BEAM-BASED ALIGNMENT SIMULATION ON FLASH-I UNDULATOR*

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Abstract

In order to ensure the SASE process can take place in the whole FLASH-I undulator section, a straight beam trajectory is mandatory which can only be achieved through beam-based alignment (BBA) method based on electron energy variations. In this paper, a detailed result of simulation is presented which demonstrates that the orbit alignment can be achieved within accuracy of a few 10 µm after several iterations. The influence of Quadrupole and BPM offsets, magnet-mover calibration errors, quadrupole gradient errors are also discussed.

INTRODUCTION

The undulator section in FLASH-I [1] consists of six permanent undulator segments with a length of 4.5 m each. The gap is fixed at 12 mm, the peak magnetic field is 0.486T, and the undulator period is λ=27.3 mm. A Pair of quadrupoles are located between undulator segments as well as upstream and downstream the undulator system, provide the focusing required to keep the beam size in the whole section both small and constant as possible.

The SASE FEL process puts very tight tolerances on the straightness of the electron beam through the FLASH-I undulator system. The BPMs and quadrupole magnets must be aligned relative close to the electron beam to an absolute accuracy of a few 10 µm. In order to achieve this goal, a Dispersion Free Steering procedure will be adopted on the FLASH-I undulator section which has been well established at LCLS at SLAC [2] and SwissFEL at PSI[3]. This LCLS BBA method uses large, deliberate energy variations of the electron beam to detect quadrupole magnet and beam position monitor (BPM) transverse offsets simultaneously. The final electron trajectory fluctuation in undulator section can be controlled within acceptable level, in addition, the spurious dispersion due to quadrupole and other field errors can also be eliminated accordingly.

ALGORITHM OVERVIEW

The Dispersion Free Steering scheme used here is based on measuring the trajectories for different energies of the electron beam, which is obtained by changing the gradient of accelerator modules upstream. A matrix expression of this scheme can be simply demonstrated as:

$$\begin{bmatrix} m_1 \\ m_2 \\ m_3 \end{bmatrix} = \left[\begin{array}{c:c:ccc} QR_1 & -I & LR_1 & & \\ QR_2 & -I & & LR_2 & \\ QR_3 & -I & & & LR_3 \end{array}\right] * \begin{bmatrix} \Delta q \\ \Delta b \\ x_{init} \end{bmatrix} \qquad (1)$$

Where the subscript number corresponds to different energy conditions, m is the BPM readings along the undulator, QR is response matrix which maps the quadrupole offset to the BPM readings downstream, $-I$ stands for minus identity matrix, LR is the response matrix of initial conditions from the entrance of undulator section to each BPM. Δq , Δb separately represent the offsets on quadrupole and BPM. x_{init} is the launch conditions includes initial position x_0 and angle x_0'.

The Eq. 1 should be solved with the singular value decomposition (SVD) method when we get all the BPM readings under each energy. But unfortunately, as one can see that Eq. 1 is ill-conditioned, the solution of the whole equation will be infinite. In practice the linear solution is solved by imposing 'soft-constraints' on the solutions to stabilize the system.

$$\textstyle\sum_i \Delta q_i = 0;\ \ \sum_i s_i \cdot \Delta q_i = 0 \qquad (2)$$

Where s_i is the quadrupole location. The main purpose of the 'soft-constrains' is to prevent the solution from diverging too far from 0. More details about the algorithm procedure can be found at [4].

SIMULATION RESULTS

Simulations have been run with ELEGANT[5] for the entire beam-based alignment procedure on the FLASH-I undulator section with 6 quadrupoles and 18 BPMs (reads both x and y plane). A set of statistical errors are included in the simulations as summarized in Table 1.

Table 1: Errors Used in Simulation

Description	Value	Unit	Comments
Quad offsets	100	µm	rms Quad offsets
BPM offsets	100	µm	rms BPM offsets
BPM resolution	1	µm	single-pulse rms resolution/noise
Incoming bias	10	σ	Initial orbit position
Incoming angle	0.1	σ	Initial orbit angle
Beam energy error	0.5	%	rms error of beam energy over scan
Quad gradient error	0.5	%	rms gradient error spread over all quads
BPM calibration error	5	%	rms calibration error spread over BPMs
mover calibration error	5	%	rms calibration error spread over movers
Undulator pole error	0.04	%	rms Undulator pole error over all poles

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The full Response Matrix was obtained using an ELEGANT optics model, then the correction procedure and data analysis were carried out on Matlab platform. In the simulation, trajectories were measured under three energies, 600MeV, 720MeV and 900MeV. Fig. 1 shows the horizontal BPM readings before and after 1st iteration with the errors in Table 1. The vertical plane was also well studied but not shown here.

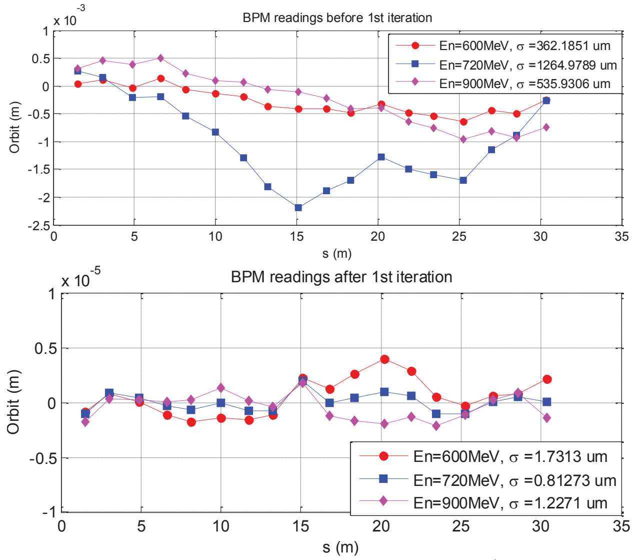

Figure 1: BPM readings before and after 1st iteration.

During the calculation, the fine structure of the fitted offsets agrees well with the true offsets. With 'soft constraint' was added, the solution (fitted offsets) was chosen by forcing both the BPM and quadrupole offsets to have no average slope or intercept.

The difference between input and fitted offsets, as shown in Fig. 2, has a linear component, it is due to the initial launch bias and the correlation of the input BPM and quadrupole offsets.

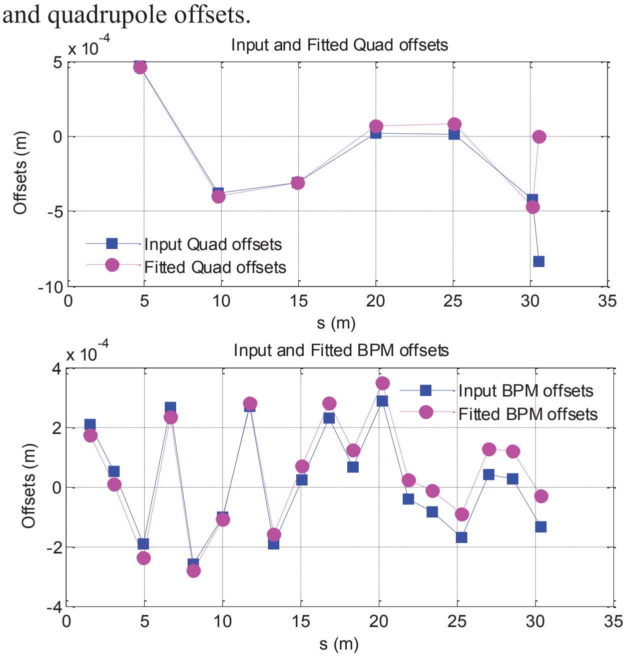

Figure 2: Input and fitted offsets.

Due to the residual offset, the absolute trajectories after correction has a tilt angle with respect to the initial axis, which reflects the difference between the axis defined by the linac beam and the axis defined by the initial quadrupole transverse centre. The influence on the radition power of SASE process due to this tilt angle is negeligible. Fig. 3 shows the absolute orbits with linear component removed just for clarity, BPM readings and quadrupole offset after 1st iteration are also shown.

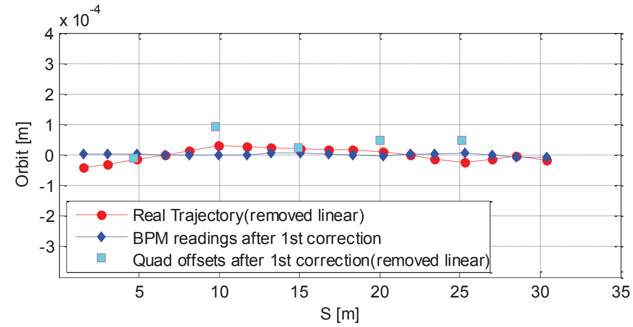

Figure 3: The absolute orbits (removed linear component), BPM readings and quadrupole offset after 1st iteration.

After the 3rd iteration, the rms of the electron trajectory over the length of the undulator with respect to a straight line achieves a value of < 10 µm, while the BPM readings achieve an rms level of 2 µm.

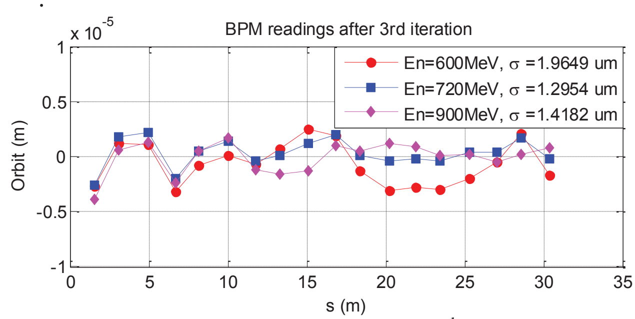

Figure 4: BPM readings after a 3rd iteration.

In practice, the BPM readings give a signal to whether the procedure is converging and when to terminate the beam based alignment process. After 2~3 iterations the BPM readings will change less and less with energy variations. This should provide a clear convergence signal that the spurious dispersion generated by the quadrupole offsets is eliminated simultaneously during the procedure.

100 random seeds have been tested with all the errors listed in Table 1 show the similar results. Then the mean rms and FWHM of these orbits during each iteration are calculated, the results are summarized below in Table 2. In most cases, after 2 to 3 iterations, the final orbit size can be controlled around a few 10µm, the mean rms orbit size after 3rd iteration is about 3~6µm, the FWHM is about 5µm. The mean rms orbit under the energy of 900MeV in each iteration are compared in Fig. 5.

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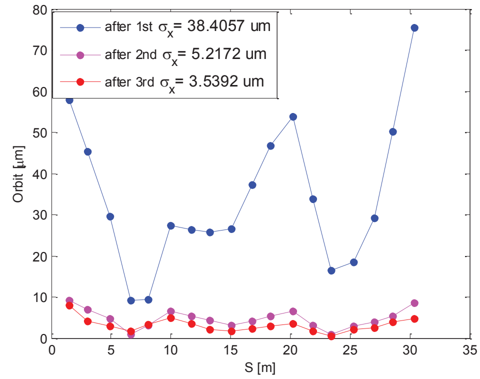

Figure 5: The mean rms orbit at 900MeV in each iteration.

SENSITIVITIES

In order to see the sensitivities of the final trajectory after 3rd iterations to the input errors, a new simulation is run using the errors listed in Table 1, except that for each run the errors are doubled with respect to Table 1. The final orbit sizes are summarized in Table 3 where the second column is the final rms orbit with previous errors in Table 1 and the last column is calculated with doubled errors.

Table 2: The Final rms Orbit Sensitivities to Input Errors

Description	With Previous error	With Doubled error
All error listed in Table 1.	3.53	5.92
Quad & BPM offsets	3.79	4.21
Beam energy error	2.55	2.71
BPM resolution	3.77	6.83
Quad gradient error	3.96	4.52
Undulator pole error	2.67	2.75

As demonstrated in Table 2, the final rms orbits are more sensitive to the resolution of Beam Position Monitor than other errors. A doubled BPM resolution can induce approximate doubled rms orbit size after 3 iterations. But all the results prove the reliability of this BBA algorithm with a final orbit less than 10 μm. Furthermore, a more precise influence of BPM resolution/noise on the final orbit is shown in Figure 6.

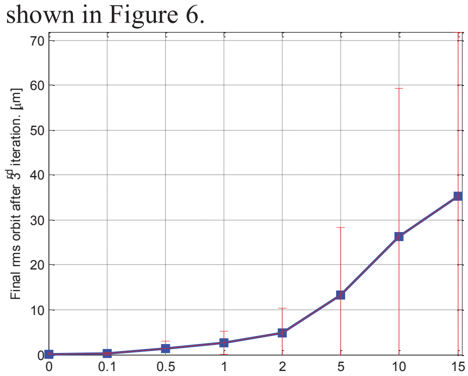

Figure 6: Influence of BPM resolution/noise to the final orbit.

SUMMARY

The beam-based alignment procedure with LCLS method works efficiently in simulations on the FLASH-I undulator. The offsets of quadrupole and BPM can be eliminated simultaneously. Detail simulations demonstrate that using this method, a less than 10μm final orbit with respect to a straight line can be achieved with high confidence after several iteration of correct procedure.

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