Preliminary Design of the Interaction Region Beam Transport Systems for JLEIC

M. Wiseman, C. Hutton, F. Lin, V. Morozov, R. Rajput-Ghoshal

***Abstract*— The Jefferson Lab Electron Ion Collider (JLEIC) is a proposed new machine for nuclear physics research. As proposed, it will deliver between 15 and 65 GeV center of mass energy collision between electrons and nuclei. It uses the existing CEBAF accelerator as a full energy injector to deliver 3 to 10 GeV electrons into a new electron collider ring. An all new ion accelerator and collider complex will deliver up to 100 GeV protons, or 40 GeV/nucleon ions. The machine will have luminosity goals of above 10^{33} cm^{-2} sec^{-1} in the whole energy range with a maximum of a few 10^{34} cm^{-2} sec^{-1}. The two collider rings use a unique figure eight layout to deliver a high degree of polarization in both beams. The machine will include room for two interaction regions with only one initially installed. The crossing angle in the primary interaction region will be 50 mrad. The whole detector region including forward detection covers about 80 meters of the JLEIC complex. This paper will describe the requirements and preliminary designs for both the ion and electron beam transport systems in the most complex 32 m region around the interaction point. The beam transport system includes three separate cryostats housing over thirty-seven superconducting magnets operating at 4.5K. The design of these cryostats must be closely integrated with the elements of the JLEIC detector.**

***Index Terms*—JLEIC, Interaction Region, Superconducting Magnets, Cryostat Design**

I. INTRODUCTION

The Jefferson Lab Electron-Ion Collider (JLEIC) is a proposed new facility for nuclear physics research that as envisioned will provide a peak luminosity over 10^{34} cm^{-2}s^{-1} with a collider center-of mass energy range ~15 to ~65 GeV, upgradable to ~140 GeV (Figure 1, Table 1). It uses the existing CEBAF accelerator to inject full energy 3 to 10 GeV electrons into an all new electron storage ring. The collider will also require an all new ion complex that will initially deliver up to 100 GeV protons or 40 Gev/nucleon ions. The figure eight design of the storage rings are approximately 2.3 km long and allow both beams to maintain a high degree of polarization. Room for two interaction regions will be include in the layout with only one initially installed. The two beams will have a crossing angle of 50 mrad at the interaction point. The whole machine design and its potential physics use is better described elsewhere [1, 2]. The detector area of the complex covers some 80 m of the machine and this paper will focus on the 32 m of the beam transport systems immediately surrounding the Interaction Point (IP). All of the designs discussed in this paper are still very much in the preliminary design phase with many details still to be determined and subject to change.

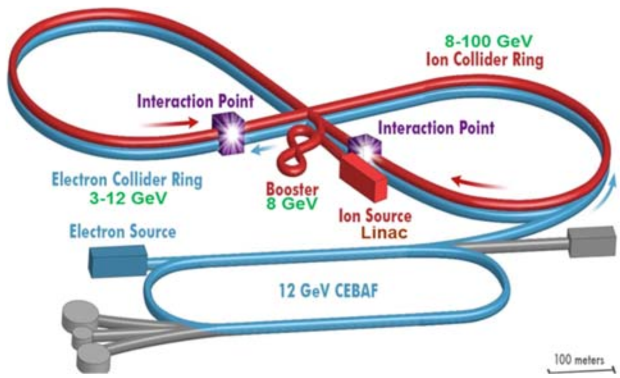

Fig. 1. The JLEIC machine configuration showing two interaction points.

TABLE I
JLEIC e-p DESIGN PARAMETERS

CM energy	[GeV]	21.9		44.7		63.3	
		p	e	p	e	p	e
Beam energy	[GeV]	40	3	100	5	100	10
Collision frequency	[MHz]	476		476		476	
Particles per bunch	[10^{10}]	0.98	3.7	0.98	3.7	0.98	0.93
Beam current	[A]	0.75	2.8	0.75	2.8	0.75	0.71
Polarization	[%]	>80	~80	>80	>80	>80	>80
RMS bunch length	[cm]	1	1	1	1	1	1
Normalized emittance	[µm-rad]	0.3 / 0.3	24 / 24	0.5 / 0.1	54 / 11	0.9 / 0.18	432 / 86
β^*, hori. / vert.	[cm]	8 / 8	13.5 / 13.5	6 / 1.2	5.1 / 1	10.5 / 2.1	4 / 0.8
Vertical beam-beam	[-]	0.015	0.092	0.015	0.068	0.002	0.009
Laslett tune-shift	[-]	0.06	Small	0.055	Small	0.03	Small
Detector space, up / dn	[m]	3.6 / 7	3.2 / 2	3.6 / 7	3.2 / 2	3.6 / 7	3.2 / 2
Hour glass		1		0.87		0.86	
Peak Luminosity/IP	[10^{33} cm^{-2} s^{-1}]	2.5		21.4		1.7	

II. MAGNET REQUIREMENTS

In The 32 m section of the beam transport systems around the interaction point is shown in Figure 2. Both the entrant and exit lines of both the electron and ion beam lines consist of three final focusing quadrupoles and a solenoid magnet to counteract the effects of the detector solenoid. The requirements for the magnets are given in Table 2. All of the magnets will operate in a 4.5 to 4.7 K liquid helium bath. The electron quadrupoles will be conventional NbTi wound cosine theta magnets. The ion

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beamline quadrupoles require higher fields and are currently planned as Nb3Sn coils. All other magnets, including the solenoids will be wound with NbTi conductor. Each of the quadrupoles in both lines will also need a corresponding skew quadrupole. In the electron line and ion beam entrant line the skew quadrupoles will be nested around the primary quadrupoles. In the ion exit line there will be four separate skew quadrupoles because the main quadrupole fields are too high to allow nesting.

TABLE II
DESIGN SPECIFICATIONS AND PRELIMINARY DESIGN INFORMATION

Magnet Location	Magnet Type	Magnet Strength	Leff (m)	R_{c_in} (mm)	R_{inner} (mm)	W_{C_rad} (mm)	R_{outer} (mm)	B_{peak} (T) from VF
Interaction Region (IR) Ion Quadrupole	QFFB3_US	-116	1	40	45	18	63	8.93
	QFFUS03S ***	-0.99	1	40	67	2	69	0.22
	QFFB2_US *	149	1.5	40	45	30	75	8
	QFFUS02S ***	0.35	1.5	40	77	2	79	0.2
	QFFB1_US	-141	1.2	30	34.5	18	52.5	7.9
	QFFUS01S ***	-1.2	1.2	30	57	2	59	0.24
	QFFDS01S	8.6	0.1	85	90.8	10	100.8	1.6
	QFFB1**	-88	1.2	85	90.8	43.6	134.4	11.5
	QFFDS02S ***	-3.7	0.1	126	133.4	10	143.4	1.8
	QFFB2 **	51	2.4	126	133.4	45	178.4	10.3
	QFFDS22S ***	-5.5	0.1	126	133.4	10	143.4	1.8
	QFFB3	-35	1.2	148	155	38	193	8.5
	QFFDS03S ***	4	0.1	148	155	10	165	1.84
Interaction Region Electron Quadrupole	Common Quad design, combined with Skew Quads	Quad ** 45 (varies from 13.63 to 44.78)	0.6	45	49.5	10	59.5	3.51
		Skew-Quad *** 9.5 (varies from 1.97 to 9.3)	0.6	45	61.5	3.25	64.8	1.25
Electron IR Solenoid	AASOLEUS	6	1.2	40	60	20	80	6
	AASOLEDS	6	1.2	40	60	20	80	6
ION IR Solenoid	AASOLEUS	6	1.2	40	60	20	80	6
	AASOLEDS	3.6	2	170	190	12	202	3.614
Corrector	IPUSCORR1	-0.14 By -0.95 Bx	0.2		34.5/ 50	9.0/ 3.0	43.5/ 53	#
	IPUSCORR2	0.15 By 1.55 Bx	0.2					

R_{c_in} = Beam tube inner radius; R_{inner} = Coil inner radius, W_{C_rad} = Coil width in radial direction; R_{outer} = Coil outer radius; B_{peak} = Peak field

*First Order Electromagnetic Optimization done and optimized design presented in rest of the paper

**First Order Electromagnetic Optimization done and optimized design presented in a separate section, magnet interaction is done without optimized design

***The peak field values are just for the skew quad alone, this value is higher when operated with the main quad

3.06 in X 1.36 in Y with both X&Y ON

In the ion beam line there will also be four sets of corrector dipoles. Two sets are shown in the figure in the ion entrant beam line. The exact location and specifications for the ion down beam correctors is still being discussed. Higher order multipole correctors will also be needed for the ion beam quadrupoles but are not required for the electron beam. The requirements for the multipole correctors are still being developed. Preliminary designs for all of these magnets are described in another paper being presented at this conference [3]. Preliminary design information on the magnets are listed in Table 2.

Also shown in Figure 2 are three magnets required for the physics detector [2]. Surrounding the interaction point there is a three Tesla, 3 m diameter solenoid. The solenoid is 4 m long with the interaction point [IP] offset 0.4 m toward the ion entrant side. Detector dipole #2 is 4.7 Tesla, 4.6 m long with a 0.8 m diameter warm bore. The requirements for Detector Dipole #1 are still being studied. This magnet needs to meet both the detector requirements and provide the ion beam corrector coils. For this paper that magnet is shown as a 1.3 Tesla, 1.5 m long, 1.0 m diameter warm bore magnet which corresponds to an earlier design concept.

Because of the close proximity of all of these magnets shielding of the fields from adjacent magnets are also of primary concern. The design of the shielding is underway and will be a combination of passive metal shields and active shielding coils [3]. The total number of magnets in the area will depend on the final multipole specification and the number of active shield coils.

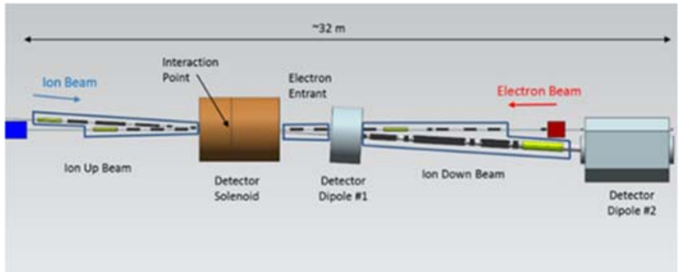

Fig. 2. The interaction region showing the detector magnets and the ion and electron beam transport area.

III. CRYOSTAT OVERVIEW

The transport magnets in the IR region will be divided into three cryostats as shown in Figure 2. They are divided by the interaction region by the detector solenoid and the two detector dipole magnets in the ion down beam line. The final design of the transport magnet cryostats will have to be closely coordinated with the detector elements in the area.

All of the magnets for both the ion and electron beam lines are based on cold bore designs. This is primarily to lower the field requirements on the ion beam quadrupoles. The magnets in the electron beam line could be either warm or cold bore. The cold bore designs in the electron line do reduce the radial space needed which is a plus as you get closer to the IP.

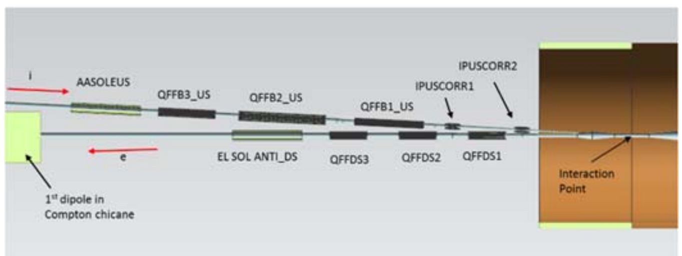

Fig. 3. Ion up beam area showing the principal magnets.

The beam line vacuum in the IP chamber and through the two detector dipoles will be warm so that detectors can be put in close proximity to the vacuum chambers. The beam line vacuum in this area will not be segmented so that it will all have to be treated as cold bore sections. All of the vacuum pumping will be placed in the warm section at the ends of the cryostats. At the end of each cryostat, room has been reserved for a warm to cold transition to minimize the heat leak. There will also need to be room for an RF shielded bellows to facilitate installation and allow for the thermal contraction of the beam line. The vacuum beamlines and bellows will also have to be studied to insure there are no trapped modes that could lead to localized power being dissipated in the area.

IV. Ion up Beam Area with Magnets

The ion up beam cryostat will be approximately 8.7 meters long in the ion beam line, 5.9 m of the electron beam line (Figure 3). There are three quadrupoles and one solenoid magnet in each of the beamlines. A skew quad is also added around each of the main quadrupoles. There are two horizontal/vertical corrector pairs in the ion beam line just up beam of the interaction point. That means there will be a minimum of eighteen magnets in this cryostat plus multipole correctors and shielding coils. As a point of reference, the Super KEKB IR cryostats have 25 and 30 superconducting magnets for the QCSL and QCSR respectively [4]. A single vacuum cryostat is required as there is no room to provide a warm to cold transition between the magnets. As such, there will be a single warm to cold transition at the inlet and exit of each beam line. Near the IP the transitions will extend into the detector solenoid. The RF bellows assembly nearest the IP will likely have to be a single assembly that includes both beam lines. The vacuum vessel consist of two cylindrical sections plus a tapered section near the interaction region to maximize the space for detectors around the cryostat (Figure 4).

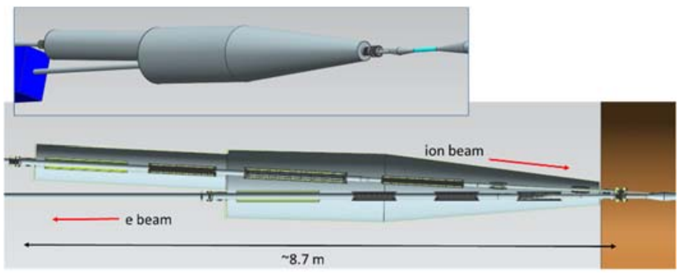

Fig.4. A cross sectional and angle view of the ion up beam cryostat.

The two corrector magnets and three to four of the quad magnets nearest the IP will be housed in a single helium vessel capturing both beam lines. For the rest of the magnets there may be multiple helium vessels inside the cryostat if that will ease the assembly of the overall structure. The magnet support structure design, collar, yokes, etc. have just been started. Initial estimates of the amount of iron yokes and or shielding coils have been made and used to set the overall radial space around each coil inside the helium vessels. Space for the insulating vacuum and thermal shield have also been included to set the overall geometry of the vacuum vessel.

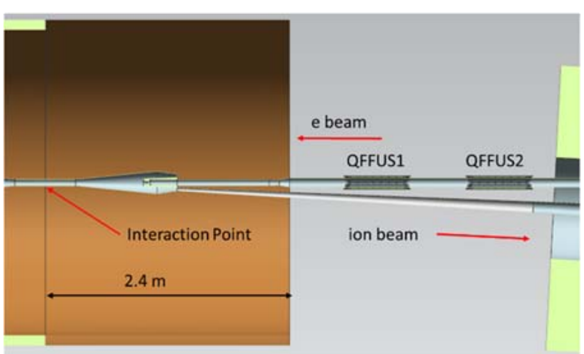

Fig.5. Ion up beam cryostat magnets on the electron beam line. A small taper may be included to localize the synchrotron radiation for cooling.

The support structure will have to accommodate the cool down contraction and resist the magnet-to-magnet interaction in this area. The whole cryostat will also have to be supported against the fields from the detector solenoid. Both the cryostat and cold mass will be supported in at least three locations with a minimum of twelve typical support rods on the cold mass. A thermal shield will be included inside of the vacuum vessel and surround the entire cold mass. The cryogenic feed and magnet lead can will be positioned on one side of the cryostat away from the detector elements.

The worst-case estimated synchrotron radiation that will enter this cryostat from the up beam quadrupoles in the electron beam line is about 1 to 2 watts, which is an acceptable heat load along the beamline [5]. This synchrotron radiation can be further reduced if needed by adding a down beam mask just up beam of the cryostat. The effect of the synchrotron radiation on the beam vacuum is currently being studied.

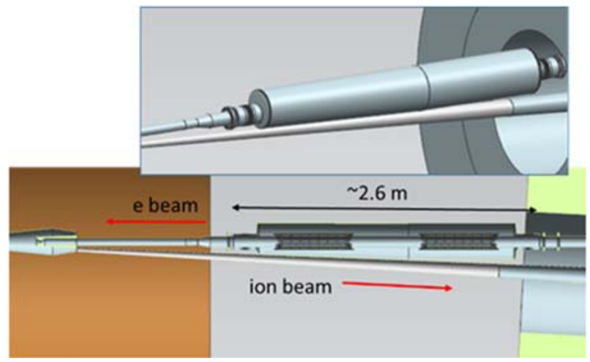

Fig.6. A cross sectional and angle view of the electron entrant cryostat.

V. Electron Entrant cryostat

Between the detector solenoid and the first detector dipole magnet will be a small cryostat, approximately 2.6 m long, containing four superconducting magnets in the electron beam line (Figure 5). The magnets include two quadrupoles with corresponding skew quadrupoles around them. The cryostat will be tapered near the IP to avoid interference with the ion vacuum beam line and to allow for the maximum acceptance angle for the detector elements (Figure 6). To avoid interference with the ion beam vacuum line, the vacuum vessel and thermal shield will centered eccentrically from the cold mass. The warm to cold transition will extend into the detector dipole on one end and stop just short of the detector solenoid on the other. In order to better shield the ion beam line from stray fields, the vacuum vessel may be made of normal iron and the ion vacuum line may be shielded as well with iron or mu metal. The cryostat and magnets will have to be supported against the fringe fields from both the detector solenoid and dipole. Eight typical magnet support rods will be needed for the cold mass in two locations. The cryogenic feed can and leads will be routed to a location compatible with the detector design.

A preliminary look at the synchrotron radiation from the final focusing quadrupoles in the electron line has been completed. No direct synchrotron radiation will impinge on the cold bore of the magnet beamline. Less than a watt will be distributed along the warm beam line from the cryostat to the detector vacuum chamber. A small taper is shown in the beam line that may be used to concentrate this power into a single location. Backscattering of photons remains to be studied and some small amount of forward scattering may be possible that will contribute to the cryogenic heat load.

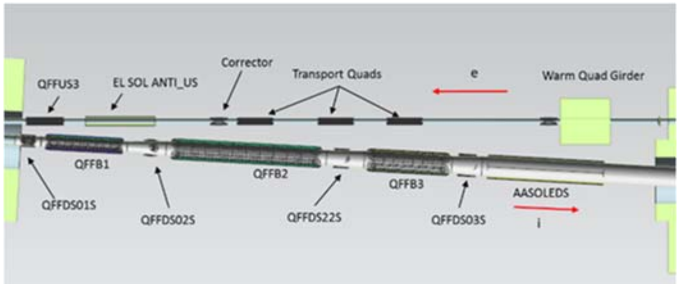

Fig.7. Ion down beam area showing the principal magnets.

VI. Ion down beam cryostat

The final cryostat for the beam transport will be located between the two detector dipoles. The ion beam line magnets are all large bore with little room between the coils and will be installed as one unit, ~10.4 meters long. This includes three quads, four skew quads, and a solenoid magnet. The electron beam line requires a single superconducting quad with skew quad around it and a solenoid. Also in the electron line between the dipoles are four additional quadrupoles and two corrector pairs. These magnets could be normal magnets, but due to the proximity of the ion line, three of them will be made superconducting as there is not radial room for the warm iron that would be required in the magnets. These three quadrupoles will be the same design as the six final focusing quadrupoles in the electron line. One of the correctors may also be made superconducting or moved just up beam of the cryostat. There will also be at least one button style beam position monitor inside the cryostat.

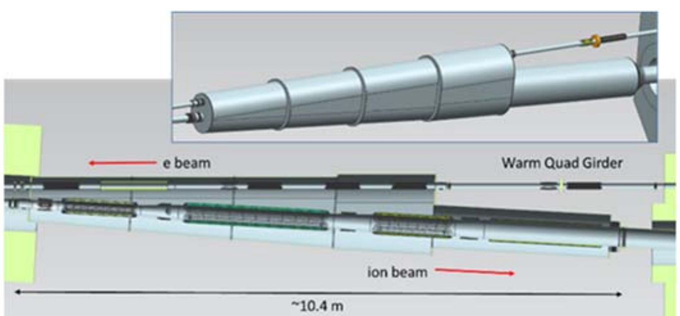

Fig.8. Section and angle view of the ion down beam cryostat.

For the preliminary design, the electron and ion beam lines will be separately supported inside a single vacuum cryostat. The cold electron beam line will be ~7.6 m in length. The cryostat and warm to cold transitions from both lines will extend into the first detector dipole. This means that the final design and assembly sequence of this area most be closely coordinated with the detector design. Due to the length of the two separate lines, it is anticipated that a minimum of twelve typical supports will be needed for each line, twenty-four total. As the designs progress it may prove advantageous to combine the two cold masses for at least part of the line. A thermal shield will surround both cold masses. The total number of magnets is a least fourteen magnets plus multipole correctors and shielding coils as required. The initial design of the ion down beam cryostat is purposely different from the ion up beam one. This will allow us to explore the two different designs before seeing which one will be most advantageous to support the magnets. As shown it is constructed from a split pipe with flat sections connecting the two halves. The flat sections will require ribbed reinforcing for the vacuum load. Around the final magnets in the ion line the vacuum vessel is a simple cylinder.

VII. Integration with the detector dipole

Much of the early work on the ion down beam area focused on developing a corrector design that could be located independently of the SB1 detector dipole. It now looks like this is not practical and work is currently underway to define a combined function magnet in this area. This magnet will need to provide the dipole function for the detector needs and the two corrector dipole pairs needed for the ion beam transport. Physics detectors are also desired between this magnet bore and the vacuum beam line. The adjacent electron beam line will also require shielding from this combined function magnet. The resulting design will then likely require changes to the local electron and ion beam transport system described in this paper.

VIII. Status and plans

During the next year we will continue to add detail to the design. We will develop the required magnet to magnet shielding and work on the cold support structure for the magnets. This will then turn into helium vessel designs that will allow us to set the vacuum vessel dimensions so that physics detector designs can be further refined. Work should start on the helium vessel supports inside the cryostats along with alignment plans. We will continue to work on shielded bellows concepts that can be used for beam impedance studies to look for higher order mode losses from the beam. If this looks promising we will then look to move and possibly add shielded bellows inside the cryostats to ease assembly and alignment. We also plan to start working on shielded vacuum pump designs that can be used in the area that would be compatible with the physics detectors. A separate group is studying the vacuum requirements needed to limit the impact from background noise on the detectors.

Acknowledgment

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