Interplay of Touschek Scattering, Intrabeam Scattering, and RF Cavities in Ultralow-emittance Storage Rings

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Published in:
Proceedings of IPAC'14

2014

INTERPLAY OF TOUSCHEK SCATTERING, INTRABEAM SCATTERING, AND RF CAVITIES IN ULTRALOW-EMITTANCE STORAGE RINGS

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Abstract

When it goes into operation in 2016, the MAX IV 3 GeV storage ring will be the first ultralow-emittance storage ring based on a multibend achromat lattice. These lattices make use of a large number of weak bending magnets which considerably reduces the amount of power radiated in the dipoles in comparison to power radiated from insertion devices. Therefore parameters such as emittance, energy spread, and radiated power are—unlike 3rd generation storage rings—no longer constant during a typical user shift. Instead, they depend on several varying parameters such as insertion device gap settings, bunch charge, bunch length, etc. Since the charge per bunch is usually high, intrabeam scattering becomes very strong creating a dependence of emittance on stored current. Furthermore, since the bunch length can vary as insertion device gaps change, the emittance blow-up from intrabeam scattering is not constant either. Therefore, the emittance, bunch length, and hence the resulting Touschek lifetime have to be calculated in a self-consistent fashion with 6D tracking taking into account not only the bare lattice and RF cavity settings, but also momentary bunch charge and gap settings. This paper demonstrates the intricate interplay between transverse emittance (insertion devices, emittance coupling), longitudinal emittance (tuning of main cavities as well as harmonic Landau cavities), and choice of stored current in an ultralow-emittance storage ring as well as some implications for brightness optimization.

INTRODUCTION

Although already proposed in the 1990s, multibend achromat (MBA) lattices have only recently started to appear in storage ring-based light source designs. The MBA lattice allows reaching ultralow emittance (i.e. transverse emittances substantially below 1 nm rad) and presents a path to fully diffraction-limited storage rings for the production of x-rays. When the MAX IV facility [1, 2] goes into operation in 2016, its 3 GeV storage ring will become the first ultralow-emittance storage ring based on a MBA [3, 4]. Its 20-fold lattice employs a 7-bend achromat to achieve 328 pm rad transverse emittance with a circumference of 528 m. As is typical for such ultralow-emittance lattices, the radiative losses in the dipoles (364 keV/turn) are low compared to what can be expected (roughly 1 MeV/turn) once the ring is fully equipped with insertion devices (IDs) and/or damping wigglers (DWs) [5]. As a consequence, the ring's zero-current emittance at any time depends on the type of installed IDs and their gap settings. As the ID gaps vary during a typical user shift, not only will this change the transverse emittance[1], it will—assuming the RF cavities are not adjusted to compensate for gap motion—change the resulting RF acceptance, bunch length, and Touschek lifetime.

In addition, in medium-energy rings the large stored current along with the ultralow transverse emittance leads to very strong intrabeam scattering (IBS) which blows up the beam's 6D emittance [7, 8]. Hence, the resulting transverse emittance in ultralow-emittance storage rings at medium energies depends on the stored charge in the bunch. Even if top-up injection and filling pattern control are used to ensure an even fill, the emittance can still vary as a result of ID gap motion and with it the amount of emittance blow-up from IBS. Furthermore, a change of bunch energy spread (as a consequence of e.g. ID gap changes) or bunch length (RF cavity settings, harmonic cavity tuning, or ID gap changes), will also influence IBS and hence the resulting equilibrium emittance. The interplay between IDs, RF cavities, and transverse emittance via IBS will be the subject of the next section.

Touschek lifetime [9, 10] relies strongly on the 6D emittance: it grows with increasing longitudinal emittance which makes harmonic Landau cavities (LCs) for bunch lengthening attractive [11]. On the other hand, in the ultralow-emittance regime transverse momenta are small compared to the large momentum acceptance (MA) and, therefore, most scattering events do not transfer enough momentum from the transverse to the longitudinal to create Touschek losses. Instead, these events along with IBS lead to a blow-up of the 6D emittance. Damping wigglers and IDs reduce the transverse emittance and can therefore further increase the Touschek lifetime in ultralow-emittance storage rings. The overall result is that Touschek lifetime will vary as a function of resulting emittance including IBS as well as bunch lengthening. Since both of these factors are determined by the type of installed IDs and momentary gap settings, the Touschek lifetime can vary during a typical user shift and needs to be calculated for each specific configuration and setting. This shall be investigated in the section following the next.

EMITTANCE AND INTRABEAM SCATTERING

As established in the Introduction, in MBA lattices with ultralow emittance, the resulting equilibrium emittance depends on the number and type of installed IDs (as well as

[1] It is assumed here that the achromat optics can be matched to an ID and its gap setting [6]. Therefore, the emittance change after a gap variation is the result of a change of radiated power, not of machine functions.

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their gap settings) and—at high stored current—is limited by IBS. The amount of emittance growth caused by IBS itself depends on the bunch charge and 6D bunch emittance. When an ID gap closes the transverse emittance of a bunch can be expected to decrease, while the bunch energy spread can be expected to grow. Furthermore, one must assume that the bunch length can be altered in this process. The result is that because of the gap change, the emittance blow-up caused by IBS must be re-evaluated.

The 6D tracking code Tracy-3 [12] has been used to calculate equilibrium emittances in all three planes taking into account IBS growth as a function of bunch charge and zero-current emittance [5]. In principle, for each ID and possible gap setting such a calculation has to be carried out. Because of the large number of possible combinations this is impractical. Instead, different lattice configurations of the MAX IV 3 GeV storage ring (where IDs, if included, are assumed to be operated with a fully closed gap) and different settings of emittance coupling have been studied: a bare lattice, a lattice with DWs, and a fully-equipped lattice, i.e. a lattice where an in-vacuum undulator (IVU) has been installed in every available long straight. Details on the IDs and lattice configurations are given in [5]. The calculations have been performed assuming two different settings of coupling: one corresponding to the baseline 8 pm rad vertical emittance (1 Å diffraction limit) and one corresponding to a reduced coupling in order to increase photon brightness [13]. The results of these calculations are displayed in Table 1.

Table 1: Emittance (in pm rad) in the MAX IV 3 GeV storage ring for two different settings of coupling and three lattice configurations.

		Zero-current	IBS	IBS & LCs
	ε_y	ε_x	ε_x	ε_x
Bare	8	320	466	364
	2	326	552	404
DWs	8	226	354	264
	2	232	436	302
Loaded	8	179	292	213
	2	185	365	247

As IDs are added to the storage ring, the emittance decreases thus increasing the charge density and intensifying IBS. In addition to comparing zero-current emittances to emittances assuming 500 mA stored beam (in an even fill, i.e. 5 nC charge per bunch), results are also displayed where all bunches are assumed to be stretched by LCs[2]. Since LCs dilute the charge density in the bunch, they weaken IBS: even in a fully ID-equipped ring emittances of roughly 200 pm rad can still be achieved. Although LCs are employed in several 3rd generation storage rings to increase lifetime, they will be indispensable in the MAX IV 3 GeV storage ring to ensure ultralow emittance is preserved at full stored current.

[2] The passive LCs of the MAX IV 3 GeV storage ring can stretch bunches beyond the natural bunch length by slightly more than a factor 5 [14].

MOMENTUM ACCEPTANCE AND LIFETIME

Achieving good Touschek lifetime depends on ensuring large MA. If the lattice MA is sufficient throughout the entire achromat and the RF cavities deliver enough accelerating voltage, the overall MA can become very large compared to the transverse momenta of the electrons in an ultralow-emittance storage ring. This ensures that Touschek lifetime in ultralow-emittance rings remains manageable despite the very high charge density in the bunch, and in fact, can improve when further lowering the transverse emittance. Therefore, ensuring large lattice MA has been one of the main goals of the nonlinear optics optimization for the MAX IV 3 GeV storage ring [3, 4].

With the lattice MA established, Touschek lifetime can be calculated as a function of RF acceptance, bunch charge and 6D emittance. This has been carried out with Tracy-3 [15] using the MAX IV 3 GeV storage ring as an example. Figure 1 shows results and confirms that the Touschek lifetime is high despite the ultralow emittance. Besides the behavior well known from 3rd generation light sources (above ≈1000 pm rad), one can recognize the entirely different behavior of ultralow-emittance rings (below ≈500 pm rad) where a sharp increase of Touschek lifetime occurs when the emittance is lowered. The MAX IV 3 GeV storage ring is clearly operated in this regime where Touschek lifetime can be expected to improve as IDs are added.

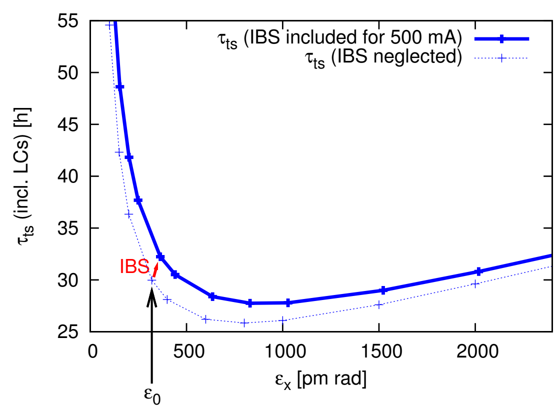

Figure 1: Touschek lifetime from 6D tracking with Tracy-3 as a function of equilibrium emittance assuming the lattice emittance could be adjusted freely while keeping the energy spread constant. The overall MA has been set to 4.5% while the vertical emittance is adjusted to 8 pm rad.

To investigate this, Touschek lifetime is calculated for different ID configurations of the storage ring as well as for different settings of coupling in a self-consistent manner. In a first step, the zero-current emittance for a given lattice including IDs and RF cavity settings is calculated from the radiation integrals. If LCs are employed, the 6D bunch

ISBN 978-3-95450-132-8

emittance has to be updated to reflect the bunch lengthening. At this point, the IBS growth rates for a specific bunch charge and emittance are calculated. Iteration then allows finding the new equilibrium emittance. From 6D tracking including vacuum apertures and possible imperfections such as field and multipole errors as well as misalignments, the local lattice MA around the ring is then derived. Finally, using the updated equilibrium emittance the Touschek lifetime can be calculated by integrating around the entire ring.

Results of such tracking studies with Tracy-3 are displayed in Table 2. For a given setting of vertical emittance,

Table 2: Touschek lifetime (in hours) in the MAX IV 3 GeV storage ring for two different settings of coupling and three lattice configurations (identical to those used in Table 1).

	ε_y [pm rad]	500 mA no LCs	500 mA incl. LCs	Incl. err. & narr. gaps
Bare	8	17.4	87.1	64.3
	2	9.6	45.9	40.7
DWs	8	20.5	114.3	66.2
	2	10.4	56.1	48.7
Loaded	8	11.7	65.0	37.7
	2	5.8	31.4	27.3

there is a slight increase of Touschek lifetime when going from the bare lattice to the moderately ID-equipped ring. This is the result of two competing effects. The RF acceptance of the bare lattice case (roughly 7.1%) is larger, therefore, increasing its Touschek lifetime. On the other hand, the bare lattice has a larger emittance which reduces the lifetime (cf. Fig. 1). When going from the moderately ID-equipped lattice to the fully loaded ring, there is a substantial decrease of Touschek lifetime. This is again the result of two competing effects. The additional emittance reduction leads to a further Touschek lifetime increase. On the other hand, the RF acceptance is now considerably reduced (5.1% for the loaded ring vs. the 6.1% of the moderately ID-equipped ring), so that the overall MA is more heavily dominated by the RF acceptance.

Since the lattice MA is large, the available RF acceptance has a strong influence on the Touschek lifetime. This is demonstrated in Fig. 2. Above 1.2 MV (corresponding to 5.2% RF acceptance) the lattice acceptance begins to dominate the overall MA and hence the lifetime starts to taper off. As the cavity voltage is further increased, the bunch length continues to reduce. Beyond 1.4 MV (corresponding to 5.9% RF acceptance) this results in a decrease of Touschek lifetime. However, a lifetime gain of up to 2–3 hours compared to the zero-current case can also be recognized as a result of the charge density dilution caused by IBS.

Finally, in order to model a realistic machine, the Touschek lifetime must also include the effect of imperfections which reduce the off-momentum dynamic aperture, as well

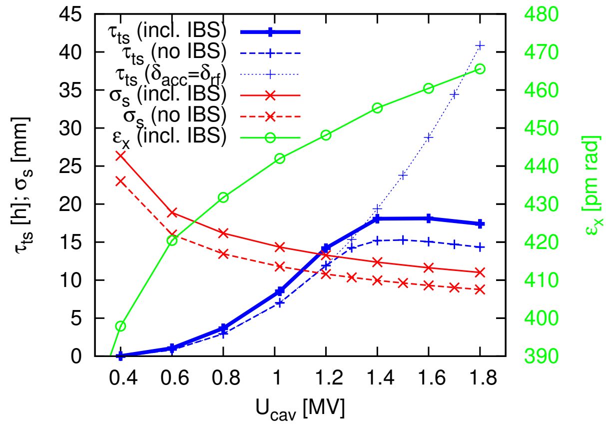

Figure 2: Touschek lifetime, bunch length, and horizontal emittance in the MAX IV 3 GeV storage ring bare lattice as functions of the RF cavity voltage. The stored current was assumed to be 500 mA with the vertical emittance always adjusted to 8 pm rad. Bunch lengthening from LCs has not been included.

as additional acceptance limitations imposed by the closed gaps of IVUs or by narrow-gap ID chambers. Results of such effects on the MAX IV 3 GeV storage ring are displayed in the last column of Table 2. When all these effects are included, a Touschek lifetime of 27.3 ± 2.1 h (≈10 h overall lifetime) results even in the case of a fully ID-equipped ring and 2 pm rad vertical emittance. The uncertainty corresponds to one standard deviation of the error seeds.

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ISBN 978-3-95450-132-8