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Orbit Correction Optimisations for the ATF2 Final Focus

A. Scarfe

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Abstract

ATF2 aims to achieve an ultra-low IP beamsize, this will require a high standard of orbit precision in the ATF2 final focus system. The ATF2 v3.8 final focus has been modelled and expected errors have been applied. Multiple methods for a global orbit correction technique have been developed, applied and tested on the final focus model. The performance of the differing orbit correction techniques have been compared and their effects on the IP beamsize have been calculated. The details of the techniques are presented, along with the comparative results from the simulations. The best performing technique has been short-listed for possible implementation as the ATF2 final focus orbit-steering software solution. The particle tracking was performed using DIMAD.

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1 Introduction

Orbit correction is a fundamental procedure in the alignment and tuning process of an accelerator. Magnet construction and installation errors lead to differences between the 'actual beam orbit' and the intended 'beam orbit' of the machine, known as the 'design orbit' or the 'reference orbit'. These differences are further increased by the effects of ground motion on the machine components. The intended beam orbit of a machine is designed so that optimum machine performance could be achieved, and it is necessary to correct the beam orbit back to this design as much as possible. Orbit correction techniques attempt to align the centroid of the beam with the centre of each magnet in the beamline. This aligning process should increase the efficiency of other tuning methods used on the accelerator, and a good orbit correction set-up should be robust enough to handle many types of magnet error and up-stream errors simultaneously.

ATF2 is an extension of the existing ATF facility in KEK, Japan, which is foreseen to start commissioning by the end of 2008. ATF2 will replace the current ATF extraction line with a longer extraction line, which leads onto a 'final focus', designed as a prototype version of the planned ILC beam delivery system (Fig. 1). The main aims of ATF2 are to demonstrate and refine the techniques required to preserve a low emittance beam along a linear transfer line, produce a 35 nanometre scale vertical beamsize at the IP and demonstrate low levels of beam jitter. If these aims are to be achieved than the precision of the orbit correction techniques used on ATF2 must be significantly higher than the precision usually expected from orbit correction techniques.

Current plans for both the ILC and ATF2 final focus sections have been designed to implement non-corrector based orbit correction process. Traditionally a sequence of horizontal and vertical corrector magnets are distributed along the length of the accelerator. These correctors individually 'kick' the beam off the current path of motion and can shift the centroid of the beam within the beam-pipe. The kicks generated by the correctors and hence the change in motion of the beam are controlled by the currents supplied to the correctors. The method currently planned for the ILC and ATF2 final focus sections will instead use magnet movers to physically move the magnets in the beamline. This method does not require the use of corrector magnets and is expected to produce 'finer granularity kicks' than correctors can, this is due to the minimum magnet mover step size producing a smaller kick differential than can be produced by the minimum current change in the correctors. Correctors rely on a digital-to-analog (DAC) converter to convert the computer chosen digital current values in to the 'real world' analog current settings used on the magnet power supplies. The minimum current step of the correctors is given by $(I_{max} - I_{min})/(2^{bits} - 1)$, where I is the current and $bits$ is the bit resolution of the DAC, the DACs used in the ATF2 extraction line correctors are expected to have a bit resolution of 11 bits. The current step equation results in an inverse relationship between the accuracy and range of the correctors. The use of magnet movers should result in greater orbit correction precision because the magnets are moved using motors which have an inherent step size limitation that is unrelated to the range limitation of the motors. As part of the work performed, both the more traditional 'corrector-based method' and the planned 'magnet mover-based method' of orbit correction will be optimised and compared using simulations performed by the DIMAD particle tracking program.

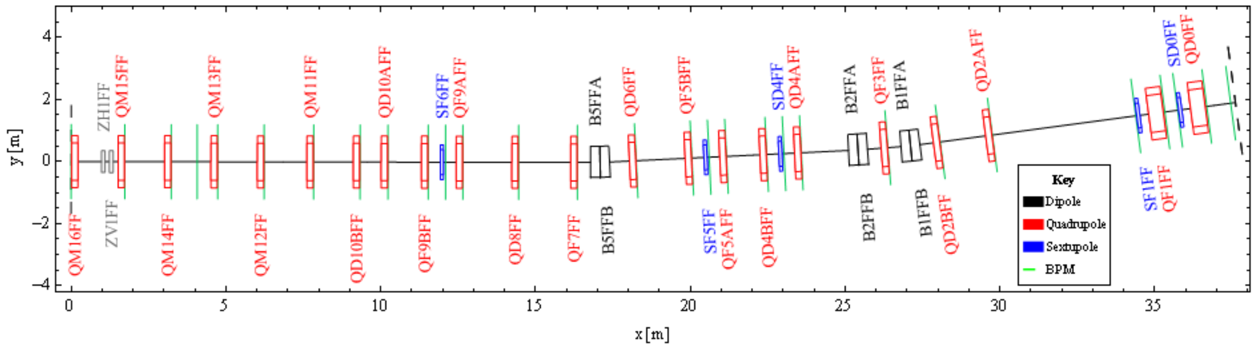

Figure 1: ATF2 v3.8 Final Focus [1], generated using the DIMADInput Mathematica package, please note that the BPM and mover numbers are in ascending order

2 General Orbit Correction Techniques

The traditional corrector-based and the magnet mover-based orbit correction methods share many basic principles and computational techniques, as a result this section will detail any common information required for the understanding of the work presented.

2.1 Beam Based Alignment

The general concept of beam based alignment is to measure the position of the beam within the beampipe and hence the deviation of the beam from the design orbit. This information is then used to calculate the corrections needed in order to eliminate the deviation between the beam orbit and the design orbit.
The position of the beam is typically measured using a beam position monitor (BPM), which calculates the relative position of the beam centroid with respect to the design trajectory. To calculate the required beam corrections it is first necessary to calculate the effect of a change in the magnet parameters on each BPM reading; by calculating the effects for every possible change it is possible to construct a 'response matrix' which details how the change in any given magnet parameter changes the beam orbit. For the corrector-based method the permissible magnet parameter changes are the horizontal and vertical kick strengths of the correctors, where as for the magnet mover-based method the permissible changes are the horizontal and vertical positions of the magnet movers.

If $\mathbf{R}$ denotes the response matrix, Δc is the applied magnet parameter changes and Δx is the Resultant change in the BPM readings, then

$$\mathbf{\Delta x} = \mathbf{R} \cdot \mathbf{\Delta c} \tag{1}$$

Hence it is possible to calculate the required magnet parameter changes that will result in a desired set of BPM readings if the response matrix is known. If the machine does not have strong cross-plane coupling, and none of the chosen magnet parameter changes cause strong coupling, it is possible to simplify the orbit correction process by decoupling the horizontal and vertical orbit correction procedures. This will result in the BPM readings, magnet changes and response matrices being directionally independent. Once the response matrix is calculated it is possible to perform orbit correction by calculating the required magnet parameters changes that would result in the BPM readings that have been recorded and then reversely applying the magnet parameter changes. Theoretically this orbit correction process should result in each BPM reading becoming zero but this is usually not the case due to the accuracy of the BPM and magnet systems, which cause errors in the orbit correction calculations.

If the number of permissible magnet parameter changes (N) is not equal to the number of BPMs (M), the response matrix becomes a M by N matrix, and so non-square. Such a matrix has no definite inverse matrix, as a result is it necessary to use a pseudo-inversion technique on the response matrix.
The method chosen for the pseudo-inversion technique is SVD [2, 3], which stands for singular value decomposition and is the subject of the next section.

2.2 SVD

One of the most important techniques implemented in both orbit correction methods is SVD, this technique is used for pseudo-inverting a rectangular matrix. The use of SVD for orbit correction purposes is not new [4], however an overview of the formalism is presented.
Given M BPMs and N magnet parameter changes, SVD formalism defines the response matrix $\mathbf{R}$ as

$$\mathbf{R} = \mathbf{U} \cdot \mathbf{W} \cdot \mathbf{V^T} \tag{2}$$

where $\mathbf{U}$ is an M by M unitary matrix, $\mathbf{V}$ is an N by N unitary matrix and $\mathbf{W}$ is an M by N matrix with non-negative values along the rectangular diagonal and zero values elsewhere.
From Eqs. (1) and (2) and the unitary nature of $\mathbf{U}$ and $\mathbf{V}$ we have

$$\mathbf{\Delta x^t} = \mathbf{W} \cdot \mathbf{\Delta c^t} \tag{3}$$

Where $\mathbf{\Delta x^t} = \mathbf{U^T} \cdot \mathbf{\Delta x}$, $\mathbf{\Delta c^t} = \mathbf{V^T} \cdot \mathbf{\Delta c}$ and $\mathbf{\Delta x^t}$ and $\mathbf{\Delta c^t}$ and the vectors in transformed BPM (t-BPM) space and transformed magnet-parameter (t-magnet-parameter) space, respectively. The matrix $\mathbf{W}$ is given by

$$\mathbf{W}_{ij} = w_{\min(ij)}\delta_{ij} \tag{4}$$

where the diagonal elements $w_n(\geq 0, 1 \leq n \leq \min(M,N))$ are the eigenvalues of the $\mathbf{W}$ matrix and represent the coupling efficiency between the t-BPMs and t-magnet-parameters.

If $\mathbf{\Delta x}$ is defined as the difference between the reference orbit and the recorded orbit then $\mathbf{\Delta c}$ is the set of magnet parameter changes required to achieve the reference orbit, as a result equation (1) can be rearranged to become

$$\mathbf{\Delta c} = \mathbf{R}_{inv} \cdot \mathbf{\Delta x} \tag{5}$$

where

$$\mathbf{R}_{inv} = \mathbf{V} \cdot \mathbf{W}_{inv} \cdot \mathbf{U}^{\mathbf{T}} \tag{6}$$

$\mathbf{W}_{inv}$ is a diagonal matrix of dimensions N by M and is given by

$$\mathbf{W}_{inv,ij} = q_{min(ij)}\delta_{ij} \tag{7}$$

where

$$q_n = \begin{cases} 0, & w_n \leq \varepsilon w_1 \\ 1/w_n, & otherwise \end{cases} \qquad (1 \leq n \leq min(M,N))$$

w_n is ordered by size in descending order, where by w_1 is the maximum value of w and $w_{min(M,N)}$ is the lowest value. ε is the singularity rejection parameter in the range [0,1]. This parameter is primarily determined by the requirements of the orbit correction technique. $q_n = 0$ corresponds to decoupled channels, which do not contribute to orbit correction.

When $\varepsilon = 0$ all eigenvalues are kept, theoretically this results in the most accurate orbit correction. When $\varepsilon = 1$, $\mathbf{R}_{inv}$ is a null matrix and there is no orbit correction. ε_m is the largest possible value of ε in order to retain all non-zero eigenvalues. Using ε_m or $\varepsilon = 0$ should result in the same $\mathbf{R}_{inv}$, however all values of ε greater than ε_m should result in different $\mathbf{R}_{inv}$.

The number of retained eigenvalues (n_{eigen}), where $0 \leq n_{eigen} \leq min(M,N)$, is related to ε by

$$\varepsilon = w_a/w_1 \qquad\qquad (where \quad a = n_{eigen}) \tag{8}$$

The outcome of this relation is that the number of retained eigenvalues is a selectable parameter and will affect the orbit correction efficiency.

One final outcome of SVD formalism is an efficiency rating for each BPM and each permissible magnet parameter change, this is because certain instances of w_n have a limiting effect on the value of ε_m (Fig. 2). In physical terms this can be explained as a BPM position having a minimal reaction to most permissible magnet parameter changes or a permissible magnet parameter change having minimal effect on most BPM readings.

The efficiency indices of the BPMs and magnet parameter changes are EB(i) and EC(i), respectively and are defined as

$$EB(i) = \sum_n w_n U_{in}^2 \qquad (1 \leq i \leq M) \tag{9}$$

$$EC(i) = \sum_n w_n V_{in}^2 \qquad (1 \leq i \leq N) \tag{10}$$

By removing low efficiency BPMs and magnet parameter changes it is possible to maximise the value of ε_m and improve the quality of the orbit correction.

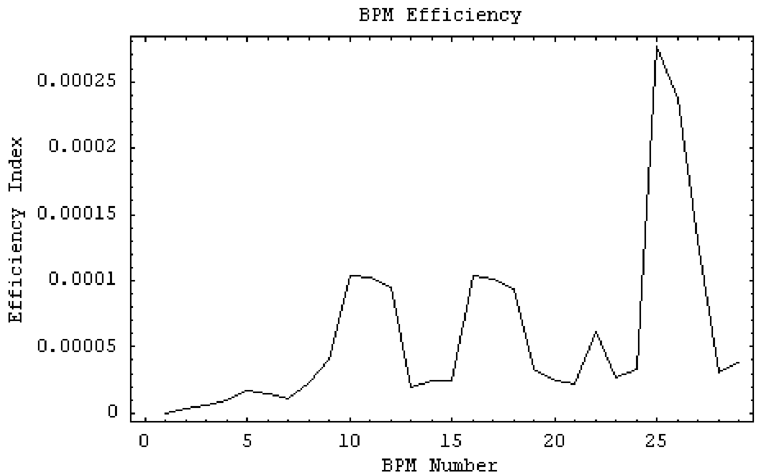

Figure 2: An evaluation of the orbit correcting efficiency of the ATF2 final focus BPMs resulting from the SVD formalism. Arbitrary units are used.

2.3 Optimisation Technique

The choices that govern the efficiency of an orbit correction set-up are:

The type of magnet parameter changes that will be used to correct the orbit;
The number of magnet parameter changes (N) that will be used;
The number of BPM readings (M) that will be used;
The number of eigenvalues (n_{eigen}) that will be retained

The first choice defines the method of orbit correction that will be used, as such this choice cannot be optimised, instead it is possible to compare the optimised set-ups of each available method so that an informed decision on which method to choose can be made.
The other three choices listed above are referred to as the 'knobs' of an orbit correction method, hence they can be optimised. Although there are limits on the available options for the knobs, many of the options available are inherently worse than the other available

options and would only result in increasing the CPU time needed to achieve optimisation, as a result many options must be ignored. For the BPM and magnet-parameter knobs only the most inefficient BPMs and magnet-parameters should be considered for exclusion, the limitations on how many BPMs and magnet-parameters should be considered for exclusion will be governed by CPU-time limitations, hence a greater amount of CPU-time may lead to a more optimum orbit correction set-up, however this may not always be the case. For the eigenvalues knob it has already been stated in the SVD formalism that a high number of eigenvalues should theoretically lead to a better orbit correction set-up, hence only the highest values of n_{eigen} should be considered, however if the limitation applied on the knob is too constricting then a more optimum orbit correction set-up may be missed.
A systematic approach to the options chosen of each knob should be taken so that all possibly good orbit correction set-ups can be investigated. To do this it is necessary to create an arbitrarily tiered system for the knobs, which will allow for a lower tiered knob to cycle through its possible options each time a higher tiered knob is set to a different option.

A measure of the efficiency of an orbit correction set-up must be chosen. This 'figure of merit' must be chosen in such a way as to take into account the amount of orbit perturbation reduction achieved by an obit correction set-up. For the work performed for this report it was decided that the orbit perturbation in each direction of motion would be calculated as the root-mean-square of all the BPM readings in the corresponding direction of motion. It was also decided that the Vertical (Y) orbit correction would be given higher weighting than the Horizontal (X) orbit correction when calculating the figure of merit, as the beam is of the order of 100 times smaller in Y then it is in X. The optimum orbit correction set-up would result in the biggest fractional decrease in the orbit perturbation. As a result the following equation was chosen as the figure of merit

$$X_{f,rms}/X_{0,rms} + 2Y_{f,rms}/Y_{0,rms} \tag{11}$$

Where X_f & Y_f are the corrected orbits and X_0 & Y_0 are the original orbits. The vertical orbit has been given a factor 2 weighting in order to emphasise the need for a flat orbit in the vertical plane, so as to reduce the amount of vertical beamsize growth generated by non-linear fields. This is because the target horizontal beamsize is a factor 100 times greater than the target vertical beamsize.

The optimum orbit correction set-up should work well under many different starting conditions, hence it is necessary to average the figure of merit for each orbit correction set-up over a sequence of errors. The errors should be 'seeded' so that the same errors can be applied to each orbit correction set-up, the number or seeds used is governed by the amount of CPU-time available but more seeds will reduce the amount of statistical error in the figure of merit. The errors chosen for the work in this report are:

BPM offset error: 30 microns;
BPM resolution: 0.1 microns;

Horizontal and vertical magnet displacement: 200 microns;
Magnet roll angle: 300 μrad;
dB/B in quadrupoles and sextupoles: 1x10^{-4} systematic, 1x10^{-4} random;

All the errors were given a Gaussian distribution and a seeded random value for the error was calculated from the distribution.

All errors are static and only regenerate when a full bunch train has been tracked, in the work in this report there were 5 bunches in a train and 5 seeds of errors, in total 25 different bunches were tracked for each orbit correction set-up, each bunch train experienced a unique set of the errors listed above.

2.4 Post-Optimisation Method Comparison

After both of the orbit correction methods used in this work have been optimised it is possible to perform a sequence of tests on each method so that a clear comparison can be made between them. There are three important tests that will be performed in this report, these will focus on the vertical direction, as this is the direction with the tightest performance targets and the one of most importance in later tuning and alignment phases of machine preparation.

2.4.1 Horizontal and Vertical Beamsize Changes Test

To achieve the goals of ATF2 it is necessary to not only have the orbit as close to the design orbit as possible but also to have an exceptionally low IP beamsize. The post-orbit correction phases of the tuning and alignment process have the responsibility of reducing the IP beamsize to the required levels. The chosen orbit correction set-up should not exacerbate the IP beamsize growth that results from the machine errors present, it is therefore necessary to measure the effect of a chosen orbit correction set-up has on the IP beamsize. The 'horizontal and vertical beamsize changes' test is designed to measure the horizontal and vertical IP beamsizes before and after orbit correction is performed when a selection of errors are applied, to do this it is necessary to track a 'suitably high population' beam along the simulated beamline, calculate the IP beamsizes, perform the orbit correction procedure, retrack the same beam through the orbit-corrected beamline and calculate the new IP beamsizes. This must be performed over several seeded errors. The number of particles used in the tracked beam and the number of seeds used will be determined by the amount of CPU-time available, a 5000 particle beam and 100 seeds or errors were chosen for this test. The best orbit correction method will be the one which results in the greatest average decrease in the IP beamsizes after the optimised orbit correction set-up has been applied.

2.4.2 Vertical Magnet Tolerance Test

The misalignment of the magnets will lead to beamsize growth at the IP which will not be fully corrected by orbit correction, as such it is necessary to sometimes physically realign the magnets, this process is limited and if the magnet causes significant beamsize growth at misalignments below this limit then the machine could become unfeasible if extra correction and magnet placement procedures are not used. This test determines how much misalignment is required on each magnet to give rise to a 10% beamsize growth at the IP.

2.4.3 Vertical Machine Tolerance Test

The machine tolerance is a measure of how much the beamsize growth changes with respect to the average misalignment of the magnets. A Gaussian vertical misalignment is applied to all magnets, the mean value of which is varied and the beamsize growth at the IP is recorded.

3 Method Specific Orbit Correction Optimisation

3.1 Corrector-Based Orbit Correction

A hypothetical multi-directional corrector is added to the end of all 22 quadrupoles in the ATF2 final focus. The multi-directional correctors can create both horizontal and vertical corrector kicks at the same time and are assumed to be perfect with the ability to create precision kicks. The correctors near the start of the line tend to be more efficient than those at the end of the line (Fig. 3). The efficiency is biased towards earlier correctors because the correctors can only affect downstream BPMs, hence an upstream corrector will be able to correct more BPM readings.

The ideal response matrix should be diagonal in nature but have a non-unity thickness to the diagonal section. The response matrices for the corrector-based orbit correction clearly show the ideal diagonality (Fig. 4) but show some anomalies as it is positioned before the first corrector.

The optimised orbit correction setting were found to be:

- BPMs 1 and 6 turned off.
- Corrector 21 turned off.
- 21 eigenvalues used for SVD (this is the maximum permissible value).

The resultant average orbit correction was 90.3% horizontal correction and 93.6% vertical correction.

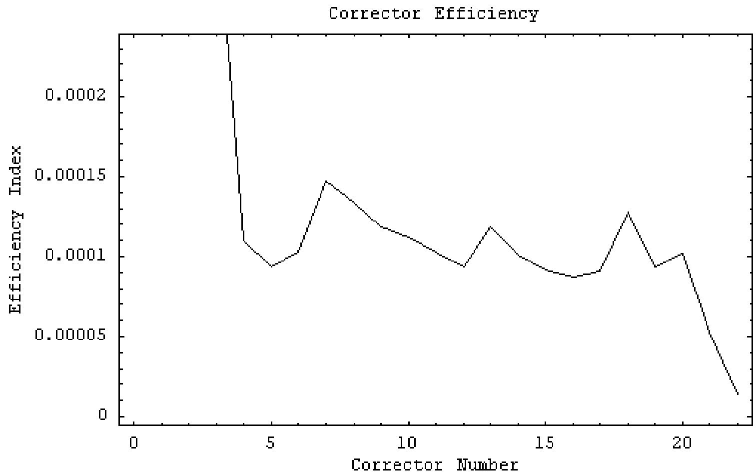

Figure 3: An evaluation of the orbit correcting efficiency of the hypothetical ATF2 final focus correctors resulting from the SVD formalism. Arbitrary units are used.

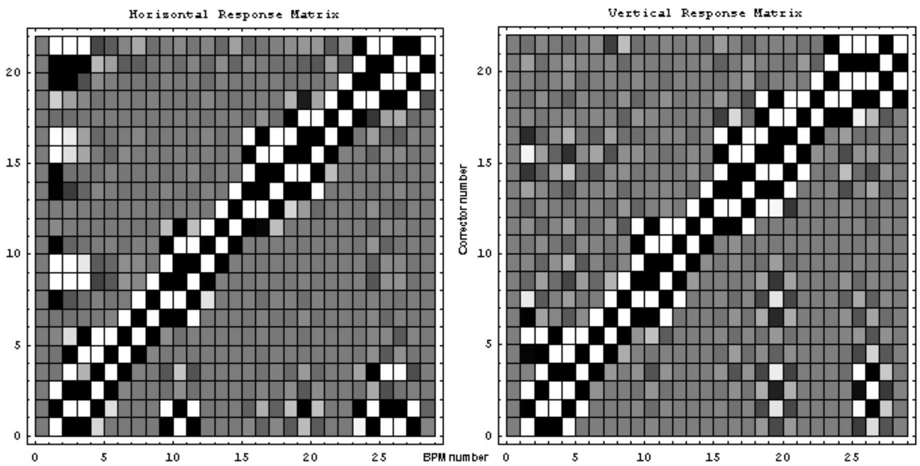

Figure 4: Density plot of the response matrices for the corrector-based orbit correction of the ATF2 final focus. Whites are large negative numbers, blacks are large positive numbers and greys are near zero numbers.

3.2 Magnet Mover-Based Orbit Correction

The ATF2 final focus will have most of the quadrupoles on magnet movers, which can move the quadrupoles horizontally and vertically. The ATF2 v3.8 lattice had been generated before a full set of magnet mover had been acquired. The ATF2 v3.8 lattice called for the removal of the first 3 magnet movers in the final focus. The repercussions of losing the first 3 magnet movers had not been tested, hence this scenario was chosen to form part of the work for this report. Two scenarios were chosen for testing, one assumed that all quadrupoles were on movers (referred to as the all magnet movers scenario) and the other assumed that the first 3 quadrupoles were not on movers (referred to as the selected magnet movers scenario). It was decided that the optimisation would be run for just the 'all magnet movers' scenario and that the 'selected magnet movers' scenario would use the same optimised settings. The first 3 magnet movers are among the 5 most efficient magnet movers in the final focus (Fig. 5), hence the decision to remove the first 3 movers in the line may reduce the overall efficiency of the magnet mover method.

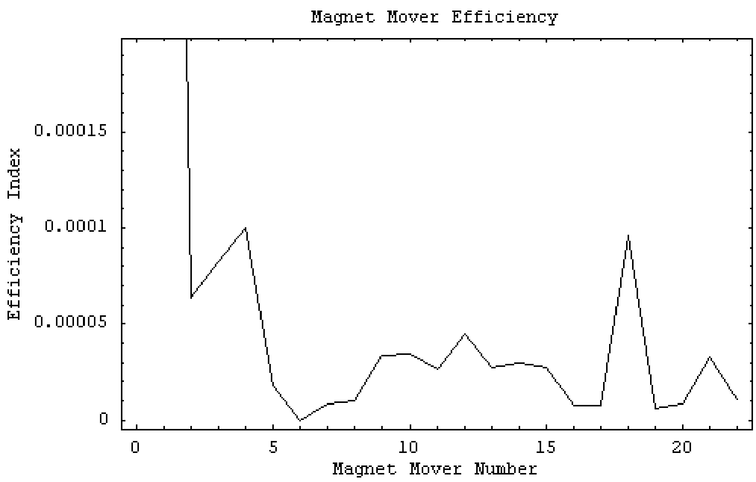

Figure 5: An evaluation of the orbit correcting efficiency of the ATF2 final focus magnet movers resulting from the SVD formalism. Arbitrary units are used.

The ideal response matrix should be diagonal in nature but have a non-unity thickness to the diagonal section. The response matrices for the magnet mover-based orbit correction clearly show the ideal diagonality but show some anomalies and clearly indicate that the first BPM is unresponsive to all the magnet movers (Fig. 6), this is because it is positioned before the first quadrupole. It must also be noted that the 6th magnet mover, which corresponds to quadrupole QM11FF, has no effect on any of the BPMs due to QM11FF being switched off in the design optics of the final focus, as a result all optimisation settings tried assumed that magnet mover 6 was not used.

The optimised orbit correction setting were found to be:

- BPMs 1 and 4 turned off.
- Magnet movers 6 and 19 turned off.
- 20 eigenvalues used for SVD (this is the maximum permissible value).

For the all magnet movers scenario this leads to average orbit corrections of 90.5% horizontal correction and 94.1% vertical correction.

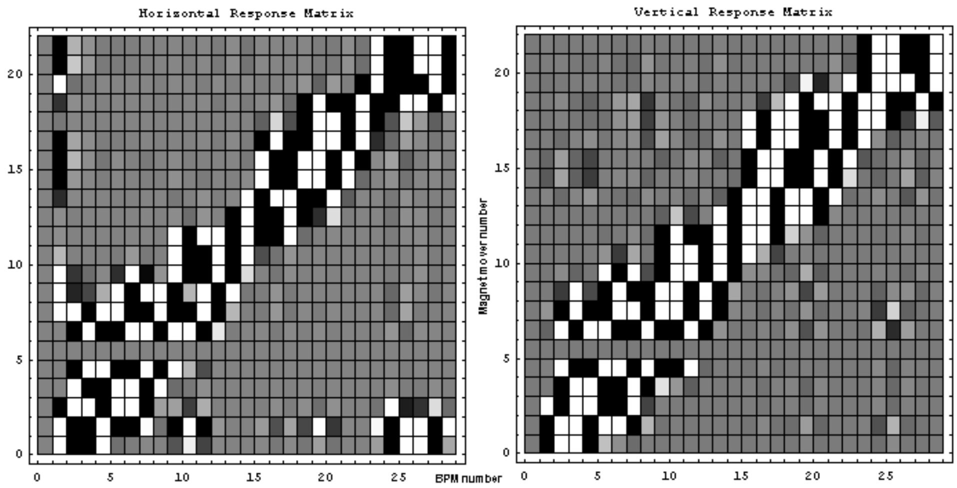

Figure 6: Density plot of the response matrices for the magnet mover-based orbit correction of the ATF2 final focus. Whites are large negative numbers, blacks are large positive numbers and greys are near zero numbers.

For the selected magnet movers scenario it was necessary to change the number of eigenvalues used in order to keep below the maximum permissible value, as such the orbit correction settings were:

- BPMs 1 and 4 turned off.
- Magnet movers 1, 2, 3, 6 and 19 turned off.
- 17 eigenvalues used for SVD (this is the maximum permissible value).

This leads to average orbit corrections of 86.8% horizontal correction and 91.2% vertical correction.

4 Post-Optimisation Analysis

4.1 Horizontal and Vertical Orbit Comparison

The optimised settings for all 3 orbit correction variants were used on the same perturbed orbit. The resultant orbits have been compared for the horizontal (Fig. 7) and vertical (Fig. 8) orbits. The optimised settings for each method resulted in only a subset of BPM readings from the original perturbed orbit being considered during the orbit correction procedure. The same subset of BPM readings were used when forming the comparative orbit graphs, the ignored BPM readings were assumed to be zero. It can be seen that the 'selected magnet movers' method has performed no orbit correction prior to the 4th magnet mover (quadrupole: QM13FF). Apart from the initial deviation caused by the lack of orbit correction in the 'selected magnet movers' method, all methods have converged to roughly the same orbit. When viewed in context of the expected BPM resolution (0.1 microns) it can be seen that the orbit has converged to within the order of magnitude of the minimum permissible orbit allowed by the expected errors. The sub-0.1 micron BPM readings have been generated by the post-simulation analysis required to centre the BPMs onto the magnet centres.

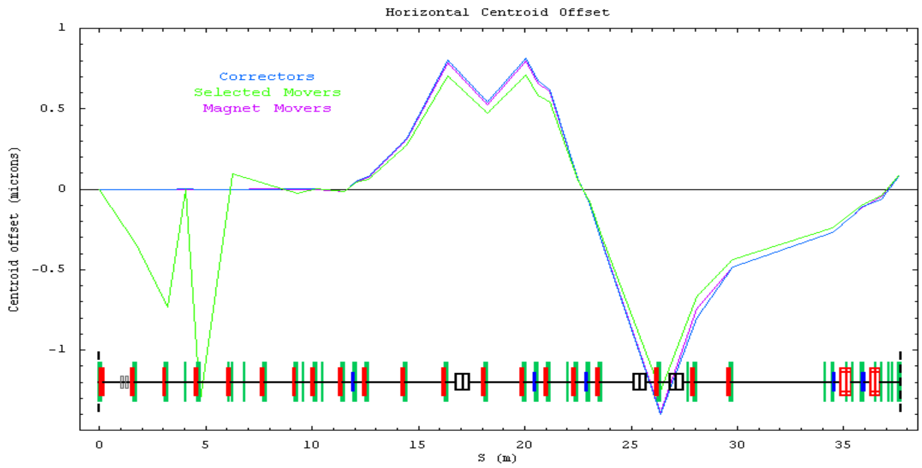

Figure 7: A comparison of the offset between the horizontal beam centroid and the element centres within the ATF2 final focus when a range of orbit correction methods are implemented

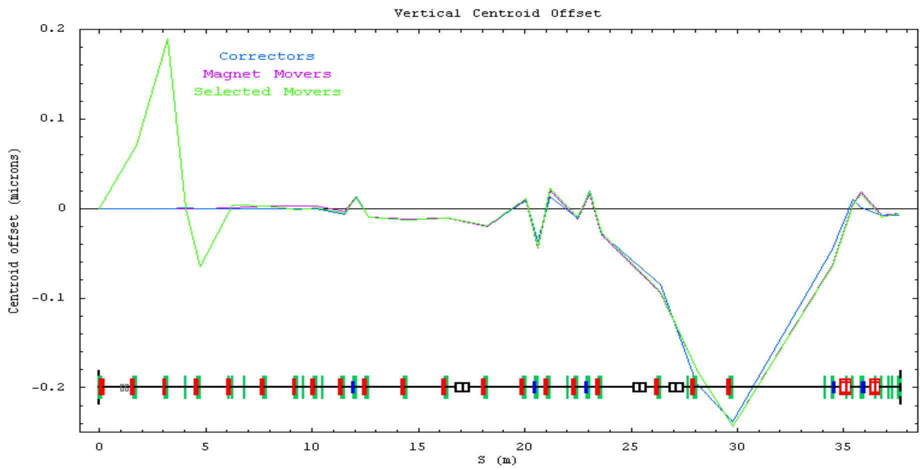

Figure 8: A comparison of the offset between the vertical beam centroid and the element centres within the ATF2 final focus when a range of orbit correction methods are implemented

4.2 Horizontal and Vertical Beamsize Changes Comparison

The IP beamsize growth before and after each correction method was measured for 100 seeds of errors. The horizontal (Fig. 9) and vertical (Fig. 10) IP beamsize growth comparisons are presented. The results have been sorted based on the initial pre-correction IP beamsize growth values. 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 average post-correction IP beamsize growth in the vertical plane (92 sigma) is much higher than the average value for the horizontal plane (7 sigma) due largely to the relative difference in the nominal sigmas (2.82 microns horizontally, 36.81 nm vertically). These results indicate that the corrected orbit may not always be the ideal orbit for ATF2's low IP beamsize goals, however the IP beamsize tuning methods planned for ATF2 are expected to be able to deal with such orders of magnitude of IP beamsize growth. It is technically impossible for an orbit correction method to completely eradicate all orbit perturbation in an accelerator due to the resolution of the BPMs. It is expected that any orbit correction method will still result in some orbit perturbation and some IP beamsize growth.

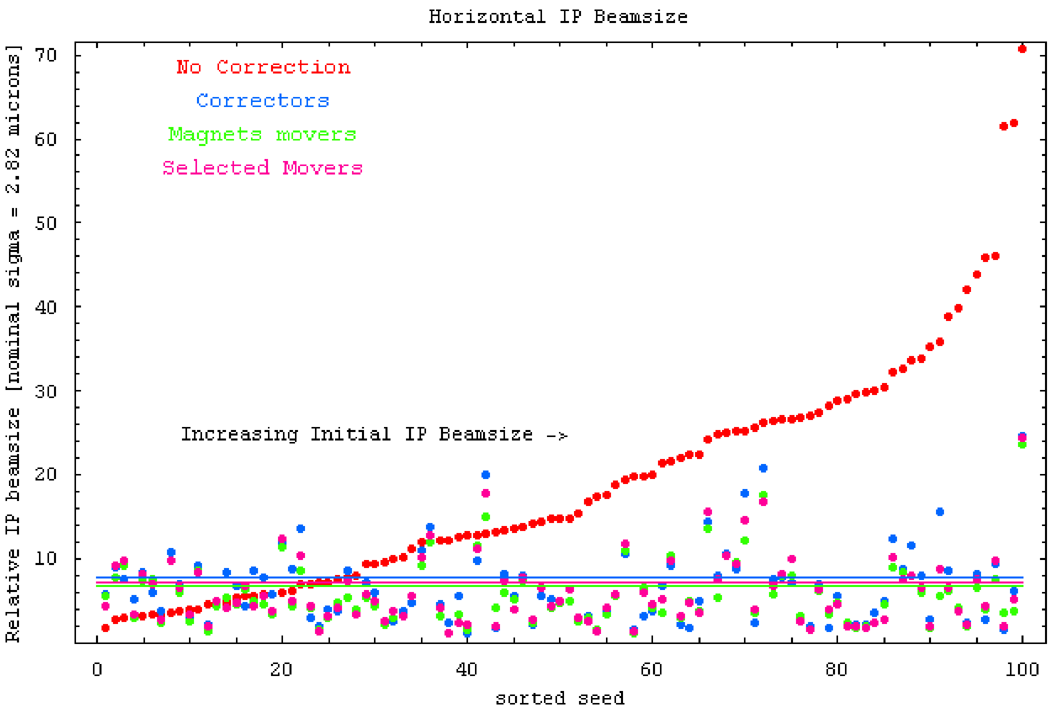

Figure 9: A comparison of the horizontal IP beamsize growth generated by errors within the ATF2 final focus when a range of orbit correction methods are implemented

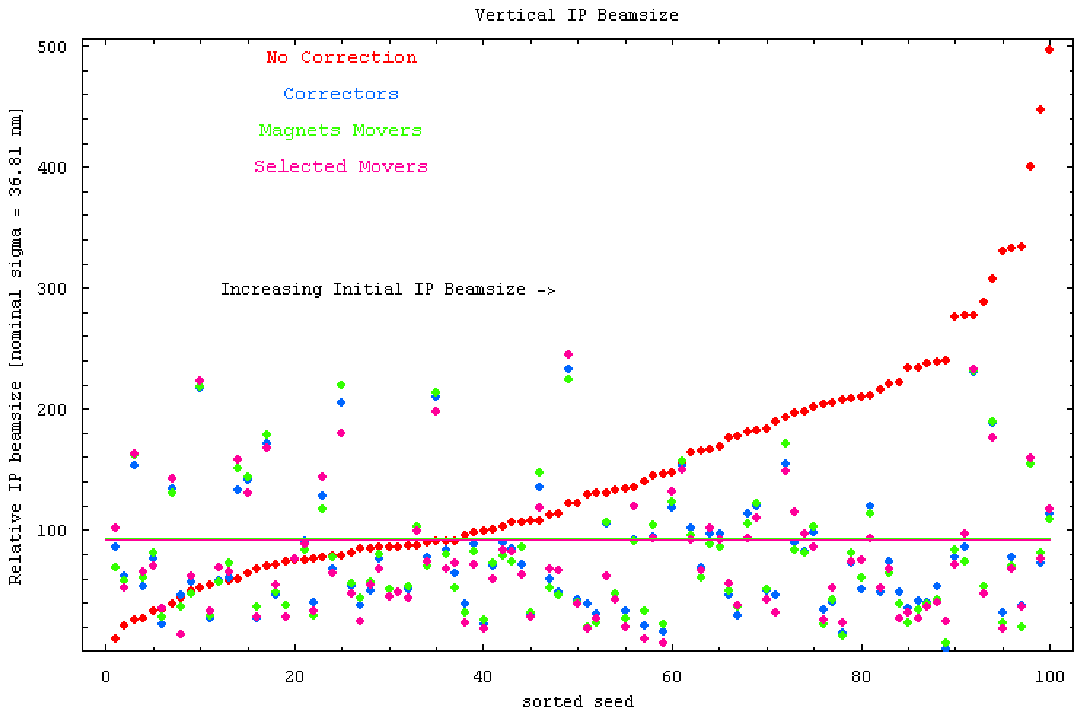

Figure 10: A comparison of the vertical IP beamsize growth generated by errors within the ATF2 final focus when a range of orbit correction methods are implemented

4.3 Vertical Magnet Tolerance Comparison

Each magnet was off-set individually with no other error sources present. The scale of misalignment that gave rise to a 10% IP beamsize growth was recorded. The values were compared for each magnet and each orbit correction method. The results show a strong dependency between sextupole misalignment and IP beamsize growth that is unaffected by the orbit correction procedures (Fig. 11).

4.4 Vertical Machine Tolerance Comparison

All magnets were given a Gaussian distributed amount of vertical misalignment. The correlation between the scale of vertical misalignment and the amount of vertical IP beamsize growth was determined (Fig. 12). During one simulation all of the sextupoles within the ATF2 final focus were switched off and orbit correction was performed. The results indicate that the majority of the IP beamsize growth comes from the misalignment of the sextupoles and is not removed during orbit correction procedures.

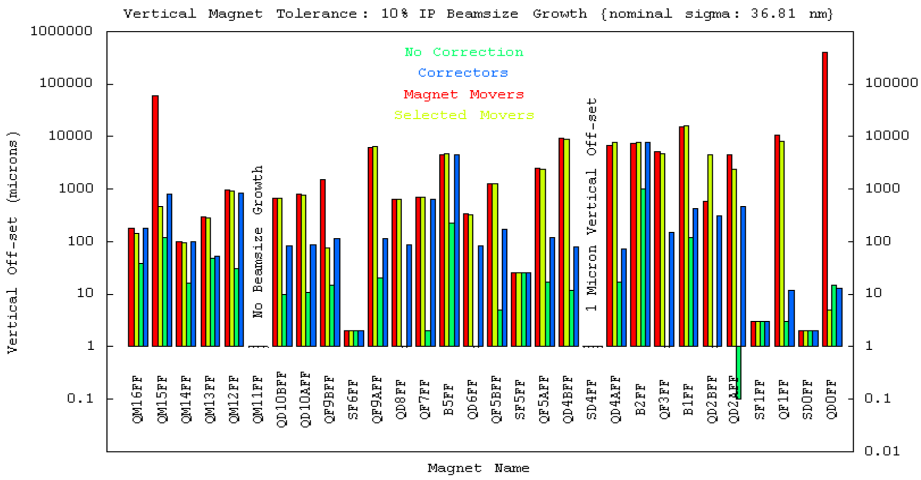

Figure 11: A comparison of the vertical magnet tolerances of the ATF2 final focus when a range of orbit correction methods are implemented

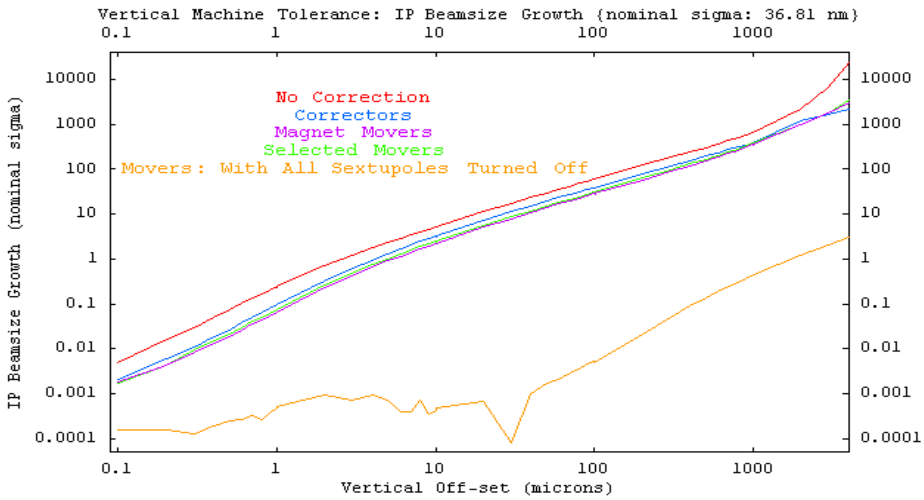

Figure 12: A comparison of the vertical machine tolerances of the ATF2 final focus when a range of orbit correction methods are implemented

4.5 Orbit Correction Method Comparison Conclusions

The all magnet movers-based orbit correction method is continually out performed both the selected magnet movers-based orbit correction method and the corrector-based orbit correction method. The selected magnet movers-based orbit correction method has been demonstrated to out perform the corrector-based orbit correction method in the majority of the comparisons made. This proves that the decision to use magnet movers for orbit correction in the ATF2 final focus was well founded, however the decision to withdraw magnet movers from the first 3 quadrupoles is not the best method for orbit correction, however the benefits of keeping the first 3 magnet movers are unlikely to outweigh the costs of keeping them. Since the all magnet mover-based orbit correction method found that magnet movers 6 and 19 should be turned off, it is the recommendation from the comparisons made that for the design optics it is best to remove magnet movers 6 and 19 but not to remove the first 3 magnet movers.

5 Fine Tuning Optimisation

The generation of the response matrix was made using a simulated lattice devoid of errors, the errors on the real machine may alter the response matrix, which would result in imperfect orbit correction on the real machine, as such the decision was made to perform the selected magnet mover-based orbit correction method with errors applied during the response matrix calculation section. Misalignments will not be applied because the response matrix measures the relative change in orbit caused by each magnet movement, as such the orbit generated by the misalignments can be considered to be zero without impacting significantly on the response matrix.

The magnet movers have been treated as perfect in previous situations, as such the effects of initial mover position errors and mover step-size limitations will be investigated. Initial magnet mover position error: 1 micron Mover step-size limitation: 300 nm

5.1 Orbit Correction Efficiency

Additional error sources were added to the optimised magnet movers method of orbit correction. These errors were included to give a more accurate simulation of how the orbit correction procedure will perform on the real machine. On the real machine the response matrices will be generated experimentally by moving each magnet mover in turn and measuring the change in the orbit. As a result the response matrices must take into account the errors that are expected on the machine. The BPM and magnet strength errors were included in the simulations that were used to generate the response matrices. The errors associated with the magnet movers were also included and the effects on the orbit correction process were compared (Table. 13).

Additional Error Source	Horizontal Figure of Merit	Vertical Figure of Merit
None	0.132	0.088
Response matrix BPM offsets	0.130	0.100
Response matrix BPM resolution	0.132	0.092
Response matrix magnet strengths	0.132	0.088
Mover step-sizes	0.132	0.088
Initial mover positions	0.131	0.088

Figure 13: Orbit Corrected Efficiency Comparison

5.2 Magnitudinal Error Dependency Test

It is now possible to test the relationship between the orbit correction efficiency and the magnitude of the errors used, it is also possible to test the relationship between IP beamsize and the magnitude of the errors used. The magnitude of each error was varied and the orbit correction figures of merit (Fig. 14) and the IP beamsize growth values (Fig. 15) were averaged over 20 seeds for each magnitude of each error. The magnet strength errors dominate the IP beamsize growth but have a minor impact on the orbit correction efficiency, the results shown previously in this report indicate that the sextupole magnets may be causing the strong correlation between magnet strength errors and IP beamsizes. The initial mover position and BPM off-set errors both appear as extra orbit perturbations when the initial orbit is analysed, however the initial mover positions cause actual orbit perturbation and at large error magnitudes can dominate the ordinary magnet misalignments while remaining insignificant at small error magnitudes. The BPM resolution and mover step-size control the efficiency of the orbit correction procedure at small magnitudes both errors do not dominate the procedure and the orbit is corrected to the smallest orbit possible within one iteration of orbit correction. At large magnitudes the BPM resolution and mover step-size make it impossible for the orbit correction procedure to work, if the resolution is too high the BPM readings are meaningless, if the step-size is too large the magnet cannot move to the required location and the orbit correction fails.

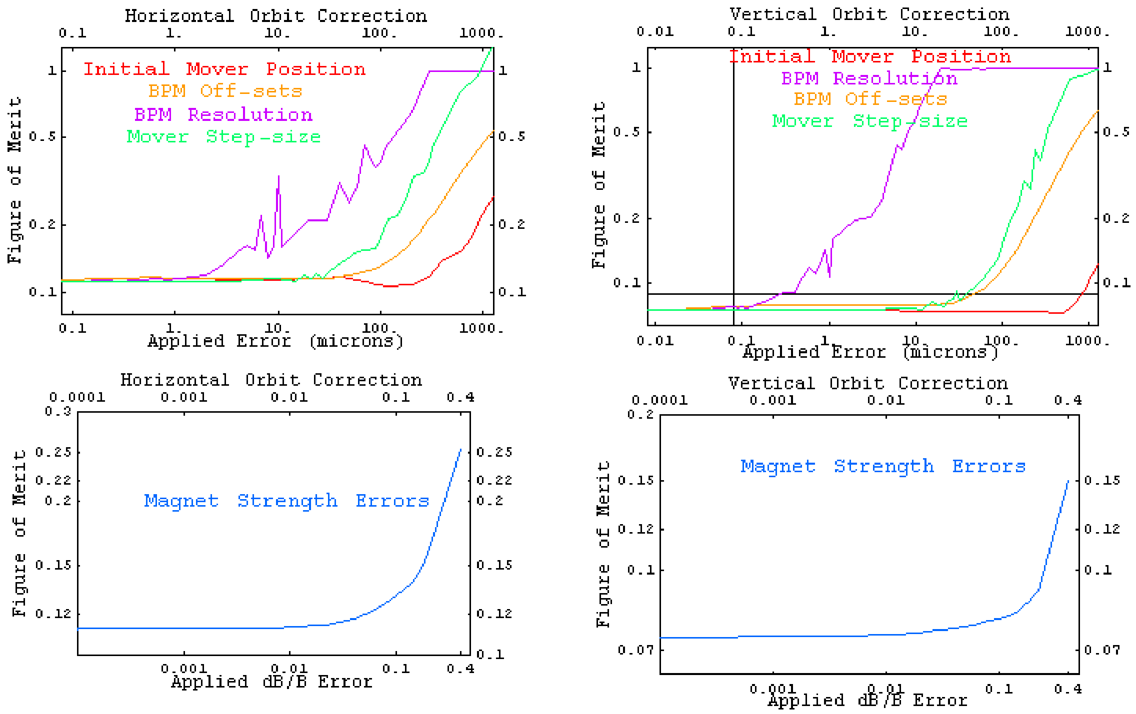

Figure 14: Correlation plots between various error magnitudes and orbit correction efficiency

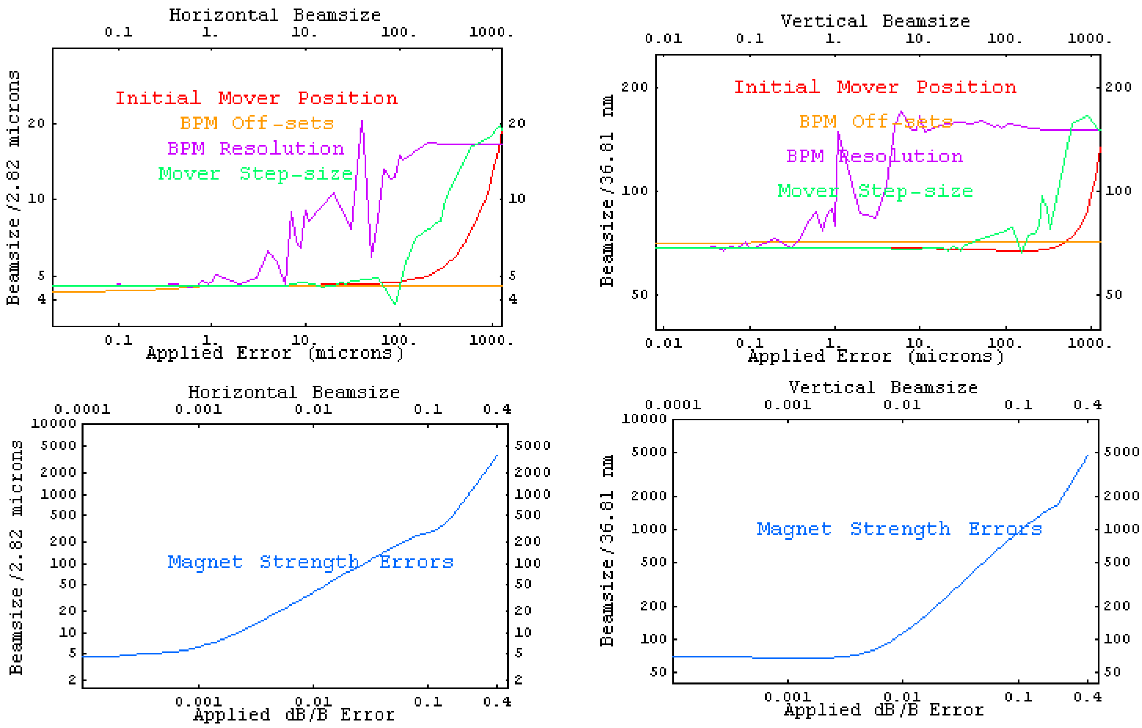

Figure 15: Correlation plots between various error magnitudes and IP beamsizes

6 Conclusion

The magnet mover system has been shown to be an effective means of controlling the orbit through the ATF2 final focus. The global orbit correction methods presented in this report can achieve a relatively flat orbit with only one iteration of the orbit correction technique if the upstream sections of ATF2 are assumed to be error-free. Future simulations will include the ATF2 extraction line that precedes the final focus, full errors will be applied to the extraction line and this is expected to degrade the performance of the orbit correction technique. Even if a flat orbit is achieved, it will be impossible for the orbit correction alone to achieve the target IP beamsize. Many other sources of beamsize growth exist that cannot be compensated for by orbit correction. The orbit correction itself will only decrease the orbit at the BPMs, the orbit may not be flat through all of the magnets even after the BPMs have recorded a flat orbit.
The magnet mover based orbit correction technique will be compared against several other orbit correction techniques that are being developed by other work groups. The overall best orbit correction technique will be developed into a software package for the ATF2 control system, which will be used regularly to correct the orbit through the final focus.

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