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CONCEPTUAL DESIGN OF THE ELECTRON-ION COLLIDER (EIC) ELECTRON STORAGE RING (ESR) BEAM ABORT SYSTEMS*

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Abstract

Two possible solutions for the electron beam abort system of the Electron Storage Ring (ESR) in the Electron-Ion Collider (EIC) are devised and discussed. The first, the *Septum Extraction Abort System* will use fast rising kicker magnets with a rectangular pulse form and a new DC septum magnet to extract the beam into the extraction beamline. The second, the *Resonant Orbit Abort System* utilizes AC dipoles to generate resonant closed orbit bumps and disposes the beam on the beam dump integrated within the ESR beam pipe aperture. A comparison of the candidates will support the selection of the ESR beam abort system.

ESR BEAM ABORT REQUIREMENTS

The Electron Storage Ring (ESR) is a vital part of the Electron-Ion Collider (EIC) that will provide polarized electron beams of various energies: 5 GeV, 10 GeV, and 18 GeV. The beams of electron synchrotrons at these energy scales can be hazardous and can damage the equipment, because of synchrotron radiation and beam power. A resilient and reliable beam abort system must be implemented for machine protection. The 10 GeV configuration with a beam current of 2.5 A will impose the highest stored beam energy of 320 kJ; and a beam dump must withstand at least 320 kJ within a single turn, over not more than ~20 µs. The ESR abort gap is 1 µs. See Table 1 and the EIC Conceptual Design Report [1].

Table 1: ESR Electron Beam Energy

Energy	Total Intensity	Stored Energy
5 GeV	2.00e+14 e-	159.83 kJ
10 GeV	2.00e+14 e-	319.67 kJ
18 GeV	1.80e+13 e-	51.85 kJ

BEAM ABORT SYSTEM LOCATION

The installation location of the beam abort system is foreseen at the IR2 Straight Section of ESR. The selection of this location is justified by the sufficient space availability, with multiple vacant 12.36 m drift sections. The *Resonant Orbit Abort System* and its beam dump will be integrated within these drift sections. The other scheme that will extract the beam from the ESR circulating ring via a kicker and a septum magnet will deposit the beam in the *stub-tunnel* in the IR2. The *stub-tunnel* was once built for the BNL ISABELLE project. The tunnel has been unoccupied since the RHIC project.

SEPTUM EXTRACTION ABORT SYSTEM

Fast extraction kickers with the total kick strength of 1.085 mrad is required to offset the beam from the ESR circulating ring orbit to the septum entrance. This kick strength shall be distributed among six kickers to increase operational redundancy. The kickers must respond in a fast manner, such that they meet the criteria shown in Table 2.

Table 2: Fast Extraction Kicker Requirements

Extraction Kicker	Parameter
Abort Gap	1 µs
Flattop Field Length	13 µs
Number of Kickers	6
Septum Kick Strength	1.085 mrad

The Septum Extraction Abort System will require a new septum magnet for the beam extraction from the ESR. The location of the septum magnet along the IR2 straight section was determined in such a way that the bend trajectory will guide the beam into the *stub-tunnel* requiring minimal kicker strength, while avoiding physical interference with other beamline elements. The horizontally elongated design of the ESR beampipe (inner radius of 40mm) provides sufficient clearance for the extracted beam to propagate towards the septum entrance.

The septum magnet design used herein features a 4 m long effective magnet length to provide the required 38 mrad bending angle. The septum extraction beam trajectory will require an opposing bend to guide the trajectory towards the *stub-tunnel*. Two existing dipole magnets (dismantled dipoles from the APS) have been secured to accomplish this inward bend. Each magnet is 3 m long with a bending radius of 40 m at 7 GeV. This is equivalent to a bending angle of 29 mrad at 18 GeV. This geometry will require the bend angle to be -22.124 mrad for each dipole.

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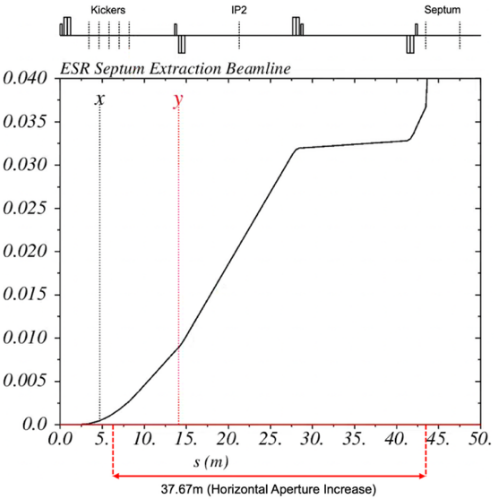

Figure 1: Horizontal orbit of the septum extraction.

The Internal Conceptual Design Report [1] lists a horizontal aperture of $x_{\text{circ}} = 15\sigma_x$+10 mm for the circulating beam as a requirement, with an additional $x_{\text{ext}} = 5\sigma_x$ for the extracted beam. Assuming the horizontal emittance of $\varepsilon_x = 28$ nm (18 GeV lattice), the horizontal beam size σ_x is 1.085 mm. Assuming the septum thickness of $x_{\text{off}} = 5$ mm, the total horizontal displacement is $x_{\text{circ}} + x_{\text{ext}} + x_{\text{off}} =$ 36.71 mm. This orbit offset will require the ESR horizontal aperture to be enlarged over a longitudinal section of 37.67 m length (Fig. 1). The beam exiting the septum will propagate along the extraction beamline and allow natural blow up. Assuming no additional quadrupole magnet is used in the extraction beamline, the beta functions at the beam dump front end surface are β_x = 780.83 m and β_y = 334.19 m (Fig. 2).

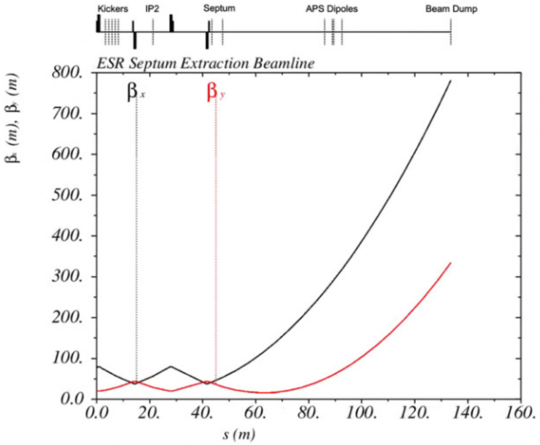

Figure 2: Beta function of the septum extraction.

The beam dump design for the Septum Extraction Abort System assumes the most pessimistic impact scenario, in which considerably small beta functions in the IR2 are used; β_x = 63.40 m and β_y = 37.09 m. The beam dump was designed using the FLUKA numerical analysis code for a 120 cm long, 10 cm diameter low density graphite cylinder. The impacting electron beam has an energy of 10 GeV with 1,160 bunches, 2.0e+14 electrons in total, resulting in a total kinetic energy of 320 kJ.

The graphite dump is exposed to the beamline vacuum. Differential pumping will be required between the beam dump surface in the extraction beamline and the main ESR circulating ring. Secondary radiation is further absorbed by the radiation absorber located in the rear end of the graphite beam dump. The radiation absorber is made of concrete with the dimensions of 40 cm wide and 100 cm long. FLUKA and ANSYS thermal stress simulation results are summarized in Fig. 3. The simulation confirms that the beam dump will withstand the anticipated energy density.

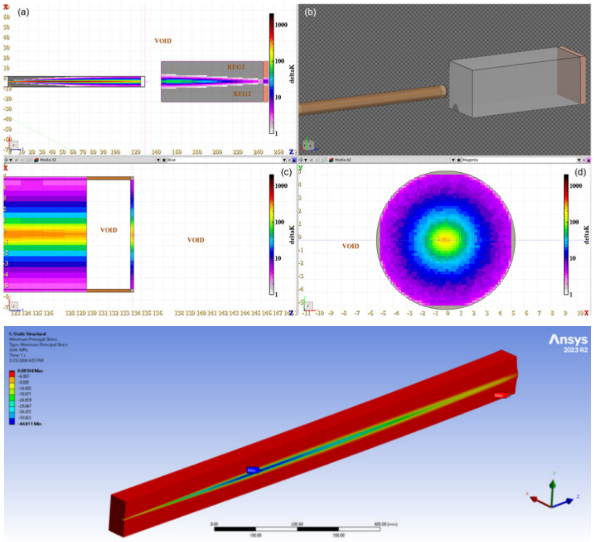

Figure 3: Beam dump of the septum extraction.

RESONANT ORBIT ABORT SYSTEM

A Resonant Orbit Abort System will use AC dipoles to create time dependent closed orbit bumps in both planes such that the maximum deflection deposits the beam on a circle in the transverse plane inside the circular beam dump (see Fig. 4). The locations of the six AC dipoles are shown in Fig. 5. They are distributed throughout the ESR IR2 straight section. Three dipoles will be configured as a three-bump system in each plane, so the beam deflection occurs only at the location of the dump.

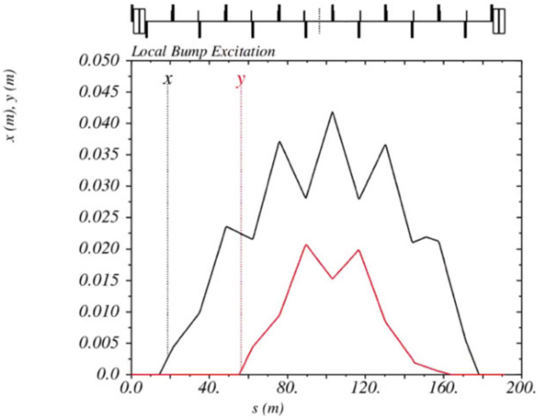

Figure 4: Resonant orbit bump.

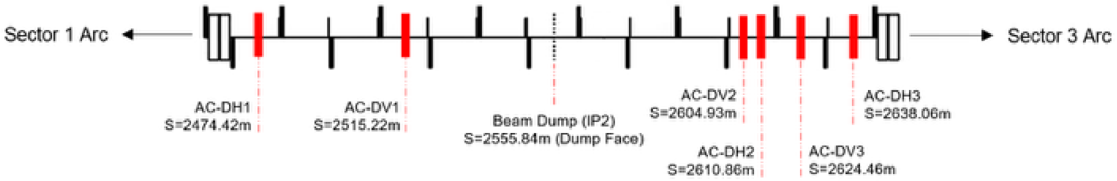

Figure 5: Locations of the AC dipoles.

The AC dipoles will ramp up to the flattop field within a one turn revolution. This mechanism will distribute the stored beam over the cross section of the circular beam dump (Fig. 6). The beam dump is designed with titanium and MoGr segments with copper coating to match the circulating ring impedance (Fig. 7). The beam dump was then simulated using FLUKA for a 320 kJ electron beam. The maximum temperature observed on the dump surface is 500 Kelvin, which is within the acceptable range for the suggested beam dump materials. The beam abort system design satisfies all requirements. However, the failure analysis is more challenging compared to the Septum Extraction Abort System; none of the AC dipoles can malfunction, or the paired AC dipole on the same plane must perform perfectly to avoid a misfire of the abort system.

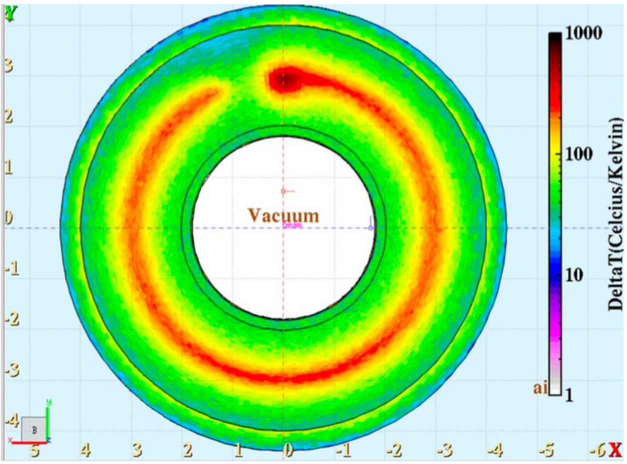

Figure 6: 320 kJ electron beam impact (FLUKA).

Figure 7: Beam dump materials and geometry (FLUKA).

CONCLUSION

Two beam abort systems responsible for the disposal of the 320 kJ of electron beam for the Electron-Ion Collider Electron Storage Ring were designed. Either design implies pros and cons in terms of the initial construction cost and the operation of the abort system and the EIC. It has been identified that, while the *Resonant Orbit Beam Abort System* appears to be more economical compared to the *Septum Extraction Abort System*, the AC dipoles require highly accurate timing and highly reliable abort switches. The pre-estimation cost of the *Resonant Orbit Beam Abort System* including six 80.65 kHz AC dipoles; is about one third of the pre-estimation cost of the *Septum Extraction Abort System* including six fast extraction kickers and the new septum magnet. However, the timing alignment challenge for the six AC dipoles makes the Resonant Orbit Beam Abort System more vulnerable to misfire and prefire; thus, comparably lower operational reliability. On the other hand, the *Septum Extraction Abort System* is straightforward, and the DC septum magnet features a comparably high operational reliability. As a result, the *Septum Extraction Abort System* appears to be more reliable.

REFERENCES

[1] *Electron-Ion Collider Conceptual Design Report*, Brookhaven National Laboratory, Upton, New York, USA, EIC CDR (Internal), 2021.