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HIGH-FIELD DESIGN CONCEPT FOR SECOND INTERACTION REGION OF THE ELECTRON-ION COLLIDER*

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Abstract

Efficient realization of the scientific potential of the Electron Ion Collider (EIC) calls for addition of a future second Interaction Region (2nd IR) and a detector in the RHIC IR8 region after the EIC project completion. The second IR and detector are needed to independently cross-check the results of the first detector, and to provide measurements with complementary acceptance. The available space in the existing RHIC IR8 and maximum fields achievable with NbTi superconducting magnet technology impose constraints on the 2nd IR performance. Since commissioning of the 2nd IR is envisioned in a few years after the first IR, such a long time frame allows for more R&D on the Nb_3Sn magnet technology. Thus, it could provide a potential alternative technology choice for the 2nd IR magnets. Presently, we are exploring its potential benefits for the 2nd IR performance, such as improvement of the luminosity and acceptance, and are also assessing the technical risks associated with use of Nb_3Sn magnets. In this paper, we present the current progress of this work.

INTRODUCTION

The start of EIC operation is planned with the single main IR located at IP6. A secondary IR is being considered as a possible later upgrade of the EIC. If warranted, it is expected to be commissioned a few years after the primary IR. This additional time frame gives the second IR an opportunity to consider a new, more advanced magnet technology such as Nb_3Sn. It can provide significantly higher fields to control the beam. This paper explores potential performance improvements that can be gained using Nb_3Sn magnets in the forward section of the second IR. Its main elements are four final focusing quadrupoles and two spectrometer dipoles. Figure 1 shows the layout of the EIC collider rings and the placement of the two IRs. The IRs are denoted according to their locations in the RHIC tunnel with the primary IR named IR6 and the second IR named IR8.

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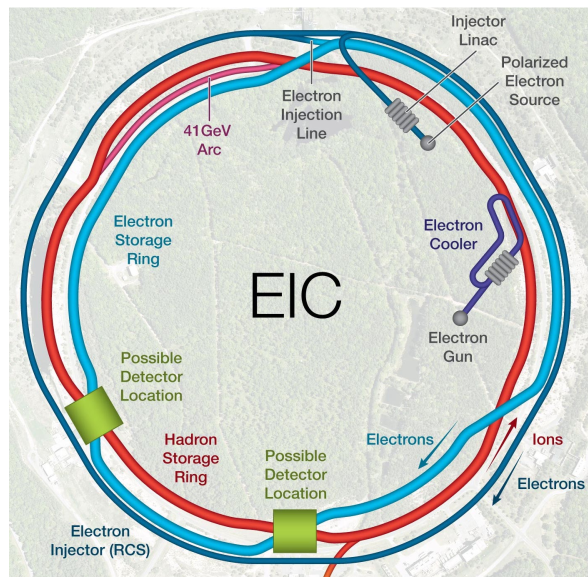

Figure 1: Layout of the EIC complex indicating the hadron storage ring (HSR), electron storage ring (ESR) and rapid cycling synchrotron (RCS). The primary IR is located at the 6 o'clock position while the second IR is located in the 8 o'clock position.

IR8 Design

The second IR is designed to provide complementary measurements to the primary IR by covering additional parameter space of the scattered particles. It has a secondary focal point in the forward ion beam line where space is reserved for placement of Roman pots. They can detect scattered charged particles with low transverse momentum ($p_T \rightarrow 0$) and longitudinal momentum close to that of the beam ($x_L \rightarrow 1$) [1,2]. To achieve this, while maintaining the necessary clearance for detection of high p_T charged particles, the magnet apertures have to be sufficiently large but, at the same time, provide high field gradients required for beam focusing. Compared to conventional NbTi magnets, Nb_3Sn magnets can be operated at about 2.7 times higher field in their coils. This significant increase of the maximum available field can be used to design larger-aperture magnets giving a higher acceptance coverage, increase the magnet

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gradients making them more compact and thus enhancing the luminosity, or provide a combination of the two.

IR LAYOUT

For the purpose of this paper, only the forward IR section is considered for implementation using Nb_3Sn magnets. The magnets in this section require large apertures and high field gradients to provide an optimal second focus configuration and wide acceptances for both charged and neutral scattered particles. With Nb_3Sn magnet design, two FFQs are sufficient to replicate the functions of four NbTi FFQs. We also consider an alternative Nb_3Sn design with three FFQs so that it can be better optimized for lower energies. In the latter design, at higher energies, the three magnets are operated as a doublet while, at lower energies, they work a triplet to better accommodate the beam envelope and provide a better acceptance.

OPTIMIZATION

Figure 2 shows the current layout using NbTi magnets. The beam parameters are taken from the EIC CDR [3] for the high acceptance case of 275 GeV protons and 10 GeV electrons. The field gradients, apertures and magnet positions (transverse shift along the radial x axis and rotation about the vertical y axis) have been simultaneously optimized to provide the necessary second focus configuration, wide clearance for acceptance of both neutral and charged scattered particles and a beam envelope clearance of 10σ. Acceptances are shown for $\pm$5mrad cones of both neutral and charged particles. One can observe the interference of the particle cones with the FFQ magnet apertures. These results were obtained using PTC tracking in MAD-X [4] and then confirmed using Geant4 tracking. For Nb_3Sn, maximum field at the aperture is set to be less than 9.2 T to leave an adequate operational margin of 20% and also taking into account a 5% field reduction at the aperture edge compared to the coil.

Luminosity

Luminosity of an electron-proton collider is given by,

$$L = H.f_b.\frac{N_p N_e}{4\pi\sqrt{\epsilon_x\beta_x^*}\sqrt{\epsilon_x\beta_x^*}}, \tag{1}$$

where H is a factor determined by the hourglass effect, f_b is the bunch frequency, $N_{p,e}$ is the corresponding number of particles per electron or ion bunch, $\epsilon_{x,y}$ is the beam emittance and $\beta_{x,y}^*$ are the beta functions at the IP.

Considering only the forward FFQs, one can lower β^* by a factor of 10 which results in a substantial luminosity increase. However, when considering the entire IR, there are several factors that limits this gain. Some of them are

- Aperture limits of the upstream FFQs which still use NbTi technology.
- Hourglass effect that may limit the benefit of lowering β^*.

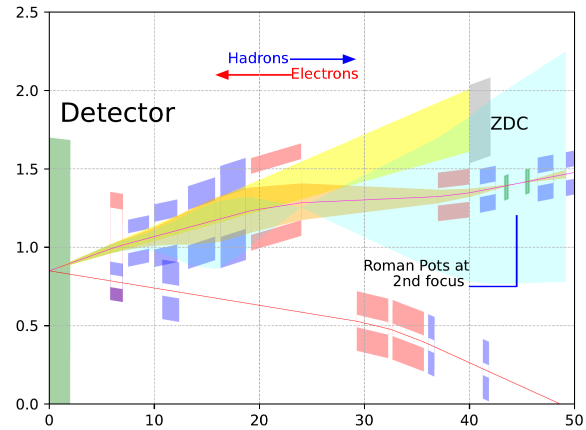

Figure 2: Forward IR layout with NbTi magnets. The green box represents the central detector, the quadrupoles are blue, the dipoles are red, and the zero degree calorimeter (ZDC) is grey. The acceptances to forward scattering particles are indicated by the shaded areas where yellow shows neutral particles within a $\pm$5 mrad cone, orange is for protons with $x_L = 1(\Delta p/p = 0)$ and $p_T \leq 1.37$ GeV and blue is for protons at $x_L = 0.5(\Delta p/p = 0.5)$ and $p_T \leq 0.69$ GeV.

- Increased chromatic contribution of the FFQs with smaller β^*, which the existing RHIC sextupole configuration may not be able to handle.

Acceptance

Figure 3 shows the acceptances for the two Nb_3Sn designs. For this study, the beam parameters were kept to the CDR values where $\beta_{x/y}^* = 80/7.2$ cm and RMS momentum spread $(\Delta p/p)$ is 6.8×10^{-4} These two layouts have been optimized to provide wide acceptances while maintaining the optimal secondary focus. In this configuration, the proton and neutron acceptances are shown to be $\pm$6 mrad. While there is an improvement of the acceptance coverage, it is important to note that these results must be validated through Geant4 simulations as they were obtained using only PTC tracking in MAD-X.

Table 1: Select parameters of the forward IR magnets for Nb_3Sn case 1. The field column lists the gradients for the quadrupoles (the names starting with Q) and B_y for the dipoles (the names starting with B).

Name	Field T/m, T	Length m	Aperture cm
QFF1A	-106.4	2.6	8.66
QFF2A	71.9	3.2	12.81
BXDS1	8.56	3	15
BXDS2	-3.67	1	5.5

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Table 2: Select parameters of the forward IR magnets for Nb_3Sn case 2.

Name	Field T/m, T	Length m	Aperture cm
QFF1A	-155	1.2	5.95
QFF2A	-65.6	1.2	9.5
QFF2B	71.6	3	12.88
BXDS1	8.6	3	14
BXDS2	-3.7	1	5.5

Comparison

A comparison of the three IR designs is given in Table 3. The maximum detectable x_L shows a slight increase for both Nb_3Sn designs compared to NbTi. It is to be compared with the fundamental limitation on the maximum detectable x_L of 0.9932 coming from the RMS momentum spread of the beam. While the horizontal chromaticity is lower for the Nb_3Sn, the vertical chromaticity is higher. For the complete EIC HSR lattice, the horizontal chromaticity is higher than the vertical. Thus, some exchange between the two may be beneficial for chromatic compensation in the EIC hadron ring. Tables 1 & 2 shows select magnet parameters for the two designs. In these preliminary designs, 0.5 m space is reserved for magnet ends/leads. As the designs mature, further engineering constraints such as support structures and cryogenics will be taken in to consideration.

Table 3: Comparison of selected optics and beam parameters of the IR designs. Subscript 2 indicates the parameters at the secondary focus.

Parameter	NbTi	Nb_3Sn option 1	Nb_3Sn option 2	Units
Energy	275	275	275	GeV
$\beta^*_{x/y}$	80/7.2	80/7.2	80/7.2	cm
$\beta_{max,x/y}$	1050/973	588/867	594/890	m
$\beta_{2,x}$	58	47	50	cm
$D_{2,x}$	0.39	0.42	0.41	m
x_L	0.99289	0.99296	0.99296	cm
dQ_x	-10.69	-7.31	-7.45	-
dQ_y	-12.89	-14.95	-13.96	-

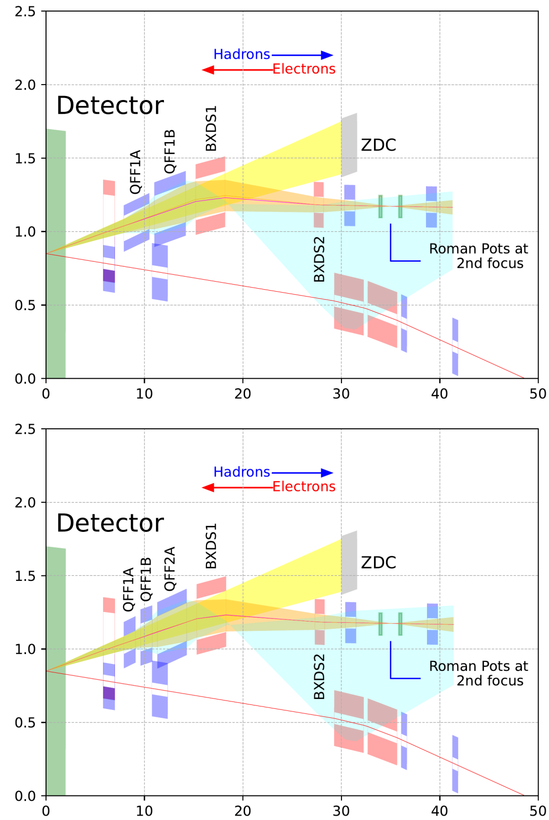

Figure 3: Forward IR layout for the two Nb_3Sn designs. Option 1 with two FFQs is show on the top and Option 2 with three FFQs is shown in bottom. The acceptances are shown at ±6 mrad for both neutrals and protons.

SUMMARY

High fields that can be provided by Nb_3Sn magnets allow for making the apertures of the magnets larger while keeping their gradients high. As shown in this paper, this potentially leads to an acceptance and/or luminosity increase. Additionally, with the space for matching being at a premium due to the geometric constraints imposed by the existing RHIC IP8 hall, any space gained by reducing the length of the forward IR section is highly beneficial. However, there are still significant engineering challenges and technical risks associated with the design and construction of Nb_3Sn magnets. In addition, given the tight spacing of the hadron and electron quads, their high fields may result in a significant cross-talk between the magnets. This paper presents a preliminary study of the benefits of using Nb_3Sn to further improve the physics capabilities of the second IR in the EIC. Taking advantage of these benefits requires further magnet R&D that could retire some of the risks associated with Nb_3Sn magnets. The envisioned schedule for construction of the 2nd IR provides one with an opportunity for timely completion of such R&D.

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