JLEIC Summary Requirements

Abstract

This document summarizes the highest level design of Jefferson Lab's electron-ion collider, JLEIC. The initial suite of numbers and text is from the Jan. 2015 design report[Abeyratne2015].

Overview of the Baseline

The JLEIC is designed to meet the requirements of the science program outlined in the EIC white paper [Abeyratne2012]. The JLEIC is designed to be a traditional ring-ring collider. The central part of this facility is a set of figure-8 collider rings as shown in Figure 1.1. The electron collider ring is made of normal conducting magnets reconditioned from the decommissioned PEP-II *e+e-* collider at SLAC, and will store an electron beam of 3 to 10 GeV. The ring also reuses the PEP-II vacuum chambers and RF systems. The stored electron beam current is up to 3 A, scaled down when the beam energy exceeds 7 GeV in order to satisfy the operational limit of 10 kW/m synchrotron radiation power for the PEP-II vacuum chambers. The ion collider ring is made of new super-ferric magnets, a cost-effective type of superconducting magnet with modest field strength (up to 3 T) and will store a beam with energy of 20 to 100 GeV for protons or up to 40 GeV per nucleon for heavy ions. The stored ion beam current is up to 0.5 A. The two collider rings are stacked vertically and housed in the same underground tunnel as shown in the left drawing of Figure 1.1. They have nearly identical circumferences of approximately 2.2 km, and fit the Jefferson Lab site as shown in Figure 1.2.

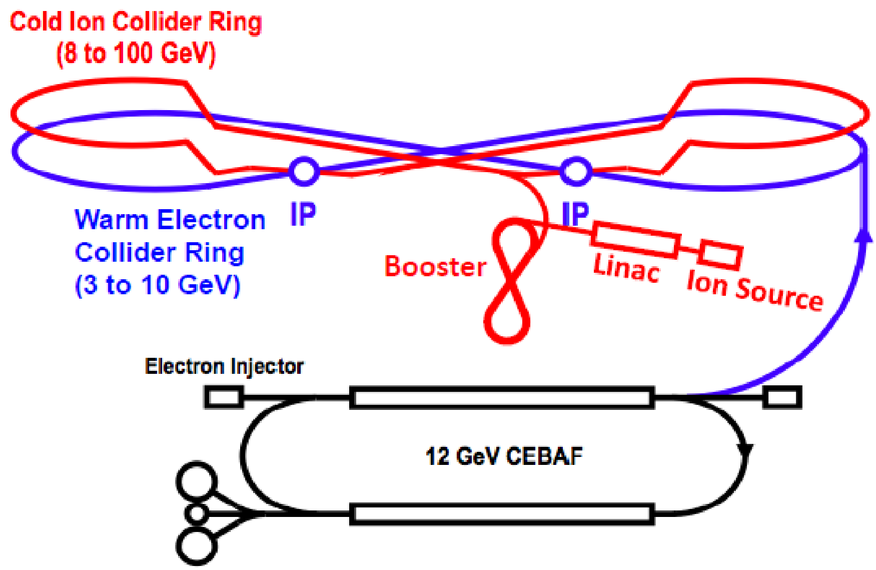

Figure 1.1: A schematic layout of MEIC. The ion collider ring is stacked vertically above the electron collider ring, and takes a vertical excursion to the plane of the electron ring for a horizontal crossing

The unique figure-8 shape of the JLEIC collider rings has been chosen to optimally preserve the ion polarization during acceleration and store [Derbenev1996]. The crossing angle is approximately 82°, partitioning a collider ring into two arcs and two long straights. The electron and ion collider rings intersect at two symmetric points, one in each of the two long straights as shown in Figure 1.1; thus two detectors can be accommodated. The ion beam executes a vertical excursion to the plane of the electron ring to realize a horizontal crossing for electron-ion collisions. The two long straights also support other utility elements of the collider rings, among them the injection/ejection systems, the RF systems, the electron cooler, and the beam polarimeters.

Figure 1.2: JLEIC on the Jefferson Lab site map

The JLEIC collider rings are supported by two injector complexes respectively. On the electron side, the CEBAF recirculating SRF linac will serve as a full-energy injector into the electron collider ring. The polarized linac beam will be extracted from CEBAF at the location near Experimental Hall D as illustrated in Figure 1.1. There is no need of further upgrade for beam energy, current, or polarization beyond the recently successfully commissioned 12 GeV upgrade. In the present conceptual design, the ion injector complex consists of sources for polarized light ions and non-polarized light to heavy ions, a cold ion linac, and one figure-8 shaped booster synchrotron. The booster accepts and accumulates protons or ions from the linac, accelerates protons to 8 GeV kinetic energy or lead ions to 3.2 GeV kinetic energy per nucleon, then transfers them to the ion collider ring.

As a consequence of reusing the PEP-II warm RF cavities and RF stations for the MEIC electron collider, the bunch repetition rate of the JLEIC stored beams is 476 MHz, lower than the previous design value of 748.5 MHz. This choice does not affect the collider luminosity significantly. A conceptual scheme has been developed for injecting the electron bunches from the CEBAF SRF linac (which has a 1.497 GHz frequency) into the collider ring as discussed subsequently. All new SRF cavities and RF stations required for the ion collider ring will have a frequency of 952 MHz, thereby enabling cost effective future improvements in luminosity and energy.

As a critical part of the luminosity concept, JLEIC selects conventional electron cooling technology for reducing the ion beam emittance. It also adopts a multi-phased cooling scheme to achieve the required high cooling efficiency. The scheme utilizes two electron coolers. One is a DC cooler in the booster synchrotron, and the other is a bunched beam cooler based on an energy recovery linac (ERL) in the collider ring. The DC cooler assists in accumulating positive ions injected from the linac and cools the ions at 2 GeV to reduce their emittance to the design values. The primary purpose of the bunched beam ERL cooler is to suppress the intra-beam scattering (IBS) and to maintain the small emittance achieved in the initial cooling stage in the booster synchrotron. Section 9 will present the MEIC beam cooling scheme in more detail.

The design of the JLEIC interaction region is aimed at achieving high luminosity in an integrated full acceptance detector. The current JLEIC detector design requires a magnet-free space of 7 m for the ion beam on the downstream side, and after optimization, only 3.6 m on the upstream side. For the electron beam, the first final focusing elements are permanent magnets which, due to their small transverse sizes, are placed inside the main detector and very close to the interaction point. The JLEIC design adopts a finite crossing of colliding beams to avoid all parasitic collisions. Following the successful experience at KEK-B [KEKB1995], the JLEIC design also utilizes a local compensation scheme based on SRF crab cavities to restore head-on collisions thus recovering the loss of luminosity caused by the crossing angle. A relatively large crossing angle (the ions cross the electrons, which are aligned with the center of the detector, with a 50 mrad angle) also enhances the detection of reacting particles. The IR design uses a combined local and global compensation scheme to control the chromatic aberrations.

A unique design feature of JLEIC is a figure-8 shape of all ion rings. As pointed out above, the feature provides optimal preservation of high polarization of ion beams while accelerating and storing the polarized ion beam. The basic property is a complete cancellation of spin precession in the left and right arcs of the figure-8 ring; thus the net spin tune is zero. The spin tune can be further controlled by a weak field spin rotation device, leading to a stable spin polarization in the figure-8 ring. The figure-8 design also improves polarization of the electron beam and more importantly provides the only practical solution for accelerating and storing medium-energy polarized deuteron beams. The orientation of electron and ion beam polarization at the interaction points are achieved by spin rotators [Chevtsov2010,Kondratenko2014].

References

S. Abeyratne et al., "MEIC Design Summary", edited by G. A. Krafft, arXiv:1504.07961 (2015)

S. Abeyratne et al., "Science requirements and conceptual design for a polarized medium energy electron-ion collider at Jefferson lab", edited by Y. Zhang and J. Bisognano, arXiv:1209.0757 (2012).

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Expected Luminosity Performance

The JLEIC nominal parameters at three representative design points in the low, medium and high CM energy regions respectively are presented in Table 2.1. The luminosity is above 10^{33} cm^{-2}sec^{-1} in all these design points for the full-acceptance detector, and reaches 4.6×10^{33} cm^{-2}sec^{-1} at the medium CM design point of approximately 45 GeV. For the second detector, as an option, the interaction region design can be optimized for reaching a higher luminosity (approximately 60% increase) while still retaining a fairly large detector acceptance. But the detector space for this case must be reduced to 4.5 m so that the interaction point beta-function, β^*, may be decreased accordingly.

It is challenging to optimize the performance of JLEIC over both a broad range of beam energy and a wide array of ion species. In particular, the luminosity of JLEIC is affected strongly by various single bunch or multi-bunch collective beam effects. These effects limit either the bunch charges or currents of either beam, and may cause large beam emittance. Therefore, design optimization has been carried out individually in each energy region, taking into account the leading region specific performance limit. Figure 2.1 illustrates the general trends of the JLEIC luminosity.

Table 2.1: MEIC main design parameters for a full-acceptance detector.

CM energy	GeV	21.9 (low)		44.7 (medium)		63.3 (high)	
		p	*e*	*p*	*E*	*p*	*e*
Beam energy	GeV	30	4	100	5	100	10
Collision frequency	MHz	476		476		159	
Particles per bunch	10^{10}	0.66	3.9	0.66	3.9	2.0	2.8
Beam current	A	0.5	3	0.5	3	0.5	0.72
Polarization	%	>70	>70	>70	>70	>70	>70
Bunch length, RMS	cm	2.5	1.2	1.0	1.2	2.5	1.2
Norm. emittance, vert./horz.	µm	0.5/0.5	74/74	1/0.5	144/72	1.2/0.6	1152/576
Horizontal and vertical β^*	cm	3 (1.2)	5 (2)	2/4 (1.6/0.8)	2.6/1.3 (1.6/0.8)	5/2.5 (2/1)	2.4/1.2 (1.6/0.8)
Vert. beam-beam parameter		0.01	0.02	0.006 (0.004)	0.014 (0.021)	0.002 (0.001)	0.013 (0.021)
Laslett tune-shift		0.055	small	0.01	small	0.01	small
Detector space	m	7/3.6 (4.5/4.5)	3.2/3 (3/3)	7/3.6 (4.5/4.5)	3.2/3 (3/3)	7/3.6 (4.5/4.5)	3.2/3 (3/3)
Hour-glass (HG) reduction factor		0.89 (0.67)		0.89 (0.74)		0.73 (0.58)	
Lumi./IP, w/HG correction, 10^{33}	$cm^{-2}s^{1}$	1.9 (3.5)		4.6 (7.5)		1.0 (1.4)	

(Values for a high-luminosity detector with a 4.5 m ion detector space are given in parentheses.)

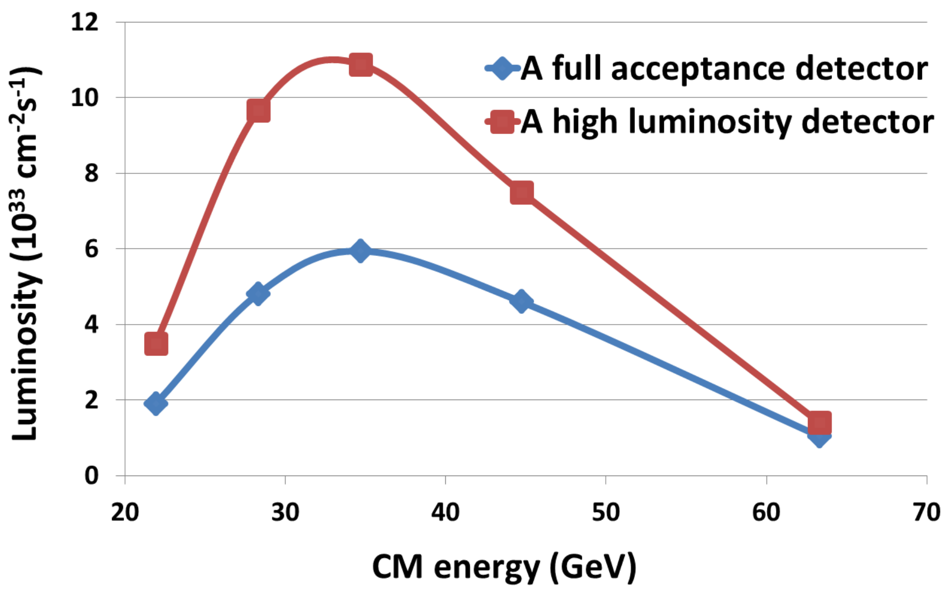

Figure 2.1: A luminosity plot of the MEIC *e-p* collision. The blue line is for a full acceptance detector, which is chosen as the primary one for MEIC. The red line is for an optional secondary detector optimized for achieving a higher luminosity.

At the low energy end, space charge of the low energy ion beam severely limits the bunch charge, particularly for short bunches. The design strategy is to allow a longer bunch length (2.5 cm) than at higher energy, thus accommodating the full bunch charge while remaining under the design limit for the Laslett space charge tune-shift limit of 0.06. However, because the bunch length is much larger than the β^*, there is a non-negligible (11%) loss of luminosity due to the hourglass effect. The resulting, luminosity for the low energy design point is shown in Table 2.1. We are considering advanced concepts such as the running-focusing scheme [Balakin1991] to recover the hour-glass effect induced luminosity loss. This topic will be the subject of a future R&D study.

At the high energies, synchrotron radiation of a high energy electron beam is the dominating effect. The electron beam current must be scaled down proportionally to the 4th power of the electron energy to reduce synchrotron radiation loading to acceptable levels. As an example, the allowable electron current is 0.72 A at 10 GeV. The design strategy is to choose a low bunch repetition rate and boost the bunch charge proportionately. For the design point of 100×10 GeV^2, the bunch frequency is reduced by a factor of three, leading to a factor of three increase of bunch charge. With this change, the proton bunch length must be increased to alleviate single bunch effects. Again, there is a significant luminosity loss due to the hour-glass effect; the computed luminosity includes these relevant effects. An additional concept applied is to mismatch the beam spot sizes at the collision point by taking advantage of very weak beam-beam interaction in this case. Since the electron emittance is very large, the electron beam spot size at collision is 70% larger than the proton beam spot size. In this regime the highly nonlinear beam-beam effect is a weak perturbation.

The medium-energy region of JLEIC is dominated by the strong-strong beam-beam effect and so the way to achieve optimized luminosity is a combination of a high bunch repetition rate, small beam emittance, and very small β^*. This energy region delivers the highest luminosity for the JLEIC. Presently, the design strategy is to relax the design values of proton or ion beam emittance because doing so does not degrade the luminosity significantly when the colliding electron and ion beam spot sizes are matched at the collision point. This design change also provides an opportunity for reducing the demands of beam cooling. This will have a great impact on the most technical R&D of MEIC. This topic will be further discussed in Section 11.

The JLEIC design parameters and luminosities for several representative *e-A* collisions are summarized in Table 2.2. They are derived based on the same design principles discussed above. In Table 2.3 the expected luminosity for $^{208}Pb^{82+}$ throughout the expected energy range possible as in Table 2.1 above.

Table 2.2: MEIC main design parameters for *e-A* collisions.

		Electron	Proton	Deuteron	Helium	Carbon	Calcium	Lead
		e	*P*	*d*	$^{3}He^{++}$	$^{12}C^{6+}$	$^{40}Ca^{20+}$	$^{208}Pb^{82+}$
Beam energy	GeV	5	100	50	66.7	50	50	39.4
Particles/bunch	10^{10}	3.9	0.66	0.66	0.33	0.11	0.033	0.008
Beam current	A	3	0.5	0.5	0.5	0.5	0.5	0.5
Polarization		> 70%	> 70%	> 70%	> 70%	-	-	-
Bunch length, RMS	cm	1.2	1	1	1	1	1	1
Norm. emit., horz./vert.	μm	144/72	1/0.5	0.5/0.25	0.7/0.35	0.5/0.25	0.5/0.25	0.5/0.25
β^*, hori. & vert.	cm	2. 6/1.3*1 (1.6/0.8)	4/2 (1.6/0.8)	4/2 (1.6/0.8)	4/2 (1.6/0.8)	4/2 (1.6/0.8)	4/2 (1.6/0.8)	5/2.5 (1.6/0.8)

Vert. beam-beam parameter		0.014[*2] (0.02)	0.006 (0.004)	0.006 (0.004)	0.006 (0.004)	0.006 (0.004)	0.006 (0.004)	0.005 (0.004)
Laslett tune-shift			0.01	0.041	0.022	0.041	0.041	0.041
Detector space, up & down stream	m	3.2 / 3 (3)	7 / 3.6 (4.5)					
Hour-glass (HG) reduction factor			0.89 (0.74)	0.89 (0.74)	0.89 (0.74)	0.89 (0.74)	0.89 (0.74)	0.89 (0.74)
Lumi./IP/**nuclei**, w/HG correction	10^{33} $cm^{-2}s^{-1}$		4.6 (7.5)	4.6 (9.2)	2.2 (3.7)	0.77 (1.37)	0.23 (0.38)	0.04 (0.08)
Lumi./IP/**nucleon**, w/HG correction,	10^{33} $cm^{-2}s^{-1}$		4.6 (7.5)	9.2 (15.1)	6.6 (11.1)	9.2 (15.1)	9.2 (15.1)	7.8 (17.3)

(Values for a high-luminosity detector with a 4.5 m ion detector space are given in parentheses.)

[*1] For a full acceptance detector, the horizontal and vertical electron β^* are 2.7 and 1.35 cm respectively for *e*-*d* collisions. For *e*-Pb collisions, the values are 4 and 2 cm for the electron beam.

[*2] For *e*-Pb collisions, the electron vertical beam-beam parameter is 0.014 for a full-acceptance detector and 0.021 for a high luminosity detector.

Table 3.3: JLEIC main design parameters for $^{208}Pb^{82+}$ in the full-acceptance detector.

CM energy	GeV	21.9 (low)		44.7 (medium)		63.3 (high)	
		$^{208}Pb^{82+}$	*e*	$^{208}Pb^{82+}$	*E*	$^{208}Pb^{82+}$	*e*
Beam energy	GeV						
Collision frequency	MHz	476		476		159	
Particles per bunch	10^{10}						
Beam current	A						
Polarization	%						
Bunch length, RMS	cm						
Norm. emittance, vert./horz.	µm						
Horizontal and vertical $\beta*$	cm						
Vert. beam-beam parameter							
Laslett tune-shift							
Detector space	m						
Hour-glass (HG) reduction factor							
Lumi./IP, w/HG correction, 10^{33}	$cm^{-2}s^{1}$						

(Values for a high-luminosity detector with a 4.5 m ion detector space are given in parentheses.)

To derive the sets of JLEIC parameters in Tables 3.1-3, limits were imposed on several key machine or beam parameters in order to reduce accelerator R&D challenges and to improve the robustness of the design. These limits are based largely on previous lepton and hadron collider experience, particularly, that of the components of the PEP-II electron ring that are being reused, and on the present state-of-the-art in accelerator technology:

- The stored beam currents are up to 0.5 A for protons or ions and 3 A for electrons.
- Electron synchrotron radiation power density should not exceed 10 kW/m.

- Maximum bending field of super-ferric magnets is 3 T.
- Maximum betatron function at a beam extension area near an IP is 2.5 km.
- The direct space-charge tune-shift of ion beams is limited to 0.06.
- The hadron beam-beam tune-shift is limited to 0.03 per interaction point.
- The electron beam-beam tune-shift is limited to 0.15 per interaction point.

Reference

V. Balakin, Travelling focus, LC-91, 1991.