

ORBIT AND DISPERSION TOOL AT EUROPEAN XFEL INJECTOR

N. G. Ghazaryan[†], CANDLE Synchrotron Research Institute, Yerevan, Armenia
E. Castro, W. Decking, Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany

Abstract

Trajectory and electron beam size play an essential role in Free Electron Laser (FEL) obtainment. Since transverse dispersion changes off-energy particle trajectories and increases the effective beam size, dispersion and orbit must constantly be controlled and corrected along the whole lattice. In this paper the principles underlying the orbit and dispersion correction tool, developed at DESY, are described. The results of its testing on European XFEL injector are presented.

INTRODUCTION

In a magnetic lattice the dispersion is generated by any type of dipole field, caused for instance by quadrupole misalignments, dipole error fields, field errors of quadrupole magnets, etc. Inside a bunch of electrons, particles with different energies have different trajectories due to dispersion. Consequently, the transverse space, occupied by the beam, increases. For optimal FEL performance it is mandatory to ensure a good beam quality in undulators [1], so the dispersion and orbit must frequently be measured and corrected along the whole lattice.

The schematic layout of the 3-kmetre long European XFEL (X-ray Free- Electron Laser) is shown in Fig. 1. The elements include 1.3 GHz RF sections (yellow), 3.9 GHz acceleration structure (red), undulators (green/red), and main dipole magnets (blue).

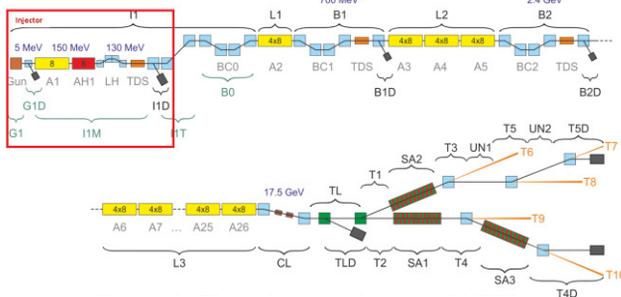


Figure 1: The schematic layout of XFEL.

Currently, the XFEL is under commissioning. For a simultaneous correction of the dispersion and beam orbit a software tool has been developed. It uses a set of corrector magnets; including quadrupoles (adjusted by movers) and the laser heater chicane dipole magnets to minimize the excursions with respect to ideal orbit/dispersion (Dispersion Free Steering), and a set of beam position monitors to measure the orbit changes. It operates based on the Singular Value Decomposition algorithm to calculate corrector angles (strengths).

This paper presents the performance details of the software tool written in MATLAB code, as well as, the results of its testing.

[†] ghazaryan@asls.candle.am

DISPERSION FREE STEERING PRINCIPLE AND FORMALISM

The dispersion free steering correction algorithm [2] guarantees that the beam orbit stays within acceptable values, minimizing the dispersion at the same time. The resulting orbit and dispersion change is achieved through the variation of the corrector's strength, which is given by:

$$\begin{pmatrix} (1-\alpha) \cdot \Delta \vec{u} \\ \alpha \cdot \Delta \vec{d} \end{pmatrix} = \begin{pmatrix} (1-\alpha) \cdot OR \\ \alpha \cdot DR \end{pmatrix} \cdot \Delta \vec{\theta} \quad (1)$$

where $\Delta \vec{u}$ and $\Delta \vec{d}$ are the vectors formed by the orbit and dispersion changes at all N monitors, respectively, $\Delta \vec{\theta}$ is the vector formed by all the M correctors' strengths, OR is the N×M orbit response matrix, DR is the N×M dispersion response matrix and α is a weight factor. In general, the optimal closed orbit and dispersion are not of the same magnitude and the weight factor α must correspondingly be adjusted. Depending on its value we can get either pure orbit ($\alpha = 0$) or pure dispersion ($\alpha = 1$) corrections. Applying the least square algorithm to equation Eq. (1), we minimize the following expression:

$$(1-\alpha)^2 \left\| \vec{u}_{measured} - OR \cdot \Delta \vec{\theta} \right\|^2 + \alpha^2 \left\| \vec{d}_{measured} - DR \cdot \Delta \vec{\theta} \right\|^2 \quad (2)$$

However, the solutions given by this approach might exceed the limits of acceptable corrector strengths. Since these settings are not feasible, the standard solution would be to disable a subset of correctors and remove the corresponding lines from the linear system of Eq. (1). Regularization can also be obtained by extending Eq. (1) to constrain sizes of corrector kicks. Moreover, when more correctors are available than BPMs, null vectors can be used to reduce corrector strengths. This leads to the following system:

$$\begin{pmatrix} (1-\alpha) \cdot \Delta \vec{u} \\ \alpha \cdot \Delta \vec{d} \\ \vec{0} \end{pmatrix} = \begin{pmatrix} (1-\alpha) \cdot OR \\ \alpha \cdot DR \\ \beta I \end{pmatrix} \cdot \Delta \vec{\theta} \quad (3)$$

where $\vec{0}$ is a null vector of dimension M, I is a unit matrix of dimension M×M, and β is a kick weight.

The goal of the orbit and dispersion correction tool is to solve the system in Eq. (3) and get the $\Delta \vec{\theta}$ that minimizes

the excursions. To solve the system, the Singular Value Decomposition method (SVD) is used [3].

RESPONSE MATRICES AND DISPERSION MEASUREMENT

In order to be able to implement the correction algorithms, two matrices are needed: the orbit (OR) and dispersion (DR) response matrices. They describe how the changes in the strength of the correctors affect the change of orbit and dispersion. These matrices can be measured directly on the accelerator, by tracking the orbit and dispersion of a particle after acting on a corrector, but this is time consuming. Instead, they can be obtained from the transfer matrices between the correctors and the BPMs. From linear transport theory for a transmission line, the beam motion evolves as:

$$\begin{aligned} x_{final} &= R_{11} \cdot x_0 + R_{12}x'_0 + R_{13} \cdot y_0 + R_{14} \cdot y'_0 + R_{16} \cdot \left(\frac{\Delta p}{p_0}\right) \\ y_{final} &= R_{31} \cdot x_0 + R_{32}x'_0 + R_{33} \cdot y_0 + R_{34} \cdot y'_0 + R_{36} \cdot \left(\frac{\Delta p}{p_0}\right) \end{aligned} \quad (4)$$

A general matrix notation including first and second-order terms is:

$$u_{i\ final} = \sum_j R_{ij} \cdot u_{0j} + \sum_{j,k} T_{ijk} \cdot u_{0j} \cdot u_{0k} \quad (5)$$

The elements of the OR matrices are then:

$$OR_{ij} = \frac{\Delta \vec{u}_i}{\Delta \theta_j} = R_{12j \rightarrow i}, R_{34j \rightarrow i} \quad (6)$$

And the DR matrix can be obtained as:

$$DR_{ij} = \frac{\Delta \vec{d}_i}{\Delta \theta_j} = T_{126j \rightarrow i}, T_{346j \rightarrow i} \quad (7)$$

where Δu_i and Δd_i are the orbit and dispersion changes in i -th BPM, respectively, caused by a $\Delta \theta_j$ change of j -th corrector strength, R_{12} / R_{34} and T_{126} / T_{346} are first and second order terms for horizontal/vertical plane, correspondingly. In our case, the OR matrix was built using the R_{12} and R_{34} terms provided by the Optics Server [4], but the DR matrix was measured empirically in the machine.

Dispersion Measurement

If the energy of the beam differs from the design energy, its trajectory may deviate from the one of a particle at the right energy. In first order, this deviation is linear in the momentum deviation $\delta = (\Delta p / p_0)$. For a transport line:

$$\Delta x_{final} = R_{16} \cdot \delta, \quad \Delta y_{final} = R_{36} \cdot \delta \quad (8)$$

R_{16} and R_{36} are often called first-order transverse dispersion.

The dispersion measurement in the tool is based on reading out the orbit for different beam energies [5] that can be changed in modules A1 or AH1 (see Fig. 1). The process is as follows:

1. Change the energy in A1.
2. Measure the orbit in the BPMs.
3. Calculate the dispersion as the slope of the second order polynomial fit of the beam position vs energy.

Figure 2 shows the screenshot of the measurement of the dispersion. The top two plots represent the beam orbit for different energies and the lower two plots show the measured dispersion (horizontal and vertical).

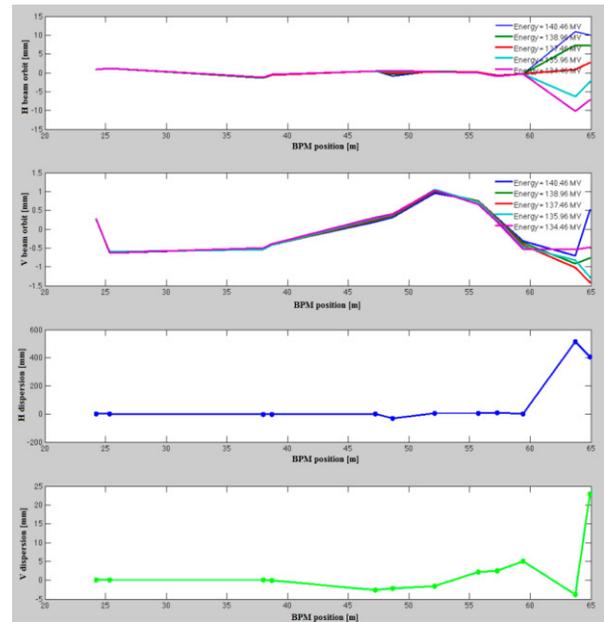


Figure 2: Example of vertical and horizontal dispersion measurements.

Dispersion Response Matrix Measurement

As it was said before, the dispersion response matrix was obtained empirically for the XFEL injector with an extra MATLAB tool developed for this purpose. Once the matrix was calculated, it was loaded into the orbit and dispersion correction tool. The process for the measurement is as follows:

1. Measure initial dispersion as described previously.
2. Apply a kick in one corrector upstream A1.
3. Measure dispersion again.
4. Set back the kick to initial value.
5. A new column in the response matrix is obtained by subtracting the measured dispersion minus the initial dispersion.
6. Repeat from point 2.

Figure 3 shows a screenshot of the calculation of the dispersion response matrix. The tool displays the following: The left plots are for the horizontal plane and the right plots for the vertical plane. The lower plots display the final matrices. The upper plots display, for each cor-

rector, the calculated dispersion. The middle plots display how the dispersion in the other plane is affected (cross-talk).

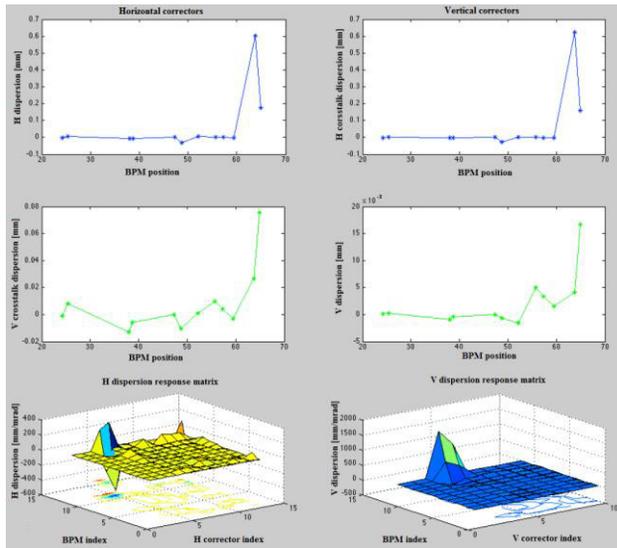


Figure 3: Example of the dispersion response matrix measurements.

BRIEF OVERVIEW OF THE TOOL

The orbit and dispersion correction tool was implemented as a GUI using a MATLAB library developed at DESY [6, 7] and interfaces several servers to get the needed information and to communicate with the elements needed for the corrections (Optics Server, Magnets and BPMs servers, etc.).

The operator can select the following:

- The elements to include in the correction algorithm.
- The correction of orbit only or dispersion and orbit at the same time.
- The plane to be corrected (horizontal or vertical).
- In case the proposed solution $\Delta\tilde{\theta}$ exceeds the limits, the strengths can be reduced by limiting the number of singular values in the SVD solution, by increasing the value of β , or by reducing the size of the calculated angles.
- Dispersion can be measured in the same GUI.

FIRST TESTS AND OUTLOOK

During the operation of XFEL injector the tool was successfully tested several times.

We tried to correct the dispersion and orbit using correctors, including the two last bending magnets in the LH chicane and we succeeded. On the plots the blue lines are the initial, the red ones are the predicted and the green lines are the corrected orbits and dispersions, respectively. In Fig. 4 the dispersion after and before correction is shown.

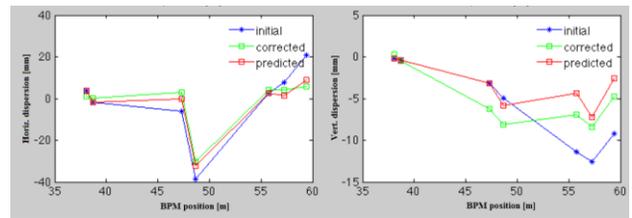


Figure 4: The dispersion screenshot of the correction tool.

We managed to improve the dispersion from almost -38.8 mm to around -30 mm at laser heater chicane (the golden dispersion being -30.1mm) and for the rest part we got an improvement of a factor 10.

We managed to improve the orbit from almost -1.5 mm to around -0.5 mm for horizontal and vertical planes. The result for the orbit is shown in Fig. 5.

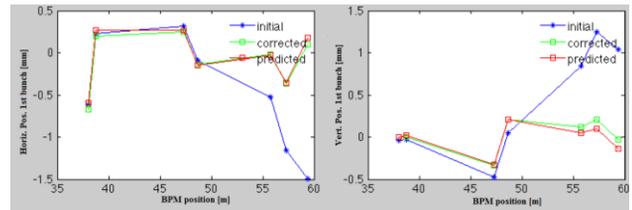


Figure 5: The orbit screenshot of the correction tool.

CONCLUSIONS

The method and the tool for correcting the dispersion and orbit at European XFEL injector, including the dispersion response matrix measurement tools are presented. The tools have been developed and successfully tested by means of simulations and measurements at XFEL injector at DESY. The future all these two tools can be used for the whole beamline as well.

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