MEIC DESIGN PROGRESS*

S. Ahmed, Ya. Derbenev, D. Douglas, R. Ent, A. Hutton, A. Kimber, G. Krafft, R. Li, F. Lin, V. Morozov, P. Nadel-Turonski, E. Nissen, F. Pilat, R. Rimmer, T. Satogata, C. Tennant, B. Terzić, H. Wang, S. Wang, B. Yunn, Y. Zhang[#]
Thomas Jefferson National Accelerator Facility (JLab), Newport News, VA 23606 USA
D. Barber, Deutsches Elektronen-Synchrotron (DESY), 22607 Hamburg, Germany
P. Chevtsov, Paul Scherrer Institut, Villigen, Switzerland
M. Sullivan, SLAC National Accelerator Laboratory, Menlo Park, CA 94305 USA
S. Manikonda, P. N. Ostroumov, Argonne National Laboratory, Argonne, IL 60439 USA
S. Abeyratne, B. Erdelyi, Northern Illinos University, DeKalb, IL 50115 USA
C. Hyde, Old Dominion University, Norfolk, VA 23529 USA
A. Kondratenko, M. Kondratenko, Sci. & Tech. Laboratory Zaryad, Novosibirsk, Russia
Yu. Filatov, Moscow Institute of Physics and Technology, Dolgoprydny, and Joint Institute for Nuclear Research, Dubna, Russia

Abstract

This paper reports the recent progress in the conceptual design of MEIC, a high luminosity polarized medium energy ring-ring electron-ion collider at JLab. The topics and achievements covered are the design of the ion large booster and the ERL circulator-ring based electron cooling facility, integration of designs of detector and interaction regions, optimization of chromatic corrections and dynamic aperture studies, and the scheme and simulations of lepton and light ion polarization in the figure-8 rings. A proposal of a test facility for the MEIC electron cooler is also discussed.

INTRODUCTION

An electron-ion collider (EIC) is a natural option for expansion of the precision measurement based nuclear science program at JLab. It opens new research frontiers with an order of magnitude increase of center of mass (CM) energy coverage over the recent successfully completed 6 GeV CEBAF fixed target program and the future 12 GeV CEBAF program after completion of the energy upgrade in 2015.

After over a decade of studies, the envisioned science program has driven this future EIC facility to a medium CM energy range. Currently, JLab takes a two-stage approach to EIC based on different CM energy coverage for a maximum science reach over the entire life of the proposed collider. During the last three years, the JLab design effort has been focused primarily on the first stage, MEIC, with CM energy up to 66 GeV, and as an accomplishment of this effort, a conceptual machine design has been completed [1].

The MEIC design concept is based on the existing CEBAF recirculating SRF linac for injection of a full energy electron beam into a new storage ring. To complete this facility, an ion injector and storage complex must be added. Figure 1 illustrates this ring-ring collider on the JLab site map. A recent comprehensive report summarizes the MEIC design studies [1] and an abridged version is available in [2] for highlights of the current machine design.

Since then, additional work has been done to complete additional technical details. Efforts have also been made in critical accelerator R&D to support the design concept. This paper provides a high level survey of this design and R&D progress.

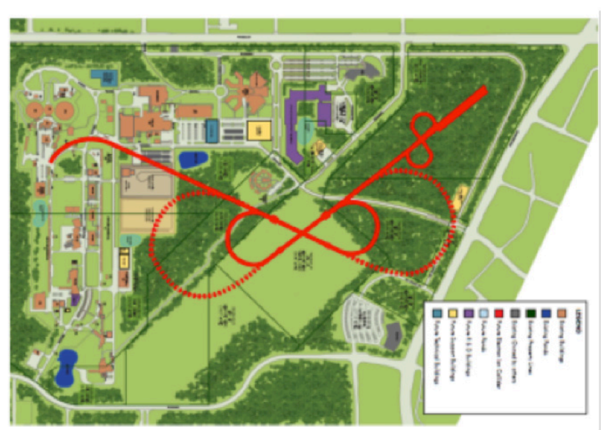

Figure 1: A schematic layout of MEIC (solid red line) and its future energy upgrade (dashed red line) on the JLab site. The ion injector (sources, SRF linac and a compact figure-8 pre-booster synchrotron) is in the upper right corner. The CEBAF linac is on the left with a transfer line to the MEIC electron storage ring.

ION LARGE BOOSTER

This booster synchrotron is a key element at the end of the ion injector chain. Its main function is to accept a 3 GeV proton beam or ion beam with the same magnetic rigidity, accelerate to 20 GeV energy for protons or a corresponding energy for ions, then transfer the beam to the collider ring. This booster is stacked vertically over

* Supported by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC05-06OR23177 and DE-AC02-06CH11357. The U.S. Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce this manuscript for U.S. Government purposes.
# yzhang@jlabl.org

the two collider rings, sharing a tunnel. The booster is meticulously designed [3] to match collider ring footprints including such special geometric features as electron spin rotators, ion Siberian snakes, and interaction regions.

The large booster has adopted a FODO lattice as its base optics in the interests of simplicity and attaining relatively high transition energy. The latter is an important design element to avoid transition crossing and associated intensity loss for any ion species. The optics is organized in large sections including four 120° quarter arcs, two long and two short straights, with optics matching between them and dispersion suppression at each end quarter arc. Spaces in the arcs are reserved for chromatic compensation sextupoles. The overall optics design is quite conservative.

A preliminary analysis gives a dipole magnet ramping rate of 1.5 T/s, thus taking 0.95 s to ramp the field to the peak value of 1.65 T. For acceleration gradient, two RF cavities, each of 120 kV operated at 45° off-crest, are placed in a dispersion free region of one long straight, requiring 60 kW total RF power [3]. A study of the scheme of ion beam formation in the ion injector is presented in [4].

ION AND ELECTRON POLARIZATION

A figure-8 shape for all the booster and collider rings is a unique design feature of MEIC for preserving the ion polarization during acceleration and storage and for greatly simplifying the spin control [1]. The mechanism is simple: the total spin procession (and the spin tune) in a figure-8 ring is zero. Further, a Siberian snake could shift the spin tune to a non-zero constant value, thus retaining energy independence. Such a figure-8 design is also particularly advantageous for the booster rings where polarization of protons and $^3He^{++}$ ions can be preserved by making the spin tune energy independent with, if the space is limited, a partial snake or other spin rotating devices [4]; this is not possible in a conventional circular synchrotron. An additional and important advantage of the figure-8 design is that it allows acceleration and storage of polarized deuterons [1], thus expending science reach enormously. This is not possible in a circular synchrotron since the required Siberian snakes would be impractical due to the deuteron's small anomalous magnetic moment. The figure-8 design is the only practical way to presently preserve the deuteron polarization in medium range collision energies.

The EIC science program requires both longitudinal and transverse polarization of light ions at all interaction points (IP). Schemes for arranging ion polarizations in the two long straights (where one to two IPs are located) of the MEIC figure-8 collider ring have been developed and are presented in [5]. For polarized protons and helium-3 ions, three spin configurations (longitudinal in all IPs, transverse in all IPs, and an alternately longitudinal in one straight and transverse in the other straight) are achievable, providing the highest flexibility of science programs at multiple detectors. For polarized deuterons, the spin configurations are further limited. The current design delivers transverse polarization in both long straights, but longitudinal polarization in only one long straight while the spin orientation at the other long straight will have an angle depending on the beam energy, due to the lack of a full snake for deuterons.

The MEIC electron ring also has a figure-8 shape since it is housed in a common tunnel with the ion collider ring. Though it should provide a similar benefit after the future energy upgrade of the collider in which the electron energy will be ramped up to 20 GeV in the ring from an 11 GeV injection energy from CEBAF, the advantage is not as significant for MEIC. Rather, control of the electron spin in a figure-8 ring, being significantly different from that in a circular ring, requires careful studies, particularly on the effect on the equilibrium polarization and its depolarization time. Some initial studies with spin tracking are presented in [6].

IR AND FORWARD DETECTION

The primary detector of MEIC is unique in its nearly full acceptance of nuclear collision products. From high energy asymmetry kinematics, reaction products are strongly biased towards small angles around the ion beam. An essential part of the new physics requires detection of these small-angle products, such as the recoiling target baryons, breakup hadrons, and all possible remnants produced when using nuclear targets, over wide ranges of momentum and charge-to-mass ratio. From the machine design and luminosity considerations, it is disadvantageous to leave a large detector space free of machine elements to allow the small-angle products to accumulate sufficient transverse separation from the incident beams. Therefore, a tight and smooth integration of the detector and the interaction region (IR) is essential for reaching an optimized balance on multiple aspects of the machine performance such as luminosity and acceptance. The proposed solution is forward detection [7], letting the small-angle particles pass through the aperture of the nearest final focusing elements (from the IP), which simultaneously performs the function of angle and momentum analyzer for the small-angle reaction products. Paper [6] presents the latest design of the IR and also the particle tracking simulations to show the detector acceptance

CHROMATIC CORRECTIONS AND DYNAMIC APERTURE

MEIC relies on small β^* to achieve high luminosities above 10^{34} $cm^{-2}s^{-1}$. A low-β insertion in an IR induces large chromatic effects. The present approach is a local correction scheme using two symmetric chromatic compensation blocks (CCB) placed on the both sides of an IP [8]. A CCB is made of eight symmetrically arranged alternating bends with seven quadrupoles placed symmetrically between them. The quadrupole strengths are adjusted to produce a total transfer matrix of the CCB that meets the symmetry requirements. Such a scheme simultaneously compensates 1st order chromaticity and

ISBN 978-3-95450-115-1

chromatic beam spot smear at the IP without inducing significant 2nd order aberrations [8].

For MEIC, the horizontal and vertical chromaticities before compensation are -278 and -268, respectively. The strengths of two sextupole families in the CCB are adjusted to reduce slopes of the chromatic betatron tune curves to zero. The tune variations are less than 0.005 and 0.01 in the horizontal and vertical directions respectively over a ±0.2% range of $\Delta p/p$, and further within 0.02 and 0.03 over a wide $\Delta p/p$ range of ±0.4% [9]. A frequency map analysis based on results of tracking simulations has demonstrated the momentum acceptance can easily reach ±0.4%, about 14 times the ion beam momentum spread, with only the linear chromaticity compensation [9].

The dynamic apertures of the collider rings are explored by tracking particles for 1000 turns with increasing initial transverse amplitudes until a boundary between survival and loss is found. Simulations show the particles having large initial amplitudes experience stronger non-linear sextupole fields, resulting in a 3rd order aberration in the form of amplitude dependent tune-shifts [9]. Therefore, families of octupoles are introduced and placed in large betatron function but dispersion-free regions. These leave the linear chromatic correction unaffected, but compensate this 3rd order aberration. With this additional compensation, the dynamic aperture is increased significantly [9].

ELECTRON COOLER AND TECHNOLOGY DEMO

The MEIC multi-stage cooling scheme [10] requires two electron coolers. One is a low energy cooler with a DC electron beam, based on matured technologies and used in the pre-booster synchrotron for assisting ion beam accumulation. The other is a high electron energy (up to 55 MeV) cooler based on several new technologies [10]: a high bunch charge and high repetition rate magnetized photo-cathode gun, an SRF ERL, and a compact circulator ring. It will be used in the collider ring for 6D phase space preparation of the colliding ion beam.

Currently, this ERL circulator cooler is placed at an optimized location, the vertex of the figure-8, of the ion collider ring, by taking advantage of this unique shape. It provides two 30 m long cooling channels for gaining higher cooling rates. Recently, a first linear optics design of the cooler has been completed [11]. Two additional key elements must be placed in the cooler beam line: an ultra fast kicker responsible for switching the electron bunch in and out of the circulator cooler ring; a set of SRF cavities (for de-chirping and re-chirping longitudinal phase) in the ERL ring for control of electron bunch length. Such bunch length manipulation is crucial to preserve an ultra small energy spread in the SRF linac (requiring very short bunch length) and to enhance the cooling efficiency (requiring a relatively long bunch length compatible with the ion bunch length at the cooling channels).

Recently, we proposed a proof-of-principle experiment [12] to demonstrate this ERL circulator cooler concept. The JLab FEL is selected as the test facility for this experiment. The presence of the two parallel IR and UV beam lines provides an opportunity for implementation of a compact circulator ring with two 180° bends already available. The FEL ERL can provide a high quality electron beam with an energy range and bunch repetition rate similar to the cooler and thus allows maximum reuse of existing hardware, dramatically reducing the capital cost of this experiment. The purpose of this experiment is to demonstrate circulations of an electron beam in a circulator ring while the beam quality is satisfactorily preserved. Specifically, we will (1) demonstrate a scheme for bunch exchange between the ERL and the circulator ring, (2) develop and test support technologies such as ERL and faster kickers, (3) study beam dynamics and collective effects in the circulator ring, and (4) test bunch length change and longitudinal phase matching between the ERL and the circulator ring. We expect this experiment will be completed in less than three years. A second phase of this test facility with a full bunch charge magnetized electron gun and also a kicker satisfying the design specification is also foreseen.

SUMMARY

The MEIC design study has advanced to a new stage since the completion of a conceptual baseline design. The accelerator team is now focusing on design optimization and critical R&D. This paper presented a survey of some progress over the last twelve months. Future work will concentrate on developing simulations and test plans on the cooler test facility, completion of dynamic aperture studies, and a clear demonstration of advantages of the figure-8 rings with spin tracking simulations.

REFERENCES

[1] "MEIC - An Intermediate Design Report of A Polarized Ring-Ring Electron-Ion Collider at Jefferson Lab", edited by J. Bisognano & Y. Zhang (2012).
[2] A. Bogacz et al., Proc. of PAC11 (2011).
[3] E. Nissen et al., Proc. of IPAC12, THPPP027 (2012).
[4] B. Erdelyi et al., Proc. of IPAC12, MOEPPB006 (2012).
[5] V. Morozov et al., Proc. of IPAC12, TUPPR079 (2012).
[6] F. Lin et al., Proc. of IPAC12, TUPPC098 (2012).
[7] V. Morozov et al., Proc. of IPAC12, TUPPR080 (2012).
[8] V. Morozov and Ya. Derbenev, Proc. IPAC11, p. 3723 (2011).
[9] F. Lin et al., Proc. of IPAC12, TUPPC099 (2012).
[10] Ya. Derbenev and Y. Zhang, Proc. of COOL09, Lanzhou, China (2009).
[11] D. Douglas and C. Tennant, JLab Technical Note 12-026 (2012).
[12] Ya. Derbenev et al., Proc. of IPAC12, TUPPR081 (2012).