PROGRESS IN FLASH OPTICS CONSOLIDATION

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Abstract

FLASH is the superconducting soft X-ray Free Electron Laser in Hamburg at DESY. A precise knowledge of the beam optics is a key aspect of the operation of a SASE FEL. A campaign of optics consolidation has started in 2013 when the second beam line FLASH2 was installed downstream of the FLASH linac. We give an update on progress of this effort and on recent results.

INTRODUCTION

The superconducting soft X-ray Free Electron Laser in Hamburg (FLASH) [1] at DESY, Germany is operating two FEL beam lines, FLASH 1 and FLASH 2 [2] to be able to serve more photon experiments at the same time. The accelerator is capable to provide long bunch trains (up to 800 bunches at 1 MHz every 100 ms).

A switch yard (two vertical flat top kickers and a horizontally deflecting Lambertson septum) distributes the subtrains to the corresponding beam line. In order to preserve the beam quality of the short low-emittance bunches from the RF photo-cathode gun along the linac and the subsequent beam transport and undulator beam lines, the optics has to be well controlled. The constraints on the optics are particularly high in the magnetic chicanes, the undulators, and the extraction arcs to FLASH1 and even more to FLASH2 [3].

A campaign of optics consolidation was started in 2013 (recommissioning of FLASH) to fulfill this conditions. In previous reports [4, 5] we presented our efforts to maintain the beam optics state of the machine close to the design optics.

The space charge dominated beam from the RF gun is routinely matched to the design optics in a dedicated matching section. We found [5] that a strong optics perturbation is located closely downstream of the matching section in a not so well instrumented area partly hidden by the warm-cold transition into the 2nd accelerating module.

The next screen is downstream of the 2nd magnetic bunch compressor chicane (BC3). It would be desirable of cause, to measure and correct the Twiss functions already into BC3, but it turned out that the degrees of freedom (independent quads) from where we believe is the end of the perturbed section to the screen downstream BC3 are insufficient to simultaneously allow a robust symmetric quad-scan *and* match the perturbed optics into the design upstream of the screen.

Here we report on our procedures to obtain a matched beam in the FLASH1 undulator section. Improving the match into the FLASH2 undulators is work in progress and will be reported in a later publication.

BEAM OPTICS RECONSTRUCTION

To introduce the theoretical background of beam optics reconstruction used here in this paper we state to a previous report [4] where the notation is described in more detail.

The beam optics reconstruction is based on beam size measurements. For each measurement $i \in [1, n]$ of the beam size σ_x^i with error $\sigma_{\sigma_x^i}$ and transfer matrix $\mathbf{R}^i$ one calculates one line of the matrix $\mathbf{M}$

$$M_{i,1-3} = \frac{1}{\sigma_{(\sigma_x^i)^2}} \begin{pmatrix} \left(R_{1,1}^i\right)^2 & 2R_{1,1}^i R_{1,2}^i & \left(R_{1,2}^i\right)^2 \end{pmatrix}.$$

To get second moments $\langle x^2\rangle$, $\langle xx'\rangle$, $\langle x'^2\rangle$ the inverse of the $n \times 3$ matrix $\mathbf{M}$ has to be calculated where n corresponds to the number of measurements with $n \geq 3$. This can be done with approaches like SVD or Gauss-Jordan algorithm

$$\begin{pmatrix} \Sigma_1 \\ \vdots \\ \Sigma_n \end{pmatrix} = \mathbf{M} \cdot \begin{pmatrix} \langle x^2\rangle \\ \langle xx'\rangle \\ \langle x'^2\rangle \end{pmatrix}, \text{with } \Sigma_n = \frac{(\sigma_x^n)^2}{\sigma_{(\sigma_x^n)^2}}.$$

With them one is able to calculate the Twiss parameters at the start point of the used transfer matrix [6]

$$\varepsilon = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}, \quad \beta = \frac{\langle x^2\rangle}{\varepsilon}, \quad \alpha = -\frac{\langle xx'\rangle}{\varepsilon}.$$

The mismatch between the two beam ellipses, the measured and the theoretical, can be expressed by two parameters the mismatch parameter m_p and the mismatch amplitude λ_p [3, 6]

$$m_p = \frac{1}{2}\left(\beta\gamma_0 - 2\alpha\alpha_0 + \beta_0\gamma\right), \quad \lambda_p = m_p + \sqrt{m_p^2 - 1},$$

with β, α and γ the Twiss parameter of the measured beam and β_0, α_0 and γ_0 of the theory ellipse. The parameters m_p, λ_p are equal or greater than 1. A value of 1 corresponds to fully agreement of theoretical and measured Twiss parameters.

EXPERIMENTAL SETUP

A sketch of the FLASH beam line and the design beta function along the beam line is depicted in Fig. 1. The section in which measurements were performed are described below.

DBC2

The DBC2 section is the dedicated matching section to match the beam optics from the RF photo cathode gun into the design optics with 5 matching quadrupoles. The design energy is 146 MeV. The Twiss parameters can be measured using four screens in a FODO channel with 45° phase advance between the screens with a resolution of about 10 µm [7]. The design beta function at the screens is $\beta_x = 2.49\,\text{m}$, $\beta_y = 2.56\,\text{m}$.

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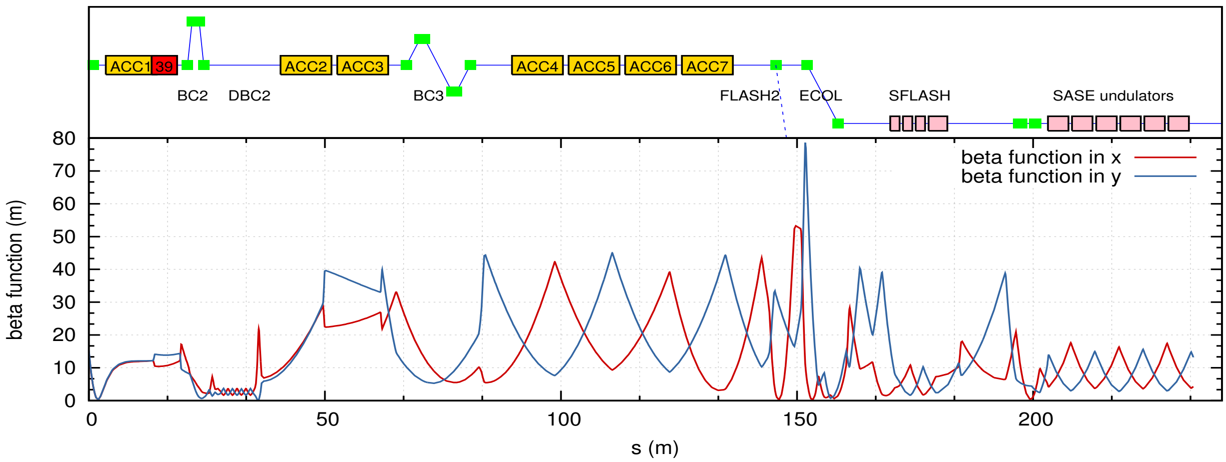

Figure 1: Theory beta functions of the FLASH1 beam line up to the end of the SASE undulator section. Above a schematic layout of the FLASH1 beam line.

Table 1: Twiss parameter and phase advance at the screens in sFLASH section. $\Delta\phi$ is the phase advance between the first and the n-th screen.

Screen	β_x/m	$\Delta\phi_x/°$	β_y/m	$\Delta\phi_y/°$
OTR1	4.18	0.0	6.91	0.0
OTR2	9.68	26.4	1.95	60.3
OTR3	1.87	71.1	9.17	95.1
OTR4	7.33	114.6	2.37	132.84

sFLASH

The sFLASH section is dedicated for seeding experiments in FLASH. However, it offers a FODO channel with four screens which is in principle suited for matching. The design energy is 350-1250 MeV. The shown measurements where done at 700 MeV. Unfortunately the section has small beta functions at the screen locations so that for higher energies one measures beam sizes which are close the resolution of the screens (see tab. 1). Therefore the accuracy of the beam width measurement can potentially be affected.

Undulator

A total of seven wire scanners, capable of horizontal and vertical scans, are located between the undulator segments [8]. Five of them are ready to be used for measurements with a 10 µm tungsten wire. The design energy is 350-1250 MeV. The measurements of this report were performed at 700 MeV. The design optics used in this report is a FODO channel optics with $\sim 35\,°$ advance between the wires. The design beta function at the first wire scanner is $\beta_x = 13.1\,\mathrm{m}$ and $\beta_y = 6.3\,\mathrm{m}$.

MEASUREMENTS

For all measurements the compression is set to minimum energy spread in the particular section, i.e. more or less on-crest in DBC2 and slightly compressed in sFLASH and the main undulator. Since the beam shape has some trajectory dependence, the trajectory through the machine is optimized towards elliptic beam spots on the screens. The measurements discussed here, were performed with a charge of 0.41 nC produced using a laser beam shaping aperture of 1.2 mm. The GUN RF amplitude was set to 54 MV m^{-1} and the GUN solenoid was used to optimize spot size on screens in DBC2 section.

The reconstructed Twiss parameters at the first screen or wire scanner in the matching section, after typically 2 — 5 iterations of matching, are listed in Table 2. The corresponding normalized phase space ellipses (green: design and blue: reconstructed) are depicted in Fig. 2. The gray lines represent the measured beam sizes transported to the reference point in the beam line. Ideally they are tangent to the phase space ellipse.

DBC2

The reconstruction of the phase space ellipse in FLASH is most robust in the DBC2 section. As can be seen in Fig. 2, the data are tangent to the reconstructed phase space ellipse, which nearly coincides with the design, indicating a fairly accurate result. The measured mismatch amplitude is below 1.1 which is in general our target value for matching.

sFLASH

The matching process lead to a mismatch amplitude in the horizontal plane which is comparable to DBC2, however, the result in the vertical plane ($\lambda_p = 1.24$) was less convincing. Furthermore the growth of the projected emittance is larger in the horizontal plane (a factor of 3) than in the vertical (65 %). A possible cause for the extreme horizontal projected emittance growth is a transverse centroid shift, depending on the longitudinal position in the bunch. Due to the unfortunate relation of the small beam size at sFLASH to the resolution of the screens in that section, the measurements at some screens are dominated by the screen resolution. This might not only affect the robustness and the

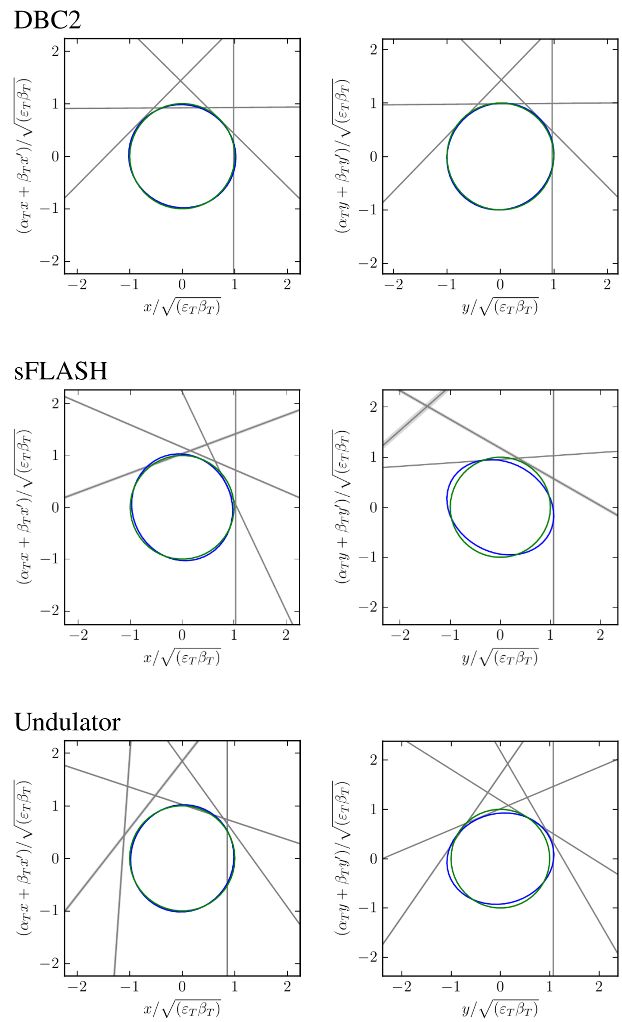

Figure 2: Normalized phase space ellipse of measurements (blue) and design optics (green) for horizontal (left column) and vertical plane (right column). The design emittance ε_T is set to the measured normalized emittance ε_N. β_T : design beta function, α_T : design alpha function.

convergence properties of the matching process, but also is a potential cause of inaccurate emittance measurements. Nevertheless, from our experience an approximately matched beam in sFLASH is easier to match into the main undulator than without.

Undulator

The beam optics reconstruction in the undulator section yields a slightly smaller horizontal emittance and mismatch amplitude than in the vertical plane. However, the measured beam sizes in the horizontal plane do not fit as well as in the vertical plane. The first and the last horizontal beam size measurements are slightly degenerate in the betatron phase. Since they are both shifted towards the same direction, combining them into their mean and transporting it to either phase would be a much better tangent to the reconstructed phase space ellipse.

Table 2: Reconstructed emittances and mismatch amplitudes at first screen/wire scanner after final matching iteration. The given errors are the statistical error from the single measurements (absolute values) and the estimated errors due to the beam profile model uncertainty (relative values).

DBC2	x plane	y plane
$\varepsilon_N/\mu m$	$0.54 \pm 0.01 \pm 10\,\%$	$0.51 \pm 0.02 \pm 10\,\%$
λ_p	$1.05 \pm 0.02 \pm 10\,\%$	$1.04 \pm 0.07 \pm 10\,\%$
sFLASH		
$\varepsilon_N/\mu m$	$1.49 \pm 0.04 \pm 10\,\%$	$0.85 \pm 0.07 \pm 10\,\%$
λ_p	$1.09 \pm 0.03 \pm 10\,\%$	$1.24 \pm 0.20 \pm 10\,\%$
Undulator		
$\varepsilon_N/\mu m$	$1.08 \pm 0.06 \pm 10\,\%$	$1.28 \pm 0.03 \pm 10\,\%$
λ_p	$1.05 \pm 0.06 \pm 10\,\%$	$1.19 \pm 0.03 \pm 10\,\%$

Error Estimates

The statistical error for pixel to micrometer conversion factor is about 1 %. The effect of resolution in DBC2 is about 2 % on emittance and 10 % on mismatch amplitude. In SFLASH the resolution is less than in DBC2 and the measured beam sizes are smaller. So the effect on the reconstructed parameters is larger. Another source of errors, however, is that the non-Gaussianess of typical FEL beams. The most obvious method to extract the beam size from a screen image, is to fit two Gaussians to the projected (horizontal/vertical) beam profiles. One may, however, use alternative model functions, e.g. asymmetrical super Gaussians [9], or the second moments in a carefully chosen range of interest with intricate background subtraction. Since asymmetrical super Gaussian includes the Gaussian as a special case, all three methods would in theory yield the same beam size for an ideal Gaussian beam. For a realistic non-Gaussian beam they will, however, lead to generally different beam sizes. To estimated the uncertainty of the emittance and the mismatch amplitude we have compared the three above methods while using two Gaussian fits with a different background treatment. The result is about 10 % error for emittance and mismatch amplitude due to the usage of various model functions. Not included are errors due to transfer matrix errors.

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