The Working Group M5 on Lepton-Hadron Colliders

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Executive Summary

A high luminosity lepton-hadron collider can provide precise and complete data essential to the ultimate understanding of the structure of matter. Lepton-hadron colliders have a unique potential in investigating various facets of QCD: the hadron space and spin structure, the space time picture of strong interactions, confinement, and the understanding of constituent masses. Furthermore, lepton-hadron colliders are essential tools for measuring structure functions in unexplored parameter regimes of x and Q^2. These will be needed to understand hadron collisions in RHIC, LHC, and VLHC.

So far HERA at DESY has been the only high-energy lepton-hadron collider. In the last year HERA has surpassed its design luminosity of $1.5 \cdot 10^{31} \mathrm{cm}^{-2} s^{-1}$, and an upgrade should soon increase the luminosity by a factor of 4. HERA has reached Bjorken x down to 10^{-4}, but to better understand the unexpected rise of parton densities at low x, new experiments with even smaller x are needed.

During the last few years several new lepton-hadron collider possibilities have been proposed. These proposed colliders come in two varieties. One is an electron linear accelerator colliding with a proton or ion ring accelerator, the other, like HERA, an electron ring accelerator colliding with a hadron ring. While conventional linacs can only provide a comparatively low average current, yielding lower luminosity than comparable ring-ring colliders, the novel technology of energy-recovery linacs might increase the available current sufficiently to make energy-recovery linac-ring colliders the favored technology for reaching high luminosities. Some technological issues are common to all proposed lepton-hadron colliders. To achieve the desired luminosity, the intra-beam scattering rates have to be compensated by cooling of the high-energy hadron beams. For high-energy proton beams this is helpful but avoidable when a moderate loss of luminosity is accepted, but for ion beams or lower energy proton beams it is mandatory. Most of the proposed lepton-hadron colliders require polarized electron or positron and polarized proton or deuteron beams. The following six projects have been discussed:

THERA is a linac-ring collider in the traditional sense, where electrons could be accelerated through one or both arms of TESLA to collide with either protons or ions in the existing 6.3km long HERA tunnel. Various combinations of electron and proton energies could be envisaged with center of mass energies of up to 1TeV. An example is a symmetric arrangement of 800GeV electrons on 800GeV protons. Due to the rather small electron current of around 80 microamperes, the luminosity would be $1.6 \cdot 10^{31} \mathrm{cm}^{-2} s^{-1}$. Assuming that TESLA has been built at DESY, then the cost of building THERA has been roughly estimated to be 120MEuro without labor. This facility is very cost effective since it makes optimal use of two then existing facilities. The construction time would be roughly 3 years.

The Electron Ion Collider (EIC) initiative in the USA covers a number of alternatives. The higher energy version, called eRHIC, would use the existing RHIC as the hadron ring to collide with polarized electrons from either a linac or a ring. For e/p collisions, the center of mass energy would be 100GeV. The linac-ring version will take advantage of the high electron currents that become available with an energy recovery linac. Two energy recovery linacs have been built so far, one at Jefferson Lab and the other at JAERI. The former has obtained energy recovery for 5mA at 50MeV. The current and the energy proposed for eRHIC are 264mA and 10GeV. The luminosity would then be approximately $10^{33} \mathrm{cm}^{-2} \mathrm{s}^{-1}$. The total cost without scientific labor would be around 300M$, and the construction time would be around 3 years.

The ring-ring collider version is more conventional. While in the linac-ring version the electron spin can be manipulate at will, the ring-ring version requires spin rotators close to the IR to provide longitudinal polarization at the experiment. Together with the two proton beam pipes and the detectors, which can only cope with a very limited amount of synchrotron radiation, this requires a quite sophisticated interaction region. The luminosity was computed to be $1.5 \cdot 10^{33} \mathrm{cm}^{-2} s^{-1}$. The projected cost is also 300M$ and the construction time would be approximately 3 years.

A green-site, lower-energy version of EIC with about 32GeV center of mass energy (named EPIC) has been proposed also in the linac-ring and ring-ring collider versions. In the linac-ring scenario, the ion ring would be 465m long and would provide protons at 50GeV. For an energy recovery linac with 264mA at 5GeV the luminosity would be $2 \cdot 10^{33} \mathrm{cm}^{-2} s^{-1}$. In the ring-ring scenario, a 1390m long 7GeV electron ring would be located on top of a 32GeV proton ring and a luminosity of $10^{33} \mathrm{cm}^{-2} s^{-1}$ could be reached. MIT-Bates has proposed an initial R&D phase of 3 years with a total cost of 15M$. In both cases the construction cost would be roughly 300M$ for a construction period of 5 years. A detector for the EIC facilities is estimated to cost 100M$.

The HERA proton ring and the HERA pre-accelerator chain can be upgraded to accelerate and store polarized protons, polarized deuterons, and light or heavy ions. This project is occasionally called HERAe/A. The center of mass energy for electron-proton collisions is 318GeV. Without electron cooling, the polarized proton option has been estimated to cost about 30MEuro, a polarized deuteron option will be substantially cheaper. For heavier ions, electron cooling is mandatory and a new ion linac would be needed. This leads to an estimated cost of 53MEuro for ions in HERA. The parton luminosity could then be roughly $7 \cdot 10^{31} \mathrm{cm}^{-2} s^{-1}$. The construction period might be around 3 years. The existing e/p accelerator makes this project much cheaper than other lepton-hadron colliders, and additionally no new detectors would need to be build.

An electron ring in the LHC tunnel is referred to as eLHC and would collide a 60GeV electron beam with the 7TeV protons. The luminosity would be $2.5 \cdot 10^{32} \mathrm{cm}^{-2} s^{-1}$ for these collisions with 1.3TeV center of mass energy. A cost estimate has not been determined. An electron ring in the VLHC booster tunnel, called epVLHC-b, has also been proposed. The new proposal of the VLHC does not require a 3TeV booster. But for the previous layout an 80GeV electron on 3TeV proton collider in the booster tunnel could have run during the construction period of the VLHC main tunnel. The luminosity would be around $2.6 \cdot 10^{32} \mathrm{cm}^{-2} s^{-1}$. For epVLHC-b the cost has been estimated to roughly 1000M$. Construction times for these two large-scale lepton-hadron colliders have not yet been determined.

Most of the facilities discussed take advantage of existing or planned hadron storage rings and are therefore rather cost efficient. Construction could begin after the following R&D issues have been addressed:

- High-current energy-recovery linacs. These linacs would also be very interesting for high-energy electron cooling and for light sources. One key issue is the loss rate that must be kept below 10^{-6}. Beam break-up is another concern. Cornell has proposed to address these issues within the next 5 years by building a 100mA, 100MeV energy recovery linac prototype.
- High-energy electron cooling. For high-energies the electron beams have to be accelerated in a linac and are therefore bunched. To reach sufficient electron intensities, the beam can be stored in an accumulator, or an energy recovery linac could be used. Various R&D issues must be investigated, including magnetized beam transport as well as electron beam brightness and matching.
- Polarized electron sources. Polarized electron guns with sufficiently high average currents have never been operated before and have to be developed.
- High-energy deuteron and proton polarization. This subject, which is being pioneered at RHIC, has to be further developed. The current of polarized proton and deuteron sources has to be increased.
- Integration of the detectors and colliders. High-energy detector requirements impact on the accelerator and IP design. For example the detectors needed to study small x physics have the special requirement of covering the forward direction. Even detectors with 4π solid angle are being discussed. Their implications for the interaction region must be taken into account.
- The detectors will only be able to handle large bunch frequencies if hadron beams with a very small amount of out-of-bunch particles are being stored. To reach the proposed 7ns bunch spacing for some of the EIC versions, the out-of-bunch particle population has to be suppressed significantly below the level in HERA, where the bunches are 96ns apart.