of the art research in plasma acceleration provides two pathways for accelerating the witness bunch to >5 GeV energies with a drive bunch of ~1 GeV. (1) One option is the use of asymmetric beam and achieving high transformer ratio [12]. It is possible to have TR on the order of 5–10 [13] with careful beam shaping, multiple/comb drive bunches [14, 15], and highly nonlinear wakefields [16]. (2) It is also possible to utilize many plasma wakefield stages where each stage has a new driver. Therefore, for the envisioned 5 GeV case for EuPRAXIA with a 0.5-1 GeV driver bunch from an RF or SRF accelerator, initially, both options were considered. However, a parameter check based on the EuPRAXIA single

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stage particle in cell (PIC) simulations against the fundamental requirements for staging suggests that for the 5 GeV case, staging would not be a suitable option [17]. Therefore, the focus of optimization studies at FLASHForward and SPARC-LAB has been concentrated on utilizing the high transformer ratio concept. In the final section, a discussion on staging and its potential as a future upgrade for the beam-driven EuPRAXIA case is presented. Figure 1 and Figure 2 show examples of the high transformer ratio achieved with a shaped triangular bunch (FLASHForward) and with a multiple comb drive bunch structure (SPARC-LAB) respectively. For the shaped triangle bunch, the maximum experimentally measured transformer ratio is six [13] and the maximum expected transformer in the comb drive bunch case is close to 8 [10]. The simulation studies for the shaped triangle bunch were performed in HiPACE [18] and the simulation studies for comb drive bunch structure were performed in Architect [19, 20]. The two simulation codes were bench-marked as part of these studies as well. Drive beam requirements for the 5 GeV EuPRACIA case, based on the most recent simulation and optimizations, is also listed in Table 1.

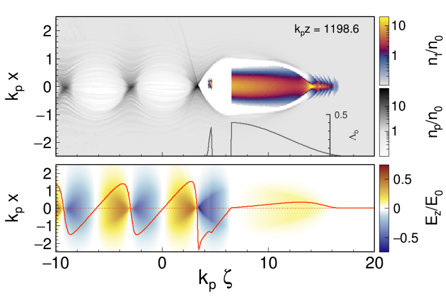

Figure 1: Snapshot shown for single drive beam, TR ~ 6 (HiPACE)

Table 1: EuPRAXIA Drive Bunch Requirements (Pre-Acceleration)

	1 GeV case	5 GeV case*
Energy GeV	0.4-0.6	0.8-1.0
Charge pC	200-300	800-1100
Peak Current kA	2	3-4
Lenght (rms) µm (fs)	4 (12)	45 (120)
$\epsilon_{norm.}$ **(rms)** mm−mrad	x/y ~2.5/5	~2.5
Energy Spread (rms) %	~ 0.2	~ 0.2

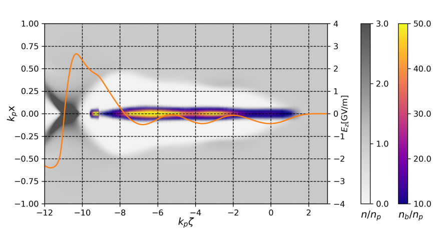

Figure 2: E_z Plotted for comb drive beam, TR ~ 8 (Architect)

Table 2: EuPRAXIA Witness Bunch Parameters after Acceleration by Drive Bunches in Table 1

	1 GeV case	5 GeV case*
Energy GeV	0.4-0.6	0.8-1.0
Charge pC	20-30	20-30
Peak Current kA	2	1-3
Lenght (rms) µm (fs)	4 (12)	3-10 (10-30)
$\epsilon_{norm.}$ **(rms)** mm−mrad	x/y ~0.8/1	~1
Energy Spread (rms) %	~ 1.1	> 1.1

MANIPULATING CORRELATED ENERGY SPREAD

The practical application of beams produced by plasma wakefield accelerators in future FEL and HEP facilities is dependent on achieving beams with finite and negligible correlated energy spread. Additionally, it has been demonstrated that control over this value allows for a more stable acceleration process in plasma. Therefore, control of the beam correlated energy spread plays a substantial role. A tunable plasma dechirper with a dechirping strength of 1.8 GeV/mm/m was developed at FLASHForward and used to remove the correlated energy spread of a 681 MeV electron bunch through the interaction of the bunch with wakefields excited in plasma. The projected energy spread was reduced from an FWHM of 1.31% to 0.33 % without reducing the stability of the incoming beam. [21]. This method is highly tunable and as shown in [22], it can be used to imprint or remove any correlation onto the beam. The complexity of matching and maintaining the achieved low finite correlated energy spread will be briefly reviewed in the final section.

FOCUSING WITH PLASMA LENSES

Unless the beam can be promptly captured using short-focal-length magnetic lenses, the beta function in the capturing lens will be many orders of magnitude larger than the in-plasma matched beta function. Increasing the strength of the focusing lens is one solution. While the use of permanent quadrupoles, with 10–100 focusing strength compared to conventional electromagnetic quadrupoles, can help it will reduce tunability. Plasma lenses which provide tunable gradients in excess of kT/m and azimuthal magnetic fields are the best candidate. Plasma lenses come in two forms: (1) passive plasma lenses [23], which use the electrostatic fields of an ion column, and (2) active plasma lenses [24–26], which use the magnetic field from an externally driven longitudinal current in a plasma.

The passive plasma lens, which is conceptually identical to a plasma density ramp, can provide very strong focusing (of order MT/m) and therefore ultra-short focal lengths, but also requires a driver. If the bunch drives its own passive plasma lens, the focusing strength will vary longitudinally across the bunch (i.e., no focusing in the front)—which will lead to emittance growth. Alternatively, a separate driver can be used, but this introduces complications of in/out coupling.

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A promising path that would also remain open for future EuPRAXIA upgrades is active plasma lensing. Active plasma lensing provides strong focusing (kT/m), although several orders of magnitude weaker than its passive counterpart. The advantage, however, is field uniformity, both longitudinally, transversely and temporally which makes use of active plasma lensing significantly simpler. Active plasma lenses are also subject to aberrations, mainly in three different categories: (1) radial temperature gradients [27], (2) passive plasma lensing effects, and (3) high current z-pinching [28, 29]. Research in this field is one of the critical research topics at FLASHForward. After demonstrating that non-uniformities lead to emittance increase of the transported beams [30] a method for suppressing radial temperature gradients was recently demonstrated [31], however, the other two categories are more fundamental and currently unavoidable. In particular, passive plasma lensing occurs for any beam of relevance to an FEL or a linear collider and it therefore appears that the use of active plasma lenses will be severely limited in this regard [32]. Nevertheless, with optimisation of lens [33] and beam parameters, it could be possible to find a working parameter compromise.

PLASMA DIAGNOSTICS

Another approach is to increase the matched beta function at the plasma interface using plasma density ramps. The plasma density can be varied from the inside to the plasma exit/entry—a so-called plasma density ramp [34–36]—such that the accelerator has a high density, but the focusing at the vacuum interface is weaker, which can increase the matched beta function dramatically. In this case, precise knowledge of the plasma density is crucial. Longitudinal electron density profiles as well as their temporal evolution have been examined in targets of various lengths and diameters in the Ionisation Test Chamber (ITC) located in the FLASHForward diagnostic lab. For plasma generation within these targets, the injected gas can be ionized by a flat-top current pulse of about 400 ns duration with variable peak current (0.2 – 1.6kA) or laser-ionization using an 800 nm, 25 TW laser system employing the same 18 meter focussing geometry as FLASHForward. Presently, it is possible to measure the plasma density in the range $10^{16} < n_e < 10^{19} cm^{-3}$ using different diagnostics: a longitudinal two-colour laser interferometer, transverse emission spectroscopy analysing the Stark broadened line profiles, and a transverse interferometer for high densities. The two-colour laser interferometer has a 50 ps time resolution, given by the length of the targets investigated, and is capable of measuring the longitudinally averaged plasma density assuming a square profile at the length of the investigated target structure. The transversely aligned spectrometer has a time resolution of $\sim 5\, ns$ and is capable of spatially resolving structures in the ten micron regime. The imaging system used allows for easy transition between longitudinal and radial plasma profile analysis. The transverse laser interferometer, which is limited to channel geometries with optical quality windows, has even higher spatial resolution down to few micrometers while having a high temporal resolution in the tens of femtoseconds.

STAGING AND FUTURE UPGRADES

Harnessing the nonlinear and high gradient fields of plasma wakefield acceleration which leads to accelerating particles to several 100s of MeV in a few centimeters is not without challenges. As discussed earlier one option for achieving the envisioned 5 GeV case for EuPRAXIA was using multiple stages of plasma wakefield acceleration with fresh drive bunches. However, the inherently strong focusing in a nonlinear plasma wakefield and the small beta-function of the beam at the exit of one plasma wakefield stage which leads to the problem of chromaticity in staging present additional set of challenges. In essence, staging is conceptually simple, and it can be broken down to two fundamental principles: (1) out-coupling of the depleted driver and in-coupling of a new one in the next stage, and (2) capture and refocusing of the accelerated witness beam [37]. Due to the energy spread of the accelerated bunch, when trying to refocus the witness bunch with an expanded beta function into the next PWFA stage with small beta function, different energy slices observe different focal lengths— the problem of *chromaticity*. The overall effect of this chromaticity is that the bunch has an apparent projected emittance growth at the waist of the focus (i.e., at the entry of the next stage).

It is possible to mitigate these effects using plasma lensing and/or plasma down-ramps. However, for parameters listed in Table 2, such ramps will have to be several centimeters long to even lessen the emittance growth. Additionally, separation of the driver and the accelerated bunch is also critical and must happen before any lensing occurs [37]—otherwise, the lower energy driver will blow up during focusing of the much higher energy accelerated bunch. Therefore, the focal length of the optic is restricted by the lower limit for the distance between the plasma exit/entry and the staging optics. Given that no kicker is fast enough to separate bunches on the sub-picosecond scale, for beam-driven PWFAs, the only foreseen option for separating the two bunches is the use of dispersive dipoles. Such a dipole would for EuPRAXIA parameters be of order 300–1000 mm long in order to separate GeV-level bunches sufficiently and hence little is gained by using focusing optics stronger than approximately 10–100 T/m. Hence, staging is a less suitable option for a compact 5 GeV EuPRAXIA accelerator whereas a good contender for future upgrades.

It is important to note that improving the beam parameters from PWFA would have an important role in the future practical use of the staging concept. To this aim, as summarized in [8], PWFA experiments, simulations, and theoretical studies, as well as conventional methods, other plasma-based mitigation techniques, and diagnostics are ongoing at FLASHForward.

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ACKNOWLEDGEMENTS

Authors would like to thank the following agencies and programs for their funding and support: European Union's Horizon 2020 research and innovation programme grant agreement No. 653782, Helmholtz Virtual Institute VH-VI-503, Helmholtz ZT-0009, and Helmholtz ARD, and the Gauss Centre for Supercomputing e.V. (www.gauss-centre.eu) for funding this project by providing computing time through the John von Neumann Institute for Computing (NIC) on the GCS Supercomputer JUWELS at Jülich Supercomputing Centre (JSC).

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