TOWARDS ULTRA-LOW BETA* IN ATF2

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Abstract

The Accelerator Test Facility 2 (ATF2) has already demonstrated the feasibility of Final Focus Systems based on the local chromaticity correction scheme and its focusing capabilities by reaching a vertical beam size at the virtual Interaction Point (IP) of less than 50 nm. The level of chromaticity in ATF2 is comparable with the expected chromaticity in ILC, but 5 times lower than in a design of CLIC. ATF2 gives the unique possibility to test CLIC chromaticity level by reducing the vertical beta function at the IP by a factor of 4 (the inverse proportionality of chromaticity with beta function value at IP is assumed). The experience collected by tuning of a more challenging machine would be beneficial for both ILC and CLIC projects.

Simulations show that the multipolar errors and final doublet fringe fields spoil the IP beam sizes at ATF2. Either increasing the value of the horizontal beta function or installing a pair of octupole magnets mitigate the impact of these aberrations. This paper summarizes the studies towards the realization of the ultra-low beta* optics in ATF2 and reports on the progress of the construction of the octupoles.

INTRODUCTION

In the future linear colliders (CLIC [1], ILC [2]) the high collision rate is achieved by colliding the beams demagnified to the nanometer size in the interaction point (IP). Strong quadrupole magnets, called final doublet (FD), are used for the beam focusing at the IP, but they also introduce the chromatic effect which causes that the off-momentum particles are not focused exactly at the focal point, leading to larger spot sizes at the IP. In the ATF2 [3], which is a Final Focus System (FFS) test facility, the IP vertical beam size is expected to be 450 nm without correcting the chromaticity and 37 nm if the chromaticity is compensated. This shows the importance of the chromaticity correction.

A novel scheme [4], based on local chromaticity correction in the FD, is tested in ATF2. Its operating principle has been already experimentally validated by measuring a beam size of about 45 nm [5–7]. Therefore, the local chromaticity correction scheme is considered as a baseline for CLIC and ILC FFS. However, the level of chromaticity in ATF2 is comparable with the ILC expectation, but a factor 5 lower than in case of CLIC. For this reason, the ultra-low β^* [8] project is studied in ATF2, reducing the value of β^* by a factor 4, set the chromaticity to be comparable with CLIC (see Table 1). Larger tuning difficulties are expected under these more demanding conditions. Experiencing with higher chromatic lattice would benefit to both CLIC and ILC.

The chromaticity roughly scales as $\zeta_y \sim L^*/\beta^*_y$, so it can be increased by decreasing the β^*_y value, initially by a factor 2 to test a halfway moderated step and finally by a factor 4, which brings the chromaticity level close to CLIC. This will cause the β_y function increase in the FFS, especially in the FD which makes the beam more sensitive to the magnetic imperfections as e.g. multipolar errors, fringe fields, and other aberrations. Some of these issues were already addressed and mitigated in order to make the ultra-low β^* project feasible [9, 14].

MULTIPOLE COMPONENTS AND FRINGE FIELDS OF THE ATF2 MAGNETS

The decrease of the IP β_y value causes that the β_y function in the Final Focus region increases, as shown in Fig. 1. As a consequence, the beam size is larger in the FF and therefore the particles (especially in the tails) are more sensitive to any aberrations and imperfections. It was reported in [9] that carefully measured multipole components [10, 11] of the ATF2 magnets are setting the main limitation in reaching the low beam size for the ultra-low β^* optics. From the simulations, where all multipole components are represented as thin multipoles with integrated gradient corresponding to the measurements, the vertical IP beam size (in rms sense) is $\sigma^*_y = 27$ nm, which is not satisfactory. The impact of the magnetic multipole components was calculated using a MAPCLASS2 [12] code including a high-order transfer map given by PTC [13].

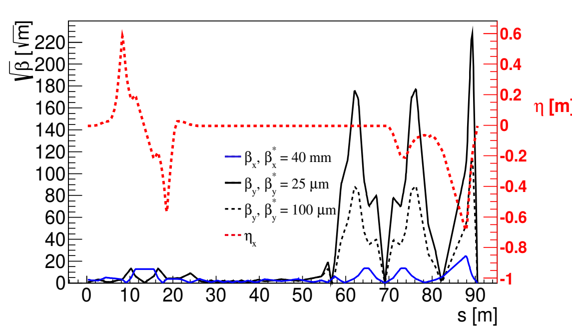

Figure 1: β functions and dispersion along the ATF2 beam line in case of nominal β^*_y and ultra-low β^*_y optics. β^*_x is increased by a factor 10 to minimize horizontal to vertical coupling.

Another limitation in reaching the low beam size in case of ultra low β optics is the magnetic fringe fields of the

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Table 1: Some of the FFS Parameters for ATF2, CLIC and ILC

	ε_y [pm]	β_x^* [mm]	β_y^* [μm]	$\sigma^*_{y,\mathrm{design}}$ [nm]	L* [m]	$\zeta_y \sim (L^*/\beta_y^*)$
ILC	0.07	11	480	5.9	3.5/4.5	7300/9400
CLIC	0.003	4	70	1	3.5	50000
ATF2 nominal	12	4/40	100	37	1	10000
ATF2 half β_y^*	12	4/40	50	30.5 (25[a])/26	1	20000
ATF2 ultra-low β_y^*	12	4/40	25	27 (20[a])/21	1	40000

[a]using octupole magnets

final doublet quadrupoles, as reported in [14]. The reason is similar as for the multipole components: in region of high β function particles become more sensitive to high order aberrations. The quadrupolar fringe fields can be represented as third order kick [15, 16] applied to particles at the both ends of the magnets. It results in effective beam size increase and increased tuning difficulty.

Both ATF2 magnets multipole components and fringe fields set a limit for the efficiency of beam focusing and require correction. Mitigation methods are described in next section.

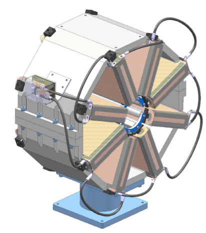

Figure 2: OCT1FF visualization. For operation simplicity the magnet is air cooled and yoke is composed of two halves which can be easily mounted on the beam line [18].

MITIGATION METHODS

From Table 1 one can see that the IP vertical beam size is significantly lower (for half and ultra-low β_y^*) when the β_x^* is increased by a factor 10. In such case, the horizontal β_x function is lowered along the FFS, which causes that particles are less sensitive to the multipole components and fringe fields. Thus, the horizontal to vertical coupling is reduced which makes the IP vertical beam size smaller, from 27 nm to 21 nm. However, in such case the horizontal beam size increases by factor $\sqrt{10}$, both effects lead to luminosity decrease of about 40%. Therefore, this is not a preferred solution for the future linear colliders.

Another mitigation method which was considered is the installation of octupole magnets in ATF2 beam line. Some of the beam dynamic aberrations are corrected with the use of sextupole magnets, but detailed analysis of ATF2 multipole components [9] revealed the strong third order contribution coming from the QD0FF (last quadrupole before the IP) magnet. Also FD fringe fields give mainly a third order kick which justifies the use of octupole magnets providing a third order magnetic field. The installation of two octupole magnets, one in dispersive and the other in non-dispersive location is considered, with a phase advance of 180° between them. The proposed locations for the octupole magnets are: OCT1FF between QD2AFF and SK1FF and OCT2FF between QD6FF and SK3FF. The technical design [17, 18] of the magnet was done at CERN, see Fig. 2 for the magnet visualization and Table 2 for the main parameters. The octupole magnets are now in the fabrication phase and other technical issues are addressed in parallel, namely the supports, power supplies, cables, alignment requirements and methods, etc. The magnets installation is planned for the beginning of 2016.

The simulated vertical beam size (σ_y^*) decreases from 27 nm to 20 nm when the octupoles are added to the beam line. Such a low beam size is very close to the limit of measuring capabilities of the IP beam size monitor (IPBSM [19]) installed at ATF2.

EXPERIMENTAL VERIFICATION OF THE ULTRA-LOW BETA* PROJECT

The ultra-low β^* optics makes the beam very sensitive to any imperfections like misalignments, magnets mispowering, additional dispersion, ground motion, wakefields, etc. Some of these effects can be mitigated by the beam tuning process, which consists in obtaining the beam design parameters by scanning the so-called tuning knobs [20, 21]. The knobs are used empirically, so that they are changed to minimise the IP beam size measured by the IPBSM. The principle of IPBSM is based on the collision between the electron beam and the interference pattern created by two crossing laser paths [19]. The number of photons generated in this collision is proportional to the convolution of the vertical electron beam distribution and the distribution of photons of the interference pattern. Altering the path length of one laser creates the modulation in number of generated photons and allows to reconstruct the vertical beam size of the electron beam.

The numerical simulations show that it is possible to achieve the design beam size only with a very fine adjustment of the 2nd and 3rd order tuning knobs. For this reason the feasibility of the ultra-low β^* project strongly depends on the IPBSM performance. There are several factors (un-smooth longitudinal laser profile, multi-mode behavior of the laser and others [22]) that can spoil the stability of the beam size monitor and in consequence prevent from reaching the goal.

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Table 2: Main Parameters of the Octupole Magnet Design [18]

	G [T/m^3]	tunability	magnetic length [mm]	aperture radius [mm]	ampere-turns per coil [A]	# of turns per coil	I [A]	power max. [W]
OCT1	6820	-90%/+20%	300	52	1800	60	30	152
OCT2	708	-90%/+20%	300	52	180	6	30	15.2

The first experience in the path towards the ultra-low β^* project realisation was performed during the December ATF2 run. The halfway optics ($\beta^*_x = 40$ mm, $\beta^*_y = 50$ μm) was designed using MAD-X and SAD simulations and then applied to the machine. The following procedure was performed in order to verify the actual β^* values. The emittance measured by the OTR monitors was 2.17 $\pm$ 0.22 nm in the horizontal plane ($\leq$ 2 nm is the expected value) and 28.84 $\pm$ 4.58 pm in the vertical plane (between 10 and 12 pm is the expected value). Knowing the emittance, β^* can be approximated as given in Eq. (1).

$$\beta^* \approx \varepsilon(\Delta f)^2\sigma^{-2}, \quad (1)$$

with ε, σ and Δf being emittance, beam size at the IP and beam waist shift, respectively. The beam waist shift was obtained by slightly changing the strength of final doublet quadrupoles, so the beam size (measured with a carbon wire scanner located at the IP) was enlarged by the beam divergence making the measurement more accurate (see Fig. 3), but keeping the β value at beam waist almost unchanged. The estimated values of β^* for the second week of the December run were β^*_x = 68.4 $\pm$ 2.9 mm, β^*_y = 51.5 $\pm$ 8.2 μm for the measured values of emittance and β^*_x = 74.1 $\pm$ 3.1 mm, β^*_y = 17.9 $\pm$ 1.8 μm assuming a 10 % uncertainty in the design emittance. This shows that a good estimate of the beam emittance is needed for a correct verification of the applied optics at the IP. This problem was already addressed during the April 2015 ATF2 run. There was a run shift dedicated to the emittance estimation directly from the beam size measurement in the large β^*_y optics, but it failed due to the machine break down caused by the serious power drop during a thunderstorm. A more precise verification of the applied optics is scheduled for the next ATF2 run, but the December data indicate that we are close to the final optics layout.

During the December 2014 run there were two sessions of beam size tuning (second and third week of December run) with the halfway optics, the minimum measured beam size was σ^*_y = 62.5 $\pm$ 1.8 nm [23], far from the expected value of around 41 nm (if ε_y = 28.84 pm is assumed). The following factors are identified to affect the measured beam size. The extraction kicker was unstable causing beam orbit fluctuations. Eventually, this malfunction ended up with a serious failure of kicker power supply, caused by a broken high-voltage diode. The performance of IPBSM was low, mainly because of the lasers instabilities causing higher signal fluctuations [24]. There was also a problem with the RF power in the damping ring, which was lower than the nominal by a factor 3 and unstable during the third week of the December run [25]. It enhanced the IPBSM fluctuation and could spoil the beam performance.

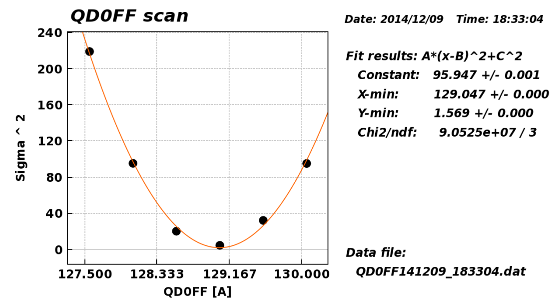

Figure 3: QD0FF scan used for the evaluation of β^*_y value. Horizontal axis stands for the current of the QD0FF quadrupole and vertical axis for the beam size at the IP measured with the carbon wire scanner.

Nevertheless, the December 2014 and April 2015 runs allowed to gain the first beam experience in ATF2 with halved β^*_y value and learn about the possible obstacles. All listed machine problems are being constantly improved in ATF2. The ultra-low β^* study is planned to be continued over the ATF2 runs in spring and autumn 2015.

CONCLUSIONS

The ATF2 Final Focus system is constantly being improved which enables an effective beam focusing at the IP. However, the still existing machine imperfections cause the IP beam size to be larger than design even for 10β^*_x optics and low beam intensity.

The difficulty of the beam focusing at IP significantly increases for the ultra-low β^* optics making its feasibility challenging. The lower β^*_y value causes the beam size to be more sensitive to the imperfections and tuning procedure to be more difficult.

Simulations show that reaching a low beam size (25 nm for half β^*_y case and 20 nm for ultra-low β^*_y case) will be possible after the installation of octupole magnets and very fine tuning of 2nd and 3rd order knobs. The IP beam size monitor (IPBSM) used for setting the knobs values will play a key role in the realization of this project and its high performance is therefore required.

The first experimental experience collected in December 2014 and April 2015 allows us to conclude that the linear parameters of the applied halfway optics are correct and further optimisation of this layout is planned for the next ATF2 runs.

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