ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB176

ESS PROTON BEAM TRAJECTORY CORRECTION

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Abstract

The proton linac of the European Spallation Source (ESS) is under construction in Lund, Sweden. Beam trajectory correction is essential to mitigate the effect of accelerator element misalignment, constituting the first step to minimise beam losses. The correction will be performed using correctors distributed along the accelerator, based on the beam position monitor (BPM) readout. Three trajectory correction techniques are considered: one-to-one steering, Singular Value Decomposition (SVD), and MICADO (selecting a subset of correctors for the trajectory correction). The performance of the three methods is simulated for the ESS linac and a comparison of the outcomes is presented.

INTRODUCTION

The European Spallation Source (ESS) is a spallation neutron source under construction in Lund, Sweden [1]. Once complete, it will consist of a 2 GeV proton linac (Fig. 1) directed towards a metal target for neutron production [2].

The first stage to be commissioned is the Normal Conducting Linac (NCL), which comprises the linac up to the Drift Tube Linac (DTL). The ion source and Radio Frequency Quadrupole (RFQ) do not have any elements for beam trajectory correction, whilst the Low Energy Beam Transport (LEBT) line only has two correctors and thus the steering in the LEBT is relatively simple. As a result, the main focus of the NCL beam trajectory correction is on the Medium Energy Beam Transport (MEBT) line and the DTL; the simulation of the trajectory correction in these two sections is presented in this paper.

The correction is performed using correctors distributed along the accelerator, based on beam position monitor (BPM) readouts. The correctors and BPMs are interleaved in the DTL. However, as there are more correctors than BPMs in the MEBT (Table 1), there are three instances where there is a pair of correctors between two consecutive BPMs, which affects the correction techniques discussed here.

Three trajectory correction techniques are envisaged for ESS: one-to-one steering, Singular Value Decomposition (SVD) based steering and MICADO (selecting a subset of correctors for the trajectory correction). These are presented below.

ONE-TO-ONE STEERING

The first method consists in performing a local correction, where the beam position offset at one BPM is minimised by using one upstream corrector, and performing this process one by one from the first BPM to the last (referred to as one-to-one steering). This method has already been tested and validated for the ESS NCL [3] and in particular it was found to provide reasonably good steering, with a stabilisation performance ~100 µm worse than that of SVD in most of the locations. Therefore, this paper will concentrate on the other two correction techniques.

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SVD BASED STEERING

The position of the beam is measured at m BPMs to construct a vector $\mathbf{b}$:

$$\mathbf{b} = \begin{pmatrix} b_1 \\ \vdots \\ b_m \end{pmatrix}. \tag{1}$$

These beam position offsets can be corrected by n correctors. The changes in corrector settings are described by a vector $\mathbf{x}$:

$$\mathbf{x} = \begin{pmatrix} x_1 \\ \vdots \\ x_n \end{pmatrix}. \tag{2}$$

The effect of $\mathbf{x}$ on the trajectory, as measured at the BPMs, is $A\mathbf{x}$, where A is a $m \times n$ response matrix. The response matrix is assembled, in advance, by calculating the beam offset at each BPM due to a unit change of each corrector.

The SVD of the response matrix A is a decomposition of the following form:

$$A = U \Sigma V^T \tag{3}$$

where U and V are orthogonal matrices, and Σ is a $m \times n$ diagonal matrix, whose diagonal entries σ_i are the singular values of A. For the case in the MEBT where $m < n$:

$$\Sigma = \begin{pmatrix} \sigma_1 & 0 & \cdots & 0 & 0 & \cdots & 0 \\ 0 & \sigma_2 & \cdots & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & 0 & 0 & \cdots & 0 \\ 0 & 0 & 0 & \sigma_m & 0 & \cdots & 0 \end{pmatrix}. \tag{4}$$

The singular values $\sigma_1, \sigma_2, \ldots$ are ordered in descending order, thus placing the singular values that will be most efficient in correcting the beam trajectory first.

Table 1: Number of Correctors and BPMs Used in the Beam Simulations for the MEBT and DTL (Note that There Exists an Eleventh Corrector in the Lattice at the End of the MEBT Which has Been Excluded from the Simulations as it is not Expected to Provide a Strong Response at Sownstream BPMs)

Section	Correctors	BPMs
MEBT	10	7
DTL	15	15

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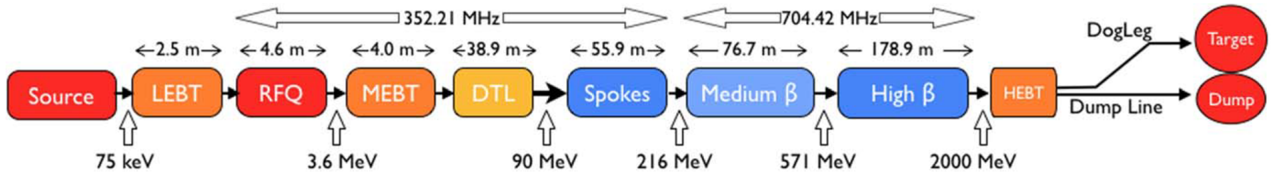
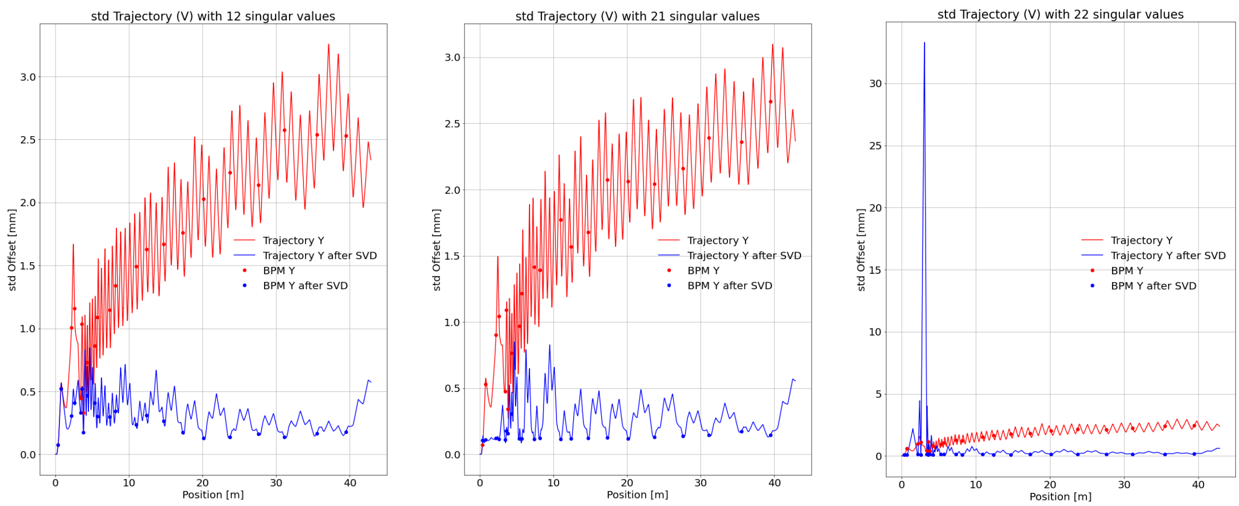


Figure 1: Overview of the ESS layout [2].



(a) (b) (c)

Figure 2: Standard deviation of the vertical beam offsets over 100 simulated machines before (red) and after (blue) SVD correction using (a) 12, (b) 21 and (c) 22 singular values. Positions are given relative to the start of the MEBT. The red and blue points show the results at the BPMs.

The change in corrector settings **x** required to perform the correction is evaluated using [4]:

$$\mathbf{x} = -A^{-1}\mathbf{b} = -V \begin{pmatrix} 1/\sigma_1 & 0 & \cdots & 0 \\ 0 & 1/\sigma_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & 0 \\ 0 & 0 & 0 & 1/\sigma_m \\ 0 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 \end{pmatrix} U^T\mathbf{b}, \quad (5)$$

where A^{-1} is the the pseudo-inverse of the response matrix. One can place a cut on the number of singular values used, removing those that are inefficient at trajectory correction by setting these $1/\sigma_i = 0$ [4].

The residual orbit **r** after applying the correction **x** is given by:

$$\mathbf{r} = \begin{pmatrix} r_1 \\ \vdots \\ r_m \end{pmatrix} = \mathbf{b} + A\mathbf{x}. \quad (6)$$

SVD provides a least-squares solution by minimising $|\mathbf{r}|^2$ [4]. Note that the SVD solution including all singular values converges to that from the conventional least square minimisation.

MICADO

The MICADO[1] algorithm [5] selects a subset of N correctors to be used for trajectory correction. It provides a global least-squares solution like SVD by finding the correction **x** which minimises $|\mathbf{r}|^2$. In this case, no cut is made on the number of singular values. The MICADO routine first identifies the single corrector which best minimises $|\mathbf{r}|^2$ and then proceeds to identify the next best corrector until the specified number of correctors has been identified.

RESULTS

The ESS MEBT and DTL section was simulated in OpenXAL [6, 7] using the measured offsets, roll angles and field errors for the DTL quadrupoles. In addition, an additional random misalignment taken from a ±200 µm uniform distribution was applied to all quadrupoles. The SVD and MICADO algorithms were executed on 100 misaligned machines, using a BPM offset error taken from a ±200 µm uniform distribution plus a BPM resolution error of 20 µm.

The reduction in the beam offset on applying SVD is shown in Fig. 2. The correction is optimised at the BPMs, as the beam offset at the BPMs constitutes the input to the correction algorithm. The correction improves when increasing

[1] In French, *Minimisation des Carrés des Distortions d'Orbite* (Least-Squares Minimisation of Orbit Distorsions).

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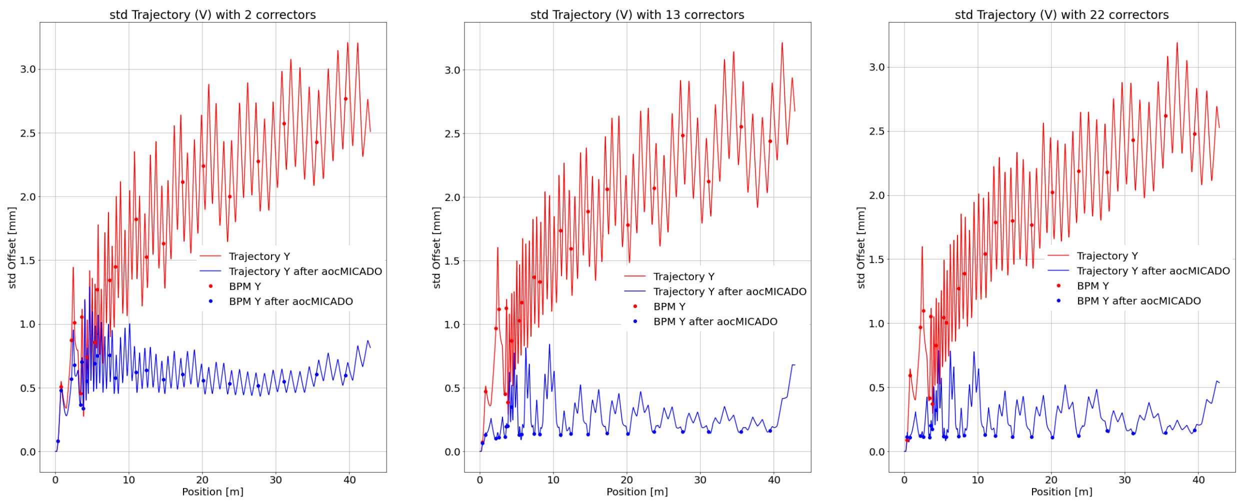

(a) (b) (c)

Figure 3: Standard deviation of the vertical beam offsets over 100 simulated machines before (red) and after (blue) aocMICADO correction using (a) $N = 2$, (b) $N = 13$ and (c) $N = 22$ correctors. Positions are given relative to the start of the MEBT. The red and blue points show the results at the BPMs.

the number of singular values from 12 to 21, reaching a standard deviation (std) offset spread of less than 0.2 mm at the BPMs and under 0.8 mm elsewhere. Note that these results are achieved after applying a single SVD correction on each misaligned machine, whereas in practice multiple SVD iterations would be performed after first executing one-to-one steering, which may improve the results further.

An important result is that on using all 22 singular values (Fig. 2(c)), an overcorrection is observed in the MEBT. This overcorrection is located at a point where there are two correctors between two consecutive BPMs, and is associated to the result of including the lowest singular value. To overcome this case of corrector redundancy [8], one can restrict the number of singular values used to obtain the performance given in Fig. 2(b).

Applying MICADO with $N \geq 14$ correctors (out of the total of 25 correctors) also leads to overcorrection in the MEBT. Note that using MICADO with all the available correctors ($N = 25$) is equivalent to performing SVD with all 22 singular values, and the same performance is observed for both, as expected.

A modified algorithm, antiovercorrection MICADO (aocMICADO), was developed for cases where there is a pair of correctors (referred to as A and B) between an adjacent BPM pair. The algorithm prevents the use of corrector A in the MIACDO routine if corrector B is already in use or vice versa. The results of running aocMICADO up to the maximum of 22 allowed correctors, shown in Fig. 3, demonstrate a successful correction with no overcorrection in the MEBT. In particular, the MICADO correction achieves a std offset spread of less than 0.2 mm at the BPMs and below 0.8 mm elsewhere even when using only 13 of the available 25 correctors (Fig. 3(b)); an almost identical performance is achieved when using the maximum of 22 correctors (Fig. 3(c)).

CONCLUSIONS

Three trajectory correction techniques are planned for the ESS NCL beam commissioning: one-to-one steering, SVD and MICADO. The one-to-one steering provides an efficient correction technique during set-up, whilst SVD and MICADO allow for a global correction to be performed. We have performed beam simulations using realistic element misalignments and BPM offset and resolution errors, to demonstrate the feasability of beam stabilisation at the sub-mm level.

We have observed that having more correctors than BPMs in the MEBT may lead to overcorrection in between consecutive BPMs, whilst continuing to provide excellent correction at the BPMs. For these cases, our simulations show that the overcorrection can be avoided by cutting on low singular values or deploying a modified MICADO alogorithm which prevents consecutive correctors to be selected if there is no BPM in between.

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