LONGITUDINAL PHASE SPACE RECONSTRUCTION AT FLASHForward USING A NOVEL X-BAND TRANSVERSE DEFLECTION CAVITY, PolariX-TDS

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Abstract

The FLASHForward project at DESY [1] is an innovative beam-driven plasma-wakefield acceleration (PWFA) experiment, aiming to accelerate electron beams to GeV energies over a few centimetres of ionised gas. These accelerated beams are assessed for their capability to drive a free-electron laser. The ultra short, low emittance, and low energy spread properties of bunches produced from certain PWFA injection schemes naturally lend themselves to this task. However, these bunch lengths, typically in the few femtosecond range, are difficult to temporally resolve with traditional diagnostic methods. In order to longitudinally diagnose these bunches it is necessary to utilise the properties of a transverse RF deflecting cavity operating in a high-frequency regime. It is proposed that this type of X-band transverse deflection system, styled the PolariX-TDS [2,3] due to its novel variable polarisation feature, will be introduced to the FLASHForward beamline in order to perform these single-shot longitudinal phase space measurements. This paper will concern itself with the efficacy of longitudinally reconstructing PWFA-bunches expected at FLASHForward with this TDS, with a focus on the variable bunch properties expected from early commissioning of the experiment.

INTRODUCTION

The FLASHForward facility [1] at DESY aims to accelerate electron beams to GeV energies over a few centimetres of ionised gas through the principle of beam-driven plasma wakefield acceleration (PWFA). The FLASHForward beamline, as outlined in Fig. 1, utilises sections of the FLASH Linac [4] to extract compressed electron bunches for injection into plasma. Longitudinal diagnosis of both the drive beam entering and the witness beam exiting the plasma are necessary for the understanding of PWFA physics processes. The witness bunches, accelerated by the high accelerating gradients and with bunch lengths typically <50 fs RMS, are expected to exit the plasma with known transverse and longitudinal bunch properties expounded by theory.

However, these accelerated FLASHForward witness bunches, generated either internally from the plasma background or externally from the bisecting of drive beams, may in reality fluctuate around or even deviate from these theoretical values. Femtosecond-level longitudinal and transverse diagnostics, provided by a transverse deflection system (TDS) operating in the X-band regime, would reveal key information about the potential fluctuations in these witness beam parameters, yielding invaluable insight into the processes and results of acceleration. This paper will concern itself with the implementation of such a TDS system at FLASHForward focussing on its ability to reconstruct longitudinal profiles of witness bunches with fluctuations in initial parameters upon exit of the plasma cell.

BEAMLINE MATCHING AND FLUCTUATIONS STUDIES

It is common practice to employ a TDS system to determine both longitudinal and transverse bunch properties. In order to successfully measure these parameters, a beamline design is required to meet certain matching constraints. The matching constraints for FLASHForward [5] led to a beamline design, sketched out in Fig. 1, optimised to give the best possible time and energy resolution for the witness bunch parameter range detailed in Table 1. Temporal resolutions for this beamline design, with a frequency of 11.988 MHz and streaking voltage of 27 MV (the likely maximum from the system planned for FLASHForward), are expected to be as low as ∼ 1 fs for certain bunch parameter working points [5].

The matched plasma Twiss functions, determined by the beam and plasma properties, are defined as $\hat{\alpha} = 0$ and $\hat{\beta} = \sqrt{2\gamma}/k_p$ [6], where γ is the relativistic gamma of the beam and k_p is the plasma wave number. At FLASHForward a driver and witness bunch pair will be generated by bisecting a FLASH-type bunch, which will then propagate

Table 1: A range of pertinent witness bunch parameters expected at FLASHForward, along with a set of theoretical parameters for a 1.5 GeV witness bunch exiting a plasma of density 5×10^{16} cm^{-3}, and values simulated by particle-in-cell code for the equivalent energy and plasma density.

Parameter	Range	Theory	Simulation
E [GeV]	0.7–2.5	1.5	1.47
$\varepsilon_{n,(x,y)}$ [μm]	0.5–5	2	2.1
$\hat{\beta}_{x,y}$ [mm]	1–10	1.8	2.8
$\hat{\alpha}_{x,y}$ [mm]	0	0	0.5
σ_t [fs]	1–100	20	17.4
σ_γ/γ (chirp) [%]	0–10	0	0.78
Q [pC]	1–500	60	57

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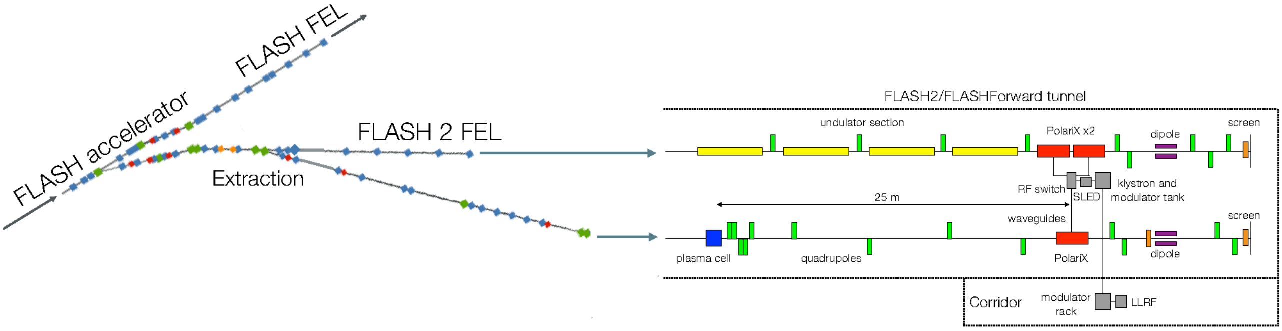

Figure 1: A schematic of the FLASH FEL user facility, demonstrating extraction into FLASH2 [7] (top beamline), with subsequent extraction into FLASHForward (bottom beamline). A sketch of the proposed experimental hall layout is also shown, with the placement of the shared RF source and respective deflecting cavities illustrated.

over a plasma acceleration length of a certain density. In this particular example a 1 GeV witness bunch would experience an accelerating gradient of ~2.5 GeV/m over a 20 cm plasma length of 5×10^{16} cm^{-3} density resulting in a final bunch energy of 1.5 GeV. A bunch with this final energy should, therefore, exit with $\hat{\beta}_{x,y}$ = 1.8 mm and $\hat{\alpha}_{x,y} = 0$. In order to mitigate the emittance blow-up from a hard-edged plasma transition a 50 mm exponentially decreasing plasma density taper is assumed. According to particle-in-cell (PIC) modelling of this type of transition, $\hat{\beta}_{x,y}$ is expected to increase by approx. an order of magnitude over this taper [8]. It is therefore assumed that the Twiss functions at the end of this transition will be approximately $\beta_{x,y}$ = 18 mm and $\alpha_{x,y} = 0$. The beamline optics may then be matched to these starting transverse parameters; the same procedure to be employed experimentally when the beamline is installed and commissioned.

The subsequent beamline matching and studies, performed in *elegant* [9], were carried out under the assumption that the previously described witness bunch exits plasma with transverse properties equal to those of theory. The validity of this theoretical model, however, has yet to be demonstrated experimentally. It is therefore prudent to investigate the effect of variations in these starting parameters, in addition to variations in the correlated energy spread (or chirp), on the longitudinal resolving power of the TDS. The plots in Fig. 2 show the temporal resolution of the system as a function of input Twiss parameters and chirp for 3D Gaussian beams – in all cases the beamline optics, matched to the theoretical witness beam working point detailed in Table 1, are kept constant. As can be seen from the plots, the resolution of the TDS only varies significantly for large fluctuations away from the matched input parameters. For this particular matched solution the departure from an optimised temporal resolution is most severe with beams of high convergence and large chirp. In this area of input parameter space the resolution increases by a factor of >4, reducing the number of time slices within the RMS of this particular bunch to two.

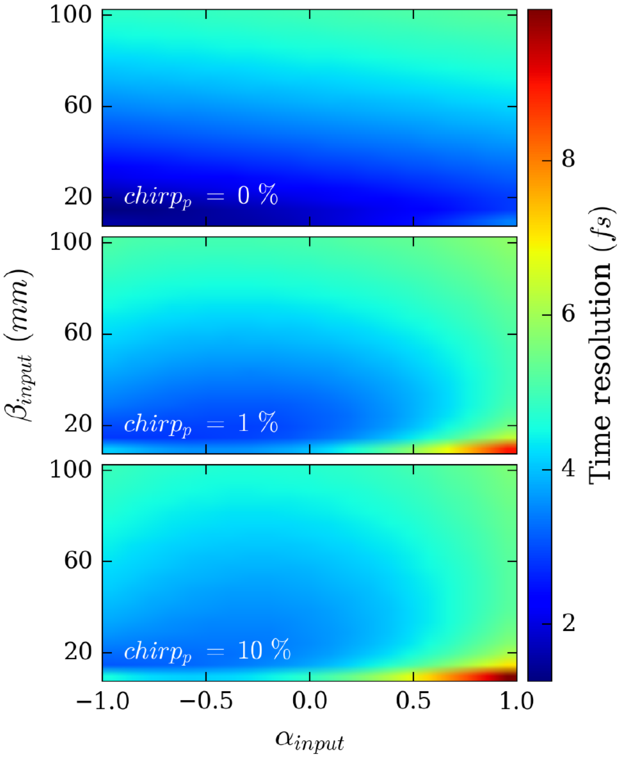

Figure 2: The variation in time resolution of the TDS as a function of input Twiss parameters, for three different cases of increasing chirp. In all three plots the beamline is matched to the theory input values found in Table 1, with the theory values then varied around this matched point.

LONGITUDINAL PHASE SPACE RECONSTRUCTION

In order to perform realistic particle tracking representative of experimentation it is preferable to generate beams in start-to-end models rather than to rely on idealised Gaussian bunches. The start-to-end framework in use at FLASHForward generates bunches in *ASTRA* [10], tracks them in *elegant*, computes beam-material interactions, e.g. double bunch generation, in *Geant4* [11], and simulates propagation through plasma in *HiPACE* [12]. After plasma the beam

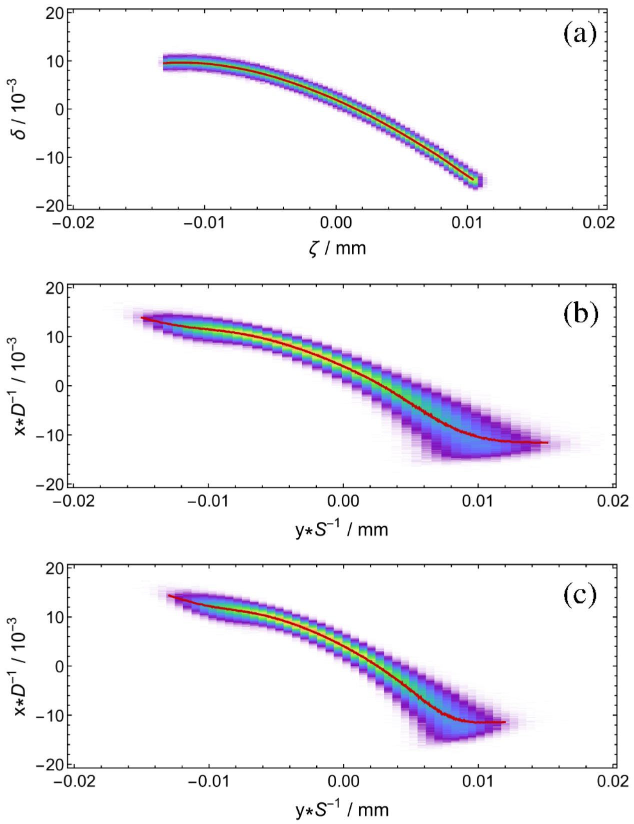

Figure 3: The longitudinal phase space as a) simulated at the exit of the plasma cell, b) reconstructed at the dispersive screen downstream of the TDS and final dipole with the lattice matched to theoretical starting values, and c) likewise but matched to input values taken from PIC simulation.

distribution is converted back to *elegant* format in order to simulate the post-plasma beamline and TDS.

The example described in the previous section, whereby a 1 GeV FLASH-type bunch is bisected and propagated over 20 cm of 5×10^{16} cm^{-3} plasma, is recreated using the aforementioned start-to-end framework. The longitudinal phase space of the resultant 1.47 GeV beam after plasma can be seen in Fig. 3a. The simulated bunch parameters for this beam at the end of the 20 cm accelerating length can be seen in Tab. 1. After the 5 cm exponential taper all bunch parameters remain constant to within a few percent except the Twiss functions, which evolve to $\beta_{x,y} = 23.9$ mm (approximately an order of magnitude larger than the matched values as outlined in the previous section) and $\alpha_{x,y} = 0.1$ rad. These simulated transverse parameters already differ from the corresponding theoretical values. A possible explanation for this could be betratron oscillations inside the plasma (around the theoretical $\hat{\beta}$) with the bunch exiting the plasma at some point before an oscillation period is complete.

It is then possible to track the distribution through the magnetic lattice matched for the theoretical starting values. The longitudinal phase space of this bunch, reconstructed at the final profile screen illustrated in Fig. 1, is shown in Fig. 3b. The $x-y$ profile on this screen is mapped to $\delta - z$ using the dispersion created by the dipole and the streak induced by the TDS (in this case operating at maximum voltage). The profile in Fig. 3b is then binned by the temporal and energy resolution of the system – $R_t = 2.45$ fs and $R_\delta = 1.24\times10^{-4}$. The reconstructed phase space differs from the longitudinal phase space due to the induced energy spread/chirp from the TDS, CSR from the deflecting dipole, and the obvious mismatch in starting Twiss parameters. However, despite these adverse effects the resolution in each plane is more than sufficient to discern a clear head-to-tail correlation for a bunch length of 17.4 fs RMS.

If the beamline were instead matched to the 'correct' i.e. simulated starting parameters then the mismatch would be removed. Experimentally speaking this would not be possible on the first matching attempt unless the Twiss values were very similar to the theoretical values. However, through an iterative process – i.e. using the streaking parameter during timing calibration as a feedback parameter to optimise the matching – the beamline matching may eventually converge. The plot in Fig. 3c shows the reconstruction of the phase space without this initial lattice mismatch. In this case the resolutions improve marginally – $R_t = 2.07$ fs and $R_\delta = 1.10 \times 10^{-4}$ – but the shape, projections, bunch length and chirp are more accurately reconstructed. For direct comparison the 3D Gaussian beam for this matched case results in almost identical resolutions – $R_t = 2.09$ fs and $R_\delta = 1.14 \times 10^{-4}$ – hinting at the possibility of speeding up this feedback loop by generating and propagating idealised bunches instead of CPU-heavy PIC simulations.

CONCLUSIONS

Simulations in *elegant* have demonstrated the TDS's robust ability to reconstruct the longitudinal phase space of FLASHForward witness bunches with resolutions as low as ~ 2 fs. Lattice mismatches arising from fluctuations in the initial witness bunch Twiss parameters exiting plasma have been explored with damaging results observed only at the extreme ends of input parameter space. In these extreme cases a scheme for iteratively rematching the beamline, through analysis of the streaking parameter as a function of optics, has been suggested, aided by comparable results between start-to-end distributions and idealised bunches. Further studies into multiple matched beamline solutions and varied PIC simulation parameter ranges will be pursued in order to investigate the rigour of this proposal.

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