A TRANSVERSE DEFLECTING STRUCTURE FOR THE PLASMA WAKEFIELD ACCELERATOR EXPERIMENT, FLASHForward

R. D'Arcy*, V. Libov, J. Osterhoff
DESY, Hamburg, Germany

Abstract

The FLASHForward project at DESY is an innovative plasma-wakefield acceleration experiment, aiming to accelerate electron beams to GeV energies over a few centimetres of ionised gas. These accelerated beams must be of sufficient quality to demonstrate free-electron laser gain; achievable only through rigorous analysis of both the drive- and accelerated-beam's longitudinal phase space. The pulse duration of these accelerated beams is typically in the few femtosecond range, and thus difficult to resolve with traditional diagnostic methods. In order to longitudinally resolve these very short bunch-lengths, it is necessary to utilise the properties of a transverse RF deflector, which maps longitudinal onto transverse co-ordinates. It is proposed that this type of device – commonly known as a Transverse Deflecting Structure (TDS) due to its 'streaking' in the transverse plane – will be introduced to the FLASHForward beam line in order to perform these single-shot longitudinal phase space measurements. The initial investigations into the realisation of this diagnostic tool are outlined.

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 Plasma Wakefield Acceleration (PWFA). The FLASHForward beam line utilises sections of the FLASH Linac [2] to extract compressed electron bunches for injection into plasma. Longitudinal diagnosis of both the drive beam entering – as well as the witness beam exiting – the plasma are necessary to the understanding of PWFA physics processes. The resulting accelerated witness bunches, with bunch lengths limited by the plasma wavelength, exit the plasma with a priori unknown bunch parameters. Expected bunch parameter ranges for both driver and witness bunches on FLASHForward can be seen in Table 1, demonstrating the diverse nature of these beams. It is therefore essential to diagnose these beams in full 6D phase space.

The longitudinal and transverse diagnostics provided by a Transverse Deflecting Structure (TDS) system would reveal key information about these drive beams, allowing for the maximising of energy gain in the plasma through bunch shaping. The capability to diagnose witness beams would also yield invaluable insight into the results of acceleration, providing a tool to differentiate between the nuances of distinct injection schemes (thus confirming the validity of particle-in-cell codes), as well as an additional resource in optimising the system for FEL gain. No prior PWFA facility has benefitted from the functionality of an X-band TDS to diagnose both drive and witness bunches. This paper will concern itself with the design, implementation, and simulations of such a system.

* richard.darcy@desy.de

PROPOSED TDS SYSTEM

Due to the proximity of the FLASHForward and FLASH2 beam lines, it is proposed that an X-band RF system is shared in order to mitigate costs. The proposed experimental plan can be seen in Fig. 1. In this setup, a low-level RF source would supply power to a klystron and modulator unit. These components would sit outside the experimental hall in the adjacent corridor. A high-power acceptance mechanical X-band RF switch would then direct 100% of the RF power to either the FLASHForward or FLASH2 waveguides and X-band TCAV sections. Once this system has been commissioned, a pulse compression unit will be installed to increase the peak power supplied to the cavities.

The voltage kick experienced by a beam travelling through a deflecting cavity is defined by

$$V[MV] = R[MV/m\sqrt{MW}]\, l[m]\, \sqrt{P[MW]} \quad , \qquad (1)$$

where R and l are the shunt impedance and length of the cavity, respectively, and P is the power supplied to the cavity. Although designs for the cavity and RF source have yet to be finalised, initial figures of $R \sim 6\ MV/m\sqrt{MW}$, $l \sim 1.0\ m$, and $P \sim 25\ MW$ are expected. For this reason, a voltage kick of 30 MV will be assumed in all further calculations unless otherwise stated.

BEAMLINE DESIGN

It is common practice to employ a TDS system for both longitudinal phase space and transverse slice emittance measurements. In order to successfully measure these param-

Table 1: Driver and Witness Bunch Parameters Expected at FLASHForward

Parameter	Driver	Witness
E [GeV]	0.5–1.2	1.2–2.5
$\Delta E/E$ (uncorrellated) [%]	<0.1	1
$\varepsilon_{n,(x,y)}$ [μm]	2–5	0.1–1
$\beta_{x,y}$ (in plasma) [mm]	20	1
σ_t [fs]	50–500	1–100
Q [pC]	20–1000	1–500

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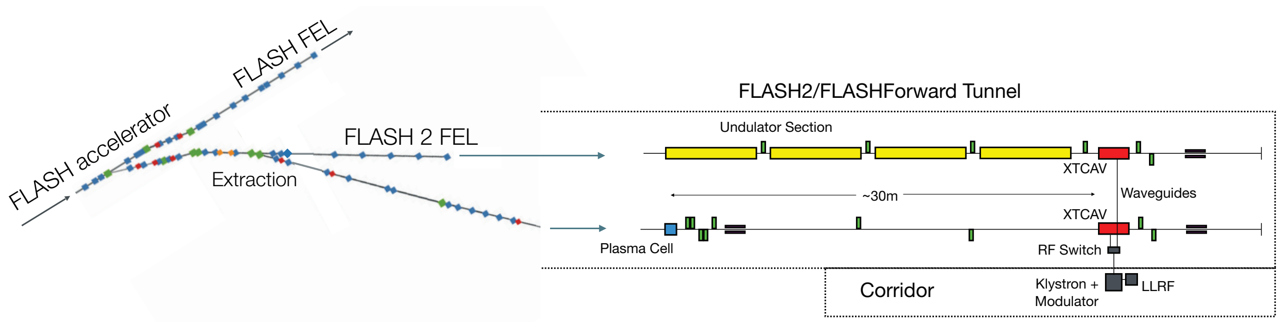

Figure 1: A schematic of the FLASH beam line, demonstrating extraction into FLASH2, with subsequent extracting into FLASHForward. A sketch of the proposed experimental hall layout is also shown, with the placement of the shared RF source and respective deflecting cavities illustrated.

eters, a beam line design is required to meet certain constraints.

For the case of the longitudinal phase space measurement, these constraints are predominantly defined by the desire to maximise the streak of the TDS,

$$S = \sqrt{\beta_y(s)\beta_y(s_0)}|\sin\mu_y(s_0,s)|\frac{eVk}{E} \quad , \tag{2}$$

where $\beta_y(s)$ and $\beta_y(s_0)$ are the vertical beta functions at the imaging screen and TDS, respectively, $\mu_y(s,s_0)$ is the vertical phase advance between the TDS and the screen, E is the beam energy, V is the cavity voltage, and k is the RF wave-number. The longitudinal resolution is thus defined as

$$R_z = \frac{\sigma_y}{S} = \sqrt{\frac{\varepsilon_y(s)}{\beta_y(s_0)}}\frac{1}{|\sin\mu_y|}\frac{E}{eVk} \quad . \tag{3}$$

From an optics standpoint, a maximal streak requires a phase advance of $n\pi/2$ (where n is an odd integer) and large beta function in the streaking plane at the TDS (chosen as y in the case of FLASHForward). The energy resolution is defined as

$$R_\delta = \frac{\sigma_x}{|D_x|} = \sqrt{\varepsilon_x}\frac{\sqrt{\beta_x}}{|D_x|} \quad , \tag{4}$$

where D_x is the dispersion introduced by the dipole downstream of the TDS. Again, in order to maximise the energy resolution, it is necessary to maximise dispersion, either with a large dipole field or a large distance between the dipole and imaging screen.

For the case of the slice emittance measurement, the constraints combine those of a typical quad scan – i.e. a progression in phase advance between the reference point, just upstream of the first scanning quadrupole (see Fig. 2 for placement) and measurement location, $\mu_x(s_{\mathrm{ref}}, s)$, ideally covering a range of $[0, \pi]$ – and, again, maximising the streak from the TDS.

A summary of all the beam line constraints required for optimisation in the case of FLASHForward are outlined in Table 2.

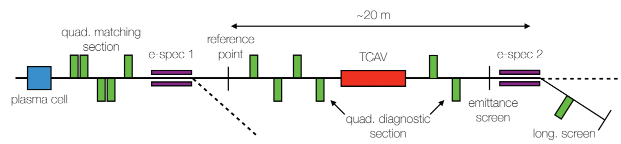

Figure 2: A sketch of the post-plasma cell beam line optics configuration defined by the constraints outlined in Tab. 2.

This particular level of control over optics cannot be achieved by a single quadrupole, but instead requires a number of quadrupoles at least equal to the number of optimisation constraints [3]. The beam line downstream of the reference point therefore requires a minimum of five quadrupoles. In this case, due to hardware availability, an additional six quadrupoles are added between the reference point and the emittance screen (four upstream of the TDS and two downstream), with a final quadrupole in the dispersive section for added experimental flexibility. A sketch of this optics configuration can be seen in Fig. 2. The variables used for optimisation are thus the strengths of the quads and the drifts between them.

Table 2: A Summary of the Optimisation Constraints Required for Slice Emittance and Longitudinal Phase Space Measurements at FLASHForward

Parameter	Constraint	Location
	in both cases	
β_y	< 10 m	screen
β_x	> 10 m	screen
μ_y	$\pi/2$	TDS to screen
β_y	> 100 m (maximised)	TDS
	slice emittance	
μ_x	$[0, \pi]$	ref. point to screen
	long. phase space	
D_x	> 0.5 m	screen

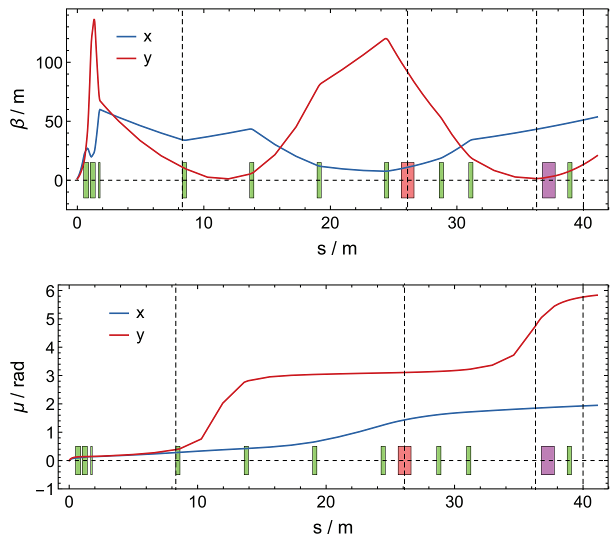

Figure 3: The beta function and phase advance in both transverse planes for the matched slice emittance midpoint case. The location of the quadrupoles (green), TDS (red), and dipole (purple) are indicated on the plot. The vertical dashed lines represent (from left to right) the reference point, centre of the TDS, emittance screen, and dispersive screen.

LINEAR OPTICS AND MATCHING

The beam line depicted in Fig. 2 was substantiated in `elegant` [4] in order to match the optics to the constraints outlined in Tab. 2.

Matching for the case of slice emittance was chosen as the first step in optimisation due to the complexity of optics required to fit the full $[0, \pi]$ phase advance range in x. The midpoint case of $\mu_x(s_{\mathrm{ref}}, s) = \mu_y(s_0, s) = \pi/2$ was used as a starting point, with a progression in μ_x around this point. The beta functions and phase advances for the matched midpoint case can be seen in Fig. 3. The values of these constraints after optimisation for this midpoint case – $\beta_y(s_0) = 99.9\ m$, $\beta_y(s) = 1.4\ m$, $\beta_x(s) = 43.2\ m$, $\mu_y(s_0, s) = 1.6\ rad$, and $\mu_x(s_{ref}, s) = 1.6\ rad$ – are all within the tolerances of the optimisation routine.

The location of, and distances between, the quads were then fixed by this midpoint solution, leaving the quad strengths as the only optimisation variables. A successful demonstration of this matching over $0<\mu_x<\pi$ can be seen in Fig. 4.

The beam line fixed by the slice emittance optimisation was then used to match for the longitudinal phase space constraints. The result of this matching, in the form of the beta functions and phase advances in both transverse planes, can be seen in Fig. 5. The values of these constraints after optimisation – $\beta_y(s_0) = 99.9\ m$, $\beta_y(s) = 2.7\ m$, $\beta_x(s) = 60.0\ m$, $\mu_y(s_0, s) = 1.6\ rad$, and $D_x = 0.87\ m$ – once again indicate successful matching.

By inputting the values from the longitudinal phase space matching to Eqs. 3 & 4, the longitudinal and energy resolutions for this case are 1.37 fs and 2×10^{-4} (respectively) for

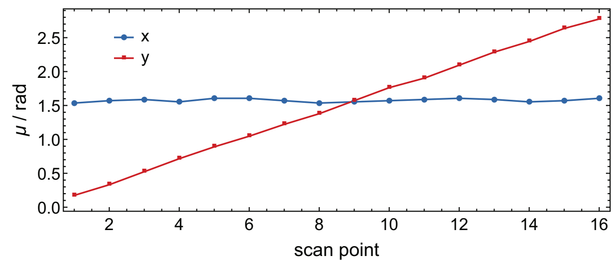

Figure 4: The evolution of μ_x over an almost full range of $[0, \pi]$, with μ_y fixed at $\pi/2$ in each case. The x-axis simply represents the optimisation scan point number.

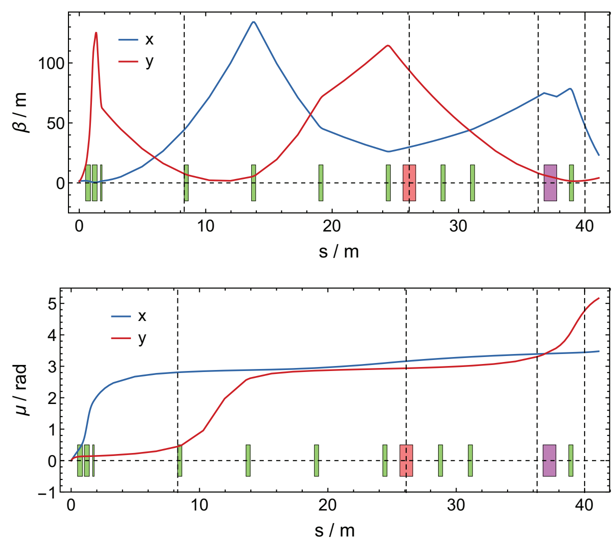

Figure 5: The beta function and phase advance in both transverse planes for the matched longitudinal phase space case. As in Fig. 3, the optics elements and screens are illustrated on each plot.

a typical FLASHForward drive beam with $E = 1\ GeV$ and $\varepsilon_{n,(x,y)} = 2\ \mu m$, and a deflecting cavity with $V = 30\ MV$ and $f = 11.99\ GHz$ ($k = 0.026\ m^{-1}$).

PARTICLE TRACKING

After matching with linear optics a distribution from a full 3D simulation of FLASH was used for particle tracking [5]. The longitudinal phase space at the exit of the plasma cell for this distribution can be seen in Fig. 6. The distribution has an irregular shape due to collective effects (e.g. coherent synchrotron radiation in the bunch compressors, space charge, etc.) experienced in the upstream Linac. Such beams with potentially harmful centroid offsets may be seen at FLASHForward, highlighting the necessity for phase space analysis. For this reason, the example distribution in Fig. 6 will be used for further analysis.

The distribution in Fig. 6 is propagated through the entirety of the beam line shown in Fig. 2. This bunch will experience a transverse kick from the TDS (mapping the longitudinal plane z onto the transverse plane y) and a bending

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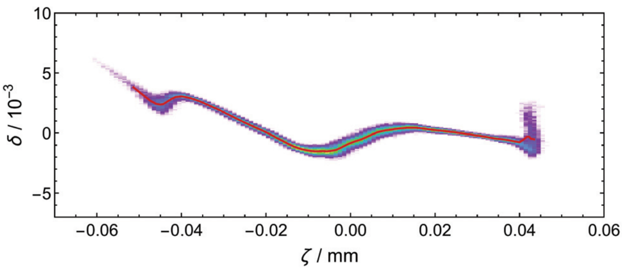

Figure 6: The longitudinal phase space of the input distribution, used for particle tracking in the FLASHForward `elegant` beam line. The y- and x-axis represent the relative energy spread and centre of mass frame of the bunch, respectively.

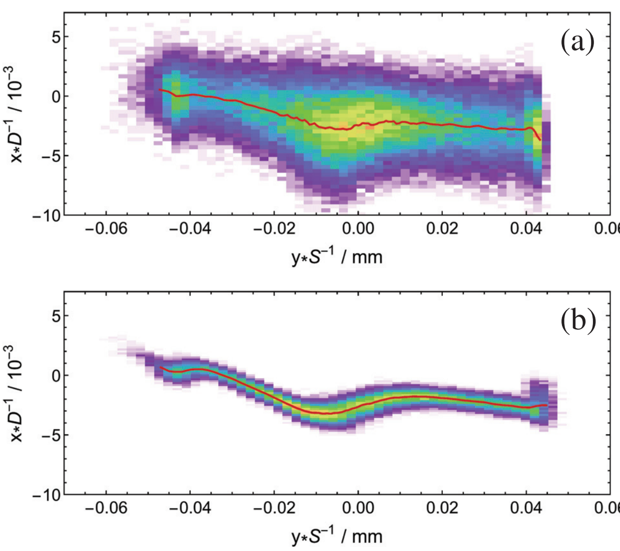

Figure 7: The reconstructed longitudinal phase space at the dispersive screen for a streaking voltage of a) 30 MV, and b) 6 MV.

force from the dipole (equating the longitudinal plane δ with the transverse plane x). This allows the longitudinal phase space distribution entering the TDS to be reconstructed from the transverse plane at the dispersive screen. This reconstruction is shown in Fig. 7 for two streaking voltages, with the axes normalised by the TDS streak and dipole-induced dispersion for x and y respectively.

According to the Panofsky-Wenzel theorem [6], off-axis particles travelling through an RF deflecting cavity experience longitudinal electric fields. This leads to the energy smearing seen in both cases, with the larger streak resulting in a larger energy smear. This smearing can be reduced through a reduction in the streak (most easily realised by decreasing the cavity voltage), however this comes at the cost of longitudinal resolution.

It is the compromise between R_z and R_δ which is of the utmost importance when attempting single-shot measurements with a TDS. The results shown here indicate that it may be difficult to find a single-shot working point for this particular drive beam scenario whilst maximising resolution in both planes.

However, the energy spread induced by a TDS is defined as,

$$\sigma_\delta = \frac{eVk}{E}\,\sigma_y \quad , \tag{5}$$

so a reduction in the emittance of the beam would reduce the induced energy spread. As can be seen in Tab. 1, the witness beams expected at FLASHForward should have much smaller emittances than those of the drive beam, leading to a reduction in energy spread.

Additionally, it has been demonstrated that the analytical energy spread induced by a TDS correlates extremely well with experimental results [7]. If these experimental results can be recreated on FLASHForward then the factors limiting high resolution longitudinal phase space measurements may be observed and quantified, aiding in offline corrective methods.

CONCLUSIONS AND OUTLOOK

A post-plasma beam line, with the inclusion of a TDS system for transverse and longitudinal diagnostics, has been designed for FLASHForward. All necessary constraints for this design have been met via substantiation and matching of the beam line in `elegant`. Both linear optics and particle tracking demonstrate successful TDS operation. The simulation package has indicated a need for compromise between the energy and longitudinal resolution when operating with typical FLASHForward drive beams. However, offline corrective methods through experimental commissioning of the system have been shown to mitigate these limitations in other systems.

The results of this study will be furthered to cover the entire parameter phase space expected for both FLASHForward drive and witness bunches – the results of which will aid in finalising the design of the TDS system. Once the system is built and installed on FLASHForward, a comparison with experimental data will be made.

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REFERENCES

[1] B. Foster *et al.*, NIM A 806 (2014) 175.
[2] K. Tiedtke, *et al.*, *New Journal of Physics* 11 (2009) 023029.
[3] E. Prat, *et al.*, *Phy. Rev. ST Accel. Beams* 17 (2014) 104401.
[4] M. Borland, Advanced Photon Source LS-287 (2000).
[5] G. Feng, private communications.
[6] W. K. H. Panofsky, W. Wenzel, *Rev. Sci. Instr.* 27:967 (1956).
[7] C. Behrens, C. Gerth, *Proc. of DIPAC11*, Hamburg, Germany (2011) TUPD31.

ISBN 978-3-95450-177-9