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CONCEPTUAL DESIGN OF THE FCC-ee BEAM DUMPING SYSTEM

A. M. Krainer*, W. Bartmann, M. Calviani, Y. Dutheil, A. Lechner, A. Perillo-Marcone, B. Andreu-Muñoz, F.-X. Nuiry, R. Ramjiawan[1], CERN, Geneva, Switzerland
[1]also at John Adams Institute, Oxford, UK

Abstract

The Future Circular electron-positron Collider (FCC-ee) will feature stored beam energies of up to 18 MJ. This is a factor 100 higher than any current or past lepton collider. A safe and reliable disposal of the beam onto a beam dump block is therefore critical for operation. To ensure the survival of the dump core blocks, transversal dilution of the beam is necessary. To reduce the complexity of the system and guarantee high system availability, an optimized, semi-passive beam dumping system has been designed. The main dump absorber design has been optimized following recent studies for high energy dump block materials for the LHC High Luminosity upgrade. First simulations regarding the radiation environment of the dumping system have been carried out, allowing the definition of preliminary constraints for the integration with respect to radiation sensitive equipment. The performance of the system has been evaluated using Monte-Carlo simulations as well as thermo-mechanical Finite-Element-Analysis to investigate potential material failure and assess safety margins. An experiment at the CERN HiRadMat facility has been carried out and preliminary results show good agreement with simulations.

INTRODUCTION

To ensure operation of the FCC-ee, beam disposal needs to be done in a safe and controlled way within one turn of the beam following a dump trigger event. The nominal operation foresees on average 2 beam dumps per day, as outlined in the FCC-ee Conceptual Design Report [1]. Depending on the operation mode, stored beam energies range from 0.3 MJ up to 18 MJ (see Table 1). To ensure the survival of the beam dump core, the beam has to be diluted. In previous studies a dilution system, similar to the one currently used for the LHC, was assumed [2]. There, dilution is achieved by using dedicated pulsed kicker magnets, followed by ~ 700 m of drift space before the dump block [3]. This dilution system works very well, but also introduces actively driven components and therefore a potential risk of dilution failure. To ensure high availability of the system and also minimizing the number of potential points of failure, a new semi-passive beam dumping system has been designed, using a defocusing triplet structure and passive beam diluters (spoilers). Particle transport simulations have been executed using the FLUKA Monte Carlo code [4–6], as well as finite element analysis, using the LS-DYNA [7, 8] explicit mechanical solver, 2-way coupled with an iterative thermal solver. In this paper the performance of this system is shown for Z pole operation, which is the most challenging due to the stored energy[1].

* alexander.krainer@cern.ch

Table 1: Parameters for different beam energies and physics modes [9]

	Z	WW	ZH	$t\bar{t}$
Beam Energy [GeV]	45.6	80	120	182.5
Bunches / beam	12000	880	272	40
Bunch population [10^{11}]	2.02	2.91	1.86	2.37
Stored beam energy [MJ]	17.7	3.28	0.97	0.28

EXTRACTION LINE LAYOUT

The extraction line is located in one of the short (~ 1.4 km long) straight sections. Since the extraction line is shorter than the full length of the straight section, flexibility for placement of other components is ensured. In Fig. 1 a schematic overview of the extraction system is shown, whereas a detailed description of this system is given in [10]. The overall length of the system is mainly defined by the chosen deflection angle of ~ 7 mrad and the resulting lateral separation between the main ring and the beam dump.

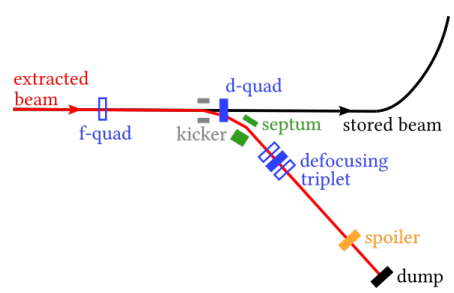

Figure 1: Schematic overview of the FCC-ee extraction system [10].

DILUTION SYSTEM

The full semi-passive dilution concept is described in [10]. Dilution of the beam is achieved in 2 steps. First the extracted beam is blown up by a defocusing magnetic triplet structure and ~ 600 m of drift space to increase the transversal beam spot size from $\sigma_x \times \sigma_y = 0.5\,\text{mm} \times 0.024\,\text{mm}$ at the triplet, to $\sigma_x \times \sigma_y = 11.3\,\text{mm} \times 1.2\,\text{mm}$ at the first spoiler. Secondly, three consecutive spoilers, made of isostatic graphite, are placed in the beam path to create dilution by multiple-Coulomb interactions. After another 70 m of drift space the beam spot size at the front of the beam dump is $\sigma_x \times \sigma_y = 21\,\text{mm} \times 11\,\text{mm}$. The full beam is then absorbed by the beam dump block.

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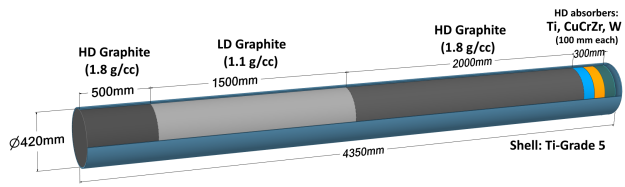


Figure 2: Schematic of the FCC-ee dump block design, showing the material for the dump core and the vessel.

BEAM DUMP

Following the experience gained with the LHC beam dump, a similar design for the dump was chosen, including recent studies and improvements for LHC Run 3 operations [3]. The dump consists of a 4.3 m long core enclosed in a titanium vessel. The core is separated in blocks of different materials and densities to progressively absorb the beam (see Fig. 2).

Energy Deposition

FLUKA energy deposition studies where carried out by simulating the extraction line from the first spoiler to the dump. The starting particle distribution was sampled using the beam optics parameters at the location in front of the first spoiler. The longitudinal peak energy density profile in the dump core is shown in Fig. 3. The results were normalized using the beam parameters in Table 1 for Z operation. The highest peak of ~ 1.9 kJ/g is located in the low density graphite section. This is about 30 % lower than peak values in the LHC beam dump [3]. In Table 2 an overview of the deposited energy in the system per component is shown. From the total beam energy of 17.7 MJ, 95.4 % are absorbed.

Table 2: Breakdown of absorbed beam energy within the dumping system

Component	Absorbed Energy [MJ]	% of total
Spoilers	0.01	0.06
Dump Core	16.78	94.75
Dump Vessel	0.10	0.56
Total	**16.89**	**95.37**

Thermo-Mechanical Response

Using these energy deposition results as input, thermo-mechanical simulations were carried out to investigate the mechanical response of the dump. With an average bunch spacing of 19.6 ns and a bunch train spacing of ~ 5.5 µs the full beam impact happens within ~ 300 µs [1]. A peak temperature of 1200 °C is reached in the low density section of the dump. This can be considered acceptable for the graphite core and safe for operation since the LHC graphite dump core during LHC Run 3 (and in the HL-LHC era) will experience higher peak temperatures during a nominal beam dump [3]. Following the experience with the LHC

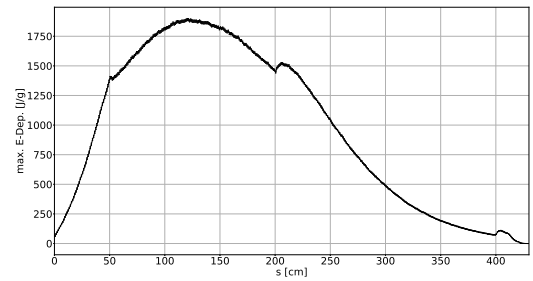
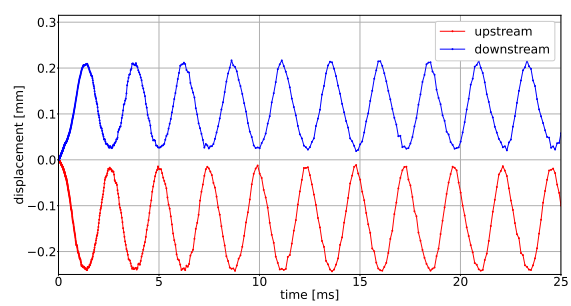
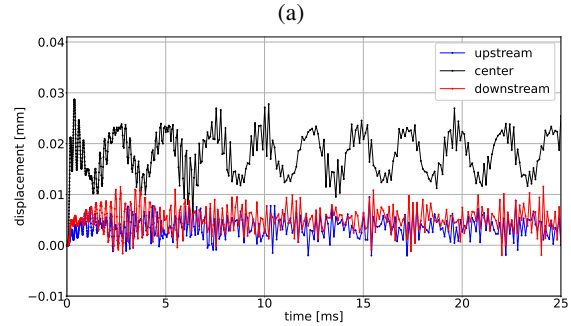


Figure 3: Longitudinal peak energy density distribution along the dump core, normalized to J/g for a full beam impact.

during Run 2, another important factor is the fast dynamic displacement response of the dump, as this gives indications for potential stresses on supporting structures as well as the dump shell. After the beam impact, the dump experiences a longitudinal "stretching" mode (Fig. 4a) as well as a fast "breathing" mode in the transversal direction (Fig. 4b). Both displacement motions are more than one order of magnitude smaller compared to the LHC beam dump block during LHC Run 3. Notably, due to the central impact and symmetric energy deposition, no bending mode is observed.



(a)



(b)

Figure 4: Dynamic response of the beam dump block. a) the longitudinal response is shown for the upstream and downstream faces. b) shows the transversal response at the upstream, middle and downstream location. The transverse vibrations are superimposed on the longitudinal vibration.

Using the Christensen failure criterion [11], potential material failure of the graphite dump core blocks was assessed. The Christensen criterion gives the probability of failure with respect to the compressive and tensile strength of the

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material. For all graphite materials, conservative values of 130 MPa for compressive strength and 40 MPa for tensile strength were used, which are average properties for the isostatic graphite grade considered here. In Fig. 5 the maximum value of the failure criterion is shown over time. The value stays well below the critical limit of 1 and a safety factor of 5 can be assumed. In a recent experiment at the CERN HiRadMat facility [12, 13], high energy beam impacts on isostatic graphite as well as carbon-carbon materials have been studied. During this experiment temperatures and stresses, similar to ones shown shown here, have been achieved and first post irradiation examinations show no detectable damage [14].

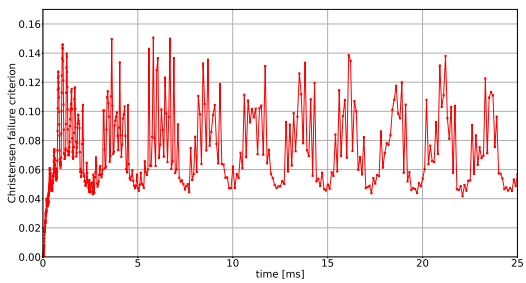

Figure 5: Chsitensen-Failure-Probability for the graphite part of the beam dump core over time.

RADIATION ENVIRONMENT

Eliminating the need for a separate extraction tunnel reduces the cost of the beam dumping system significantly. However, this results in having the beam dump in the straight section in close proximity (within a few meters) to the collider ring. It is therefore necessary to investigate the radiation environment along the extraction line to ensure compatibility with electronics in that region. To assess cumulative radiation damage, the annual dose as well as the Silicon 1 MeV-neutron equivalent (Si-1 MeV eq.) fluence have been simulated with FLUKA for one year, assuming 200 days of operation with 2 beam dumps per day. For the dump block 50 cm of iron shielding were assumed. Dose (Fig. 6a) and Si-1 MeV eq. fluence (Fig. 6b) are shown along the straight section at the location of the main ring, which corresponds to a horizontal separation from the extraction line of 4.5 m at the first spoiler, up to about 5 m at the dump block. Additionally, the contribution of the dump block is shown for both parameters. Comparing this to the total dose clearly shows that the main contribution comes from showers induced in the spoilers. For the Si-1 MeV eq. fluence it is exactly the opposite, where the main contribution comes from the dump itself. Compared to the radiation environment in the arc of the main ring [15], which is dominated by synchrotron radiation, the annual dose coming from the beam dump is more than 4 orders of magnitude smaller. The Si-1 MeV eq. fluence is ~ 1 order of magnitude lower than in the arcs. To estimate Single Event Effects (SEEs) High Energy Hadron equivalent (HEH eq.) fluence and thermal neutron equivalent fluence where used. For thermal neutrons the peak value of $2 \times 10^9\,\mathrm{cm}^{-2}$, at the main ring, is again 2 orders of magnitude lower than in the arcs, the HEH eq. fluence is higher with a maximum value of $1.5 \times 10^{10}\,\mathrm{cm}^{-2}$. Additional shielding could be necessary if electronics are placed next to the beam dump, if SEEs are a concern.

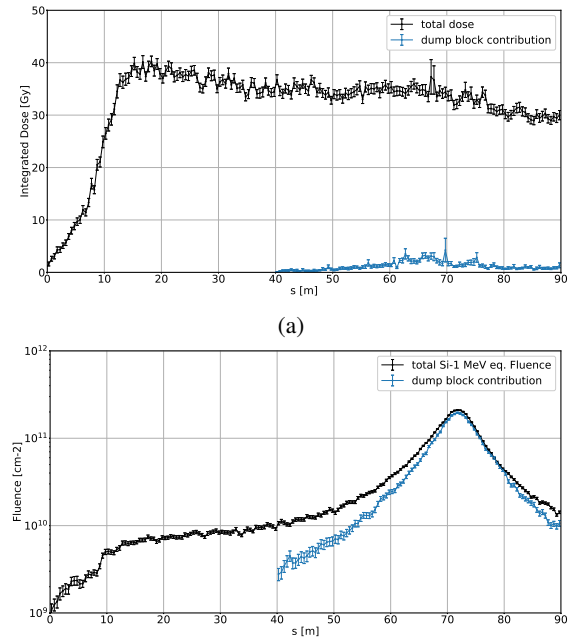

Figure 6: Radiation environment along the main ring in the straight section, starting from the location of the first spoiler, for one operational year (200 days with 2 dumps/day). a) Integrated dose. b) Silicon 1 MeV-neutron equivalent fluence.

CONCLUSION

An updated design of the FCC-ee beam dumping system has been presented and first evaluations regarding performance and thermo-mechanical response have been done. The presented beam dump system is capable of absorbing stored beam energies of 17.7 MJ as foreseen for the Z operation mode of the FCC-ee. Simulations regarding potential material failure in the dump core have been carried out and results show a safety factor of 3 against material failure. Shortly after beam impact, vibrations and relative displacements of up to 1 mm have been observed which need to be taken into account for the support structure of the beam dump. Regarding the placement of the beam dumping system within the accelerator complex, first simulations of the radiation environment along the extraction line have been done. Compared to the arc, all values (with the exception of HEH eq. fluence) are much lower. However, they still need to be taken into account for the placement of electronics sensitive to radiation damage. Especially considering Single Event Effects in operation critical equipment, additional shielding might be necessary.

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