

MEASUREMENTS OF THE OPTICAL FUNCTIONS AT FLASH

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Abstract

In 2013/2014 a 2nd beam line (FLASH2) was installed at the superconducting soft x-ray Free Electron Laser FLASH at DESY (Hamburg, Germany). The design optics was modified to accommodate for the extraction from the main linac into the 2nd beam line. During the recommissioning of FLASH we took the opportunity to start an optics consolidation campaign in the complete machine. Although the campaign is still ongoing we report on the methods and first results.

INTRODUCTION

FLASH [1] is a soft x-ray free electron laser driven by a superconducting linac capable of providing long bunch trains (800 bunches at 1 MHz every 100 ms). In order to serve more photon users, a second beam line (FLASH2) [2] and a switch yard (flat-top kicker and Lambertson septum), capable of delivering bunches from every train to both beam lines, were installed. The optics in the main linac and the switch yard had to be adapted to accommodate the extraction into FLASH2 and to preserve the beam quality [3]. Since the beam waist in the septum is crucial for maintaining a good projected emittance [3], a campaign was started for better control of the optical functions along the linac. Starting point is an improved matching of the bunches from the RF photo cathode gun into the design optics in the designated matching section ACC1/UBC2/BC2/DBC2 (see Fig. 1). Once the match is achieved, the consistency of the optics downstream needs to be verified and potentially corrected. We employ the Orbit Response Matrix (ORM) technique and a generalized multi screen / multi quad scan method. So far we have only first results for the (common) FLASH linac and the (old) FLASH1 beam line. The main point of this paper is the description of the tools we have implemented and to report the preliminary results.

THEORY

Our tools consist of a suite of shell scripts and c-programs utilizing a version of MAD8 which has been extended for linacs [4, 5] as optics engine. The actual machine optics is reconstructed by reading the magnet currents from the control system, a “database” of calibration curves and an assumed energy profile (user input). The current design optics from the RF gun to the FLASH1 dump is shown in fig. 1.

Orbit Response Matrix (ORM) Technique

In a linac the (i, j) -th element of the ORM is defined as the linearized response of a given coordinate (q_i) at the i -th

monitor (BPM) to a kick θ_j from the j -th steerer

$$\Delta q_i = \left(\mathbf{R}_{i \leftarrow j} \right)_{q,p} \Delta \theta_j \quad (1)$$

where for the moment we neglect inter plane coupling, $\mathbf{R}_{i \leftarrow j}$ is the transport matrix from s_j to s_i [6], and $q, p = 1, 2$ for the horizontal and $q, p = 3, 4$ for the vertical phase plane. In a linac $\mathbf{R}_{i \leftarrow j} \equiv 0$ for $s_i < s_j$. The measured ORM however, contains calibration errors of both monitors (a_i) and steerers (b_j),

$$\mathbf{R}_{i \leftarrow j}^{\text{meas}} = a_i \mathbf{R}_{i \leftarrow j}^{\text{machine}} \{k_1^{(l)} : s_l \in (s_j, s_i)\} b_j \quad (2)$$

where the $k_1^{(l)}$ are the quadrupole strengths in-between steerer and monitor. Thus, before non-linear minimization can be applied to identify and/or correct focusing errors, robust estimates of the a_i 's and b_j 's have to be extracted from the ORM data while fulfilling suitable consistency constraints [7].

Generalized Multi Screen Multi Quadrupole Scans

Given a reference point s_0 , $L \geq 1$ screens (or wire scanner) at $\{s_l\}_{1 \leq l \leq L}$ and $M \geq 0$ singly powered quadrupoles at $\{s_m\}_{1 \leq m \leq M} \subset (s_0, s_L)$, one may select N M -tuples of quadrupole strengths $\{k_1^{m,n}\}_{1 \leq n \leq N; 1 \leq m \leq M}$ and measure the beam sizes $\sigma_{n,l}$ (in the chosen plane) for the n -th quadrupole setting at the l -th screen. Then, using the super-index $\mu := (n, l)$

$$\mathbf{M} \begin{pmatrix} \sigma_0^2 \\ \text{Cov}(q,p)_0 \\ \sigma_{p,0}^2 \end{pmatrix} = \begin{pmatrix} \sigma_{n=1,l=1}^2 \\ \dots \\ \sigma_\mu^2 \\ \dots \\ \sigma_{n=N,l=L}^2 \end{pmatrix}. \quad (3)$$

Here the μ -th row of \mathbf{M} is given [8]

$$\mathbf{M}_{\mu,1 \dots 3} = \left(\left(\mathbf{R}_{l \leftarrow 0}^{(n)} \right)_{q,q}^2, 2 \left(\mathbf{R}_{l \leftarrow 0}^{(n)} \right)_{q,q} \left(\mathbf{R}_{l \leftarrow 0}^{(n)} \right)_{q,p}, \left(\mathbf{R}_{l \leftarrow 0}^{(n)} \right)_{q,p}^2 \right).$$

Solving (3) in the least square sense for the 2nd moments at s_0 gives the Twiss functions at s_0 via $\sigma_0^2 = \beta_0 \varepsilon$, $\text{Cov}(q,p)_0 = -\alpha \varepsilon$, $\sigma_{p,0}^2 = \gamma_0 \varepsilon$, and $\varepsilon^2 = \sigma_0^2 \sigma_{p,0}^2 - \text{Cov}(q,p)_0^2$. Weighting of the rows and improving the condition (i.e. using regularized SVD techniques) can significantly improve the quality of the results. Well established limiting cases are the quad scan ($L = 1, M = 1, N \gg 1$) and the multi screen method ($L \geq 3, M = 0, N = 1$).

The mismatch between the measured beam ellipse and the design ellipse, can be expressed by two parameters, the mismatch parameter m_p and the mismatch amplitude λ_p [3, 6]: $m_p = 1/2 (\beta \hat{\gamma} - 2\alpha \hat{\alpha} + \hat{\beta} \gamma)$, and $\lambda_p = m_p + \sqrt{m_p^2 - 1}$,

with the Twiss parameters β , α and γ of the measured beam and $\hat{\beta}$, $\hat{\alpha}$ and $\hat{\gamma}$ of the design ellipse. One easily shows that $m_p \geq 1$ and $\lambda_p \geq 1$ and that a value of 1 corresponds to a perfect match. m_p describes the emittance dilution through filamentation while λ_p describes the β -beat amplitude.

MULTI SCREEN/QUADUPOLE SCANS

First we matched the beam from the injector into the design optics of the linac using a four screen method ($L = 4$, $M = 0$, $N = 1$) in a designated diagnostic FODO channel and varying 7 upstream quadrupoles. Despite a large initial mismatch ($\lambda_p \approx 4$ with design quadrupoles settings which neglect space charge), the match converged after 3 iterations. Tab. 1 proves the success of the matching procedure through the reasonably good agreement between design optics and measurement. At FLASH the four screen method can only be applied in a few sections since the distances between the screens / wire scanners are typically too large so that the estimate of the $\mathbf{M}_{\mu,1\dots 3}$ is too sensitive by itself to optics errors and thus the reconstructed Twiss functions are too inaccurate. We have tested the multi quadrupole scan method ($L = 1$, here $M = 3$ & $N = 10$) at another screen inside the DBC2 section after matching the injector using the four screen method. Tab. 2 shows that the multi quadrupole method yields results which are consistent inside the error bars with the four screen method. The injector match in fact partly invalidated the precomputed optimal set of k_1 -values. As we will see in the next section there is a perturbation to the optics very close downstream the DBC2 section. Multi screen/quad measurements downstream of DBC2 seem to confirm this but so far did not give a hint on the actual source of the perturbation.

A potential problem of the multi quadrupole method is too little phase advance between quadrupole and screen phase advance is too low.

ORM MEASUREMENTS

Figure 2 shows the orbit response along the whole FLASH/FLASH1 beam line for selected steerers. The orbit response is calculated by a linear fit to the BPM readings for five steerer kick strengths using the fit function implemented in gnuplot [9] weighted by the rms error of 30 BPM readings for each kick strength. The error for the slope is the error of the fit calculated by gnuplot. A matlab tool [7] performs the fitting of the steerer calibrations and the BPM gains. In this analysis the model is fitted to the measurement.

By scaling the steerer strengths with one scaling parameter b_j for each steerer *type* and the BPM gains it is possible to achieve agreement between model and measurement in both planes downstream of the first accelerator module ACC1 and upstream of the second accelerator module ACC2 within the errors. For fitting of the scaling factors in the injector up to ACC2 only the response up to ACC2 is used. The steerer scaling factor of the steerer *type* used in DBC2 is about ≈ 0.7 , for the steerer in ACC1 ≈ 1.8 horizontal and ≈ 1.5 vertical. The BPM gains are reduced by $\approx 30\%$. An

Table 1: Twiss Parameter and Mismatch at OTR4DBC2 using the Four Screen Method

plane	β (m)	α	ε (μm)	λ_p
x	2.45	-1.15	1.16	1.036
y	2.38	1.19	3.15	1.096

Table 2: Twiss Parameter and Mismatch at Q2DBC2 using a Multi Quadrupole Scan

plane	β (m)	α	ε (μm)	λ_p
x	1.85	1.53	1.06	1.186
y	3.82	-2.50	3.00	1.206

intrinsic complication is that the BPMs were calibrated using the steerers so that the steerer calibration and the BPM gains are coupled.

At the beginning of the second accelerator module ACC2 a strong distortion of the orbit response and sudden coupling between the horizontal and vertical plane was measured (see Fig. 2). The location of the distortion was discovered earlier [7] and some potential sources were eliminated. However the actual cause of the optics error has not yet been identified. This effect complicates further analysis because the beam from the gun matched to the design not far upstream into the screen OTR4DBC2. The perturbation of the response is stronger for some steerers than for others. In the horizontal plane some responses are in very good agreement with the model until the entrance to the undulator section, where we had problems with the BPM readings. Due to time constraints the ORM measurement in the vertical plane could not be done with carefully optimized steerer strengths.

CONCLUSION

We present test of a multi quadrupole scan method in DBC2 and proof the result with a matching in DBC2 with four screen method, our standard method to match into design optics.

Since a severe distortion of the optics and coupling between the planes at the end of DBC2 is still measured performing quad scans along the linac and ORM measurements we are now able to analyze the optics distortion in more detail and probably to locate it. Also we will try to correct the optics distortion with a matching downstream of the distortion to ensure the right optical function at the septum.

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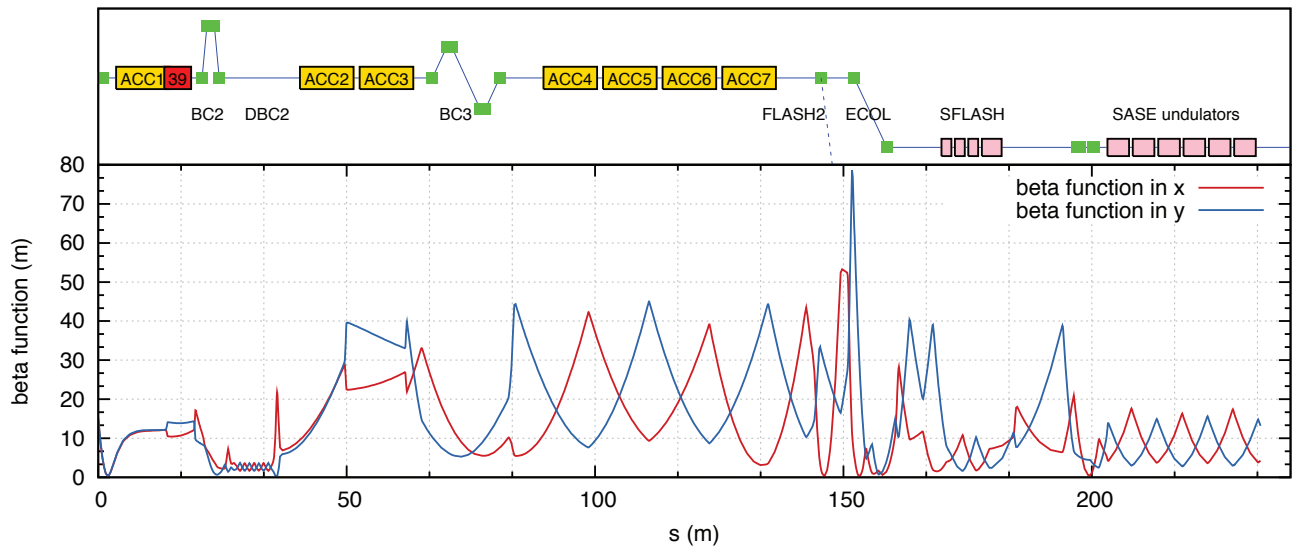


Figure 1: Theory beta functions of the FLASH1 beamline up to the end of the SASE undulator section. Above a schematic layout of the FLASH1 beam line.

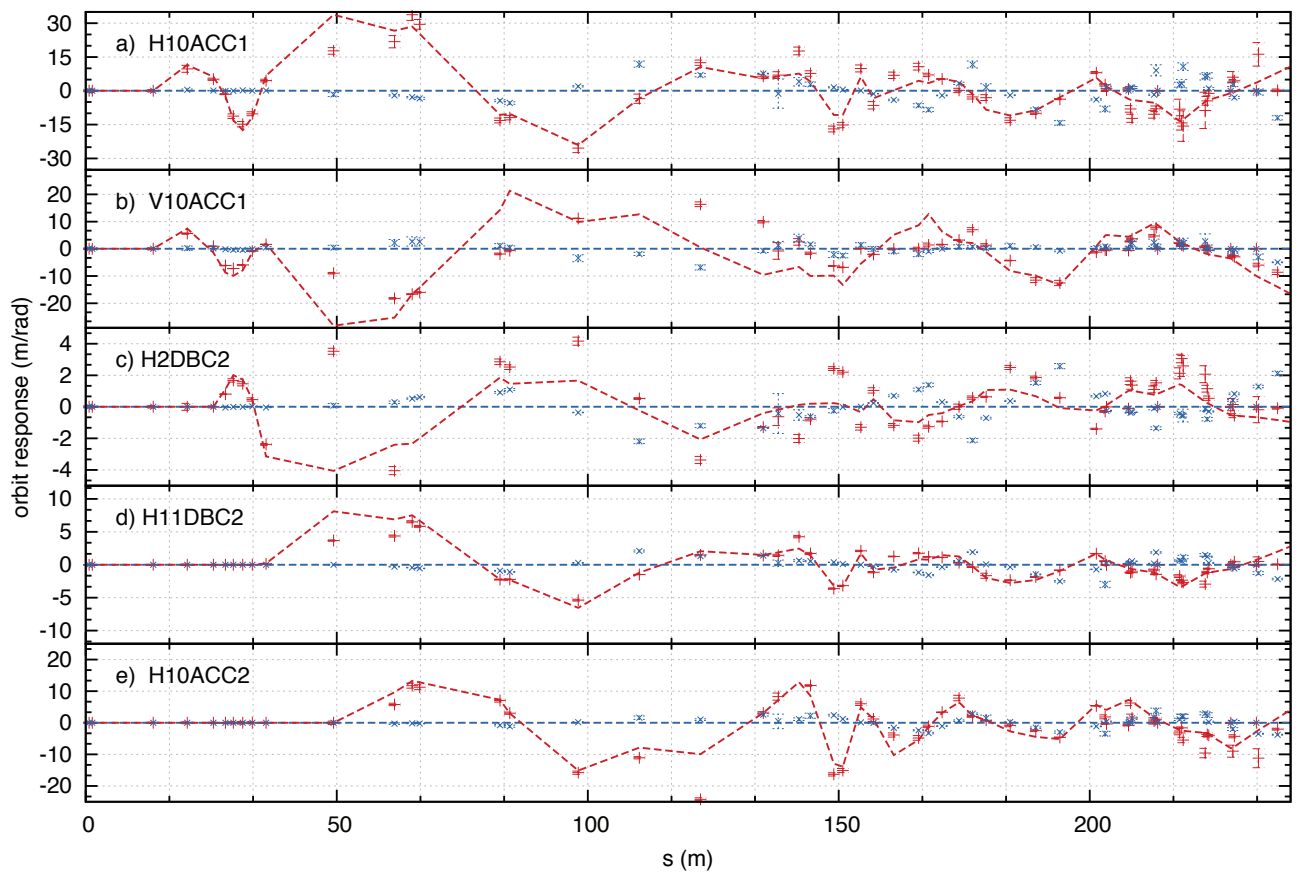


Figure 2: Orbit response of selected steerers in the injector section. The BPM responses are shown as marks with rms error as bars in the plot (red uncoupled, blue coupled). The dashed line is the expected orbit response of the model with a fitted steerer kick and BPM gains for upstream of $s = 40$ m.

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