USPAS Course
on
Recirculated and Energy Recovered
Linear Accelerators

G. A. Krafft and L. Merminga

Jefferson Lab

and

Ivan Bazarov

Cornell University

Lecture 18: ERLs for High Energy and Nuclear Physics
Outline

- Introduction
- The role of ERLs in HENP
- Nuclear Physics Motivation for Electron-Ion Colliders
- Beam Requirements
- ERL-Based Electron Cooling
- ERL-Based Electron-Ion Colliders
  - e-RHIC
  - ELIC
- Key R&D Issues
- Conclusions
The Role of ERLs in High Energy and Nuclear Physics

- Electron cooling of hadron storage rings

The requirements:
1. Low-energy
2. High brightness
3. High-Charge
4. High-current

- Provide electron beams for high-luminosity colliders.

The requirements:
1. High-energy
2. Polarization
3. High-current
A high luminosity polarized electron – light ion collider has been proposed as a powerful new microscope to probe the partonic (quarks and gluons) structure of matter.

Over the past two decades we have learned a great amount about the hadronic structure.

Some crucial questions remain open:

- What is the structure of the proton and neutron in terms of their quark and gluon constituents?
- How do quarks and gluons evolve into hadrons?
- What is the quark-gluon origin of nuclear binding?
Nuclear Physics Requirements

The features of the facility necessary to address these issues:

- **Center-of-mass energy between 20 GeV and 150 GeV**
  with energy asymmetry of ~10
- **CW Luminosity from $10^{33}$ to $10^{35}$ cm$^{-2}$ sec$^{-1}$**
- **Ion species of interest: protons, deuterons, $^3$He, heavy ions**
- **Longitudinal polarization of both beams in the interaction region $\geq 50\% - 80\%$ required for the study of generalized parton distributions and transversity**
- **Transverse polarization of ions extremely desirable**
- **Spin-flip of both beams extremely desirable**
Electron Cooling
ERL-Based Electron Cooler

RHIC electron cooler is based on a 200 mA, 55 MeV ERL 20 nC per bunch, 9.4 MHz
Luminosity of Electron Cooled RHIC (RHIC-II)

RHIC-II  Luminosity (Au 100 GeV)
N=10^9 per bunch, 112 bunches

Alexei Fedotov

<\L> = 7 \times 10^{27}

E-cooling: factor of 10 increase in average luminosity per store
### Cryo-module

- e⁻ 15-20 MeV
- Phase adjustment chicane
- SC RF Gun
- Laser
- e⁻ 4-5 MeV

### Vacuum system
- 1 MW 700 MHz Klystron
- SRF cavity
- 50 kW 700 MHz system

### Controls & Diagnostics
- Magnets, vacuum
- Laser
- Klystron PS
- Beam dump

### Klystron PS
- Klystron
- e⁻ 4-5 MeV
Two Proposed Electron-Ion Colliders

**ELIC**
- Multi-turn circulation ring for electrons
  - Lower injector current
  - Need injection / ejection
  - Partial benefit for electron beam-beam
- Very high bunch frequency
- Novel ion ring complex of “figure 8” rings
- Light ions only

**eRHIC**
- Single pass ERL
  - High e source current required
  - Simplified structure
  - Maximum benefit from beam-beam in electron machine
- Bunch frequency of RHIC
- Well known ion ring
- All ions
# eRHIC Beam Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RHIC</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ring circumference [m]</td>
<td>3834</td>
<td></td>
</tr>
<tr>
<td>Number of bunches</td>
<td>360</td>
<td></td>
</tr>
<tr>
<td>Beam rep-rate [MHz]</td>
<td>28.15</td>
<td></td>
</tr>
<tr>
<td><strong>Protons: number of bunches</strong></td>
<td>360</td>
<td>120</td>
</tr>
<tr>
<td>Beam energy [GeV]</td>
<td>26 - 250</td>
<td></td>
</tr>
<tr>
<td>Protons per bunch (max)</td>
<td>$2.0 \cdot 10^{11}$</td>
<td>$6 \cdot 10^{11}$</td>
</tr>
<tr>
<td>Normalized 96% emittance [\mu m]</td>
<td>14.5</td>
<td></td>
</tr>
<tr>
<td>$\beta^*$ [m]</td>
<td>0.26</td>
<td></td>
</tr>
<tr>
<td>RMS Bunch length [m]</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Beam-beam tune shift in eRHIC</td>
<td>0.005</td>
<td></td>
</tr>
<tr>
<td>Synchrotron tune, $Q_s$</td>
<td>0.0028</td>
<td>see [2.4]</td>
</tr>
<tr>
<td><strong>Gold ions: number of bunches</strong></td>
<td>360</td>
<td>120</td>
</tr>
<tr>
<td>Beam energy [GeV/u]</td>
<td>50 - 100</td>
<td></td>
</tr>
<tr>
<td>Ions per bunch (max)</td>
<td>$2.0 \cdot 10^9$</td>
<td>$6 \cdot 10^9$</td>
</tr>
<tr>
<td>Normalized 96% emittance [\mu m]</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>$\beta^*$ [m]</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>RMS Bunch length [m]</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Beam-beam tune shift</td>
<td>0.005</td>
<td></td>
</tr>
<tr>
<td>Synchrotron tune, $Q_s$</td>
<td>0.0026</td>
<td></td>
</tr>
<tr>
<td><strong>Electrons:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam rep-rate [MHz]</td>
<td>28.15</td>
<td>9.38</td>
</tr>
<tr>
<td>Beam energy [GeV]</td>
<td>2 - 10</td>
<td></td>
</tr>
<tr>
<td>RMS normalized emittance [\mu m]</td>
<td>5 - 50</td>
<td>for $N_e = 10^{10} / 10^{11}$ e per bunch</td>
</tr>
<tr>
<td>$\beta^*$</td>
<td>$\sim 1$ m, to fit beam-size of hadron beam</td>
<td></td>
</tr>
<tr>
<td>RMS Bunch length [m]</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Electrons per bunch</td>
<td>0.1 - $1.0 \cdot 10^{11}$</td>
<td></td>
</tr>
<tr>
<td>Charge per bunch [nC]</td>
<td>1.6 - 16</td>
<td></td>
</tr>
<tr>
<td>Average e-beam current [A]</td>
<td>0.045 - 0.45</td>
<td>0.015 - 0.15</td>
</tr>
</tbody>
</table>
ELIC Design

Ion Linac and pre-booster

Electron Cooling

3 -7 GeV electrons

30 -150 GeV light ions

Solenoid

Snake

Electron Injector

CEBAF with Energy Recovery

Beam Dump
CEBAF with Energy Recovery

- Install 50 CEBAF Upgrade (7-cell) cryomodules at gradient up to 23 MV/m
- Single-pass CEBAF energy up to 7 GeV
- After collisions with 30 - 150 GeV ions
- Electrons are decelerated for energy recovery
Circulator Ring

Injector

1/\(f_c\) \(\rightarrow\) \(\leftarrow\) \(C_{CR}/c\) \(\rightarrow\) \(\leftarrow\) \(\sim 100 \, C_{CR}/c\) \(\rightarrow\) \(\leftarrow\)
## ELIC Parameters at different CM energies

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>GeV</td>
<td>150/7</td>
<td>100/5</td>
<td>30/3</td>
</tr>
<tr>
<td>Cooling beam energy</td>
<td>MeV</td>
<td>75</td>
<td>50</td>
<td>15</td>
</tr>
<tr>
<td>Bunch collision rate</td>
<td>GHz</td>
<td>1.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of particles/bunch</td>
<td>10^10</td>
<td>.4/1.0</td>
<td>.4/1.1</td>
<td>.12/1.7</td>
</tr>
<tr>
<td>Beam current</td>
<td>A</td>
<td>1/2.4</td>
<td>1/2.7</td>
<td>.3/4.1</td>
</tr>
<tr>
<td>Cooling beam current</td>
<td>A</td>
<td>2</td>
<td>2</td>
<td>.6</td>
</tr>
<tr>
<td>Energy spread, rms</td>
<td>10^{-4}</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bunch length, rms</td>
<td>mm</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beta-star</td>
<td>mm</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal emittance, norm</td>
<td>µm</td>
<td>1/100</td>
<td>.7/70</td>
<td>.2/43</td>
</tr>
<tr>
<td>Vertical emittance, norm</td>
<td>µm</td>
<td>.04/4</td>
<td>.06/6</td>
<td>.2/43</td>
</tr>
<tr>
<td>Number of interaction points</td>
<td></td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam-beam tune shift (vertical) per IP</td>
<td></td>
<td>.01/.086</td>
<td>.01/.073</td>
<td>.01/.007</td>
</tr>
<tr>
<td>Space charge tune shift in p-beam</td>
<td></td>
<td>.015</td>
<td>.03</td>
<td>.06</td>
</tr>
<tr>
<td>Luminosity per IP*, 10^{34}</td>
<td>cm^{-2} s^{-1}</td>
<td>7.7</td>
<td>5.6</td>
<td>.8</td>
</tr>
<tr>
<td>Core &amp; luminosity IBS lifetime</td>
<td>h</td>
<td>24</td>
<td>24</td>
<td>&gt; 24</td>
</tr>
<tr>
<td>Lifetime due to background scattering</td>
<td>h</td>
<td>200</td>
<td>&gt; 200</td>
<td>&gt; 200</td>
</tr>
</tbody>
</table>
## Luminosity Evolution of ELIC

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>GeV</td>
<td>150/7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cooling beam energy</td>
<td>MeV</td>
<td>75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bunch collision rate</td>
<td>GHz</td>
<td>.15</td>
<td>.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Number of particles/bunch</td>
<td>$10^{10}$</td>
<td>.4/1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam current</td>
<td>A</td>
<td>.1/.24</td>
<td>.3/.8</td>
<td>1/2.4</td>
</tr>
<tr>
<td>Cooling beam current</td>
<td>A</td>
<td>.2</td>
<td>.6</td>
<td>2</td>
</tr>
<tr>
<td>Energy spread, rms</td>
<td>$10^{-4}$</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bunch length, rms</td>
<td>mm</td>
<td>25/5</td>
<td>10/5</td>
<td>5/5</td>
</tr>
<tr>
<td>Beta-star</td>
<td>mm</td>
<td>25</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Horizontal emittance, norm</td>
<td>µm</td>
<td>1/100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical emittance, norm</td>
<td>µm</td>
<td>.04/4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of interaction points</td>
<td></td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam-beam tune shift (vertical) per IP</td>
<td></td>
<td>.01/.086</td>
<td>.01/.086</td>
<td>.01/.086</td>
</tr>
<tr>
<td>Space charge tune shift in p-beam</td>
<td></td>
<td>.003</td>
<td>.007</td>
<td>.015</td>
</tr>
<tr>
<td>Luminosity per IP², $10^{34}$</td>
<td>cm⁻² s⁻¹</td>
<td>.15</td>
<td>1.2</td>
<td>7.7</td>
</tr>
</tbody>
</table>
Accelerator Physics & Technology of the ERL

- Electron Source
  - State of the art in high average current, polarized sources:
    ~1 mA at 80% polarization
  - State of the art in high average current, unpolarized sources:
    JLab FEL Upgrade achieved 10 mA
  - Circulator ring concept greatly reduces source requirements

- Accelerator Transport in the ERL
  - Demonstrate energy recovery with large energy ratio → more later
  - High current stability in the ERL → adequate damping of long. and transverse HOMs

- SRF/RF/Cryogenics issues
Accelerator Physics Issues of the Electron-Ion Collisions

- IR design integrated with real detector geometry
- Beam-beam head-tail instability
  - The beam-beam force due to the relative offset between the head of the proton bunch and the electron beam will deflect the electrons. The deflected electrons subsequently interact with the tail of the proton bunch through beam-beam kick
  - The electron beam acts as a transverse impedance to the proton bunch, and can lead to an instability
  - The instability has been observed in numerical simulations during the beam-beam studies of linac-ring B-Factory. Linear theory predicts threshold current.
  - Landau damping introduced by tunespread caused by electron beam and perhaps chromaticity expected to increase the threshold current of the instability.
  - Simulation methods have been developed to study the general nonlinear problem.
High Energy Demonstration of Energy Recovery at CEBAF

- Energy recovery had been demonstrated at the FEL for a single cryomodule, and has been extended in the FEL Upgrade to two (later three) cryomodules.

- **CEBAF-ER** is a high energy (GeV scale) demonstration of energy recovery – 40 cryomodules.
  
  • Demonstrate sufficient operational control of two coupled beams of substantially different energies in a common transport channel, in the presence of steering, focusing errors.
  
  • Quantify evolution of transverse phase space during acceleration and energy recovery.
  
  • Test the dynamic range of system: large ratio of final to injected beam energies.
Special installation of a $\lambda_{RF}/2$ path length delay chicane, dump and beamline diagnostics.
Demonstrated the feasibility of energy recovering a high energy (1 GeV) beam through a large (~1 km circumference), superconducting (39 cryomodules) machine.

- 80 µA of CW beam accelerated to 1055 MeV and energy recovered at 55 MeV.
- 1 µA of CW beam, accelerated to 1020 MeV and energy recovered at 20 MeV, was steered to the ER dump -> Performance limit at low injection energy.

- Tested the dynamic range on system performance by demonstrating high final-to-injector energy ratios (E_{final}/E_{inj}) of 20:1 and 50:1.
Key R&D Issues

Key R&D issues include:

- High charge per bunch and high average current polarized electron source

- High energy electron cooling of protons/ions
  - Electron cooling of 150 GeV protons requires 75 MeV electrons. Practical only if based on SRF-ERL technology, demonstrated and routinely used at the JLab FEL
  - BNL/BINF, in collaboration with JLab, pursuing an ERL-based electron cooling device for heavy ions at RHIC

- Integration of interaction region design with detector geometry

- High current and high energy demonstration of energy recovery
Conclusions

- An excellent scientific case starts developing for a high luminosity, polarized electron-light ion collider, to address fundamental questions in Hadron Physics.

- ERL-based JLab design studies have led to an approach that promises luminosities from $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$ up to nearly $10^{35} \text{ cm}^{-2} \text{ sec}^{-1}$, for electron-light ion collisions at a center-of-mass energy between 20 and 65 GeV.

- ERL-based BNL design studies have led to luminosities of $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$ up to nearly $10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$ for electrons with any ion up to 100 GeV CM.

- Planned R&D will address open readiness issues.

Many thanks to Ilan Ben-Zvi for providing part of this material.