ATF2 FINAL FOCUS ORBIT CORRECTION AND TUNING OPTIMISATION*

A. Scarfe, R. B. Appleby, University of Manchester and the Cockcroft Institute, Manchester, UK
J. K. Jones, D. Angal-Kalinin, ASTeC, STFC Daresbury Laboratory, Warrington, Cheshire, UK

Abstract

ATF2 is an upgrade to the ATF facility at KEK, Japan consisting of a replacement to the current ATF extraction line and the addition of a final focus section. The final focus system has been designed to test the local chromaticity correction scheme as proposed for future linear colliders. The final focus system focuses the ultra-low emittance beams at the collision point in the linear collider. To provide the required small beam sizes and to maintain the beam sizes to nanometer level requires optimised orbit correction and tuning procedures. In this paper the optimisation of the orbit correction using a global SVD method is discussed, along with the progress on final focus tuning knob analysis. The tuning algorithms used at ATF2 will provide an important feedback for future linear colliders (including the ILC and CLIC).

ORBIT CORRECTION WITHIN THE ATF2 FINAL FOCUS

The ATF2 final focus is a ∼38m long extension to the current ATF extraction line, which has been designed to test the proposed final focus designs of future linear colliders, specifically the change to a local chromaticity-correcting scheme. The line is designed to achieve nano-meter scale beam sizes at the interaction point, and to test both the production and tuning of such small beams, as well as the long term stability requirements to maintain them. The ATF2 final focus contains: 22 quadrupoles; 32 cavity BPMs; 5 sextupoles; 1 pair of dipolar correctors. The lack of dipole correctors is indicative of the non-traditional approach to orbit correction that the ATF2 final focus will take. Traditionally trajectory correction is performed using a set of dual-plane correctors, generating current-dependent kicks in the beam orbit. By controlling the corrector currents the beam trajectory can be controlled. The ATF2 will, however, eschew dipole correctors in favor of magnet movers, a movable platform on which the magnet rests, and which physically moves the quadrupoles transversely with respect to the beam. Transverse motion of the quadrupoles produces dipole fields equivalent to those produced by dipole correctors. Theoretically the magnet movers should be able to create finer granularity kicks than the correctors due to the smaller mover step-size as compared to the corrector currents. The success of the magnet mover method will rely directly on whether it is possible to create an trajectory correction procedure that is as good as, if not better than, a more traditional orbit correction procedure, otherwise the application of the magnet mover method may not be enough to maintain a stable orbit within the ATF2 final focus.

The ATF2 final focus v3.8 [1] has had three magnet movers removed from the beamline since the last iteration, due to the possibility of supply limitations. It is suggested that they are removed from the first 3 magnets in the line. This decision will be tested in simulation, along with the decision to use the magnet mover method of orbit correction.

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ORBIT CORRECTION OPTIMISATION PROCEDURES

Since the general method of orbit correction is the same for the traditional corrector method, and the magnet mover method it is useful to refer to both the correctors and magnet movers by the name ‘controllers’ when discussing their role in altering the beam orbit. The controller-BPM relationships can be ‘mapped’ to a response matrix ($\mathbf{R}$). If the kick change at each controller is $\mathbf{\Delta c}$ and the response produced at each BPM is $\mathbf{\Delta x}$ then

$$\mathbf{\Delta x} = \mathbf{R}.\mathbf{\Delta c} \quad (1)$$

If the BPM readings are known and the response matrix has been measured, the kick changes needed to correct the orbit are

$$\mathbf{\Delta c} = -\mathbf{R_{inv}}.\mathbf{\Delta x} \quad (2)$$

where $\mathbf{R_{inv}}$ is the inverse of the response matrix. If the response matrix is rectangular then there is no definite inverse of the response matrix, in this case $\mathbf{R_{inv}}$ is the pseudo-inverse of the response matrix and is imperfect. Pseudo-inversion is a product of singular value decomposition **SVD**, whose mathematical formulation is broadly available in the literature [2, 3].

The remainder of this section will give a brief overview of the use of SVD in orbit correction procedures, a more detailed explanation can be found in the literature [4]. If ‘M’ is defined as the number of BPMs, ‘N’ is defined as the number of controllers and M and N are non-equal, using SVD the response matrix can be written as

$$\mathbf{R} = \mathbf{U}.\mathbf{W}.\mathbf{V^T} \quad (3)$$

where $\mathbf{U}$, $\mathbf{W}$ and $\mathbf{V^T}$ each have special properties. Given Eqs.(2) and (3) we can define $\mathbf{R_{inv}}$ as

$$\mathbf{R_{inv}} = \mathbf{V}.\mathbf{W_{inv}}.\mathbf{U^T} \quad (4)$$

$\mathbf{W_{inv}}$ is a diagonal matrix of dimensions N X M and the elements are given by

$$W_{inv,ij} = q_{min(ij)}\delta_{ij} \quad (5)$$

$$q_n = \begin{cases} 0, & w_n \leq \varepsilon w_{max} \\ 1/w^n, & \text{otherwise} \end{cases} \qquad (1 \leq n \leq \min(M, N))$$

ε is the singularity rejection parameter in the range [0,1]. This parameter is primarily determined by the requirements of the orbit correction technique. ε controls the number of non-zero eigenvalues of $\mathbf{W}$ that are retained for orbit correction, this results in the number of retained eigenvalues being a selectable parameter.

The selectable parameters governing the efficiency of an orbit correction procedure are:

- The type of controller used in the orbit correction procedure.
- The number of controllers used (N) for orbit correction.
- The number of BPMs used (M) for orbit correction.
- The number of $\mathbf{W}$ matrix eigenvalues retained during the pseudo-inversion of the response matrix.

The comparative efficiency of each orbit correction procedure ψ can be defined as

$$\psi = X_{f,rms}/X_{0,rms} + 2Y_{f,rms}/Y_{0,rms} \qquad (6)$$

where X_f & Y_f are the corrected orbits and X_0 & Y_0 are the original orbits. The vertical direction has a factor 2 weighting due to the 'flat' aspect ratio of the beam.

A combined corrector was included at the end of each quadrupole during simulation tests of the traditional corrector-based orbit correction method.

CORRECTION METHOD COMPARISON

The orbit correction procedures for the traditional corrector-based and the magnet mover-based methods of orbit correction have been optimised and compared (see Table 1), the magnet mover-based method has also been tested with the first three magnet movers removed, referred to as the 'selected movers' method.

Table 1: A Comparison of the Efficiency (see Eqn. 6) of the Optimised Orbit Correction Procedures of Each Controller Type

Controller Type	X_f/X_0	Y_f/Y_0	ψ
Correctors	0.097	0.064	0.225
Magnet Movers	0.095	0.059	0.213
Selected Movers	0.132	0.088	0.308

The magnet mover-based method has been demonstrated to show some improvement over the traditional corrector-based method, however this benefit is lost if not all magnets are on movers, hence a full compliment of magnet movers is needed in order to optimise the ATF2 final focus orbit correction procedure.

Since ATF2 requires a small beamsize, it is important for the orbit correction procedure to not increase the beamsize at the IP by a significant amount (10%), as such it is necessary to compare the IP beamsize growth caused by the different correction methods. The IP beamsize growth before and after each correction method was measured for 100 seeds of errors. It was found that the orbit correction procedures do not always reduce the IP beamsize growth caused by the orbit perturbations and all orbit correction methods have a similar mean beamsize growth value.

The IP beamsize growth's dependency on the misalignment of the magnets within the ATF2 final focus can be determined either on a magnet-by-magnet basis or on a machine-wide basis. In the former of these two options each magnet is off-set individually with no other error sources present and the scale of misalignment that gives rise to a 10% IP beamsize growth is recorded and the values are compared for each magnet and each orbit correction method (Fig. 1). The figure shows a strong dependency between sextupole misalignment and IP beamsize growth, this dependency is unaffected by the orbit correction procedures because none of the orbit correction procedures rely on corrections made at sextupole positions.

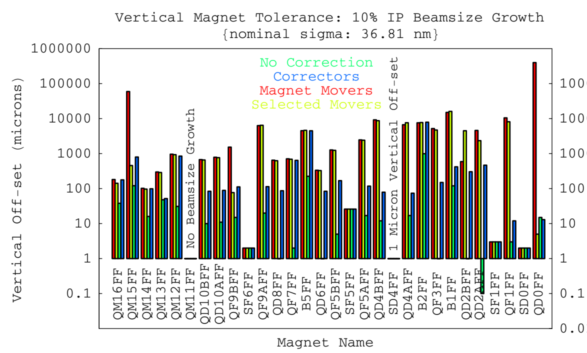

Figure 1: A comparison of the vertical IP beamsize dependency on the vertical misalignment of individual magnets when various orbit correction methods are applied

In the latter of the two misalignment dependency tests, all magnets are given a Gaussian distributed amount of vertical misalignment and the correlation between the scale of vertical misalignment and the amount of vertical IP beamsize growth is determined. The results show an overall reduction in the level of IP beamsize growth when orbit correction procedures are applied, however there is little difference in the amount of reduction caused by each orbit correction procedure. The majority of IP beamsize growth caused by vertical magnet misalignment remained after all orbit correction procedures.

SEXTUPOLE-BASED TUNING KNOBS

Although the previous sections have dealt with optimising the trajectory of the ATF2 final focus line, residual trajectory errors will still remain. These residuals can give rise to higher order errors on the beam and these higher order terms can lead to beam blow up, and thus reduce the effective "luminosity" at the IP.

Correction of these higher order errors in the analogous ILC beam delivery system has previously been investigated [5] using a traditional approach to correction. A new approach to optimisation of the beam size at the IP is to rethink the problem in terms of a so-called beam-response-matrix. In this method the solution is re-imagined as a rotation/compression of the disturbed beam, $beam_{err}$, back to the desired nominal beam, $beam_0$. This is graphically demonstrated in Fig. 2. The rotation/compression of the

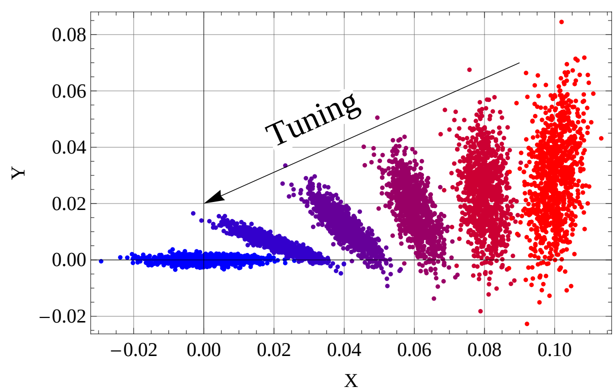

Figure 2: Beam response matrix tuning from the error beam (red) to the nominal beam (blue).

beam is achieved through a set of tuning knobs. These knobs are created by calculating the 6x6 matrix given by

$$R = beam_0^{-1}.beam_{err} - I \quad (7)$$

for each of the final 5 sextupoles in the final focus section, and for each of 4 degrees of freedom: horizontal motion; vertical motion; rotation around S, field strength change. The final set of 20 matrices can then be used to create the orthogonal tuning knobs.

TUNING KNOB OPTIMISATION

Tuning knobs are not created for all of the terms in the matrix, but instead are created only for those terms that have a strong influence on the beam size in both planes. Taking into account the lack of orthogonality for some tuning knobs, 9 are finally created. These are: xx, xy, x'x', x'y, x'y', yy, y'x, y'x', y'y. Generating these orthogonal tuning knobs can be performed via a matrix inversion technique, such as SVD. However, using this method does not create orthogonal tuning knobs over a wide range of amplitudes. Instead, several optimisation routines are used. Initially a real-valued genetic algorithm is used to orthogonalise the tuning knobs. Orthogonality is defined as the ratio of the desired matrix element to the maximum of all other matrix elements, averaged over several amplitudes. Once optimised with the genetic algorithm, the tuning knobs are further optimised through a Nelder-Mead simplex algorithm, using the same optimisation parameters.

TUNING KNOB RESULTS

To test the effectiveness of the tuning knobs, the ATF2 final-focus line model is analysed with representative errors. These errors include both transverse offsets, rotations and field errors in all of the final-focus line magnets. The trajectory of the line is then corrected using the optimised methods described in the previous section. The beam rotation tuning knobs are then applied one-by-one, in no particular order. The application of the tuning knobs is performed through another Nelder-Mead simplex optimiser, varying sextupole strengths in relation to the defined tuning knob, which optimises on the final beam sizes at the IP. The optimisation algorithm is run twice to allow for the randomised application order of the tuning knobs.

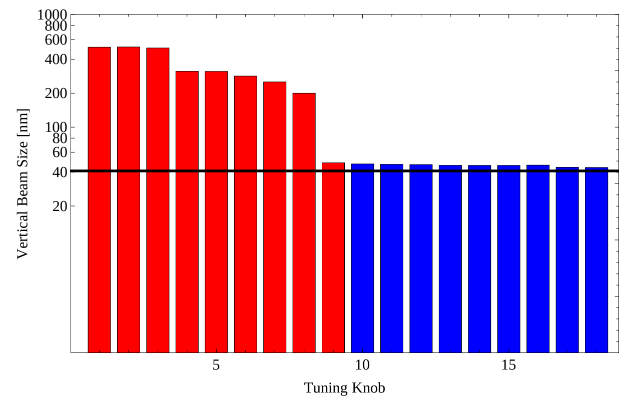

Figure 3: A representative example of vertical beam size tuning using the beam rotation method.

The results, illustrated in Fig. 3, clearly show that it is possible to achieve a tuned beam spot size less than 10% larger than the nominal beam. Averaged over many seeds, this optimisation procedure produces an R.M.S. beam size increase of $<$15%, with realistic errors and 2 iterations of the algorithm. Analysis of the results has also shown that the final beam size tuning is directly related to the trajectory correction system, and thus optimising of the correction subsytem is important for achieving minimal beam sizes at the IP of the ATF2 final focus line.

REFERENCES

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