BEAM PHYSICS IN FUTURE ELECTRON HADRON COLLIDERS

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Abstract

High-energy electron-hadron collisions could support a rich research programme in particle and nuclear physics. Several future projects are being proposed around the world, in particular eRHIC at BNL, MEIC at TJNAF in the US, and LHeC at CERN in Europe. This paper will highlight some of the accelerator physics issues, and describe related technical developments and challenges for these machines. In particular, optics design and beam dynamics studies are discussed, including longitudinal phase space manipulation, coherent synchrotron radiation, beam-beam kink instability, ion effects, as well as mitigation measures for beam break up and for space-charge induced emittance growth, all of which could limit the machine performance. Finally, first steps are presented towards an LHeC R&D facility, which should investigate relevant beam-physics processes.

INTRODUCTION

Particle colliders for high energy physics have been at the forefront of scientific discoveries for more than half a century. Leptons have been used to probe the partonic structure of the proton from the late 1960s, starting in fixed target deep inelastic scattering experiments, and continuing to the *e-p* collider HERA. With the first *e-p* collider HERA, remarkable results have been obtained on the parton structure of the proton, which are now crucial for the interpretation of the LHC data and include the discovery of a high density gluon and sea quark component in the proton. One can thus reflect on the valuable insight gained in revealing the structure of matter and evaluate priorities for future *e-p* or electron-ion (*e-A*) colliders [1]. Despite previous successes, many fundamental physics aspects have not yet been verified experimentally, and several future projects are under consideration in the USA and Europe and have good prospects of becoming operational and deliver results in the next 20 years. These projects intend to extend the knowledge achieved at HERA, and to provide new exploration tools by involving lepton collisions with heavy ions as well as with polarized protons and polarized light ions. These proposed colliders come in two varieties. One is an electron linear accelerator colliding with a proton or ion ring accelerator, the other, an *e*-ring accelerator colliding with a hadron ring. All of the future *e-A* colliders are based on the extension of already existing machines: LHeC at CERN [2], ENC at GSI [3], eRHIC at BNL [4] and MEIC at TJNAF [5]. Two colliders, ENC and MEIC are based on the ring-ring (RR) scenario, while the BNL and CERN teams selected the linac-ring (LR) option with energy recovery. The physics programs to a large degree are complimentary to each other and to the LHC physics [6]. In particular, with highest energies, the LHeC can be made a next Higgs factory. New ideas and technologies are applied in the accelerator designs and the intent of this paper is to present the key accelerator physics issues, referring to 3 possible future machines which are quite different in approach: eRHIC, MEIC and LHeC. This paper is organized as follows. The first part contains a brief overview on the parameter choices of the main future colliders worldwide. The focus here is on an understanding of the central characteristics of each machine and of the various common challenges. In the second part, among all the possible issues that these accelerators present, some selected subjects are described with related studies to analyze and compare the merits of different approaches. Special emphasis will be placed on the clear identification of the beam physics limits and accelerator technology limits highlighting aspects that need to be addressed by further research. The final section contains a summary of the future plans at CERN with special regard to the scientific and technical R&D activity for the development of an LHeC ERL test facility which will allow addressing relevant physics issues.

FUTURE ELECTRON-ION COLLIDERS

Since the very beginning, the focus of the *e-p* and *e-A* colliders studies has centered on achieving ultra-high luminosity and higher center-of-mass energy (CME). The eRHIC and ELIC machines consider their operation at the CME area of 20÷100 GeV, with luminosities ranging in $10^{32}÷10^{34}$ cm^{-2}s^{-1} values. Compared to the other machines, the LHeC provides the unique possibility of exploring *e-p* collisions in the TeV center of mass regime. The LHeC will collide the 7 TeV protons circulating in the LHC, therefore representing an interesting possibility for a further exploitation of the existing LHC infrastructure investment, with a high energy *e*-beam at a single collision point. As a result of the combination of SC accelerating structures and the energy recovery technique, a luminosity at least 2 orders of magnitude greater than the one achieved by HERA can be reached. The proposed machine layout consists of a 500 MeV polarized injector, two CW 10 GeV SC linacs and a recirculator system. Each beam recirculates up to 3 times through both linacs to boost the energy to 60 GeV. As the beam is focused and collided, it is bent by 180°, and then it is sent back through the first linac, at a decelerating phase. During deceleration the energy stored in the beam is converted to RF energy and the final beam, at its original injection energy, is directed to a beam dump. The baseline 60 GeV ERL option proposed can give an *e-p* luminosity of 10^{33} cm^{-2}s^{-1} (extensions to 10^{34} cm^{-2}s^{-1} and beyond are being considered), a beam current of 6.4 mA, with less than 100 MW total electrical power required.

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A similar approach of exploiting an existing beam facility and adding an accelerator for another species is taken in the collider projects eRHIC at BNL. The eRHIC design is based on one of the RHIC hadron rings which can accelerate polarized light ion beams to 100÷130 GeV/nucleon and polarized protons up to 325 GeV, and a new 5÷30 GeV multi-pass ERL to accelerate polarized electrons. It means that eRHIC will cover the CME range from 44.7 GeV to 197.5 GeV for polarized *e-p*, and from 31.6 GeV to 125 GeV for electron heavy-ion collisions. The machine will rely on SRF technology for production and acceleration of electrons, cooling of hadron beams and realizing crab crossing collision scheme. The injection system consists of a 10 MeV linac and 600 MeV single-pass ERL. Two 2.45 GeV SRF linacs in combination with six passes form the main ERL to generate 50 mA of polarized *e*-current. Multiple collision points are possible.

In the present baseline the central part of the proposed MEIC is a pair of figure-8 shaped storage rings, which accommodate the colliding electron and ion beams, respectively. The electron ring is made of normal conducting magnets and will store an *e*-beam of 3 to 11 GeV. The CEBAF SRF linac serves as a full-energy injector into the electron collider ring, requiring no further upgrade for energy, beam current, or polarization beyond the 12 GeV upgrade. The ion collider ring is made of high-field SC magnets and will store a beam with energy of 20 to 100 GeV for protons or up to 40 GeV per nucleon for light to heavy ions. The ion beams are generated and accelerated in a new ion injector complex. In addition, two large figure-8 high-energy collider rings will be added for a future energy upgrade for reaching up to 20 GeV electrons, 250 GeV protons or 100 GeV/u ions. The upgraded high-energy collider can use the same experimental halls and, possibly, the same detectors as MEIC, and the medium-energy ion collider ring would then serve as the final booster in the staged acceleration of ion beams.

CHALLENGES

Each of the future *e-A* colliders faces significant challenges and an intense accelerator R&D program is needed. A list of primary beam dynamics concerns is the following:

- *e*-beam energy losses and energy spread caused by the interaction with the beam environment (cavities, resistive walls, pipe roughness);
- incoherent and coherent synchrotron radiation (SR) related effects: energy losses, transverse and longitudinal emittance increase of the e-beam;
- effective energy loss and energy spread compensation schemes;
- *e*-beam filling patterns; ion accumulation;
- *e*-beam break-up (BBU), single beam and multi-pass;
- *e*-beam-ion and intra-beam scattering effects;
- *e*-beam polarization: depolarization effects;
- possible effects due to crab cavities;
- detailed beam dynamics with coherent electron cooling (CeC);
- beam-beam effects, including the *e*-beam disruption and the hadron beam kink instability.

Some of these topics will be discussed in the following sections.

Electron Beam Polarization

A key feature of *e-A* colliders is high polarization (over 80%) of the *e*-beam at all collision points. Many issues have to be carefully considered, such as a polarized source, self-polarization and depolarization, polarization time, and spin rotator. The MEIC electron ring is designed to store, manipulate and preserve a highly polarized *e*-beam. The MEIC polarized beam is provided by the CEBAF accelerator. Currently, the electron polarization from CEBAF at 6 GeV is above 85%. It is expected that a similarly high polarization will be achieved after completion of the 12 GeV upgrade. The equilibrium electron polarization is arranged to be vertical in the arcs of the figure-8 collider ring and anti-parallel to the arc dipole magnetic fields (see Fig. 1), in order to take advantage of the preservation of polarization by the Sokolov-Ternov (S-T) effect. Longitudinal

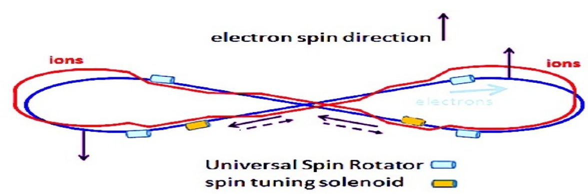

Figure 1: Diagram of polarization orientation at MEIC [5].

polarization is achieved at the collision points by utilizing 90° universal spin rotators (USR) each of which consists of a set of solenoids and dipoles placed at the end of an arc. To eliminate the transverse coupling introduced by the solenoids, each solenoid is split into two equal halves and 5 quadrupoles (in 3 families) are inserted between the halves. One or more spin tuning solenoids are needed to control the closed orbit spin tune and keep it away from resonances. Figure 2 illustrates how the USR works by showing a step-by-step rotation of an electron spin. The equilibrium

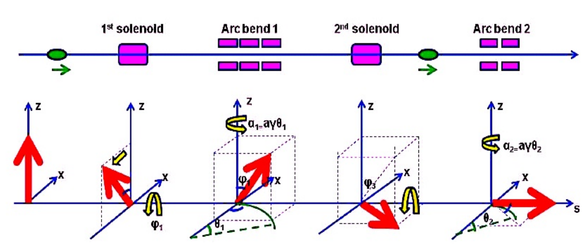

Figure 2: Schematic drawing of the USR at MEIC [5].

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beam polarization and its lifetime depend on competition between the S-T effect and radiative depolarization. The calculated equilibrium polarization and lifetime show significant depolarization even with perfect alignment. First calculations confirmed that the spin rotators and the sections between them are the main source of depolarization. The latter must be suppressed by spin matching which can be performed by manipulating the optics and layout of the lattice to achieve spin transparency between the two spin rotators. Regarding LHeC, Fig. 3 depicts the calculated spin vector spread, without any spin rotators, as a function of momentum spread for particles at 20, 40 and 60 GeV. While at eRHIC the loss of polarization is acceptable, for the high energy of LHeC the effective polarization can be reduced by 10% due to the spread of the spin vectors. For this reason to produce longitudinally oriented polarization at the LHeC collision point, a design with two spin rotators has been adopted. A low energy spin rotator first brings the polarization into the vertical direction and later a high energy spin rotator close to the IP realigns the spin vector in the longitudinal direction. The LHeC high energy spin

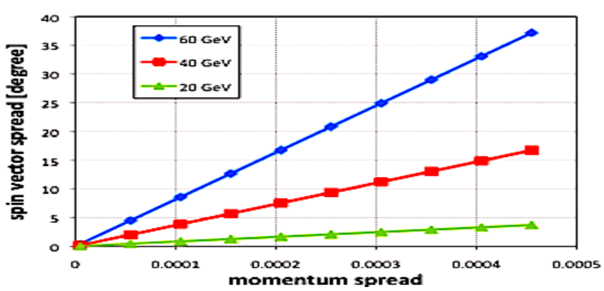

Figure 3: Angular spread of the spin vectors for off-momentum particles at 20, 40 and 60 GeV in the LHeC complex [7].

rotator consists of 4 helical dipoles with alternating helicity, similar to the RHIC proton spin rotator, placed in the straight section between the end of the second linac and the final focusing system. Besides saving space by being short, this approach also has the advantage of providing an independent full control of the direction of the polarization, as well as a nearly energy-independent spin rotation for the same magnetic field. The ∼MW SR power emitted by the 60 GeV *e*-beam passing through the spin rotator determines the minimum length of the system. In the present design, for a 60 GeV *e*-beam, the magnetic fields of the inner and outer pairs are 0.46 T and 0.37 T, respectively [2].

Optics Design and SR in Return Arcs

Control of SR effects on beam phase-space such as cumulative emittance and momentum growth due to quantum excitations is important for a high luminosity collider. In this section we briefly revisit the impact of SR from bending magnets for the intense beam at eRHIC and LHeC. The lattice design for both ERL based machines includes arcs placed above each other connected to the linacs by splitters and combiners. For LHeC a quasi isochronous arc optics design has been adopted, which simultaneously ensures a small value of emittance dilution and low momentum compaction, and therefore mitigates both transverse emittance growth and bunch length increase. The choice of large arc radius (1 km) is dictated by limiting energy loss due to SR at top energy (60 GeV) to less than 1%. Energy losses from resistive wall and coherent SR have both been shown to be negligible compared with the energy loss due to incoherent SR. The standard arc building block is 52 m long, and contains 4 quadrupoles and 2 (split into 10) dipoles. The values of the curly-H function and M_{56} are taylored as required by emittance dilution and isochronicity or beam size conditions, respectively, for arcs of different energies, transiting from a quasi-isochronous optics yielding a small beam size for the 2 lowest energy arcs, to a TME-optics for the 2 arcs at highest energy. The LHeC arc dipoles have a 25 mm gap and a maximum field of 0.264 T, at 60 GeV. The highest energy arc (before the final collision), gives a net normalized emittance increase of 4.5 μm. All the lower arcs together, with less emittance preserving optics, contribute a total of about 25% of the last arc, so that the total emittance dilution is 5.6 μm. At the interaction point, the SR induced RMS energy spread is only $2{\cdot}10^{-4}$, at the final arc, after deceleration, the energy spread reaches about 0.22%, while at the beam dump it grows to a full 4.5%. The *e*-beam looses about 2 GeV over all arc passes and the highest compensating RF voltage required is 750 MV for the energy loss at 60 GeV.

The lattice of the 6-passes for the eRHIC ERL arcs is based on low-emittance near-isochronous arc modules, supporting perfect isochronicity of complete paths. The standard building block is 35 m long, and contains 7 dipoles and 9 quadrupoles. The eRHIC arc dipoles have a gap of 5 mm and, at 30 GeV, a maximum field of 0.43 T. In view of the small gap and high beam current, resistive-wall wake fields and surface-roughness effects are under careful investigation. At 30 GeV peak lepton energy, with a dipole bending radius of 234 m, the total energy loss per electron due to SR is about 770 MeV over all arc passes; at 20 GeV it is only 150 MeV. A single double harmonic compensator at (almost) the highest energy delivering 389 MeV per passage compensates for the energy loss from SR and other, smaller effects like resistive wall and linac-cavity HOMs.

Multipass BBU and Beam-beam

In ERLs, the excitation of HOMs induced by the recirculating *e*-bunches can add up constructively and cause instabilities. Depending on the details of the machine optics, the deflection produced by a mode can translate into a transverse displacement at the cavity after recirculation. The recirculated beam induces, in turn, an HOM voltage which depends on the magnitude and direction of the beam displacement. Thus, the recirculated beam completes a feedback loop which can become unstable if the average beam current exceeds the threshold for stability. BBU is of particular concern in the design of high average current ERLs utilizing SRF technology. If not sufficiently damped by the HOM couplers, dipole modes with quality factors several orders of magnitude higher than in normal conducting cavities can exist, providing a threat for BBU to develop. The BBU threshold is increased by the natural chromaticity of the arcs if the latter is uncorrected [9]. A thorough suite of simulations to characterize the BBU instability have been conducted for the two ERL based machines LHeC and eRHIC. The LHeC BBU study is based on a new code that assumes point-like bunches and takes a number of dipole wakefield modes into account. A cavity-to-cavity frequency spread of the wakefield modes can also be modelled. In the simulation, one can offset a single bunch of a long train by one unit and determine the final position in phase space of all other bunches. Figure 4 shows the multi-bunch BBU adopting ILC-type (1.3 GHz) and SPL-type (720 MHz) cavities for a bunch with $3{\cdot}10^9$ electrons. The beam remains stable in both cases. Another key limit-

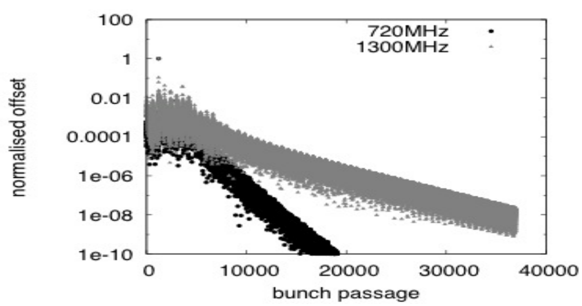

Figure 4: Multi-bunch BBU. Amplitudes along the full simulated train for the baseline lattice of LHeC [8].

ing factor to collider luminosity is beam-beam interactions. These can cause serious emittance growth of the colliding beams and fast reduction of luminosity. In particular the collision distorts the *e*-beam, which may be mitigated by proper matching of the exit beamline. The beam-beam effect can also amplify a perturbation and, thereby lower the BBU threshold. In Fig. 5 multi-bunch BBU including beam-beam effects is shown, again for two different cavity-types and for a bunch with $3{\times}10^9$ electrons. The beam remains stable in both cases but with a very small margin in the case of the ILC-type cavities.

Fast Beam-ion Instability

Collision of beam particles with the residual gas in the beam pipe leads to the production of positive ions that can be trapped in the beam. Their presence modifies the betatron function of the beam and can also lead to a BBU-like instability, since bunches with an offset will induce a coherent motion in the ions (and vice versa) [10]. This can in turn lead to a kick of the ions on the following bunches. The LHeC whole racetrack is ∼9 km, 1/3 of the LHC circumference, so that ion clearing gaps can be incorporated in the bunch train whose arrival times for successive passes coincide in the linacs and which, in addition, always correspond to the same partner hadron bunches in the LHC (so

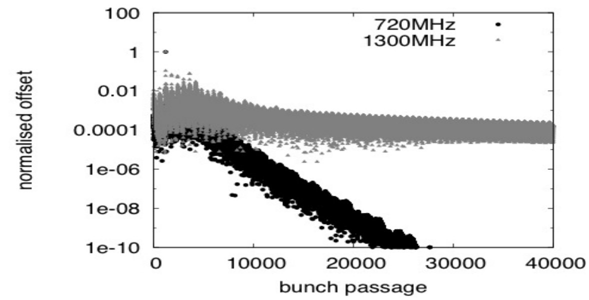

Figure 5: Multi-bunch BBU with beam-beam effect. Amplitudes along the full simulated train for the baseline lattice of LHeC [8].

that the LHC would comprise hadron bunches which collide on every turn and some others which never collide). In these clearing gaps the ions drift away from the beam orbit. A good vacuum quality is also needed to further slow down the build up of a significant ion density during the bunch train passages between successive clearing gaps. For the LHeC cold linacs, with a clearing gap of 10μs every 30μs, partial gas pressures of 10^{-11} hPa at 1.8 K are required at the position of the beam to render the residual fast beam-ion instability harmless, whereas a partial pressure below 10^{-9} hPa should be sufficient in the warm arcs. Similar tolerances apply to eRHIC.

Electron Cooling

Cooling of ion and hadron beams at collision energy is of critical importance for the performance of eRHIC and MEIC. An effective cooling process would allow to cool the beams beyond their natural emittances and also to either overcome or to significantly mitigate limitations caused by the hour-glass effect and intra-beam scattering. New concepts have been proposed recently to cool hadron beams. The most notable one among them is CeC. It is an *e*-beam based cooling system in which the accompanying *e*-beam provides feedback, similar to stochastic cooling, with an extremely high frequency bandwidth (THz range) by use of the FEL amplification mechanism in an undulator. This concept has been adopted for the eRHIC design. A sketch of the schematic layout is shown in Fig. 6. In the modula-

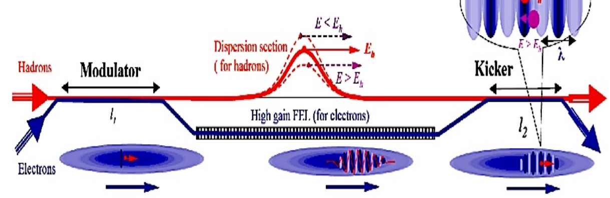

Figure 6: General schematic of CeC [11].

tor, each hadron induces density modulation in *e*-beam that is amplified in the high-gain FEL; in the kicker, the hadrons interact with the self-induced electric field of the *e*-beam

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and receive energy kicks toward their central energy. The process reduces the hadron energy spread, i.e. cools the hadron beam. A recent proposal is to use the microbunching instability instead of the FEL process as amplifier for the CeC scheme [12].

The MEIC baseline design does not invoke the CeC method, but it adopts a scheme of multi-stage cooling for supporting its high luminosities. Electron cooling is utilized not only for assisting ion beam formation but also during collisions. The latter is particularly important for preserving the collider luminosity and its lifetime by suppressing IBS induced heating. The scheme utilizes *e*-cooling at four different stages (at the pre-booster, injection and top energy, during collision) of the ion beam life cycle for achieving distinct goals in beam formation and maintenance. Figure 7 illustrates the *e*-cooler based on a magnetized photocathode gun, an ERL and a compact circulator ring. A high charge electron bunch from an injector is accelerated in an SRF linac up to 55 MeV and then sent to a circulator ring with an optically matched cooling channel for the ion bunch. The *e*-bunch circulates a large number of revolutions (up to 100) in the circulator cooler ring before its quality degrades significantly due to intra- and inter-beam scattering, and then returns to the same SRF linac for energy recovery. The *e*-cooling happens in both long straight sections as the circulator ring is placed in the vertex of the figure-8.

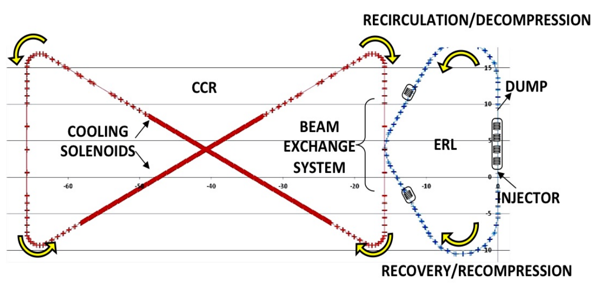

Figure 7: Schematic drawing of an ERL circulator cooling facility for MEIC [5].

FUTURE PLANS AT CERN

The development of a CW SC recirculating ERL for LHeC would prepare for many possible future projects. With some additional arcs, using 4 instead of 3 passes through the linacs, a machine like the LHeC ERL (without energy recovery) could also operate as Higgs factory $\gamma\gamma$ collider. The LHeC project will pursue the construction of a dedicated ERL test facility, the design of which will be prepared over the next two years. This test facilty could later be converted into the LHeC injector, including energy recovery. The purposes are first, confirming the feasibility of the LHeC ERL design by demonstrating stable intense *e*-beams with the intended parameters (current, bunch spacing, bunch length); secondly, testing novel components such as a (polarized) DC electron gun, SC RF cavities, cryomodule design and feedback diagnostics; finally, experimental studies of the lattice dependence of stability criteria. The realization of this facility will allow addressing several physics challenges such as maintaining high beam brightness through preservation of the 6D emittance, managing the phase space during acceleration and energy recovery, stable acceleration and deceleration of high current beams in CW mode operation. The design must also allow addressing other performance aspects such as longitudinal phase space manipulations, effects of coherent SR, longitudinal space charge and ions, halo and beam loss and microbunching instability.

SUMMARY

Electron-hadron colliders provide outstanding research potential. Several proposals aiming at very high luminosity, two-to-four orders of magnitude beyond the luminosity demonstrated by HERA, are under consideration in several laboratories all over the world. All these projects promote advanced research in accelerator physics and technologies. Additional R&D is needed. Further improvements to overcome the state-of-art include investigation of polarized electron guns, high-energy deuteron and proton polarization, integration of the detectors and colliders, high-energy *e*-cooling, high current and high brightness beam ERL operation, along with more detailed studies of multi-bunch BBU, beam-ion instability and beam-beam effects.

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