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APPLICATION OF BEAM-BASED ALIGNMENT TO THE CLEAR FACILITY

A. Aksoy[1] *, A. Malyzhenkov, A. Latina, P. Korysko[2], R. Corsini, W. Farabolini
CERN, Geneva, Switzerland
[1] also at Ankara University, Ankara, Turkiye, [2] also at University of Oxford, Oxford, UK

Abstract

The CERN Linear Electron Accelerator for Research (CLEAR) has been operating since 2017 as a user facility providing beams for a large variety of experiments. Its RF photocathode-based linear accelerator can accelerate electrons up to 220 MeV with a bunch charge of 0.1-1.5 nC with single or up to 150 bunches per train. The need of flexibility in providing various beam parameters following user demands causes drawbacks and complexity in operating the accelerator. Standard beam steering based on the sequential variation of quadrupole and corrector magnets, performed by an operator manually, results in a very time-consuming process. This paper presents a tool we developed for automatic and global Beam-Based Alignment (BBA) for CLEAR based on dispersion-free steering and one-to-one corrections to transport beams with various charges and time structures.

INTRODUCTION

The CLEAR user facility based on a 200 MeV electron linac is operated at CERN for various experiments, providing high availability, easy access, and high-quality electron beams. The facility offers R&D opportunities in many areas, such as novel accelerating techniques (like high-gradient RF or THz acceleration), beam instrumentation, testing of electronic components, medical studies on novel radiotherapy methods, etc. [1–3]. A schematic layout of the CLEAR beamline is shown in Fig. 1. The linac, which provides an electron beam covering a large range of parameters [1] as shown in Table 1, is composed of an S-Band RF gun and three S-Band travelling wave accelerating structures.

Table 1: Main Parameters of CLEAR Electron Beam

Parameter	Value	Unit
Beam Energy	30-200	MeV
RMS Energy Spread	<0.2	%
Bunch Length	0.1-10	ps
Bunch Frequency	1.5 / 3.0	GHz
Bunch Charge	0.02-1.5	nC
RMS emittance (norm.)	1-50	mm.mrad
Pulse Repetition Rate	0.833-10	Hz
Nb of bunches per pulse	1-150	#

CLEAR provides beams to a large number of users needing different beam optics for their experiments. Frequently changing the beam parameters starting from the photoinjector often implies applying a new beam orbit correction. Standard beam steering is based on the sequential variation of quadrupole and corrector magnets and is performed by an operator manually. To overcome this time-consuming process, we developed a tool for automatic and global Beam-Based Alignment (BBA) in CLEAR based on one-to-one and Dispersion-Free-Steering (DFS) orbit corrections [4]. This tool has been implemented in the control system.

* avni.aksoy@cern.ch

ORBIT CORRECTION

Transversely misaligned quadrupoles and structures introduce dipole kicks to the bunch, thus causing an orbit shift downstream the beamline. Typically these kicks introduce orbit displacements much larger than the components alignment errors themselves. The kicks are minimized by steering the beam orbit with correctors toward the target orbit. The target orbit may be specified only at one or a few selected locations, or throughout the beam path. This method is referred to as global orbit correction. In general, the objective of orbit correction is to minimize the difference between the measured beam orbit and the target orbit:

$$\chi^2 = \sum_{i=1}^{\text{bpms}} (x_i - \hat{x}_i)^2, \tag{1}$$

where x_i and $\hat{x}_i$ are the measured orbit and the target orbit (which is generally zero) on the i^{th} beam position monitor (BPM), respectively. When the orbit vector is $\boldsymbol{X}_0$, we need to find the desired kick vector $\boldsymbol{\Theta}$ by the corrector magnets to minimize the difference between the measured orbit and the target orbit. After the correction $\boldsymbol{\Theta}$ is applied to the machine, the orbit will change. The predicted new orbit can be computed as:

$$\boldsymbol{X} = \boldsymbol{X}_0 + \boldsymbol{R}\boldsymbol{\Theta}, \tag{2}$$

where $\boldsymbol{R}$ is the orbit response matrix, whose elements are given by:

$$R_{i,j} = \frac{\Delta x_i}{\Delta \theta_j}, \tag{3}$$

where Δx_i is the orbit change at beam position monitor (BPM) i for a kick angle $\Delta\theta_j$ introduced by corrector j. To find the desired kick vector $\boldsymbol{\Theta}$, one needs to minimize Eq. (1) in the least square sense. The desired kick vector can be computed as

$$\boldsymbol{\Theta} = (\boldsymbol{R}^T\boldsymbol{R})^{-1}\boldsymbol{R}^T\Delta\boldsymbol{X} \tag{4}$$

where $\Delta\boldsymbol{X} = \boldsymbol{X} - \hat{\boldsymbol{X}}$ is the difference between the measured beam orbit and the orbit target. To first order, R_{ij} is identical

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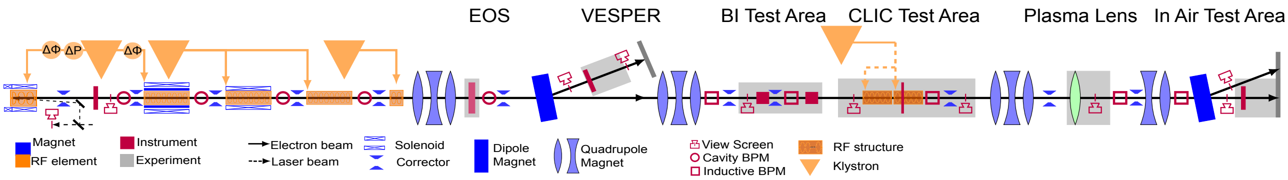

Figure 1: Schematic layout of CLEAR beamline.

to the element M_{12} of the linear transfer matrix M from the j^{th} corrector to the i^{th} BPM. The response matrix can be calculated using orbit differences and, to the first order, is independent of the absolute beam trajectory. The response matrix, on the other hand, can, in principle, be extracted from a computer model of the machine, and improved in accuracy with measurements on the beamline. The accuracy of the response matrix then depends on the quality of the model, which relies on the sensitivity of the diagnostic components of the machine. The response matrix is inferred from measurements on the machine for the tool developed.

Eq. (2) describes the one-to-one correction method, which attempts to steer the beam to the target trajectory by minimizing the reading of each BPM using appropriate corrector strengths. This requires to know the target orbit. Such a technique is useful to ensure that the beam travels through the machine without hitting the vacuum chamber, but in general, since the technique does not take into account the systematic errors introduced by misaligned BPMs, it is not sufficient to minimize nonlinear effects.

DFS [5] is a variant correction scheme that attempts simultaneously to steer the beam to its target orbit and to correct the beam dispersion. Similar to Eq. (1) the objective of DFS is given by:

$$\chi^2 = \sum_{i=1}^{\text{bpms}} x_i^2 + \omega \sum_{i=1}^{\text{bpms}} (x_i' - x_i)^2 + \kappa \sum_{j=1}^{\text{corrs}} \theta_j^2, \tag{5}$$

where x_i' is the orbit of an off-energy test beam, the parameters ω and κ are free and must be tuned to achieve the best performance. The least squares solution of Eq. (5) can be written as:

$$\begin{pmatrix} \boldsymbol{X} \\ \omega(\boldsymbol{X} - \boldsymbol{X}') \\ 0 \end{pmatrix} = \begin{pmatrix} \boldsymbol{R} \\ \omega(\boldsymbol{R} - \boldsymbol{R}') \\ \kappa \boldsymbol{I} \end{pmatrix} \times \boldsymbol{\Theta}, \tag{6}$$

where $\boldsymbol{R}'$ is the response matrix of the test beams used to quantify the dispersion, and $\boldsymbol{I}$ is the identity matrix [6]. DFS requires a test beam that follows a dispersive trajectory to measure the dispersion. This is obtained by creating an energy difference upstream of the beamline section to be corrected and then measuring the orbit deviation in the BPMs.

EXPERIMENT

As it is shown in Fig. 1 the CLEAR linac can be split into two sections: a) an injector, consisting of the RF gun and the first accelerating structure, where the bunches are created and accelerated up to about 50 MeV, and b) the main accelerating section with the two last structures where the beam is accelerated to final energies before being sent to the experimental beamline. The space-charge-dominated injector region requires precise transverse and longitudinal tuning to achieve a specific bunch, pulse charge, bunch length, etc. The main accelerator is then used to optimize the energy spread and reach the final requested energies. Small changes in the injector region easily lead to full beam loss justifying the strategy to limit the use of BBA to the rest of the beamline. Last but not least, the facility is equipped with 5 Cavity BPMs and 5 Inductive BPMs. Due to problems with acquisition systems, only the last 2 cavity BPMs and the 4 inductive BPMs could successfully be implemented in the experiments.

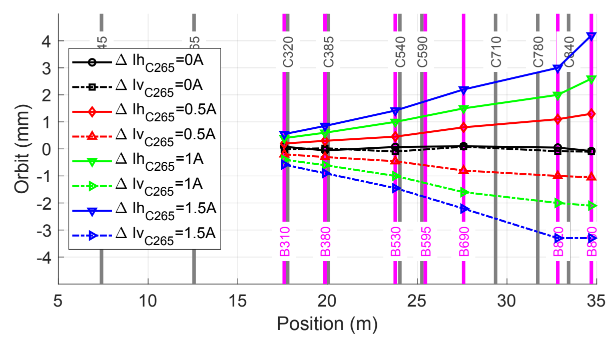

Figure 2: Example of BPM calibration study.

In order to identify the target orbit required for one-to-one correction, a ballistic orbit measurement has been carried out by switching off all the quadrupole and corrector magnets downstream of the last accelerating structure. The beam is steered on the axis of the last two cavity BPMs (B310,B380) by using the preceding two correctors (C245,C265), and transported to the end of the beamline. The resulting beam orbit has been defined as the target orbit. Beam-based calibration of BPMs was performed after subtracting the offset of BPMs from the target orbit. Figure 2 shows the BPM position readings versus the 4$^{\text{th}}$ (C265) corrector current for both horizontal and vertical directions. BPMs are indicated in magenta and correctors in gray. The BPM response is relatively linear in low offset regions but behaves nonlinearly above 2.5 mm. As mentioned, the BPM595 does not provide a realistic signal.

The orbit response matrix is usually measured by exciting each corrector one by one and recording the excited orbit to the matrix. The accuracy of this method depends on the corrector strength limitations and the BPM resolution. In Ref. [7], it has been shown that using many small excita-

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tions over time to gradually improve the system knowledge with the help of system identification (SI) algorithms will reduce the effects of the measurement noise. However, in this method, one needs to excite correctors one by one to find out the orbit response of j^{th} corrector on i^{th} BPM. On the other hand, Eq. (2) can be solved by several sets of excitations by the well-known singular value decomposition (SVD) method [8]. With this method, one can find the zero-orbit for initial corrector strengths and simultaneously the response matrix. Obviously, to have better statistics in the least square problems, one must have more data sets to minimize errors. Both methods were deployed in the control system, and the response matrix was created by exciting correctors in order or randomly. Figures 3 and 4 show the response matrices created by the SI technique as in Ref [7] and SVD, respectively.

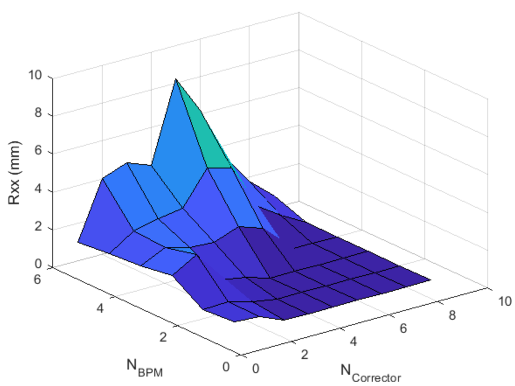

Figure 3: Response matrix created by SI algorithm.

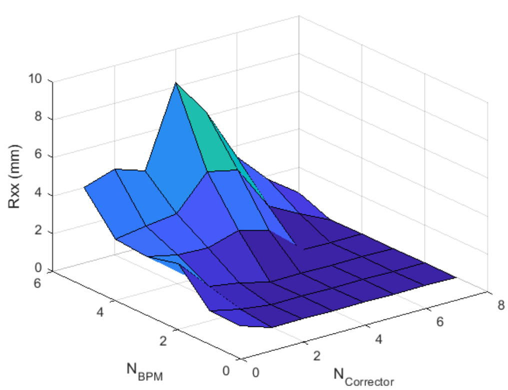

Figure 4: Response matrix created by SVD solution.

As one can see, the response matrices are very similar, which implies both methods can be used for the CLEAR beamline. A train of 10, 300 pC bunches was used for the automated orbit correction phase. The energy is reduced from 200 MeV to 180 MeV by reducing the klystron power. The SVD-based response matrix is generated by employing an algorithm which randomly excites correctors and checks the beam loss at the end of the beamline, saving the orbit only if the losses are less than 25%. After several corrector excitations and filtering of the orbit measurement over 20 pulses, the response matrix is created.

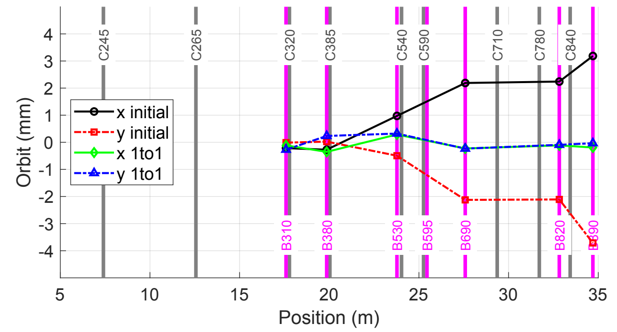

Figure 5: The beam orbit before and after one-to-one correction.

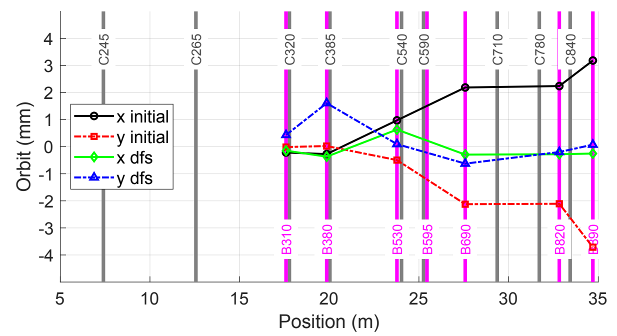

Figure 6: The beam orbit before and after DFS correction.

As mentioned earlier, the orbit that was measured when all magnets were switched off is referred to as the target orbit for both one-to-one and DFS correction. Figures 5 and 6 show the initial and corrected orbits after several iterations of one-to-one and DFS correction. The one-to-one method successfully aligns the beam to the target orbit, while DFS, in an attempt to minimize dispersion, kicks the beam off-axis in the vertical plane, as visible at BPM C385 in Fig. 6. Here, dispersion is likely introduced in the second triplet between positions 20 and 24 m.

CONCLUSION

We have successfully implemented an automated one-to-one and DFS orbit correction algorithms to the CLEAR control system. The experimental test shows that the orbit error can be corrected with several (i.e. 3-5) iterations. The correction is based on a model automatically identified via a series of measurements. The DFS converges to a solution where the total orbit error and the dispersive orbit variation is minimized, while one-to-one tries to align to the target orbit. By properly choosing the singular values of the response matrix and the weights for dispersive orbit and corrector strengths, the DFS correction converges faster. This development should significantly speed up and ease the beam set-up at CLEAR for the user experiments.

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