INTRODUCTION

Here we report on the electron beamline extension of the free-electron laser (FEL) in Hamburg (FLASH) at DESY towards beam-driven wakefield acceleration (PWFA) experiments. The approved and well advanced project, officially referred to as FLASHForward, will accommodate a third electron beam extraction line next to the original FLASH facility and in parallel to the FLASH-II extension. FLASHForward will share the same accelerator tunnel and infrastructure as FLASH-II but is planned to operate independent of the FEL user facilities FLASH and FLASH-II. In this note, we report on the electron beam extraction strategy, taking into account boundary conditions and beam dynamics constraints, and discuss the design of the entire electron beam transport up to the entrance of the plasma cell, where PWFA experiments will finally be carried out.

BEAMLINE DESIGN STRATEGY

The FLASH facility, as has been mentioned above, is operated with a superconducting r.f. accelerator and can thus provide multiple bunches in a bunch train. This provides the ultimate possibility to split the bunch train in parts and individually distribute the sub-trains along different beamlines. FLASH-II uses a fast kicker magnet in conjunction with a septum to extract parts of the up to 800 μs long pulse train with up to 800 bunches (at 1 μs spacing). A sketch of the electron beam switching area is shown in Fig. 1. The electron beams are accelerated and longitudinally compressed in two stages with a final main accelerator downstream of the second bunch compressor (BC). Downstream of the final accelerator the electron beams get distributed along the different beamlines, where one of the three, FLASHForward, is dedicated for exploration of PWFA concepts. In order to maintain the high brightness of the electron beams and provide unique capabilities in PWFA at FLASHForward, special care has to be taken in the design of the electron beam extraction and transport as is discussed in the following.
at the FLASH facility is depicted in Fig. 1. The electron bunches that get transported to FLASH-II can be split again and further distributed to FLASHForward. In contrast to the FLASH-II switching, FLASHForward cannot make use of a kicker + septum combination as there is not enough distance between both components (in beam optics terminology: there is not sufficient phase advance in between) in order to gain enough offset in the septum magnet. Hence, FLASHForward must adopt an extraction system made of pulsed dipole magnets, referred to as pulsed bends in following. To significantly reduce the costs of the extraction system, we decided for a relatively simple but cheap half-sine pulse generator for the switching fields instead of an expensive and not-well elaborated flat-top pulse generator. This half-sine pulse restricts the FLASHForward beamline to 1 - 3 bunches from the pulse train available in FLASH-2 before the extraction. This, in turn, also reduces the costs and efforts of the machine protection and radiation safety as the average beam power of a few bunches is rather low.

The design of the beamline underlies several technical boundary conditions where some of them are in turn related to beam dynamics constraints. First of all, the vacuum chamber inside the pulsed bends must allow transmission of the pulsed magnetic fields with 111.5 µs rise time, which can only be achieved by ceramic chambers of very thin thickness. At the same time, the thin ceramic chamber must be rigid enough over the entire length of the magnets (∼300mm) to resist the atmospheric pressure. The design of the magnets with only a few winding turns takes into account the impedance match with respect the half-sine pulse (at 2.24 kHz) generator. Figure 2 presents a technical drawing (cross section) for one of the pulsed bends, the lower plot depicts the array of two subsequent pulsed bends with their ceramic vacuum chamber. The total angle between FLASH-II and FLASHForward is 8 deg. The bends have a magnetic length of 294 mm and a nominal bending angle of 4 deg. The operation of FLASHForward directly downstream of the extraction is 8 deg.

![Pulsed bend system for the electron beam extraction at FLASHForward](image)

FIG. 2: Pulsed bend system for the electron beam extraction at FLASHForward. The upper plot shows a technical drawing (cross section along beam path) for one of the pulsed bends. The bends have a magnetic length of 294 mm and a nominal bending angle of 4 deg. The lower plot depicts the array of two subsequent pulsed bends with their ceramic vacuum chamber. The total angle between FLASH-II and FLASHForward directly downstream of the extraction is 8 deg.

ELECTRON BEAMLINE AND OPTICS

The FLASHForward beamline uses the tunnel of FLASH-II and is therefore in parallel to FLASH-II at a distance of 4 m. After the extraction when the beamlines are parallel again, the horizontal dispersion, which is generated by the extraction bends, should be closed, i.e., zero again. This achromatic beam translation system also generates longitudinal dispersion (also referred to as $R_{56}$), which can result in bunch compression in the presence of energy chirp. The operation in first order can be expressed as $C = (1 - h R_{56})^{-1}$, where $h$ is the linear energy chirp. The operation of FLASHForward is designed to be as independent as possible of the beam parameters used in FLASH and FLASH-2. This and a generally increased flexibility for dedicated beam times lead to the demand for a tunable $R_{56}$. Besides light peak current of several kiloamperes (> 2.5 kA), the...
FIG. 3: Transverse position (top) of the magnets and beta functions (bottom) along the beamline in FLASHForward starting with the extraction from FLASH to FLASH-II (labeled as FLASH 1 and FLASH 2 in the figure). A horizontal beam waist in the pulsed bends mitigates emittance growth due to CSR effects, and the overall small beta functions keep chromatic effects below a tolerable level. The final focus section with its large beta functions upstream the plasma cell is clearly recognizable.

FIG. 4: Longitudinal and horizontal transverse dispersion (labeled as $R_{56}$ and $R_{16}$, respectively) along the FLASHForward beamline starting upstream of the pulsed bends and ending at the plasma cell. The position of the reverse bend is indicated, and the approximate range of variable $R_{56}$ is given.

PWFA experiments also require small transverse beam sizes ($< 7 \mu m$) in both planes, and a good pointing stability of about $10 \mu m$ spatially and 0.5 mrad in angle. The peak current can be controlled by the chirp and $R_{56}$, and the transverse beam size can be changed by optics, where the transverse emittance limits the achievable beam size for a given optics condition. In general, the small emittance of FLASH - a mandatory condition for lasing in an FEL - should be preserved during the beam transport in FLASHForward. Besides CSR effects, which have been mentioned above, also chromatic effects can degrade the beam quality and have to be taken into account in the beamline design. To minimize the magnet field jitter of the pulsed bends as a source for pointing jitter at the plasma cell, a sufficient phase advance has been found for the optics solution. In this context, the phase advance basically describes how an angular kick gets translated to an offset along the beam transport. Figure 3 presents the longitudinal and horizontal dispersion along the FLASHForward design beamline starting upstream of the pulsed bends and ending at the plasma cell. It fulfills all discussed requirements and also those not particularly mentioned here, e.g., closed angular dispersion, closed second-order transverse dispersion, or a horizontal beam waist in the bending magnets. Not shown in Fig. 3 are three sextupole magnets to control the chromatic and second-order effects as well as several steering magnets along the beamline for orbit correction.

In order to control the compression via the longitudinal dispersion $R_{56}$ (see the compression factor $C$ above), we inserted an additional bend (so-called “reverse bend”) within the dispersive region of the extraction beamline. The longitudinal dispersion is defined via $R_{56} = \int D(s')/\rho(s')ds'$, hence we can tune dispersion by the dispersion $D \equiv R_{16}$ at the position of the reverse bend and by its bending radius. The latter is fixed however, so effective tuning will be done by changing the optics upstream of the reverse bend. The bend is referred to as “reverse” as its bending angle has a different sign compared to the dispersion, and its $R_{56}$ contribu-
Effects are in a reasonable limit. The vertical plane shows the assumed in the calculations but still the chromatic effects would appear as a perfect circle with unity radius. Any beam mismatch would result in a phase space ellipse with semi-axes describing the mismatch, there is also a graphical representation. By transforming the transverse phase space (\{x,x'\} and \{y,y'\} for the horizontal and vertical plane, respectively) significantly. A metric for chromatic effects along a beam transport line can be the mismatch parameter defined as \( B_{\text{mag}} = 1/2(\beta \gamma - 2\alpha + \beta \gamma) \) with the Courant-Snyder (CS) parameters \( \alpha, \beta, \gamma \) describing the phase space ellipse. The CS parameters with and without tilde represent the actual and the design case, respectively. Deviations arise from chromatic effects and describe a mismatch (mismatched beams have \( B_{\text{mag}} > 1 \)). Beside a value describing the mismatch, there is also a graphical representation. By transforming the transverse phase space coordinates (in the following only shown for the horizontal plane; likewise for the vertical case) via the design CS parameters downstream of the extraction with

\[
\begin{pmatrix}
u \\ v
\end{pmatrix} = \begin{pmatrix}
\frac{1}{\sqrt{\beta}} & 0 \\
\frac{\alpha}{\sqrt{\beta}} & \sqrt{\beta}
\end{pmatrix} \cdot \begin{pmatrix} x \\ x'
\end{pmatrix},
\]

a perfectly matched beam that is not subject to chromatic effects would appear as a perfect circle with unity radius. Any beam mismatch would result in a phase space ellipse with semi-axes \( \neq 1 \). Figure 5 shows a calculation for both the mismatch parameter \( B_{\text{mag}} \) and its graphical representation in the \( \{u,v\} \)-phase space. A rather pessimistic energy deviation of \( \pm 1.5\% \) has been assumed in the calculations but still the chromatic effects are in a reasonable limit. The vertical plane shows

\[ \max(B_{\text{mag}}) = 1.03 \]

\[ \max(B_{\text{mag}}) = 1.69 \]

\[ \max(B_{\text{mag}}) = 1.59 \]

\[ \max(B_{\text{mag}}) = 1.03 \]

A small focus at the plasma cell entrance is essential for performing effective PWFA experiments, hence preserving the emittance and beam matching (re-matching upstream the plasma cell is possible though) along the FLASHForward beamline, including closed longitudinal dispersion (isochronous).

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The last section downstream of the dispersive extraction beam and thus directly upstream of the plasma cell is the "matching and final focus" section. A sketch of this section with its magnets is depicted in Fig. 6. After the last, dispersion-closing bends of the extraction, we planned with a matching section consisting of four quadrupoles plus one quadrupole for doing a scan in order to measure the emittance and the actual optics. The beam size measurements for this purpose will be carried out using an imaging station (labeled as OTR in Fig. 6), which accommodates different screens. Once the beam is matched, it gets focused down, by using the final focusing quadrupoles, to beta functions at the plasma cell entrance of 25 and 35 mm in the horizontal and vertical plane, respectively. The achieved steering resolution at the plasma cell entrance amounts to better than 1 \( \mu \)m in position and to better than 10 \( \mu \)rad in angle.

**SUMMARY AND CONCLUSIONS**

In summary, we presented the design consideration of the FLASHForward electron beamline for PWFA experiments. The optics and beam dynamics calculations meet all requirements. Chromatic effects are not significant, and CSR effects are the limiting factor. Nevertheless, the beamline allows mitigation of the degrading CSR effects by careful control of the compression (via energy chirp and tunable longitudinal dispersion). The technical drawings are almost completed, and the magnets and beams diagnostics are either available or ordered.

The first components of the FLASHForward beamline will be installed during a coming shutdown in May 2015, and further shutdowns are scheduled for 2016. The post-plasma beamline design, which includes electron beam capturing, special beam diagnostics, and subsequent beam transport to undulator magnets, is also in good progress and will be finalized soon.