TUNABILITY STUDY OF THE ULTRA-LOW BETA* OPTICS AT ATF2 WITH NEW OCTUPOLE SETUP AND TUNING KNOBS

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Abstract

The main goal of the Accelerator Test Facility 2 (ATF2) is to demonstrate the feasibility of future linear colliders' final focus systems. The Ultra-low beta* optics of ATF2 is designed to have the same chromaticity level as CLIC. To ease the tuning procedure, a pair of octupoles was installed in ATF2 in 2017. This paper reports the optimizations performed to the octupoles' setup for Ultra-low beta* optics including the new alignment technique, based on the waist shift and the new tunning knobs constructed for this optics. The full tuning procedure including the static errors is simulated for this setup.

INTRODUCTION

One of the key ingredients for the high luminosity at the Future Linear Collider (CLIC [1] and ILC [2]) is the small beam spot at the IP, usually at the nanometer level. Demagnification is performed in the Final Focus System (FFS). The last pair of quadrupoles in the FFS is referred to as Final Doublet (FD) and is responsible for the nanometer beam size at the IP. FD is also a strong source of aberrations, mainly chromaticity. To cancel it, the FFS design, of both CLIC and ILC, utilizes the local chromaticity correction scheme [3]. The ATF2 [4] project at KEK was proposed to test this new scheme. The baseline optics of ATF2 is called Nominal optics. In CLIC, the chromaticity is 5 times larger than in the Nominal design of ATF2. To study CLIC design's feasibility, an optics with 4 times smaller vertical β_y^* has been proposed [5], see Table 1. On the other hand, the optics with larger chromaticity is more sensitive to beamline imperfections and features more tuning difficulties. To reduce the impact of the multipole errors, the optics with 25 times larger β_x^* was used in the tuning [6] of the Ultra-low optics.

Table 1: Key Parameters of the FFS of ATF2

Optics	Nominal	Ultra-low[a]
Beam energy [GeV]	1.3	
Vertical emittance [pm]	12	
Horizontal emittance [nm]	1.2	
Energy spread [%]	0.008	
IP beta-function β_x^* / β_y^* [mm]	4/0.1	4/0.025
Vertical chromaticity ξ_y	10000	40000
Vertical beam size [nm]	37	27 (20[b])

[a] $1\beta_x^* \times 0.25\beta_y^*$ optics.
[b] with octupoles

Table 2: Main Parameters of the Octupoles

	OCT1FF	OCT2FF
Max. integr. gradient [T/m^2]	7663	390
Max. integr. strength [m^{-3}]	730	90
Max. current [A]	50	50
Magnetic length [mm]	300	300
$1\beta_x^* \times 0.25\beta_y^*$, design k_{3L} [m^{-3}]	-19.24	-35.51
$25\beta_x^* \times 0.25\beta_y^*$, design k_{3L} [m^{-3}]	102.61	730.0

In 2017, two octupoles, namely OCT1FF and OCT2FF, were manufactured according to the specifications in [7] and were installed in the ATF2 beamline. Their locations are indicated in Fig. 1. The octupoles aim to assist in the beam size tuning by canceling 3$^{\text{rd}}$ order aberrations. The strong sources of these aberrations are the multipole components of the QD0FF (the last quadrupole before the IP) [8], and the fringe fields in the FD [9]. The main parameters of the octupoles are given in Table 2. The vertical beam size evaluated for the $1\beta_x^* \times 0.25\beta_y^*$ and $25\beta_x^* \times 0.25\beta_y^*$ Ultra-low optics is shown in Fig. 2. The octupoles' impact is measured in the vertical beam size reduction of 9.4 nm and 2.1 nm for $1\beta_x^* \times 0.25\beta_y^*$ and $25\beta_x^* \times 0.25\beta_y^*$ optics, respectively. Such a beam size change is foreseen to be visible in 174° mode of the IP Beam Size Monitor (IPBSM) [10]. In 2019, the OCT1FF and OCT2FF were swapped to reflect the need to have a stronger octupole at the OCT2FF location, which is crucial for $25\beta_x^* \times 0.25\beta_y^*$ optics, see Table 2.

This paper reports the new octupole alignment technique tested in the December 2019 and March 2020 Ultra-low tuning runs. It also reports the tuning simulations performed for $25\beta_x^* \times 0.25\beta_y^*$ Ultra-low optics with the new tuning knobs and including the octupoles.

OCTUPOLE ALIGNMENT USING WAIST SHIFT

Octupoles alignment is required to minimize the feed down to lower order multipoles. A transversely displaced octupole generates sextupolar, quadrupolar and dipolar magnetic fields. For a thin octupole, misaligned by Δx and Δy with respect to the beam orbit in the horizontal and vertical planes respectively, the particle experiences a vertical kick given by:

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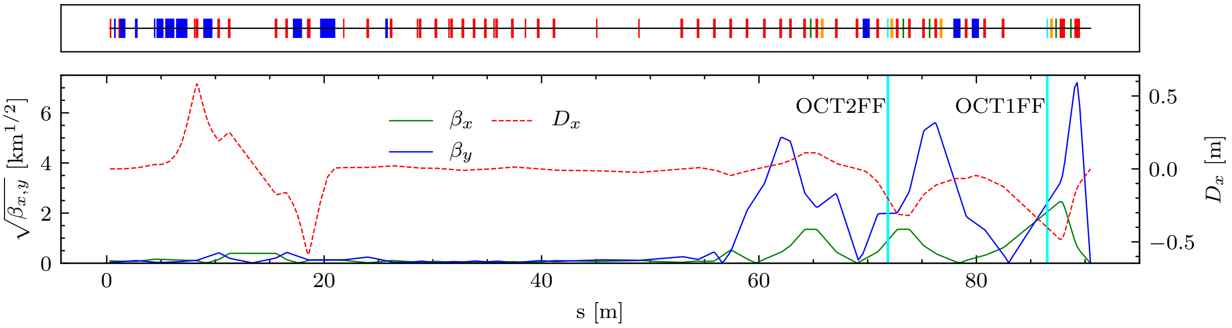

Figure 1: Horizontal and vertical beta-function and horizontal dispersion for the $1\beta_x \times 0.25\beta_y$ optics. In cyan are indicated the locations of the octupoles. The same labels are kept after the octupoles swap.

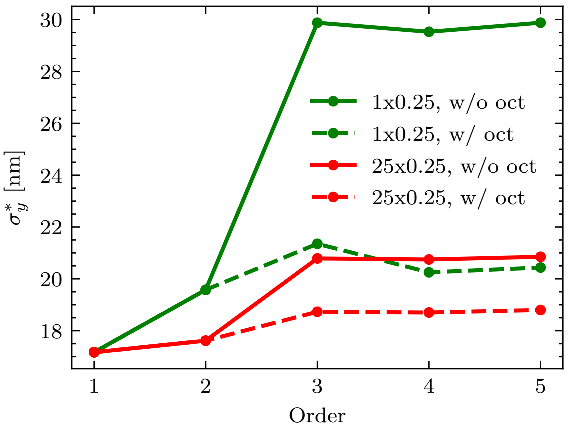

Figure 2: Vertical beam size at the virtual IP as a function of the map order for the $1\beta_x^* \times 0.25\beta_y^*$ (green) and $25\beta_x^* \times 0.25\beta_y^*$ (red) Ultra-low optics. The calculation includes the multipole components of the magnets.

$$\Delta y' = \overbrace{\frac{k_{3L}}{6}(3yx^2 - y^3)}^{\text{Normal Octupole}} - \overbrace{\frac{k_{3L}\Delta y}{2}(y^2 - x^2)}^{\text{Normal sextupole}} + \overbrace{k_{3L}\Delta xxy}^{\text{Skew sextupole}} - \overbrace{\frac{k_{3L}(\Delta y^2 - \Delta x^2)}{2}}^{\text{Normal quadrupole}}y + \overbrace{k_{3L}\Delta x\Delta yx}^{\text{Skew quadrupole}} + \overbrace{\frac{k_{3L}}{6}(3\Delta y\Delta x^2 - \Delta y^3)}^{\text{Dipole}} , \tag{1}$$

where k_{3L} is the integrated strength of the octupole. The traditional beam based alignment (BBA) is performed by measuring the beam orbit at the downstream BPMs. In this case, the orbit deviation is based on the dipolar component of the misaligned magnet. Such an alignment strongly relies on the precision of the orbit measurements. With the presence of the orbit jitter, even for the stronger octupole, usage of the beamline BPMs for the alignment is rather challenging [11].

The new alignment technique has been applied to OCT2FF, after the octupole swap. The normal quadrupole kick from the octupole feed-down propagates to the virtual IP and causes a longitudinal shift of the beam waist as:

$$\Delta s_{x,y} \approx \pm\Delta k \beta_{x,y}\beta^*_{x,y}\cos 2\Delta\mu_{x,y} , \tag{2}$$

where $\beta_{x,y}$ is the beta-function at the octupole location, $\Delta\mu_{x,y}$ is the phase advance between the octupole and the Virtual IP, and $\Delta k = \frac{k_{3L}(\Delta x^2 - \Delta y^2)}{2}$ is the associated quadrupole kick. The shift of the vertical beam waist is expected to be quadratic on the octupole offsets $\Delta s_y \propto (\Delta y^2 - \Delta x^2)$. Measurement of Δs_y is performed with the IPBSM. The octupole is set to the maximum current, and for a given octupole offset, the waist shift (AY) knob [12] scan is performed. We assume the beam is already well-tuned, such that the initial waist shift can be neglected. The AY knob strength that is needed to correct the waist shift is proportional to Δs_y.

The waist shift is evaluated for a set of the octupole offsets, both in horizontal and vertical planes. In this case, the center of the fitted parabola corresponds to the magnetic center of the magnet. Such an alignment was performed in December 2019 and in March 2020 Ultra-low β_y^* tuning weeks, see Fig. 3. In both cases, the vertical beam size was tuned to approximately 100 nm in 30° mode of the IPBSM. The octupole alignment was performed in the same IPBSM mode. In this case the alignment precision has been estimated to approximately 100 µm.

SIMULATION OF THE BEAM SIZE TUNING PROCESS

To study the possible ways to improve the tuning performance of the Ultra-low optics, a new set of tuning knobs has been designed for the Ultra-low $25\beta_x^* \times 0.25\beta_y^*$ optics [13]. The tuning knobs are used to correct the multipolar errors and static imperfections in the ATF2 beamline. There are three key linear knobs to correct the longitudinal shift of the vertical waist (AY), the vertical dispersion (EY), and the $< x', y >$ coupling at the IP (Coup2). There are also nonlinear knobs aimed to correct the residual 2nd order aberrations (Y24, Y46, Y22, Y26, Y44, Y66) (refer to [12]). To evaluate the effectiveness of the tuning knobs, a simulation of the tuning process, including the static errors, is performed. The errors considered in the study are shown in Table 3.

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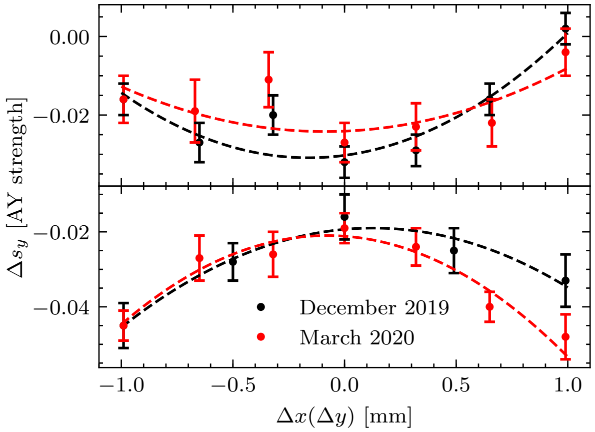

Figure 3: Waist shift measurements for the horizontal (top) and vertical (bottom) displacements of the OCT2FF magnet.

Table 3: Summary Table of the Errors Considered in the Tuning Studies

Element	Error	
Quadrupole, Sextupole, Octupole	Misalignment [μm]	100
	Roll [μrad]	200
	Strength [%]	0.1
	BBA accuracy [μm]	100[a]
Strip line BPM	Accuracy [μm]	5
C-band cavity BPM	Accuracy [μm]	0.2

[a] Uniform distribution.

Simulations are performed through a software, written in Python programming language, which is interfaced to MADX [14]. It also uses Mapclass [15] to evaluate the beam size. The simulation follows the tuning routine at ATF2:

1. Beam orbit correction.
2. Dispersion correction.
3. Waist adjustment at the IP.
4. Sextupoles are aligned according to the BBA precision.
5. The beam size is tuned with the tuning knobs.
6. The octupole BBA is performed on OCT2FF.
7. The strength of OCT2FF is iterated.

In the simulations, the number of iterations of the tuning knobs is chosen to reflect the beam tuning in the actual machine. From the approximation that one knob scan takes approximately 30 minutes, we set the number of the iterations to 51, which corresponds to around 25 hours of the beam tuning. The same number of knob iterations was performed during the Ultra-low tuning week of June 2019. The sufficient statistic is acquired by running the tuning simulations on 100 machines with random static errors assigned to the elements, according to Table 3. In addition, for comparison, the tuning simulations are performed with the tuning knobs constructed for the Nominal optics $10\beta_x^* \times 1\beta_y^*$ [12] which are referred to as “Nominal” knobs.

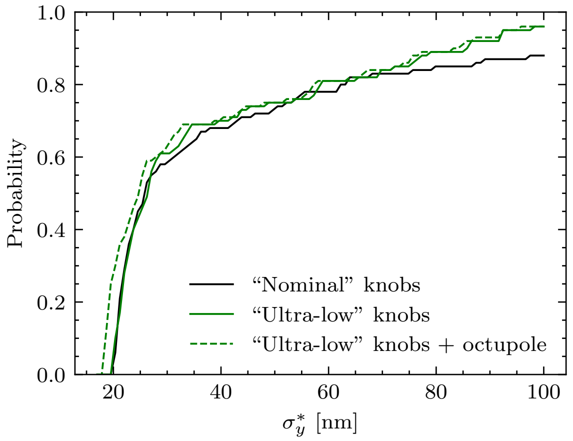

Figure 4: Cumulative distribution of the beam size at the Virtual IP at the end of the tuning process for 2 sets of the knobs.

The results of the tuning simulations are shown in Fig. 4. The “Nominal” and “Ultra-low” knobs show a similar performance with the median value of 26 nm. However, when tuned with “Nominal” knobs, 12% of the machines have a beam size larger than 100 nm, compared to 4% when “Ultra-low” knobs are used. One can also see that the octupoles’ impact is only visible when the vertical beam size is tuned to around 30 nm. In this case, octupoles provide a reduction of around 2.5 nm, allowing 25% of the machines to reach 20 nm beam size.

CONCLUSION

A new octupole alignment technique has been developed based on the waist shift measurement. It was successfully tested in two Ultra-low tuning runs in December 2019 and in March 2020. This alignment can be performed in both 30° and 174° mode of the IPBSM, covering the beam size range from 20 nm to few hundreds of nanometers. At the same time, the beam size reduction due to the octupoles is evaluated in the tuning simulations to be about 2.5 nm but requires the beam size to be tuned to 30 nm or smaller. The new set of tuning knobs for the Ultra-low optics has also been tested in the simulations and compared to the tuning with the “Nominal” knobs. They show a similar probability to reach the small beam size, but with “Ultra-low” knobs, the beam size is less likely to be larger than 100 nm at the end of the tuning. The “Ultra-low” knobs had also been used during the tuning week in March 2020. They proved to be effective for the aberration correction, as the beam size was reduced to approximately 100 nm in 30° degree mode.

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