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AN INDUCTION-TYPE SEPTUM MAGNET FOR THE HADRON AND ELECTRON INJECTION OF THE EIC COMPLEX

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DISCLAIMER

AN INDUCTION-TYPE SEPTUM MAGNET FOR THE HADRON AND ELECTRON INJECTION OF THE EIC COMPLEX*

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Abstract

The design of the electron Ion Collider (EIC) project is under way to be built at the Brookhaven National Laboratory (BNL) with the collaboration of the Thomas Jefferson National Accelerator Facility (TJNAF). The Rapid Cycling Synchrotron (RCS) which is part of the EIC accelerator complex will accelerate the electron beam up to 18 GeV, and the beam will be injected into the Electron Storage Ring (ESR) to collide with the hadron beam circulating in the Hadron Storage Ring (HSR) which is a modified version of the Relativistic Heavy Ion Collider (RHIC). All three synchrotrons will be located in the same tunnel. This technical note provides information on the latest electromagnetic design of the induction-type septum magnet which will be employed by EIC to Inject the beam into the HSR and RCS and also extract the beam from the RCS.

INTRODUCTION

The EIC accelerator complex [1] shown in Fig. 1 will facilitate the collisions of various hadron species at energies up to 270 GeV/amu with electrons at energies 5, 10, and 18 GeV. The hadron-ions will be pre-accelerated in the Alternating Gradient Synchrotron (AGS) and injected into the Hadron Storage Ring (HSR) [2] for final acceleration and beam storage. The electrons will be accelerated in the Rapid Cycling Synchrotron (RCS) and injected into the electron Strorage Ring (ESR) to collide with the hadron-ions stored in the HSR. This paper discusses the electromagnetic design of the induction Septum magnet to be used for beam injection into HSR and RCS Fig. 2 and beam extraction from RCS. One mechanical description of an induction type of magnet is given in [3]. The present paper provides a modified design of such a septum magnet and detailed information on the electromagnetic study performed with the transient-module of the OPERA computer code [4].

INDUCTION SEPTA TO BE USED IN EIC

Three similar induction septa-magnets will be used in the EIC; two septa-magnets will be used in the beam injection/extraction systems of the RCS and the third septum magnet in the beam injection system of the HSR. The goal of this electromagnetic design is twofold: one to calculate the field in the injection and the circulating beam regions

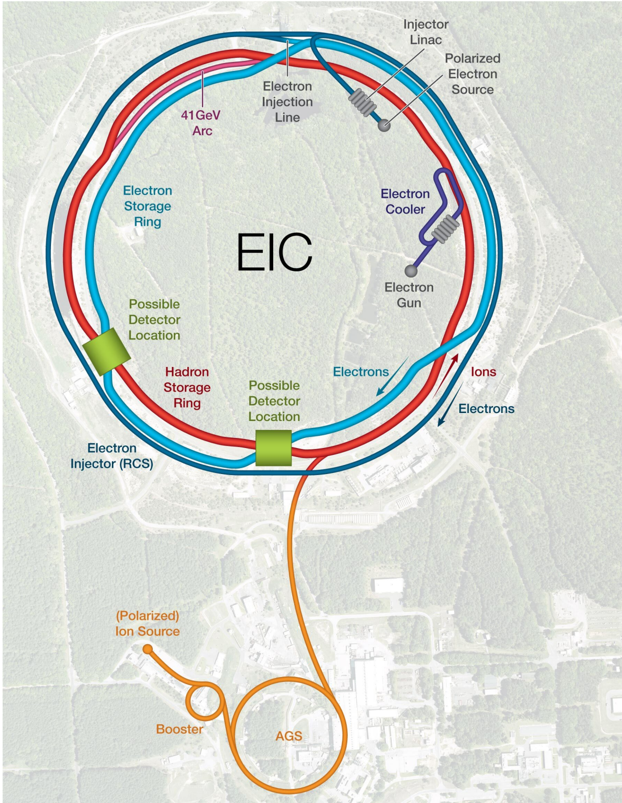

Figure 1: Schematic diagram of the EIC complex. The AGS in the bottom of the picture will provide the hadrons, and the electrons will be accelerated with the RCS and injected into the EIC ring.

during the excitation of the magnet, and second to minimize the septum thickness which is currently ~10 mm. The minimization of the septum thickness will also minimize the strength of the injection/extraction kicker magnets because the injected/extracted beams will be injected/extracted closer to the reference orbit at the location of the septum magnet. This paper will focus on the electromagnetic design of the induction septum magnet and more specifically in the calculation of the B-fields in the injection and circulating beam regions of the magnets, and the Ohmic losses in the laminations of the magnet. A description of the extraction and injection systems is also given in [5]. The top figure in Fig. 2 shows the location of the hadron Injection Septum in the HSR, and to bottom figure shows the location of the electron extraction septum from the RCS.

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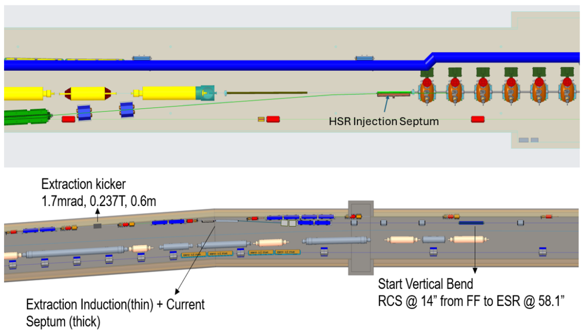

Figure 2: The location of the HSR Injection Induction-Septum (Top Figure) injects the hadron beam into the Hadron ring, and the location of the RCS Extraction Induction-Septum (Bottom Figure), extracts the e-beam from the RCS electron ring. Notice the Extraction septum from the RCS (Bottom Figure) is a combination of induction Septum, and current septum placed in series.

MECHANICAL DESIGN OF THE MAGNET

An isometric view of the mechanical design of the septum magnet is shown in Fig. 3. The iron core of the magnet is made of iron laminations of 0.35 mm thick and a section of the laminations is shown in Fig. 4. The laminations are electrically isolated from each other and the assumed permeability is lineal of μ=4000 and conductivity σ=1.0x10^7 Siemens. In the OPERA model each lamination is split in half Fig. 4 for better accuracy of calculating the Eddy currents formed in each lamination. To speedup the calculations only 32 mm of laminations are included of total 92 laminations. The rest of the iron core of the magnet in the OPERA model is magnetic iron with zero conductivity. The coil of the magnet shown in Fig. 3 is wound around the back leg of the magnet. The eddy currents generated in the septum which is shown in Fig. 3 in combination with the excitation current in the coils create a uniform field in the injected beam region. To minimize the stray field in the circulating beam region the circulating beam pipe is made of two concentric but electrically isolated pipes. The inner cylinder made of copper and the outer of magnetic iron. Both pipes are conductive but electrically isolated from each other. In addition we insert a septum cover shown in Fig. 3 which further reduces the B-field in the circulating beam region. The injection beam pipe is made of inconel material of low conductivity to minimize the Eddy currents during the excitation of the magnet. The total septum thickness is 10 mm and consist of the sum of the thicknesses of the following materials:

1.0 Circulating-beam-pipe of 2.0 mm thick, which is made of two electrically isolated concentric cylinders (Iron outside Copper inside).
2.0 the Septum-Cover 2.5 mm thick made of Copper.
3.0 the Septum made of copper 3.5 mm thick
4.0 the injection-beam-pipe made of inconel 2.0 mm thick, all items #1 to #4 listed above are shown in Fig. 3.

EM DESIGN OF SEPTUM MAGNET

The principle of operation of the induction septum is based on the eddy currents generated on the septum of the magnet shown in Fig. 3 during the excitation of the magnet's coil. The effect of the eddy-currents is twofold, first to generate a uniform field in the injection beam region and second to minimize the B-field in the circulating beam region. To excite the magnet in the OPERA code a voltage shape of almost half sine wave of frequency of 4.85 kHz is being used and its a functional form is shown in Fig. 5. This figure shows three Voltage forms: a) a half-sine wave form (black curve), b) a half-sine wave followed with a negative extension (green curve), and c) an incomplete half-sine wave form followed by slow-fall of the Voltage (red curve). The Voltage curve (c: red curve in Fig. 5) above provides the minimum B-field strength in the circulating beam region as shown in the next section, thus the effect of the septum's B-field in the circulating beam region on the circulating beam is minimized.

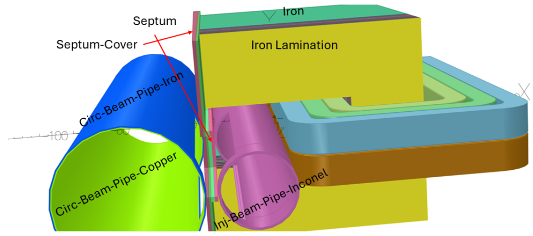

Figure 3: An isometric view of the Induction septum.The grey materiar represent the iron laminations, followed by the green material which is the iron. The circulating beam pipe is made of two electrical isolated pipes of copper inside and iron outside both conductive. The Injection beam pipe is of inconel material. The septum is made of copper material, and a septum cover is added to reduce the field in the circulating field region.

RESULTS FROM THE EM STUDY

The electromagnetic calculations of the magnet model shown in Fig. 3 were performed using the AC-module of the OPERA code. Three different Voltage curves V(t) shown in Fig. 5 were used to excite the coil of the magnet, and the results from the excitation of the magnet by the red in color voltage curve are shown in a section below. The voltage curve (red) provided superior results (minimum B-field in the circulating field region as compare to the field in the main field region).

Fields in Injection and Circulating Beam Regions

This subsection shows the B-fields in the injection field region of the magnet as a function of time. As a reminder

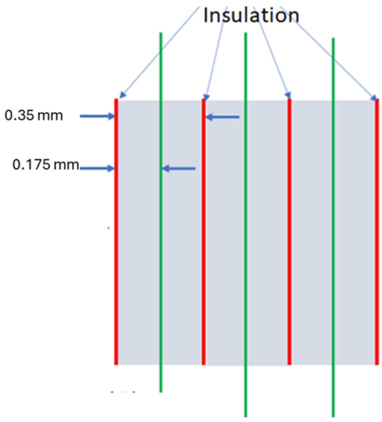

Figure 4: Each lamination is 0.35 mm thick and its electically isolated from the next. In the OPERA code each lamination is split in two sections, to provide more accurate results of the Eddy Currents formed in each lamination.

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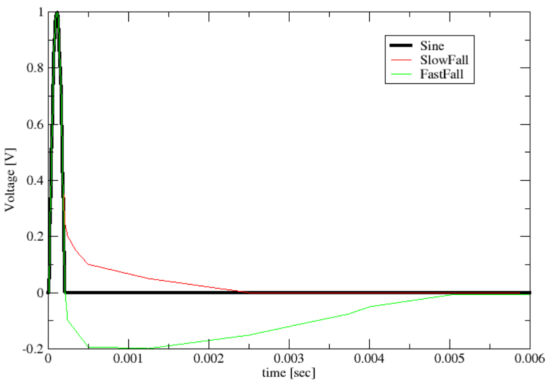

Figure 5: Three Voltage pulses to excite the magnet at a repetition rate of 1 Hz. A half-sine wave (black curve), a half-sine wave followed by a negative curve (green curve) , and a half-sine wave followed by a positive curve (red curve)

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the magnet is excited with the Voltage shape shown by the red curve in Fig. 5 which provides the smallest ratio of the B-field in the circulating Field region over the B-field in the injection field region. Additional calculations are being performed to optimized the Voltage vs time curve which will minimize the ratio of the B-field in the circulating field region to the B-field in the injection field region. In addition a new geometry will be implemented to modify the geometry of the injection-circulating beams to shield the the circulating field region from the stray main field of the injection field region. Calculations of B-fields of the magnet excited by similar curves as the red curve in Fig. 5 are under way to obtain even additional reduction of the B-field in the circulating field region. To characterize the B-field in the injection field region during the beam injection, the harmonics of the B-field along the direction of the beam are

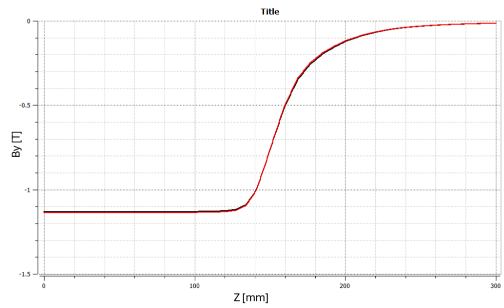

Figure 6: The Dipole component of the field B-field in the injected beam region along the z-axis and at a radius of 10 cm during beam injection.

calculated at a radius of 10 mm. Fig. 6, shows the dipole field component as a function of z- direction in the injected field region and Fig. 7 the three higher components of the B-field along the same direction. The calculated integrals along the z-direction of the field harmonics at the injection field region and at the circulating field region appear in the 1^{st} row and 2^{nd} row of Table 1 respectively.

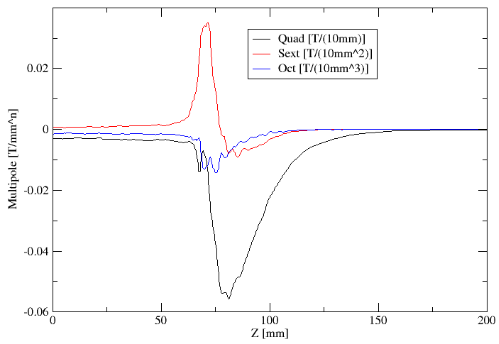

Figure 7: The Quad, Sextupole and Octupole along the z-axis, at a radius R=10 mm in the injection field region.

Table 1: Integrated Multipoles at a radius R=10 mm, along the z-direction in the Injection Field region (row 1) and the Circulating Field region (row 2)

Region	Dipole [T*mm]	Quad [T]	Sextupole [T/mm]	Octupole [T/mm^2]
Injection	92.38	-1.77	0.19	-0.33
Circulating	-0.31	0.08	0.05	0.02

OHMIC LOSSES IN THE MAGNET

This section reports on the Ohmic loses on the various conducting parts of the magnet, (Laminations, Circulating beam pipe, Injection beam pipe). The Transient-OPERA

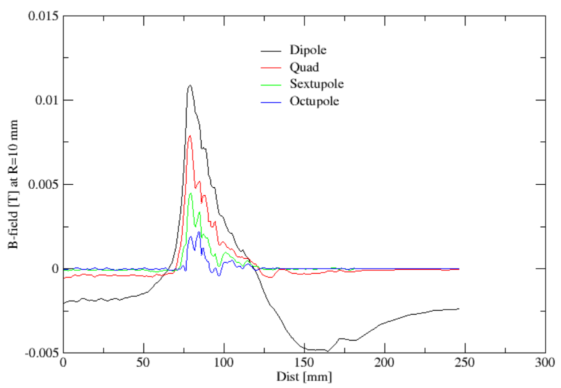

Figure 8: The B-field Harmonics along the circulating beam direction.

module was used in the calculations but only 93 laminations, 0.35 mm thick each, were used in the core of the magnet to speed up the calculation. The 93 laminations were placed at the exit of the magnet as shown in Fig. 3. Each laminations was electrically isolated from the next and to increase the accuracy of the calculations of the eddy currents in the laminations, each lamination in the OPERA model was split in two sections as shown in Fig. 4. The Ohmic losses in the 92 laminations during a voltage pulse shown in Fig. 5 were calculate to be 5.51 J. To make a good estimate of the beam losses in the laminations of a 90 cm long laminated magnet, we separate the calculated losses in two parts, the ohmic losses in the fringe field part of the magnet, of 4.0 J and the those in the uniform field part 1.5 J. For a 90 cm long magnet the total lamination losses are 60 J in the laminations in the uniform part of the magnet and 2*4.0 J for the fringe field part for total of 68 J. Given that the magnet will be excited every second the power consumed in the laminations due to the eddy currents will be 68 W. The Ohmic losses

Table 2: Ohmic losses in Watts for the conducting parts of a 90 cm long magnet. The repetition rate for the excitation of the septum magnet is 1 Hz.

Lam	Circ.Pipe	Inj.Pipe	Septum	Sept.Cover
68	2.0	24.0	12.0	12.0

in the circulating and Injection beam pipe respectively are calculated to be 2.0 W an 24 W for the 90 cm long magnet and appear in Table 2.

FUTURE STUDIES ON THE DESIGN

To minimize even more the B-field in the circulating beam region additional calculations are planned on the design of this induction septum. In particular we are planning to modify the geometry of the connection of the circulating beam pipe with that of the injection beam pipe to shield even more the circulating beam region from the stray field of the magnet. Fig. 9 shows the connection of the circulating and injection beam pipes which will reduce even more the stray field in the circulating beam region. The shape of the fall

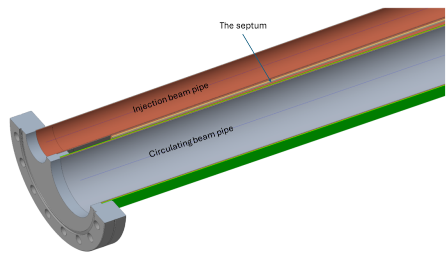

Figure 9: The join pipes of the circulating and injection beams.

off of the sinusoidal voltage pulse is also very important and more studies will be done to optimize the fall off of the voltage pulse which will minimize even more the B-field in the circulating field region as compared to the B-filed in the injection field region.

CONCLUSION

Electromagnetic field calculations were performed on an Induction type of septum magnet using the OPERA computer code. The magnetic fields harmonics in the both, the circulating field region and and the injected field region were calculated. The ohmic losses in the conductive parts of the magnet during the excitation of the magnet were also calculated. Based on the results of the Calculations the magnet is considered good to be employed in the EIC. Additional improvements, on the magnet to reduced the B-field in the circulating beam regions are under way.

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