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TESTS OF BEAM-BASED ALIGNMENT 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 in guaranteeing the low emittance transport throughout such machines. BBA algorithms designed to improve the beam transmission in a linac by simultaneously optimising the trajectory and minimising the residual dispersion, have thoughtfully been studied in theory over the last years, and successfully verified experimentally. One such technique is called Dispersion-Free Steering (DFS). A careful study of the DFS performance at the SLAC test facility FACET lead us to design a beam-based technique specifically targeted to reduce the impact of transverse short-range wakefields, rather than of the dispersion, being the wakefields the limiting factor to the FACET performance. This technique is called Wakefield-Free Steering (WFS). The results of the first tests of WFS at FACET are presented in this paper.

INTRODUCTION

In ILC and CLIC it is planned to perform dispersion-free steering (DFS) 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 minimising the average offset of the different beams in the beam position monitors (BPMs) and, simultaneously, the difference between the beam trajectories. We proposed to implement DFS at the SLAC test facility FACET [3] and the results of these successful tests have been presented in [4].To compute the correction, beam-based alignment algorithms rely greatly on the knowledge of the response matrix, or "model", of the system. We found that ensuring a good knowledge of the model is 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 [5].

WAKEFIELD-FREE STEERING

In order to stabilise the beam, one orbit correction technique, called "one-to-one" (or 1:1), is commonly used to steer the beam to a nominal "golden" trajectory, using BPM readings and the orbit response matrix to counteract machine drifts. This technique is useful to keep the beam stable, but it doesn't guarantee that the target trajectory is optimal for emittance transport. To overcome this limitation, dispersion-free steering comes to help attempting to minimise the residual dispersion while controlling the orbit. In order to evaluate the dispersion and correct it, DFS makes use of a test beam with different energy, which "excites" the residual dispersion and makes it measurable. In dispersion-dominated machines DFS is extremely effective in preserving the emittance [6]. On the contrary, in wakefield-dominated machines the impact of DFS can be limited. In such cases, an algorithm similar to DFS has been studied to target the impact of the wakefields: wakefield-free steering (WFS). Similarly to DFS, WFS uses a test beam to "excite" the unwanted transverse wakefield effects and to make them measurable via the BPM readings. The test beam for WFS is one with modified charge.

DFS and WFS can be applied simultaneously, using two test beams. Mathematically, applying DFS and WFS simultaneously corresponds to solving the following system of equations:

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

where $\mathbf{R}$, $\mathbf{D}$ 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 beam with different charge; $\boldsymbol{\eta}$ and $\boldsymbol{\eta_0}$ are respectively the measured and the target dispersion. These quantities must be measured at each step of correction. The other parameters are free and need to be tuned on a particular machine to achieve best performance: 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. The factor β is always chosen empirically, whereas the weighting factors $\omega_{d,w}$ can be estimated using the formula:

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

as given in [6]. Since oftentimes the effective r.m.s misalignment of the BPMs, $\sigma_{\text{bpm offset}}$, and the real resolution of the BPMs, $\sigma_{\text{bpm precision}}$ are unknown, the optimum of the weighting factors can differ from the value given by the formula. An empirical optimisation of these parameters is necessary to achieve best performance, the optimum depending on the specificities of the machine.

Several ways exist for creating the energy difference necessary for dispersion-free steering. We preferred the method already in use at FACET: the phase shifters of one or more kystrons are moved to modify the energy gain in some sectors.

The wakefield dipolar kick due to off-axis accelerating structures can be expressed as:

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$$\Delta y' = \frac{Ne^2 L}{P_{\parallel} c} \cdot \left\langle W_{\perp}^{1} \right\rangle \cdot \Delta y_s,$$

where N is the bunch population, L is the length of the structure and $P_{\parallel}$ is the longitudinal momentum of the bunch at the structure, $\left\langle W_{\perp}^{1} \right\rangle$ is the dipolar wakefield averaged over a bunch length, and Δy_s is the relative offset between the beam and the structure axis. By increasing or decreasing the bunch charge, N, one excites wakefield of different intensities. Using the intensity of the wake as a leverage, aim of the WFS algorithm is minimising the wakefield kicks, that is, WFS finds the orbit that minimises Δy_s. Ultimately, this corresponds to steering the beam to go through the electromagnetic center of the structures, regardless of their absolute transverse offset.

SIMULATIONS OF BBA

A simulation of the SLAC linac from sector 2 to sector 19 was performed to evaluate the performance of dispersion-free steering and wakefield-free steering, using the tracking code PLACET [7]. In our simulations, prior to apply DFS and WFS, the elements were randomly misaligned to simulate systematic misalignments, and 1:1 correction was applied to find an initial "golden orbit". Then DFS and WFS were applied. A summary of the relevant parameters of the simulation is presented in Tabb. 1 and 2. All results reported are the average of 100 random misalignment configurations.

Table 1: Systematic Misalignment Errors and BPM Precision Values used for in the SLC linac simulation.

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

BBA Parameters Study

In order to create the energy difference necessary to measure the dispersion in simulation, 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 $\beta = 1$ and $\omega_{d,w} = 40$ as working point of our algorithms. Furthermore, the linac has been divided in 16 bins, with 50% overlap. For applying WFS, the test beam has been obtained reducing the bunch charge to 50% of its nominal value. The results of the simulations are shown in Fig. 1, strikingly proving the effectiveness of WFS.

Since the performance of DFS and WFS depends on the weights $\omega_{d,w}$, a scan of these parameters has been performed to explore the parameters space. Figure 2 shows the resulting emittance growth after correction as a function of the weight for each individual sources of emittance growth. This study renders manifest how WFS is more effective than DFS in the case of the SLAC linac. The top plot shows that DFS successfully removes the effect of the BPMs alignment error, but at large weights it suffers from the impact of BPM

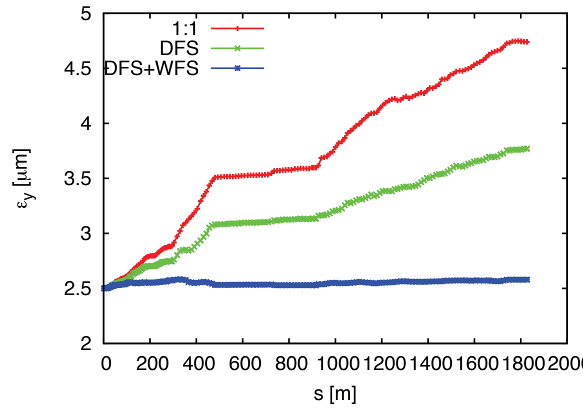

Figure 1: Vertical emittance growth in the SLAC linac under the effect of static imperfections after dispersion-free steering and wakefield-free steering.

precision errors. Also, this plot shows that the accelerating structures are the main sources of emittance growth, due to wakefields, and that DFS is unable to reduce it. WFS comes in the bottom plot, where one can immediately observe how effective this method is in minimising the wakefield-induced emittance growth.

Table 2: Relevant Beam Parameters at Sector-2 Injection

Symbol	Value
$\gamma\epsilon_x$	30 μm
$\gamma\epsilon_y$	2.5 μm
σ_z	1 mm
σ_E	1%
q	3.24 nC
E_0	1.19 GeV

A study on the sensitivity of WFS to the test-beam charge has been performed, as it is shown in Fig. 3. This plot shows that the lower is the charge, the more effective is the algorithm. Nevertheless, a lower limit on the charge exists and comes from the BPMs, whose measurement might become inaccurate at too low charges. For the experiment we chose to work with 80% of the nominal charge.

EXPERIMENTAL RESULTS

In March 2014 we performed several measurements of DFS and WFS in the first 300 meters of SLAC linac, where the impact of the wakefields is particularly strong given the considerable length of the bunches, about 1 mm.

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 [4, 5]. In order to achieve the required BPM resolution (better than 5 μm) we have needed to average the measurement of 100 shots. Including the time required by the control system and the fact that the linac was running at 10 Hz repetition rate, the measurement of each response

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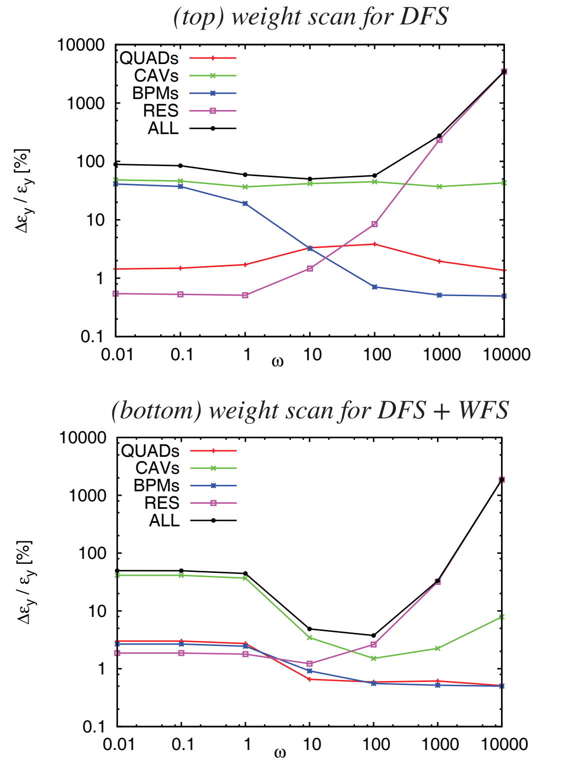

Figure 2: Emittance growth after DFS and WFS as a function of the weight (here indicated as ω). The contributions of each individual sources of emittance growth are isolated. The labels indicate: QUADs, the impact of quadrupole misalignments; CAVs the impact of accelerating cavity misalignments; BPMs, the impact of BPM misalignments; RES, the impact of BPM resolution errors; and ALL, the sum of all these imperfections.

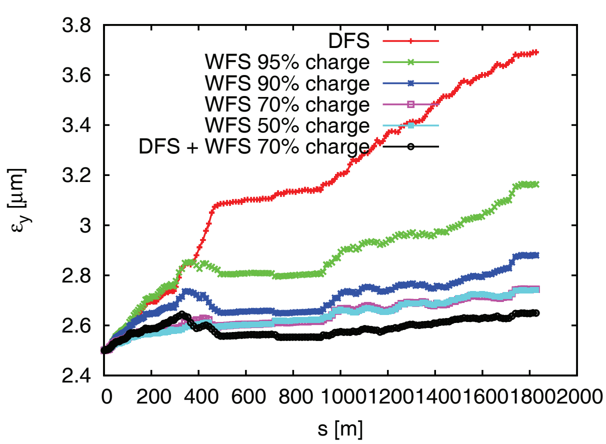

Figure 3: Sensitivity of WFS to the charge of the test beam.

matrix took about 2 hours. After this measurement, the correction is applied.

The result of the correction is summarised in Fig. 4, where the vertical emittance after correction is shown against the weight ω_w, for three points. The initial emittance before correction corresponds to $\omega_w = 0$ and was measured, using a quad scan at the end of the corrected section, to be 5.4 μm. The emittance after correction was 1.4 μm at the theoretical optimum $\omega_w = 40$. From repeated measurements, the precision was measured to be $\approx \pm 0.4$ μm.

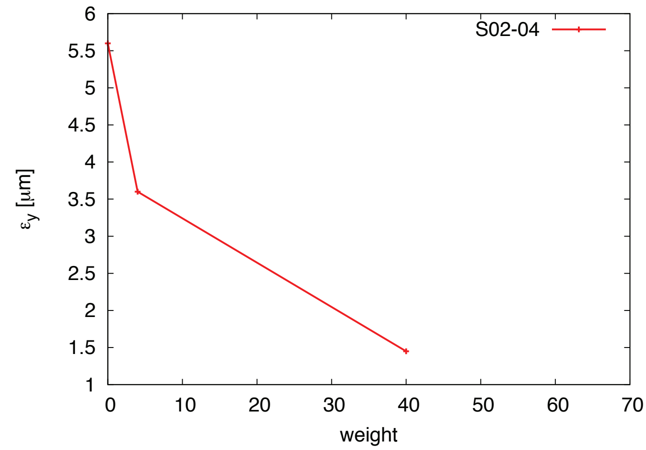

Figure 4: Vertical emittance after WFS as a function of the weight ω_w, measured at the SLAC linac at the end of sector 4.

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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 studied. The SLAC linac is a perfect test-bench for it, given the strong wakefields and relatively long bunches at the beginning of the linac, as simulations have confirmed. Experimental tests of combined DFS and WFS have been performed, showing the effectiveness of this technique. Since the results of DFS and WFS sounds very appealing also to the FEL community, tests of DFS and WFS are also foreseen to be performed at FERMI@Elettra, Trieste. We are working to make our steering tools an operational instrument of beam quality improvement.

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