New Accelerator Projects: Rare Isotope Facilities and Electron Ion Colliders

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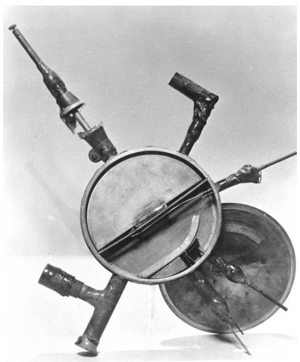
Presently there are two major areas of new accelerator projects in particle physics: a next generation of Rare Isotope facilities in the field of Nuclear Structure Physics and high luminosity Electron Ion Colliders as next generation QCD faciliies in the field of Hadron Physics. This paper presents a review of the present and future facilities and the required novel accelerator technologies for these two types of accelerator projects.

1 Introduction

Over the last century progress in accelerator technology is motivated by and has driven advances in both particle and nuclear physics. This started with Ernest Lawrence's first cyclotron built in 1932, small enough to fit in one's hand, and continues today with large hadron collider such as Brookhaven's Relativistic Heavy Ion Collider (RHIC) (Fig. 1) and CERN's Large Hadron Collider (LHC). Presently there are two major areas of new accelerator projects in particle physics: a next generation of Rare Isotope facilities in the field of Nuclear Structure Physics and high luminosity Electron Ion Colliders a next generation QCD facilities in the field of Hadron Physics.



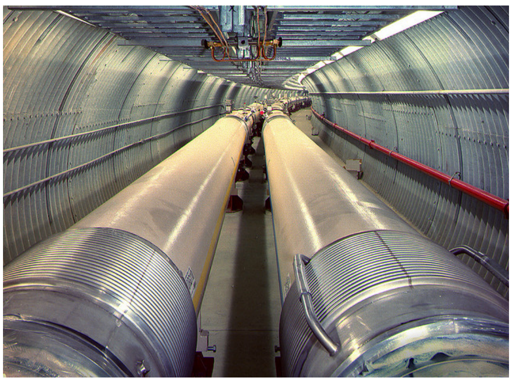


Figure 1: Accelerators used for nuclear and particle physics spanned an enormous range of scales form Ernest Lawrence's cyclotron that fit into one's hand to large hadron colliders such as the 3.8 km circumference Relativistic Heavy Ion Collider at BNL

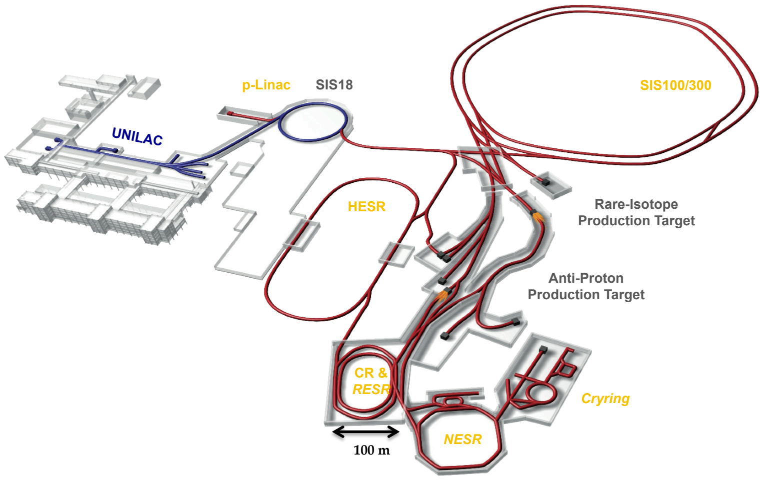


Figure 2: Layout of the FAIR facility near Darmstadt, Germany

2 Next generation of Rare Isotope facilities

The next generation of Rare Isotope facilities will dramatically increase the intensity of the driver accelerator. The three facilities under construction or close to the start of construction use a heavy ion driver beam. Enabling technologies are: Continuous Wave (CW), superconducting RF (SRF) Linear accelerators for partially stripped heavy ion beams; radiation hardened devices to strip electrons from the beams such as high speed rotating Carbon disks, liquid Lithium films or stable plasma windows; highly efficient heavy ion sources and charge breeders such as high intensity Electron Beam Ion Sources (EBIS) and high intensity Electron Cyclotron Resonance (ECR) sources; and acceleration of high intensity, partially stripped heavy ion beams in synchrotrons using Ultra High Vacuum (UHV) together with continuous collimation.

Three new Rare Isotope facilities are under construction or close to the start of construction:

- Construction has started for the Facility for Rare Isotope Beams (FRIB), a 0.2 GeV/n, 400 kW heavy ion driver that will produce beams of radioactive isotopes through fragmentation of uranium beam on a high power target. This will be the first installation of a large, CW SRF linac for hadron beams. It requires cavities for non-relativistic particle with a high quality factor to minimize the cryogenic cooling power. The heavy ion beams are produced partially stripped and then pass through an ion stripper for additional charge stripping as they gain energy. The ion stripper for the high intensity beams will be implemented either with a liquid metal film or a high pressure gas target. The construction period is planned from 2014 to 2020.

- The GSI laboratory near Darmstadt, Germany, is expanding its facility with a 30 GeV proton-equivalent heavy ion driver plus multiple accumulation and storage rings. The new facility will be called "Facility for Antiproton and Ion Research" (FAIR) (Fig. 2). The new 30 GeV synchrotron will be using fast cycling super-ferric magnets and will be optimized for the acceleration and storage of high intensity, partially stripped uranium ions. Construction has started and is now planned to be completed by about 2020.

- At the Institute of Modern Physics (IMP) in Lanzhou, China, preparations have started for a high intensity Heavy Ion Accelerator Facility (HIAF). The focus will also be on the production of rare isotopes and of high density plasma. The planned intensity of uranium beams in the SRF linac will be four times the planned intensity at FRIB. Construction is planned for the 2015 - 2021 period.

3 Electron Ion Colliders

There is renewed interest in a electron-ion collider with dramatically increased luminosity compared to the very successful electron-proton HERA facility at DESY. Most of the new proposals would also use polarized proton and light ion beams as well as heavy ion beams. Fig. 3 gives an overview of the peak luminosity versus center-of-mass energy for past, existing and future electron-proton facilities. Past and present facilities are indicated in black. The two proposals in the U.S. (MEIC at JLab and eRHIC at BNL) focus on the collision of polarized electrons with polarized protons at very high luminosity to measure the gluon spin structure at low x and electrons colliding with heavy ions for high-resolution imaging of gluon-dominated matter.

Two types of schemes to reach very high electron-ion luminosities are being pursued:

- The first scheme has the electron and hadron beam both circulating in a storage ring. In this case the beam-beam effects of the hadron beam on the lower energy electron beam severely limits the brightness of the hadron beam in order to keep the electron beam stable. To reach high luminosity many lower intensity bunches, with bunch spacing as short as 1 ns, are then needed, which then requires the operation with a large crossing angle to

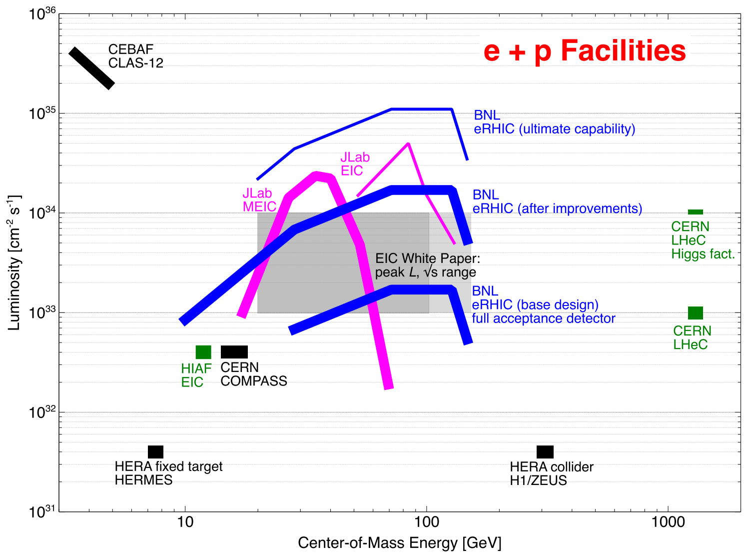


Figure 3: History and plans of the peak luminosity vs center-of-mass energy of lepton-hadron colliders

avoid parasitic collisions. This scheme is pursued for MEIC at JLab and HIAF-EIC at IMP.

- The second scheme uses an electron beam accelerated in a Energy Recovery Linac (ERL) to collide with a hadron beam in a storage ring. Since there is only a single collision of an electron bunch with the hadron beam a much higher beam-beam effect and therefore luminosity is possible. However the electron beam has to be continuously replenished from the source. This requires a new high intensity polarized electron source. This scheme is planned for eRHIC at BNL and LHeC at CERN.

3.1 MEIC at JLab

The first stage EIC proposal at JLab is called Medium Energy Electron-Ion Collider (MEIC) and would add a 3 - 12 GeV electron storage ring, using the present CEBAF as a full energy injector, and a new polarized proton (20 - 100 GeV) and heavy ion (12 - 40 GeV/n) accelerator complex (Fig. 4). The high luminosity of about $10^{34} cm^{-2} s^{-1}$ would be achieved with a very short bunch spacing of 1.3 ns as well as strong electron cooling of the ion beams. The whole complex would be laid out in the shape of a figure-8 to preserve beam polarization, including polarized deuteron beams, without needing Siberian snakes. Construction of this first stage could start after the present 12 GeV CEBAF upgrade is completed. A second stage would include a 20 GeV electron ring and a 250 GeV proton ring.

3.2 HIAF-EIC at IMP

The IMP laboratory in Lanzhou, China, also has plans to upgrade its HIAF to a Electron-Ion Collider by adding Figure-8 shaped polarized electron and proton rings. The electron energy will be 3 GeV, colliding with a 12 GeV polarized proton beam. With electron cooling of the proton beam a luminosity of $3 - 5 \times 10^{32} cm^{-2} s^{-1}$ could be reached.

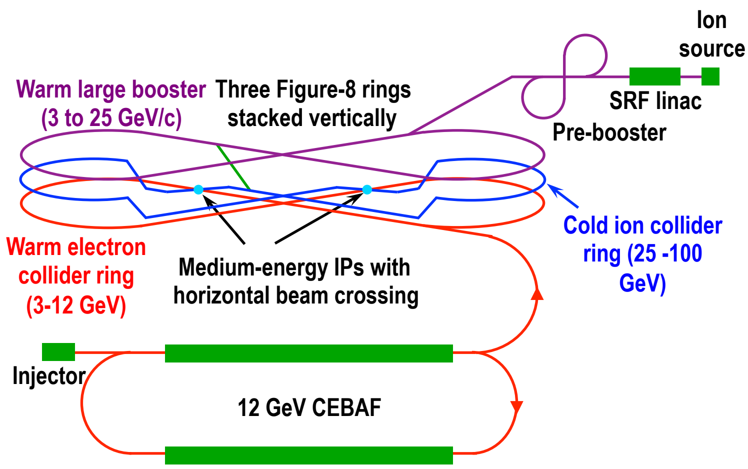


Figure 4: Layout of the proposed MEIC facility at JLab.

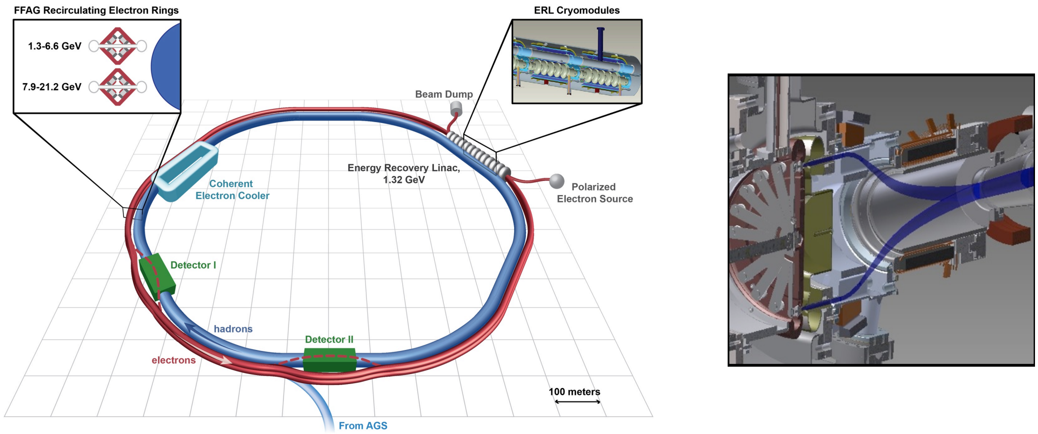


Figure 5: Layout of the proposed eRHIC facility at BNL (left) and schematic view of the high current, polarized "Gatling" electron source (right).

3.3 eRHIC at BNL

eRHIC at BNL would add a 21.2 GeV electron accelerator, based on an Energy Recovery Linac (ERL) with up to 16 recirculating passes inside the existing RHIC tunnel, to collide with the existing RHIC beams of 250 GeV polarized protons and 100 GeV/n heavy ions (Fig. 5). The 16 beam passes will be transported around the RHIC tunnel with two Fixed Field Alternating Gradient (FFAG) arcs. With the ERL the electron bunches would collide with the ion bunches only once and would allow for a very large disruption from the beam-beam interaction, which results in luminosities of about $2 \times 10^{33} cm^{-2} s^{-1}$. With modest upgrades (such as coating of the RHIC vacuum chambers) the luminosity could be increased ten-fold to about $2 \times 10^{34} cm^{-2} s^{-1}$. Because of the single pass nature of the collider a very intense (50 mA) polarized electron gun is required, which is about a factor of ten beyond the state-of-the-art. R&D is underway to build such an electron source that houses 24 individual cathodes that can be used one after the other in the style of a "Gatling" machine gun. A schematic view of this Gatling gun is shown on the right side of Fig. 5. To reach the high luminosity the ion beam will also have to be strongly cooled using coherent electron cooling. Construction of the eRHIC facility could be completed by 2024.

3.4 LHeC at CERN

There is also a proposal to collide a polarized electron beam from a 60 GeV ERL with the high energy LHC proton or heavy ion beam. Such a facility, called LHeC, would continue the search for lepton-quarks, started at HERA, but also could produce a copious number of Higgs particles if the luminosity could be increased to $10^{34} cm^{-2} s^{-1}$. The 60 GeV ERL would be the highest energy device of its kind and would use three recirculation arcs and a 20 GeV CW SRF Linac. The ERL would be in a tunnel separate from the LHC tunnel and the electron beam would collide with the LHC beam in a single interaction region. The highest luminosities would require that the electron bunch is captured by the space charge of the hadron beam at the collision point. The layout of the LHeC facility is shown in Fig. 6. Construction could occur

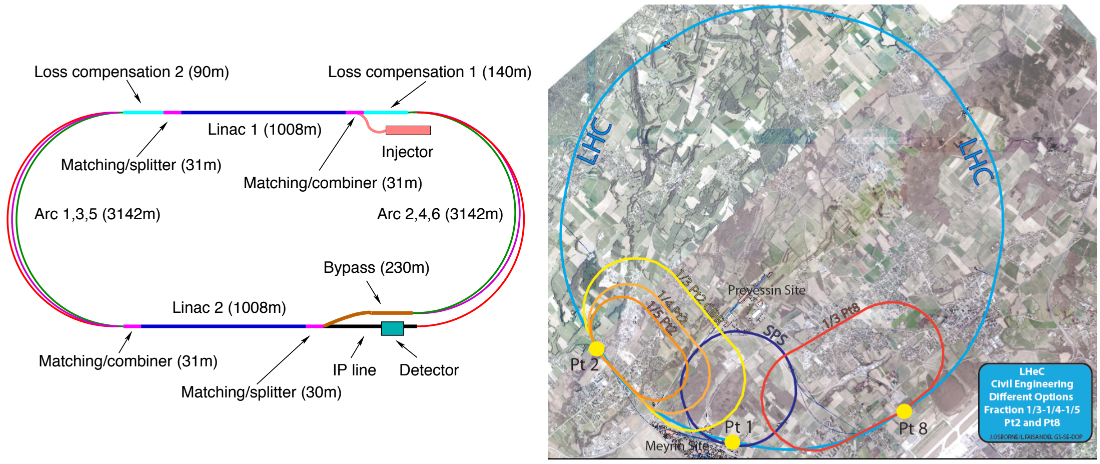


Figure 6: The 60 GeV ERL for LHeC is shown on the left. On the right are the possible locations for the electron ERL in the LHC ring.

during the 2020s.

4 Acknowledgments

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