PROGRESS IN ULTRA-LOW BETA* STUDY AT ATF2

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Abstract

A nanometer beam size in the interaction point (IP) is required in case of future linear colliders for achieving the desired rate of particle collisions. KEK Accelerator Test Facility (ATF2), a scaled down implementation of the beam delivery system (BDS), serves for investigating the limits of electron beam focusing at the interaction point. The goal of the ultra-low β^* study is to lower the IP vertical beam size by lowering the β^*_{y} value while keeping the β^*_{x} value unchanged. Good control over the beam optics is therefore required.

The first experience with low β^* optics revealed a mismatch between the optics designed in the model with respect to the beam parameters observed in the experiment. Additionally, existing methods of beam parameters characterization at the IP were biased with high uncertainties making it difficult to set the desired optics.

In this paper we report on the new method introduced in ATF2 for IP beam parameters characterization which gives a good control over the applied optics and makes the ultra-low β^* study possible to conduct. It can be also used for verifying the performance of some of the existing beam instrumentation devices.

INTRODUCTION

The future linear colliders (CLIC [1], ILC [2]) require nanometer beams size in the interaction point (IP) in order to achieve the desired rate of particle collisions. Beam focusing at the IP is done by the final doublet (FD) – two strong quadrupole magnets located just upstream from the IP. These magnets are also a source of strong chromatic effect which causes off-momentum particles to be not exactly focus at the IP, leading to larger spot sizes. In the ATF2 [3], which is a final focus system (FFS) test facility, the IP vertical beam size can be decreased from a few hundreds of nanometers to about 40 nm if the chromaticity is corrected. This shows the importance of the chromaticity correction.

A novel design of a final focus system [4] intended to correct the chromatic aberration locally at the final doublet is being tested in ATF2. This technique was already validated by measuring a beam size of less than 45 nm [5–8]. Therefore, the local chromaticity correction scheme is considered as a baseline for ILC and a strong candidate for CLIC. However, in case of CLIC the expected level of chromaticity is higher by about a factor 5. For this reason, the ultra-low β^* [9] project is studied in ATF2 with the aim of increasing the level of chromaticity close to the CLIC one by decreasing the value of β^*_{y} by a factor 4, see Table 1 for details. With larger chromaticity also a larger tuning difficulty is expected, so collecting the experience of operation under these conditions is beneficial both for CLIC and ILC. Moreover, limits of IP beam focusing can be explored.

A good control over the optics and IP beam parameters is required for feasibility of this study. A very small vertical IP beam size of less than 100 nm makes the beam diagnostics very challenging. The existing methods of IP optics parameters characterization turned out to be not sufficient. A new method based on very fine beam waist shift and precise IP beam size measurement has been implemented for the beam diagnostics at the IP and its details are described in this paper.

BEAM DIAGNOSTICS AT THE IP

Quadrupole scan is a widely used method (also in ATF2 [10]) for measuring the beam transverse parameters. Since we are interested in the beam parameters at the beam waist at the IP, the FD quadrupoles strength is being varied and both horizontal and vertical beam sizes are measured using the IP wire scanner. An increase of the transverse beam size is given by the beam divergence, so the beam parameters can be resolved by fitting Eq. (1) to the measured beam size $\sigma_{x,y}$, where $\varepsilon_{x,y}$ stands for the transverse emittance, $\beta^*_{x,y}$ for the IP β value and $\Delta f_{x,y}$ for the longitudinal distance between the wire position and actual beam waist position.

$$\sigma^2_{x,y} = \varepsilon_{x,y}\beta^*_{x,y} + \frac{\varepsilon_{x,y}}{\beta^*_{x,y}}(\Delta f_{x,y})^2. \tag{1}$$

Similarly to the method described in [10] the measured beam size has to be corrected for residual dispersion at the IP and for the geometric properties of the wire, as given in Eq. (2).

$$\sigma^2_{x,y} = \sigma^2_{x,y\ measured} - \left(\frac{\sigma_E}{E}\right)^2 D^2_{x,y} - \left(\frac{d}{4}\right)^2, \tag{2}$$

where $\sigma_{\mathrm{E}}/\mathrm{E}$ is the relative energy spread (equal to 0.0006 for low beam intensity of 10^9 e^-/bunch) and d = 5 μm is the carbon wire diameter.

The minimum measurable beam size with the wire scanner is in the range 1/4 – 1/2 of the wire diameter, which is not an obstacle for horizontal beam size measurement (6 – 10 μm is the usual value in recent operation). However, the vertical beam size is expected to be smaller than 1 μm even for the beginning of the operation and it cannot be precisely measured when the beam waist is at the wire location. Instead, the beam waist is shifted out of the the wire location so that the beam divergence can be resolved using the Eq. (3).

$$\sigma^2_y \approx \frac{\varepsilon_y}{\beta^*_y}(\Delta f_y)^2. \tag{3}$$

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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]	$\sigma^*_{y,design}$ [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

Example of vertical beam divergence evaluation is presented on Fig. 1.

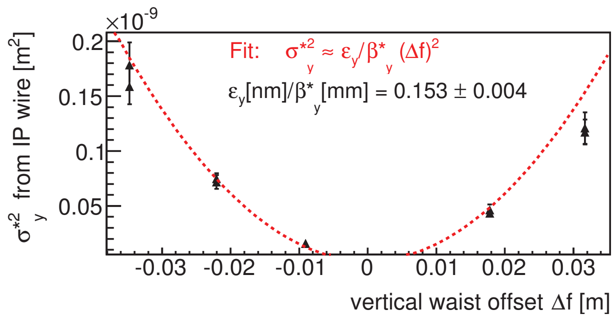

Figure 1: Example of QD0FF scan for vertical beam parameters evaluation at the IP from the last week of February 2016 operation. Lower cut for the beam size measurement was set to 3 μm. Only the ratio ε_y/β_y^* can be resolved. The effects of dispersion and wire properties are subtracted.

Knowledge of β_y^* is necessary for judging if the desired optics was correctly implemented. For the horizontal plane both emittance and β^* can be resolved but in the vertical plane the β^* value can be calculated only if the vertical emittance is known, e.g. measured upstream. In the last week of February 2016 operation the vertical emittance was measured in the damping ring (DR) using XSR monitor [11] and after extraction in the extraction line (EXT) using the multi-OTR system [12]. Table 2 contains the measured values of emittance and corresponding values of β_y^*. The large difference in terms of vertical emittance might imply that the mOTR measurement is biased with large unknown systematic error. On the other hand the XSR measurement cannot be used either as some emittance growth is expected after beam extraction from the damping ring [13]. A new method for IP vertical emittance evaluation was therefore introduced and will be described in next section.

Table 2: β_y^* evaluation based on two emittance measurements and QD0FF scan performed in the last week of February 2016 operation. The matching target was $\beta_y^* = 50$ μm.

	ε_y [pm]	β_y^* [μm]
DR (XSR)	4.4 ± 0.4	29.0 ± 3.0
EXT (mOTR)	15.3 ± 1.5	100.0 ± 10.1

NEW METHOD FOR IP VERTICAL EMITTANCE MEASUREMENT

As mentioned, the quadrupole scan method cannot be applied in the vertical plane to resolve both the emittance and β^* value since the vertical beam size at waist is too small to be measured by the wire scanner. This obstacle can be overcome by using the Shintake monitor [14, 15] located at the IP for measuring the vertical beam size. It is an interference monitor where two laser beams cross in the plane transverse to the electron beam in order to form a vertical interference pattern. The beam size is inferred from the modulation (Eq. (4)) of the resulting Compton scattered photon signal detected by a downstream photon detector. Three laser crossing angle modes (2-8 degree, 30 degree, 174 degree) extend the dynamic range from 5 μm to 20 nm. The 30 degree mode with a dynamic range of 85 nm to 340 nm is the most reliable and its systematic errors can be accurately measured, so this mode should be chosen to perform the scan.

$$M = C\,|cos\theta|\,\exp\left[-2\left(k_y\sigma_y\right)^2\right],\qquad k_y = \pi/d,\ d = \frac{\lambda}{2sin\left(\theta/2\right)}, \tag{4}$$

where C is the modulation reduction factor which represents the overall systematic effect causing a decrease of the observed modulation due to the monitor imperfections, θ is the crossing angle and λ is the laser wavelength.
However, there is a second problem. The QD0FF power supply resolution is too large to apply very fine, well controlled changes of the beam vertical waist position such that the vertical beam size is kept within the dynamic range of Shintake monitor in 30 degree mode. This obstacle can be overcome by using the vertical beam waist position knob [16] (so called α_y knob) for changing the waist longitudinal position. This knob makes use of deliberate horizontal movements of the FFS normal-sextupole magnets and it is orthonormal, so it modifies the waist position without changing the other optics parameters. The relation between α_y knob amplitude and beam waist offset is depicted on Fig. 2.

In normal operation the vertical size of well tuned beam is expected to be about 40 nm. In the last week of February 2016 operation the optics was rematched with target β^* values of $\beta_x^* = 40$ mm and $\beta_y^* = 2.5$ mm (β_y^* being 25 times larger than nominal) in order to increase the vertical beam

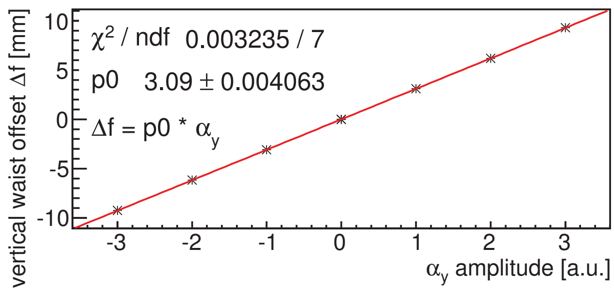

Figure 2: The relation between α_y knob amplitude and beam waist offset.

size at the IP such that it can be measured in 30 degree mode of the Shintake monitor. The α_y scan was then performed and measured data were fitted (see Fig. 3) with the formula (Eq. (5)) coming from combining Eq. (1) with Eq. (4).

$$M = C\,|cos\theta|\,\exp\left[-2k_y^2\left(\varepsilon_y\beta_y^* + \frac{\varepsilon_y}{\beta_y^*}\left(p_0\Delta\alpha_y\right)^2\right)\right]. \qquad (5)$$

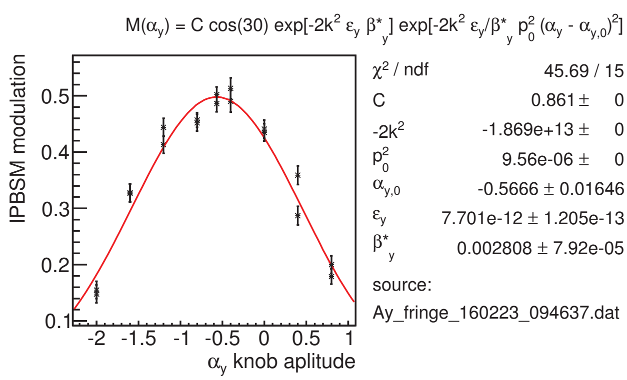

Figure 3: The α_y scan to resolve the vertical emittance at the IP and β_y^* value.

The modulation reduction factor in 30 degree mode (C_{30}) was estimated in the same beam operation in the following way. The optics was rematched again with target β^* values of $\beta_\mathrm{x}^* = 40$ mm and $\beta_\mathrm{y}^* = 50$ μm in order to decrease the vertical beam size such that it can be measured both in 30 and 174 degree mode. Modulation produced by the well tuned beam was then measured in these two modes by taking 10 consecutive Shintake monitor scans, the results are $M_{174} = 0.374 \pm 0.016$ and $M_{30} = 0.709 \pm 0.016$. Using the modulation in 174 degree mode (M_{174}) the corresponding beam size (σ_{174}) was calculated according to Eq. (6).

$$\sigma_{174} = \frac{1}{2k_y}\sqrt{2\ln\left(\frac{C_{174}\,|cos\theta|}{M_{174}}\right)}, \qquad (6)$$

where C_{174} is the modulation reduction factor in 174 degree mode that cannot be measured but can be estimated in a complex offline analysis. The procedure was described in a PhD thesis of J. Yan [15], where two values of C_{174} representing its lower limit can be found, namely $C_{174} > 0.754$ for 12 June 2014 and $C_{174} > 0.831$ for 13 June 2014. It was decided to assume $C_{174} = 0.8 \pm 0.1$ in case of our study. Knowing σ_{174}, the expected modulation in 30 degree mode ($M_{30,\mathrm{exp}}(\sigma_{174})$) can be calculated and compared with a measured value ($M_{30,\mathrm{meas}}$). The ratio of these two is the modulation reduction factor in 30 degree mode, see Eq. (7).

$$C_{30} = \frac{M_{30,\mathrm{meas}}}{M_{30,\mathrm{exp}}(\sigma_{174})} = 0.861 \pm 0.021. \qquad (7)$$

As presented on Fig. 3 the vertical beam parameters at the IP, namely vertical emittance and β_y^* value, can be resolved from fitting α_y scan data with formula given in Eq. (5). In our case the results are: $\varepsilon_\mathrm{y} = 7.7 \pm 0.3$ pm and $\beta_\mathrm{y}^* = 2.81 \pm 0.12$ mm (matching target was $\beta_\mathrm{y}^* = 2.5$ mm). Vertical emittance measured with this method was compared with the measurements done both by XSR in the DR and mOTR in EXT line during the same week of operation, see Fig. 4. A vertical emittance growth between the DR and IP by a nearly factor 2 is observed. These data also confirm that there might be some issues with mOTR system especially in case of very low vertical emittance.

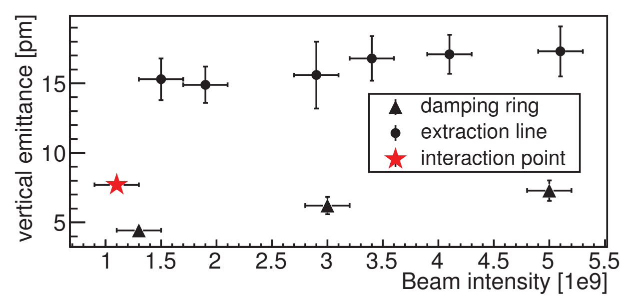

Figure 4: Comparison of measured vertical emittance at 3 locations using different methods in beam intensity dependence. Emittance at the IP was measured only for one beam intensity but this study is ongoing.

Such calculated vertical emittance was then used to verify if the half β_y^* optics was correctly applied. The vertical beam divergence measured using QD0FF scan (Fig. 1) was $\beta_\mathrm{y}'^* = (1.53 \pm 0.04) \cdot 10^{-7}$ which gives $\beta_\mathrm{y}^* = \varepsilon_\mathrm{y}/\beta_\mathrm{y}'^* = 50.3 \pm 2.3$ μm. The β_y^* value agrees with the matching target (50 μm) prooving that the desired optics was correctly applied to the machine.

CONCLUSION

A new method to measure the vertical beam parameters at the IP has been implemented in ATF2. It is based on very fine, well controlled beam waist shift and precise beam size measurement at the IP. It gives a good estimation of vertical beam emittance which is necessary in ultra-low β^* study to correctly set the desired optics using the QD0FF scan. The results also give an indication of actual emittance growth during the beam extraction and suggest that there might be some issues with the mOTR system.

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