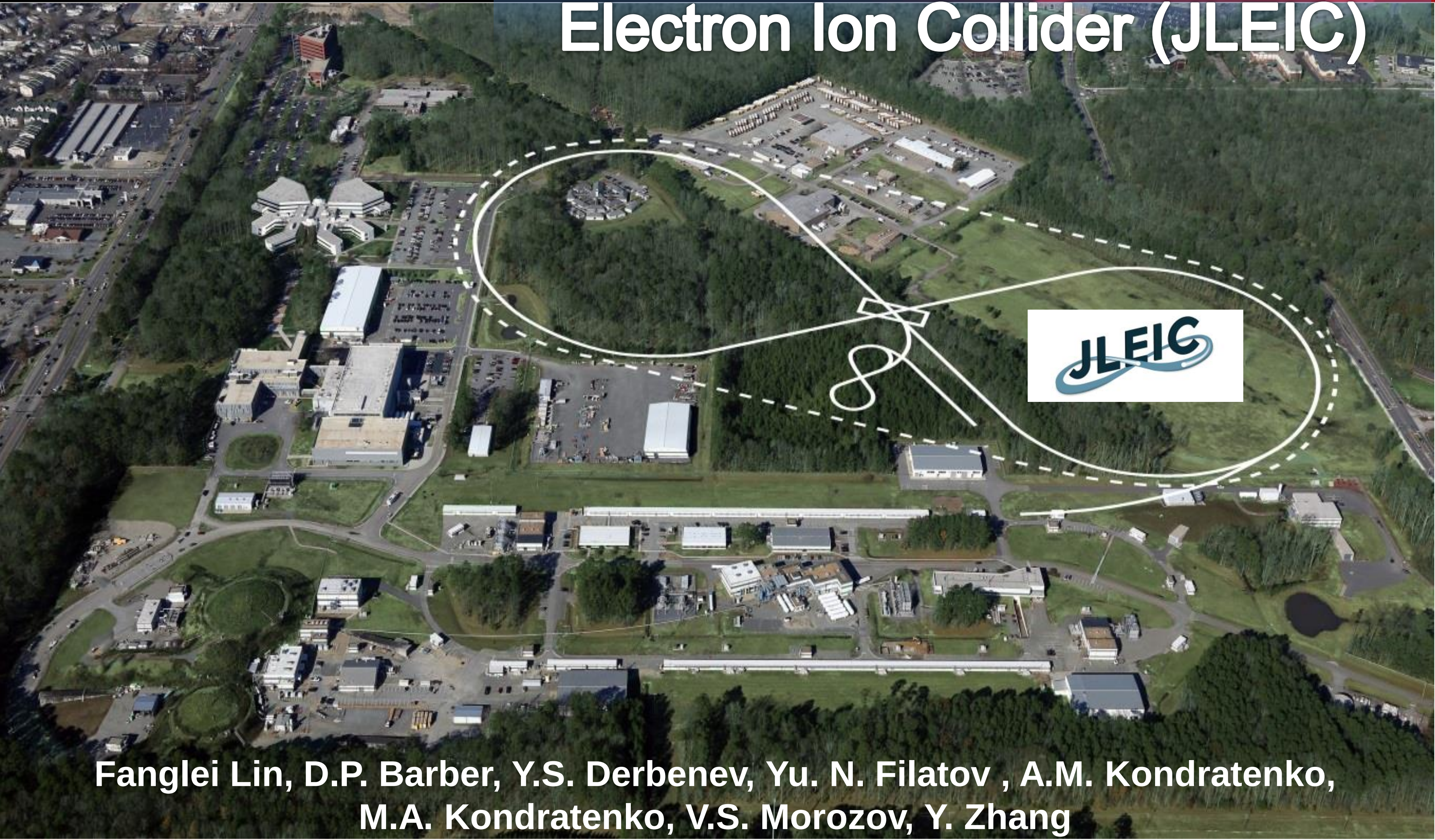
Spin Dynamics at Jefferson Lab Electron Ion Collider (JLEIC)



Fanglei Lin, D.P. Barber, Y.S. Derbenev, Yu. N. Filatov , A.M. Kondratenko, M.A. Kondratenko, V.S. Morozov, Y. Zhang

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

Outline

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

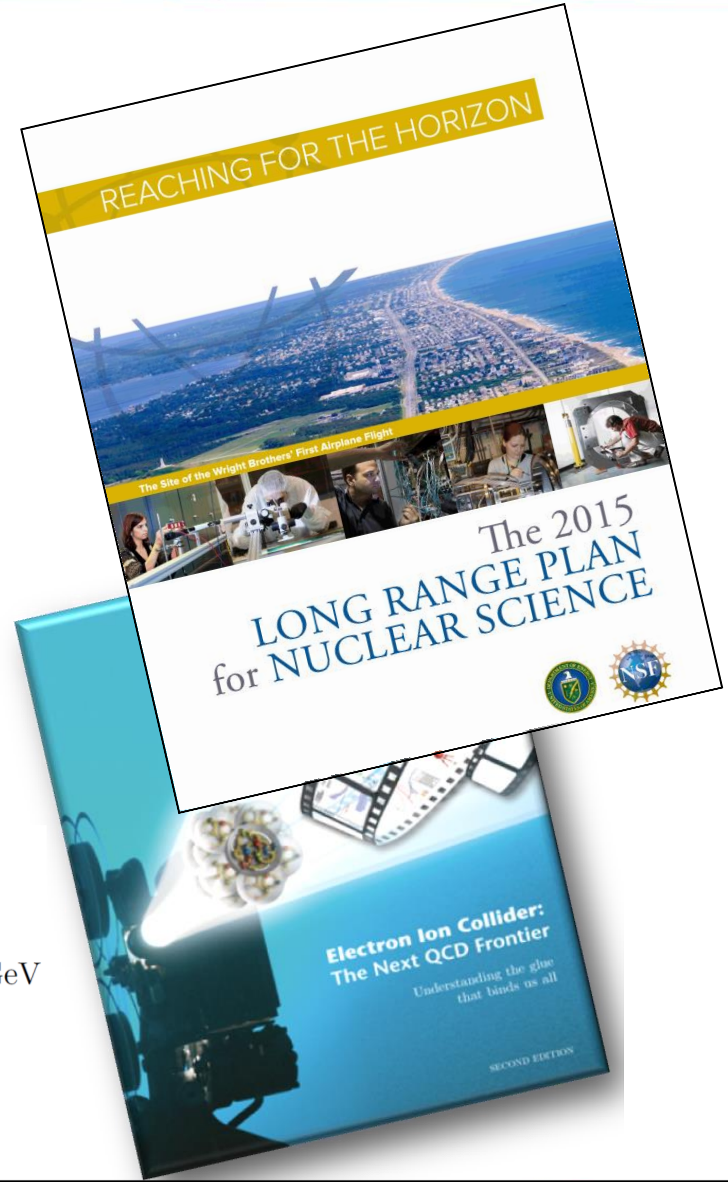
- **JLEIC polarization design and simulation**
  - Ion polarization
  - Electron polarization

- **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"



REACHING FOR THE HORIZON

The Site of the Wright Brothers' First Airplane Flight

The 2015 LONG RANGE PLAN for NUCLEAR SCIENCE

Electron Ion Collider: The Next QCD Frontier

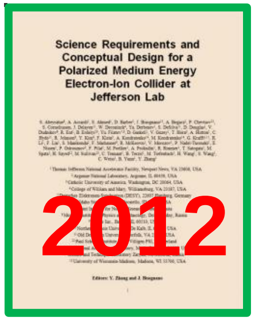
Understanding the glue that binds us all

SECOND EDITION

EIC Community White Paper arXiv:1212.1701

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

JLEIC Baseline Design



Science Requirements and Conceptual Design for a Polarized Medium Energy Electron-Ion Collider at Jefferson Lab

2012

arXiv:1209.0757

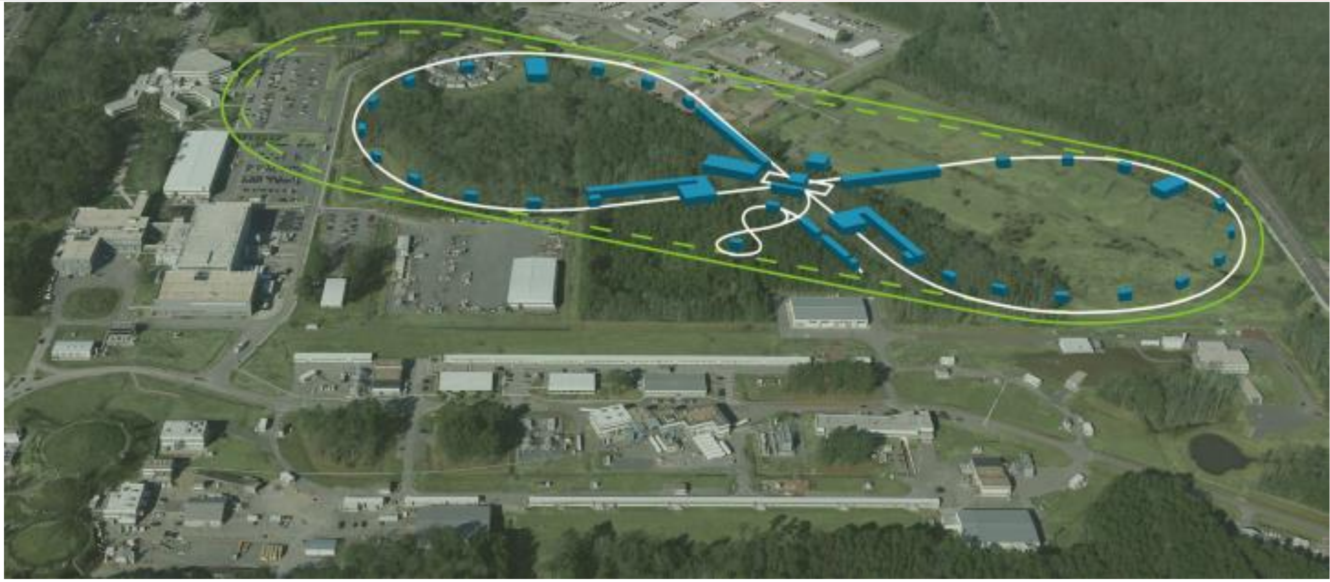
MEIC Design Summary

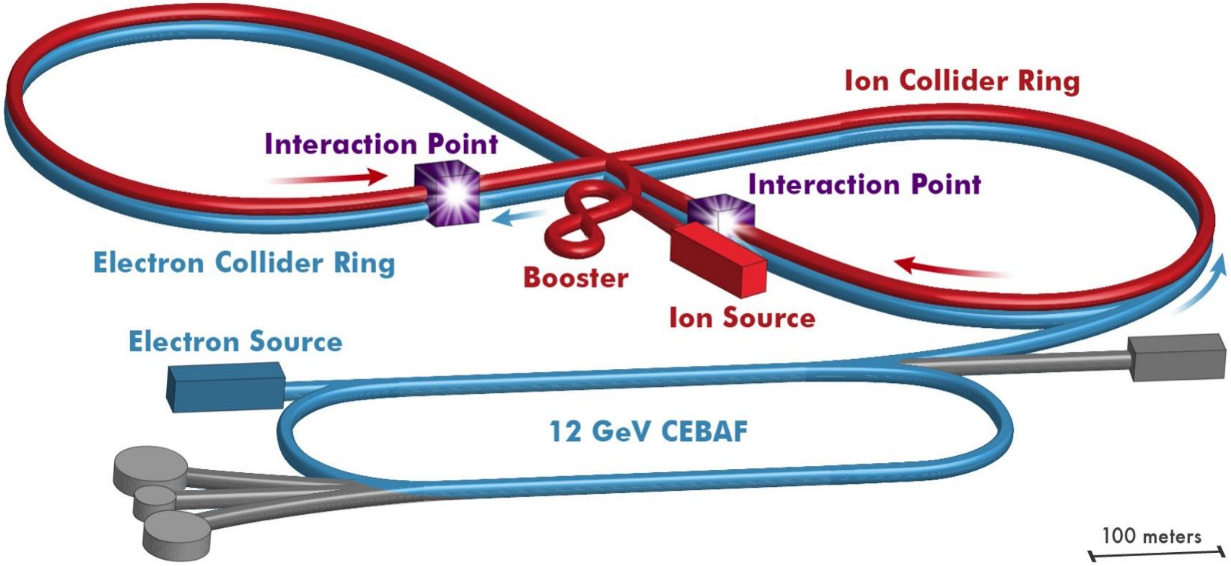
January 20, 2015

Author List

2015

arXiv:1504.07961





- Electron complex
  - CEBAF
  - Electron collider ring
- Ion complex
  - Ion source
  - Linac
  - Booster
  - Ion collider ring

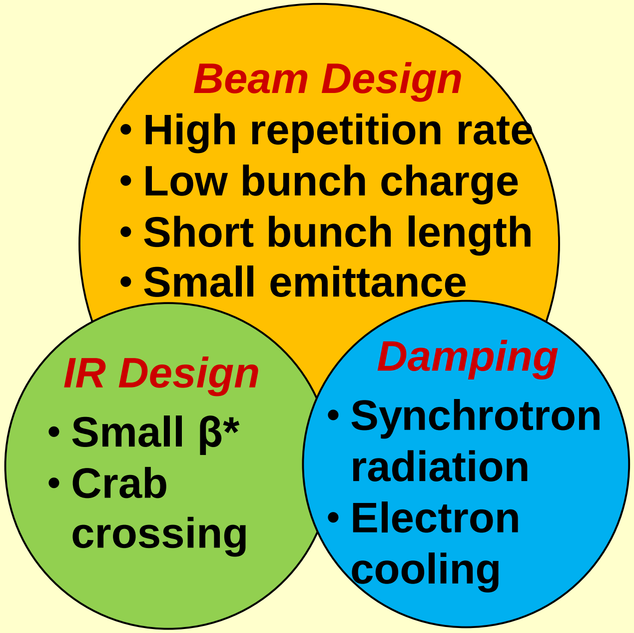
JLEIC Strategy for High Luminosity and Polarization

High Luminosity

- Based on ***high bunch repetition rate CW colliding beams***

$$L = f\,\frac{n_1 n_2}{4\pi\sigma^*_x\sigma^*_y} \sim f\,\frac{n_1 n_2}{\varepsilon\beta^*_y}$$

- KEK-B reached > **$2\text{x}10^{34}$ /cm^2/s**



Beam Design

- **High repetition rate**
- **Low bunch charge**
- **Short bunch length**
- **Small emittance**

IR Design

- **Small β***
- **Crab crossing**

Damping

- **Synchrotron radiation**
- **Electron cooling**

High Polarization

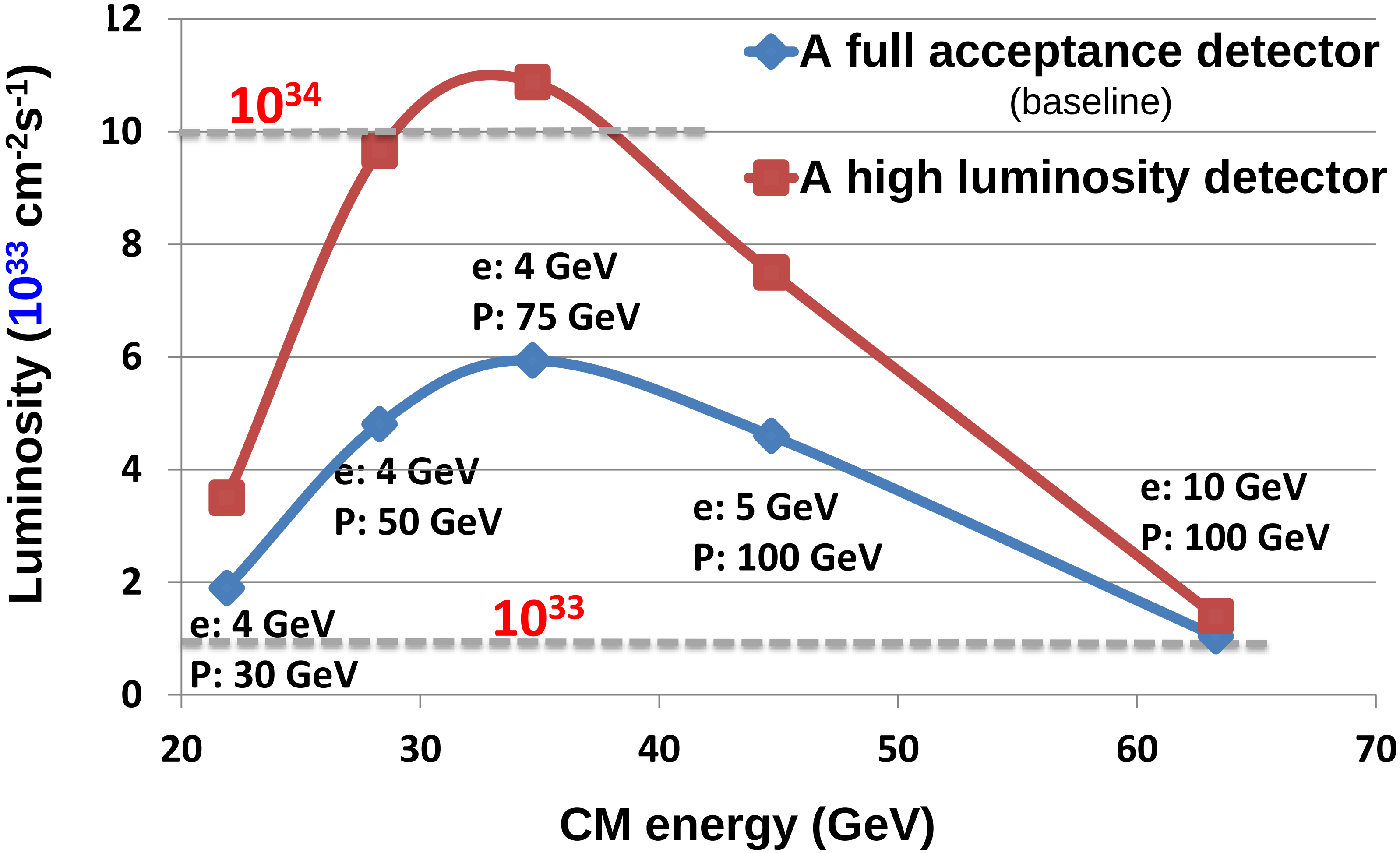
- Collider rings are in a figure-8 shape
  ➔ critical advantages for both beams
- Spin precessions in the left & right parts of the ring are ***exactly cancelled***
- Net spin precession (***spin tune***) is **zero**, thus ***energy independent***
- Spin can be ***controlled*** & ***stabilized*** by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

Excellent Detector integration

Interaction region is designed to support

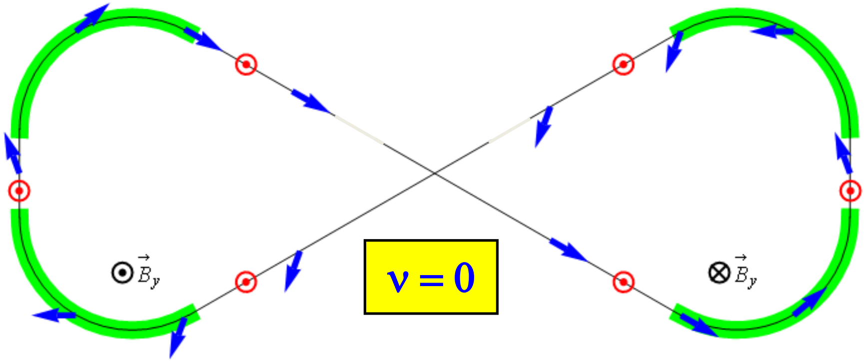
- ***Full acceptance*** detection (including forward tagging)
- Low detector ***background***

e-p Collision Luminosity



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

$$w_0 = w_{\text{coherent}} + w_{\text{emittance}}, \qquad w_{\text{emittance}} << w_{\text{coherent}}.$$

is composed of

  - coherent part w_{coherent} due to closed orbit excursions
  - incoherent part $w_{\text{emittance}}$ due to transverse and longitudinal emittances

- The coherent part $\left|w_0^{(k)}\right| = \alpha_k \left|\gamma G F(\theta_k)\right|$

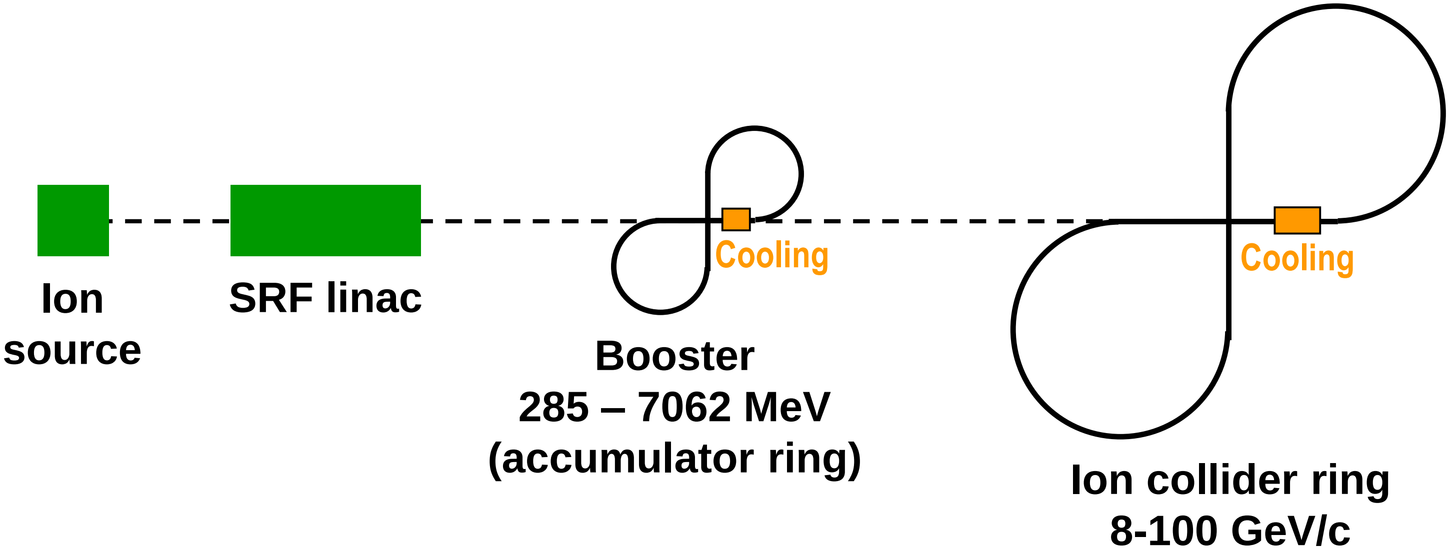
where $F(\theta)$ is the spin response function, arises due to radial fields from

  - 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 $\nu >> w_0$

Ion Polarization Requirements

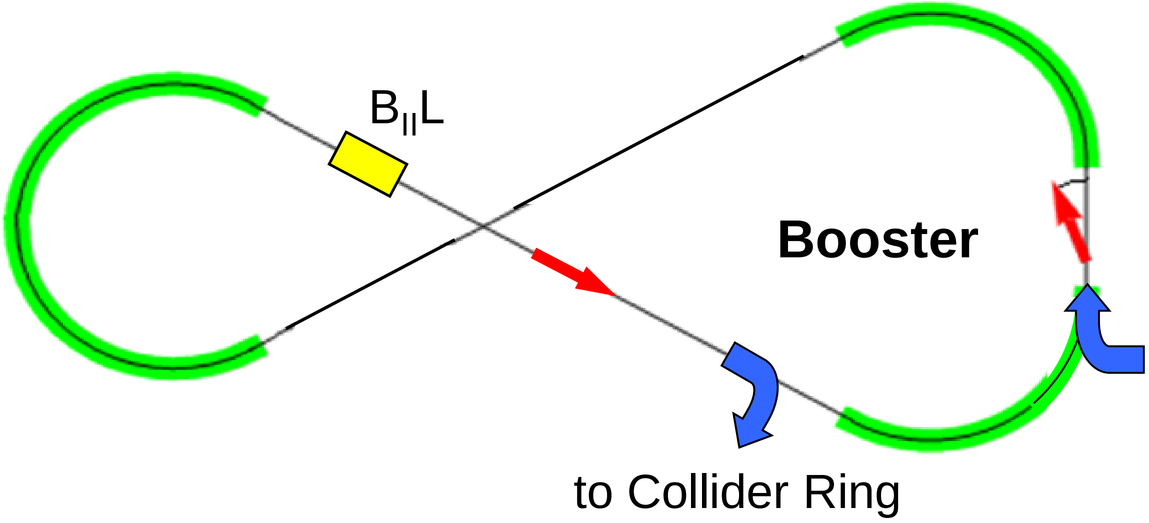
- Major JLEIC ion complex components



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

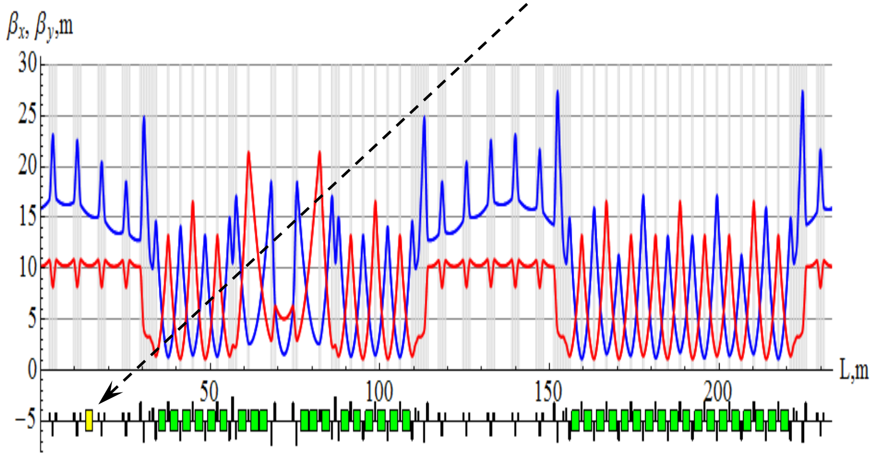
Pre-Acceleration & Spin Matching

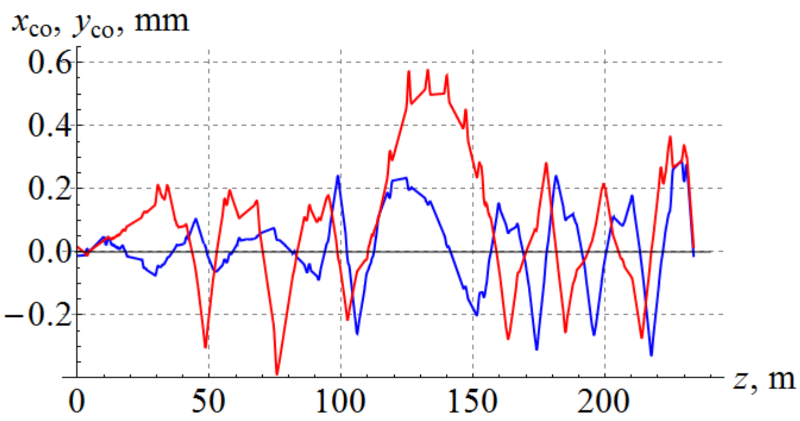
- Polarization in Booster stabilized and preserved by a single weak solenoid
  - **0.6 T·m** at 8 GeV/c
  - ν_d / ν_p = 0.003 / 0.01
- Longitudinal polarization in the straight with the solenoid
- Conventional 8 GeV accelerators require $B_{||}L$ of **~30 Tm** for protons and **~100 Tm** for deuterons



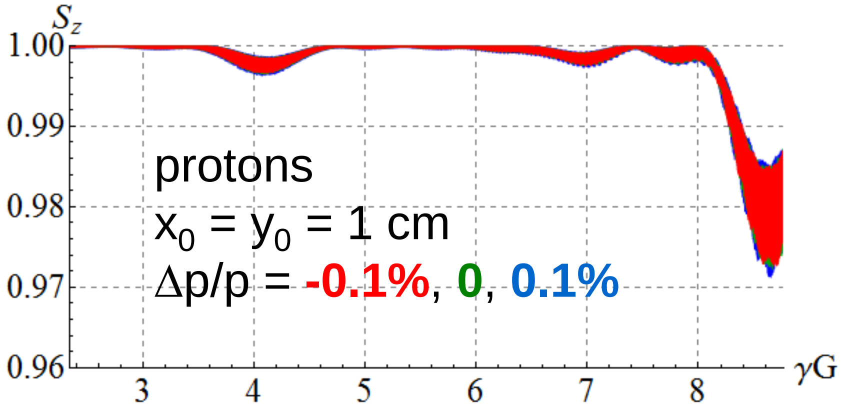
Spin Dynamics in Booster

- 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)

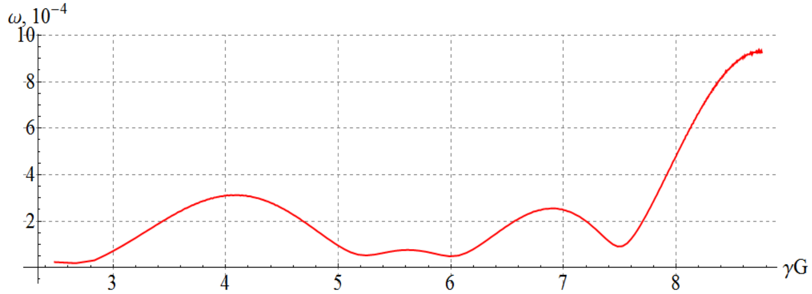


protons

$x_0 = y_0 = 1$ cm

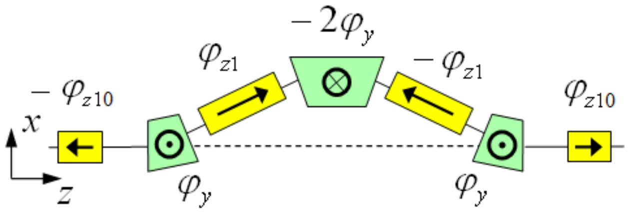
Δp/p = **-0.1%**, **0**, **0.1%**

coherent part of the spin resonance strength



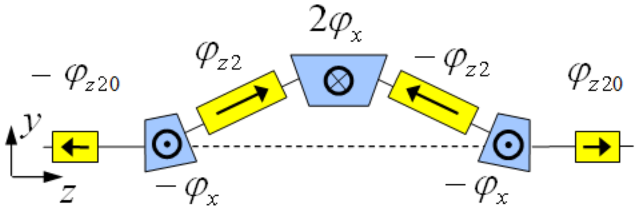
Polarization Control in Ion Collider Ring

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

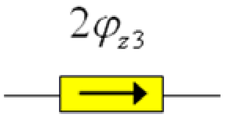


$L_{tot} = 7$ m, $\Delta x = 15$ mm, $B_{dip}^{max} = 3$ T, $B_{sol}^{max} = 3.6$ T

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

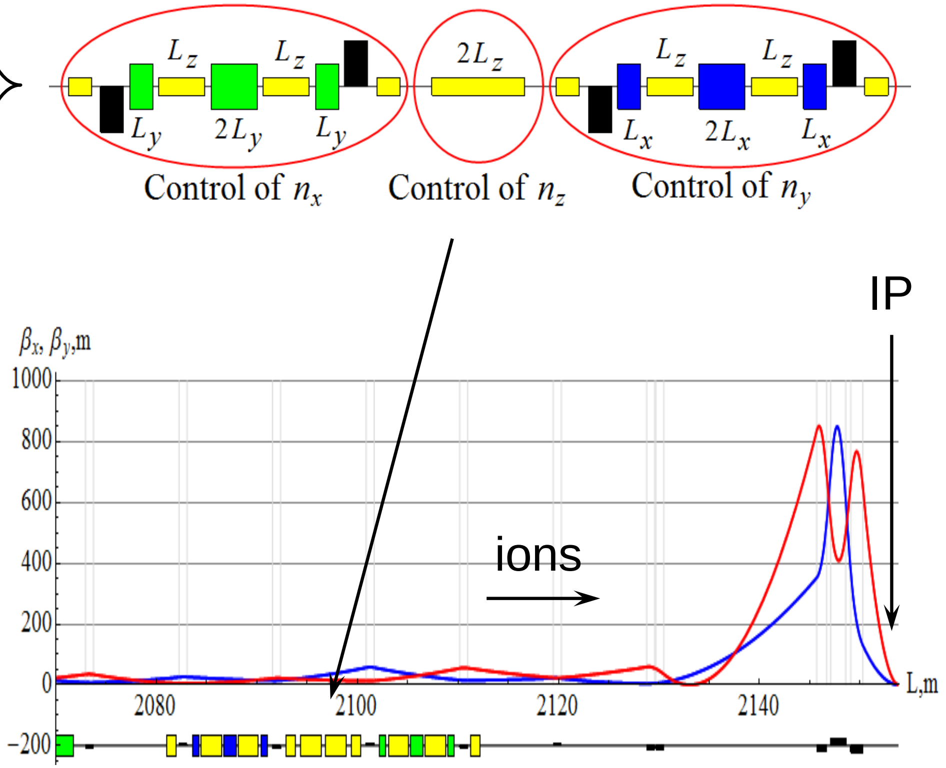


- Module for control of the longitudinal component



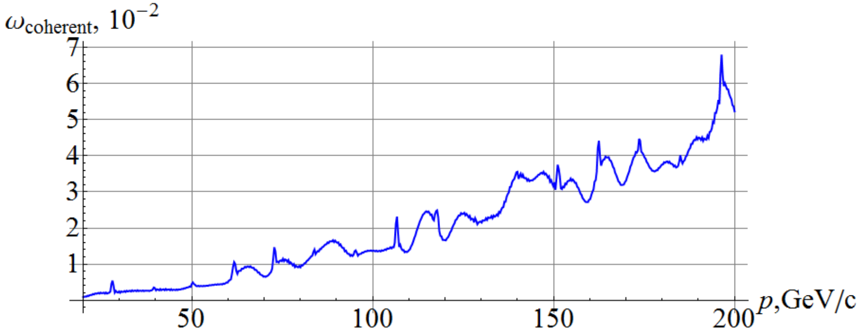
$L_x = L_y = 0.6$ m, $L_{zi} = 2$ m, $L_{zi0} = 1$ m, $\alpha_{orb} = 0.31°$

3D spin rotator

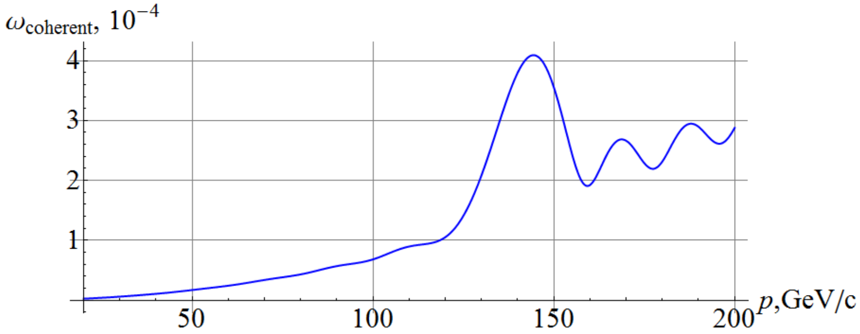


Zero-Integer Spin Resonance in Ion Collider Ring

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

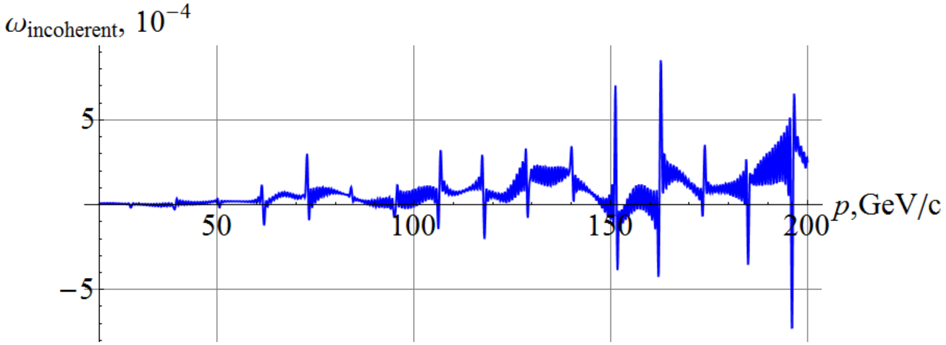


Protons

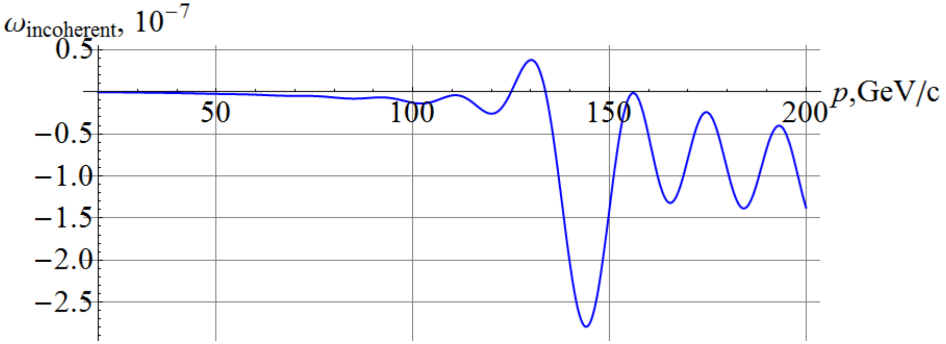


Deuterons

- Incoherent part of resonance strength
  - Assuming normalized vertical beam emittance of 0.07 μm-rad



Protons



Deuterons

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

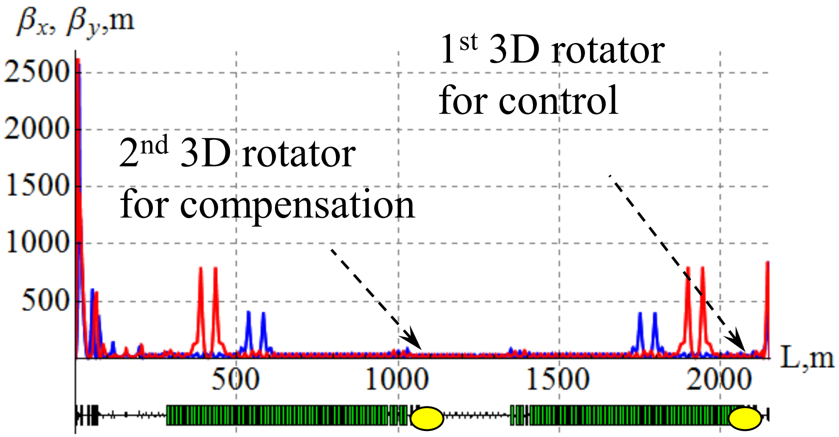
- Spin resonance strength after compensation

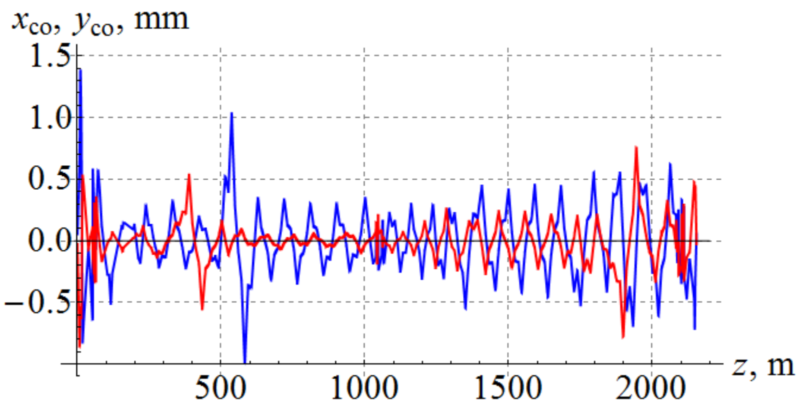
$$w_0 \sim w_{\text{emittance}} \quad \Rightarrow \quad |w_0|_p < 10^{-3}, \quad |w_0|_d < 10^{-5}$$

- 2T × 4m solenoids in the 3D spin rotator allow setting proton spin tune $\nu_p = 10^{-2}$ and deuteron spin tune $\nu_d = 10^{-4}$

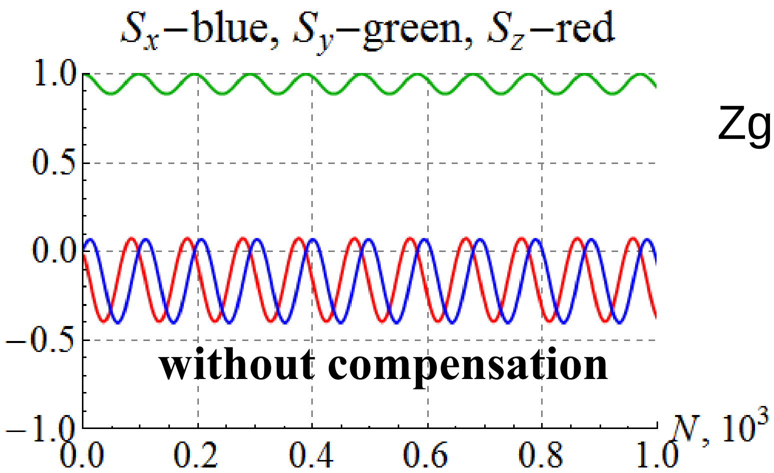
Spin Dynamics in Ion Collider Ring

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

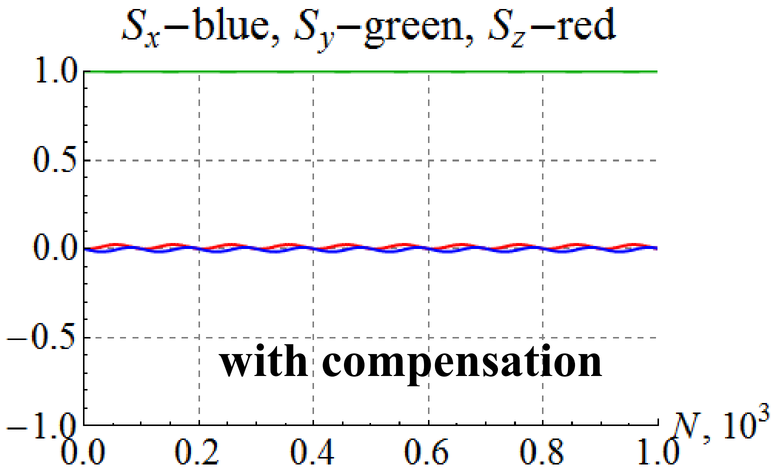




- Example of vertical proton polarization at IP. The 1st 3D rotator: $\nu = 10^{-2}$, $n_y=1$. The 2nd 3D rotator is used for compensation of coherent part of the zero-integer spin resonance strength

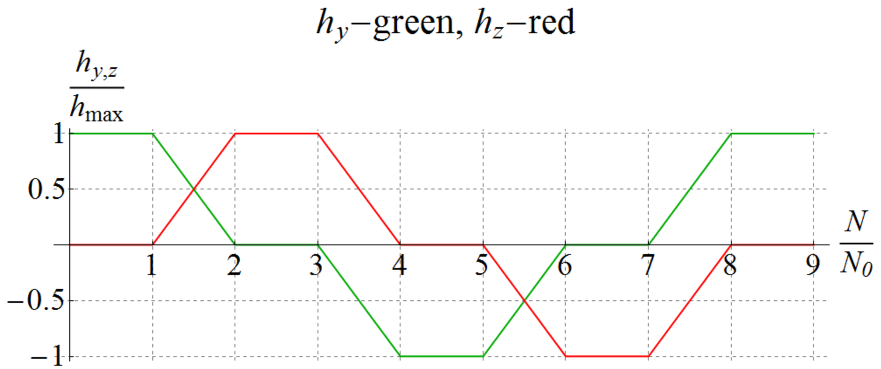


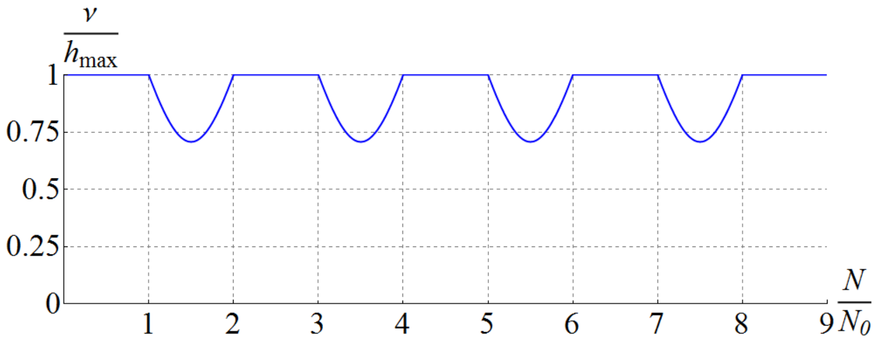
Zgoubi



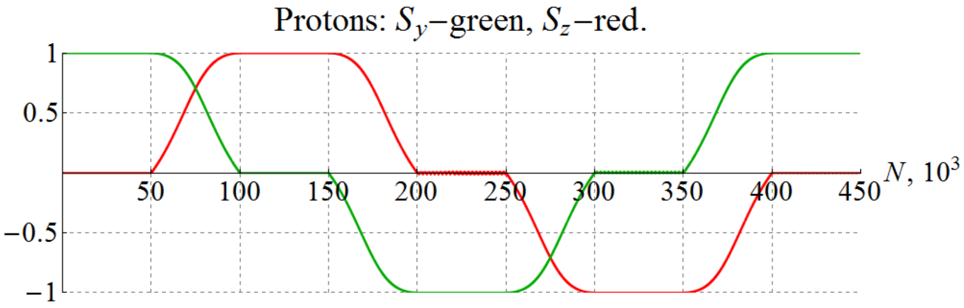
Spin Flip

- Adiabaticity criterion: spin reversal time must be much longer than spin precession period
- $\Rightarrow \tau_{\text{flip}} \gg 1$ 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)



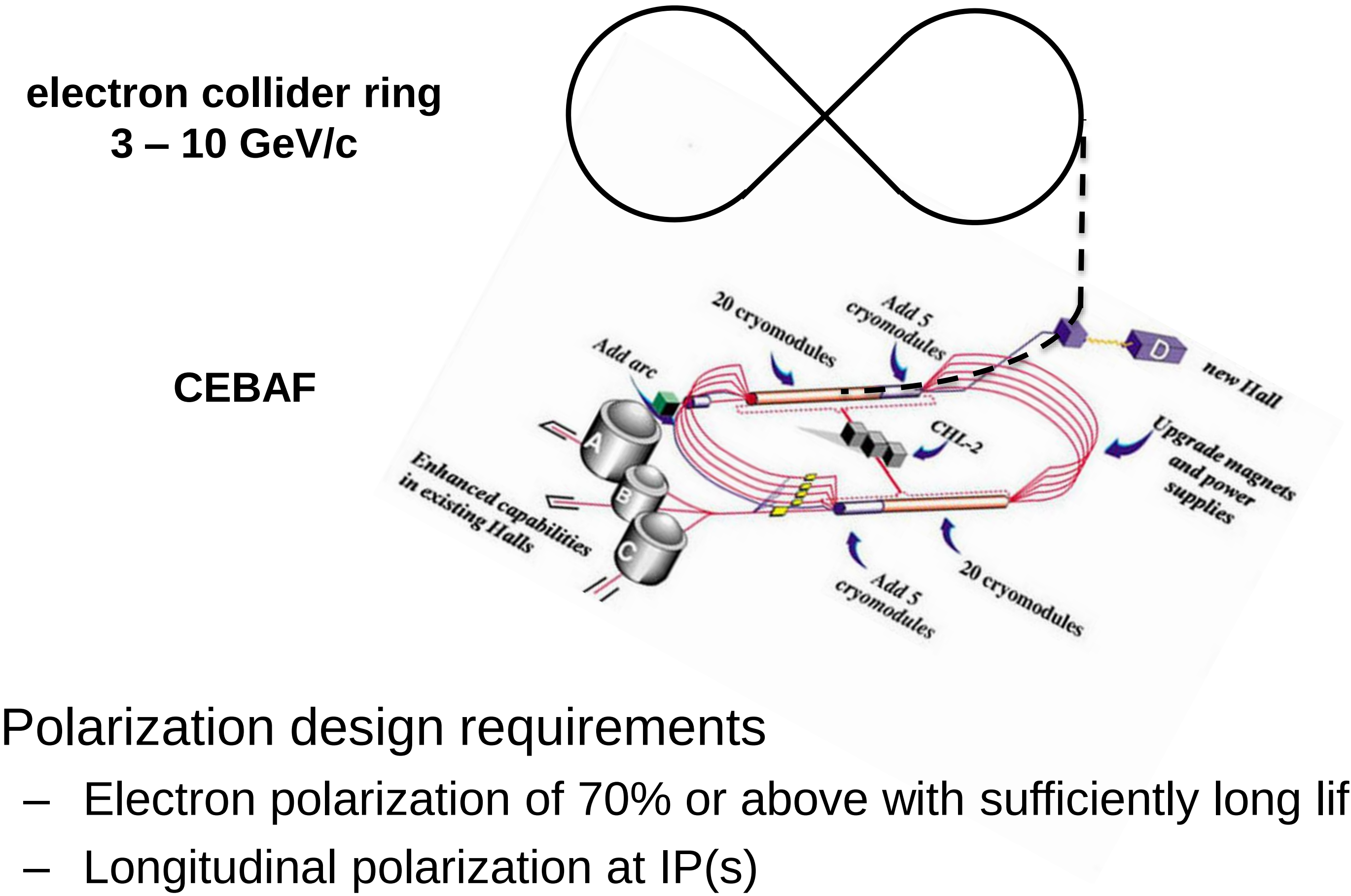


- Vertical & longitudinal components of proton polarization vs time at 100 GeV/c



Electron Polarization Requirements

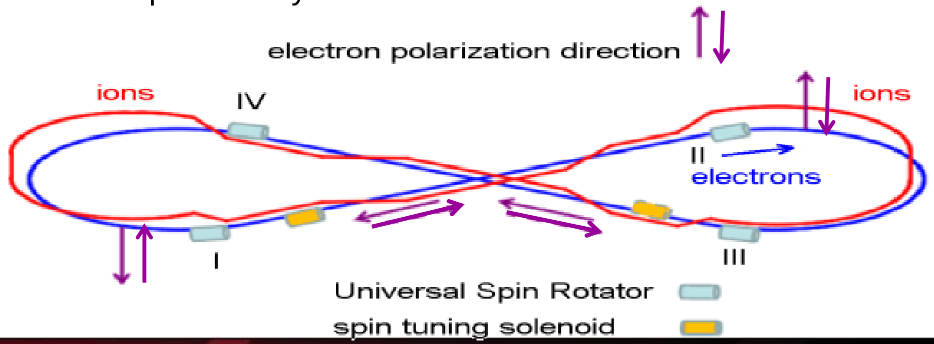
- Major JLEIC electron complex components



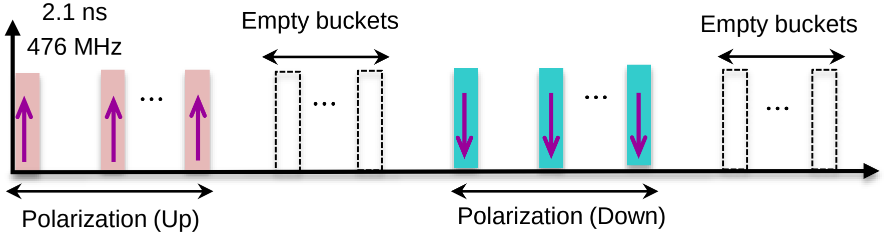
- Polarization design requirements
  - Electron polarization of 70% or above with sufficiently long lifetime
  - Longitudinal polarization at IP(s)
  - Spin flipping

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

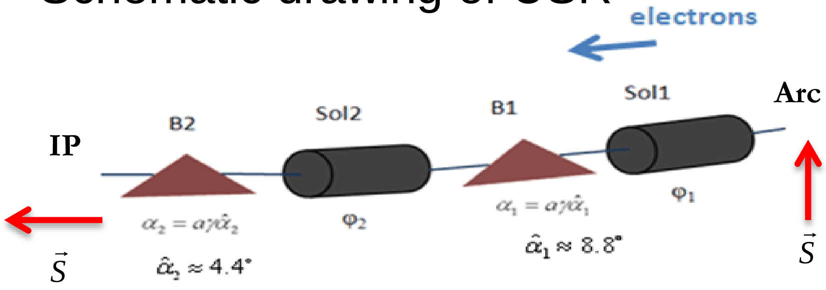


bunch train & polarization pattern (in arcs)



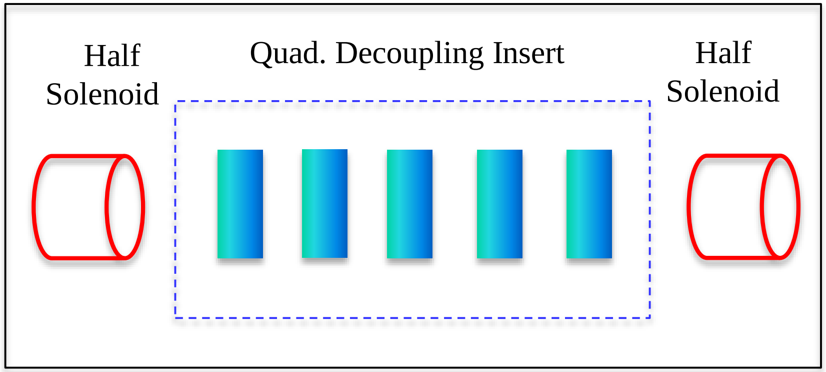
Universal Spin Rotator (USR)

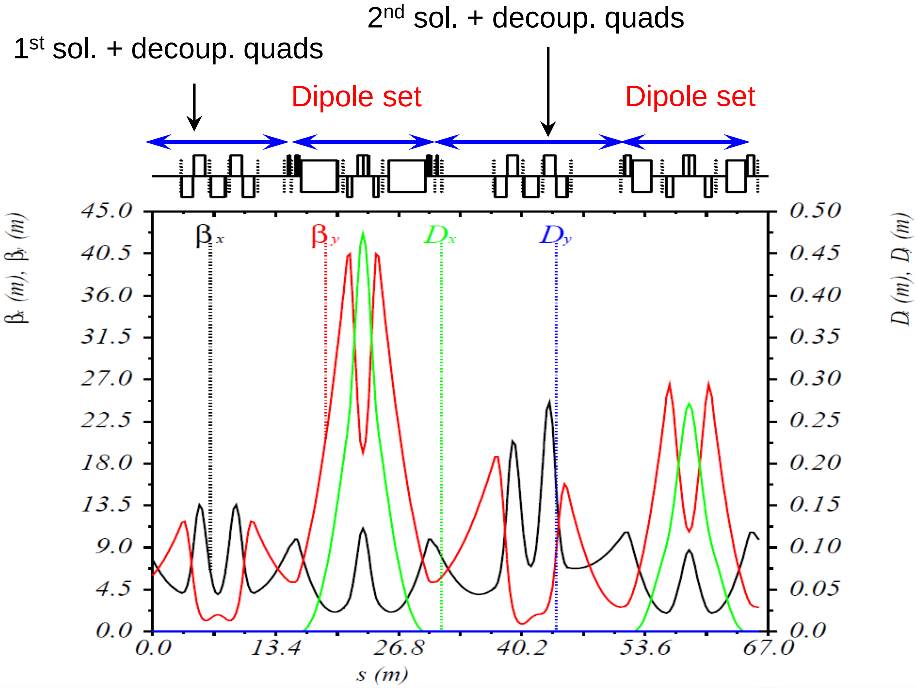
- Schematic drawing of USR



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

- Solenoid decoupling & Lattice function



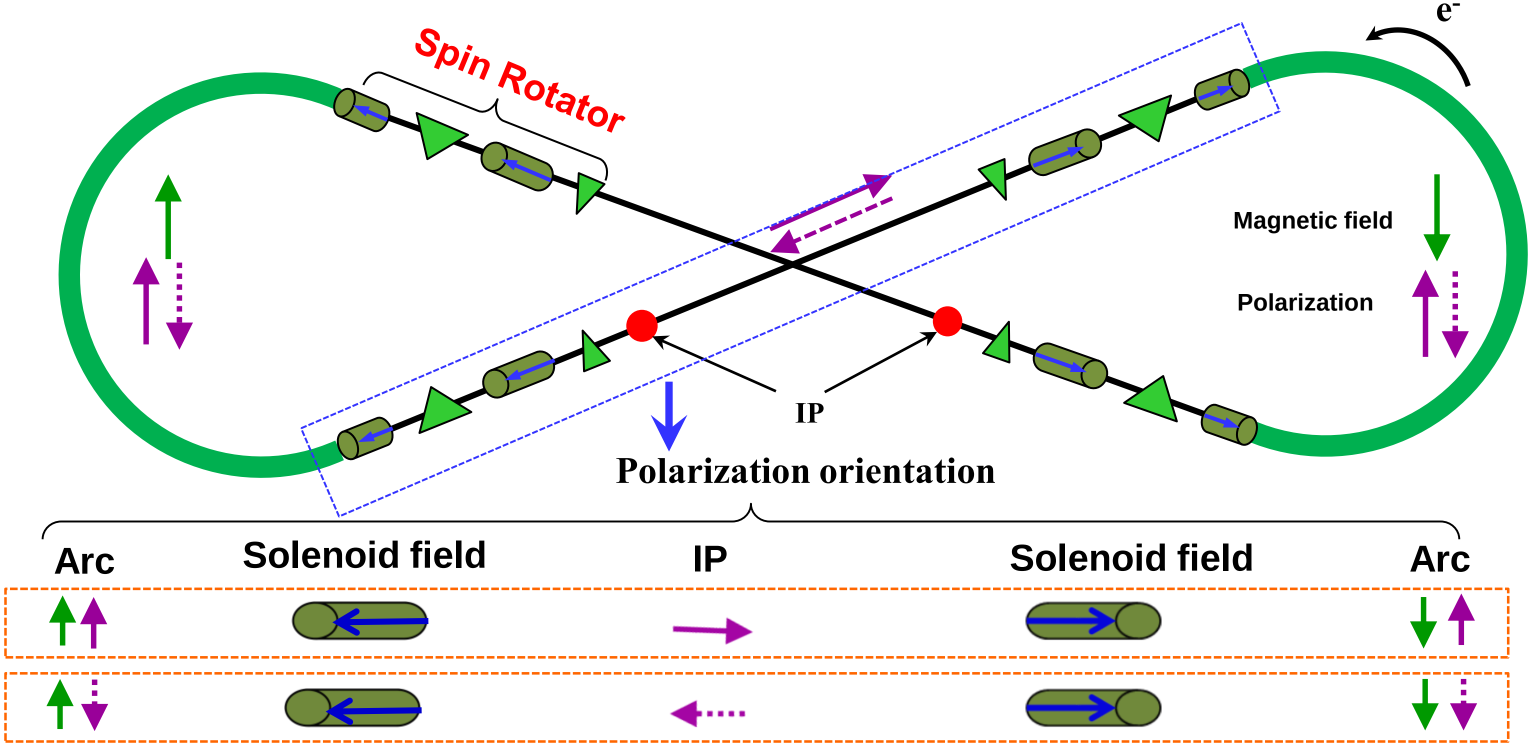


- Parameters of USR for JLEIC

E	Solenoid 1		Arc Dipole 1	Solenoid 2		Arc Dipole 2
	Spin Rotation	BDL	Spin Rotation	Spin Rotation	BDL	Spin Rotation
GeV	rad	T·m	rad	rad	T·m	rad
3	π/2	15.7	π/3	0	0	π/6
4.5	π/4	11.8	π/2	π/2	23.6	π/4
6	0.62	12.3	2π/3	1.91	38.2	π/3
9	π/6	15.7	π	2π/3	62.8	π/2
12	0.62	24.6	4π/3	1.91	76.4	2π/3

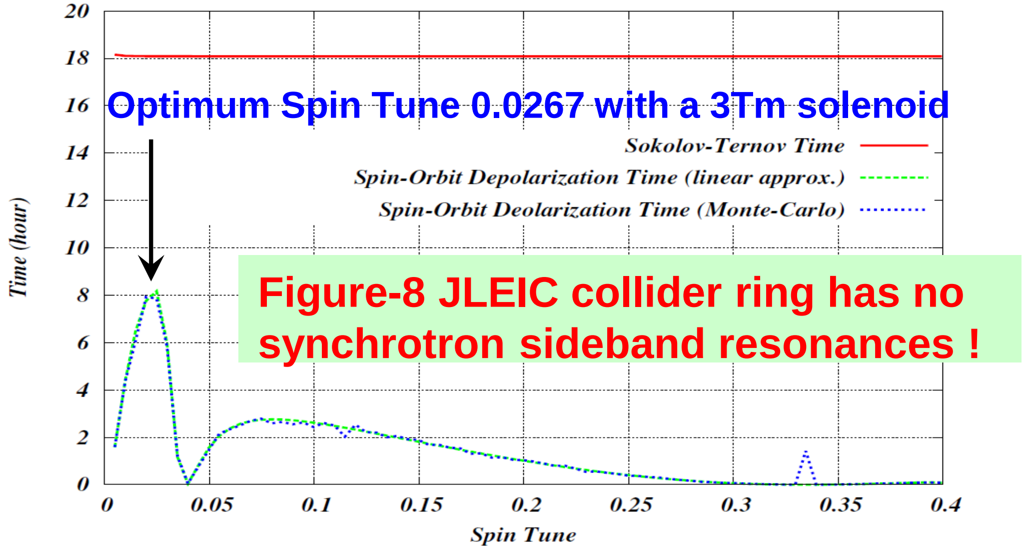
Electron Polarization Configuration

- 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



Polarization Simulation

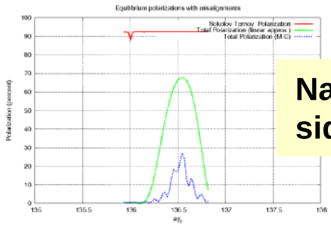
- Spin tune scan @ 5 GeV
  - Longitudinal field spin tuning solenoid is inserted in the straight where the polarization is longitudinal.
  - 500 particles Monte-Carlo simulation using SLICKTRACK (developed by D.P. Barber).
  - Main field errors, quads vertical misalignment and dipole role, are introduced.



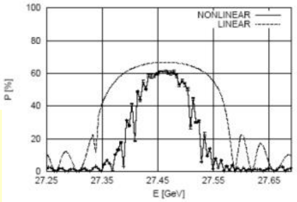
Optimum Spin Tune 0.0267 with a 3Tm solenoid

Figure-8 JLEIC collider ring has no synchrotron sideband resonances !

Typical LHeC calculations with very good alignment, rotators but artificial spin matching in SLICKTRACK. Note the sync. sideband effects.

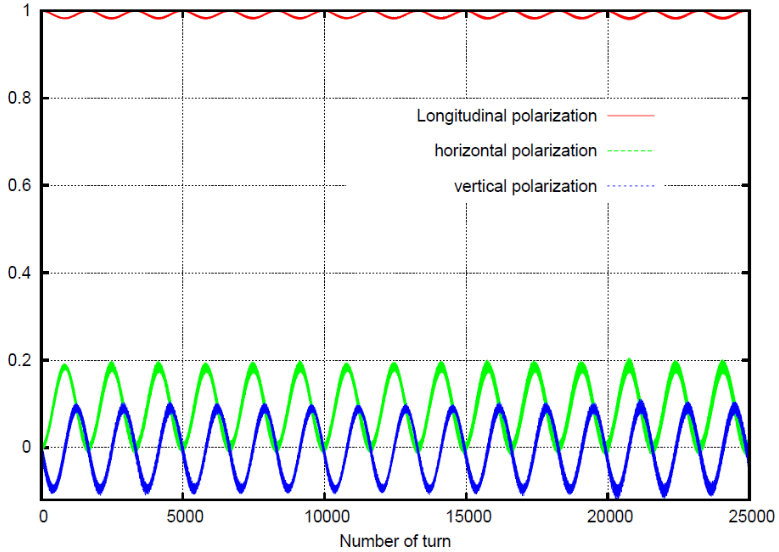


Nasty, nasty sidebands !



Polarization vs. energy for a HERA Upgrade lattice including the H1 and ZEUS solenoids: comparison of first order calculation (SLIM) and higher order calculations (SITROS).
M. Berglund, DESY–THESIS 2001–044 (2001).

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



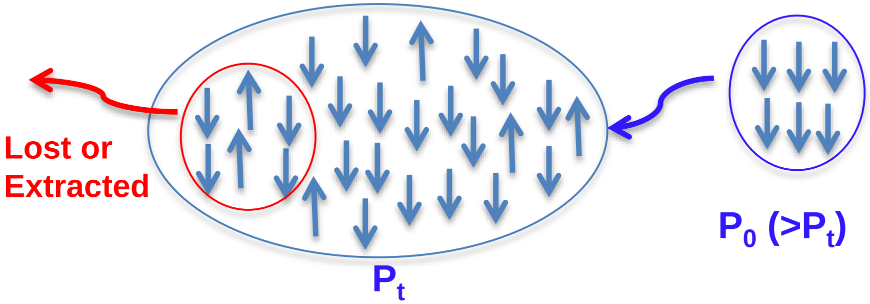
- Oscillation of spin components is due to the misaligned initial spin direction and invariant spin field.
- This can be experimentally calibrated by adjusting the spin rotator settings.

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

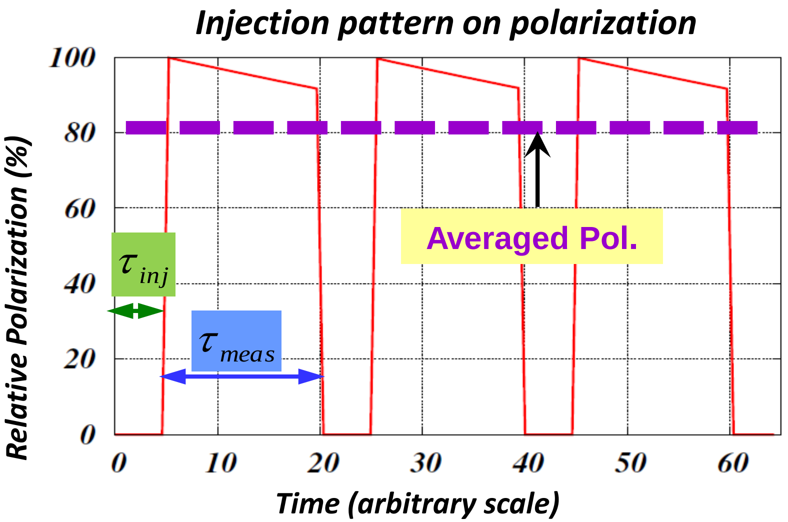
From John T. Seeman, SLAC-PUB-5933, Sep. 1992

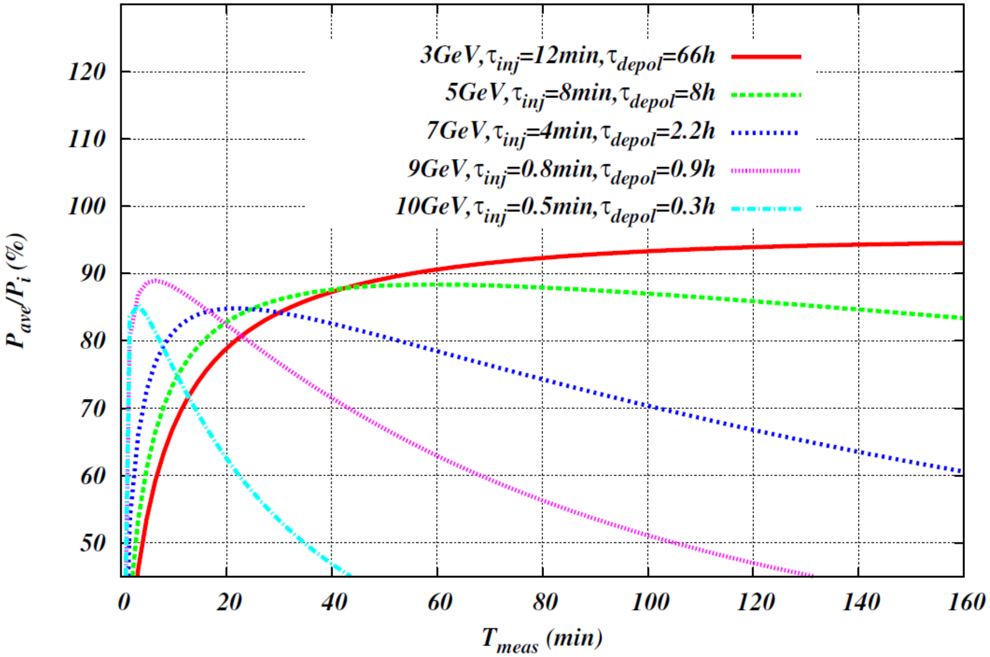
- JLEIC considers the continuous injection of the electron beams to
  - Obtain a high average luminosity
  - Reach a high equilibrium polarization



  - 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



$$FOM \propto \left\langle P^2 \right\rangle_T = \frac{\int P^2(t)dt}{T} = \frac{\int_0^{\tau_{meas}} P_i^2 \cdot e^{-\frac{2t}{\tau_{depol}}} dt}{\tau_{inj} + \tau_{meas}}$$

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

Energy (GeV)	τ_{inj} (min)	τ_{opt_meas} (min)	$(P_{ave}/P_i)_{max}$ *
3	12	160	0.94
5	8	60	0.88
7	4	20	0.85
9	0.8	6	0.89
10	0.5	2.5	0.86

P_i : Initial polarization

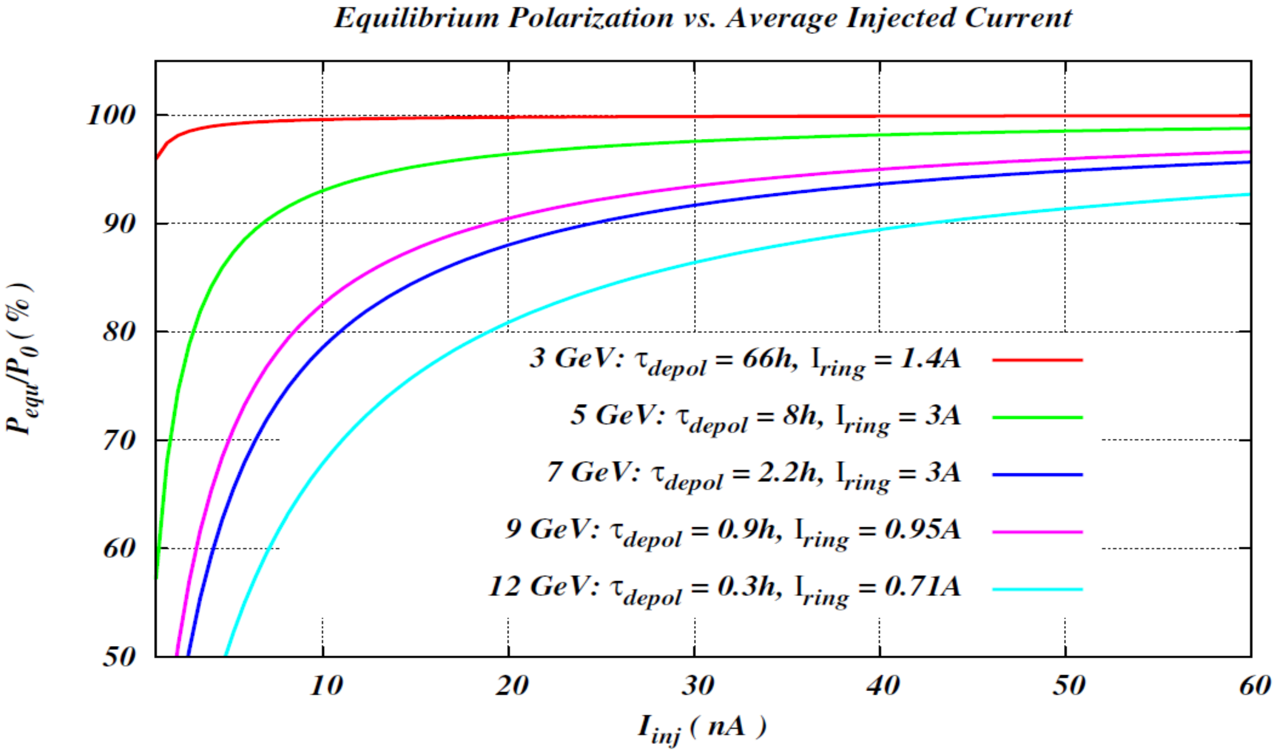
τ_{inj} : Injection time

τ_{depol} : Depolarization time

τ_{meas} : Measurement time

Polarization w Cont. Injection

- Polarization w/ continuous injection $P_{t+\Delta t} = (1-\frac{\Delta N}{N})(P_t + \frac{\Delta P_t}{\Delta t}\Delta t) + \frac{\Delta N}{N} P_0$
- 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 $BL = B\rho\Delta\theta$ ~ 70 Tm
    - Extra space for quadrupoles, etc.
- Racetrack booster
  - Proton & He^3 polarization: OK
    - Requires ~10 m long Siberian snake with ~30 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 >~1 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 $\sim\gamma^{-2}$
  - 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