A $\sqrt{s} = 1$ TeV ep COLLIDER AT FERMILAB

D. KRAKAUER, J. REPOND, J. NOREM
High Energy Physics Division, Argonne National Laboratory, Argonne, IL 60439

One of the major projects being considered for future construction at Fermilab is a Very Large Hadron Collider (VLHC). This project will require a new High Energy Booster ring, 33 km in circumference, to provide 3 TeV proton beams for injection into the VLHC. Here we discuss the possibility to build an ep collider in the VLHC Booster tunnel. A LEP-like $e^\pm$ beam (83 GeV) would collide with one of the proton beams (3 TeV) to create a $\sqrt{s} \approx 1$ TeV ep collider. Design groups at Argonne and Fermilab have established that it is feasible to build electron injection at the existing infrastructure, and provide a machine with luminosity exceeding $10^{32}$ cm$^{-2}$ s$^{-1}$.

1 Overview

There are self-evident reasons to pursue collider-based lepton-hadron DIS studies that extend the HERA physics program to even higher energies and higher integrated luminosities. Such a physics program would complement studies at the next generation of high energy $e^+e^-$ (NLC) and pp (LHC) machines in the years beyond HERA. The next generation ep collider should extend our reach in $(1/x, Q^2)$ up at least an order of magnitude, and provide at least an order of magnitude increase in delivered luminosity compared to the upgraded HERA to fully exploit the new kinematic reach. Polarized $e^\pm$ beams, and baryon/electron detectors at small angles to the beams are also good ideas.

This presentation discusses how these goals might be achieved at an ep collider sited at the High Energy Booster of a future Very Large Hadron Collider (VLHC) at Fermilab. An active team of physicists at Argonne and Fermilab have concluded that it should be possible to build, with reasonable incremental costs, an ep collider with center-of-mass energy $\sqrt{s} \approx 990$ GeV$^2$ and integrated luminosity $\int L dt \approx 1$ fb$^{-1}$/yr, that could begin operation as early as a few years after the LHC startup.

2 The VLHC at Fermilab

Along with the muon-collider, described by J. Yu in these proceedings, the VLHC is one of the two high-energy colliders being considered for the long-term future of Fermilab. The VLHC will be a superconducting proton-proton collider with $\sqrt{s} > 100$ TeV and $\mathcal{L} \sim 10^{34}$ cm$^{-2}$ s$^{-1}$. Two different designs have been considered for the magnet technology and tunnel needed to contain...
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the > 50 TeV beams; low-field (2.4 T) magnets in a 550 km ring, or high-field (12.1 T) magnets in a 90-km ring. Although technically feasible with existing technology, the machine must be ultra-inexpensive. To be practical, the accelerator designers must reduce the tunnel+magnet+beamline costs to less than 100M$ / TeV.

The VLHC requires a new fast-cycling High Energy Booster (HEB) to inject 3 TeV protons into the VLHC ring. Using the above numbers, HEB construction must be less than around 300 M$. Attaining this goal, through improved magnet construction and civil engineering, is the primary near-term milestone of the VLHC designers.

Whatever technology is chosen, it is likely that the HEB will be constructed ahead of the VLHC. One scenario has the HEB funded in advance of full VLHC approval, so HEB can serve as a working prototype and proof-of-principle to build multi-TeV machines at extremely low relative cost. The HEB will extend beyond the Fermilab boundaries, and so early approval would also give experience building accelerators offsite for the first time in America.

The HEB may be available for years before the VLHC, so various options are under consideration to utilize the 3TeV x 3TeV HEB to do physics prior to full VLHC construction. We feel strongly that an ep option would have the most credible motivation and make the best physics contributions to science of that time. We also hope that an ep machine would attract a large international collaboration.

3 Electron options at Fermilab

One proposed layout of the beam-lines is shown in Figure 1. The electron linac and positron accumulator are based on existing machines built for Argonne's 8 GeV Advanced Photon Source (APS) and can be accommodated within existing buildings at Fermilab. The magnet supplies for the (low-energy) booster and the Main Injector should allow for control of the extremely low currents needed for low-energy electron injection and transport through the existing (proton) beam elements.

APS physicists have made a zeroth order design for an electron ring in the HEB tunnel which might be constructed for a fraction of the cost of LEP while still providing quality beams for ep collisions. The total cost, the maximum electron beam energy and maximum electron current (and luminosity) are all determined by the maximum available DC RF power, which is constrained to be 50 MW in the present design. This corresponds to an 58 mA beam of electrons at 83 GeV.

Detailed estimates of beam emittances, beam tune and bunch size have
help in the 3 TeV VLHC Booster

4.3 - 4.5 GeV
Electron Linac
0.4 GeV Accumulator
0.4 GeV Booster
0.4 - 4.5 GeV
Two way lin & cut

Figure 1: Schematic diagram for injector/accelerator chain for the ep collider. The new e-beam components, including linac and positron accumulator, fit in existing halls. Both e and p beams will use the existing Fermilab Main Injector (oval) to feed the HEB (labelled "3 TeV Injector" in the diagram). For scale, note that the full circle is the existing 1 TeV Tevatron "Main Ring". The full VLHC is not shown.

Table 1 summarizes only the most basic and important parameters for the HEB ep collider, compared to HERA after its upgrade. Because the HEB will extend beyond the Fermilab boundary, the VLHC HEB ep collider is abbreviated as the "SiteBuster" from here on.

4 The SiteBuster ep Physics Program

There is insufficient space to consider the physics program in detail, but the reader is directed to the A. DeRoeck"s summary paper for a nice introduction to the topics. Here we will simply compare and contrast some differences between the SiteBuster and the other DIS-colliders discussed in this conference.

First, it is worth noting the energy asymmetry between the lepton and hadron beams is very similar at the SiteBuster $38 GeV^{3800 GeV}$ compared to HERA $38 GeV$ and so most experiences in optimizing the detector for the DIS event topologies can be carried over directly from HERA to the...
Table 1: Parameters for the SiteBuster $ep$ collider, compared to HERA

<table>
<thead>
<tr>
<th>Parameter</th>
<th>unit</th>
<th>SiteBuster $ep$</th>
<th>HERA</th>
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<tbody>
<tr>
<td>Circumference</td>
<td>km</td>
<td>34.000</td>
<td>6.336</td>
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<tr>
<td>Bend Radius</td>
<td>km</td>
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<td>0.297</td>
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<tr>
<td>$e$ current</td>
<td>A</td>
<td>0.058</td>
<td>0.058</td>
</tr>
<tr>
<td>$p$ current</td>
<td>A</td>
<td>0.420</td>
<td>0.140</td>
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<tr>
<td>$N$ bunches</td>
<td></td>
<td>&gt; 996</td>
<td>180</td>
</tr>
<tr>
<td>Luminosity$_{max}$</td>
<td>$10^{31}cm^{-2}s^{-1}$</td>
<td>45.2</td>
<td>6.90</td>
</tr>
<tr>
<td>Luminosity / Year</td>
<td>$fb^{-1}$</td>
<td>0.829</td>
<td>0.105</td>
</tr>
<tr>
<td>Electron Energy</td>
<td>GeV</td>
<td>83</td>
<td>30</td>
</tr>
<tr>
<td>Proton Energy</td>
<td>GeV</td>
<td>3000</td>
<td>900</td>
</tr>
<tr>
<td>Max $Q^2$ at $z = 0.5$</td>
<td>$10^3 GeV^2$</td>
<td>488</td>
<td>54</td>
</tr>
</tbody>
</table>

SiteBuster.

For exploring the extremely low-$z$ region, such as when searching for gluon shadowing or $F_2$-saturation, at a fixed $\sqrt{s}$ one wants to maximize the beam asymmetry. Here, the beam asymmetry favors the SiteBuster compared to $\mu p$ or $LC - HERA p$ options - where it will be difficult to detect scattered leptons in the detector at $Q^2 < 50 GeV^2$. The LEP@LHC option gives the best kinematic coverage of the low-$z$, moderate $Q^2$ region. The small angle tagger at the SiteBuster would detect electrons centered at $z \sim 4 \times 10^{-6}, Q^2 \sim 1.5 GeV^2$ but extending down to $z \sim 6 \times 10^{-7}$ at $Q^2 \sim 0.7 GeV^2$.

For measurements of $F_2$ and $xF_3$ all of the proposed experiments will have reasonable overlap with existing HERA measurements. Given $1 fb^{-1}$/yr at SiteBuster, the experiment could expect to collect nearly a million $Q^2 > 1000 GeV^2$ NC DIS events. For $e^{-}p$ scattering, there will be 50,000 each CC and NC events with $Q^2 > 9000 GeV^2$.

For studying events high $\hat{s}$ one prefers more balanced beam energies, which hurts the LEP@LHC option despite its enhanced $\sqrt{s}$. However, because the most energetic electrons get scattered to the most-forward angles, if the beams are absolutely symmetric (say 500 GeV $\times$ 1000 GeV), the highest $Q^2$ events will be lost through the proton-beam hole. Here the SiteBuster follows HERA's example and maintains full acceptance up to the highest attainable $Q^2$.

We conclude given it's low incremental cost, broad cutting-edge physics program and aggressive time frame (coincident with LHC), an $ep$ program at the HEB may be a very attractive proposal. We look forward to collaboration and encouragement of any interested colleagues.