BEAM LIFETIME IN LOW EMITTANCE RINGS

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Abstract

This paper reviews the main effects that cause beam losses determining the beam lifetime in low emittance (low-ε) rings: Touschek, beam-gas scattering and radiative Bhabha process. These effects have been studied by means of a macroparticle tracking code based on the Monte Carlo technique that evaluates particle losses and lifetime. It has been developed during the high luminosity SuperB factory design [1], extending the simulation code used to handle the Touschek effect at the Frascati Φ-factory DAΦNE [2].

A brief description of the simulation tool developed to handle them is given. As an example for its capabilities, in this paper there are reported also the simulation results obtained for the high luminosity flavor factory SuperB, based on the crab-waist collision scheme [3]. This scheme provides a higher luminosity with respect to standard collision scheme, but it requires very careful evaluations of the losses at the final focus (FF). Detailed background evaluations are crucial for the success of the projects based on this scheme (SuperB, SuperKEKB, τ/charm factory). However, this simulation code can be very useful for lifetime evaluation in all low-ε rings, synchrotron radiation sources and colliders.

INTRODUCTION

The simulation tool presented here has been developed for the Touschek effect [4], and then extended to beam-gas and radiative Bhabha in view of the Superb factory design. Depending on the process under study, the macroparticles representing a population of bunch particles are extracted from a Gaussian beam distribution and according to the proper cross-section. This extraction is performed for each small lattice section; typically, once every 3 elements is enough to have good stability in the numerical results. Radiative Bhabha particles start, of course, only from IP. The macroparticles are then tracked from their scattering point all along the ring with a lattice imported by MAD [5] for a few machine turns, or until they are lost either for exceeding the radio-frequency (RF) acceptance or the physical aperture, or intercepted by scrapers. The lifetime τ is evaluated from its definition as the inverse of the relative rate of loss $1/\tau = -(1/N)(dN/dt)$, where N is the number of bunch particles and *dN/dt* the rate of loss, determined by the tracking simulation.

This simulation tool allows investigations on beam loss patterns (simulation of primaries for full background simulations with GEANT into detectors and shieldings design), horizontal and vertical collimators to intercept scattered particles that would be lost in the IR. More specifically, for the Touschek effect (discussed in the first section) this simulation code can give indications on improvements on momentum aperture; for the beam-gas scattering (second section) it is useful to determine the vacuum requirements; multi-turns losses of the radiative Bhabha process (third section) can be investigated with this tracking approach. Table 1 reports the main contributions to lifetime for the SuperB main rings resulting from simulations and the total lifetime combining these effects (last row).

Table 1: Lifetime Contributions at SuperB Calculated with the Code, Beam Parameters in [1] and Collimators at Set

Loss effect	HER Lifetime (s)	LER Lifetime (s)
Radiative Bhabha	290*/280+	380*/420+
Touschek	1320	420
Elastic beam-gas	3040	1420
Inelastic beam-gas	72 hrs	77 hrs
Total Lifetime	220	180

* 1% momentum acceptance assumed in integrated formula;
\+ momentum acceptance calculated with tracking MonteCarlo

TOUSCHEK LIFETIME

The beam lifetime in most medium energy synchrotron light sources and high luminosity colliders is limited by the Touschek effect, which describes the momentum transfer from the transverse into the longitudinal direction due to binary collisions between electrons. In this process small transverse momentum fluctuations are transformed, due to the relativistic Lorentz factor, into magnified longitudinal ones. Off-momentum particles can exceed the RF momentum acceptance, or they may hit the aperture when displaced by dispersion. In both cases they get lost. The effect was first observed in the storage ring ADA and B. Touschek explained it, hence the name *Touschek scattering* [6].

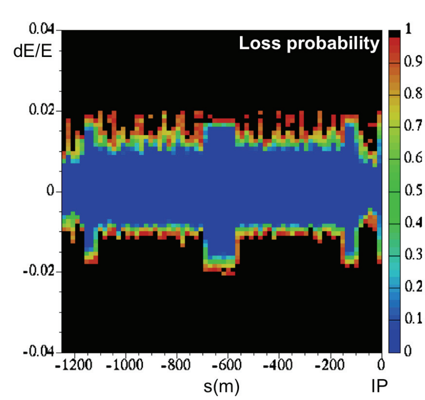

Figure 1: Momentum aperture (left scale) and corresponding particles loss probability (right scale) as a function of the longitudinal position along the ring of the LER Superb.

While top-up injection relaxes the constraint on lifetime, it remains a limiting factor due to the increased demands on small beam emittance and current stability from the users of light sources and high luminosity colliders. Low-ε rings have greater particle density, leading to a higher rate of scattering events, and they tend to have reduced momentum acceptance, leading to a higher rate of loss for Touschek scattered particles. Thus, a realistic estimation is crucial, as proved during the DAΦNE data taking to handle Touschek lifetime and backgrounds.

There are three different ways to calculate Touschek lifetime: assume the machine momentum acceptance and calculate the formula of the Touschek lifetime averaging on the whole lattice; calculate the local momentum acceptance through the lattice elements and calculate the formula for each small section of the lattice and then sum up these terms and, lastly, track the macroparticles through a nonlinear lattice, so dynamic aperture is calculated intrinsically and the momentum acceptance calculated for each macroparticle. We adopted this last procedure, as it appears from Fig. 1: for each longitudinal position *s* it is not simply calculated the momentum aperture, but also its corresponding loss probability.

The macroparticles have transverse coordinates randomly extracted from a Gaussian distribution and an energy deviation extracted from proper Touschek energy spectra. These particles are weighted by the Touschek scattering probability given by:

$$\frac{1}{\tau} = \frac{\sqrt{\pi} r_e^2 c N}{\gamma^3 (4\pi)^{3/2} V \sigma'_x \varepsilon^2} C(u_{\min}) \qquad (1)$$

where r_e is the classical electron radius; c is the speed of light; γ is the beam relativistic Lorentz factor, m_e is the electron rest mass; V is the bunch volume $V=\sigma_x\ \sigma_y\ \sigma_z$; $\varepsilon=\Delta E/E$ is the maximum relative energy deviation; $\sigma'_x = \sqrt{\frac{\varepsilon_x}{\beta} + \sigma_p^2\left(D'_x + D_x\frac{\alpha_x}{\beta_x}\right)^2}$; $u_{min}=\left(\frac{\varepsilon}{\gamma\sigma'_x}\right)^2$. $C(u_{min})$ is properly evaluated also for very large values of u_{min}, i.e. for very small emittance, and it is given by:

$$C(u_{min}) = \int_{u_{min}}^{\infty}\frac{1}{u^2}\left[u - u_{min} - \frac{1}{2}\ln\left(\frac{u}{u_{min}}\right)\right]e^{-u}du.$$

Fig. 2 shows the Touschek lifetime contributions (evaluated by formula (1)) as a function of the horizontal emittance ε_x, for different regions of the LER SuperB lattice V16 [7]. Without going into any lattice details, the pink curves of Fig. 2 represent the cells contribution to lifetime as a function of ε_x, showing an increase at ultra-low-ε, while the FF regions (in blue) contribute to lifetime with a completely different behavior, never enhancing for very low-ε values. Ultimate storage rings (USRs) aim to work with ultra-low-ε values, in the region where Touschek lifetime increases again. The Touschek effect will be studied carefully in this region, for different machine lattices. However, these simulations give a clear indication that the enhancement of Touschek lifetime at ultra-low-ε values is foreseen when there is no FF, i.e. in synchrotron light sources. Differently, in a low-ε collider the FF determines an overall beam lifetime reduction, being by far the dominant contribution.

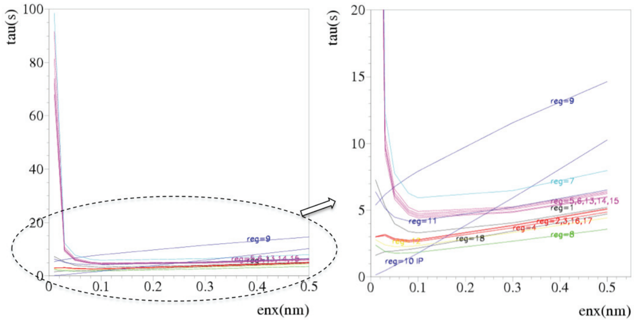

Figure 2: Lifetime contribution from different lattice regions as a function of ε_x. Right plot: zoomed view of the circled dashed black region shown in the left plot.

BEAM-GAS SCATTERING

The beam-gas scattering is a single beam effect in which beam particles can get lost by an elastic or inelastic scattering with the residual gas molecules -either with nuclei or electrons- in the vacuum chamber, affecting beam lifetime. In colliders, if this beam-gas scattering is close to the IR, it also induces backgrounds in the detectors. In the elastic process the bunch particle is transversally deflected by a gas nuclei, increasing its betatron oscillation amplitude and there is no energy loss. If the gained scattering angle is large enough to exceed the physical aperture or the dynamic aperture, this particle is lost. In the inelastic process there can be either Bremsstrahlung on nuclei or energy transfer from the bunch particle to the electrons of the residual gas. In both cases the circulating particle loses energy and it can get lost either for physical/dynamic aperture or for exceeding RF acceptance. All these processes have been included in the beam-gas simulation, using the Monte Carlo technique. Analogously to Touschek lifetime evaluation, now the Touschek scattering probability is replaced by the elastic/inelastic differential cross-section. The beam-gas scattering occurs along the ring and lifetime is evaluated by the integration of the local evaluation of the rate of particle loss. The implemented procedure can be summarized as: $1/\tau = \rho c \int_0^L \int_{u_{min}}^{u_{max}} \frac{d\sigma}{du} du \frac{dL}{L}$, where ρ is the density of the residual gas related to the gas pressure $3.217 \cdot 10^{22} \cdot P[Torr] atoms/cm^3$ (from which beam-gas scattering is proportional to vacuum pressure and to beam current), c is the speed of light, L is the ring length, $d\sigma/du$ is the elastic or inelastic differential cross-section, the integration term u is dp/p for inelastic, $d\theta$ for elastic scattering.

Elastic scattering is stronger in high β-function locations. So, in colliders and especially in the IR of high luminosity factories the elastic beam-gas scattering is much stronger than the inelastic one (see Table 1). The scattering angle gained by the bunch particle interacting with a residual ion is maximum at the low-β defocusing quadrupole at the IR (QD0), where the betatron function

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is maximum. So, QD0 is the hottest location for the elastic scattering process. Simulations at SuperB predict most of the losses vertically at this position and two vertical collimators are placed in the FF upstream the IR resulting sufficient to control particle losses in the detectors. They are at about -45 m and -25 m far from IP (lower plot of Fig. 3), corresponding to a position where two defocusing sextupoles are placed. Technically, to intercept the scattered particles that otherwise would be lost at the QD0, they could be designed as masks with the same beam-stay-clear as that at the QD0. Two movable jaws close to these sextupoles would be additional knobs very useful to tune IR backgrounds. Fig. 3 shows the *x* and *y* trajectories in the FF upstream the IR of the LER of elastic scattered particles that are not intercepted by the vertical collimators and that get lost at the IR. A constant pressure of *1=nTorr* along the ring has been assumed and a gas composition of *Z=8* for these beam-gas studies.

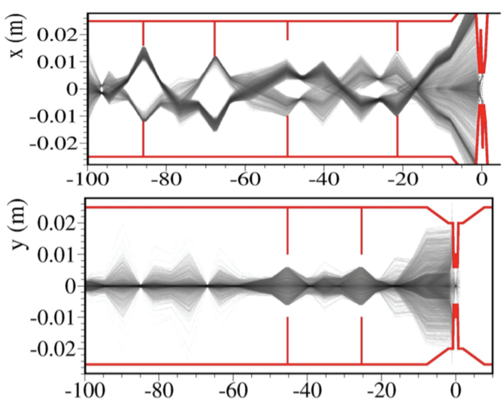

Figure 3: Horizontal and vertical trajectories (upper and lower plots) of particles that get lost at IR after an elastic beam-gas scattering with a gas nuclei. Red lines in the pipe represent the collimators jaws (IP is at s=0m).

RADIATIVE BHABHA LIFETIME

Radiative Bhabha scattering is the dominant effect to beam losses and lifetime of low-ε flavor factories. The macroparticles representing the final state radiative Bhabha are generated at the IP with the proper differential cross-section [8-9] and then tracked as for the Touschek and beam-gas particles.

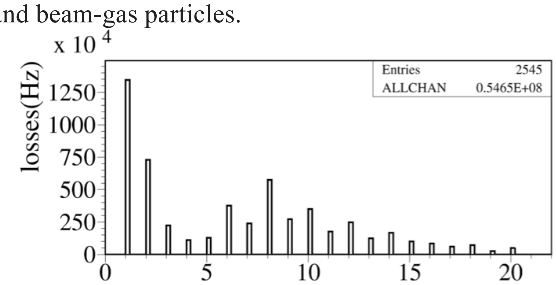

Figure 4: HER losses from the radiative Bhabha process as a function of machine turns, no collimators inserted.

This novel approach allows detailed studies of multi-turn IR losses due to radiative Bhabha scattering with an energy deviation smaller than RF acceptance, investigating -for the first time- this potentially important source of background in the detector. Fortunately, simulations evidence that these particles are lost in the very first turns, as appears from Fig. 4 where losses are plotted as a function of machine turns. In addition, they have the same betatron phase as Touschek particles, so that horizontal collimators placed for Touschek particles appear very effective in intercepting multi-turns radiative Bhabha scattered particles. This is clear comparing the trajectories plotted in Fig. 5 with the loss locations pointed by the colored arrows and the red jaws of the horizontal collimators in the upper plot of Fig. 3. Large angle losses have been accounted only for the lifetime estimation, found in very good agreement with the one obtained with the integrated cross–section (slight difference in Table 1); large angle losses have not been used as primaries for background simulations, as correctly simulated with the BBBREM generator [9].

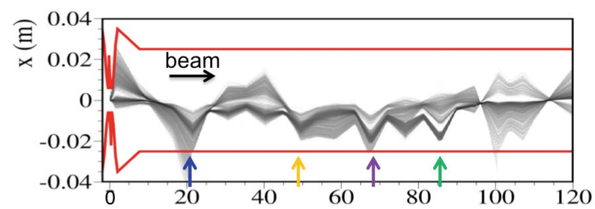

Figure 5: LER SuperB trajectories of Bhabha final states particles starting from the IP into the downstream FF.

CONCLUSIONS

This paper summarizes the approach used to model the lifetime effects such as Touschek, beam-gas and radiative Bhabha scattering with a tracking simulation tool initially developed for handling the DAΦNE lifetime and backgrounds (only Touschek), then extended for the SuperB factory design, resulting useful to define the nominal parameters, the collimators systems and to investigate multi-turn radiative Bhabha particles. This code has been benchmarked on DAΦNE, but comparisons with measurements are foreseen also on other low-ε rings. The studies performed for Superb are being revised for the Tau Charm Factory project on the Tor Vergata site, taking profit of all the work done for the SuperB.

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