

TOOLBOX FOR APPLYING BEAM-BASED ALIGNMENT TO LINACS

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MOTIVATION

The performance of future linear colliders such as CLIC or ILC [1, 2] will depend critically on beam-based alignment (BBA) techniques and feedback systems, which will play a crucial role in transporting the beams through the linacs of such machines with minimal emittance growth. The complexity of such techniques is dramatically magnified by the number of correctors and monitors involved in the calculations, where figures go easily beyond the thousands. With such large numbers of parameters, corrections techniques based on human intervention and operators' touch, are not a viable option.

Powerful sets of automatic beam-based alignment techniques have been studied during the last years, and their effectiveness has been accurately assessed with computer simulations. In recent times, the authors of this paper have performed consistent and extensive experimental tests of BBA on real linacs. The main objectives of these tests were at least two: 1) trying to address the effectiveness of such techniques in real operational environments, and 2) trying to establish how far one can go with an automatic application of such procedures, aiming at requiring minimal human intervention.

Tests of BBA have been performed at the FACET linac at SLAC [3], and at Fermi@Elettra in Trieste [4]. The results in terms of emittance preservation have been very promising, as it has been documented elsewhere [5]. To enhance the automatization potential and simplify the operational procedures, powerful tools have been developed and equipped with a graphical user interface (GUI). The GUI allows the user to access all the parameters that control the beam-steering procedures.

Using these tools, it is possible to apply orbit, dispersion, and wakefield correction, separately or simultaneously, while tracking the response matrices, monitoring the relevant observables, and recording on disk the results for post-processing the data. These tools have been used and consolidated in real experiments, and allowed to span a significant fraction of the large parameters space. These tools as well as some of the experimental results are presented in this paper.

INTRODUCTION

Beam-based alignment algorithms have been designed to ensure beam transmission with minimal emittance growth in linacs. Two such techniques are Dispersion-Free Steering (DFS) and Wakefield-Free Steering (WFS), which optimise the trajectory and simultaneously minimise the residual dispersion and wakefields. Details on the DFS and

WFS procedures can be found in [5, 6], where it is shown that the combined application of dispersion and wakefield correction can be computed using the following system of equations:

$$\begin{pmatrix} \mathbf{b} \\ \omega_d (\boldsymbol{\eta} - \boldsymbol{\eta}_0) \\ \omega_w (\mathbf{b}_w - \mathbf{b}) \\ \mathbf{0} \end{pmatrix} = \begin{pmatrix} \mathbf{R} \\ \mathbf{D} \\ \mathbf{W} \\ \mathbf{I} \end{pmatrix} \boldsymbol{\theta}.$$

In this equation \mathbf{R} , \mathbf{D} and \mathbf{W} are respectively the orbit, the dispersion and the wakefield response matrices; \mathbf{I} is the identity matrix; and $\boldsymbol{\theta}$ is the vector of correctors, i.e. the *unknowns* of the system. On the left-hand side \mathbf{b} , \mathbf{b}_w , $\boldsymbol{\eta}$, and $\boldsymbol{\eta}_0$ are the observables: \mathbf{b} is the vector of BPM readings for the beam in nominal conditions; \mathbf{b}_w is the vector of BPM readings for the WFS test-beam with different charge; $\boldsymbol{\eta}$ and $\boldsymbol{\eta}_0$ are respectively the measured and the target dispersion for the DFS. These quantities must be measured at each step of correction. The other parameters are: ω_d is a weighting factor for the dispersion correction, ω_w is a weighting factor for the wakefield correction, β is a regulatory parameter to condition the system. In theory, the weighting factors ω can be estimated using the formula:

$$\omega_{d,w}^2 = \frac{\sigma_{\text{bpm offset}}^2 + \sigma_{\text{bpm precision}}^2}{2\sigma_{\text{bpm precision}}^2},$$

as given in [7]; in practice an empirical fine tuning of these parameters is needed to achieve best performance.

The solution to this system of equations can be found using a least-square method. One may rewrite the system as

$$\mathbf{A}\Delta x = \boldsymbol{\theta},$$

where \mathbf{A} represents the response matrices, and Δx represents the difference between the measured observables and their target values, the solution is the set of correctors $\boldsymbol{\theta}$ that minimises:

$$\|\mathbf{A}\Delta x - g\boldsymbol{\theta}\|$$

where g is the correction gain.

The matrices \mathbf{R} , \mathbf{D} and \mathbf{W} need to be measured experimentally, using a System-Identification Algorithm as described in [8], prior to the BBA correction. The application of the BBA correction occurs at a later moment, and is subject to the values of the free parameters. Two MATLAB tools have been created to control these two phases of the correction procedure: the first is called SysID, and the second BBA.

SYSID TOOL

The user interface of SYSID tool is presented in Fig. 1. The basic function of this tool is to allow the user to select which correctors he intends to measure, and to excite such correctors while recording the response of all BPMs in the beamline. In the window, the left-hand side panel shows the list of selected correctors, and displays how many iterations have been performed per each corrector. The right-hand side panel allows to set the desired amplitude of the oscillations excited to measure the trajectory response. The tool implements an adaptive scheme, thanks to which the target amplitude is always reached based on the information from previous measurements.

The main features of the SysID are its flexibility and robustness. The tool does not depend on any state file (that could get corrupted in case of software failure), but it detects at startup the overall state of the measurement by analysing the files present on disk. This implies that SysID can be interrupted in any moment with no danger at restart. For instance in case one abruptly interrupts the data acquisition for any reason, the last excited corrector is reset and the original state of the machine is restored. Once restarted, SysID will automatically continue from the last corrector that was measured.

Each excited orbit is stored in an independent file, which name carries the information about the corrector it refers to and about the number of iteration. Should the experimentalist realise that a corrector is faulty, or that certain measurements need to be redone, it will be sufficient for him/her to delete the affected files from disk and restart the acquisition. The SysID will automatically remeasure all correctors that are detected as missing.

The computation of the response matrix from the acquired files can simply be performed running a MATLAB script in the same directory where the data files are located. The system-identification algorithms are such that no prior information on “which corrector was excited in a specific data file” is required. The algorithms figure out automatically which trajectories were excited and by which corrector. The longitudinal position of each corrector and BPM in the beamline must be known to enforce a zero matrix element in the response when causality imposes it.

BBA TOOL

The user interface of the BBA tool is shown in Fig. 2. Even at a first glance, it immediately shows the complexity and the large number of parameters that have to be tuned to achieve best performance. The interface is divided into four panels, horizontally distributed:

1. the left-most panel allows the user to select which correctors should be used during the correction and to select which correction scheme each corrector should affect. The options are three: orbit correction, dispersion-free steering, and wakefield-free steering;
2. the second panel, very similarly, allows the user to se-

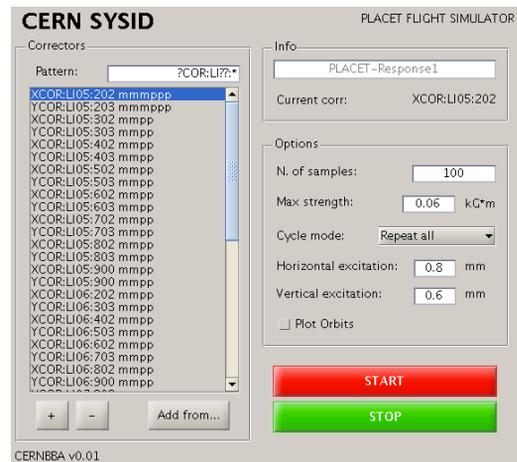


Figure 1: The graphic-user interface of the SysID tool.

lect which BPMs should be used, and which specific correction (orbit, DFS, WFS) each BPM should affect;

3. the third panel stands at the very core of the BBA procedure and is divided, vertically, in two sub panels: the top one allows the user to select which response matrices should be used for the correction, the bottom one allows to set up all the free parameters that have been mentioned previously;
4. the right-most panel allows the user to define how to change the energy for dispersion measurement (and how to reset it), as well as how to change the bunch charge for wakefield measurement (and, again, how to reset it). These instructions appear as generic MATLAB calls that the user can define in any arbitrary form.

As said, the most important panel is probably the central one, which allows the user to fully control the BBA procedure. The top part of this section allows the user to select which response matrices must be used for the correction, e.g. the results of the SysID measurements. The bottom sub panel is the most important one, as it allows to set up all parameters that have been mentioned previously. From top to bottom, it allows to set: the correction gain g , the weights $\omega_{o,d,w}$ (expliciting ω_o for the orbit correction, tacitly set to 1 in the previous equations), and (bottom line) the number of singular values that have to be considered when computing the correction. This is a measure to improve the conditioning of the system. The BBA tool allows also to enforce a feed-forward scheme which flattens the orbit in some specific BPMs. This is intended to be used to control the trajectory at the linac end, while one is correcting the orbit at the linac beginning.

During the correction, each response matrix is updated, iteration per iteration, to include the information coming from the newly measured orbits. This makes the algorithms capable of improving the system knowledge while the experiment is being performed.

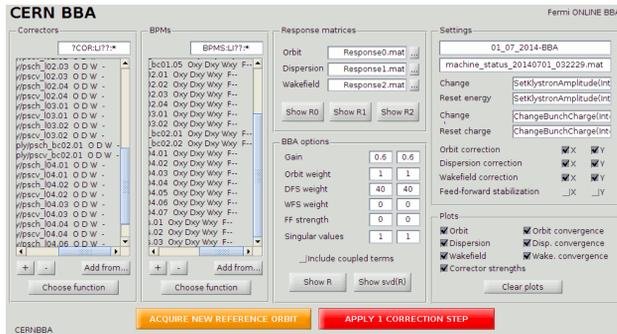
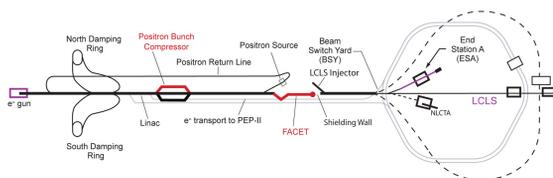


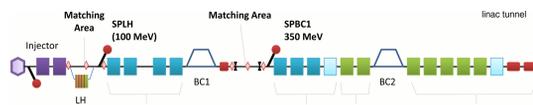
Figure 2: The graphic-user interface of the BBA tool.

EXPERIMENTAL SETUP

We performed our tests at FACET at SLAC, in the USA [3], and at Fermi at Elettra, in Italy [4]. At SLAC, the first 2 km of the SLC linac are used to inject electron/positron bunches in the FACET experimental area. At Fermi@Elettra, about 300 meters of linac are used to accelerate and compress the bunches prior to sending them to the undulator lines. Figure 3 shows the layout of both machines. We performed tests of DFS and WFS at both machines. In the SLAC case we used 44 correctors in X and 44 in Y in the first 300 meters of the linac, where the effect of the wakefields is believed to be stronger. At Fermi, we used 20 correctors in X and 20 in Y over the entire length of the linacs.



(the SLAC accelerator complex, including the linac and FACET)



(the Fermi Free-Electron Laser at Elettra)

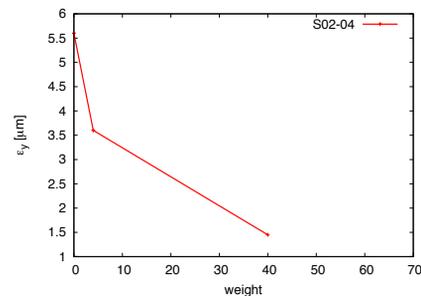
Figure 3: The linacs used for our tests.

EXPERIMENTAL RESULTS

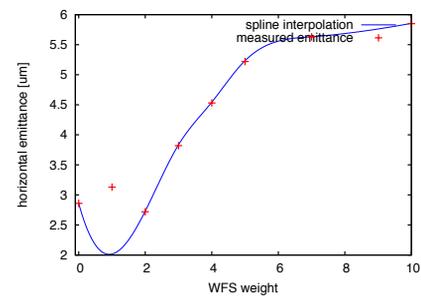
In both machines, the experimental procedure was: 1) measure the nominal optics, 2) measure the dispersive optics, 3) measure the wakefield optics; 4) apply the correction. Steps 1) to 3) consist in measuring the response matrix of orbit, dispersion, and wakefields respectively. The details of this operation are reported in [5, 8].

The result of the WFS correction is summarised in Fig. 4, where the emittance after correction is shown against the

weight ω_w . In both cases the initial emittance before correction corresponds to $\omega_w = 0$. At FACET the initial vertical emittance was measured, using a quad scan at the end of the corrected section, to be $5.4 \mu\text{m}$. The emittance after correction was $1.4 \mu\text{m}$ at the theoretical optimum $\omega_w = 40$. From repeated measurements, the precision was measured to be $\approx \pm 0.4 \mu\text{m}$. At Fermi, the initial horizontal emittance was $2.86 \mu\text{m}$. The emittance after correction at the optimum of the ω_w , was $2.70 \mu\text{m}$. The resolution of the measurement is $0.05 \mu\text{m}$.



(case of FACET)



(case of Fermi)

Figure 4: Vertical emittance after WFS as a function of the weight ω_w .

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CONCLUSIONS AND OUTLOOK

A beam steering technique meant to simultaneously reduce the impact of dispersion and wakefields on the emittance in a linac has been tested at FACET and at Fermi@Elettra. In order to make this procedure as automatic and as simple as possible, a set of new tools has been developed. They have been optimised for robustness, and feature a friendly graphical user interface that allows to set the input parameters in an easy way. The results of the experiments are very encouraging.

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