The Working Group M5 on Lepton-Hadron Colliders

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I. 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 1.6TeV. 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 $10^{33}\text{cm}^{-2}s^{-1}$. 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 $1.5\cdot10^{33}\text{cm}^{-2}s^{-1}$. 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 $2\cdot10^{33}\text{cm}^{-2}s^{-1}$. 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 $10^{33}\text{cm}^{-2}s^{-1}$ 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 $7\cdot10^{31}\text{cm}^{-2}s^{-1}$. 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 $2.5\cdot10^{32}\text{cm}^{-2}s^{-1}$ 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 $2.6\cdot10^{32}\text{cm}^{-2}s^{-1}$. 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 4 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.

II. Report of the Working Group

The world's only lepton-hadron collider, HERA at DESY, reached and surpassed its design luminosity in 2000, and the aspects of QCD which have been analyzed with this collider turned out to be far more interesting and fruitful than expected. To supplement the results of HERA, several new lepton-hadron colliders have been proposed during the past few years. The desire to bring together the people who worked on these different proposals and to analyze and compare the merits and limits of these proposals lead to the following charge of the lepton-hadron collider working-group:

> Perform a survey of the present status as well as the vision of the future promise of the various lepton-hadron colliders. The colliders to be covered include those currently in operation, currently under construction, or envisaged as a possibility for the future, in the US and abroad. Special emphasis should be placed on the clear identification of the beam physics limits and accelerator technology limits and an examination of the extent that they have been addressed by past research or need to be addressed by further research. Identify new and promising ideas even though they may need additional work. These issues should

be addressed for all of the leading technical realizations of the lepton-hadron colliders. Finally, the group should summarize in a brief report (a few pages) the highest priority research topics for different technological realizations of lepton-hadron systems and provide an approximate schedule for key R&D developments. The group is also asked to provide comprehensive presentations to high-energy and accelerator physicists in plenary sessions during the Snowmass workshop.

A. ***The Physics Case for Lepton-Hadron Colliders***

1. Introduction

Leptons have been used to probe the partonic structure of the proton from the late 1960's, starting in fixed target deep inelastic scattering (DIS) experiments, and continuing to the present electron-proton (e-p) collider HERA. There has been a steady increase in the resolving power of DIS throughout this period, and along with this, an increasing understanding of partons containing smaller and smaller momentum fractions (x) of the proton. After 10 years of e-p scattering at HERA, we can reflect on the insight gained in the structure of the proton and the dynamics of strong interactions between quarks and gluons, and we can evaluate priorities for future e-p or electron-ion (e-A) colliders. For that it has to be identified in which research domains the merits of e-p and e-A colliders are unique, and in which domains such a collider would be redundant with respect to existing or future e-e and p-p colliders.

2. Why e-p?

As far as we know, point-like electrons make ideal probes to study proton structure, since, in an e-p inelastic collision, there are no leftover pieces of the electron to confuse us in our evaluation of the proton's content. The electron scatters intact and, if detected, can be used to completely reconstruct the properties of the e-p collision. By selecting the scattered electron energy and angle, the scale of the hard scattering between the probe and the partonic components of the proton can be known and experimentally selected. At an e-p collider, the theory of strong interactions between the quarks and gluons (QCD) can be studied in a very background free environment. This includes not only static properties but also investigations of QCD as a function of various kinematic variables. Also, at higher center of mass energies, some unknown but theorized new physics processes, especially those with unique couplings to e-p scattering, e.g. R- parity violating leptoquarks, can be investigated.

Finally, an understanding of proton structure, as well as an understanding of QCD parameters and dynamics is necessary to understand potential new physics from future hadron-hadron colliders, e.g. RHIC, LHC, or VLHC.

The impressive precision tests of the standard model and resulting constraints on its possible extensions constitute the highlights of the research program at the LEP (e-e) and at the TEVATRON (p-p) collider. The HERA (e-p) collider results, unique in several other research domains, are not competitive with LEP and TEVATRON results in this field.

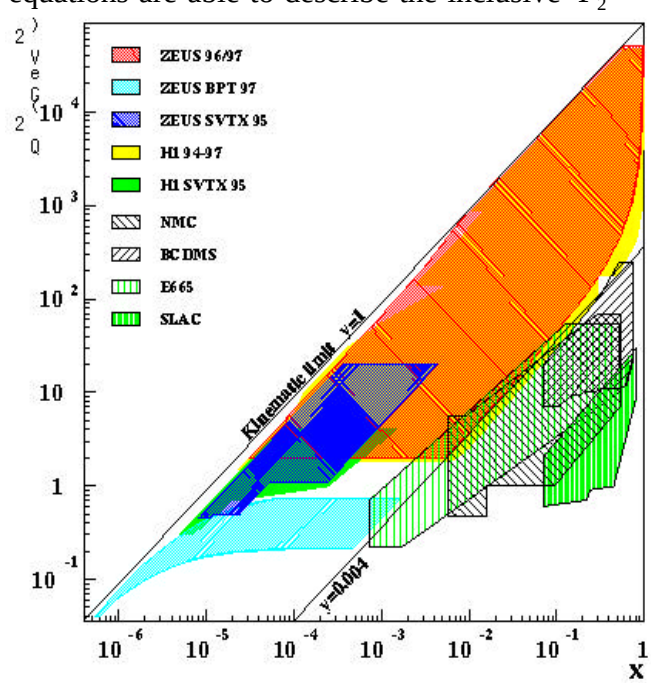
A similar statement is true for the future high-energy frontier e-p colliders being discussed here. Therefore e-p colliders should not try to compete with LHC, TESLA or VLHC in the fields where these accelerators have their strongest research potential, but e-p colliders can be highly complementary to the short distance frontier of particle physics.

3. Physics Priorities at a Future e-p Collider

HERA was planned as a tool to investigate electro-weak unification in deep inelastic neutral and charged current scattering, to measure proton structure functions, and to search for new physics in the 100GeV center of mass energy range. It could also discover a wide range of exotic physics signatures, e.g. leptoquarks, quark sub-structure, excited electrons, SUSY, and others, as well as to measure proton structure functions. So far, HERA was most powerful in its contributions to the understanding of the physics of small momentum fraction partons – low x physics. After the ongoing luminosity upgrade of HERA, a program of high x and high Q^2 will be pursued in the next few years to probe the electro-weak physics sector and the physics beyond the Standard Model. What we can project from our experience at HERA is that a future high-energy e-p collider will be a very powerful tool to be used in the study of perturbative QCD dynamics, possible physics beyond the Standard Model at high x and high Q^2, and parton densities at low x. With sufficient luminosity, high x quarks can be studied at very high resolution – the parton density functions (pdfs) can be measured and decomposed by flavor. Finally, at higher center of mass energies ($\sqrt{s}$), searches for new physics that might only couple to e-p interactions can be performed.

a) Perturbative QCD Dynamics at Low x

Parton evolution has traditionally been described by sets of linear equations denoted by : DGLAP (evolution in Q^2 at fixed x), BFKL (evolution in 1/x at fixed Q^2), and DLLA (evolution in both variables). At HERA, even at small x, the DGLAP equations are able to describe the inclusive F_2 structure function data – as long as the input gluon distribution at some small scale is large enough. Figure 1 shows the range in x and Q^2 which has been accessed with HERA.



If extremely low x values became accessible at future lepton-hadron colliders, non-linear effects in parton evolution should begin to show up in the data. At some point unitarity constraints require that parton evolution saturates (evolution is balanced by parton re-combinations). This is a region of highly non-linear behavior even though the coupling is small, because the density of states is at its maximum value. For inclusive measurements, this unitarity boundary should be reached at $x \approx 10^{-6}$ with $Q^2 = 10\ \mathrm{GeV}^2$.

Figure 1: Range of HERA in x and Q^2

Finally, the approach to the high density QCD regime may start in small regions of the proton before spreading throughout its volume. This phenomenon can be studied by choosing forward-going jets, which represent scattering from a small region of the proton at low x. The rise in cross section as x decreases, but with the jet momentum fraction kept fixed, could show saturation effects if they exist. These small regions have been denoted "hot spots".

b) Proton Structure

At a future e-p collider, the kinematic reach for inclusive measurements of the proton structure function, $F_2(x, Q^2)$, could be extended both x and Q^2 by several orders of magnitude over the regime of HERA. Flavor decomposition comes from substituting positrons for electrons and from exclusive measurements using vertex tagging or exclusive meson production. These methods have strong implications for detector design of a future collider. An e-p collider is the best place to measure structure functions, which will be important in the understanding of potential new physics signals in hadron-hadron collisions at RHIC, LHC, or VLHC.

c) Beyond the Standard Model

Probably the most obvious choice to search for new physics at a future e-p collider concerns leptoquarks. Evidence for R-parity violating SUSY has the same signature as a leptoquark in e-p scattering, so this would also be a natural search topic. If leptoquarks are found, a future e-p collider would be an ideal place to study, e.g., spins, fermion numbers, and branching fractions of these objects. With unpolarized proton beams one will discover these processes if they exist, polarized proton beams would be essential to understand the helicity structures and properties.

4. Why polarized e-p or e-d ?

For the proton there are two spin independent structure functions $F_1(x, Q^2)$ and $F_2(x, Q^2)$ which are determined by electromagnetic unpolarized e-p scattering. One of the principal interests and accomplishments of HERA research has been the accurate measurement of F_2 for very small x and high Q^2 and the observation of the rapid rise of F_2 at small x. This has provided a critical test of perturbative quantum chromodynamics (pQCD) in the region where the gluon density is high and it is of major theoretical interest. The spin dependent structure function $g_1(x, Q^2)$ provides information on the spin structure of the proton and its importance is comparable to that of F_2. It will be most valuable to extend greatly with a polarized e-p collider the kinematic range of information on g_1. With present fixed target data on $g_1(x, Q^2)$ the range is $0.003<x<0.7$ with $1<Q^2<100\ \mathrm{GeV}^2$. The region in x and Q^2 which have been accessed so far are shown in Figure 2. A polarized collider could extend the region to lower x by a factor of 10 to 1000 and to higher Q^2 also by a factor of 10 to 1000.

pQCD predicts that $g_1(x, Q^2)$ will decrease dramatically at low x where the gluon density is high, in contrast to the observed rapid rise in F_2 at low x. Such behavior would provide an important test of pQCD. In particular, g_1 is sensitive to large logarithms of 1/x, having a (ln 1/x)^2 dependence, and thus perturbative low-x effects are much more strongly enhanced than for non-polarized structure function measurements.

With a polarized collider data on $g_1(x, Q^2)$ the polarized gluon distribution function $\Delta G(x, Q^2)$ and its first moment $\int_0^1 \Delta G(x, Q^2)dx$ could be determined through the evaluation of the spin structure functions which is predicted by perturbative QCD. The

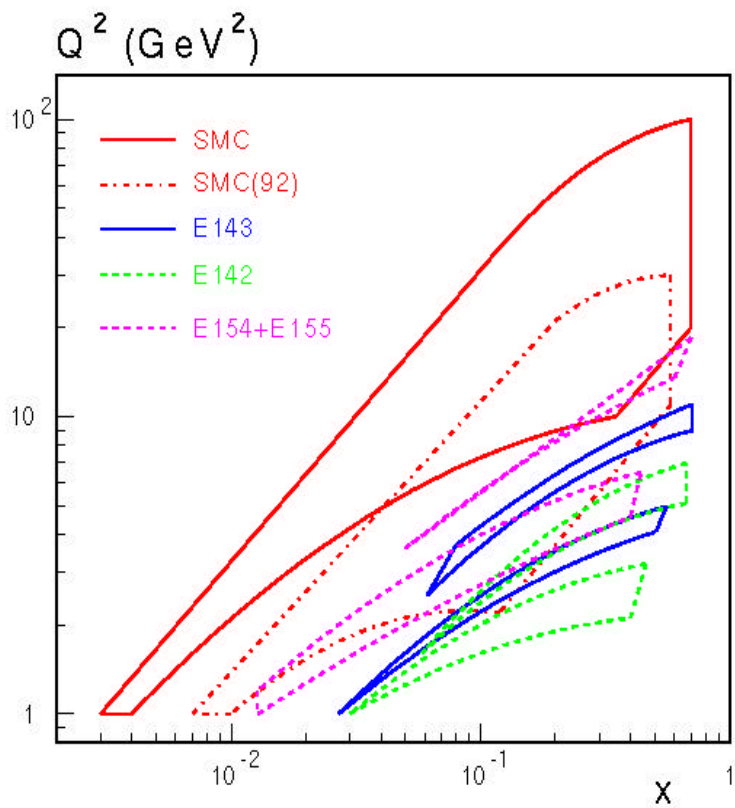


Figure 2: Present polarized physics range in x and Q^2

quantities $\Delta G(x, Q^2)$ and $\int_0^1 \Delta G(x, Q^2)dx$ which are of central importance for the proton spin structure, are largely unknown at present and are needed to solve the nucleon spin puzzle. This is the main focus of the COMPASS experiment at CERN and the experiments at RHIC which will collect polarized p-p data. The big trump card of e-p collisions at high energy at eRHIC, HERA, or THERA is the additional sensitivity to the polarized gluon density via photon gluon fusion (PGF) processes through direct observation of, for example, dijets. Realistic studies of the data obtainable on $g_1(x, Q^2)$ and on ΔG from dijets, which include next to leading order (NLO) treatment,

detector characteristics, and radiative corrections indicate that the data will be accurate and useful. Apart from using dijets, the polarized gluon distribution can be accessed by analyzing events with high p_T tracks, via forward-backward particle asymmetries, and by jet and particle production in photo-production events. In all, a polarized collider can access the polarized gluon distribution in a variety of different ways, allowing the gluon density to be pinned down.

Most of the topics studied now at HERA with unpolarized protons have their counterpart in polarized e-p scattering. A few examples are the following: The polarized structure function g_5 allows access so the polarized parton distributions of different quark flavors separately. Photo-production gives a unique opportunity to measure and study the polarized parton distribution in the photon, which is an entirely unexplored area as far as existing data is concerned. Disentangling of a chiral structure of any anomaly from beyond the Standard Model that could be observed becomes possible. Search limits for new phenomena at large Q^2 can be extended. One could study the polarization effects of diffraction in deep inelastic scattering that were found to be a potential referee on the perturbative or non-perturbative nature of this phenomenon. Polarization effects in the proton target region could be studied to further understand target universality. The transition from zero Q^2 to a few GeV^2 could be measured, and there are more subjects that one could mention. All of these physics programs mentioned above could be pursued at HERA if the proton beam there is polarized. All of the programs could be pursued except for the study of high Q^2 phenomena beyond the Standard Model could also be pursued with a significantly better statistical accuracy at the EIC due to its higher luminosity.

When polarized electrons are scattered off polarized, one can tag the remnant parton after the interaction and therefore distinguish between e-p and e-n scattering. This allows to determine the polarized structure functions for the neutron as well as for the proton. One of the most important spin sum rule to be tested in the recent past by polarized DIS fixed target experiment has been the Bjorken sum rule. It is one of the most fundamental relations to be tested in physics with minimal underlying assumptions. With possible future spin structure function measurements of the neutron at low x with polarized colliders one could reduce the present uncertainty in the Bjorken sum rule by factors of 10 to 15 compared to the present limits of 10%.

5. Why e-A?

The domain in which e-p and e-A colliders have unmatched merits is the domain of strong interactions. And therefore it is desirable to design a future e-p and e-A collider that is a facility for generic QCD studies. In such a facility, exploring the high-energy frontier is of secondary importance. It seems natural to expect that to explore low x phenomena, one needs to have higher center of mass energy in future lepton-hadron collisions, i.e. collisions between TESLA and HERA or electron proton collisions in the LHC or a VLHC tunnel. But it has been proposed that one could explore high parton density phenomena efficiently by using heavy nuclei at intermediate energies in the collisions instead of high-energy protons. Thus using the highest possible energy beam of nuclei at RHIC and a possible future electron beam of about 10 GeV/c one could explore low x physics phenomena such as saturation and coherence length effects. This is the essence of the motivation for the electron-ion collider (EIC) proposed at BNL or of storing ions rather than protons in HERA.

Furthermore, e-p and e-A collisions are indispensable to investigate quark and gluon interactions at distances comparable to the size of hadrons, where collective partonic degrees of motion are of importance and QCD currently has a limited predictive power. Important parameters that define the quality of a future e-p or e-A collider for that regime include:

- A large range of center of mass energies (10-100 GeV)
- Most suitable ratio of nucleon/lepton energy (10-20)
- High luminosity and quality of particle beams
- High degree of polarization in both beams.
- A large number of ion species. Heavy ions and deuterons are indispensable, but covering a large range of atomic numbers is very desirable.
- Low beam emittances
- An interaction region which allows for a full-event-detector
- Provisions of extending to p-p or p-A collision program (a three-beam-collider)

While the highest achievable luminosity of around $10^{33}\mathrm{cm}^{-2}s^{-1}$ is necessary for high precision measurements of spin asymmetries, for studies of exclusive and semi-exclusive processes, rare fluctuations of nuclear densities, and other studies, there exists a vast physics program which can be started already with luminosities three orders of magnitude smaller. As a thumb rule the beam divergences at the interaction point should be kept largely below the level of Fermi energy/nucleon energy (around $5 \cdot 10^{-4}$). Therefore the luminosity should be optimized rather by emittance reduction than by minimizing the beta function at the interaction point.

6. Detectors for Future e-p Options

Two general configurations have been considered for study – an asymmetric e-p beam configuration similar to HERA, and a more symmetric option, which could be achieved in THERA. The symmetric or asymmetric choice of beam energies has a large impact on the layout of the detectors[vi]. With ambitious attempts to either go to higher beam energies for electron and proton/hadron beams in the future colliders such as THERA at DESY, or attempts to use high intensity nuclear beams in collision facilities such as EIC at BNL, the beam optics and the detector design put severe restrictions on each other. It would be best to address these issues in an early stage of the beam and detector design of all future electron-hadron collider projects.

B. Status of HERA

Since HERA is the only operating Lepton-Hadron Collider, it is instructive to learn from its experience. Similarly H1 and ZEUS are uniquely the only operating high-energy lepton-hadron collider experiments. With a length of 6336m, HERA is the largest accelerator at DESY in Hamburg. It provides collisions between a 920GeV proton beam and a 27.5GeV polarized electron beam and supplies four high-energy-physics experiments. Besides e-p collisions in H1 and ZEUS there are

Table 1: HERA's pre-accelerators

	Protons	Electrons	
20 keV	Source	Source	150 keV
750 keV	RFQ	Linac II	450 MeV
50 MeV	Linac III	Pia	450 MeV
8 GeV	DESY III	DESY II	7 GeV
40 GeV	PETRA	PETRA	12 GeV
920 GeV	HERA-p	HERA-e	27.5 GeV

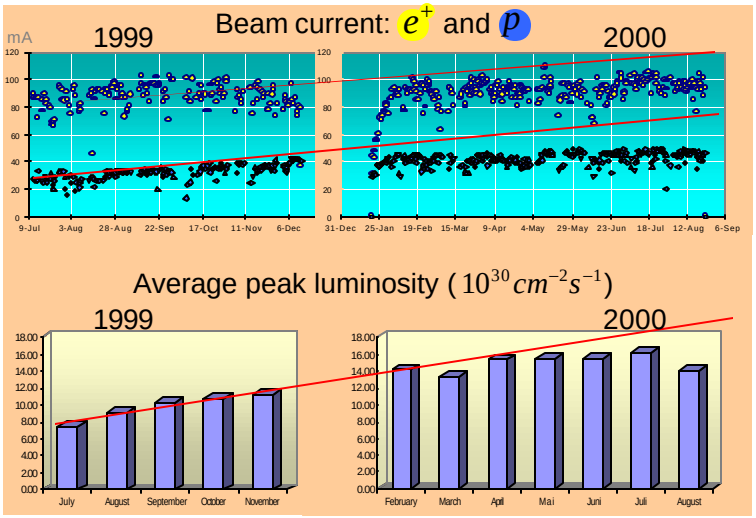


Figure 3: Improvement of HERA parameters

HERMES and HERA-B, which have a fixed target. HERA-B scrapes the proton halo with wires and HERMES has a polarized gas storage cell target in the polarized electron beam to analyze the polarized quark-gluon-structure of the nucleons. HERMES is currently the only experiment which takes advantage of the typically 60% polarization of the electron beam, since up to the year 2000, spin rotators for generating longitudinal polarization had only been installed at this experiment.

Altogether there are 10 accelerators at DESY, 8 of which are required for providing protons and electrons or positrons for HERA. This pre-accelerator complex was already installed before HERA was built. The energy of the pre-accelerators are shown in Table 1. Together with necessary changes in this complex, the construction of HERA has cost approximately $0.6B (corrected for 2001 terms).

Several parameters contribute to the integrated luminosity of HERA. Figure 3 (top) shows the beam currents. Over the years the electron current (blue, lower points) has increased to 50mA, close to its design value at 56mA. Also the proton current (yellow, upper points) has increased and currently saturates at about 100mA. These currents and slight optical modifications have lead to an increase

in the luminosity. The design value of $1.5 \cdot 10^{31} \mathrm{cm}^{-2} \mathrm{s}^{-1}$ has now been reached and surpassed (bottom). The increase in currents and in luminosity has saturated, and to obtain a further increase of luminosity an upgrade project is required. For equal proton emittances in x and y and assuming that the proton beam size at the interaction point (IP) can always be matched by the electron beam, the luminosity can be increased by boosting the proton phase space density, by increasing the e current, or by a decrease of the p beta functions at the collision point. These three measures have been found to be about equally expensive but modifying the interaction region for obtaining smaller beta functions was found to be the safest method. In order to focus the proton beam more strongly in the experimental region, shown in Figure 4, the electron beam has to be separated from the proton beam as early as possible[i,ii,iii,iv]. Whereas the first proton quadruple is currently 26m after the IP this distance will be only 10m after the luminosity upgrade. Additionally the upgrade project includes 60m long spin rotators at both sides of the H1

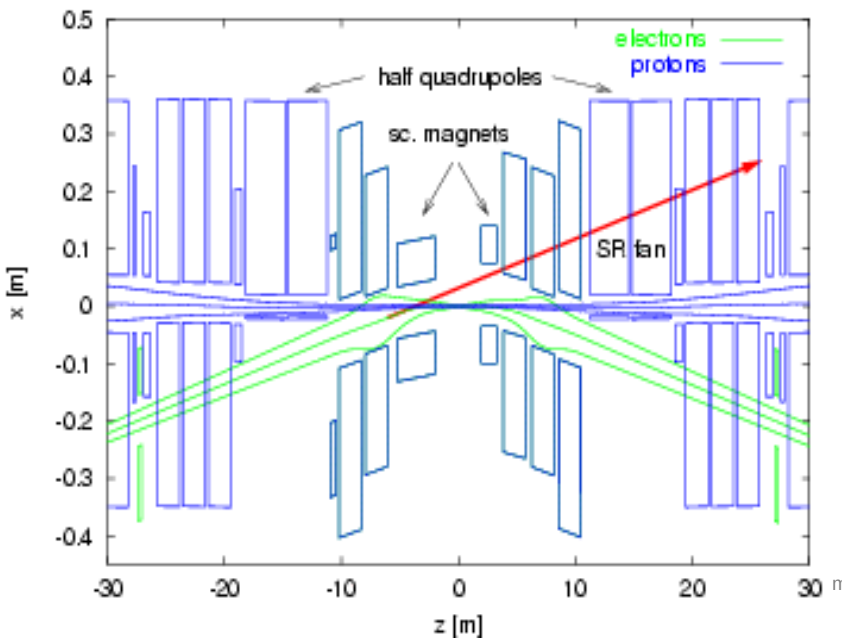


Figure 4: HERA's upgraded interaction region

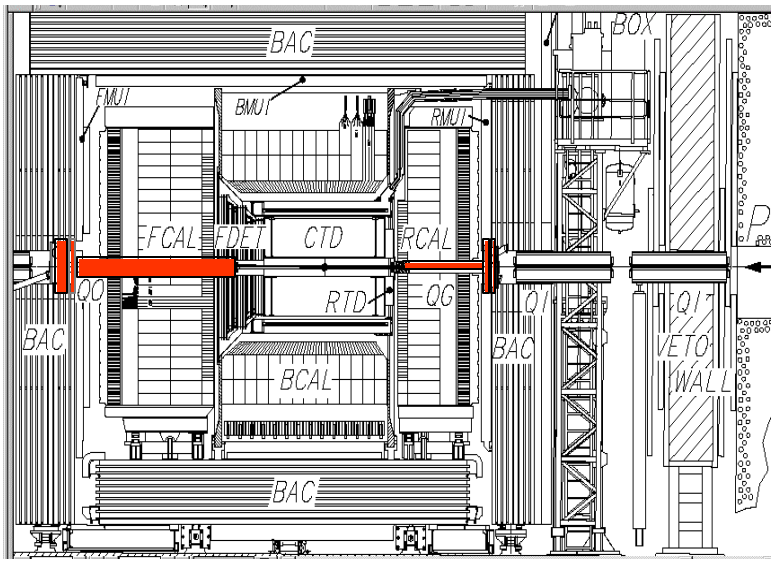


Figure 5: Superconducting magnets inside HERA's detectors

and ZEUS detectors. The complete upgrade involves 448m of new vacuum pipes, 4 superconducting magnets for early separation of the e and p beams inside the detectors with a distance of only 2m from the IP, and 54 normal conducting magnets. The superconducting magnets were built by BNL whereas the Efremov Institute in St. Petersburg built the normal conducting magnets.

While the magnet arrangement around the detectors is currently symmetric, it will no longer be symmetric after the upgrade as shown in Figure 5. Due to the bends inside the detectors the synchrotron radiation can no longer be collimated before the experiment but has to be guided through the beam pipe. Starting at 11m after the IP, the radiation fan has its own beam pipe leading to a radiation absorber. Scattered electrons are collimated before the detector by a bend section, and gas scattering close to the detector is minimized by as many NEG pumps as possible.

Owing to the simultaneous presence of the proton beam, the electron beam, and the synchrotron radiation beam, some of the vacuum components are quite complicated.

Table 2: Major parameters of HERA before and after the luminosity upgrade

Parameter	up to 2000		after the upgrade	
	HERA-e	HERA-p	HERA-e	HERA-p
E(GeV)	27.5	920	27.5	920
I(mA)	50	100	58	140
$N_{ppb}(10^{10})$	3.5	7.3	4.0	10.3
n_{tot}/n_{col}	189/174	180/174	189/174	180/174
$\beta_x^\star/\beta_y^\star$(m)	0.90/0.60	7.0/0.5	0.63/0.26	2.45/0.18
ϵ_x(nm)	41	$\frac{5000}{\beta\gamma}$	20	$\frac{5000}{\beta\gamma}$
ϵ_y/ϵ_x	10%	1	17%	1
$\sigma_x/\sigma_y(\mu$m)	192/50	189/50	112/30	112/30
σ_z(mm)	11.2	191	10.3	191
$2\Delta\nu_x$	0.024	0.0026	0.068	0.0031
$2\Delta\nu_y$	0.061	0.0007	0.103	0.0009
$\mathcal{L}(\mathrm{cm}^{-2}\mathrm{s}^{-1})$	$16.9\cdot10^{30}$		$75.7\cdot10^{30}$	
$\mathcal{L}_s(\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{mA}^{-2})$	$0.66\cdot10^{30}$		$1.82\cdot10^{30}$	

The detectors themselves have also needed major rebuilds. Previously there were no magnets inside the detector except of its huge solenoid for particle identification and the corresponding compensation solenoid. Now, after the luminosity upgrade, there are two combined function magnets inside each detector which are superconducting, not to obtain strong fields, but to allow for a small diameter which can be fitted inside the detectors. The compensation solenoid has been eliminated and coupling compensation will be done by skew quadrupole windings in these superconducting magnets. Together with the asymmetry of the interaction region, this makes spin matching more difficult and providing longitudinal electron polarization in the experiment becomes quite challenging.

Important parameters of the luminosity upgrade project are shown in Table 2. One of the critical points will be the exceptionally large vertical electron beam-beam tune shift due to the 2 collider experiments. The luminosity and the specific luminosity are given in the conventional units of $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and $\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{mA}^{-2}$.

C. *Technology of Future Lepton-Hadron Colliders*

Working group M5 on lepton hadron colliders has not emphasized HERA, but has focused instead on the new lepton-hadron collider possibilities which have been proposed within the last few years. These projects use a stored proton or ion beam and collide these particles with electrons or positrons from either a storage ring or from a linac. While conventional linacs can only provide a comparatively low current yielding lower luminosity than comparable ring-ring colliders, the novel technology of energy-recovery linacs might increase the available current drastically, so that energy-recovery linac-ring colliders might become the favored technology for reaching high luminosities. To achieve the desired luminosity, the intra-beam scattering rates have to be compensated by cooling of the high-energy hadron beams. For protons cooling is helpful but avoidable when a moderate loss of luminosity is accepted, but for ions it is mandatory. Most of the

proposed lepton-hadron colliders require polarized electrons or positron and polarized proton or deuteron beam. One more issue which will be common to all future lepton-hadron colliders is the desire to analyze scattering at very small Bjorken x and therefore in the extreme forward direction. This requires detectors that are partially integrated in the beam pipe and therefore impinges with the interaction region design of the colliders.

These items concerning the technology of future lepton-hadron colliders will be covered one by one in the following sections.

1. Ring-Ring and Linac-Ring Colliders

A lepton-hadron collider can comprise either an electron linac colliding with a proton or ion ring accelerator, or, like HERA, it can comprise an electron ring accelerator next to a hadron ring. Electron-proton colliders with center of mass energies between 14GeV and 1000GeV and luminosities up to the 10^{33} level have been proposed recently[v,vi,vii,viii,ix]. Longitudinal polarization of the electron beam in the interaction region at the 50% to 80% level appears to be crucial for the majority of experiments. Linac-ring colliders provide an alternative to the traditional ring-ring accelerator designs[x]. Although linac-ring colliders are not as well understood as ring-ring colliders, comparable luminosities appear feasible, while the linac-ring option presents significant advantages with spin manipulations, reduction of synchrotron radiation load in the interaction region due to the absence of spin rotators, and a wide range of continuous energy variability. Due to RF power and beam dump requirements, the linac-ring luminosity can only compete with the luminosity of a comparable ring-ring collider if the electron linac recovers the beam energy. This technology was demonstrated at Jefferson Lab's IR FEL, with cw current up to 5mA and beam energy up to 50MeV[xi]. Also JEARI has successfully operated an energy recovered FEL.

Energy recovery is the process by which the energy invested in accelerating a beam is returned to the rf cavities by decelerating the same beam. Some of the benefits of energy recovery are: a) the required rf power becomes nearly independent of beam current, b) the overall system efficiency is increased, c) the electron beam power to be disposed of at the beam dumps is reduced by the ratio of final to injected energy.
Self-consistent sets of parameters for electron-proton linac-ring colliders have been developed and are presented in Table 1. The first two point designs correspond to 50GeV protons colliding with 5 GeV electrons[xii], the third design, eRHIC, is based on the existing RHIC storage ring. The linac technology assumed here uses TESLA cavities operating at Q_0 of approximately $1 \cdot 10^{10}$ and accelerating gradient of approximately 20MV/m.

Accelerator physics topics relevant to the proton ring include intra-beam scattering, collective instabilities, and the emittance growth of the electron beam due to a single collision with the protons. All these effects impose limitations of the proton bunch population. The intra-beam scattering diffusion rates are such that electron cooling of the protons would be required. Accelerator physics topics relevant to the energy-recovery linacs include transport and beam-loss issues, Higher Order Mode power dissipation, multipass, multi-bunch Beam Breakup (BBU) instabilities, and the beam-beam induced head-tail instability, the latter possibly being the limiting mechanism.

Luminosities at the 10^{33} level appear attainable in the three linac-ring machines. No showstoppers have been found but a number of important issues have been identified that would require focused R&D before such a facility is designed and built. These topics include: a) Development of a high current polarized electron source that delivers about 250mA with about 80% polarization. Currently the state of the art for 80% polarized sources is 1mA[xiii,xiv]. b) Demonstration of high current (about 200mA) energy recovery, which includes understanding and controlling beam loss, possibly developing feedback for the multibunch BBU instability, and understanding of HOM power dissipation issues. c) High-energy electron cooling and its ramifications for Laslett and beam-beam tuneshifts. d) Theoretical and, if possible, experimental investigation of the beam-beam kink instability and feedback.

In order to reduce the average current in the energy recovery linac, the use of a hybrid version of a linac-ring and ring-ring collider has been suggested where a high peak current of around 250mA could fill an electron ring in which the bunches rotate for 50 turns before their energy is recovered. This would reduce the average current of polarized electrons to 5mA.

2. Energy-Recovery Linac (ERL)

Over the past several decades, several recirculated superconducting-RF (SRF) systems have been built for nuclear physics and FEL applications. The Stanford SCA is a 2 pass system with 50 μA and 100MeV per pass, and has an 1.3GHz RF system. The University of Illinois had a 6 pass system with 1 μA and 20MeV per pass, and also has a 1.3GHz RF system. The SDALINAC at the Darmstadt University of Technology has a 3 pass system with 60MeV per pass, and uses a 3GHz RF system). CEBAF at Jefferson Lab is a 5 pass system with 200 μA and 1200 MeV per pass, with an RF system of 1.5GHz, and the Infrared Free Electron Laser at Jefferson Lab has 2 passes with 5000 μA and 50MeV per pass and also uses 1.5GHz cavities. While in all other applications the beam is recirculated at the accelerating phase of the RF system to increase the energy, the electrons in the IFEL recirculate at the decelerating phase so transfer their energy to the RF field. Figure 6 shows a schematic layout of this energy-recovery IFEL. These machines have demonstrated by measurements the following beam properties:

- Beam normalized emittances less than 4mm mrad at up to 60pC bunch charge.
- Short bunches at the 100fsec level.
- Small energy spread at the $3 \cdot 10^{-5}$ level.
- Easily changed electron beam polarization at the 85% level.
- Small beam losses of much less than 0.2%, which can probably be made even smaller.
- Good position and pointing stability at the several 10 μm level.

These accomplishments were all made in the context of having a CW electron accelerator with high average accelerating gradient, possible because of the development of high gradient superconducting cavities.

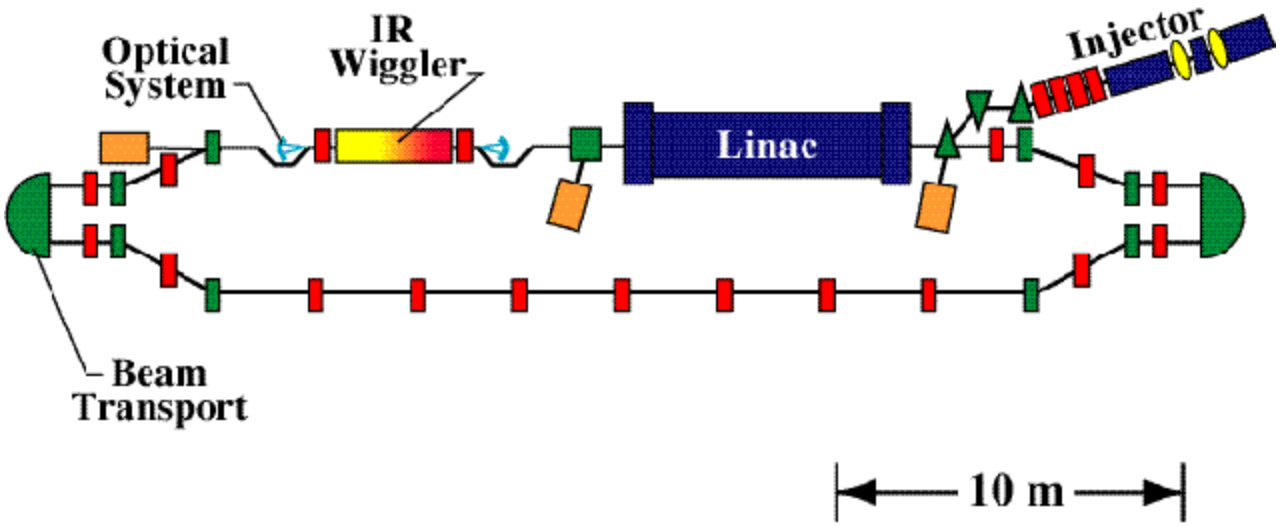


Figure 6: The Jefferson Laboratory IR FEL with energy recovery linac.

Recently, recirculating, energy-recovering linacs have attracted much attention and are being considered not only for linac-ring colliders but also for electron cooling of proton and ion beams, as drivers for synchrotron radiation sources[xv], and for high average power FELs. The following applications of energy recovery linacs will be investigated in the indicated laboratories: a) High-energy electron cooling (BNL), b) Electron-Ion Colliders (BNL, JLAB), c) Higher power lasers (JLAB), d) Recirculated linac light sources (Cornell/JLAB, BNL), 100-200mA at 7GeV are being discussed[xvi,xvii]. And to address some of the technical issues of energy recovery with a smaller scale prototype, a 50-100MeV accelerator with100-200mA of beam has been proposed to be build at Cornell.

Because the light source application seems to have smallest uncertainty and the largest efforts directed on it at present, it is highly likely that much of the development work on these ideas will be accomplished earliest by light source based work. It is interesting that this situation is in direct contrast to the situation when storage rings were developed, first for High-Energy Physics applications.

3. High-Energy Beam Cooling

The luminosity of a collider is degraded when either multiple scattering in an internal target, intra-beam scattering, or beam-beam induced diffusion processes dilute the phase space density of the hadron beam. These dilution effects can be compensated by continuous electron cooling of the hadron beam. The highest electron energy successfully used for cooling was 300keV in the Lanzhou cooler. FNAL is developing a device with 4.3MeV electrons for cooling of 8GeV antiprotons. Producing the required electron current for the static accelerating voltage is already a huge effort for these energies. The technology might be upgraded to produce maximally about 14MeV electrons, corresponding to 28GeV protons. But for higher energies a linear accelerator definitely has to be used. The electron bunch structure is adapted to the bunch structure of the ion bunches that have to be cooled so that an optimal use of the electron current is achieved. Because of the bunched electron beam, this technique is referred to as bunched-beam high-energy electron cooling.

Recombination of electrons and ions is an important effect in high-energy electron cooling. Avoiding recombination requires a large electron velocity and cooling will be poor, except if one uses a large magnetic field, typically a solenoid field, in which the electrons spiral. This is called magnetized electron cooling. To avoid enlargement of the emittance while transporting the beam through a solenoid focusing-channel, a suitable matching system must be used. One option could be the conversion of a magnetized beam to a flat beam, which can then be transported by a quadrupole channel.

It can become difficult to provide sufficient current at the required electron energy, for example at 50MeV for the 100GeV Gold beam in RHIC. Electron storage rings have been proposed to accumulate the required current. Also, energy recovery linacs could solve this problem, since they allow for much higher currents. In most circumstances they would probably be the cheaper solution. If the bunch length of the short electron bunches should be adjusted to the long ion bunches, debunching, and subsequent rebunching before the energy recovery, is required. However, whether one can also cool effectively when the electron bunches are not matched to the length of the ion bunches still has to be analyzed.

a) Electron Cooling at FNAL

The new recycler ring at FNAL accumulates antiprotons at a fixed energy of 8GeV. To reduce the longitudinal and transverse emittances by about a factor of 3 during 8 hours, this ring requires cooling. A continuous beam electron cooling system with a 0.5A electron beam at 4.3MeV is currently being constructed. The solenoid field at the gun has 600Gauss; the 20m long solenoid field of the cooling section has 150Gauss. In this cooler, the beam transport is, for the first time, not continuously magnetized. Although the geometric emittance outside the solenoids is 100 times that inside, no problematic emittance increase has been seen in simulations. The 20m long cooling section solenoid has 10 sections with a magnetic field from 50 to 150 Gauss. A field accuracy of 0.3Gauss cm is required and has been reached by adjusting steerers. The electron acceleration has already been tested, however, without the cooling section. The next step will be to transport the electron beam through the cooling section. Figure 7 shows a photo of the 5MeV Pelletron that produces the accelerating voltage.

Figure 7: The Fermilab electron cooler Pelletron accelerator.

b) High-Energy Electron Cooling at DESY

The possibility of using electron cooling to counterbalance intra-beam scattering (IBS) of ion beams during accelerator and storage at the high HERA energies for heavy ions of about 450GeV has been investigated. However, electron cooling would not only be essential for collisions of heavy ions with electrons but also the e-p luminosity could be increased by a factor of 2 and a reduction of the proton emittance would reduce depolarizing effects for polarized proton beams.

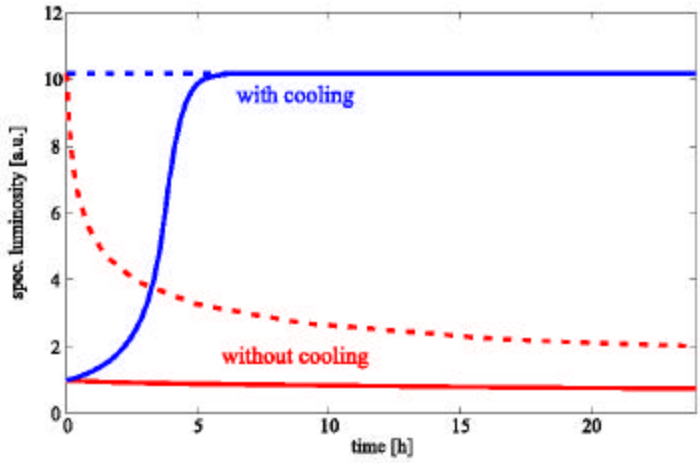


Figure 8: HERA's e-A luminosity for different cooling options in PETRA and HERA

Cooling at high energy is extremely slow since the longitudinal cooling time is roughly proportional to the 4th power of the energy and the transverse cooling time is roughly proportional to the 3rd power of the energy. However, if one had a small enough emittance at high energy to start with, the IBS could possibly be balanced since the longitudinal and transverse cooling times are proportional to the 2nd and 3rd power of the emittance. This gave rise to the idea of pre-cooling in PETRA at 15GeV[xviii,xix,xx]. The luminosity curves for 330GeV/u Gold in Figure 8 show how low the luminosity would be without cooling (red, bottom curve) and how it would diminish if only a precooler in PETRA were used. (red, bottom dashes). If there were only cooling in HERA, the luminosity would slowly rise (blue, top curve) whereas is stays high when the beam is cooled in PETRA as well as in HERA.

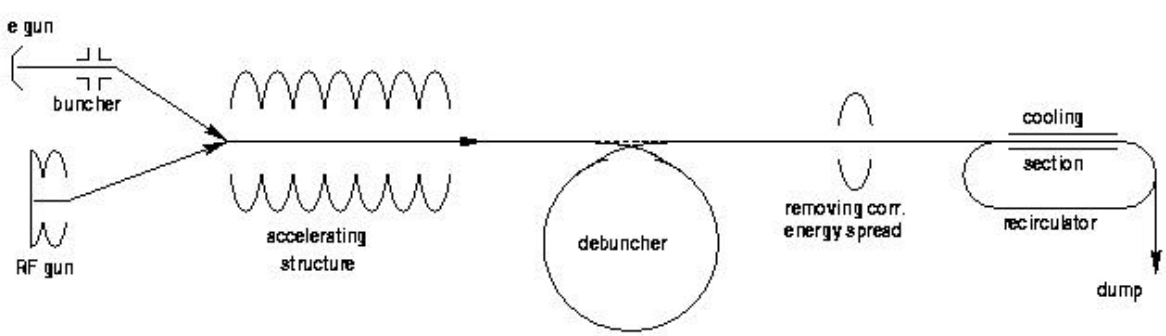


Figure 9: Setup for electron cooling of ions in PETRA

Table 3: Parameters for electron cooling in HERA

Cooler type	mag. linac		non mag. linac	storage ring (non mag.)	
Hadron	Au^{197}_{79}	proton	Au^{197}_{79}	Au^{197}_{79}	proton
L_{cool} (m)	50			120	
E_{hadron} (GeV/nucl.)	7.3	18	7.3	330	820
$\varepsilon_{Nx,h}$ (10^{-6}m) 1σ	4.0	4.0	4.0	1.0	3.3
$\varepsilon_{Ny,h}$ (10^{-6}m) 1σ	3.0	4.0	3.0	0.25	0.8
$\Delta p/p$ (10^{-4}) (hadrons)	5.0	4.0	5.0	2.7	2.1
σ_z (m) (hadrons)	0.6	0.5	0.6	0.4	0.31
N_{hadron} (10^9)	0.5	100	0.5	0.5	100
$E_{electron}$ (MeV)	4	9.8	4	180	450
$N_{electron}$ (10^9)	30		3.0	50	200
$Q_{electron}$ (nC)	5.0		0.5	8.3	33.3
I_{peak} (A)	1.2		0.12	3.1	18.1
I_{ave} (mA)	52		5.2	86	350
$\varepsilon_{Nx,e}$ (10^{-6}m) 1σ	3.0		4.0	6.3	7.0
$\varepsilon_{Ny,e}$ (10^{-6}m) 1σ	3.0		4.0	1.6	1.8
$\Delta p/p$ (10^{-4}) (electrons)	5.0			7.4	4.4
σ_z (m) (electrons)	0.5			0.32	0.22
$\tau_{IBS,l}$ (s)	630	4200	630	1080	9 * 3600
τ_{IBS} (s)	580	3600	580	1800	33 * 3600
$\tau_{cool,l}$ (s)	2	240	29	1080	9 * 3600
τ_{cool} (s)	1.5	300	22	1800	33 * 3600

There are various possible options for a pre-cooler in PETRA. For this medium energy case, magnetized as well as non-magnetized cooling were considered. For electron cooling at high energy, a large number of electrons per bunch is needed. This usually causes problems at the low energy end of the linac. The way out of this problem is to put the source as well as the linac into a solenoidal magnetic field. The proposed electron accelerator is a 7.5MeV, 208MHz traveling wave linac immersed in a magnetic field, schematically shown in Figure 9. In the following magnetized transport, the ratio of the transverse emittances outside and inside the solenoid is between 250 and 300. This makes the matching difficult and this topic has to be pursued further. Two crucial parameters for this matching are the energy spread and geometric aberrations caused by the non-linearities of the solenoids. The relative energy spread should be smaller than a few times 10^{-3}. Simulations have shown that an RF gun can yield an energy spread which is almost a factor of ten lower than that of a thermionic gun. To avoid running the RF gun in a CW mode, a recirculating electron ring is proposed. Simulations including non-linear optics, space charge, and chromatic effects confirm that the electron beam quality is preserved.

Subsequently the proton or ion emittances are kept small with an electron cooler ring in HERA sketched in Figure 10. To obtain a sufficient electron current, a storage ring option with a 120m long cooler section has been chosen. The arcs would have a diameter of 16m and would therefore not fit into the HERA tunnel, and 37 cooling wigglers at 1 Tesla reduce the damping time of the electrons. While a comparison between ring and conventional linac has shown that the ring is a better choice for HERA, an energy recovery linac might also be very attractive in the energy regime of 200MeV for ion cooling and 400MeV for proton cooling. But such an ERL cooler has not been investigated for HERA yet.

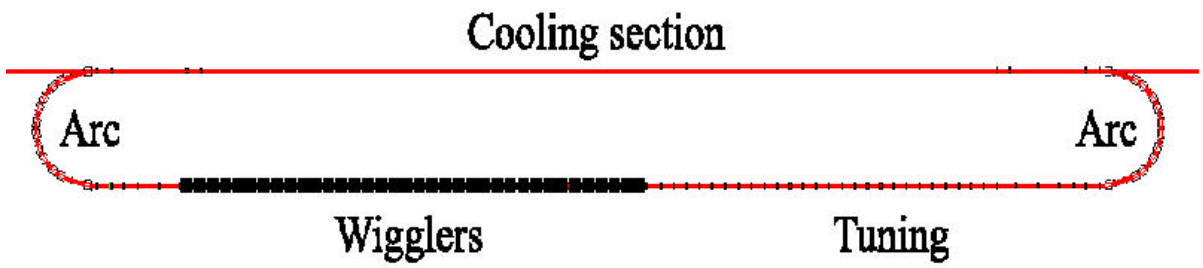


Figure 10: A cooler ring for HERA

The coolers for PETRA and for HERA would have a bunched electron beam to use the complete electron current for cooling the bunched hadron beams. For doubling the luminosity for e-p collisions for example, simulations have shown the feasibility of cooling emittances of 5mm mrad in PETRA to 3.3mm mrad horizontally and 0.8mm mrad vertically. The emittances can then be preserved at 3.8mm mrad and 0.9 in HERA.

Table 4 contains most of the parameters that are relevant for electron cooling. The hadron beam emittances for medium energy cooling are the initial values whereas for the high energy cooling the final i.e. equilibrium emittances are given. In principle these are the goals for medium energy cooling. The electron parameters are values that seem to be achievable at least according to simulations. At the bottom of Table 3, the initial cooling times are compared with the initial intra-beam scattering lifetimes for the medium energy case. For high energy cooling in HERA, the storage ring option is shown. An energy recovery cooler will certainly be very interesting, but has not been investigated yet.

While magnetized beam transport has so far always involved a solenoid, the transverse velocities and therefore the recombination of ions and electrons could be better controlled with an undulator scheme. The feasibility and efficiency of such a scheme should be the subject of a comprehensive study.

c) High-Energy Electron Cooling at RHIC

High-energy electron cooling is being developed for the Relativistic Heavy Ion Collider complex (RHIC) at Brookhaven. The work is done under a collaboration between Brookhaven National Laboratory and the Budker Institute of Nuclear Physics. Cooling of gold ions has been emphasized in a study. The results have been reported[xxi] and show that an order of magnitude increase in the luminosity of RHIC can be obtained. The RHIC cooler will use an energy recovery linac for the electron source, as shown schematically in Figure 11. Cooling will be done with about 10^{10} electrons per bunch, at an energy of 50 MeV (to cool 100 GeV/A gold ions). RHIC consists of two rings in which counter-rotating beams of particles collide head-on at up to six interaction points.

Table 4. RHIC parameter

Number of bunches per ring	60	Rms transverse emittance (cm*rad)	$1.0*10^{-4}$
Circumference (m)	3834	Momentum spread $\Delta p/p$	$1.0*10^{-3}$

Revolution frequency (kHz)	78	Bunch Length r.m.s. [m]	0.22
Horizontal tune	28.19	Beta-function at IP [m]	2
Vertical tune	29.18	Average luminosity over 10 h [$cm^{-2}s^{-1}$]	$2*10^{26}$
Transition energy γ_t	22.8	Top energy [γ]	106.6

Initial luminosity at ion*ion collision $L := \frac{Ni^2 \cdot \gamma \cdot \beta}{4 \cdot \pi \cdot \varepsilon ni \cdot \beta 0} \cdot \frac{c \cdot \beta}{Dbb}$ $L = 2.139 \times 10^{27}$ $cm^{-2}s^{-1}$ longitudinal emittance leads to losses of ions by escaping the available longitudinal bucket area and decreasing Ni.

The electron cooling can suppress the growth of beam emittances. It leads to increasing both in the peak luminosity and average luminosity by saving starting luminosity during longer period of time. The continuous cooling can help to suppress the action of nonlinear resonances at beam-beam interaction and to achieve more high beam-beam tune shift. Using cooling is helpful for controlling the beam tail that produces background in the detectors. Only cooling can offer the possibility to accumulate an intense ion beam at injection (if the injection chain cannot produce an intensive ion beam in a short time). As may be easy to see from the table above, the average luminosity over 10 hours is significantly smaller than the initial peak luminosity. The reason for this is a large growth of the transverse and longitudinal emittances as a result of inter-beam scattering (IBS) and beam-beam effect with external noise.

When we introduce electron cooling, we may introduce also new difficulties. Among the problems associated with the practical realization of electron cooling there is a process that adds a new channel of ion losses. The positive ions may capture an electron during the period that they overlap in the cooling section and drop out of the beam. The efficiency of the ion-electron recombination process is inversely proportional to the transverse velocity of the electrons at the cooling section. However, using a very high transverse electron velocity can decrease the efficiency of the cooling. The solution to this problem consists of using a strong magnetization cooling. This method was discovered at the cooling experiment on the storage ring NAP-M at INP.

The parameter for the electron beam of the electron cooler for RHIC are presented in Table 5.

Table 5. Parameters for electron cooling of gold ions in RHIC.

Parameter	Symbol	Value	Units
Electron beam energy	E_e	50	MeV
Peak electron beam current	J_e	1	A
Length of electron bunch	L_e	50	cm
Cooler fraction of ring circumference	η_e	0.0078	
Number of electron at bunch	N_e	10^{10}	
DC electron current	$Je_{DC}=e*N_e*f_b$	7.4	mA
Beta function at cooling section	β_x	60	m
Ion beam radius	$a_e=\sqrt{(\varepsilon_m*\beta_x/\gamma\beta)}$	0.08	cm
Ion beam divergence at cooling sect.	$\theta=\sqrt{(\varepsilon_m/(\beta_x\beta_y))}$	$1.3\cdot10^{-5}$	rad
Ion transverse velocity (ion's reference system)	$V_i=\gamma\beta_c\theta$	$3.8\cdot10^{7}$	cm/s
Electron beam density (ion's reference system)	n_e	10^{8}	cm^{-3}

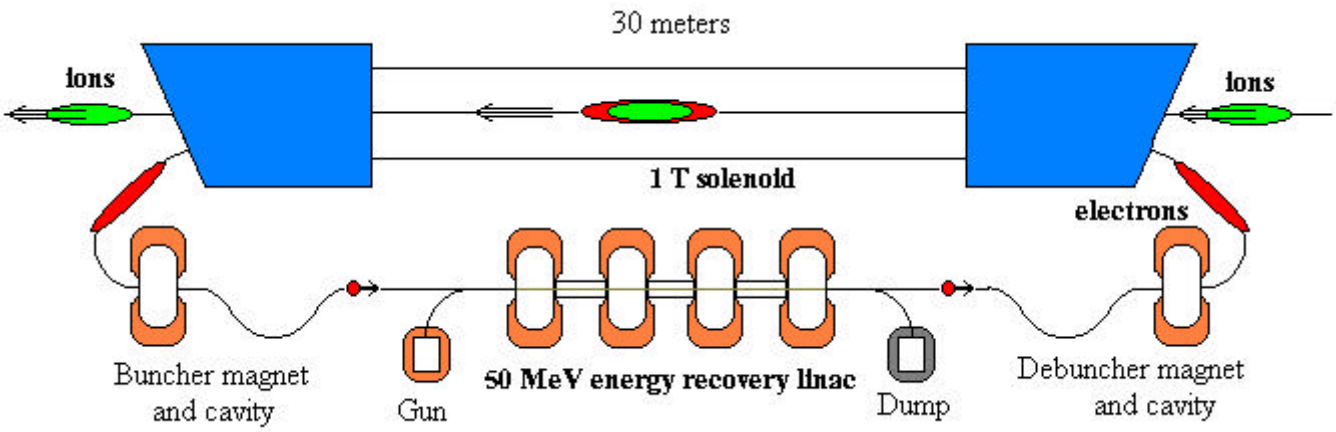


Figure 11: Schematic layout for the energy recovery linac in the RHIC cooler.

d) Stochastic Cooling

Further subjects related to high energy cooling are: bunched beam stochastic cooling and optical stochastic cooling. A high-bandwidth detection system is necessary to resolve the position of a sub-bunch of individual particles, so that a high bandwidth kicker system can subsequently correct this position. While stochastic cooling of coasting beams is regularly done in the antiproton accumulator at FNAL, it has never been tested successfully for bunched beams, although a proof-of-principle has been obtained for bunched beams in the accumulator. Whenever bunched beam stochastic cooling has been tried (TEVATRON, SPS, HERA), coherent lines in the beam spectrum made it impossible to detect the oscillations of sub-bunches, which the cooler should compensate. These lines might be due to wake fields traveling along the beam pipe, which could be absorbed before the pickup, but even then there could be modes that oscillate in the pickup itself and produce coherent lines. Subjects of R&D would be:

- Can the current state of the art bandwidth of 4GHz be increased to 10GHz
- Can the sources of coherent signals be eliminated.

Optical stochastic cooling of heavy ions can in principle be faster in proportion to the square of the ion charge compared to that of proton beams. But optical stochastic cooling has so far not been tested sufficiently to consider its application for a lepton-hadron collider in the near future. But R&D in this field should nevertheless be encouraged.

4. Polarization for Electrons, Protons, and Deuterons

a) Acceleration and Storage of Polarized Protons

The acceleration of polarized protons has been developed and tested successfully in the AGS. Figure 12 shows that a 50% polarization has been obtained at the injection energy of RHIC. This has been achieved by crossing all integer spin resonances with a partial snake and by crossing the major intrinsic spin-orbit resonances with an rf-dipole. In 2000, polarized protons were injected into RHIC for the first time. Since there was only one Siberian Snake in each ring of RHIC at that time, the polarization was horizontal. But it could be accelerated to the first depolarizing resonance and the polarization could be measured. This is a proof of principle of polarization in RHIC and acceleration of polarized beam in RHIC with two Siberian Snakes is planned for the end of the year 2001. Accelerating polarized beam in HERA will be more difficult, however, since HERA has vertical bends, it has no super period, and it operates at nearly 4 times the energy as RHIC.

b) Acceleration and Storage of Polarized Deuterons

The magnetic anomaly is –0.143 for deuterons, whereas it is 1.79 for protons. This small value of the magnetic anomaly makes Siberian Snakes impractical for deuterons. But it leaves the possibility to undertake all the measures of fast and adiabatic crossing of individual spin resonances in a ring, which were developed and implemented for polarized proton beams at the ZGS and in recent years at the AGS. Fast crossing methods seem prospective for a deuteron energy range below 100GeV, as in the EPIC collider. At higher energies of up to 250GeV in RHIC and 1TeV in HERA or in the Tevatron, the adiabatic crossing of spin resonances based on coherent beam excitation by static or RF dipoles has been estimated to be efficient. A technique with static dipoles can also be used in order to transform the injected and accelerated vertical polarization to the stable longitudinal direction in energy regimes near spin-resonance values. The possibility of RF spin flipping has also been estimated and appears to be a realistic scenario, including a possibility of RF-trapped longitudinal polarization at half-integer spin tune. In a talk by Ya.Derbenev, an exotic scheme of a twisted spin synchrotron was discussed. It has the shape of an 8 and a polarization that is up in one loop and down in the other. Such a ring could possibility have stable longitudinal spins in the whole energy range and its merits should be analyzed further.

c) Polarimetry for Protons and Deuterons

Significant R&D effort is being conducted into reliable polarimetry of circulating polarized proton beams. The very small magnetic moment of the proton makes it very difficult to use electromagnetic probes and therefore nuclear reactions with a large figure of merit (cross section times the square of the analyzing power) have traditionally been used. At lower energies elastic scattering from carbon or hydrogen targets or inclusive proton production from a carbon target give fast polarization measurements with reasonably well known analyzing powers. At energies above 20-30GeV very few reactions are known to have sizable analyzing powers. Inclusive pion production at x=0.5 and p_T=0.5GeV was measured at 200GeV and has an analyzing power of

about 20% but a polarimeter based on this reaction would require large spectrometers. Very small angle elastic scattering in the Coulomb-Nuclear-Interference region ($t \approx -0.001\text{GeV}^2$) has an analyzing power of 2-4%, which is approximately independent of beam energy. A fast polarimeter has been developed for RHIC using small angle scattering from an ultra-thin carbon target detecting the recoil carbon. For absolute beam polarization a polarized hydrogen jet target will be used which will allow the comparison of the jet polarization with the beam polarization using again the small-angle elastic scattering reaction. The jet polarization can be measured to about 3%. These last two polarimeters allow for fast and accurate polarimetry at all beam energies.

d) Polarized proton or deuteron sourses

Today polarized H^- beams can be produced either by a polarized atomic beam source (ABS) or in an optically pumped polarized ion source (OPPIS) with the record of 60% polarization for 5mA. However, experts claim that currents of up to 20mA could be possible. For polarization monitoring and optimization, polarimeters will have to be installed at several crucial places in the accelerator chain. The polarimeters up to DESY~III could be similar to the AGS polarimeters.

e) Electron Polarization Buildup

Electrons in storage rings can become spin polarized due to emission of synchrotron radiation. This is the so-called Sokolov-Ternov effect. In flat rings without uncompensated solenoids the polarization is perpendicular to the machine plane and has a maximum value of $P_{ST} = 92.4\%$. However real rings have misalignments, inhomogeneous fields, vertical bends etc and synchrotron radiation excites orbit motion. This leads to depolarization. So, synchrotron radiation not only creates polarization but also causes loss of polarization. The equilibrium polarization that can be attained is the result of a balance between the two effects.

To obtain the longitudinal polarization preferred by experimenters, the polarization vector, which is vertical in the arcs, must be rotated into the longitudinal direction before an interaction point and back to the vertical afterwards using magnet systems called spin rotators. The inclusion of rotator magnets can lead to strong depolarization if no countermeasures are taken. However this source of depolarization can in principle be combated by a special choice/adjustment of the optic called strong synchro-beta Spin-matching.

In spite of these difficulties, up to 70% longitudinal polarization *has* been achieved at high energy, namely at 27.5 GeV in the electron-proton collider HERA. Spin matching works. Up to 57% vertical polarization has been achieved at 46 GeV in LEP. In 1999 7% vertical polarization was achieved in LEP at 60 GeV.

Some new e-p or e-ion storage rings are now being considered. They require high luminosity ($10^{33}\text{cm}^{-2}\text{sec}^{-1}$ or more) and longitudinally polarized electrons and protons. With the system of spin rotators (effectively each pair represents a Siberian Snake) suggested for a 10GeV electron ring in the RHIC tunnel, the Sokolov-Ternov effect would vanish so that a pre-polarized beam would have to be injected either from a linear accelerator or from a polarizing injector. The latter has the advantage that polarized positrons could be provided. However, it is conceivable that the polarization lifetime could then be several hours with some attention to spin matching.

For a 3.5 to 7GeV electron ring of the EPIC project, the polarization rate at the central energy of 5.25 GeV would be hours unless polarizing wigglers were installed. Up to about 90% polarization might then be attained. In any case careful calculations of the rates of depolarization in such rings are essential.

Recommendations for obtaining high self-polarization or large polarization lifetime for injected polarization.

- Include polarization in the design (lattice, rotators, optic, spin matching) from the start - it should not be an "add on".
- Pay particular attention to:
  - Alignment control and beam position monitoring and provide facilities for beam-based monitor calibration so that the depolarizing effects of misalignment can be minimized and harmonic closed orbit spin matching can be facilitated.
  - Careful solenoid compensation - provide local anti-solenoids if possible.
- Use the spin transfer matrix formalism for spin matching in exotic machines and understand the physics of the spin-orbit coupling of each section of the ring. Ensure that spin matching is not hindered by a lack of independent quadrupole circuits.
- Pay close attention to polarimetry. Fast precise polarimeters are essential for facilitating fast adjustment of the orbit or tunes. Build the machine around the polarimeter(s) so that bremsstrahlung and synchrotron radiation backgrounds are avoided.
- There is plenty of software available for detailed numerical calculations. The theory of depolarization for linear orbit motion is well established.
- Very interesting depolarization effects due to beam-beam forces have been seen at HERA and LEP. For future high luminosity ring-ring colliders it will be very important to have a good understanding of these effects and to be able to carry out reliable simulations with tracking codes. This could become a high priority for running in the presence of intense proton beams.

f) Polarized Electron Sources

The development of a polarized electron source for an electron-hadron collider presents several significant challenges. The most obvious of these is that the required average current is nearly three orders of magnitude greater than the highest average current of high polarization electrons yet demonstrated. Of the various methods developed to produce polarized electron beams, only photoemission from negative electron affinity (NEA) GaAs photocathodes appears capable of delivering the necessary average current of up to about 250mA. A demonstration that GaAs photocathodes can support the delivery of high average current unpolarized beams may come reasonably soon, as part of work associated with energy-recovered linacs for light sources.

A second challenge is that of the laser to illuminate the GaAs photocathode. A laser providing about 300 Watts of 850nm light, with an appropriate time structure, is required to deliver the desired average current from a typical high polarization cathode. Such lasers do not currently exist. Even a laser supporting the desired average current from a moderate (~ 40%) polarization cathode would require some development beyond what is presently available. Some active cooling of the cathode, particularly in the high polarization case, will be necessary.

The operational lifetime of GaAs photocathodes in present day polarized sources is limited only by ion back bombardment, and thus the total charge per unit area delivered from the cathode. Accordingly, it is necessary to achieve an excellent vacuum in the cathode-anode gap of the gun to support the delivery of the required average current for a useful period of time. In the guns currently in operation at Jefferson Lab, 1/e lifetimes of the quantum efficiency of about $2 \cdot 10^5$ Coulomb/cm^2 have been observed. While this lifetime may be adequate for the electron-hadron collider application, further improvements to the vacuum are very desirable.

Surface photovoltage effects have been observed in polarized electron guns delivering large bunch charges. This effect limits the charge per bunch deliverable and may be important in the electron-hadron collider case. A group at Nagoya has demonstrated that making a cathode with a high dopant density at the cathode surface may mitigate the effect. While this solution looks promising, there has been no demonstration of a high bunch charge, high average current CW beam from a GaAs cathode. Such a demonstration is necessary before one can be fully confident this problem is under control.

The emittance requirement of 60mm mrad (normalized) for the electron beam is very modest, and permits the use of a fairly large (several cm^2) cathode area. Many of the difficulties in providing the polarized beam required for the present application would be significantly eased if there were a photoemission cathode capable of delivering high polarization with a reasonably high (few %) quantum efficiency. While no such cathode has been demonstrated, there is at least one class of materials, which in principle should meet this need. These are the ternary II-IV-V_2 chalcopyrites. These materials are not commonly available, though a number of them have been grown in the past. Photocathode preparation on these materials is difficult, but the use of atomic hydrogen cleaning may make this easier. Were the potential of these materials to be realized, an electron source for the high average current needs of an electron-hadron collider would be much easier to build.

D. Future Lepton-Hadron Colliders under Consideration

1. THERA, the TESLA on HERA collider

THERA is a genuine linac ring collider, where electrons could be accelerated through both arms of TESLA to collide with either protons or ions in the existing 6.3km 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. An interesting feature of this proposal is a traveling focus where the waist of the proton beam travels along the long proton bunch, so that the short electron beam collides with each part of the proton beam at the smallest possible proton beam diameter. The hourglass effect would be avoided. Due to the typically rather small average electron current in linacs, here around 90 A, the luminosity would be 1.6×10^{31}. In a symmetric arrangement with 500GeV beams, the luminosity would be 2.5×10^{31}.

The luminosity is limited by the electron beam power, the intra-beam scattering limit of the proton beam's emittance, and the beta function of the protons. An ambitious but not unrealistic parameter set is shown in Table 6. These parameters assume an electron energy of 250GeV, where both TESLA linacs are operated at half gradient and with twice the pulse current; the proton energy is 920GeV. The luminosity includes the effect of a crossing angle and of a reduction due to the

hourglass effect. While both scenarios require electron cooling, the optimistic schenario uses RF quadrupoles to obtain the traveling focus mentioned.

Table 6: Parameter sets for THERA

	Moderately…	optimistic
N_e p. bunch	$2.5 \cdot 10^{10}$	$2.5 \cdot 10^{10}$
rep. Rate	5Hz	5Hz
bunch spacing	211ns	211ns
pulse length	1.2ms	1.2ms
av. power P_e	28.5MW	28.5MW
N_p p. bunch	10^{11}	10^{11}
$\beta_{px,y}$	0.1m	0.1m,0.025m
$\gamma\varepsilon_{px,y}$	10^{-6} m	10^{-6}, $0.25 \cdot 10^{-6}$ m
$\sigma_{x,y}$ at IP (same e and p)	9.7µm	9.7, 2.4µm
IBS growth time	2…3h	1…1.5h
beam-beam ΔQ_p	0.003	0.0049
Luminosity	$5 \cdot 10^{30}$	$2 \cdot 10^{31}$

2. The Electron Ion Collider (EIC) Project

In the past year, the idea of a polarized electron-proton (e-p) or electron-ion (e-A) collider (EIC) of high luminosity (10^{33}cm^{-2}s^{-1} or more) and center-of-mass energies from 15 to 100 GeV has gathered momentum. A white paper was produced in March 2001 and submitted to the NSAC Long-Range Planning Meeting where a considerable range of collider scenarios was discussed. The EIC is envisaged to be a variable energy machine allowing center of mass energies between 20 and 100GeV. EIC running at high energy could be eRHIC and at low energies it could be EPIC. Both are described below. When eRHIC is built with an electron linac, it can be run at lower center of mass energies, which is the main interest of the EPIC Community.

Luminosities of 10^{33} cm^{-2}s^{-1} or more are feasible in ring-ring e-p (A) colliders with center of mass energies between 15 and 100 GeV provided modest electron cooling is applied to the proton (ion) beam. Critical beam parameters such as tune shift and bunch populations are within limits reached at present colliders. R&D is needed on electron cooling and is proposed by BNL in collaboration with the Budker Institute. Development and testing of self-polarization in booster rings, in order to inject a polarized electron beam into a collider, is proposed at Bates, again as an MIT/Budker collaboration which would lead to substantially cheaper injection schemes compared to full-energy injection linacs.

The linac-ring variants have the advantage of more flexible electron beam polarization (spin reversal and energy independence). They also show some potential for higher luminosities although this has not been borne out in the present designs. Luminosities of 10^{33} cm^{-2}s^{-1} already require much stronger electron cooling to compensate for the limited electron currents which themselves call for serious R&D efforts to reach the required thousand fold increase in polarized source beam currents and corresponding low-loss beam transport. In addition, energy recuperation from the electron beam is a necessity given the 1-3 GW of beam power which again requires R&D efforts.

Finally, there is the problem of developing suitable detector systems and matching them with the beam optics elements in the interaction regions. Because of the small bunch spacings and beta-functions required for high luminosity, space around the IP will be extremely tight, calling for novel approaches to integrated IP and detector design.

3. eRHIC, Electron-Hadron Collisions with RHIC

a) The Linac-Ring Version of eRHIC

The linac-ring collider proposed for RHIC requires an energy-recovery linac to obtain sufficient current to reach a luminosity of around $10^{33} cm^{-2} s^{-1}$. A proposed set of parameters is shown in Table 7.

This scheme is a so-called point design at this stage and no layout or detailed concept has been worked out yet. The limited electron current requires a proton emittance that is four times smaller than the corresponding ring-ring version to approach similar luminosity, which is described below. On the other hand, for this eRHIC version, the absence of extensive spin rotators and ease of spin manipulation could well be a significant advantage in view of the limited space for such devices inside the existing RHIC lattice. A complication however, is the generally accepted requirement for at least two interaction regions.

Table 7: Parameters of three point-designs for a linac-ring collider

Parameter	Units	**eRHIC**	
		e^- Linac	RHIC (p)
Beam Energy	GeV	10	250
Ring Circumference	M	-	3833
N_{bunch}	Ppb	$3x10^{10}$	$.93x10^{11}$
F_c	MHz	56	
I_{ave}	A	0.270	0.83
σ^*	µm	33	33
ε	Nm	2.5	2.5
β^*	Cm	36	36
σ_z	Cm	0.3	10
ξ_{pr}	-	-	0.0046
$\Delta\nu_L$	-	-	0.001
D_e	-	1.2	-
Luminosity	$Cm^{-2}sec^{-1}$	1.14×10^{33}	

b) Ring-Ring Version of eRHIC

There is also a proposal to use an electron ring in the RHIC tunnel, shown red in Figure 12, which can lead to a luminosity of around $10^{33} cm^{-2} s^{-1}$. A 10 GeV electron ring would be added to a polarized RHIC ring which stores 250GeV protons or 100GeV gold ions. Polarized electrons could be injected via a rather expensive 10 GeV linac. This expense could be avoided by accelerating unpolarized electrons in a 1GeV linac and using a polarizing 1-10GeV booster ring of 420m circumference with a Sokolov-Ternov polarization time of 74s. The interaction region of such a ring is rather complicated, since there are two proton beam-lines and an electron beam-line with spin rotators which all lead to a detector that can only cope with a very limited amount of synchrotron radiation. The basic specifications are shown in Table 8. The electron current of 3A is rather high, but the other parameters are reasonably conservative and may leave room for improved luminosity.

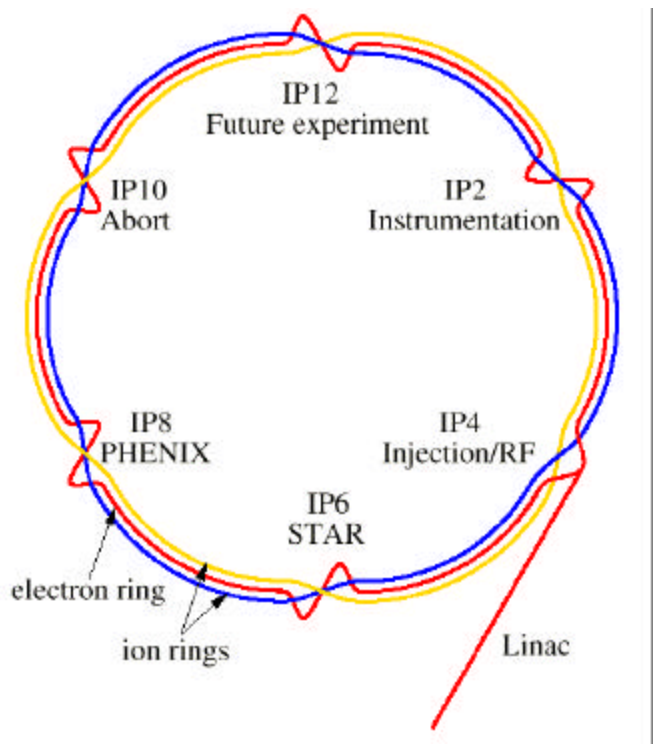


Figure 12: Ring-Ring layout of eRHIC

Table 8: Parameters for the ring-ring version of the eRHIC

	Units	Electron Ring	Proton (Au) Ring
Energy	GeV	10	250 (100)
Bunch populations, $N_{e,p}$		$1\cdot10^{11}(2.4\cdot10^{11})$	$9\cdot10^{11}(1.2\cdot10^{9})$
Collision frequency, f_c	MHz	197	
Beam sizes at IP, σ	μm	100	100
Beam emittances, ε	nm	12	12
Beta functions, at IP, β	m	0.8	0.8
Tune shifts, $\xi_{e,p}$		0.09	0.0038 (0.009)
Beam currents, $I_{e,p}$	A	2.8 (7.6)	3.2 (3.0)
Ring circumference, C	m	3833	3833
Linear radiated power	kW/m	7.5 (18.3)	-
Stored beam energy	kWs	400 (980)	9350 (9450)
Luminosity, L	$cm^{-2}s^{-1}$	$1.5\cdot10^{33}(4.6\cdot10^{31})$	

4. EPIC, the High Luminosity Electron (Polarized) Ion Collider

a) The Linac-Ring Version of EPIC

Table 9: Parameters of three point-designs for a linac-ring collider

Parameter	Units	**Point Design 1**		**Point Design 2**	
		e^- Linac	p-Ring	e^- Linac	p-Ring
Beam Energy	GeV	5	50	5	50
Ring Circumference	M	-	460	-	460
N_{bunch}	Ppb	1.1×10^{10}	1×10^{11}	1.1×10^{10}	1×10^{11}
F_C	MHz	150		150	
I_{ave}	A	0.264	2.4	0.264	2.4
σ^*	μm	25	60	25	25
ε	Nm	6	36	6	6
β^*	Cm	10	10	10	10
σ_z	Cm	0.1	10	0.1	10
ξ_{pr}	-	-	0.004	-	0.004
$\Delta\nu_L$	-	-	0.004	-	0.024
D_e	-	0.78	-	4.6	-
Luminosity	$Cm^{-2}sec^{-1}$	6.2×10^{32}		2.1×10^{33}	

The proposed electron polarized ion collider with about 32GeV center of mass energy would either be built with an electron ring or with an energy-recovery linac for 5GeV.

A detailed concept or a layout of the linac-ring collider version does not yet exist. A set of parameters for two point designs are included in the summary Table 9. Noteworthy is the very much smaller emittance required of the proton beam compared to the 32 GeV ring-ring design shown below, in order to compensate for the smaller electron current. Strong electron cooling would have to be developed to reach this emittance. The linac would yield a 5GeV electron beam whereas the ring would store 50GeV protons, or ions with the corresponding magnetic regidity.

b) The ring-ring version of EPIC

On the initiative of the MIT-Bates Linear Accelerator Center, the Budker Institute in Novosibirsk (I. A. Koop, et al.) has worked out a concept of a 3.5 to 7 GeV electron ring and a 16-32 GeV proton ring with two intersection points.[xxii] The proton ring is constructed in one plane. The spin is kept in the same plane by Siberian Snakes providing longitudinal polarization in both intersection regions for proton energies of multiples of 0.523 GeV ("magic energies"). Polarized beam is injected by a 0.5 GeV linac and a 3 GeV booster and then ramped to the final energy in the ring.

The electron ring runs above the proton ring in the arcs and descends to the intersection points in the two main straight sections. The spin is vertical in the arcs. Solenoids and dipoles in the straight sections rotate the spin into the horizontal plane. At the interaction points, polarizations are longitudinal at 5.25 GeV and rotate by ± 30° in the horizontal plane between 3.5 and 7 GeV maintaining at least 87% longitudinal polarization. A simple, but expensive injection scheme consists of accelerating polarized electrons to full energy by a linac. A potentially much cheaper scheme calls for a 1 GeV unpolarized injection, ramping the electron ring to 3.5-7 GeV, and Sokolov-Ternov polarization buildup enhanced by wigglers. This scheme needs to be tested experimentally e.g. at the Bates South Hall Ring.

Table 10: Parameters for the ring-ring version of EPIC

	Units	Electron Ring	Proton Ring
Energy	GeV	7	32
Bunch population, $N_{e,p}$		$3 \cdot 10^{10}$	$1 \cdot 10^{11}$
Collision frequency, f_c	MHz	200	
Beam sizes at IP, σ	μm	65	65
Beam emittances, ε	nm	42	42
Beta functions at IP, β	m	0.1	0.1
Tune shift, $\xi_{e,p}$		0.04	0.0026
Beam currents, $I_{e,p}$	A	1.0	3.2
Ring circumference, C	m	1387.94	1387.35
Arc radius	m	108.5	108.5
Bending radius	m	63.53	63.53
Luminosity, L	$cm^{-2}s^{-1}$	$1.1 \cdot 10^{33}$	

The specifications of the proposed collider are shown in Table 10. Both beam profiles are "round" and beta functions at the interaction point and beam emittances are the same for both beams. Bunch densities and tune shifts are within limits reached at other colliders (B factories, etc.) and can be considered conservative.

5. Upgrade Possibilities for HERA

a) Polarized protons in HERA

One long term future possibility for HERA is complementing HERA's polarized electron beam with polarized protons. Whereas the electron beam polarizes itself by emission of spin flip synchrotron radiation, the only feasible way of obtaining a high energy polarized proton beam is currently the acceleration of polarized protons after creation in a polarized H^- source[xxiii]. A proton beam at DESY is then accelerated by an RFQ to 750keV, then by the LINAC~III to 50MeV, by the DESY~III synchrotron to a momentum of 7.5GeV/c, by the PETRA synchrotron to 40GeV/c and then by HERA-p to 920GeV/c. The 4 main challenges for the DESY polarized proton project are therefore:

(1) Production of a 20mA pulsed H^- beam.
(2) Polarimetry at various stages in the acceleration chain.
(3) Acceleration through the complete accelerator chain with little loss of polarization.
(4) Storage of a polarized beam at the top energy over many hours with little loss of polarization.

After a polarized proton beam has been accelerated to the high energy of 920GeV, the polarization has to be stable for several hours in order to be useful for the experiments H1 and ZEUS. Furthermore the polarization in all parts of the beam has to be nearly parallel during this storage time.

Resonance effects can depolarize the beam at beam energies where the number of spin rotations during one turn around the ring is in resonance with the betatron tunes. First-order resonances can be avoided by fixing to an energy independent value of 0.5 by Siberian Snakes. However, can strongly vary over the beam's phase space and higher-order depolarizing resonance effects can occur at specific phase space amplitudes in the beam. After finding a stable combination of 4 Siberian Snakes, simulation of the acceleration process shows that between 75% and 85% of the polarization which was injected into HERA at 40GeV could remain at 800GeV if no misalignments would be present in the ring[xxiv]. In addition to the 4 Siberian Snakes, 8 "flattening snakes" to compensate HERA's non-flat regions and 4 spin rotators would be required.

b) Polarized deuterons in HERA

For deuterons the magnetic anomaly G and therefore spin perturbations in a transverse magnetic field are smaller by a factor of 12.5 than for protons. Furthermore the energy of deuterons in HERA would be only half of that for protons. Therefore the perturbations of spins due to transverse magnetic fields are smaller by a factor of 25 for deuterons. Additionally 25 times fewer resonances have to be crossed when accelerating a deuteron beam and the energies where resonances occur are 12.5 times further apart so that higher order effects due to an overlap are strongly reduced.

Nevertheless, rotating transverse deuteron spins into the longitudinal direction has been very difficult in the past. Novel ideas for rotating a transverse polarization into the longitudinal by means of magnetic rf dipole fields[xxv] might change this situation significantly.

c) Light and heavy Ions in HERA

To accelerate an arbitrary light or heavy ion beam in HERA, a new LINAC would be required. For deuterons or some lighter ions however the current LINAC could be used in the $2\beta\lambda$ mode which would lead to a beam which would leave the LINAC with half the speed of the proton beam. Currently the frequency sweep of the RF cavities in DESY III is about 3; it then would have to be around 6, which is intolerable. Therefore either a modified RF system in DESY III would be required or one would need to inject at a harmonic number of e.g. 22 and then rebunch to the current harmonic number 11 after acceleration to higher particle velocities. The following accelerators PETRA and HERA would also require a larger frequency sweep, but these should be achievable by rebuilding the tuners of the cavities.

With the current optics in PETRA and in HERA, the transition energy γ_t would have to be crossed during the acceleration; a complication which is currently not encountered in any of the DESY accelerators. First investigations show however that a change of optics could lead to a sufficiently reduced γ_t so that it will not have to be crossed.

To extend to heavier ions we need a new source and LINAC, also at least an order of magnitude vacuum improvement in the 8GeV synchrotron DESY III. Injection via charge exchange won't work so that a new injection system in DESY III will also be needed.

The largest remaining problem with ions in HERA is intra-beam scattering (IBS). The high energy physics community requests that the luminosity for electron nucleon scattering $A \cdot L$ for ions with A nucleons will not be smaller than the current luminosity.

Table 11 shows the number of particles per bunch N_{ppb} needed to obtain this luminosity for three different ions. The IBS times become unacceptably small for heavy ions in HERA. So that the requested luminosities can only be obtained by balancing the IBS by a cooling mechanism.

Table 11: IBS times for ions in HERA

	Ion Species		
	Deuteron	$^{16}O^{8+}$	$^{208}Pb^{82+}$
e_N (mm mrad)	2.5	2.5	2.0
N_{ppb}	$5 \cdot 10^{10}$	$6 \cdot 10^{9}$	$4.8 \cdot 10^{8}$
Sum of IBS times	140min	20min	2.5min
Luminosity	$3.5 \cdot 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	$4.4 \cdot 10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	$3.4 \cdot 10^{29}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

6. eLHC, Electron-Proton Collisions with LHC

The particle and accelerator physics of lepton-hadron collisions in the LHC tunnel were studied at La Thuile[xxvi] in 1987, at Aachen[xxvii] in 1990, and for the CERN Scientific Policy Committee in 1995[xxviii]. Since then there has been little design activity for lepton-hadron collisions in the LHC tunnel. LEP has been removed from the future LHC tunnel. The LHC will be installed close to the tunnel floor, and a future lepton ring above it. In principle, a passage for the lepton ring will be left free. The LHC Project Leader must authorize exceptions from this principle. There is no such exception up to now.

A generic lepton-hadron experiment and a generic lepton-hadron interaction region has been designed. Following[xxix,xxx], the parameters shown in Table 12 were obtained.

Table 12: Parameter list for a lepton-hadron collider in the LHC tunnel

	Leptons (e+/e-)	Hadron (p)
Beam energy	60GeV	7000GeV
Bunch population	$0.685 \cdot 10^{11}$	$1 \cdot 10^{11}$
Norm. hor./vert. emittance	1120 mm /341 mm	3.75 mm /3.75 mm
Free space to quads	$\pm$7.5m	$\pm$90m
Hor./vert. b^* at IP	0.85m/0.26m	16m/1.5m
Beam radius s of round beam at IP	89.9 mm	27.5 mm
Hor./vert. beam-beam tune shift	$30.8 \cdot 10^{-3}/30.8 \cdot 10^{-3}$	$3.4 \cdot 10^{-3}/1.0 \cdot 10^{-3}$
Number of bunches	1000	1000
Average beam current	180mA	123mA
Luminosity	$2.5 \cdot 10^{32}$ cm^{-2}s^{-1}	

The hadron bunch parameters are those in the LHC design. The amplitude functions at the IP are arrived at by approximately scaling from LEP and LHC in proportion to the distance of the first quadrupole from the interaction point. The beam-beam tune shifts and are equal to or smaller than the values observed in LEP or assumed for LHC. The lepton bunch current is smaller than in LEP.

With the assumed number of bunches k=1000 the first parasitic collisions occur at ±13 m from the IP where the two beams can be separated by 6 sigma with a full crossing angle of approximately 0.635mrad. Since the average lepton current is much higher than in LEP, the e-ring needs powerful electron injectors. The synchrotron radiation loss on a turn is 370 MeV and the radiated power is 45.6 MW, if the bending radius is 3096m as in LEP. The critical energy is E_c=155keV. The average synchrotron radiation power density of 2.1kW/m is higher than in LEP. Shielding between the lepton and hadron rings by a factor much larger than 2000 will have to be constructed to limit the synchrotron radiation power absorbed in the super-conducting hadron magnets to less than 1 W/m.

Although the polarization time in the lepton ring is only 1.43 h, the observed polarization in LEP at 60 GeV was only about 3% to 7%. This suggests that it is unlikely that useful degrees of polarization can be obtained in the lepton ring. Single-beam, single-bunch phenomena are not more harmful than they were in LEP and are expected to be in LHC, since the bunch populations are not larger. However, single-beam, coupled-bunch phenomena in the e-ring may be more severe, since the number of bunches is much larger.

Lepton-ion collisions can also be envisaged. The e-Pb luminosity was estimated to about $10^{29}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ per Pb nucleus[xxxi].

7. epVLHC, Electron-Proton Collisions with VLHC

An electron ring in the VLHC booster tunnel has also been investigated. The new proposal of the VLHC does not require a 3TeV booster. But for the previous layout an investigation was made of whether it would be sensible to produce 80GeV electron on 3TeV proton collisions in the booster tunnel during the construction period of the VLHC main tunnel. The parameters are a similar to LEP and to the LHC. The proton ring was assumed to be the low field VLHC ring.

The transmission line magnet for the protons produces very large fringe fields and these would have to be shielded out of the low field electron ring, ultimately requiring more iron than the electron ring magnets themselves.

In addition water-cooling capacities would be needed because the transmission line magnet would not require any surface facilities over the 30km circumference. If one assumes that all cooling water could be brought to Fermilab and put in the cooling ponds there, a water flow of $40\,\mathrm{m}^3$ per minute would be required.

If LEP cavities were used, the number of proton bunches and the number of electron bunches would only fit after debunching and rebunching the protons. This would lead to a collision frequency of about 10MHz and to a luminosity of about $2.6\cdot 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The total cost would have been around 1000M$.

E. Research and Development Issues for Future Lepton-Hadron Colliders

Most of the facilities discussed take advantage of existing or planned hadron storage rings and are therefore rather cost efficient. They could begin construction 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 high frequency bunch train of sufficiently high bunch charge have never been operated before and have to be developed. So far, all methods to produce high polarization in electron sources had to involve very thin cathodes with a small quantum efficiency. The use of Calcopyrites rather than GaAs for photocathodes could resolve this problem and has to be tested.

- 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 4 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.

F. List of Talks in the Working Group M5 at Snowmass 2001

Physics issues (Chair: Max Klein)
Overview of lepton hadron collision (Abhay Desphande)
Physics of electron ion collisions (Witek Krasny)

Linac-ring colliders (Chair: Brett Parker)
Linac-ring colliders (Lia Merminga)
Physics with THERA, the TESLA on HERA collider (Max Klein)
Physics with polarized beams in lepton-hadron colliders (Albert DeRoeck)
An overview of luminosity limitations (Ferdinand Willeke)

Interaction regions (Chair: Eberhard Keil)
Detector issues of lepton-hadron colliders (Witek Krasny)
The accelerator side of interaction regions (Mike Seidel)
Ideas for a linac-ring collider: TESLA on HERA (Reinhard Brinkmann)
Panel discussion about the interaction regions of various colliders

Polarization (Chair: SY Lee)
Proton polarization (Thomas Roser)
Electron polarization in rings (Desmond Barber)
Polarized deuterons in colliders (Yaroslav Derbenev)
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