ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-THPME116

STUDIES ON A DIAGNOSTIC PULSE FOR FLASH

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Abstract

The long-term stability of the beam optics at FLASH is crucial for all connected experiments and the operation of the new second beamline FLASH2. It is therefore desirable to have a simple procedure to monitor the beam optics routinely and at the same time minimally invasive. This way user operation is not disturbed. An automated procedure, which has been successfully employed at the SLAC linac is presented in the context of FLASH. The betatron oscillations of selectively kicked pulses are recorded using BPMs at a fixed time interval. An online algorithm is then used to extract the betatron phase advance, as well as potential growth of the betatron oscillation amplitude and the Twiss parameters beta and alpha. Using this method, the long-term beam optics stability can be monitored in order to identify potential sources of drifts.

INTRODUCTION

The high-gain free-electron laser FLASH at DESY, Germany produces ultra-short X-ray pulses with a duration less than 30 fs FWHH. These pulses are generated by the SASE process using a high brightness electron beam, which can be tuned to energies between 370 MeV and 1.25 GeV. This corresponds to a photon wavelength range between roughly 45 nm and 4 nm. Electron bunches are created by a laser-driven photoinjector and then accelerated by seven 1.3 GHz superconducting accelerator modules (*TESLA-type*). X-ray pulses are then generated inside the 27 m long undulator section. Figure 1 shows a schematic layout of the FLASH machine. [1–3]

Since FLASH is a user facility, the long-term stability of the beam optics is crucial for all connected user experiments and the operation of the new second beamline FLASH2. In addition to that the seeding experiment sFLASH also demands for high beam optics stability. In the following a simple procedure to monitor the beam optics routinely and at the same time minimally invasive is proposed, with the goal to provide the operators an additional tool to monitor the overall machine stability. First test measurements are presented.

METHOD

The diagnostic pulse method - which has already been successfully employed at the SLAC linac [4] - is based on the idea of extracting beam optics stability information by measuring kicker magnet induced betatron oscillations of selected pulses periodically. These oscillations are measured by all available beam position monitors downstream the location of the kick. An online tool then analyzes the data. This way a long-term history of beam optics stability can be compiled.

The aim of the method is to reveal the cause of beam optics errors, which lead to symptoms like the loss of SASE signal or a trigger of the machine protection system. Figure 2 shows an *Elegant* [5] calculation of the betatron phase advance difference between the design optics and a scenario were one power supply delivers the wrong output current. Errors like this should easily be detectable by the diagnostic pulse method.

In order to be able to calculate beam optics related physical quantities from the BPM data it is necessary to induce the oscillations at two different positions (1 and 2) along the linac. The distance in phase advance should be close to $\pi/2$. The transport of the two oscillations is given by

$$\begin{pmatrix} x_1 \\ x_1' \end{pmatrix}_i = \mathbf{R}_i \cdot \begin{pmatrix} x_1 \\ x_1' \end{pmatrix}_0 , \qquad \begin{pmatrix} x_2 \\ x_2' \end{pmatrix}_i = \mathbf{R}_i \cdot \begin{pmatrix} x_2 \\ x_2' \end{pmatrix}_0 \tag{1}$$

where 0 indicates the initial point and i all of the downstream locations. From this data it is now possible to calculate the R-matrix elements by solving the set of equations given by equation 1. Due to the fact that only the spatial coordinates are recorded by the BPMs, the angular coordinates (x_i') must be obtained by a least square trajectory fit. From equation 1 it can be seen that the fit problem can be expressed in matrix formalism as

$$\mathbf{X} = \hat{\mathbf{M}} \cdot \mathbf{p}, \tag{2}$$

where $\mathbf{X}$ is an n-dimensional vector of positional data obtained by n downstream BPMs, $\hat{\mathbf{M}}$ is a an $n \times 2$ matrix of fixed model parameters (here: R-matrix elements taken from optics calculations using *Elegant*) and $\mathbf{p}$ is an 2-dimensional vector of the free parameters (here: x and x'). Therefore it is possible to calculate $\mathbf{p}$ by analytically minimizing χ^2 [6] and hence

$$\mathbf{p} = (\hat{\mathbf{M}}^{\mathrm{T}}\hat{\mathbf{M}})^{-1}\hat{\mathbf{M}}^{\mathrm{T}}\mathbf{X}. \tag{3}$$

Having obtained the *measured* R-matrix elements it is now possible to calculate the Twiss parameteres α, β, as well as the betatron phase advance Ψ, oscillation amplitude A and the mismatch parameter B_{mag} per plane x and y (see **APPENDIX**).

Zero-Crossing Method

Another way to obtain the betatron phase advance is to fit the positions of the zero-crossings of the betatron oscillations. This method allows the fast evaluation of the data in steps of π.

Both the analytical trajectory fit and the zero-crossing method are implemented in the online tool.

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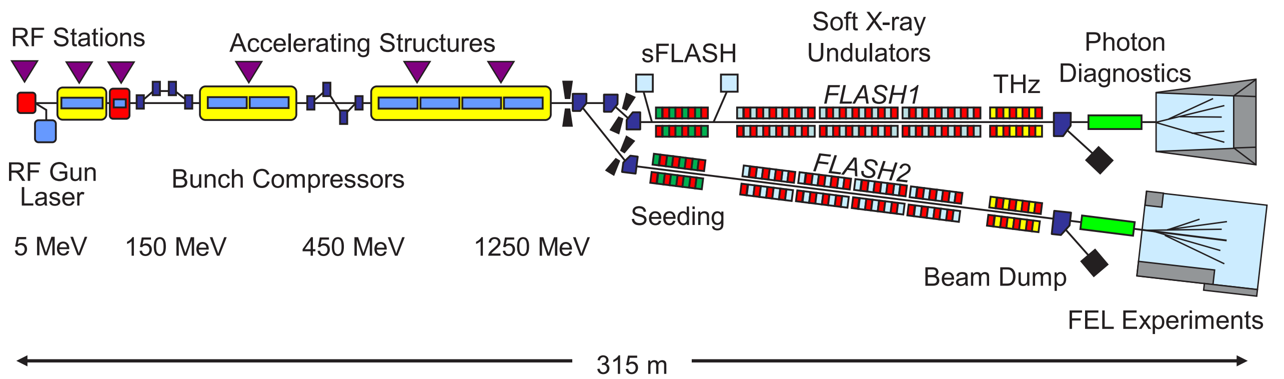

Figure 1: Schematic overview of FLASH with its two beamlines FLASH1 and FLASH2. The beam direction is from left to right. The schematic is not to scale.

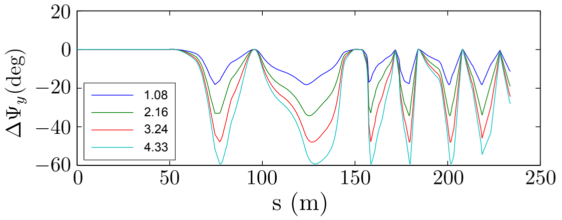

Figure 2: *Elegant* calculation of the phase advance difference with respect to the design optics in vertical direction. Four different error scenarios (given in terms of $\beta_0 \cdot \Delta k \cdot L_{\mathrm{eff}}$) are plotted for the power supply of a quadrupole located at $s = 50\,\mathrm{m}$.

FIRST MEASUREMENTS

For the test measurements normal dipole steerer magnets were used to induce the betatron oscillations. In a future implementation of the monitoring system fast kickers should be used in order to measure as minimally invasive as possible. In a first experiment, two magnet pairs located after the first bunch compressor with a suitable phase advance have been used (see table 1). The first measurement was performed with a beam energy of 685 MeV and 0.5 nC single bunch charge during the morning shift of 20th March 2014. The second was performed with a similar setting in terms of energy but with 0.25 nC charge during the night shift of 24th March 2014. The machine was tuned to SASE operation in both cases. A custom data acquisition and processing tool was used. Five data sets consisting of two kicks (positive and negative direction) for each steerer pair were recorded and compared to a reference orbit, which was taken prior to every measurement. During the measurement it was possible to restore SASE radiation after each kick without any problems. This is important to note as the method is supposed to be minimally invasive in the future.

Table 1: Steerer Magnet Pairs used for the First Test Measurements

Steerer 1	**Steerer 2**	**ΔΨ (deg)**
H5DBC2@29.75 m	H9DBC2@33.65 m	92.38
V6DBC2@30.74 m	V10DBC2@35.73 m	90.08

Online Tool

The online tool interfaces directly with the control system and performs the measurement automatically. The code structure is modular and can easily be upgraded to a server that records the optics stability history and makes it available on the control system. The data is analyzed online. For the first two measurement sessions 50 data sets were taken at 10 Hz and averaged. Each full measurement - including beam deflection in two directions and going back to the original machine settings - took approximately 5 min. Considering the time it takes to adjust the steerer magnets and the fact that one deflection direction is sufficient, the measurement time can be reduced to <5 sec. This of course can be reduced further, or even eliminated completely by using fast kickers (currently bunch trains are produced with $f_{\mathrm{bu}} = 1\,\mathrm{MHz}$).

Results

Figures 3 and 4 show the measured phase advance for five different kicks during the morning shift of 20th March 2014. The data are compared to the theoretical phase advance obtained with *Elegant* based on the actual machine parameters of the respective measurement shift. It can be seen that the data are in good agreement with the theory up to $s \approx 200\,\mathrm{m}$. This is the beginning of the undulator section. From there on the data is very noisy. This can be attributed to the fact that the jitter of the BPM readings in the undulator section was an order of magnitude higher than the one of the BPM readings in the linac section. The normalized jitter of the oscillation zero-crossing positions is shown in figure 5. The vertical kick data shows another interesting feature. The data from 10:05 and 10:34 differs substantially from the theroretical curve starting from $s \approx 150\,\mathrm{m}$, which corresponds to the to the energy collimation section downstream the acceleration modules (see fig. 1). A similar result was recorded during

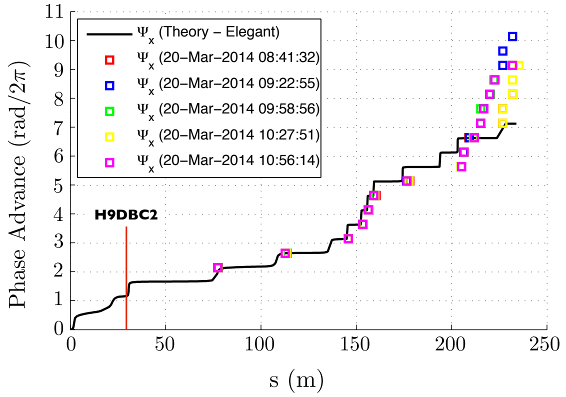

Figure 3: Horizontal phase advance vs. longitudinal position for a positive kick in the x plane using the steerer magnet H9DBC2. Multiple measurements are shown (note: data points are hidden behind the last data set (violett)).

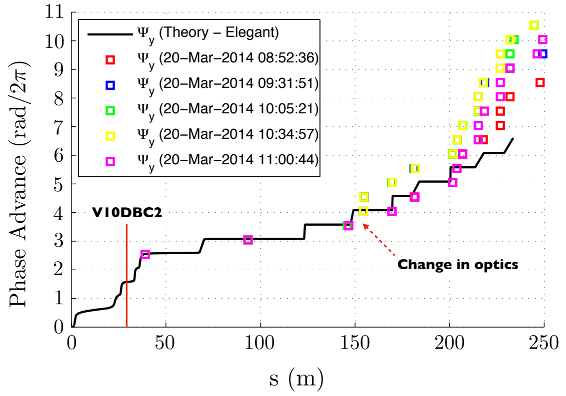

Figure 4: Vertical phase advance vs. longitudinal position for a negative kick in the y plane using the steerer magnet V10DBC2. Multiple measurements are shown (note: data points are hidden behind the last data set (violett)).

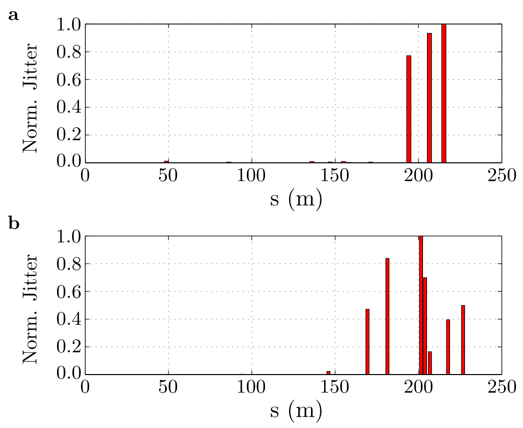

Figure 5: Jitter of the zero-crossing positions for both the horizontal (**a**) and vertical (**b**) betatron oscillation. The values are normalized to the maximum.

the second measurement shift on 24th March 2014. The cause of this change in optics is still under investigation.

CONCLUSION

First studies on the feasibility of a diagnostic pulse at FLASH were performed and evaluated. From the results it can be seen that the diagnostic pulse can be used to reveal possible beam optics errors fast and in future implementations non-invasively. The cause of the observed significant change of the vertical phase advance still needs investigation. A long term history of calculated Twiss parameters, betatron phase advance and B_{mag} would allow more in-depth studies on the correlation of beam optics errors with potential error sources like magnet power supplies or RF components. A way to obtain these quantities from BPM data was presented. Apart from that, the tool could also be very helpful in revealing minor errors like wrongly calibrated BPMs.

APPENDIX

The following physical quantities can be calculated from the least-squares trajectory fit.

$$\begin{aligned}
\Psi_l &= \arctan\left(\frac{\tilde{R}_{12}}{\tilde{R}_{11}}\right), \\
A_l &= \sqrt{\det(\mathbf{R})} \cdot \sqrt{\frac{E}{E_0}}, \\
\beta_l &= \frac{(c\tilde{R}_{11} + s\tilde{R}_{12})^2}{\det(\mathbf{R})} \cdot \beta, \\
\alpha_l &= \frac{(c\tilde{R}_{11} + s\tilde{R}_{12}) \cdot (c\tilde{R}_{21} + s\tilde{R}_{22})}{\det(\mathbf{R})} + \frac{\beta_l}{\beta} \cdot \alpha,
\end{aligned} \tag{4}$$

where tilde refers to the *measured* matrix elements transformed to *design* (semi)–normal form coordinates according to [7] and l to the measured quantity. Also $c = \cos(\Psi_l)$ and $s = \sin(\Psi_l)$. The mismatch parameter B_{mag} can be calculated via

$$B_{\mathrm{mag}} = \frac{1}{2} \cdot \left[\frac{\beta}{\beta_l} + \frac{\beta_l}{\beta} + \beta\beta_l\left(\frac{\alpha_l}{\beta_l} - \frac{\alpha}{\beta}\right)^2\right] \tag{5}$$

and is equal to 1 in the perfectly matched case. Note that $\mathbf{R}$ corresponds to the measured R-matrix.

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