EXTRACTION LINE AND BEAM DUMP FOR THE FUTURE ELECTRON POSITRON CIRCULAR COLLIDER*

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Abstract

The conceptual design of an extraction line and beam dump for the future electron positron circular collider is presented. The proposed extraction line, consisting of abort kicker system, spoilers and beam diagnostics apparatus transports the electron and positron beams to the main beam dumps. The beam must be spread over a large surface in order not to damage the beam dump and the window, which separates the ring from the dump. The extraction line redistributes bunches at different location on the face of beam dump. Monte Carlo simulations using FLUKA have been performed to estimate the distribution of energy deposition on the window and beam dump to find the optimal absorber and its dimensions.

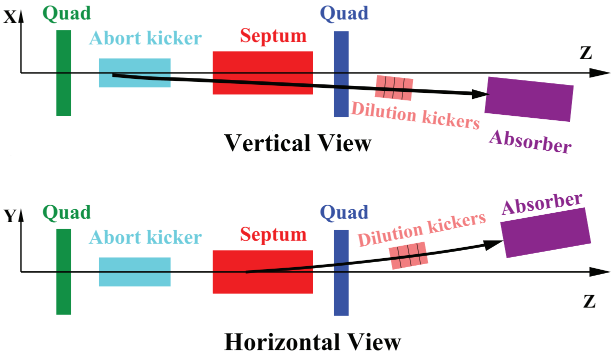

Figure 1: Schematic layout of the extraction system. The horizontal extraction kicker and vertical bending septum magnet are marked in yellow and red, respectively.

INTRODUCTION

The Future Circular Collider (FCC) is a high-luminosity and high-precision e^+e^- storage ring collider. The FCC-ee study includes the design of a high-luminosity e^+e^- collider serving as Z, W, Higgs and top factory, with luminosities ranging from $\approx 10^{36}$ to $\approx 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ per collision point at the Z pole and $t\bar{t}$ threshold, respectively.The design of FCC-ee provides separate e^+e^- channels allowing very large luminosities to be considered in up to four interaction points. In a 100 km tunnel, the accessible centre of mass energy range spans from the Z pole (90 GeV) to above the top pair threshold (350 GeV) [1].

The key part of modern high energy colliders operation is the machine-protection system. Safe operation requires systems for beam dumping, beam instrumentation and absorbers, etc. One of the important collider systems is the extraction line directing the particle bunches to the beam dump. It is important to be able to dump the electron and positron beams in a controlled way in the main collider. The function of the beam dump system is to reliably absorb the power from the electron and positron beams. For safe, long-term operation, the beam dump must be able to withstand the thermal stress and possible fatigue stress.

We have considered several actually implemented or proposed concepts of beam dump systems for various past and future e^+e^- colliders, such as LEP [2], KEK [3] and CLIC [4]. Both solid [2, 3] and water based [4] absorbers are considered for use in the FCC-ee beam dump system.

The FCC-ee design is a part of the global Future Circular Collider (FCC) study. The FCC-ee will be a potential intermediate step towards a 100 TeV hadron collider, FCC-hh, sharing the same tunnel infrastructure. Therefore, it is reasonable to assume that part of the FCC-hh beam dump infrastructure [5], e.g. the tunnel for the extraction line or galleries hosting powering systems, may be shared with the FCC-ee beam extraction system. Also key concepts of the existing LHC beam dump [6] may be adopted and adapted for the FCC-ee.

The proposed FCC-ee beam dump system must have the capability to absorb an energy ranging from 0.4 MJ/beam (for $t\bar{t}$) to 22 MJ/beam (for Z factory). A preliminary beam dump design for the lower current operation mode of FCC-ee (Higgs factory) was discussed at the FCC Week 2016 [7]. In this paper, we include the most challenging operation mode, namely the Z factory. After discussing the components and the magnet parameters of the extraction line, we will present results of Monte-Carlo shower simulations, comparing the energy deposition in various beam-absorber candidate materials.

EXTRACTION LINE

The extraction line is designed to transport the electron and positron beams from the main ring to the main beam dump. The concept of the beam dump system has been adopted from CERN LHC [6] as baseline for the FCC-ee dumping system where energy of 22 MJ of high current beam must be absorbed. We can use one of the six straight sections with a length of 1.4 km for the extraction line. The layout of the extraction line system consists of abort kicker, septum magnet, dilution kickers system and absorber as shown in Fig. 1.

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Table 1: Beam Parameters used in Monte-Carlo Simulations

FCC-ee	**Units**	**Z**	$\mathbf{t\bar{t}}$
Beam Energy	GeV	45.5	175
Beam current	mA	1450	6.6
Bunches\beam		16 700	98
Bunch population	10^{11}	1.8	1.4
ε_x	nm	0.2	1.3
ε_y	pm	1.0	2.6
σ_x	mm	0.45	1.15
$\sigma_{x'}$	μrad	0.45	1.15
σ_y	μm	32	51.0
$\sigma_{y'}$	μrad	32	51.0
σ_p	‰	0.1	0.2

A set of special magnets can be pulsed very rapidly to kick the whole beam out of the machine in a single turn. The revolution time for FCC-ee is 333 μsec. During this time the whole beam should be removed from the main ring. A fast pulsed kicker magnet deflects the beam in the horizontal (or vertical) direction by about 0.37 mrad. For a kicker length of 1 m, this deflection would correspond to a magnetic field required of 56 mT or to an electric field of 17 MV/m. After 135 m, this deflection angle would shift the beam transversely by 50 mm, which is enough to move the beam outside of circulating beam aperture and into the high-field aperture of a septum magnet. The septum magnet provides a strong vertical (or horizontal) deflection, which after a further distance of 100 m, the extracted beam is sufficiently separated from the collider storage ring that dilution kickers can be installed. The septum magnet deflects the beam vertically (or horizontally) by 2.4 mrad. Assuming a septum-magnet length of 3 m, the required magnetic field strength is about 120 mT. The extracted beam is transported through a 600 m long vacuum line to increase its beam size, and it is then deposited on dedicated absorber blocks, specially designed to take the enormous power.

In order not to melt the absorber material, the beam is spread over the front surface of the dump, by means of horizontal and vertical dilution kicker magnets, located about 100 m downstream of the septum [5,6]. Dilution kickers are used to distribute the bunches on the face of beam dump. These kickers should deflect the beam by up to ± 90 cm in the horizontal and vertical direction, if we assume cylindrical beam dump with a diameter of 100 cm. With a distance between the dilution kicker and the beam dump of 600 m, the deflection angle required from the dilution kicker system is 1.5 mrad. This angle can be obtained by means of kickers with a length 3 m and a magnetic field strength of 75 mT, or from 9-m long kickers with an effective electric field of 22 MV/m.

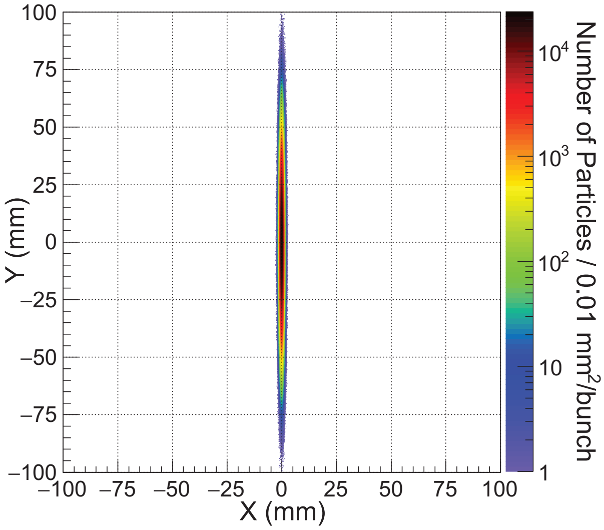

Figure 2: Beam spatial distribution on the face of the beam dump.

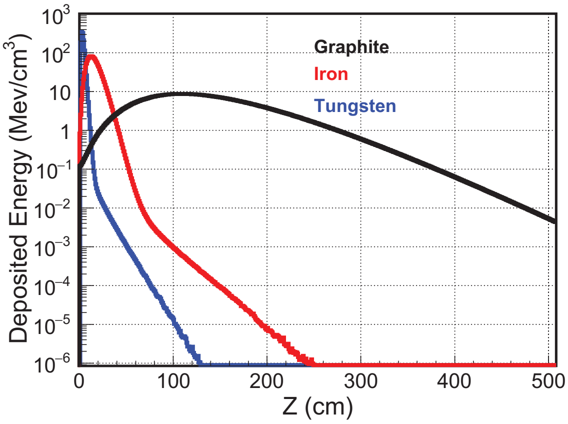

Figure 3: Longitudinal distribution of the deposited energy in graphite (black), iron (red) and tungsten (blue) absorbers.

BEAM DUMP

The important and sensitive component of the beam dumping system is the absorber. We have examined several materials from low to high Z as a possible absorbers, taking into account the critical properties of melting temperature, etc. We considered dumps made from one block of a single material. Both low-Z and high-Z materials are considered. For our simulation study reported in the following, we have chosen graphite, iron and tungsten as candidate absorber materials.

Monte Carlo simulations were carried out to investigate the energy deposition in the absorber and, then, to estimate the resulting temperature rise in the absorber. This procedure allow us to compare various media and to determine the optimal dimensions of the absorber.

More specifically, the energy deposition by the primary beam on the dump was calculated using the FLUKA Monte Carlo simulation code [8]. We consider a scenario with a realistic beam. The present optics easily allows for beta functions between 100 m to 2000 m, both in x and y, in any of the straight sections. If we assume $\beta_x = \beta_y = 1000$ m, we

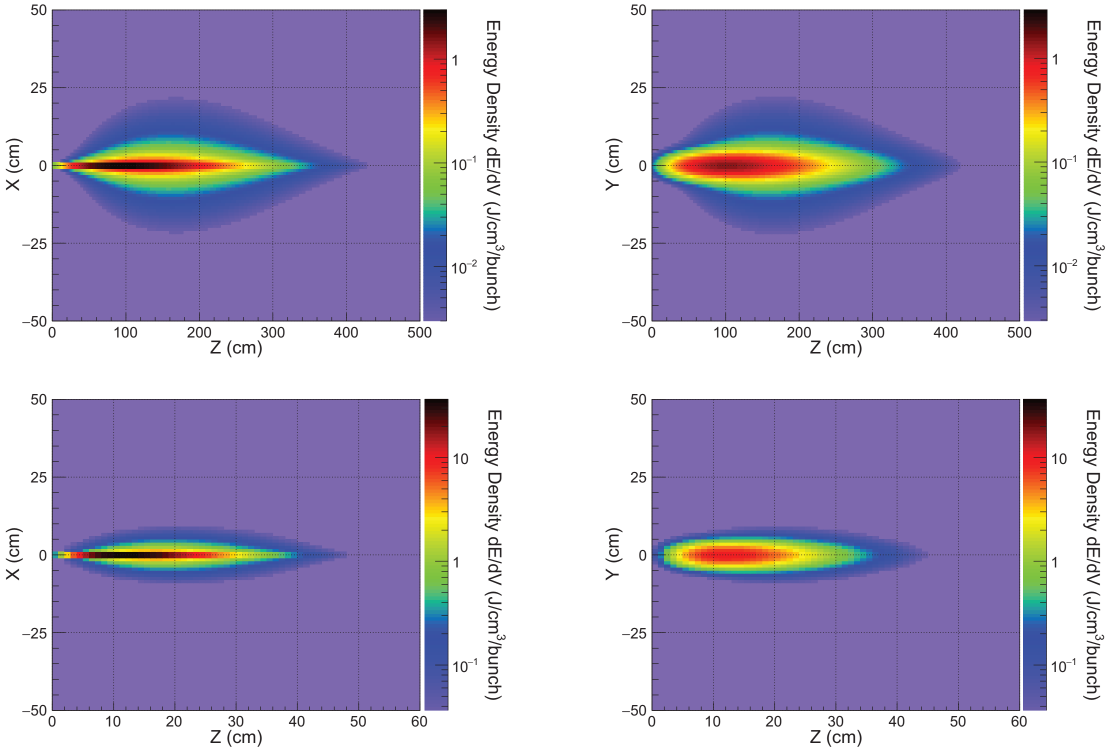

Figure 4: The deposited energy density in the graphite (top plots) and iron (bottom plots), on the $X - Z$ and $Y - Z$ plane, respectively.

obtain the beam parameters listed in Table 1. The simulations were performed for the highest-current beam, i.e. for Z-production.

A cylinder with 100 cm radius and a length of 500 cmh was chosen as shape of the absorber. One electron bunch containing 1.8×10^{11} particles, with an energy of 45.6 GeV, initiates a shower inside the absorber made from different materials. The spatial distribution of the electron beam in front of the beam-dump face is shown in Fig. 2. One can see that after 600 m drift through the extraction line the beam area amoputns to about 10 mm^2, largely increased from the initial value 0.0144 mm^2 at the location of the abort kicker.

The electron bunch with a distribution as shown above hits, and penetrates into, the beam dump, causing an electromagnetic shower and deposits energy in the dump medium. The energy penetration depths for graphite, iron and tungsten absorbers are compared in Fig. 3. The maximum of the energy deposition occurs at a depth of 110 cm for graphite, 14 cm for iron and 4 cm for tungsten.

Figure 4 presents the deposited energy density contours for the graphite and iron absorbers. We remark that the main energy deposition is concentrated within a narrow cylinder around the beam trajectory. The transverse sizes of the energy deposition, obtained from a Gaussian fit, are compiled in Table 2. In the future this table will be used as an input for the detailed design of the beam dilution kicker system.

Table 2: Transverse Extent of the Simulated Energy Deposition Obtained from a Gaussian Fit.

Material	σ_x **(cm)**	σ_y **(cm)**
Graphite	1.1	2.6
Iron	0.68	2.2
Tungsten	0.58	2.0

We can estimate the temperature rise ΔT in the beam dump, corresponding to the beam parameters of Table 1. Namely, the maximum energy deposition density by one bunch of electrons in the graphite is found to be 0.54 J/cm^3, which is equivalent to 0.24 J/g. The associated peak temperature rise in the graphite due to the impact of one bunch of electrons is 0.5 °C. The peak temperature rise for iron is 2.0 °C, and for tungsten it is 13.0 °C. These results show that all three materials would meltwhen an full electron beam consisting of 16700 bunches hits the same locations on the dump. Thus a beam dilution system will be an essential component for the extraction line of the FCC-ee.

CONCLUSION

Preliminary considerations for the FCC-ee beam dump system were reported, for the most challenging operation scenario of the Z factory. The FCC-hh infrastructure may be used to extract beams from the FCC-ee. Tentative parameters for the kicker and the septum magnets are proposed. Monte-Carlo simulations have examined the energy deposition in different candidate absorber materials. The simulation results reveal the necessity of a kicker-based dilution system, as is being used at the LHC, for safe beam-dump operation. Detailed design studies have started for the FCC-ee main dump, which needs to withstand the full beam power ranging from 0.4 MJ/beam (for $t\bar{t}$) to 22 MJ/beam (for Z factory).

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