DESIGN AND HIGH ORDER OPTIMIZATION OF THE ATF2 LATTICES*

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Abstract

The next generation of future linear colliders (LC) demands nano-meter beam sizes at the interaction point (IP) in order to reach the required luminosity. The final focus system (FFS) of a LC is meant to deliver such small beam sizes. The Accelerator Test Facility (ATF) aims to test the feasibility of the new local chromaticity correction scheme which the future LCs are based on. To this end the ATF2 nominal and ultra-low beta* lattices are design to vertically focus the beam at the IP to 37nm and 23nm, respectively if error-free lattices are considered. However simulations show that the measured field errors of the ATF2 magnets preclude to reach the mentioned spot sizes. This paper describes the optimization of high order aberrations of the ATF2 lattices in order to minimize the detrimental effect of the measured multipole components for both ATF2 lattices. Specifically three solutions are studied, the replacement of the last focusing quadrupole (QF1FF), insertion of octupole magnets and optics modification. By applying the mentioned cures the design vertical beam size at the IP is almost recovered for both ATF2 lattices.

INTRODUCTION

The International Linear Collider (ILC) [1] and the Compact Linear Collider (CLIC) [2] projects are designed to deliver a luminosity at the interaction point (IP) above $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ by colliding e^+e^- beams of vertical sizes in the nanometre scale. The final focus system (FFS) provides the required beam focusing by means of two strong quadrupole magnets, so called Final Doublet (FD), which are located at a distance L* upstream the collision point. The FD generates chromaticity due to the inherent energy spread of the particle beam which needs to be corrected in order to preserve the vertical IP beam size.

The ATF2 [3] beam line is the extension of the Accelerator Test Facility (ATF) meant to validate the feasibility of the final focus systems (FFS) based on the local chromaticity correction scheme, first proposed in [4]. To this end the ATF2 nominal and ultra-low lattices are designed to obtain a σ_y^* of 37 nm and 23 nm respectively. The nominal lattice is the scaled-down version of the FFS of ILC while the ATF2 ultra-low β^* lattice [5] features a β_y^* a factor 4 smaller than nominal, in order to increase the chromaticity to a value similar to that of the CLIC FFS. This challenging optics explores the feasibility of ultra-low β^* lattices.

Reducing the value of β_y^* imposes tight constraints on the magnetic field tolerances of the FFS magnets, particularly for those magnets located at high beta regions, e.g. FD. The lattice design that recovers the design vertical spot size σ_{y0}^* for both ATF2 lattices is described in the following.

LATTICE DESIGN

In order to overcome the destructive impact in terms $\sigma_{x,y}^*$ of the multipole components of the ATF2 magnets, described in [6], different solutions have been considered in [7]. These include replacing the FD, reducing the vertical emittance or increasing the β_x^*. Reducing the vertical emittance is not a cost effective solution. Increasing the value of the β_x^* by a factor 4 effectively reduces the impact of the multipole magnets for both ATF2 lattices, yet it is not the preferred solution since it deviates from the IP beam aspect ratio that the ATF2 nominal lattice was designed for to mirror that of the ILC FFS. In 2012 it was decided to insert 4 skew sextupole magnets [8] meant to compensate for the skew sextupole components of those quadrupole magnets that do not meet the required tolerances, see [9]. Further the focusing quadrupole magnet of the FD was replaced by a 4Q17 type recycled from the PEP-II ring, due to its better field quality. As a result of these beam line modifications the impact of the multipole components becomes negligible for the ATF2 nominal lattice. Although these modifications also minimise the impact of the multipole components for the ATF2 ultra-low β^* lattice, they are not sufficient. The σ_y^* obtained is still 30% larger than design value. The analysis of the high order aberrations of the IP beam size carried out in [10] by the MAPCLASS code [11] determines that a chromatic third order (octupole) component is the main contributor to the calculated $\Delta\sigma_y^*$. The insertion of a pair of octupole magnets is proposed in [10] as an effective solution for compensating this particular aberration.

Octupole Magnets

Two octupole magnets located at dispersion and dispersion-free regions of the ATF2 beam line, namely OCT1FF and OCT2FF respectively, counteract the effect of the chromatic octupole aberration on the vertical IP beam size. It is found that these octupole magnets can reduce the σ_y^* down to 24 nm. More details can be found in [10].

In terms of field quality, the tolerances have been evaluated for both decapole and dodecapole components, Table 1 summarises the tolerances for both octupole magnets. Tighter tolerances are found for the OCT1FF which is located at the dispersion region but all of them are easily achievable from the point of view of magnet design. CERN has taken the initiative to design and construct a pair

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Table 1: Relative Tolerance Evaluated at a Radius equal to 1 cm for the Octupole Magnets OCT1FF and OCT2FF. Each tolerance represents a vertical beam size growth at the IP of 2%.

Component	**Decapole**		**Dodecapole**	
	Normal	Skew	Normal	Skew
Units	$[10^{-1}]$	$[10^{-1}]$	$[10^{-1}]$	$[10^{-1}]$
OCT1FF	2	1	4	1
OCT2FF	7	4	6	12

of octupole magnets to be inserted in the ATF2 beam line, see [12] for more details.

TUNING PROCEDURE

The tuning procedure consists in bringing the accelerator to its design performance under realistic error imperfections. When errors are included into simulations, the IP beam sizes are well above their design values. The tuning procedure is applied to compensate for the IP beam size aberrations caused by the machine imperfections. The tuning determines the feasibility of a lattice. The procedure of tuning ATF2 consists of an initial alignment of the ATF2 magnets using the beam itself, so called BBA. This technique centres the beam at the magnetic center of the magnets within 100 μm [13]. The typical σ_y^* at this stage is of the order of a few μm respectively, see Fig. 1. The final IP spot tuning after the BBA is based on a set of orthogonal tuning knobs that target the residual beam size aberrations at the IP.

Tuning Errors Conditions

The error conditions considered in this simulation are transverse misalignments, rotations along the longitudinal axis and strength errors of the magnetic fields. 100 simulated machines are set up with different initial error conditions. Each error is assigned to the quadrupole, sextupole and octupole magnets following a random Gaussian distribution of width σ_{error}. Also the measured multipole content of the ATF2 magnets and a measurement error of the IP beam size monitor are included into the tuning study. Table 2 summarises the values of σ_{error} for each error.

Table 2: Errors σ_{error} Assumed for the Tuning Simulation Study.

Error	σ_{error}
Horizontal misalignment [μm]	100
Vertical misalignment [μm]	100
Tilt along s-coordinate [μm]	300
Strength [%]	0.1
IP measurement [%]	10

Tuning Knobs

The available 5 normal sextupole magnets of ATF2 are used to construct 8 linear knobs that target the waists α_x^*, α_y^* (longitudinal displacement of the focal point), energy dispersions η_x^*, η_y^* and $\eta_y'^*$ and couplings between x and y ($< x, y >$), p_x and y ($< p_x, y >$) and p_x and p_y (p_x, p_y) at the IP. Each knob uses different combinations of transverse displacements of the normal sextupole magnets. Since the orthogonality may not be fully guaranteed it is common practise to scan the whole set of knobs a few times. Figure 1 shows the evolution of the mean of the vertical IP spot size $< \sigma_y^* >$ (solid line) over 100 different seeds, after each scan of the linear knobs.

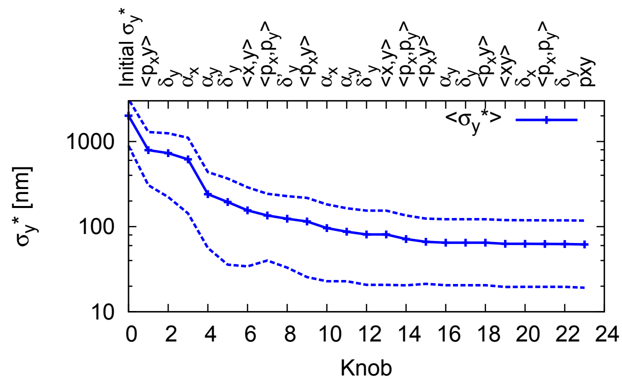

Figure 1: Evolution of $< \sigma_y^* >$ after scanning each of the linear knobs shown in the upper axis. The solid line refers to the mean value of σ_y^* of the 100 simulated machines and the upper and lower dashed curves represent the mean $\pm$ rms error, respectively.

The linear knobs bring σ_y^* from a few μm down to $\approx$ 100 nm in about ten knob scans, after that the tuning speed decreases notably and the beam size converges to above 60 nm after scanning the set of linear knobs 3 times. This $< \sigma_y^* >$ represents almost a factor 3 above the design value. In terms of the confidence level, only 33 % of the simulated machines reach a final $\sigma_y^* < 1.2\ \sigma_{y0}^*$ as shown by the red curve in Fig. 3.
At this stage, further study of the higher order aberrations of σ_y^* of the 100 different machines after scanning the linear knobs is conducted using the MAPCLASS code in combination with MADX [14]. MADX evaluates the map from the entrance of ATF2 to the IP to the desired order. MAPCLASS uses this map to transport a Gaussian distribution meant to represent the beam at ATF2. The study reveals that the 2nd order aberrations that contribute most to $\Delta\sigma_y^*$ using the so called *transport notation* are related to: $T_{y,p_x,y}$, T_{y,x,p_y}, $T_{y,\delta,\delta}$ and $T_{y,x,x}$ coefficients. In addition to these aberrations, it is also worth noting the contributions from the 3rd order which are more severe than those of the second order, the most notable being related to the coefficients: $U_{y,x,x,x}$, $U_{y,x,\delta,\delta}$, $U_{y,x,x,y}$, U_{y,x,x,p_x} and $U_{y,x,y,\delta}$, as shown in Fig. 2. The two line-points shown in Fig. 2 represent the average contribution to $\Delta\sigma_y^*$ over

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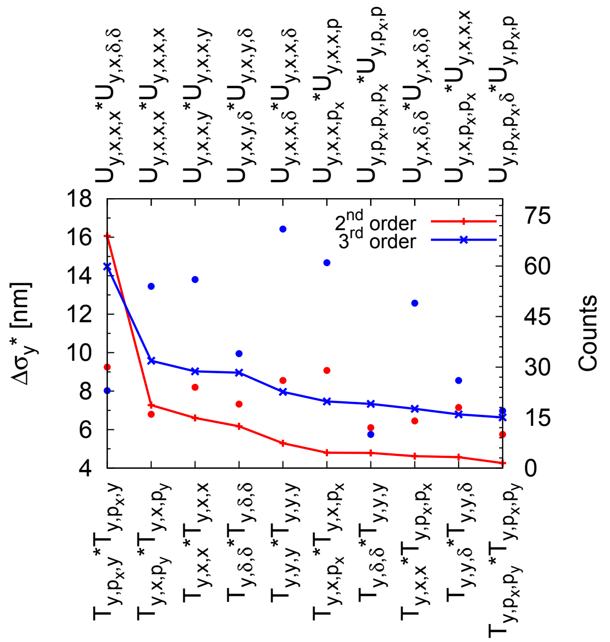

Figure 2: Most relevant high order aberrations that remain after applying the linear tuning knobs. Red curve refers to the 2$^{\rm nd}$ order aberrations, namely $T_{i,j,k}$ (lower axis). Blue curve represents the 3$^{\rm rd}$ order aberrations, namely $U_{i,j,k,l}$ (upper axis)

the simulated machines from the aberration labelled on the horizontal axes. The lower and upper axes show the 2$^{\rm nd}$ (red) and 3$^{\rm rd}$ (blue) order coefficients. The number of occurrences of each aberration is shown by the single points using the same color code, and should be read on the right axis.

Taking advantage of the 4 skew sextupole magnets installed along the ATF2 beam line, a set of 4 knobs are constructed in order to compensate for the above mentioned $T_{i,j,k}$ aberrations. The 2 octupole magnets are used to obtain 2 additional knobs for taking care of the $U_{y,x,x,x}$ and $U_{y,x,\delta,\delta}$ aberrations. These knobs are based on strength variations. The number of machines that reach a $\sigma_y^* < 1.2\ \sigma_{y0}^*$ increases from 33% to 54% after applying the linear and 2$^{\rm nd}$ order knobs. When the octupole knobs are included into the tuning procedure, the percentage of tuned machines with $\sigma_y^* < 1.2\ \sigma_{y0}^*$ increases to 63% as shown in Fig. 3. Figure 3 compares the confidence level of the tuning strategies, namely linear knobs (red), linear plus 2$^{\rm nd}$ order knobs (green) and linear plus 2$^{\rm nd}$ order plus octupole knobs (blue). The confidence level represents the number machines that reach a $\sigma_y^* < 1.2\ \sigma_{y0}^*$.

SUMMARY

The present multipole content of the ATF2 magnets increases the vertical beam size at the IP by less than 5% when the ATF2 nominal lattice is considered in simulations. By contrast, the impact of these multipole errors

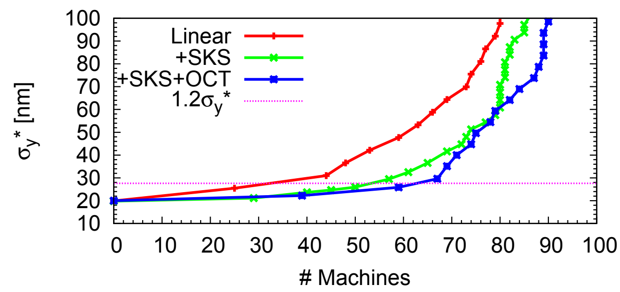

Figure 3: Confidence curves obtained for the 3 tuning strategies. The magenta line indicates the 1.2 σ_{y0}^* value.

increases σ_y^* by 30% for the ATF2 ultra-low β^* design. Simulation shows that 2 octupole magnets can effectively reduce the impact on the beam size by less than 5%. The calculated tolerances of the magnetic field errors of these octupole magnets do not represent any difficulty from a magnet design point of view. An additional benefit is found when studying the tuning performance of the ultra-low β^* lattice under realistic error imperfections. Thanks to the knobs based on these octupole magnets, the percentage of machines that reach a final $\sigma_y^* < 1.2\ \sigma_{y0}^*$ increases from 54 % up to 63 %.

REFERENCES

[1] ILC Global Design Effort, "ILC Technical Design Report," http://www.linearcollider.org/ILC/Publications/Technical-Design-Report.

[2] "CLIC Conceptual Design Report," *CERN-2012-007*.

[3] H. Braun *et al*, "ATF2 Proposal. Vol. 1," *CLIC-Note-636*, (2005).

[4] P. Raimondi and A. Seryi, *Phys. Rev. Lett. 86*, (2001).

[5] P. Bambade *et al*, "ATF2 Ultra-Low IP Betas Proposal," *CLIC-Note-792*, (2009).

[6] R. Tomás *et al*, "ATF2 ultra-low IP betas proposal," *Proc. of PAC'09*, Vancouver, (2009).

[7] E. Marin *et al*, "Scenarios for the ATF2 Ultra-low betas proposal," Proc. of IPAC,10 (2010).

[8] T. Okugi *et al*, "Linear and 2nd order optics correction of ATF2 final focus beamline," to be submitted to *Phys. Rev. ST-AB*.

[9] E. Marin, "Design and higher order optimisation of FFS for linear colliders," *PhD Thesis*, (2012).

[10] E. Marin *et al*, submitted to *Phys. Rev. ST-AB*.

[11] R. Tomás, "MAPCLASS: a code to optimize high order aberrations," *CERN-AB AB-Note-2006-017 (ABP)*, (2006).

[12] M. Modena, "Progress with FFS magnets for CLIC, ILC and ATF2," Meeting: *CLIC and ILC BDS*, CERN (2013).

[13] M. Woodley, "EXT: Summary of activities, software development and tuning performance," *11th ATF2 Project Meeting*, 2011.

[14] "MAD-X Home page," `http://frs.home.cern.ch/frs/Xdoc/mad-X.html`