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BEAM-GAS BACKGROUND CHARACTERIZATION IN THE FCC-ee IR*

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Abstract

The MDISim toolkit is used to evaluate and characterize the beam-gas induced background in the FCC-ee interaction region. MDISim allows to construct in GEANT4 the actual beam lattice structure with geometry and magnetic elements in order to perform a full simulation enabling to study the location where the beam gas scattering occurs as well as the loss point of scattered particles. We compare simulation results with expectations from analytical expressions and discuss the impact of possible local pressure rises by gas desorption induced by synchrotron radiation.

INTRODUCTION

The international Future Circular Collider (FCC) study [1] aims at a design of p-p, e^+e^-, e-p colliders to be built in a new 100 km tunnel in the Geneva region. The final goal is a hadron collider (FCC-hh) at centre-of-mass energy of the order of 100 TeV, with an e^+e^- collider (FCC-ee) as a possible intermediate step in a centre of mass energy range between 90 and 375 GeV. To reach such unprecedented energies, in addition to the requirement for ultra high luminosities, a careful study of all the background sources both in the machine and in the experimental area must be performed. We discuss here the impact of beam gas scattering in FCC-ee and give an estimate of the losses in the interaction region.

MOTIVATION AND SCOPE

The interaction of beam particles with residual gas molecules in the beam pipe gives a contribution to the beam lifetime and it may induce beam backgrounds in the detectors. This effect is not a major issue also thanks to the very good vacuum conditions foreseen in FCC-ee. However, a full simulation is needed to establish the required vacuum pressure in running conditions. A constant gas pressure of 10^{-7} Pa is assumed for our study (10^{-9} mbar, according to the unit often used by the vacuum community).

At the Z pole with a beam energy of 45.6 GeV and a beam current of 1390 mA a lifetime of about 100 hrs is equivalent to a scattering rate of about 78.6 MHz/km/beam. Table 1 shows a theoretical estimate of the inelastic beam-gas (BG) scattering rates for two different gases, where the cross section per gas is calculated as in [2], using the number of protons in the molecule and an energy acceptance of 2%. The scattering rate for N_2 at 10^{-9} mbar and at 300 K is just about 2~3 times larger than the given value for 100 hrs of beam lifetime. This implies that we should expect a lifetime of the order of tens of hours from inelastic beam gas scattering at such pressure.

Table 1: Inelastic scattering rates for two different gases in the beam pipe at a pressure of 10^{-7} Pa and temperature of 300 K

Gas	Cross Sect. [barn]	Scattering Rate [MHz/km/beam]
H_2	0.328	6.7
N_2	9.386	192.3

However, if the lifetime estimate from analytical formulas is limited by average values like the machine energy acceptance, the loss rates can be evaluated only by a particle tracking simulation. A precise and effective methodology to perform a detailed study is provided by MDISim [3], a toolkit that combines existing standard tools (MAD-X [4], ROOT [5] and GEANT4 [6]). It reads the MAD-X optics files, and uses its twiss output file to generate the geometry and the magnetic field information in a format which can be directly imported in Geant4 to perform full tracking, including the generation of secondaries and detailed modelling of the relevant processes. This code has been initially developed for Synchrotron Radiation studies [7].

Synchrotron radiation is the main background source that drives the FCC-ee interaction region (IR) design. Other background sources are scattering process leading to particles loss. Based on the experience with LEP [8], we expect in order of their contribution to the beam lifetime : Beamstrahlung (few hours), Radiative Bhabha scattering (10 hours), beam-gas lifetime (100 hours), Thermal photon, Compton scattering (50 hours) and Touschek scattering (well over 100 hours). The first two processes are present in collision, they generate backgrounds at the interaction point and are mostly forward leaving the IR. Detailed background

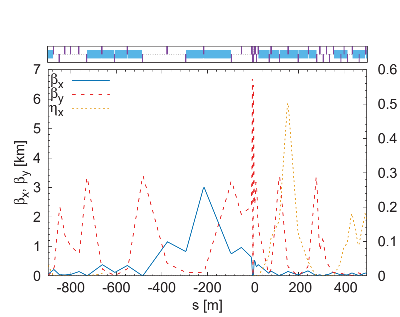

Figure 1: β and dispersion functions in the interaction region; the interaction point is at s=0 m.

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studies are in progress to design the Machine Detector Interface region with proper shieldings and collimators [9]. The impact of machine beam losses in the detector is being considered with full Geant-4 simulation for all the background sources. Ref. [10] shows an example if this study.

We concentrate in this paper on the beam gas scattering process and we focus in the IR, where beam gas scattered particles may induce background in the detector. First estimates indicate that they are sustainable for the detector, in particular they do not seem to impact significantly on the luminosity calorimeter [11].

Beam gas induced background has been studied in B-factories (PEP-II and KEKB) and recently in Super-B factories (SuperB and SuperKEKB) [12–16] with different simulation tools. We propose here a novel Monte Carlo approach that interfaces MAD-X directly with Geant-4.

SIMULATION SETUP

The MDISim toolkit was used to generate the files needed to perform a full GEANT4 simulation from the optics file available for FCC-ee. In particular, the four lattice configurations for the different beam running energies (45.6, 80, 120 and 182.5 GeV) were reconstructed in the Monte Carlo (MC). The optics version fcc_ee_208 [17] was used for this study. Figure 1 shows the optics in the IR region for one of the four running energy configurations. A constant beam pipe diameter of 70 mm is considered throughout the ring except for the section from -10 m to 10 m around the IP, shown in Fig. 2. The vacuum chamber in QC2 has a diameter of 40 mm, in QC1 of 30 mm. The transition is considered in the simulation with conical tapering from 30 mm to 40 mm as well as from 40 mm to 70 mm (from QC2 to the arcs) in about one meter of longitudinal distance. The beam pipe

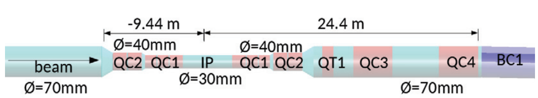

Figure 2: Vacuum chamber dimensions in the IR.

with magnetic elements was reconstructed in the simulation from ±850 m from the IP. Primary particles were generated starting at -830 m from the IP, with realistic distributions in transverse phase space, according to the optical parameters of the beam in that point of the machine, and tracked for about 1000 m.

The study presented in this paper focuses on inelastic beam gas (BG) interaction. The selection of a "Beam Gas event" is performed according to the following steps:

- if the primary particle inside the pipe undergoes an "eBrem" interaction with a non null energy transfer, we flag this event as "BG candidate", and save the position and energy of the beam particle ($X_{BG}, Y_{BG}, Z_{BG}, E_{BG}$) at the point in which the BG interaction has occurred;
- if the scattered particle eventually hits the beam pipe, thus getting lost, we declare it a "BG particle loss", and dump the information of both the BG point, and the position, direction and energy in which the particle hits the pipe ($X_{Exit}, Y_{Exit}, Z_{Exit}, CX_{Exit}, CX_{Exit}, CX_{Exit}, E_{Exit}$).

The simulations are performed considering inelastic scattering as only primary process and by using large bias factors, typically 10^9 in the gas pressure to obtain significant results in reasonable amounts of CPU time. This is taken into account in normalized rate estimates. For a reference pressure of 10^9 mbar we calculate the rates according to:

$$N_{loss}/beam = \frac{N_{lossMC}}{N_{MC}} N_p N_b \frac{10^{-9}\text{mbar}}{P_{MC}},$$

where N_{lossMC} is the total number of particles lost in the simulation, N_{MC} is the number of primary particles generated in the MC, N_p is the number of particles per bunch, N_b is the number of bunches in the beam, and P_{MC} is the gas pressure used in the simulation. The loss rate, R_{loss}, in $KHz/beam$ is then obtained as

$$R_{loss} = \frac{N_{loss}/beam}{\Delta t},$$

where Δt is the revolution time (0.333 ms).

For the simulation gas of N_2 molecules was considered, representing a worst case scenario, since the actual compound is expected to contain only a certain fraction of this molecule.

SIMULATION RESULTS

We benchmarked our MC simulation results with the analytic formula [19] for an arc cell, expecting this comparison more accurate than for the IR. In the arc cell, in fact, the beam sizes and energy acceptance don't undergo dramatic changes as for the IR and average values used in the analytic formula give a more accurate estimate. The analytic formula in 1 km of arc cell gives 192.3 kHz/m/beam to be compared with 189.1 kHz/m/beam by our MC simulation, suggesting a very good agreement.

We illustrate in the following the results of our MC simulations for the high intensity run (beam energy is 45.6 GeV); rates for the other energy runs scenarios are consistent with the rescaling of beam current.

Figure 3 shows the longitudinal distribution of the loss points, corresponding to the positions where the beam gas scattered particles hit the vacuum chamber. As highlighted by Fig. 4, the peak visible around the IP corresponds to the longitudinal location where the vacuum chamber gets smaller , as it approaches the IR. In both figures, the vertical axis has been normalized to represent the expected rate at each position. The integral of these plots thus allows to calculate the total rate of particles expected to be lost by hitting the pipe for the nominal current and with a constant vacuum of 10^{-7} Pa.

Figure 5 shows the remaining fraction of the initial energy of the particles that exit the pipe due to BG interaction. The

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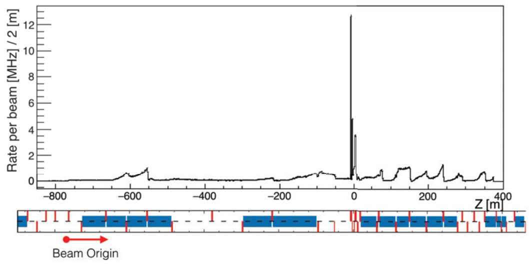

Figure 3: Loss map: particles losses by hitting the vacuum chamber. The machine lattice is shown below and the normalization is described in the text.

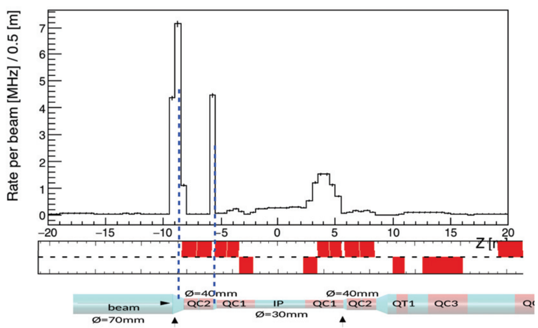

Figure 4: Loss map in the IR.The loss peaks correspond to the restriction of the vacuum chamber between the last drift and final focus quadrupole QC2.

particles are predominantly scattered at very low angles and hit the beam pipe at shallow angles, as shown in Fig. 6.

Table 2 gives the expected particle loss rates both for the whole simulated machine section and for the ± 20 m around the IP, for all the four energy runs.

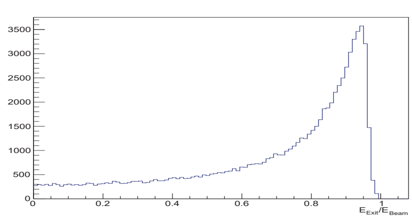

Figure 5: Fraction of the remaining energy of beam gas scattered particles exiting the beam pipe after a BG interaction.

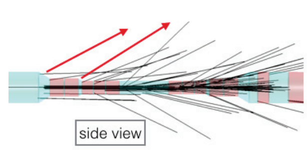

Figure 6: Tracks of beam gas scattered particles shown in the loss location where they hit the pipe, the black line gives an indication of their divergence. Full simulation is needed to see if primaries are absorbed by the pipe or if secondaries are produced when hitting the pipe.

Table 2: Expected particle loss rate both for 1 km of machine section (R_{MDI}), and for the ±20 m around the IP (R_{ZOOM}), for all the four energy runs

	I [mA]	R_{MDI} [MHz]	R_{ZOOM} [MHz]	R_{MDI}/I [MHz/A]
Z	1390	147	29.2	105
W	147	15.8	3.43	107
H	29	2.96	0.536	102
T	5.4	0.526	0.0959	97

LOCAL PRESSURE VARIATIONS

Up to this stage of the analysis, it was assumed a constant gas pressure through the simulated arc. However, this is not the actual case, since the final pressure profile will be determined by the effect of the abundant synchrotron radiation emitted by the beam and of the pumps foreseen in the vacuum system.

To evaluate the impact on our study of such a phenomenon, a realistic pressure profile for about 600 m upstream the IP was obtained for fcc_213 optics at the t-pole energy (the configuration in which the effect of SR is expected to be more relevant) with SynRad + MolFlow [18]. This pressure profile was then used to weight the results of our BG study at the corresponding machine configuration; Fig. 7 shows the comparison of the simulations with and without a pressure profile. We note that when a more realistic pressure profile is taken into account more abundant particle losses in several areas of the machine are found, with an overall increase of about 40% of expected losses.

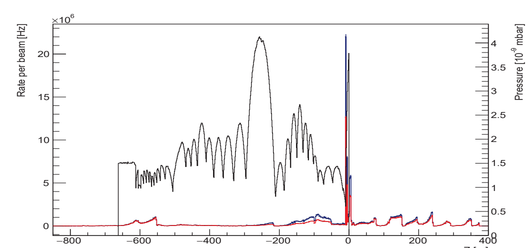

Figure 7: (Color online) Comparison of z exit position of BG scattered particles with (blue) and without (in red) the actual pressure profile of the machine (black).

CONCLUSIONS

We have described detailed studies of inelastic beam-gas scattering and simulated the expected loss maps using a novel MC approach, the toolkit MDISim. These predictions have been compared with the analytical formula in one arc cell showing a very good agreement.

We predict loss rates of roughly 100 MHz per Ampere of beam current in the IR. As expected, the highest loss rate is found in the Z-pole configuration (beam energy of 45.6 GeV), essentially due to the high current configuration foreseen for this run. IR losses are concentrated in the regions where

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the vacuum chamber gets smaller as the beam approaches the IP. We also mentioned that these particles are ready to be tracked with full simulation in the detector and that preliminary results are encouraging.

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