

CONTRIBUTION OF OPTICAL ABERRATIONS TO SPOT-SIZE INCREASE WITH BUNCH INTENSITY AT ATF2

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Abstract

A primary goal of ATF2 (Accelerator Test Facility 2) at KEK is to demonstrate an unprecedentedly low vertical beam size at the interaction point (IP) of about 37 nm. Measurements over the past years indicate that the ATF2 vertical beam size, achieved after tuning, strongly rises with bunch intensity. This increase could have several different origins. For example, it could be due to wake fields occurring between the ATF damping ring and the IP, and/or be due to changes in the transverse emittances and energy spread in the damping ring, which are known to increase with intensity as a result of intrabeam scattering (IBS). In this paper we address the second possibility. Past measurements and simulations of the IBS effects in the ATF damping ring and in the extraction line are used to model the intensity-dependent initial emittances and energy spread at the entrance of the final focus. Using this model, particle tracking simulations predict the IP vertical beam size growth expected from the known optical aberrations for initial beam parameters corresponding to varying bunch intensities. We consider both the nominal final-focus optics and a relaxed optics with ten times increased horizontal IP beta function, which has also been used in operation. Comparing simulation results with emittance measurements at different locations allows us to draw some conclusions about the impact of IBS in the damping ring on the IP spot size, and about possible single-bunch wakefields in the ATF2.

INTRODUCTION

Between the end of 2012 and the spring of 2014 a significant reduction of the vertical beam size was achieved [3] at ATF2 [1, 2]. This improvement coincided with two major modifications: (1) an increase of the horizontal beta function at the focal point, β_x^* , by a factor of 10 (in the following called the "10 β_x optics"), and (2) a 10-fold reduction of the bunch intensity.

The 10 β_x optics decreases the horizontal beam size at almost all the quadrupole magnets of the ATF2 final-focus system, which minimizes the effect of most optical imperfections (e.g. x-y coupling, residual sextupole aberrations) on the vertical beam size at the IP [4]. In parallel, the lower bunch charge weakens single-bunch wake fields [5], and it also minimizes the emittance and momentum spread of the incoming beam, extracted from the damping ring.

In this paper we investigate the IP vertical beam size as a function of beam charge in ATF2 using MAD-X [6] sim-

ulations based on the PTC [7] tracking routines. Both the design optics and the relaxed 10 β_x optics are considered. The latter optics is actually in use.

Our simulations do not include any wake fields in the extraction line or in the final focus, but they do take into account the measured dependence of the damping-ring transverse emittance and momentum spread on the bunch charge. Our simulations also incorporate the measured high-order imperfections of the final-focus magnets, i.e. their multipolar field errors. On the other hand, off-center field errors of damping-ring magnets [8] or the nonlinear components of the septum field affecting the kicked beam during extraction are not considered.

INTENSITY-DEPENDENT SPOT SIZE

In 2003 the dependence of the ATF damping-ring emittance and momentum spread on the beam intensity was measured [9, 10]. Figures 2a and b summarize the emittance measurements (grey bands). The measured growth of the momentum spread with rising bunch intensity [10], shown in Fig. 1 (upper curve), is included in all our simulations. The strong intensity dependence of the emittance, and, especially, of the momentum spread, is due to IBS [10].

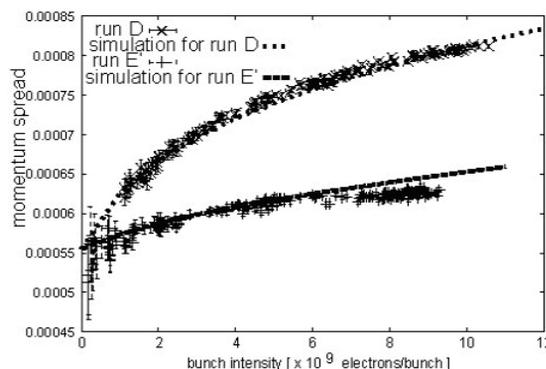


Figure 1: Measured rms momentum spread in the damping ring as a function of the bunch charge compared with IBS simulations [10]. The upper curve was obtained in standard operation, far from the coupling resonance, and it is used for our simulations.

We next examine how this beam emittance increase affects the IP vertical beam size. Three cases are considered: The first case assumes the beam emittances measured in the damping ring (DR). In the second case a constant increment is added to model the emittance of the beam extracted from

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the damping ring to the extraction line (EXT). In the last case, the beam emittance measured in the EXT line is considered.

For all three cases the corresponding IP vertical beam size is calculated in order to study if the intensity dependent growth of emittance and momentum spread could be responsible for the observed intensity-dependent beam size. The results are presented in Figs. 2c and d, and described in the following.

The grey bands in Figs. 2c and 2d present the IP vertical beam size calculated for the beam parameters in the damping ring, considering both types of optics. The IP vertical beam size does increase together with damping-ring emittance and momentum spread, but it does so much less strongly than the vertical beam size computed from the beam parameters in the extraction line, where the measured horizontal and vertical emittances are much larger than in the damping ring. Indeed, the vertical emittance plotted as a grey band in Figs. 2a and b is lower than the design value in the final-focus line (12 pm) and significantly lower than some of the values measured in the extraction line. For simplicity we assume that during beam extraction from the damping ring the emittance is enlarged by a constant value, independently of the bunch intensity. We set this constant shift to 7 pm in the vertical plane and to 0.57 nm in the horizontal plane, so as to obtain the design emittance values at the nominal bunch intensity N_b of $5 \cdot 10^9 e^-$. The corresponding emittance values are shown as red bands in Figs. 2a and 2b, together with the associated vertical IP beam size in Figs. 2c and 2d. At nominal bunch intensity N_b of $5 \cdot 10^9 e^-$ with the $10\beta_x$ optics the calculated vertical IP beam size roughly equals its design value of 37 nm; with the nominal optics it is at most a few nm larger.

In October and November 2014 the beam emittance in the extraction line was measured as a function of bunch intensity [11, 12]. The measurement data are represented as points in Figs. 2a and b. The emittances (especially the vertical one) measured in the extraction line increase with intensity much faster than those in the damping ring. Possible wake-field effects are being investigated and mitigated [13, 14]. The values of the vertical IP beam size simulated for the emittances measured in the extraction line, shown as plotting symbols in Figs. 2c and 2d, demonstrate that the optical aberrations of the final focus do not prevent ATF2 from reaching the targeted low beam size (e.g. $\sigma_y^* < 40$ nm) at low bunch intensity ($N_b < 1.5 \cdot 10^9 e^-$). This prediction is consistent with the experimental observations: The lowest measured vertical IP beam sizes for bunch intensities $N_b < 10^9 e^-$ were 53 nm in May 2014 [3], 44 nm [15] in June 2014, and 52 nm [16] in November 2014. At nominal intensity of $N_b \sim 5 \cdot 10^9 e^-$ much larger spot sizes were obtained, i.e. well above 100 nm. Possible explanations include a degraded beam-orbit stability (compromising the spot-size tuning), wake fields, and less accurate performance of the beam size monitors.

On the other hand, for high beam intensity the simulated IP vertical beam size is already significantly increased, even for our simplified model, if we assume the emittance values

measured in the extraction line instead of those in the damping ring. Without improving the latter, a reduction of the beam intensity is necessary for reaching the design vertical spot size at the focal point.

In Figs. 2a and 2b the horizontal and vertical emittances increase monotonically with beam intensity, both in the damping ring, and even more in the extraction line. A larger vertical emittance has a direct first-order impact on the vertical beam size, but the increased horizontal emittance can also play an important role due to optical aberrations, which ultimately limit the spot size that can be achieved by a final focus system. The relevant aberrations are proportional to terms of the form $\theta_x^m \theta_y^n \delta^p$ where $\theta_x \equiv \sqrt{\epsilon_x/\beta_x^*}$, $\theta_y \equiv \sqrt{\epsilon_y/\beta_y^*}$ denote the horizontal or vertical rms divergence at the focal point and δ the rms momentum spread, with m , n , and p integers between 0 and 5. All three terms entering in the strength of the aberrations increase with beam intensity. In addition, the aberrations involving the horizontal emittance get weaker for a larger horizontal IP beta function.

The dependence on the horizontal emittance was investigated in simulations, by keeping the vertical emittance constant (at 12 pm) and by varying the horizontal emittance. The results are presented in Fig. 3. In case of the nominal optics, the vertical IP beam size increases by nearly 10% if the horizontal emittance is raised from 0.8 to 3 nm. By contrast, for the $10\beta_x$ optics, this effect is much weaker, as expected.

An analysis of the intensity dependence was also performed for a proposed future ultra-low β^* optics [4, 17, 18], which aims at $\beta_x^* = 4$ mm and $\beta_y^* = 25$ μ m. As the optical aberrations of the final focus scale with powers of the IP divergences, they should also be strong for this new optics. Lowering β_y^* by a factor 4 reduces the linear vertical beam size by a factor 2. In the absence of aberrations the rms spot size should be well below 20 nm (for the ATF2 vertical design emittance of 12 pm). Simulation results for the ultra-low β^* optics, shown in Fig. 4, indicate that even at low intensity the beam size will be much larger, and that, indeed, the intensity dependence will be significant.

CONCLUSIONS

The increase of damping-ring beam emittance and momentum spread due to IBS should not prevent one from reaching the design vertical beam size at the IP, even for the nominal beam intensity. The emittances measured in the extraction line, i.e. between the damping ring and the ATF2 final focus, are much larger than those in the damping ring, by up to a factor 2 in both planes, and these show an even stronger dependence on the bunch intensity. This intensity-dependent emittance blow up could be due to nonlinear fields during extraction which would amplify the emittance growth and, especially, momentum-spread increase with intensity generated in the damping ring. Other possible explanations include the persistent presence of strong wake fields in this region of the machine. and, perhaps, an insufficient control of spurious dispersion and coupling in the extraction line.

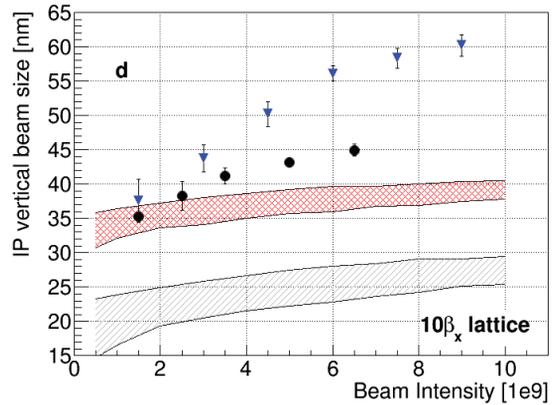
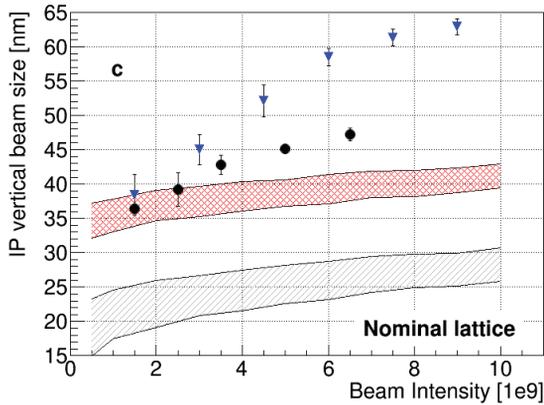
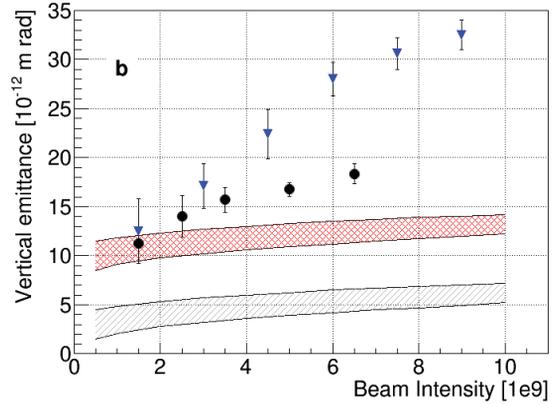
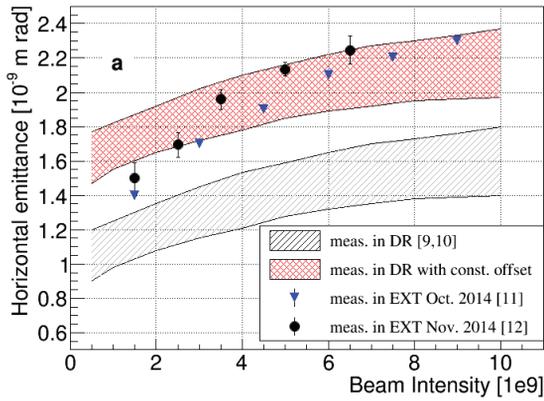


Figure 2: Top: Emittances versus bunch charge. The grey band represents the beam emittance measured in the damping ring [9, 10], red band accounts for the beam emittance in the EXT line assuming a constant offset term (added to the data in the grey band), and the points correspond to the emittance measured in the EXT line in autumn 2014 [11, 12]. The emittance is plotted as a function of beam intensity. Bottom: Simulated vertical IP beam size as a function of bunch intensity, considering the emittance values from the upper two pictures and the charge-dependent momentum spread of Fig. 1), for the nominal (left) and relaxed optics (right).

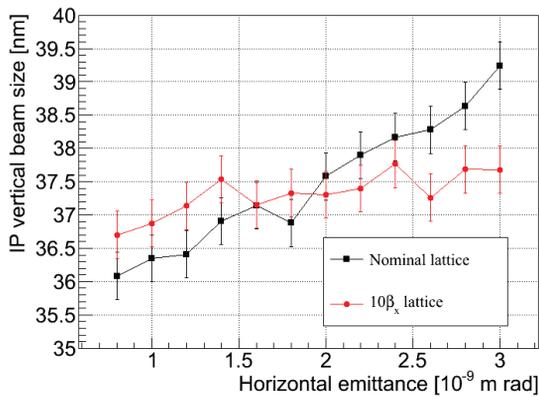


Figure 3: Vertical spot size vs. horizontal emittance.

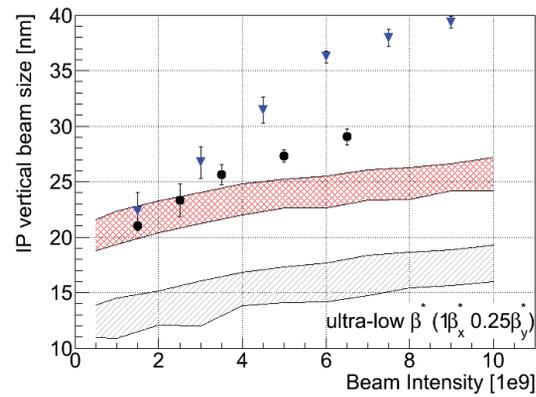


Figure 4: Vertical IP beam size for the ultra-low β^* optics in the beam intensity dependence.

Our simulations suggest that curing this emittance blow up is mandatory for reaching the ATF2 design vertical IP beam size at the design bunch intensity.

5: Beam Dynamics and EM Fields

D01 - Beam Optics - Lattices, Correction Schemes, Transport

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