JLEIC and Electron Cooling: An Introduction

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Collider Luminosity

- Luminosity formula: \( L = \frac{f}{2\pi} \frac{N_e N_p}{\Sigma_x \Sigma_y} \), \( \Sigma_x = (\sigma_{xe}^2 + \sigma_{xp}^2)^{1/2} \), \( \Sigma_y = (\sigma_{ye}^2 + \sigma_{yp}^2)^{1/2} \)

- General design rule: \( \sigma_{xe} = \sigma_{xp} \), \( \sigma_{ye} = \sigma_{yp} \) (for beam-beam effect)

- Beam spot size at a collision point: \( \sigma_x = (\varepsilon_x \beta^*_x)^{1/2} \)

- \( \beta \)-function characterizes the beam optics
  - It describes focusing/defocusing of the beam in the beam transport system (a ring),
  - It is determined by distribution and strength of quadrupoles (dipoles guide particle motion)
  - \( \beta^* \) is the value of \( \beta \)-function at a collision point

- \( \varepsilon_x \) is called beam emittance, it characterizes the volume a particle beam (bunch) occupies in the phase space.

- Luminosity optimization: making the beam spot size at IP as small as possible
  - \( \Rightarrow \) small \( \beta^* \) \( \Rightarrow \) better optics design \( \Rightarrow \) limited by many factors (magnet imperfection, etc)
  - \( \Rightarrow \) small beam emittance \( \varepsilon_x \) \( \Rightarrow \) damping by cooling
Reduction of Emittance

- There are many different definitions:
  - geometry (RMS) emittance
  - normalized emittance: geometric emittance multiplied by $\beta\gamma$ (a relativistic invariant)
  - 95% emittance: 4 sigma phase space volume for a Gaussian distribution

- According to Liouville's theorem, the phase space volume in a classical Hamiltonian system is an invariant; The magnet system (dipoles and quads) is a Hamiltonian system

- To achieve a reduction of beam emittance (phase space volume), one must introduce a dissipative force such that the extended system is no longer a Hamiltonian system

- This process of emittance reduction is called beam cooling

- The JLEIC electron beam has synchrotron radiation damping (strong and rapid)

- For the JLEIC proton/ion beams, energy is too low so there is no radiation damping

- Typical values of proton normalized emittance: no cooling $\sim 2$ to $3$ mm mrad
  after cooling $\sim 0.1$ to $0.5$ mm mrad
Beam Cooling

- Two types of beam cooling
  - Through feedback ➔ stochastic cooling
  - Through particle-particle (including photons) interactions/collisions ➔ electron cooling, laser cooling and muon cooling

- One important parameter is cooling time

- Stochastic cooling (pickup-kicker)
  - Cooling time ~ number or particles / signal amplifier bandwidth
  - Good for heavy ions (for RHIC, and likely JLEIC Pb)
  - Not good for protons (p vs. $^{208}$Pb$^{+82}$, 82 times more particles)
  - Coherent Electron Cooling: increasing bandwidth through SASE FEL

- Electron cooling
  - Arrange co-moving of cold electron and hot proton/ions
  - Like cold water cools hot water, cold gas cools hot gas
  - Heat diffusive motion through particle-particle interaction (Coulomb collisions)
  - Highly efficient (especially if the beam emittance is not very large, ~ a few mm mrad)
Electron Cooling: An Illustration

Theorist

Inventor

magnetized cooling

Pioneers
Multi-Step Cooling for High Performance

- **Cooling of the JLEIC protons/ions**
  - achieves a small emittance
  - achieves a short bunch length of 1 to 2 cm (with strong SRF)
  - enables ultra strong final focusing and crab crossing
  - suppresses intra-beam scatterings (IBS), maintaining beam emittance
  - expands luminosity lifetime

- **Cooling time**
  It is advantage to cool at
  - Low energy
  - When emittance is not big
  \[
  \tau_{cool} \sim \gamma^2 \frac{\Delta \gamma}{\gamma} \sigma_z \varepsilon_{4d}
  \]

- **Multi-step scheme**
  - taking advantages of high cooling efficiency at low energy or/and with small emittance
**JLEIC Multi-Step Cooling Scheme**

<table>
<thead>
<tr>
<th>Ring</th>
<th>Cooler</th>
<th>Function</th>
<th>Ion energy</th>
<th>Electron energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Booster ring</td>
<td>DC</td>
<td>Injection/accumulation of positive ions</td>
<td>0.11 ~ 0.19 (injection)</td>
<td>0.062 ~ 0.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Emittance reduction</td>
<td>2</td>
<td>1.1</td>
</tr>
<tr>
<td>Collider ring</td>
<td>Bunched Beam (BB)</td>
<td>Maintain emittance during stacking</td>
<td>7.9</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maintain emittance</td>
<td>Up to 100</td>
<td>Up to 55</td>
</tr>
</tbody>
</table>

- DC cooling for emittance reduction
- BB (bunched beam) cooling for emittance preservation
- We anticipate up to 2 orders of magnitude increase of combined cooling rate
DC Cooling at 2 GeV

Simulation:

- Cooling time: ~30 min at 8 GeV (from 2 $\mu$m rad to 0.5 $\mu$m rad)
- DC cooler: 10 m and 2 A

DC cooling at 8 GeV, 2 A electron current, 10 m cooling length
Such DC Cooler is Available

2 MeV DC Cooler at COSY, Juelich, Germany
What Happens if No Cooling During Beam Store (Collision)?

Intra-beam scattering (IBS) causes rapid emittance growth

Collider 100GeV 1um 0.5um 7e-4 2cm IBS

In the graph, the emittance growth is shown over time. The graph indicates that the emittance increases rapidly as time progresses, with specific time points highlighted:

- 30 min
- 60 min
- 90 min
- 120 min
- 150 min
- 180 min
- 210 min
- 240 min

The momentum spread is also shown, with parameters $\varepsilon_x$, $\varepsilon_y$, and $\delta_p/p$. The graph is from the Jefferson Lab, Thomas Jefferson National Accelerator Facility.
JLEIC Bunched Beam ERL e-Cooler

Requirement and technology challenges

- Proton collision energy up to 100 GeV
  - energy of the cooling electron beam is up to 55 MeV
  (for meeting the condition of co-moving with same velocity)
  - can not be a DC cooler, must use a SRF linac
  - Both proton and cooling electron beams are bunched with very short RMS length
- Need several ampere current (orders of magnitude beyond state-of-art)
- High beam power: ~100 MW

Technology choices

- Energy-recovery-linac (ERL)
- Magnetized beam/photo-gun
- Circulator cooler ring

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CCR</th>
<th>ERL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch revolutions in CCR</td>
<td>~25</td>
<td></td>
</tr>
<tr>
<td>Current in CCR/ERL</td>
<td>A</td>
<td>1.5/0.06</td>
</tr>
<tr>
<td>Electrons/bunch</td>
<td>$10^{10}$</td>
<td>1.25</td>
</tr>
<tr>
<td>Bunch repetition in CCR/ERL</td>
<td>MHz</td>
<td>476/30</td>
</tr>
</tbody>
</table>
Accelerator R&D

• High energy bunched beam electron cooling is essential for achieving ultra high luminosity for JLEIC, without it we loss about 3 to 5 times luminosity

• This is the No. 1 technology risk of JLEIC, hence the highest priority R&D

• We are conducting aggressive R&D on high energy electron cooling
  – Conceptual/analytic and simulation studies: design optimization and accurate production of cooling rate
  – Design of a bunched beam ERL based e-cooler (by a working group)
  – Development of key technology for this cooler: magnetized photo-cathode electron gun (LDRD), fast kicker
  – Experiment to demonstrate cooling of ions by a bunched electron beam
  – Development of a test facility using JLab LERF (formally ERL FEL) for testing a circulator electron cooler

• We have engaged in collaborations with other US lab and international institutions, and are making efforts to expend this collaborations