PERFORMANCE OF LINEAR COLLIDER BEAM-BASED ALIGNMENT ALGORITHMS AT FACET

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Abstract

The performance of future linear colliders will depend critically on beam-based alignment (BBA) and feedback systems, which will play a crucial role both in the linear and in the non-linear systems of such machines, e.g., the linac and the final-focus. Due to its characteristics, FACET is an ideal test-bench for BBA algorithms and linear collider beam-dynamics in general. We present the results of extensive computer simulations and their experimental verification.

INTRODUCTION

In ILC and CLIC it is planned to perform dispersion-free steering in the main linacs [1, 2]. To this end the beams are accelerated with different gradients to evaluate the dispersion. The beam steering is then performed by minimizing the average offset of the different beams in the beam position monitors (BPMs) and, at the same time, minimizing the difference between the beam trajectories. This method is meant to correct both the orbit and the dispersion at the same time (DFS). We propose to implement this method in FACET. The algorithm should: take all available BPM measurements in every cycle (train to train), from this information estimate the correction, which involves some matrix multiplications, then apply it.

For calculating the correction, beam-based alignment algorithms rely greatly on the knowledge of the response matrix, or "model", of the system. Ensuring a good knowledge of the model is therefore a crucial step that must precede the application of any BBA techniques. Several techniques exist to measure the model; given its robustness and rapidity of convergence, we opted for the online system identification algorithm presented in [3].

SYSTEM IDENTIFICATION

Running the system identification algorithm requires to be able to read BPMs and set correctors. The system identification algorithm uses the correctors to excite small beam oscillations that are slightly above the noise level of the BPMs. We have chosen to excite orbits with maximum 1 mm excursion. Several orbit measurements of the oscillations are combined using the recursive least square algorithm (RLS) to average out the BPMs noise and reconstruct the response matrix.

BEAM-BASED ALIGNMENT

One-to-one correction technique steers the beam to its nominal trajectory using the BPM readings and the orbit response matrix. This is useful to get the beam go through the machine, but it is generally not sufficient because it does not correct the systematic errors introduced by the misaligned BPMs. To overcome this limitation, dispersion-free steering attempts not just to steer the beam to its nominal orbit, but also to correct the beam dispersion at the same time. Applying DFS corresponds to solving the following system of equations:

$$\begin{pmatrix} & & \mathbf{b} \\ \omega & \cdot & (\boldsymbol{\eta}-\boldsymbol{\eta_0}) \\ & & \mathbf{0} \end{pmatrix} = \begin{pmatrix} & & \mathbf{R} \\ \omega & \cdot & \mathbf{D} \\ \beta & \cdot & \mathbf{I} \end{pmatrix} \boldsymbol{\theta},$$

where $\mathbf{R}$ and $\mathbf{D}$ are the orbit and the dispersion response matrices, $\mathbf{I}$ is the identity matrix; $\boldsymbol{\theta}$ is the vector of (unknown) corrections; $\mathbf{b}$, $\boldsymbol{\eta}$, and $\boldsymbol{\eta_0}$ are the observables: the BPM readings, the measured dispersion and the target dispersions; whereas the other parameters are free and need to be tuned to achieve best performance: ω is a weighting factor to balance between the orbit and the dispersion correction, and finally β is a free parameter to be tuned to limit the amplitude of the corrections. The factor β is always chosen empirically, whereas the weighting factor ω can be estimated using the formula:

$$\omega^2 = \frac{\sigma^2_{\text{bpm offset}} + \sigma^2_{\text{bpm precision}}}{2\sigma^2_{\text{bpm precision}}}.$$

A careful choice of the free parameters is crucial to achieve optimal performance.

Dispersion-free steering requires the use of a test-beam with different energy to measure the dispersion along the linac. We see at least three possible ways for creating the energy difference necessary for dispersion-free steering: moving the phase shifters to modify the energy gain in some sectors, changing the klystron amplitudes (or switching off some klystrons), and using BPM readings from both positrons and electrons trains to evaluate the dispersion along the line.

SIMULATIONS

A simulation of the SLC linac from sector 2 to sector 19 has been performed to evaluate the performance of dispersion-free steering, using the tracking code PLACET [4]. In the following, a few details on the beam-based alignment techniques that have been used will be given. The results of the simulations will also be illustrated. Prior to apply dispersion-free steering it is beneficial to apply 1-to-1 correction. A summary of the relevant parameters of the simulation is presented in Tab. 1. BPM resolution is 5 μm, as averaged measure over 100 orbit samples.

System Identification

The system identification algorithm runs to identify the linac response. The quality parameter used to quantify the

ISBN 978-3-95450-115-1

Table 1: (top) Misalignment and BPM precision values used for in the SLC linac simulation. (bottom) Relevant beam parameters at sector-2 injection.

Symbol	Value, RMS
$\sigma_{\text{quadrupole offset}}$	100 μm
$\sigma_{\text{bpm offset}}$	100 μm
$\sigma_{\text{bpm precision}}$	5 μm

Symbol	Value
$\gamma\epsilon_x$	$3.0 \cdot 10^{-5}$ m $\cdot$ rad
$\gamma\epsilon_y$	$0.25 \cdot 10^{-5}$ m $\cdot$ rad
σ_z	1 mm
σ_E	1%
q	3.24 nC
E_0	1.19 GeV

algorithm convergence is the "Frobenius" distance between the estimated response matrix and the "theoretical" matrix, calculated numerically:

$$\delta R = \frac{\|\Delta R\|_{\text{F}}}{\|R\|_{\text{F}}} = \frac{\|R_{\text{measured}} - R_{\text{theoretical}}\|_{\text{F}}}{\|R_{\text{theoretical}}\|_{\text{F}}}.$$

The definition of "Frobenius" norm is $\|R\|_{\text{F}} = \sqrt{\text{tr}\,(RR^T)}$. The result of the simulations, showing the convergence for different values of the permitted excitation, are shown in Fig. 1. There the black line, that is the line manifesting the quickest convergence, corresponds to the realistic case of 1 mm orbit oscillation.

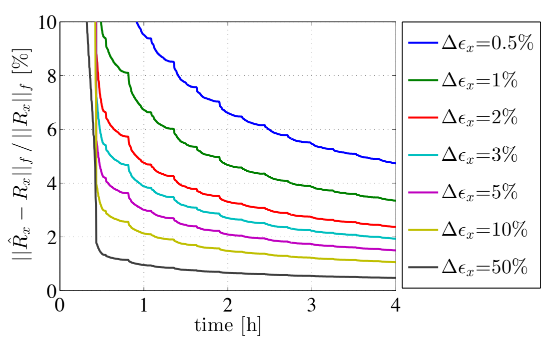

Figure 1: Convergence of the system identification algorithm. A relative error of 1% is considered sufficient to perform BBA. The result is the average of 100 random seeds.

Beam-Based Alignment

In order to create the energy difference necessary to measure the dispersion, we have offset the sub-booster phases, in sectors 2-6 and 11-16, by -5 degrees. A careful selection of the free parameters has lead us to select $\beta = 1$ [μm/kV], $\omega = 14$ as working point of our algorithms. Furthermore, the linac has been divided in 16 bins, with 50% overlap. The results of the simulations are shown in Fig. 2.

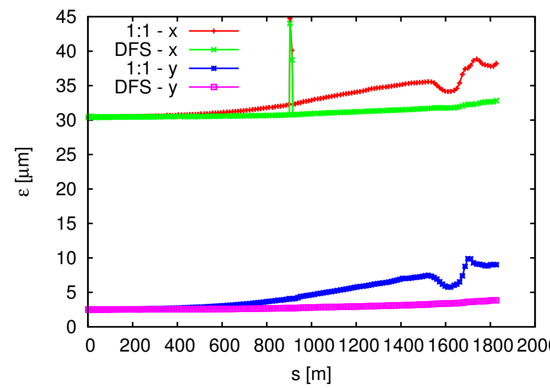

Figure 2: Emittance growth with static imperfections, after beam-based alignment. The result is the average of 100 random seeds.

Beam-Based Alignment with an Imperfect Model

In order to simulate the impact of an imperfect model knowledge, we have applied BBA using imperfect response matrices of arbitrary relative error with respect to the theoretical one. Given a matrix $R_{\text{theoretical}}$, one can create a matrix with arbitrary r.m.s. relative error "derr" using the following algorithm:

1. define:

$$R_{\textsf{mask}} := \begin{cases} 1 & \text{if } R_{\text{theoretical},ij} \neq 0 \\ 0 & \text{if } R_{\text{theoretical},ij} = 0 \end{cases}$$

2. calculate:

$$R_{\textsf{imperfect}} := R_{\text{theoretical}} + \frac{\|R_{\text{theoretical}}\|_{\text{F}}}{\|R_{\text{mask}}\|_{\text{F}}} \cdot$$

$$\cdot\, (R_{\text{mask}}\ \texttt{.*}\ \texttt{randn(size(}R_{\textsf{mask}}\texttt{))}) \cdot \texttt{derr}$$

where R_{mask} is a matrix containing one for the elements of $R_{\text{theoretical}}$ that are different than zero and zero for all the others; "`randn()`" is a matrix with normally distributed random elements, the same size as $R_{\text{theoretical}}$; and "`deer`" is the desired relative error.

We have simulated the emittance growth of 1000 random seeds using the same set of free parameters described in the previous paragraph. We simulated 1000 random seeds because the numerical sampling of the system must not just take into account the randomness of the misalignments, but also the arbitrariness of the response matrix; so each seed is subject to a different set of misalignments and a different imperfect response matrix. Figure 3 shows the impact of a 1% error and 5% error on the performance of our BBA.

EXPERIMENTAL VERIFICATION

We propose to verify the performance of the alignment algorithms at the 2 km FACET SLC linac. The alignment will be performed in bins of 2-3 betatron oscillations length, which corresponds to a few 100 meters of linac length. 50% overlap between the bins is foreseen. The

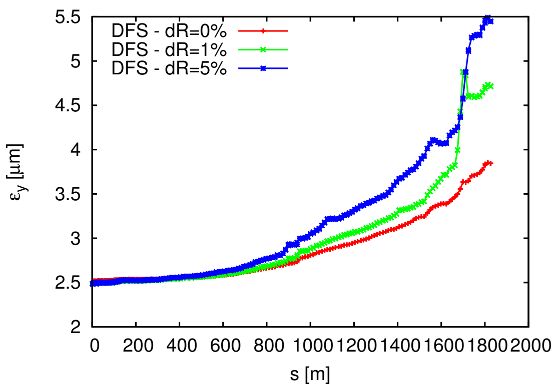

Figure 3: Emittance growth after dispersion-free steering with imperfect model, compared to the case with perfect mode. The results are the average of 1000 random seeds.

dispersion-free steering depends strongly on the BPM effective resolution. By averaging over 100 orbits per machine set-point we find an effective BPM resolution of 3 μm. At 10 Hz machine operating rate, identifying one full bin of the machine takes in the order of 1 hour.

A flight-simulator tool for FACET was developed using PLACET. PLACET interfaces with the SLAC hardware using a Matlab script that dumps the complete machine state, including real-time energy profiles and real-time magnet settings, at a given point in time. We generate automatically a machine model from the machine state, with no dependence on static model information. Longitudinal and transverse wakes are included in the model using the Karl Bane approximation [5]. This tool has proved very useful for optimizing parameters for the alignment algorithms using a realistic machine.

The experimental procedure is: 1) identify the nominal optics, 2) apply global orbit correction, 3) identify the dispersive optics (after changing the klystron settings) and 4) apply the dispersion-free steering. Since the alignment is done in bins, it is important that the effect of new corrector settings on a bin upstream is compensated for downstream. If not losses may be induced downstream, especially close to the FACET experimental area, leading to MPS issues. A feed-forward was implemented to compensate the effect of the correctors as follows; the response on two bpms in sector 17-18 to the bin correctors was calculated, and four corrector in sector 17 were used to compensate this effect. The advantage with this approach with respect to using existing orbit feed-backs is that the compensation is applied at the same time as the bin correction.

FACET test-beam time in April 2012 was assigned to this work, however, due to unforeseen circumstances (a major power cut occurring the week the test-beam time was scheduled) only a fraction of the allocated beam time had been given at the time of writing of this paper, and the experiments could not be completed as planned. The beam time allocated allowed for identification of the nominal optics and attempts at global orbit correction of a 300 meter bin. Significant coupling was observed in the nominal response matrices. For the correction, we applied also the coupling response matrices, R_{xy} and R_{yx}. In principle the correction should then not be affected by the coupling. Unfortunately the implemented feed-forward did not work perfectly, possibly due to klystron problems when identifying the optics, which slowed down the correction work, and no clear conclusion of the goodness of the correction algorithms can be extracted before completing the experiments.

ACKNOWLEDGEMENTS

We would like to thank Nate Lipkowitz for his tremendous work to create a user-friendly interface to the SCP; and Jean-Pierre Delahaye for his support and his inspiring participation in our experiment (night shifts included).

CONCLUSIONS AND OUTLOOK

Simulations show that the SLC linac can be significantly improved by applying the proposed alignment algorithms. We plan to complete the experimental verification at FACET, building on the experience from the initial beam time this spring. A number of improvements will be done for the next beam time:

- improvement of the feed-forward in order to ensure a constant state of the machine downstream when applying correction to a bin;
- the SLC linac has correctors for both electrons and positron, future corrections should only use the electron correctors. This will reduce the identification time of the machine by a factor 2;
- as the “golden” orbit of the SLC linac is deviating significantly from the zero orbit, we will not steer the global orbit correction to zero, as this may significantly deteriorate the state of the machine; instead, we will try to apply dispersion-free steering to the machine weighting against the golden orbit (instead of the zero orbit).

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