Spin Dynamics at Jefferson Lab Electron Ion Collider (JLEIC)

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SPIN’16, Urbana-Champaign, Sep 25-30 2016
Outline

- Introduction of Jefferson Lab Electron-Ion Collider (JLEIC) design

- JLEIC polarization design and simulation
  - Ion polarization
  - Electron polarization

- Summary and Outlook
Electron Ion Collider

Recommendations in NSAC LRP 2015:

1. Continue existing projects: CEBAF, FRIB, RHIC.
2. “…a U.S.-led ton-scale neutrinoless double beta decay experiment”
3. “…a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB”
4. “…small-scale and mid-scale projects and initiatives that enable forefront research at universities and laboratories”

EIC Community White Paper arXiv:1212.1701

- Highly polarized (~70%) electron and nucleon beams
- Ion beams from deuteron to the heaviest nuclei (uranium or lead)
- Variable center of mass energies from ~20 – ~100 GeV, upgradable to ~140 GeV
- High collision luminosity ~10^{33-34} cm^{-2} s^{-1}
- Possibilities of having more than one interaction region
JLEIC Baseline Design

2012

arXiv:1209.0757

2015

arXiv:1504.07961

arXiv:1209.0757

- Electron complex
  - CEBAF
  - Electron collider ring
- Ion complex
  - Ion source
  - Linac
  - Booster
  - Ion collider ring
JLEIC Strategy for High Luminosity and Polarization

High Luminosity
- Based on high bunch repetition rate CW colliding beams
  \[ L = \frac{f n_1 n_2}{4\pi \sigma_x \sigma_y} \sim \frac{n_1 n_2}{\varepsilon \beta_y} \]
- KEK-B reached > $2 \times 10^{34}$ /cm$^2$/s

High Polarization
- Collider rings are in a figure-8 shape → critical advantages for both beams
- Spin precessions in the left & right parts of the ring are exactly cancelled
- Net spin precession (spin tune) is zero, thus energy independent
- Spin can be controlled & stabilized by small solenoids or other compact spin rotators

Excellent Detector integration
Interaction region is designed to support
- Full acceptance detection (including forward tagging)
- Low detector background
e-p Collision Luminosity

Luminosity ($10^{33} \text{ cm}^{-2} \text{s}^{-1}$) vs CM energy (GeV)

A full acceptance detector (baseline)
A high luminosity detector

- e: 4 GeV, P: 75 GeV
- e: 4 GeV, P: 50 GeV
- e: 5 GeV, P: 100 GeV
- e: 10 GeV, P: 100 GeV

$10^{34}$
$10^{33}$

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Spin Motion in Figure-8 Ring

- Properties of a figure-8 structure
  - Spin precessions in the two arcs are exactly cancelled
  - In an ideal structure (without perturbations) all solutions are periodic
  - The spin tune is zero independent of energy

- A figure-8 ring provides unique capabilities for polarization control
  - It allows for stabilization and control of the polarization by small field integrals
  - Spin rotators are compact, easily rampable and give no orbit distortion
  - It eliminates depolarization problem during acceleration
    - Spin tune remains constant for all ion species avoiding spin resonance crossing
  - It provides efficient polarization control of any particles including deuterons
  - It is currently the only practical way to accommodate polarized deuterons
  - Electron quantum depolarization is reduced due to energy independent spin tune
  - It allows for a spin flipping system with a spin reversal time of ~1 s
  - It makes possible ultra-high precision experiments with polarized beams
Zero-Integer Spin Resonance & Spin Stability Criterion

- The total zero-integer spin resonance strength

\[ W_0 = W_{\text{coherent}} + W_{\text{emittance}}, \quad W_{\text{emittance}} \ll W_{\text{coherent}}. \]

is composed of

- coherent part \( W_{\text{coherent}} \) due to closed orbit excursions
- incoherent part \( W_{\text{emittance}} \) due to transverse and longitudinal emittances

- The coherent part

\[ |W_0^{(k)}| = \alpha_k |\gamma G F(\theta_k)| \]

where \( F(\theta) \) is the spin response function, arises due to radial fields from

- dipole roll \( \alpha_k = \alpha_{\text{orb}} \Delta \alpha \)
- vertical quadrupole misalignments \( \alpha_k = \frac{\partial B_y}{\partial x} \frac{L}{B\rho} \Delta y \)

- Spin stability criterion

- the spin tune induced by a spin rotator must significantly exceed the strength of the zero-integer spin resonance \( \nu \gg W_0 \)
Ion Polarization Requirements

- Major JLEIC ion complex components

- Polarization design requirements
  - High polarization (~80%) of protons and light ions (d, $^3$He$^{++}$, and possibly $^6$Li$^{+++}$)
  - Both longitudinal and transverse polarization orientations available at all IPs
  - Sufficiently long polarization lifetime
  - Spin flipping
Pre-Acceleration & Spin Matching

- Polarization in Booster stabilized and preserved by a single weak solenoid
  - 0.6 T·m at 8 GeV/c
  - $\nu_d / \nu_p = 0.003 / 0.01$
- Longitudinal polarization in the straight with the solenoid
- Conventional 8 GeV accelerators require $B_{||}L$ of $\sim 30$ Tm for protons and $\sim 100$ Tm for deuterons
Spin Dynamics in Booster

- Acceleration in figure-8 booster with transverse quadrupole misalignments
- 0.3 Tm (maximum) spin stabilizing solenoid

- Spin tracking simulation using Zgoubi (developed by F. Meot, BNL)

\[ \beta, \beta_m \]

\[ x_{\text{co}}, y_{\text{co}}, \text{mm} \]

\[ x_0 = y_0 = 1 \text{ cm} \]
\[ \Delta p/p = -0.1\%, 0, 0.1\% \]

coherent part of the spin resonance strength
Polarization Control in Ion Collider Ring

- **3D spin rotator**: control of the radial, vertical, and longitudinal spin components
- Module for control of the radial component (fixed radial orbit bump)

![Diagram of 3D spin rotator]

\[ \Phi_{z10}, \Phi_{z1}, -2\Phi_y, \Phi_{z10} \]

- Module for control of the vertical component (fixed vertical orbit bump)

![Diagram of vertical control module]

- Module for control of the longitudinal component

![Diagram of longitudinal control module]

\[ L_{tot} = 7 \text{ m, } \Delta x = 15 \text{ mm, } B_{dip}^{max} = 3 \text{ T, } B_{sol}^{max} = 3.6 \text{ T} \]

\[ L_{x} = L_{y} = 0.6 \text{ m, } L_{zi} = 2 \text{ m, } L_{z10} = 1 \text{ m, } \alpha_{orb} = 0.31^\circ \]
Zero-Integer Spin Resonance in Ion Collider Ring

- Coherent part of resonance strength
  - Assuming RMS close orbit distortion of ~200 μm

- Incoherent part of resonance strength
  - Assuming normalized vertical beam emittance of 0.07 μm-rad
Compensation of Zero-Integer Resonance

- In linear approximation, the zero-integer spin resonance strength is determined by two components of spin perturbation lying in the ring’s plane
  \[ w_0 \approx w_{\text{coherent}} = w_x + i w_z \]
  and can be compensated by correcting devices whose spin rotation axis lies in the same plane.

- Additional 3D spin rotator can be used to compensate the coherent part of the zero-integer spin resonance strength.

- Spin resonance strength after compensation
  \[ w_0 \sim w_{\text{emittance}} \Rightarrow |w_0|_p < 10^{-3}, \ |w_0|_d < 10^{-5} \]

- 2T \times 4m solenoids in the 3D spin rotator allow setting proton spin tune \( \nu_p = 10^{-2} \) and deuteron spin tune \( \nu_d = 10^{-4} \).
Spin Dynamics in Ion Collider Ring

- 60 GeV/c figure-8 ion collider ring with transverse quadrupole misalignments

- Example of vertical proton polarization at IP. The 1\textsuperscript{st} 3D rotator: $\nu = 10^{-2}$, $n_y = 1$. The 2\textsuperscript{nd} 3D rotator is used for compensation of coherent part of the zero-integer spin resonance strength

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure.png}
\caption{Spin evolution with and without compensation computed by Zgoubi.}
\end{figure}
Spin Flip

- Adiabaticity criterion: spin reversal time must be much longer than spin precession period
  \[ \tau_{\text{flip}} >> 1 \text{ ms for protons and 0.1 s for deuterons} \]
- Vertical \( (h_y) \) & longitudinal \( (h_z) \) spin field components as set by the spin rotator vs time \( \Rightarrow \) Spin tune vs time (changes due to piece-wise linear shape)

Vertical \& longitudinal components of proton polarization vs time at 100 GeV/c

Protons: \( S_y \text{—green}, S_z \text{—red}. \)
Electron Polarization Requirements

- Major JLEIC electron complex components

- Electron collider ring
  - 3 – 10 GeV/c

- CEBAF

- Polarization design requirements
  - Electron polarization of 70% or above with sufficiently long lifetime
  - Longitudinal polarization at IP(s)
  - Spin flipping
Electron Polarization Strategies

- Highly vertically polarized electron beams are injected from CEBAF
  - avoid spin decoherence, simplify spin transport from CEBAF to MEIC, alleviate the detector background
- Polarization is designed to be vertical in the JLEIC arc to avoid spin diffusion and longitudinal at collision points using spin rotators
- Universal spin rotator (fixed orbit) rotates the electron polarization from 3 to 12GeV
- Desired spin flipping is implemented by changing the source polarization
- Polarization configuration with figure-8 geometry removes electron spin tune energy dependence
  - Significantly suppress the synchrotron sideband resonance
- Continuous injection of electron bunch trains from the CEBAF is considered to
  - preserve and/or replenish the electron polarization, especially at higher energies
- Spin matching in some key regions is considered to further improve polarization lifetime
- Compton polarimeter is considered to measure the electron polarization
  - Two long opposite polarized bunch trains (instead of alternate polarization between bunches) simplify the Compton polarimetry

Polarization configuration with figure-8 geometry removes electron spin tune energy dependence.
## Universal Spin Rotator (USR)

### Schematic drawing of USR

![Schematic drawing of USR](image)

*P. Chevtsov et al., Jlab-TN-10-026*

### Solenoid decoupling & Lattice function

![Solenoid decoupling & Lattice function](image)

### Parameters of USR for JLEIC

<table>
<thead>
<tr>
<th>E (GeV)</th>
<th>Solenoid 1</th>
<th>Arc Dipole 1</th>
<th>Solenoid 2</th>
<th>Arc Dipole 2</th>
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<tbody>
<tr>
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<td>Spin Rotation</td>
<td>BDL (T·m)</td>
<td>Spin Rotation</td>
<td>BDL (T·m)</td>
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<td>4$\pi/3$</td>
<td>1.91</td>
</tr>
</tbody>
</table>

*F. Lin et al., SPIN’2016, Urbana-Champaign, Sep 25-30 2016*
Electron Polarization Configuration

- Unchanged polarization in two arcs by having opposite solenoid field directions in two spin rotators in the same long straight section
  - figure-8 removes spin tune energy dependence and reduces the synchrotron sideband resonances
  - First order spin perturbation in the solenoids for off-momentum particles vanishes with opposite longitudinal solenoid fields in the pair of spin rotators in the same long straight
  - Sokolov-Ternov self-polarization process has a net depolarization effect, but the polarization lifetime is still large with highly-polarized injected electron beams
  - Two polarization states coexist in the collider ring and have the same polarization degradation

![Diagram showing electron polarization configuration](image)
Polarization Simulation

- **Spin tune scan @ 5 GeV**
  - Longitudinal field spin tuning solenoid is inserted in the straight where the polarization is longitudinal.
  - 500 particles Monte-Carlo simulation using SLICKTRACK (developed by D.P. Barber).
  - Main field errors, quads vertical misalignment and dipole role, are introduced.

- **Optimum Spin Tune 0.0267 with a 3Tm solenoid**

- **Preliminary spin tracking**
  - 10 particles Monte-Carlo simulation using Zgoubi (developed by F. Meot, BNL).
  - Initial polarization is longitudinal.
  - Perfect machine, no errors.

- Oscillation of spin components is due to the misaligned initial spin direction and invariant spin field.
- This can be experimentally calibrated by adjusting the spin rotator settings.
Continuous Injection

Continuous injection (or top-off injection or trickle injection) has been applied in many modern electron storage ring light sources to maintain a constant beam current, and colliders (such as PEP-II, SuperB) to gain the average luminosity
- Average luminosity is always near the peak luminosity
- The collider looks like a “DC” accelerator allowing an improved operational consistency

From John T. Seeman, SLAC-PUB-5933, Sep. 1992

JLEIC considers the continuous injection of the electron beams to
- Obtain a high average luminosity
- Reach a high equilibrium polarization

- Note that
  - If the beam lifetime is shorter than the polarization lifetime, continuous injection maintains the beam current and improves the polarization as well
  - If the beam lifetime is longer than the polarization lifetime, beam lifetime has to been shorten (collimation, scraping, or reduce the dynamic aperture)
Polarization w/o Cont. Injection

**Injection pattern on polarization**

![Diagram of injection pattern on polarization]

\[ FOM \propto \left\langle P^2 \right\rangle_T = \frac{\int P^2(t)dt}{T} = \frac{\tau_{\text{meas}}^2}{\tau_{\text{inj}} + \tau_{\text{meas}}} \]

\[ \Rightarrow \frac{P_{\text{ave}}}{P_i} = \sqrt{\frac{2 \tau_{\text{meas}}^2}{(1-e^{-\frac{2t}{\tau_{\text{depol}}}}) \cdot 2 \cdot \frac{\tau_{\text{inj}}}{\tau_{\text{depol}}} + \frac{\tau_{\text{meas}}}{\tau_{\text{depol}}}}} \]

- \( P_i \): Initial polarization
- \( \tau_{\text{inj}} \): Injection time
- \( \tau_{\text{depol}} \): Depolarization time
- \( \tau_{\text{meas}} \): Measurement time

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>( \tau_{\text{inj}} ) (min)</th>
<th>( \tau_{\text{opt_meas}} ) (min)</th>
<th>( \frac{P_{\text{ave}}}{P_i} ) max</th>
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<td>0.8</td>
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<tr>
<td>10</td>
<td>0.5</td>
<td>2.5</td>
<td>0.86</td>
</tr>
</tbody>
</table>
Polarization w Cont. Injection

- Polarization w/ continuous injection
  \[ P_{i+\Delta t} = (1 - \frac{\Delta N}{N})(P_i + \frac{\Delta P_i}{\Delta t}) + \frac{\Delta N}{N} P_0 \]

- Equilibrium polarization
  \[ P_{equ} = P_0 (1 + \frac{T_{rev} I_{ring}}{\tau_{dk} I_{inj}})^{-1} \]

A relatively low average injected beam current of tens-of-nA level can maintain a high equilibrium polarization in the whole energy range.
Summary and Outlook

- JLEIC rings adopt a figure-8 shape for better preservation and control of polarization.
- Both proton and electron polarization schemes have been designed
  - Ion polarization
    - Polarized source (ABPIS) + figure-8 shape rings + weak solenoid for booster and 3D spin rotator for collider ring
  - Electron polarization
    - Polarized CEBAF + figure-8 shape ring + spin rotator + polarization configuration + continuous injection
- Spin tracking numerically validated a figure-8 based polarization control schemes for the whole JLEIC complex.

Outlook

- Study of effects of non-linear fields and higher-order spin resonances
- Evaluation and compensation of the spin effect of the detector solenoid
- Study of the effect of ion transition energy crossing on the spin
- Suppression of the beam-beam effect on the spin
Thank You for Your Attention!
Back Up
Figure-8 vs Racetrack Booster

- **Figure-8 booster**
  - Same optics for all polarized and unpolarized ion beams
  - Universally good and simple solution for polarization of any particles
  - No restriction on the field ramp rate
  - Additional arc bending angle of 150°
    - Additional integrated dipole field $BL = B_ρΔθ \sim 70 \text{Tm}$
    - Extra space for quadrupoles, etc.

- **Racetrack booster**
  - Proton & He$^3$ polarization: OK
    - Requires $\sim 10 \text{ m}$ long Siberian snake with $\sim 30 \text{Tm}$ longitudinal field integral
    - Snake field must ramp with energy
    - Different optics for each ion species
    - Allows one to shorten circumference by about 10 m

  - Deuteron polarization: OK with fast ramp
    - Can be handled with care
    - Field ramp rate must be $>\sim 1 \text{T/s}$
    - Betatron tune jumps may be needed to cross spin resonances (this technique changes the optics during jumps)
**Figure-8 vs Racetrack Collider Ring**

- **Figure 8 collider ring**
  - Same optics for all polarized and unpolarized ion beams
  - Good for polarization
  - Stable optics during acceleration and spin manipulation
  - Additional arc bending angle of 163.4°
    - Additional integrated dipole field BL ~ 950 Tm
    - Extra space for quadrupoles, etc.

- **Racetrack collider ring**
  - **Proton polarization:** probably OK but challenging
    - Problem with optics stability especially at low energies
    - Requires two full dipole Siberian snakes with a total field integral of ~50 Tm
    - Figure-8 features can be preserved
    - At low energies of ~8 GeV, the snakes introduce a significant tune shift (~0.2), which must be compensated; the tune shift changes nonlinearly with energy \( \gamma^{-2} \)
  - **Deuteron polarization:** realistically NO
    - Cannot be preserved unless the ramp time to 100 GeV/c is less than ~1 s
      - At the present acceleration rate, polarization is lost by ~10 GeV/c
    - Even if polarization is preserved during acceleration, there is no guarantee of sufficient polarization lifetime; in fact, it will most likely be short