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

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DISCLAIMER

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

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Abstract

Two beam abort system candidates of the Electron-Ion Collier (EIC) Electron Storage Ring (ESR) are devised and discussed. The proposed candidates are based on an existing Lambertson magnet in RHIC inventory, or a brand-new Septum magnet. A comprehensive comparison is provided in this article in support of the Record of Decision.

ESR ELECTRON BEAM ENERGY

The Electron Storage Ring (ESR) is a vital part of the Electron-Ion Collider (EIC) that will provide polarized electron beams of various energy configurations: 5 GeV, 10 GeV, and 18 GeV. A resilient and reliable beam abort system must be implemented for machine protection in case of a failure. The 10 GeV configuration will impose the highest beam energy of 320 kJ; such a beam dump must withstand at least 320 kJ within one revolution period, but no later than ~20 microseconds. See Table 1 and the EIC Conceptual Design Report [1].

Table 1: ESR Electron Beam Energy

Energy	Total Intensity	Beam 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

A beam abort system will be installed in the IR2 Straight Section of the ESR. The selection of this location is justified by the comparably larger space availability; 12.36m drift sections with less instrument occupancy. Moreover, the *stub-tunnel* in the IR2 that was built for the spectrometer of the BNL ISABELLE project is available. A beam dump inside this tunnel is ideal for secondary radiation shielding (Fig 1).

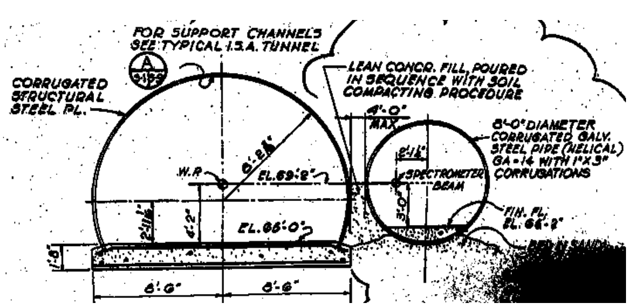

Figure 1: BNL-ISABELLE Spectrometer Tunnel

LAMBERTSON EXTRACTION

The Lambertson extraction concept will reuse the RHIC Yellow Injection Lambertson magnet for ESR beam extraction. The main advantage includes cost savings by refraining from designing and manufacturing a new magnet. The location of the Lambertson magnet was determined in such a way that the bent trajectory will guide the beam into the stub tunnel. Due to the orientation of the Lambertson extraction beampipe, the Lambertson magnet must be positioned as follows; yawed 14.97 degrees counterclockwise w.r.t the beam orbit, 0.1 degrees pitched downward, and -4.12 mm vertical translation from the circulating orbit (see Fig. 2).

This repositioning results in a vertical bend of -3.5961 mrad by the Lambertson magnet. The Lambertson magnet is designed to operate at a maximum bend angle of 38 mrad. At the selected location, the horizontal bend from the Lambertson magnet must be 28.7 mrad, with an operating magnetic field of 0.95 Tesla. It is not feasible to install the Lambertson magnet further upstream with the given kicker angle budget ($\theta_y = 1$~2 mrad) due to the large offset from the circulating orbit to the Lambertson magnet extraction chamber (y_{off} = 30 mm). Locations anywhere further upstream would require a larger kicker angle (θ_y > 2 mrad), which would increase the cost.

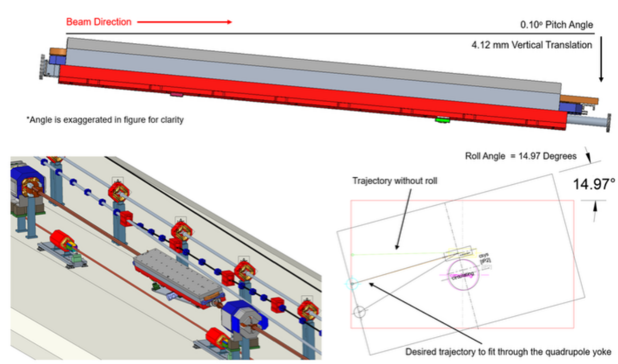

Figure 2: Lambertson Magnet Installation Requirements

LAMBERTSON ORBIT REQUIREMENTS

The entrance of the Lambertson magnet is located 0.89 m downstream of the end of the SX50 sextupole magnet. β_x and β_y at the Lambertson entrance are 42.45 m and 39.11 m, respectively. The Internal Conceptual Design report requires a vertical aperture of $y_{\text{circ}} = 15\sigma_y$+5 mm for the circulating beam, with an additional $y_{\text{ext}} = 5\sigma_y$ for the extracted beam. Assuming the vertical emittance of ε_y = 14 nm (fully coupled beam, 18 GeV lattice), the vertical beam size σ_y is 0.740 mm. Given that the Lambertson magnet has a vertical offset of y_{off}=30 mm between the circulating beam and the cross-sectional center of the extracted beampipe, the total vertical displacement requirement is $y_{\mathrm{circ}}+y_{\mathrm{ext}}+y_{\mathrm{off}}$ = 49.80 mm. Assuming the kicker assembly will be installed at IP2 (bend center), the total required kick is 1.452 mrad. See Table 2.

Table 2: Lambertson Extraction Parameters

Lambertson Entrance	**Parameter**
y_{circ}	$15\sigma_y$+5 mm
ε_y	14 nm
β_x	42.45 m
β_y	39.11 m
$y_{\mathrm{circ}}+y_{\mathrm{ext}}+y_{\mathrm{off}}$	49.80 mm
θ_y	1.452 mrad

Since the inner vertical aperture of the ESR beampipe is 36 mm in diameter; the aperture between the extraction kickers and the Lambertson magnet entrance must be enlarged due to the $y_{\mathrm{circ}}+y_{\mathrm{ext}}+y_{\mathrm{off}}$ clearance requirements. Some aperture modifications have been conceptually designed including the conical slit and the beampipe reshaping section. The conical slit will allow the beam to enter the Lambertson magnet. The Lambertson magnet will also require modifications including installing a copper pipe to match the impedance requirements of the ESR. The total length of the beamline modification is 45.65 m (Fig. 3). The aperture modification will not interfere with ESR quadrupoles, however, accommodating sextupoles would be problematic due to their pole arrangements. The ESR will only require sextupoles for the 2-IP (dual detector) lattice and will operate with 1-IP for several years. Therefore, the sextupole interference concerns can be omitted at this time. Upon the 2-IP upgrade, larger aperture sextupole or alternative lattices must be designed in IR2.

As the extracted beam orbit deviates from the central orbit, the quadrupole magnets between the extraction kicker and the Lambertson magnet will impose an additional kick. This is due to the dipole component of the quadrupoles. The optics and orbit simulations were performed on MAD-X, with the ESR 10 GeV lattice version 6.3.1. For more accurate analysis of the quadrupole kick, *EFCOMP* (magnetic field error module) was applied to all multipoles (n>2), with DKN = 2.0e-3 (m^{-2}). This module was used since it allows defining the radius of the multipole. The simulation was done with a quadrupole pole tip radius of 16 mm.

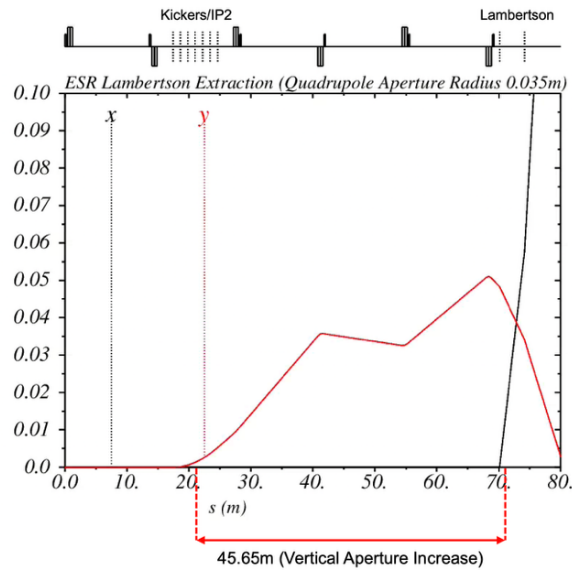

Figure 3: Vertical Orbit of the Lambertson Extraction

BETA FUNCTION OF THE LAMBERTSON EXTRACTION BEAMLINE

The beam size is determined by equilibrium emittance and beta function $\beta(s)$ at the specific longitudinal location (s). Larger beam sizes are of particular interest for the beam dump, as they reduce the energy density of the beam upon impact. A reduction in the energy density is important for the operating lifetime of such a beam dump. The extracted beam enters the extraction beamline upon exiting the Lambertson magnet. The extraction beamline may not utilize additional quadrupole magnets to further expand the beam size. Such a configuration will result in a β_x of 497.82 m and a β_y of 154.21 m at the impact surface of the beam dump. This may be the most economical configuration as no additional quadrupole magnets are used (Fig. 4).

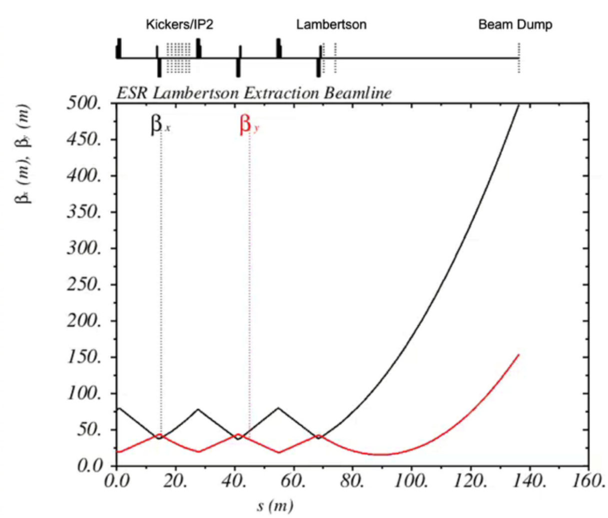

Figure 4: Beta Function of the Lambertson Extraction

LAMBERTSON: BEAM TRAJECTORY

The global beam trajectory from the extraction kicker to the beam dump of the Lambertson extraction configuration is shown in Fig. 5. Note that the Lambertson magnet will induce a vertical ($-y$) bend, while simultaneously will bend towards ($+x$). The beam dump impact surface coordinates are (x,y) = (1.84 m, –0.297 m). The 3D layout of the Lambertson extraction configuration was generated in CREO (Fig. 6).

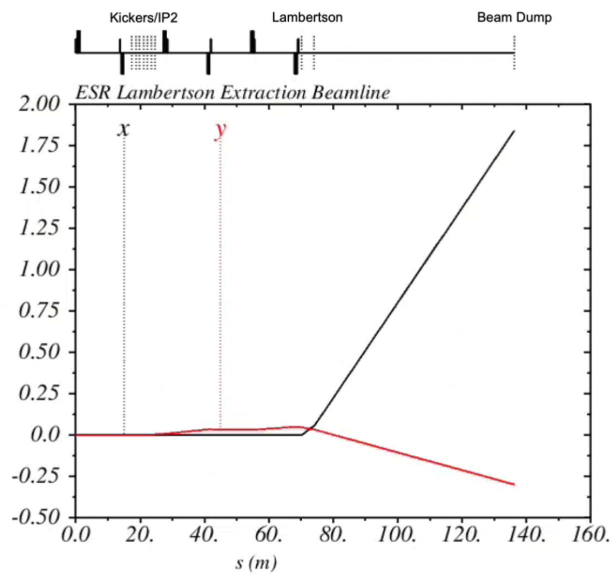

Figure 5: Beam Trajectory of the Lambertson Extraction

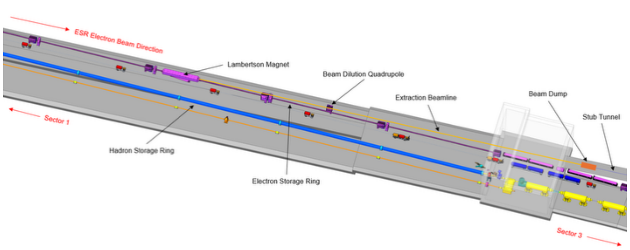

Figure 6: Lambertson Extraction Beamline Layout

SEPTUM EXTRACTION

The Septum extraction configuration will require a new septum magnet for the beam extraction from the ESR. The main advantage of this approach includes a straightforward horizontal extraction with a smaller extraction kick angle requirement compared to the Lambertson configuration. The location of the Septum magnet was determined with the same principle as the Lambertson extraction concept; in such a way that the bent trajectory will guide the beam into the *stub-tunnel*. The horizontally elongated design of the ESR beampipe (inner radius 40mm) provides a better clearance for the extracted beam to propagate towards the septum entrance. While the horizontal beampipe still needs enlargement between the kickers and the septum, no hardware modifications as found in the Lambertson configuration are required. Moreover, the ESR quadrupole design provides an opening in the horizontal plane that will not cause any interference between the extraction beamline and the circulating ring magnets, as is the case with the Lambertson configuration.

The bend angle of the Septum magnet must be designed to be 38 mrad. The Septum magnet design herein used features 4 m long effective magnet length to provide 38 mrad. Note that the actual magnet design may differ and the lattice will be adjusted accordingly. Note that the Septum magnet is installed on the upstream location (near SX48) compared to the Lambertson magnet (near SX50), with the Septum magnet featuring a greater bend angle (38 mrad versus 28.7 mrad). The Septum extraction beam trajectory will require an opposing bend to guide the trajectory towards the *stub-tunnel*. Two APS dipole magnets have been secured to accomplish this inward bend. Each magnet is 3 m long (magnetic core length) with a bending radius of 40 m at 7 GeV. This is equivalent to a bending angle of 29 mrad at 18 GeV. The first dipole will be placed at 38.5 m past the Septum exit, along the extraction beamline. The second dipole will be placed at 0.5 m past the end of the first dipole. This geometry will require the bend angle to be -22.124 mrad for each dipole.

SEPTUM ORBIT REQUIREMENTS

The entrance of the Septum magnet is located 1.0 m downstream of the end of the SX48 sextupole magnet (s = 43.58 m from the front end of SX45 sextupole magnet). β_x and β_y at the Septum magnet entrance are 42.02 m, and 39.83 m, respectively. The Internal Conceptual Design Report requires a horizontal aperture of $x_{\text{circ}} = 15\sigma_x + 10$ mm for the circulating beam, with an additional $x_{\text{ext}} = 5\sigma_x$ for the extracted beam. Assuming the horizontal emittance of ε_x = 28 nm (18 GeV lattice), the horizontal beam size σ_x is 1.085 mm. Assuming a Septum thickness of x_{off} = 5 mm between the circulating beam and the cross-sectional center of the extracted beampipe, the total horizontal displacement requirement is $x_{\text{circ}}+x_{\text{ext}}+x_{\text{off}}$ = 36.71 mm. Assuming the kicker assembly will be installed at 15.5 m upstream of IP2, the total required kick is 1.083 mrad. The parameters are summarized in Table 3.

Table 3: Septum Extraction Parameters

Septum Entrance	Parameter
x_{circ}	$15\sigma_x$+10 mm
ε_x	28 nm
β_x	42.02 m
β_y	39.83 m
$x_{\text{circ}}+x_{\text{ext}}+x_{\text{off}}$	36.71 mm
θ_x	1.083 mrad

Note the extraction kicker assembly is located upstream of IP2, meanwhile the kickers are located at IP2 for the Lambertson extraction configuration. This was an intentional decision to compensate for the closer Septum location, which is located upstream of the Lambertson magnet position. This maintains manageable and comparable kicker angle requirements (Fig. 7).

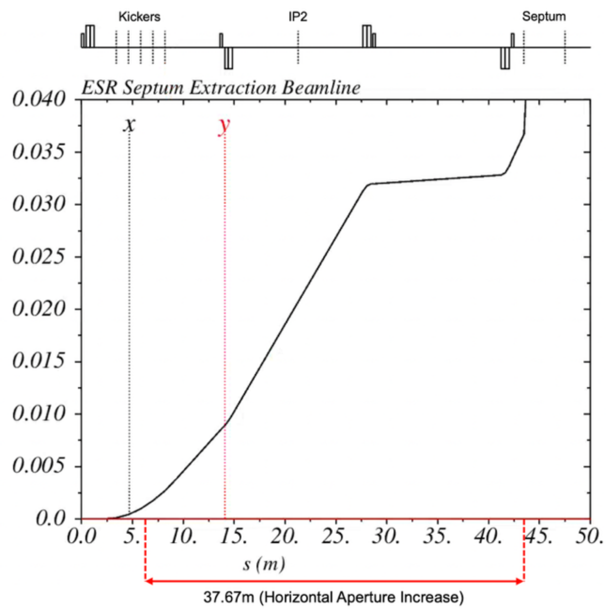

Figure 7: Horizontal Orbit of the Septum Extraction

BETA FUNCTION OF THE SEPTUM EXTRACTION BEAMLINE

The preference for a low beam energy density at the dump surface applies to the Septum extraction candidate as well. Assuming no additional quadrupole magnets are used in the extraction beamline, the beta functions at the beam dump surface are β_x = 780.83 m and β_y = 334.19 m (Fig. 8).

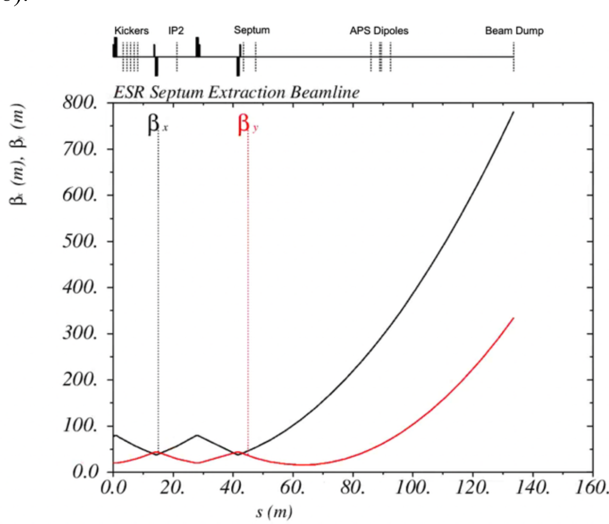

Figure 8: Beta Function of the Septum Extraction

SEPTUM: BEAM TRAJECTORY

The global beam trajectory from the extraction kicker to the beam dump of the Septum extraction configuration is shown in Fig. 9. Note that the Septum magnet will induce a horizontal (+*x*) bend only. The beam dump impact surface coordinates are (*x, y*) = (2.59 m, 0 m). The beam dump is located at 133.54 m from the beginning of the SX45 sextupole magnet.

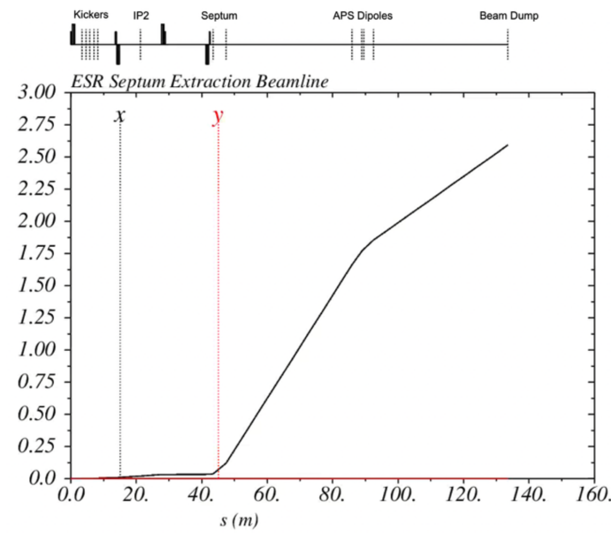

Figure 9: Beam Trajectory of the Septum Extraction

Two APS dipole magnets will be placed on the extraction beamline. This is because the Septum magnet has a bend angle of 38 mrad, which is to avoid a physical interference between the extraction beampipe, and the circulating beam magnets located downstream of the Septum magnet. These dipoles were acquired from ANL together with their quadrupoles and sextupoles. The specifications of these dipole magnets can be found in Table 4, and from the design manual [2].

Table 4: APS Dipole Specifications

APS Dipole	Parameter
Magnetic Length	3.06 m
Core Length	3.00 m
Bending Radius	38.9611 m
Magnetic Field	0.599 T
Number of Magnets	2
Angle of Bend	-11.062 mrad

The upstream end of the first APS dipole is located 38.5 m downstream of the end of the Septum magnet. The end of the first APS dipole is followed by a 0.5m drift space, and the second APS dipole will be placed. In this configuration, each dipole should be powered at -0.011062 rad. This trajectory will guide the beam into the beam dump located at (*x, y*) = (2.59 m, 0 m).

The beta functions within the APS dipole magnet apertures may appear concerning; with the maximum beta function reaching 336.40 m (Table 5). The beampipe aperture for the dipole magnets is 80 mm wide, 36 mm tall. The 3D layout of the Septum extraction configuration was generated in CREO (Fig. 10).

Table 5: Beta Functions in the APS Dipole Apertures

Beta Functions	Parameter
APS Dipole-A Entrance β_x	280.77 m
APS Dipole-A Entrance β_y	56.07 m
APS Dipole-A Exit β_x	305.79 m
APS Dipole-A Exit β_y	66.67 m
APS Dipole-B Entrance β_x	310.07 m
APS Dipole-B Entrance β_y	68.07 m
APS Dipole-B Exit β_x	336.40 m
APS Dipole-B Exit β_y	79.64 m
Maximum Beam Size σ_{max}	3.070 mm
$5\sigma_{max}$	15.35 mm

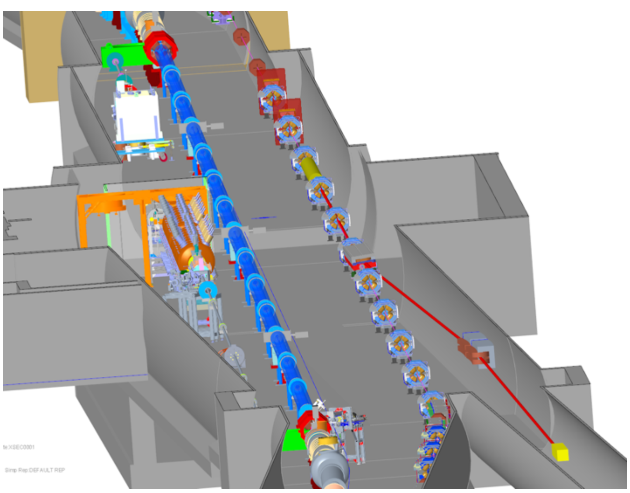
Figure 10: Septum Extraction Beamline Layout

KICKER ANGLE REDUCTION

One of the main factors that contributes to the cost of the beam abort system is the cost of the fast extraction kickers. An attempt was made to reduce the total kicker strength required by the extraction kickers; a squeeze of the IR2 straight section beta functions. The squeeze of the vertical beta function results in the increase in the horizontal beta function (Fig. 11). This increases the horizontal beam size; the beam approaches closer to the pole radius of that quadrupole.

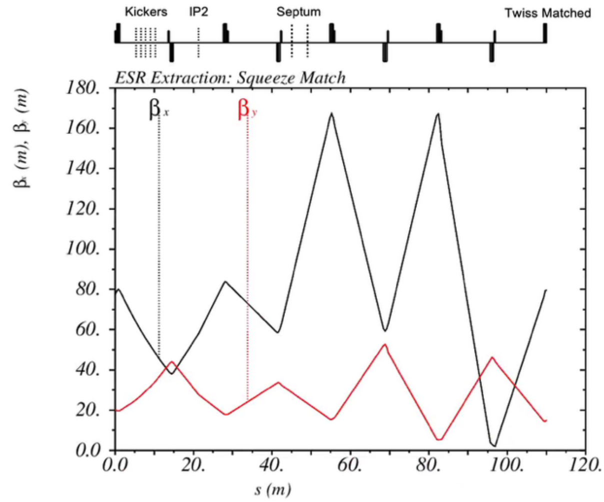

Figure 11: IR2 Optics Modification

The vertically focusing quadrupole located upstream of the Septum magnet will kick the beam outward and the kick is more effective than what was found in Figure 7 and effectively compensates for the horizontal kick (Fig. 12). This method resulted in a reduction of the kicker strength by 0.2 mrad; this is not worthwhile due to an excessive increase in the horizontal beta functions past the Septum magnet. Furthermore, recall $x_{\text{circ}}+x_{\text{ext}}+x_{\text{off}}$; the increase in horizontal beta functions also increase the orbit offset requirements at the Septum magnet. The effort to reduce such fast extraction kicker strengths is therefore not worthwhile. Moreover, a reasonable number of kickers of five to six is more favorable as it improves the operational reliability and redundancy of the beam abort system.

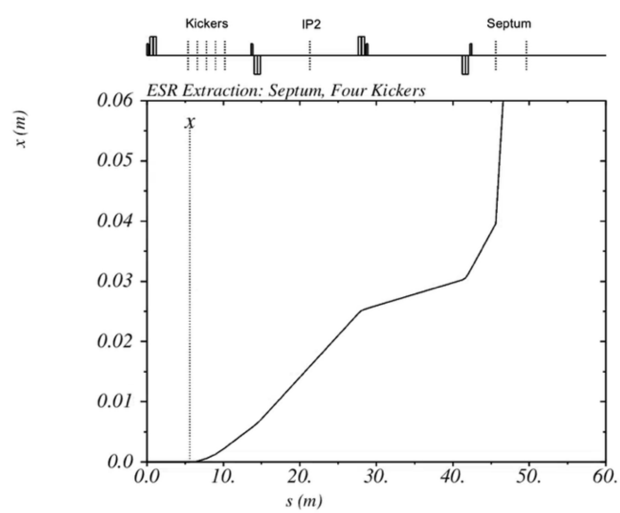

Figure 12: Additional Quadrupole Kick

REQUIREMENTS OF THE ABORT SYSTEM EXTRACTION KICKERS

The requirements of the extraction kickers for both Lambertson and Septum configurations are listed in Table 6.

Table 6: Extraction Kicker Specifications

Extraction Kicker	Parameter
Abort Gap	1 µs
Flattop Field Length	13 µs
Number of Kickers	6
Lambertson Kick Strength	1.452 mrad
Septum Kick Strength	1.085 mrad

BEAM DUMP DESIGN

The beam dump for the ESR beam abort system assumes the most pessimistic impact scenario, in which considerably smaller beta functions at the dump surface are used (Table 7). The beam dump was designed on FLUKA with a 120 cm long, 10 cm diameter low density graphite cylinder. The bombarding 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. Note that the optics assumed for this beam dump design results in much higher power density at the dump than the actual beam optics parameters. This is an intentional design choice to ensure that the beam dump can withstand the highest possible beam power density with sufficient safety margin.

Table 7: Maximum Beam Energy Density Optics

Pessimistic Beam Optics	Parameter
β_x	63.40 m
α_x	-1.715
γ_x	0.000981
β_y	37.09 m
α_y	1.133
γ_y	0.00166
$\varepsilon_{x,rms}$	24.0e-9 m
$\varepsilon_{y,rms}$	2.0e-9 m

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. To separate the vacuum and the ambient environment, a titanium window is used that absorbs some of the beam. Note that the vacuum window is placed on the rear end of the graphite beam dump, and the beam dump is exposed to the vacuum. This is because there is no vacuum window that can withstand the full of the beam without being diluted. The graphite beam dump is kept under vacuum such that no contact will be made with oxygen gas. The graphite beam dump is subject to combust upon contacting oxygen while the temperature is high due to the beam impact. The differential pumping is expected to separate the vacuum between the ESR circulating ring and the extraction beampipe. The graphite beam dump is exposed to the extraction beamline vacuum; a considerable level of outgassing is anticipated, in which differential pumping will act as vacuum boundary. Not all the beam energy is absorbed by the graphite beam dump and some of the beams are converted into secondary electromagnetic showers. This secondary radiation is further absorbed by the radiation absorber located at 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. The FLUKA and the ANSYS thermal stress simulation results are shown in Figure 13.

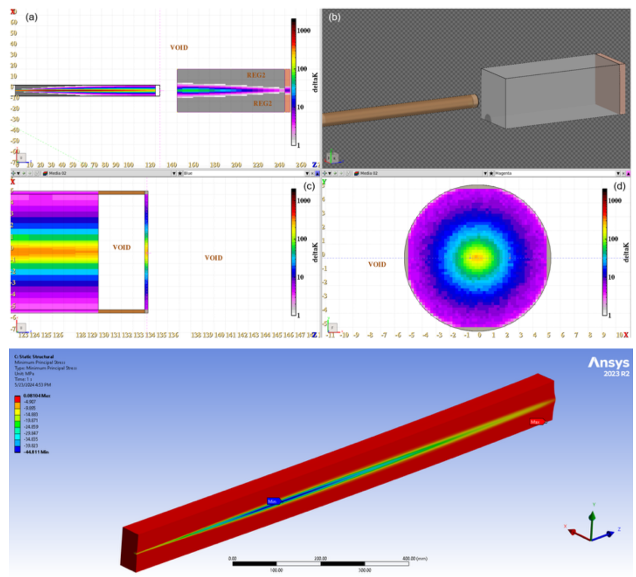

Figure 13: Beam Dump Design and Simulation

While the beam dump and the secondary radiation absorber can withstand the thermal stress from the beam parameters given in Table 7, a safety factor of 2 is preferred to maintain the system for several decades. This can be achieved by further diluting the beam energy density, which is already demonstrated in Figure 4 and Figure 8.

COST ESTIMATE AND COMPARISON

The designs of the two ESR Beam Abort System candidates are summarized in Table 8 for the Lambertson extraction, and Table 9 for the Septum extraction, followed by the cost estimates in Table 10 for the Lambertson extraction, and Table 11 for the Septum extraction. The Lambertson extraction will require 45.65 m of the ESR aperture to be enlarged, both horizontal and vertical. The Septum extraction will require 25.56 m of the ESR aperture to be enlarged, horizontal only. The cost of the graphite beam dump and the Lambertson magnet copper chamber, vertical and horizontal beamline modification, and conical slit are directly quoted from vendors. The cost of the Lambertson magnet is excluded since it already exists in the inventory. For the Septum extraction, the cost of the two APS dipole magnets is excluded since it exists in the inventory. The horizontal beamline modification cost will be estimated at

30% than that of the Lambertson candidate's beamline modification hardware, given that its geometry is simpler and shorter. Note that the fast extraction abort kicker costs are not included in the cost estimate at this time. Nonetheless, it is a fact that the Septum extraction candidate will require 0.36 mrad (30%) less of a kick strength compared to the Lambertson extraction candidate.

Table 8: Lambertson Extraction System Configuration

Subject	**Parameter**
Kicker Strength	1.45 mrad
Aperture Modification	45.65 m
*Specialty Items	3
Magnet Modifications (*Subject to 2-IP*)	SX46, SX47, SX49, SX50
Beam Trajectory	Horizontal and Vertical
New Magnet Requirements	None

Table 9: Septum Extraction System Configuration

Subject	**Parameter**
Kicker Strength	1.09 mrad
Aperture Modification	25.56
**Specialty Item	1
Magnet Modifications (*Subject to 2-IP*)	SX46, SX47
Beam Trajectory	Horizontal
New Magnet Requirements	Septum

Table 10: Lambertson Extraction Cost Estimation

Subject	**Cost (USD)**
Abort Kickers (1.45 mrad)	*TBD*
Lambertson Magnet Copper Chamber	1,900
Conical Slit	6,000
Extraction Beamline and Differential Pumping	200,000
Enlarged Sextupole	23,000/pc
Elongated ESR Beampipe	5,900
Solid State Abort Switch	*TBD*
Graphite Beam Dump	1,300
Installation and Miscellaneous	*TBD*
SUBTOTAL	238,100 + *TBD*

Table 11: Septum Extraction Cost Estimation

Subject	**Cost (USD)**
Abort Kickers (1.09 mrad)	*TBD*
Septum Magnet	150,000
Extraction Beamline and Differential Pumping	200,000
Elongated ESR Beampipe	5,900
Solid State Abort Switch	*TBD*
Graphite Beam Dump	1,300
Installation and Miscellaneous	*TBD*
SUBTOTAL	354,100 + *TBD*

CONCLUSION

The Electron Storage Ring of the Electron-Ion Collider will store polarized high energy electrons at high intensities, with the maximum total beam energy of 320 kJ. Since this energy is destructive a highly reliable and repetitive beam abort system is crucial for machine protection. Both ESR beam abort system candidates, Lambertson and Septum extraction schemes, are straightforward and reliable in terms of their mechanisms. Furthermore, both types of extraction magnets are operated in DC mode. The Lambertson configuration features a higher complexity compared to the Septum configuration. While the Lambertson magnet exists in the inventory, it will require some modifications, namely installing a copper chamber to match the impedance requirements of the ESR. In addition, the circulating beampipe will need more modifications compared to the Septum extraction candidate, such as a conical slit and elongation of the vertical aperture. Upon the future upgrade of the EIC with two interaction regions and detectors, new, large aperture sextupole magnets will need to be designed and procured; four magnets for the Lambertson extraction scheme and two magnets for the Septum extraction approach.

The fast extraction kickers are yet to be designed. The latest discussion suggests that a ferrite ring based extraction kicker design will fulfil the requirements. It is advised that stripline kickers will be inefficient and too long. It is also expected that solid state abort switches may be adapted to increase the abort system reliability. At first glance the Lambertson configuration appears to be more economical compared to the Septum configuration. However, the base difference in cost is approximately 100,000 USD in component cost. It is unknown whether the complexity aspects of the Lambertson configuration will increase the engineering and labor cost, and there is no projection whether the *TBD* items and other unlisted items will adjust the overall cost linearly. Finally, it is expected that the 30% difference in required kick angle will tip the scale in favour of the Septum based scheme.

REFERENCES

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

[2] 7 GeV Advanced Photon Source Conceptual Design Report, ANL-87-15, Argonne National Laboratory, Lemont, Illinois, USA