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# Electron-Ion Collider Projects and Their Accelerator R&D needs

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## 34.1 Electron-Ion collider projects around the world

Several designs of future electron-ion colliders have been under consideration in recent years. All of them are based at an existing accelerator facility. These are ENC at GSI [1], MEIC at Jefferson Lab [2], LHeC at CERN [3], and eRHIC at Brookhaven [4, 5]. Table 34-1 lists these electron-ion collider designs and the corresponding facilities from which they are derived.

The last report on the Electron-Nucleon Collider (ENC) at the FAIR facility at GSI/Darmstadt is from 2011 and it seems that the accelerator design has been frozen since that time.

A new electron-ion collider, called EIC@HIAF, has recently been proposed at the Institute of Modern Physics in Lanzhou, China, as part of a planned Heavy Ion Accelerator Facility (HIAF). No details of the accelerator design have been released, so far, besides that the first stage would be 3 GeV electrons on 12 GeV protons with a luminosity of $10^{32} - 10^{33}$ cm$^{-2}$s$^{-1}$, while the second stage assumes 10 GeV electrons on 100 GeV protons with a luminosity of $10^{35}$cm$^{-2}$s$^{-1}$ .

Table 34-2 summarizes the beam parameters and luminosities of the electron-ion colliders for the mode of operation with the highest luminosity. The parameters achieved at the first electron-proton collider HERA are also listed for a comparison.

| | Ring-Ring | | | Linac-Ring | |
|---|---|---|---|---|---|
| | ENC | MEIC | LHeC RR | LHeC LR | eRHIC |
| CM energy, GeV | 14 | 15-70 (140) | 1300 | 1300 (2000) | 30 - 70 (175) |
| Based at | HESR FAIR (GSI) | CEBAF (JLab) | LHC (CERN) | LHC (CERN) | RHIC (BNL) |

**Table 34-1.** *Electron-Ion Colliders: Center-of-mass energies are shown for electron-proton operation.*

| | **HERA** | | **ENC** | | **MEIC 1st stage** | | **MEIC 2nd stage** | | **eRHIC 1st stage** | | **eRHIC** | | **LHeC linac-ring** | | **LHeC ring-ring** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | p | e | p | e | p | e | p | e | p | e | p | e | p | e | p | e |
| Energy, GeV | 920 | 27.5 | 15 | 3 | 60 | 5 | 250 | 10 | 250 | 5 | 250 | 20 | 7000 | 60 | 7000 | 60 |
| Bunch frequency [MHz] | 10.4 | | 52 (104) | | 750 | | 750 | | 14.1 | | 14.1 | | 20 | | 40 | |
| Bunch intensity ]$10^{11}$] | 0.72 | 0.29 | 0.54 (0.36) | 2.3 | 0.04 | 0.25 | 0.04 | 0.25 | 2 | 0.22 | 4 | 0.22 | 1.7 | 0.02 | 1.7 | 0.2 |
| Beam current [A] | 0.1 | 0.04 | 0.45 (0.6) | 1.9 | 0.5 | 3 | 0.5 | 3 | 0.42 | 0.05 | 0.83 | 0.05 | 0.43 | 0.006 | 0.86 | 0.1 |
| Norm. rms emittance x/y [$\mu$m] | 5 | 1100 /180 | 2.3 /0.8 | 930 /320 | 0.35 /0.07 | 54 /11 | 0.45 /0.02 | 32 /13 | 0.18 | 6.5 | 0.18 | 26 | 3.75 | 50 | 3.75 | 580 /290 |
| $\beta^*$ x/y [cm] | 245 /18 | 63 /26 | 30 (10) | 30 | 4 /0.8 | 4 /0.8 | 16 /0.8 | 16 /0.8 | 5 | 5 | 5 | 5 | 10 | 12 | 180 /50 | 18 /10 |
| Beam size at IP, x/y [$\mu$m] | 112/30 | | 200/120 | | 15/3 | | 15/3 | | 6/6 | | 6/6 | | 7/7 | | 30/16 | |
| Bunch length [cm] | 19 | 1 | 30 (20) | 8 | 1 | 0.75 | 1 | 0.75 | 8 | 0.4 | 5 | 0.2 | 8 | 0.03 | 8 | 1 |
| Polarization [%] | 0 | 45 | 80 | 70 | 80 | 80 | 70 | 80 | 70 | 70 | 70 | 80 | 0 | 90 | 0 | 40 |
| Peak luminosity $10^{33} cm^{-2} s^{-1}$ | 0.04 | | 0.2 (0.6) | | 14.2 | | 52 | | 11 | | 27 | | 1.0 | | 1.8 | |

**Table 34-2.** *The main beam parameters and luminosities of future EICs and the past HERA collider.*

# 34.2 Accelerator technology R&D items

## 34.2.1 Enabling technologies

### 34.2.1.1 Cooling of hadron beams (ENC, MEIC, eRHIC)

Small transverse and longitudinal emittances of the hadron beam enable a high electron-ion collider luminosity. In the designs with medium hadron energy this calls for the application of powerful cooling techniques:

- *Coherent electron cooling:* This novel cooling technique is under development for eRHIC. A proof-of-principle experiment is planned for 2015.
- *Electron cooling:* An electron cooler based on a high-current re-circulator ring fed by an ERL is under development for MEIC. Tests are planned for 2016.

### 34.2.1.2 Low $\beta^*$ interaction region (All EIC designs)

IR designs face the issues of strong focusing of beams at the collision point and fast separation of beams after the collision. The synchrotron radiation fan produced by electrons in the IR magnets has to be kept away from hitting the pipe inside or in the vicinity of the detectors and in superconducting magnets. The requirements imposed by the detector integration have to be satisfied and chromatic corrections have to be accomplished while maintaining an acceptable dynamic aperture.

The approaches considered are:

- Special design of IR magnets, including Nb3Sn superconductor technology
- Vacuum chamber design
- Collimators, absorbers and masks at the appropriate locations to provide protection from synchrotron radiation
- Integrated dipole field in the detector design
- Crossing angle geometry (in some designs)

### 34.2.1.3 Crab-crossing (eRHIC, MEIC)

Crab-cavities have to be used in the designs with a large crossing angle and bunch length to maximize the luminosity. Corresponding R&D includes designing and prototyping the superconducting crab-cavities and the study of the beam dynamics in the presence of crab crossing.

### 34.2.1.4 High beam power ERL and high beam current SRF cavities (eRHIC, LHeC LR)

This includes the SRF cavities able to operate with high average and peak beam currents, providing effective damping of high-order modes, the cryomodule design and the issues related with containing high beam power. The R&D ERL facility at BNL aims to explore CW operation of an ERL with an average current of up to 0.3 A.

#### 34.2.1.5 Preserving e-beam polarization in ring-ring schemes (LHeC RR, MEIC)

The spin matching and the harmonic correction techniques have to be investigated to minimize the beam depolarization due to synchrotron radiation, especially in the presence of spin rotators and solenoidal detector magnets.

#### 34.2.1.6 High current polarized electron source (eRHIC, LHeC LR)

The linac-ring designs utilize the high-current polarized electron source, with the average current ranging from 6 mA (LHeC LR) to 50 mA (eRHIC). Considered approaches are a Gatling gun or large-size cathode gun to produce up to 50 mA current

#### 34.2.1.7 Proton and light ion polarization (eRHIC, MEIC)

This includes the preservation of the beam polarization at the acceleration, the polarization orientation control at the interaction points and the precise polarization measurement. Study of polarization survival in the novel figure-8 shaped ring used in the MEIC design, which allows for the acceleration of polarized deuterons. For both MEIC and eRHIC, the production, the acceleration and the polarimetry of polarized He-3 ions is being explored.

#### 34.2.1.8 Beam-beam effects in the linac-ring scheme (eRHIC, LHeC LR)

The linac-ring scheme introduces non-standard beam-beam effects, which have to be explored to understand the limits on the luminosity and the beam parameters. The effects include the electron beam disruption, the hadron beam kink instability and the effect of the electron beam parameter fluctuation on the hadron beam.

#### 34.2.1.9 Intense positron beam in the linac-ring scheme (LHeC LR)

The goal is to achieve the luminosity of positron-ion collisions acceptable for physics experiments. Considered techniques: advanced targets for the positron production, the use of powerful gamma beam source, and the schemes for positron beam recycling, cooling and reuse.

#### 34.2.1.10 Matching electron and hadron bunch frequencies at different hadron energies (ENC, MEIC)

For hadrons that are not ultra-relativistic the change of the hadron energy considerably affects the hadron revolution frequency. Special provisions have to be made in these collider designs to match the bunch frequencies of hadrons and electrons at different hadron energies. This could include a variable circumference for the electron or hadron accelerators.

### 34.2.2 Cost saving technologies

- *eRHIC:* The magnets with small 8 and 13 mm gaps present a cost-effective solution for eRHIC recirculation arcs. R&D efforts include designing and prototyping small-gap magnets and corresponding vacuum chamber.
- *LHeC:* Combined coil and joke magnet designs for the three beam passages through the LHeC ERL can provide for a compact and cost efficient magnet design of the ERL return arcs.
- *eRHIC:* A Fixed-Field Accelerator Gradient (FFAG) lattice is considered as an alternative solution for eRHIC recirculation arcs. Such a lattice, especially, with the use of permanent magnets, may provide sizable reduction of the machine cost.

# References


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