ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-TUPWA035

PROGRESS IN OPTICS STUDIES AT FLASH

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Abstract

FLASH is the superconducting soft X-ray Free Electron Laser in Hamburg at DESY, Germany. Good control over the beam optics is a key aspect of the operation of a SASE FEL. In 2013 a second beam line, FLASH2, was assembled and the modifications necessary to feed the two beam lines were installed downstream of the FLASH linac. As reported before [1] we started a campaign of optics consolidation. We give an update on the progress of this effort and on results.

INRODUCTION

The superconducting soft X-ray Free Electron Laser in Hamburg (FLASH) [2] at DESY, Germany has recently been upgraded to operate two FEL beam lines, FLASH1 and FLASH2 [3], to potentially serve more users. For optimum FEL performance several several optical criteria have to be met. The most critical ones are the beam waists in the bunch compressors and at he septum of the switchyard (switching the e^- beam between FLASH1 and FLASH2) [4] and matching in the periodic solution of the in the FEL undulators of the two beam lines. In theory it suffices to match the space charge dominated beam from the RF photo cathode gun to the design optics of the linac to meet all the conditions at least for an uncompressed bunch. However it is a well known but not well understood fact that in FLASH the optics is strongly perturbed almost right after the matching point. A campaign of optics consolidation was started in 2013 and described in [1].

THEORY

This section is partial repetition of [1]. Our tools consist of a suite of shell scripts and c–programs utilizing a version of MAD8 which has been extended for linacs [5, 6] as optics engine. The actual machine optics is reconstructed by reading the magnet currents from the control system.

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

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

where for the moment we neglect inter plane coupling, $\mathbf{R}_{i\leftarrow j}$ is the transport matrix from s_j to s_i [7], 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 contains calibration errors of both monitors (a_i) and steerers (b_j),

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

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 [8]. Many BPMs in FLASH have been calibrated in a beam based way, relying on the calibration of nearby upstream steerers. This introduces coupling between the a_i's and the b_i's ans is thus an additional complication

MEASUREMENTS

In this section the measurements are presented to investigate the optics perturbation we are expecting at the end of DBC2 section up to the end of ACC2 section. As mentioned before, this has been done by mainly using the ORM technique. Figure 2 shows the relative difference of the measured and theoretical orbit response from UBC2 to DBC3 section for design optics.

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 10 BPM readings for each kick strength. The error for the slope is the error of the fit calculated by gnuplot. A python code performs the fit of the steerer calibrations and BPM gains. In this analysis the measurement data is fitted to the model data. The fit program performs a minimization of the error of the difference ORM weighted by the error of the orbit response using an iterative method based on SVD algorithm.

The ORM measurement in Fig. 2 is representative for a whole set of ORMs taken in the design optics with the injector matched for 0.3 nC. It shows a quite good correspondence between model and measurement up to BPM 11DBC2 for both planes. The fitted steerer calibrations are between 0.9 and 1.15 except H10ACC1 with 0.5. The fitted BPM gains between 0.9 and 1.4 except BPM 9ACC2 with 2.9 in x and 2.4 in y plane and 9ACC3 with 1.6 in x and 1.1 in y plane.

The calibration of BPM UBC2 (1.8 in x and 1.2 in y plane) is far off because it has been calibrated using a nearby steerer whose calibration if far off (H10ACC1). The steerers in UBC2 and DBC2 are of the same type so that in this analysis the mean of the fitted steerer calibrations is used because the steerer calibrations should be almost the same for all these steerers. Whenever the section over which the response was measured intersects with the stretch from approximately BPM 11DBC2 to the steerers in ACC2, the model does not fit the measurements. However the response of the two steerers ACC2 and ACC3 are in good agreement with the theoretical prediction. Thus it is clear that there must be a noticeable optics perturbation located in that section. So far this is not a new result and just reconfirms the findings of many others, e.g. [8]

We have a couple of candidates for causing the perturbation described above, see Fig. 2. Several of them are hidden

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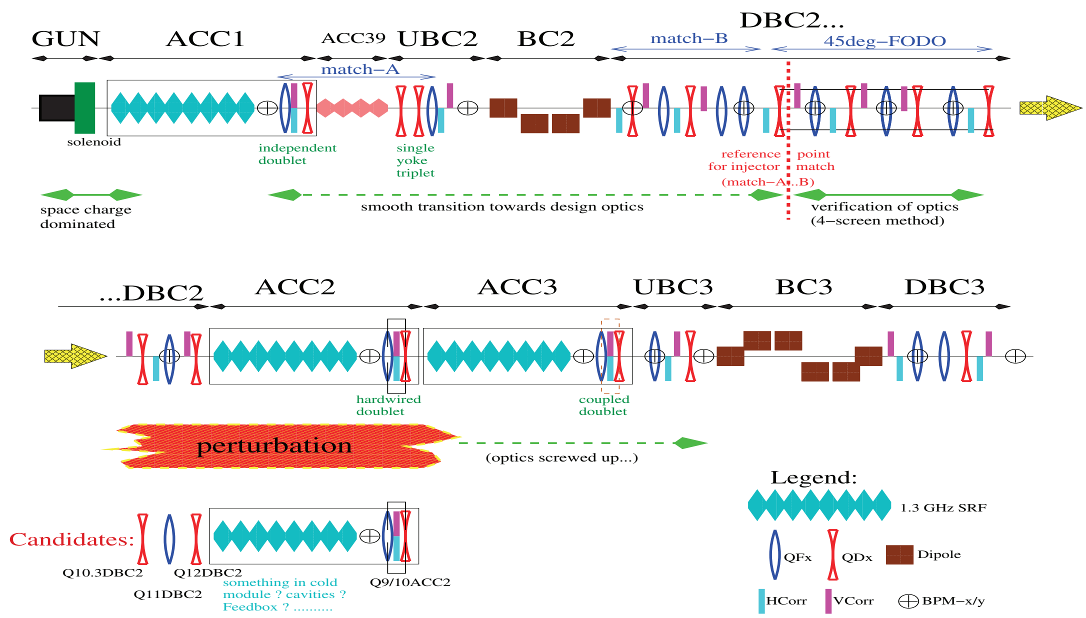

Figure 1: Schematic of the investigated section of FLASH with all relevant beam line elements. It indicates the location of the optics perturbation and possible candidates causes this perturbation.

inside the cryo module or inside the cryo feedbox, but others are standard beam line elements and can be switched on and off more or less independently. So far we have taken ORMs in 3 non–standard settings: Q11/Q12DBC2 and Q9/Q10ACC1 off ; RF off in ACC23 ; Q10.3/Q11/Q12DBC2 off. The later one being the reference state for the ORM in Fig. 3. In all cases the optics has been adapted to the switched off elements. Whenever quadrupoles where turned of they have in fact been demagnetized using an exponentially damped sequence of current set points to minimize the residual remanent field at zero current.

Figure 3 shows the ORM for the case of switched off quadrupoles in DBC2 Q10.3DBC2, Q11DBC2 and Q12DBC2. Model and measurement show a good correspondence up to BPM 11DBC2 again. Here the fitted steerer calibrations are between 0.8 and 1.3 while the BPM gains are for horizontal plane 0.9 and 1.25 and vertical plane 1.5 and 2.0 except the BPMs in the disturbed section.

Inside the range from BPM 9ACC2 to 2UBC2 there is clearly again strong deviations from the model. However, the response seen in the DBC3 steerers is much closer to the theoretical prediction than before. These results were qualitatively verified by repeating the ORM around a changed reference orbit. The other two set ups (last two of warm triplet and cold doublet off ; and ACC23 off) produced ORMs with even less clear improvement. However all 3 non–standard cases show enhanced deviations from the model in the cold BPMs. This might be to some extent due to unavoidable larger beta–functions in the cold module but it might as well be caused by the known strong (2-dimensional) nonlinearities of the cold cavity BPMs in the cold modules in FLASH.

CONCLUSION

To improve our understanding of possible causes of the perturbation, we have taken ORMs with various beam line elements (quadrupoles and RF) switched off. So far the local disturbance measured at the cold BPMs and unfortunately also at the two adjacent warm BPMs could never be improved. However, we have first indications that the warm triplet upstream of ACC2 may contain a perturbation that, when switched off at least improves the response outside the range of the 4 “bad” BPMs mentioned above. First basic hardware tests have already performed on the triplet magnets without any findings but more sophisticated (time consuming!) test are planned for the next possible time slot.

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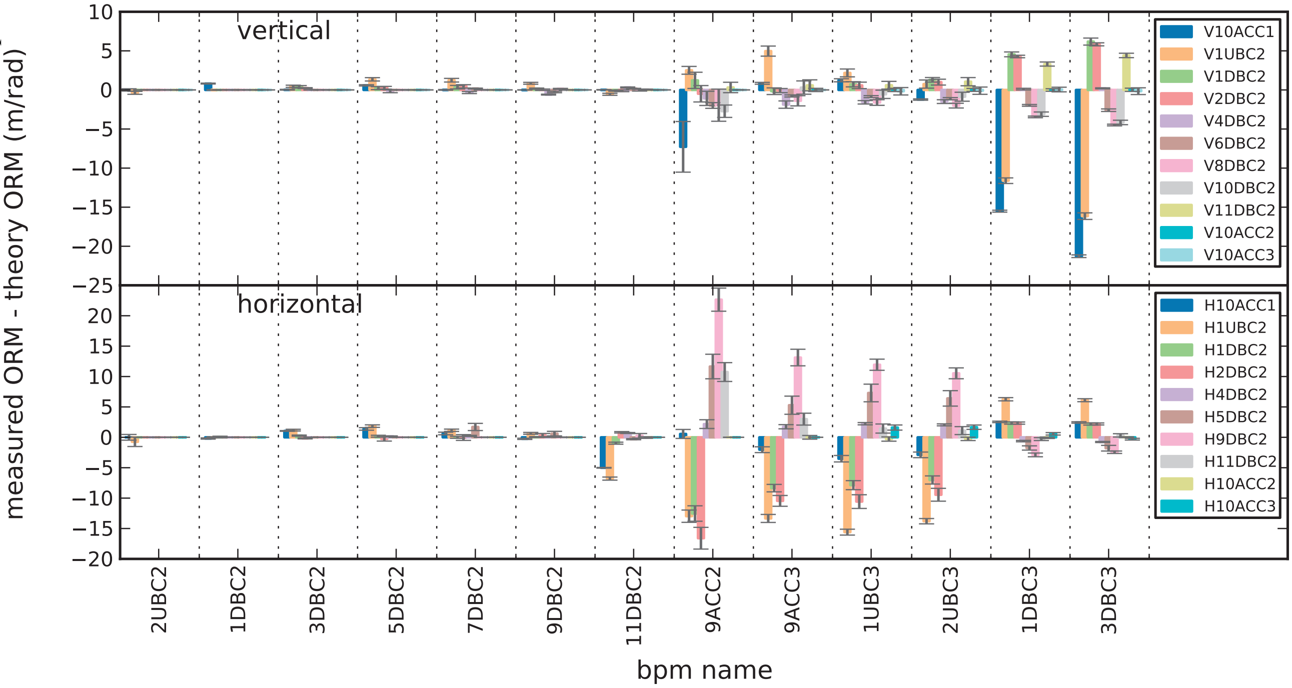

Figure 2: Difference of measured orbit response and theory orbit response for design optics.

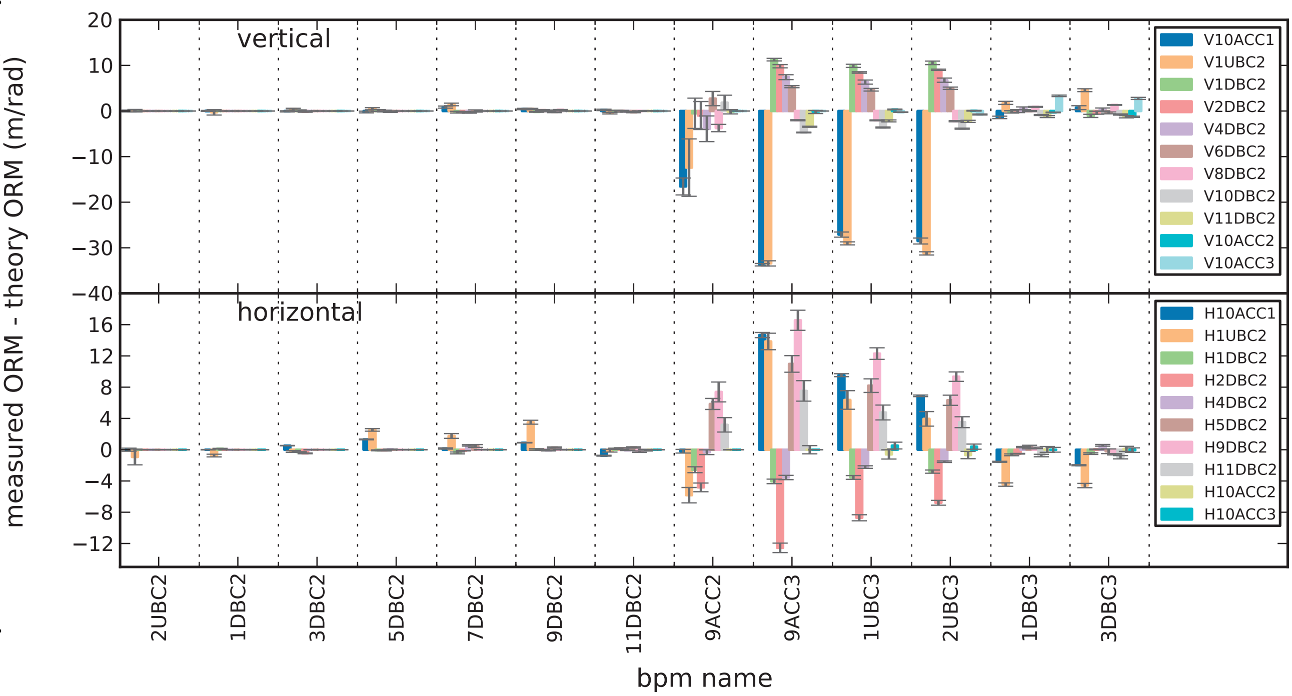

Figure 3: Difference of measured orbit response and theory orbit response for the case of switched off quadrupoles Q10.3DBC2 Q11DBC2 and Q12DBC2.

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