LOST PARTICLES IN THE IR AND ISSUES FOR BEAM INDUCED BACKGROUNDS IN HIGGS FACTORIES

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Abstract

The loss of beam particles has to be well under control in high energy and high luminosity e+e- colliders -namely Higgs Factories- especially at the interaction regions. In the design stage the main beam related effects causing particle losses need to be studied in details by means of full simulation to check that machine induced background rates are tolerable for the experiments and, if not, conceive an efficient collimation system to intercept particles that would eventually be lost in the Interaction region (IR). These studies can also give a realistic evaluation of beam lifetime.

We will review how main beam backgrounds have been handled at SuperB and DAΦNE and we will mention the LEP experience. A first tracking simulation of the Touschek and radiative Bhabha particles for the CEPC IR case are presented as a starting point for losses evaluation.

Synchrotron Radiation, essentially determined by the beam energy, is a key issue for the IR design of Higgs Factories. A first description of the tools under development for the SR evaluation in view of the FCC-ee design study is given.

INTRODUCTION

We can distinguish backgrounds from two main sources: losses of beam particles and synchrotron radiation (SR). Particle effects that cause beam losses can be generated by single beam effects -mainly Touschek and beam-gas scattering- or they can be generated at the IP -mainly beamstrahlung, radiative Bhabha, e^+e^- pairs production- usually referred to as *IP backgrounds*.

Both sources have been deeply studied for past and present machines; beam particles effects have been studied extensively for upgrades of B factories; on the other hand LEP has been the highest energy lepton collider, experience on this machine can be very helpful.

Unlike linear colliders, circular machines have to cope also with beam halo. For lepton high-energy colliders this issue has to be considered particularly for the vertical plane, where the emittance is low. An off-momentum halo at the IR may be generated by beam-beam effects and by beamstrahlung, which gets stronger as the beam energy increases.

The first concern for particle losses is the implication of beam degradation itself, with a consequent loss of luminosity, lifetime reduction and need of increase the frequency injection. The second concern is the background that beam losses can generate at the IR: particle losses may shower into detectors causing damages and they may fake triggers.

BEAM PARTICLE LOSSES

In this section a short description of the main effects for beam losses is presented, with a summary of the approach used for SuperB factories and LEP. First considerations for future high energy colliders, such as the Chinese HF CEPC [1] and FCC [2] are also presented.

Depending on machine's parameters such as energy, beam density and energy spread, the beam particle losses will be driven by one of the processes mentioned in the introduction. We can say that for rings with beam energies of E_{beam}=120 GeV such as CEPC and even higher (maximum energy foreseen for FCC-ee is 175 GeV), beamstrahlung will typically be the dominant effect, followed by radiative Bhabha, e+e- pairs production, beam-gas and Touschek.

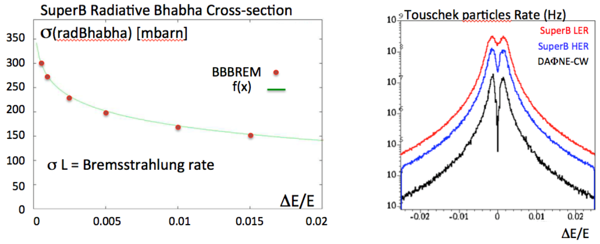

Figure 1: Left: SuperB radiative Bhabha cross-section vs ΔE/E; right: rate of Touschek particles in SuperB LER (red), HER (blue) and DAFNE Crab-waist (black) for 1 single bunch nominal current (1.49 and 10 mA, respectively).

For CEPC and FCC which are in the design phase, dedicated calculations for backgrounds are planned. As an example in Table 1, we report the lifetime evaluation performed for the SuperB factory with a Monte Carlo numerical tracking code developed for this purpose. SuperKEKB used an analogous approach [3].

Table 1: Lifetime Contributions at SuperB Calculated with the Code, Beam Parameters in [4] 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

Some of these processes are very non-linearly dependent on energy acceptance (see two examples in Fig. 1). Numerical tracking gives accurate particle losses and lifetime estimation, more realistic than the one obtained by assuming the ring's energy acceptance. Fig. 2 gives an example of the Touschek Monte Carlo tracking, where for each longitudinal position *s* it is not simply calculated the momentum aperture, but also its corresponding loss probability.

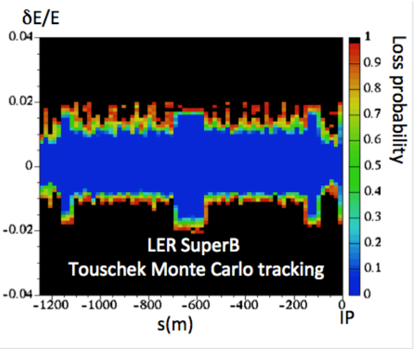

Figure 2: Energy acceptance (left axis) with loss probability of Touschek particles (right axis) through the LER SuperB.

Beamstrahlung

Beamstrahlung is synchrotron radiation in the field of the opposing beam [5]. When two charged bunches collide, the electro-magnetic field of each bunch bends the trajectories of the opposite bunch particles and energetic photons are emitted, and the off-energy bunch particles can get lost in the IR producing backgrounds from debris, luminosity drop and enlargement of the beam energy spread. It is very strongly dependent on the ring's energy acceptance [6], so, for a given machine parameter's set, the remedy is to increase the energy acceptance as high as possible at the IP.

This effect is the dominant one at the high energies of the HF. Full simulation is needed for tracking of the lost IR particles into the detector; multi-turn tracking are also envisaged.

Radiative Bhabha

Radiative Bhabha scattering is enhanced by the expected luminosity increase with the crab-waist collision scheme, being proportional to luminosity. And, in fact, being the dominant effect for Super-B factories it has been studied in great details. The particle losses due to this effect are essentially determined by the energy acceptance at the IP, that needs to be larger than 1% to get acceptable lifetimes. This condition is challenging due to the strong squeezing of the beams in the IR obtained with the crab-waist scheme [7].

In order to estimate this effect as a background source, the off-energy e+/e- need to be tracked after the IP, as well as the emitted photons, which may produce neutrons in secondary interactions. Radiative Bhabha scattering occurs only at the IP. We distinguish two cases:

- Bhabha final states particles have large energy deviation;
- Bhabha final states particles have small energy deviation, so that they can be lost after few machine turns.

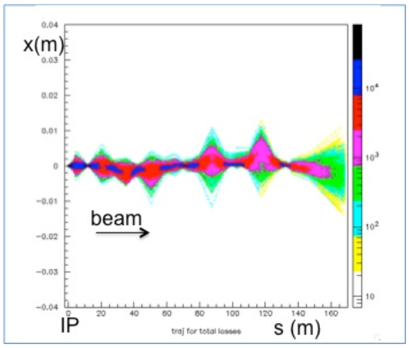

Figure 3: CEPC radiative Bhabha trajectories upstream the IP, in the FFS (April 2014 lattice).

In the first case spent particles get lost immediately, close to detectors. These particles are well simulated with the BBBREM [8] generator and then tracked into detectors with GEANT4. There is little dependence on the machine lattice, only the Final Focus design really matters. In the second case a multi-turn tracking code is needed to simulate spent particles from the IP through the ring. At SuperB, as well as SuperKEKB it has been found that most of these particles get lost in the first, or, in a small percentage, in the second turn.

Figure 3 shows first tracking simulations for radiative Bhabha trajectories, assuming a constant physical aperture of 3 cm through the CEPC IR using the same Monte Carlo tracking code as used for SuperB studies. The April 2014 CEPC lattice [9] has been used.

The CEPC IR beam sigmas calculated from the lattice are shown in Fig. 4.

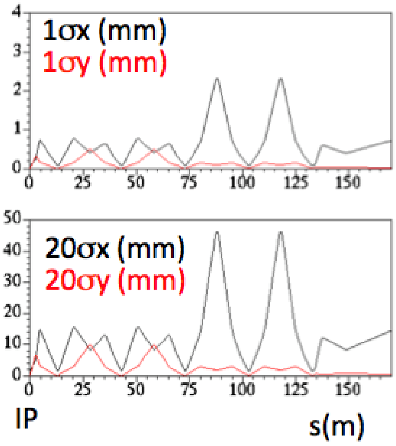

Figure 4: CEPC IR: σ_x and σ_y (0 is at IP).

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. The circulating particle gets scattered to high amplitude or it loses energy and it can get lost either for physical/dynamic aperture or for exceeding the RF acceptance.

Coulomb beam-gas scattering is proportional to the gas pressure in the beam pipe, to the beam current and to the average and peak β-functions [10]. The rate follows longitudinally the pressure maps. It is not energy dependent at the first order but if there is high gas pressure due to SR outgassing (dynamic pressure), then the scattering rate is proportional to I^2. This effect is increased in the factories with the CW scheme, due to the high β-functions in the IR doublet. For HF this effect could be important as well, given the squeezing of the beams at IP, so we think dedicated studies with particle tracking are recommended, similarly to SuperB and SuperKEKB approach. In fact, most losses are located in the vertical plane at the defocusing low-β quadrupoles, which are much larger than at B factories (see the numbers in second row of Table 2 which should be compared to about 12 km for CEPC).

Table 2: Coulomb Beam-gas Main Parameters for Three LER *B*-Factories.

	unit	KEK LER	SuperKEKB LER	SuperB LER
Vert. apert. at QD0	mm	35	13.5	6
β_y (max) at QD0	m	600	2900	1497
$<\beta_y>$	m	23	48	47
Coulomb Lifetime	hrs/min	>10	35 min	24 min

At LEP off-energy particle background was generated by both beam-gas bremsstrahlung and thermal photon scattering [11] : τ_B=430 hours with P = 10^{-10} Torr; from 45 GeV to 65 GeV the dynamic pressure increased by a factor 5. An example of beam-gas bremsstrahlung simulation for the LER SuperB is shown in Fig. 5; left plot indicates that it is mainly a first and second turn effect, right plot is useful for finding good locations for horizontal collimators. Similar approach is proposed for Higgs factories.

A general requirement for elastic and inelastic beam-gas scattering is a pression below 10^{-9} Torr, but this has to be checked with the lattice and physical apertures.

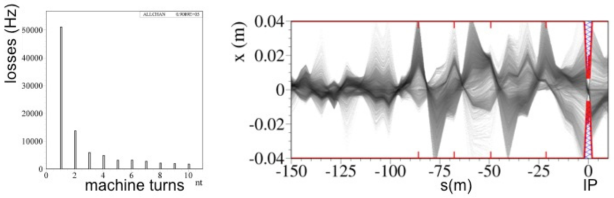

Figure 5: LER SuperB beam-gas bremsstrahlung Monte Carlo simulations.

Touschek Losses

Touschek effect [12] is a Coulomb scattering between particles in a stored bunch that induces an energy exchange between transverse and longitudinal motions; in this process small transverse momentum fluctuations are transformed into magnified longitudinal fluctuations due to the relativistic Lorentz factor in the transformation. Off-momentum particles can exceed the RF momentum acceptance, or they may hit the aperture when displaced by dispersion. The Touschek effect is determined by many parameters, like the beam energy, the bunch density, the H-invariant, dispersion and phase advance; of course also the physical aperture through the ring plays a role. The scattering rate is proportional to beam density $1/\gamma^3$, so it stronger the lower the beam energy.

For a low-energy collider as DAΦNE the Touschek effect determines lifetime and induced backgrounds. For this machine great effort has been spent during the years of runs to control this effect. However, this effect is important for all the upgrades of the flavour factories, even at energies higher than the Φ–factory not only because of their relatively low energy, but also because they have dense colliding beams, and the super-squeezed beams are obtained with large low-β quads at the IR that give a reduced momentum acceptance. So, if we consider that the data taking can be fruitful only if the luminosity to backgrounds ratio is acceptable -and not only by increasing the luminosity- in this sense the real limit of these storage rings performance comes from the non-linear dynamics and the momentum aperture.

There are different possibilities to calculate the Touschek lifetime:

- Assume as input the machine momentum acceptance and perform the calculation averaging on the whole lattice;
- Calculate the momentum acceptance and the formula locally for each small section of the lattice and sum up;
- Perform the tracking of the macro-particles with the Monte Carlo technique with non-linear kicks included; in this case the momentum acceptance is calculated for each macro-particle (see Fig. 2).

This last approach, the most accurate one, has been used for the DAΦNE, Superb and τ/charm studies [13].

Generally, from the scaling law Touschek rate is inversely proportional to $\gamma^3(\sigma_x\ \sigma_y\ \sigma_z)$, so that we can argue that for low emittance synchrotron light sources, which have no IP and relatively low energy, Touschek effect is a major issue impacting lifetime: the cure is continuous injection by topping-up. In low-ε colliders and relatively low energy Touschek effect is a major issue as well, but now both for lifetime and IR losses: the cure is top-up injection and collimation, together with a good design of the IR physical aperture. In low-ε colliders and very high energies (Higgs Factories) Touschek effect is not the dominant effect. However, tracking simulation is useful to check that Touschek losses are not dangerous. First tracking of Touschek particles has been done for CEPC IR [9] assuming a constant physical aperture of 3 cm. Touschek trajectories generated upstream the final focus, starting from -150 m from IP are tracked and shown in Fig. 6. The blue lines indicate possible attempt for horizontal collimators, to be checked with simulations.

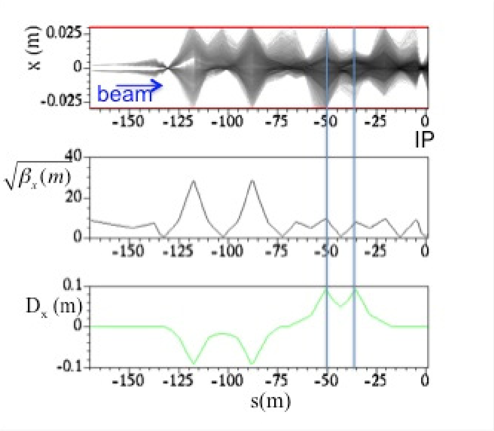

Figure 6: Touschek trajectories through CEPC Final Focus upstream the IP (upper) showing larger amplitude in correspondence of high β_x (middle) and D_x (lower plot).

IR SYNCHROTRON RADIATION

There are many issues to be addressed regarding SR in the IR in a new design of HF, some are:

- SR power from IR dipoles and quadrupoles;
- Calculation of the rate of photons through the detector beam pipe;
- Scattering rate and incidence on detector beam pipe;
- Add in the calculation the compensating solenoids and the detector field;
- Calculation of the backscattered photons;
- Forward scattered photon rate from upstream bend magnets.

Table 3: Typical Fields for FCC-ee with LEP Ones

	unit	**LEP**	**FCC-ee**
Energy	GeV	100	175
Bending fields	Tesla	0.1	0.06
Mean γ energy	MeV	0.2	0.4

Some of the concerns regard the compatibility of the stay-clear apertures with effective masking of incoming SR; the edge scattering from upstream the SR masks; the backscattering from downstream aperture limitations.

The LEP physics beam energy was between 45 GeV and 104.5 GeV with a bending radius of 3026 m. LEP had a circumference of 26658.9 m, 8 straight sections with +/- 284 m around IPs and 4 IRs. The distance of the first superconducting quadrupole L* was 3.7 m. The tunnel construction started in September 1983, and LEP operated from 1989 to 2000. It was a flat and symmetric machine with no crossing angle and few (4-12) bunches. The maximum power in synchrotron radiation was 18 MW, with a maximum energy loss per turn in synchrotron radiation 3.5 GeV. There were about 100 collimators to reduce the machine-induced backgrounds and to eliminate any direct or single reflected radiation to experiments in the IP region [11]. Still the dominant backgrounds were synchrotron radiation followed by backgrounds from off-momentum particles generated in beam-gas or thermal photon scattering.

At LEP systematic measurements of beam halo were performed using scrapers and loss monitors [14, 15]. Significant non-Gaussian tails were observed, in particular in the vertical plane. They were generated by beam-beam effects and particle scattering and enhanced by high chromaticity. Typical fields are shown in Table 3. Fig. 7 shows the layout of one LEP IR with horizontal and vertical collimators.

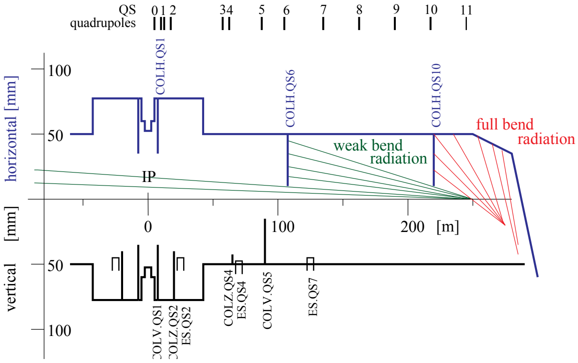

Figure 7: LEP: Straight section at a LEP IP in the horizontal (top) and vertical (bottom) planes.

CONCLUSIONS

The design of the IR is critical for the success of a collider. A careful trade-off between the constraints of machine and detector has to be found. In this frame the simulations of all the effects that induce machine backgrounds are essential, and they should be as realistic as possible.

We are approaching the FCC-ee IR challenges starting to develop the software tools for these dedicated studies: a SR Monte Carlo integrated in Geant4 is under development. The basis is MAD-X lattice using ROOT as main geometry and interface tool. SR fans and estimate of energy flows are evaluated for the desired IR, combining machine tracking and detector model.

Provided the estimates of beam losses at IR, the Machine Detector Interface issues such as shielding, masking, collimation system, will follow, as well as estimates on the radiation limits: peak residual dose rate in the tunnel in non-controlled areas, ground water activation, peak energy deposition and absorbed dose, air activation. The general approach for background handling is quite straightforward: collection of background generators for generating primaries, transport of primaries with

GEANT4 into sub-detectors, shieldings design to intercept showers, background impact determination in the subsystems with the implemented shieldings.

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REFERENCES

[1] Q. Qin *et al.* "Overview: CEPC", presented at the 55th ICFA ABDW Workshop on High Luminosity Circular e^+e^- Colliders – Higgs Factory (HF2014), Beijing, China, paper THP3H2, these proceedings.

[2] F. Zimmermann *et al.*, "FCC-ee Overview", presented at the 55th ICFA ABDW Workshop on High Luminosity Circular e^+e^- Colliders – Higgs Factory (HF2014), Beijing, China, paper FRT3A1, these proceedings.

[3] H. Nakayama *et al.,* "SuperKEKB Background Simulations, Including Issues for Detector Shielding", presented at the 55th ICFA ABDW Workshop on High Luminosity Circular e^+e^- Colliders – Higgs Factory (HF2014), Beijing, China, paper FRT3A1, these proceedings.

[4] M.E. Biagini *et al.*, "SuperB CDR2", arXiv: 1009.6178v3, (2010).

[5] V.I. Telnov, PRL 110 (2013) 114801.

[6] K. Ohmi, "Beam-beam Effects in CEPC and TLEP", presented at the 55th ICFA ABDW Workshop on High Luminosity Circular e^+e^- Colliders – Higgs Factory (HF2014), Beijing, China, paper FRT3B1, these proceedings.

[7] M. Zobov *et al.*, Phys. Rev. Lett. **104** 174801 (2010).

[8] R. Kleiss, H. Burkhardt, Comp.Phys.Comm.81 372 (1994).

[9] CEPC April 2014 lattice, Q. Qin private communication.

[10] J. Le Duff, NIM A239 (1985) 83.

[11] NIM A 403 (1998) 205-246.

[12] C. Bernardini *et al.*, Phys. Rev. Lett., **10** 407 (1963).

[13] M. Boscolo, P. Raimondi, PRST-AB 15 104201 (2012) and ref. therein.

[14] H. Burkhardt, "BEAM LIFETIME AND BEAM TAILS IN LEP." CERN-SL-99-061-AP and Proc. e+ e+ Factories 1999, KEK, Tsukuba 1999.

[15] Transverse beam tails due to inelastic scattering, Phys. Rev. ST Accel. Beams 3, 091001 (2000).

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