Spin Transparency Mode in JLEIC

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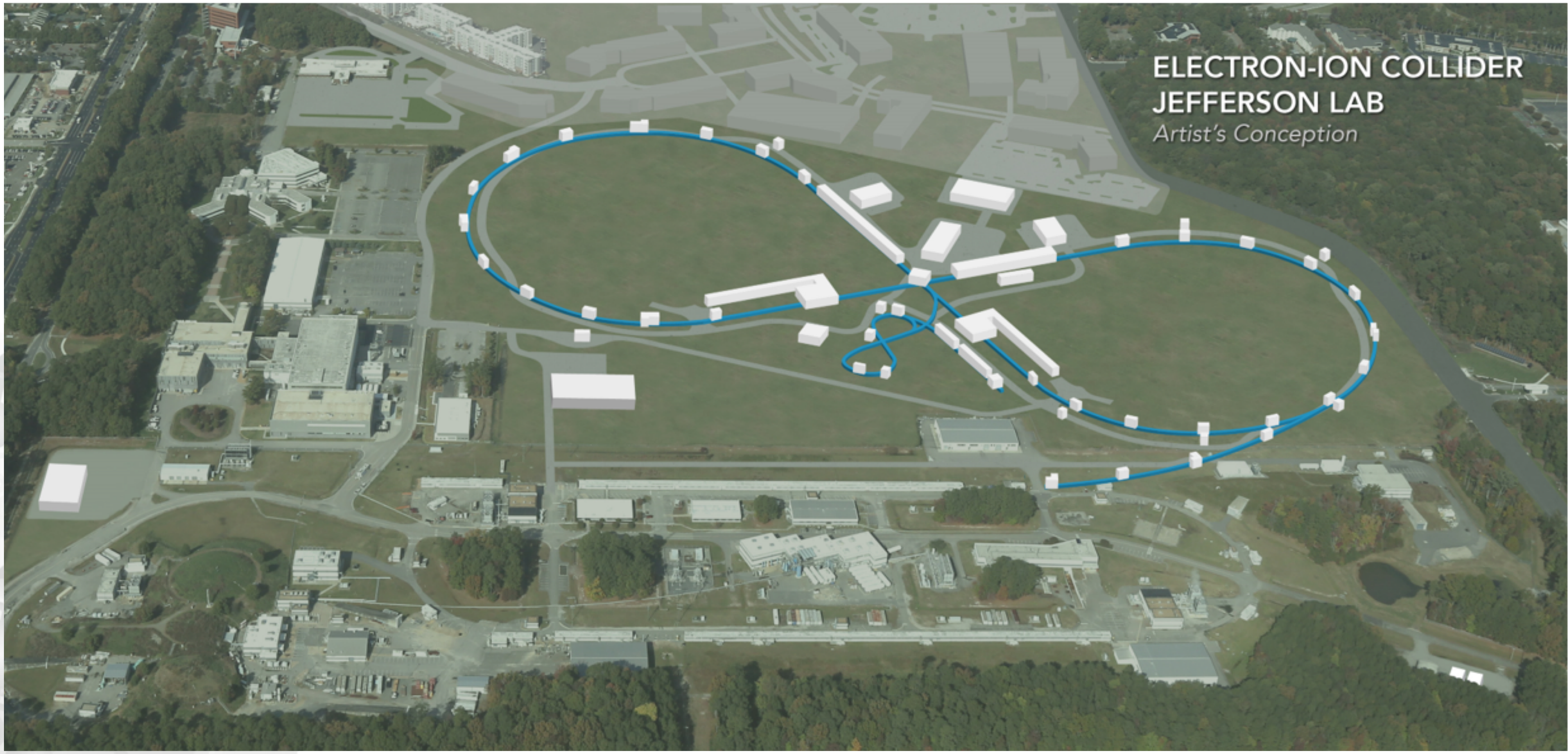


23rd International Spin Symposium (SPIN2018), Ferrara, Italy, September 10-14, 2018

Polarization Requirements

- Ion 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

- Electron polarization design requirements
  - High polarization (~80%)
  - Longitudinal polarization orientation at all IPs
  - Sufficiently long polarization lifetime
  - Opposite polarization states

Spin Resonances

- Spin tune (number of spin precession per turn) in a conventional ring
$$\nu_s = G\gamma, \;\; G_d \approx -0.143$$
- A spin resonance occurs whenever the spin precession becomes synchronized with the frequency of spin perturbing fields
  - Imperfection resonances due to alignment and field errors
$$\nu_s = k, \quad E_d = 13.12k\,\mathrm{GeV}$$
  - Intrinsic resonances due to betatron oscillations
$$\nu_s = k \pm \nu_y$$
  - Coupling and higher-order resonances
$$\nu_s = k + l\nu_x + m\nu_y + j\nu_{synch}$$
- As ν_s changes during acceleration, many resonances are crossed causing depolarization
- Even at a fixed energy, a finite spread of ν_s may overlap higher-order resonances limiting polarization lifetime

Siberian Snake

- Device rotating spin by some angle about an axis in horizontal plane
  - A "full" Siberian snake rotates the spin by 180°
  - Overcomes all imperfection and most intrinsic resonances
- Spin tune with a snake

$$\nu_s = \frac{1}{\pi}\cos^{-1}\left[\cos(G\gamma\pi)\cos\frac{\varphi}{2}\right], \quad \varphi = \pi \ \Rightarrow \nu_s = \frac{1}{2}$$

- Solenoidal Siberian snake at low energies
  - No orbit excursion
  - Field integral grows with momentum

$$\varphi = \frac{Ze(1+G)}{p}\int B_{\parallel} ds$$

$$\varphi = \pi, \ \ p = 9\ \mathrm{GeV/c} \quad \Rightarrow \quad \int B_{\parallel} ds \approx 34\ \mathrm{Tm\ for}\ p\ \mathrm{and}\ 110\ \mathrm{Tm\ for}\ d$$

- Dipole Siberian snake at high energies
  - Orbit excursion is inversely proportional to momentum
  - Almost energy-independent field integral

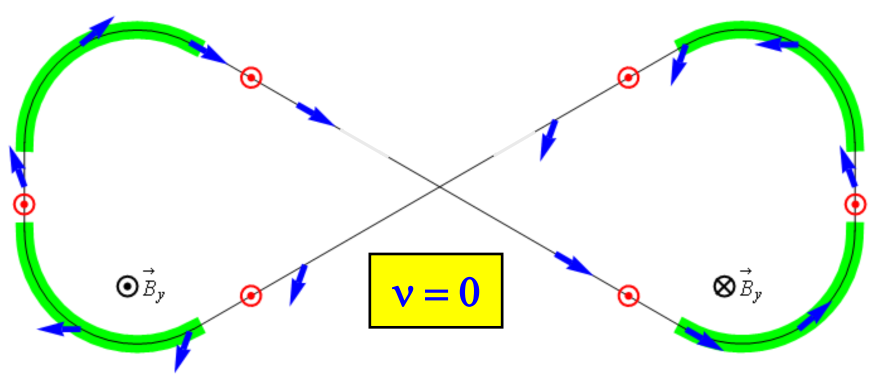
$$\varphi = \frac{Ze\ G\gamma}{p}\int B_{\perp} ds$$

$$\varphi = \pi, \ \ p = 100\ \mathrm{GeV/c} \quad \Rightarrow \quad \int B_{\perp} ds \approx 5.5\ \mathrm{Tm\ for}\ p\ \mathrm{and}\ 158\ \mathrm{Tm\ for}\ d$$

  In reality, orbit control requirements lead to an increase of the field integral by a factor of ~3 or so, e.g. to ~ 20 Tm as in RHIC
- Medium energies are still a problem
- Full deuteron Siberian snake is not practical for medium to high energies

Figure-8 Scheme

- Figure-8 ring is transparent to the spin motion: in an ideal structure, spin precession in one arc is cancelled by the other
- Without additional fields, **spin rotation is a priori unknown** and occurs only due to closed orbit excursion and beam emittances
- Additional fields are introduced to **stabilize the spin motion** by producing a spin rotation that is much greater than that due to imperfections
- Required integrals of the additional fields are almost two orders of magnitude lower than those of full Siberian snakes
  - e.g. ~3 Tm vs. < 400 Tm for deuterons at 100 GeV
- Figure-8 is an **indispensable solution for deuterons in the whole EIC energy range and protons in the low-to-medium energy range** as well as an excellent alternative solutions for high-energy protons and electrons



Zero-Integer Spin Resonance and Spin Stability Criterion

- Total zero-integer spin resonance strength

$$\vec{w}_0 = \vec{w}_{coherent} + \vec{w}_{emittance}\,, \qquad |\vec{w}_{emittance}| \ll |\vec{w}_{coherent}|$$

  is composed of
  - coherent part $w_{coherent}$ due to closed orbit excursions (due to imperfections); it does not lead to depolarization but causes coherent spin rotation about a priori unknown direction
  - incoherent part $w_{emittance}$ due to transverse and longitudinal emittances (proportional to beam emittance), it causes spin tune spread potentially leading to depolarization
- Spin stability criterion
  - the spin tune induced by a spin rotator must significantly exceed the strength of the incoherent part of the zero-integer spin resonance

$$\nu \gg |\vec{w}_{emittance}|$$

  - for proton beam $\nu_p = 10^{-2}$
  - for deuteron beam $\nu_d = 10^{-4}$

Spin Response Function

- The periodic spin response function $F(z)$ is the spin Green's function; it describes spin response to a local perturbing radial field and resulting closed orbit excursion
- $F(z)$ is determined by ideal linear lattice. For an uncoupled flat ring, it is expressed through the Floquet function of vertical betatron oscillations $f_y(z)$:

$$F(z) = \frac{e^{i\Psi_y}}{2i}\left[f_y^* \int_{-\infty}^{z} \left(\frac{de^{-i\Psi_y}}{dz}\right)\frac{df_y}{dz}dz - f_y \int_{-\infty}^{z} \left(\frac{de^{-i\Psi_y}}{dz}\right)\frac{df_y^*}{dz}dz\right], \qquad \Psi_y = \gamma G \int_0^z \frac{B_y}{B\rho}dz.$$

- As orbit, spin is most sensitive to perturbations in large-β areas
- Beam-beam effect on the spin can be suppressed by minimizing the spin response function at IP
- Contribution of a periodic radial perturbing field δB_x to the coherent part of the resonance strength

$$w = \frac{\gamma G}{2\pi}\oint \frac{\delta B_x}{B\rho} F \exp\left(-i\Psi_y\right) dz$$

  - dipole roll $\delta B_x = B\,\Delta\alpha$
  - vertical quadrupole misalignment $\delta B_x = \frac{\partial B_x}{\partial y}\Delta y$

JLEIC

Statistical Model

- The rms strength of the spin resonance due to Q uncorrelated segments of length l_k with radial fields $h_k \equiv h_x(z_k)$ normalized to $B\rho/R$ where R is the average radius for circumference $C = 2\pi R$

$$\overline{|\omega_{coh}|^2} = (\gamma G)^2 \sum_{k=1}^{Q} \left(\frac{l_k}{C}\right)^2 \overline{h_k^2}\, |F_k|^2$$

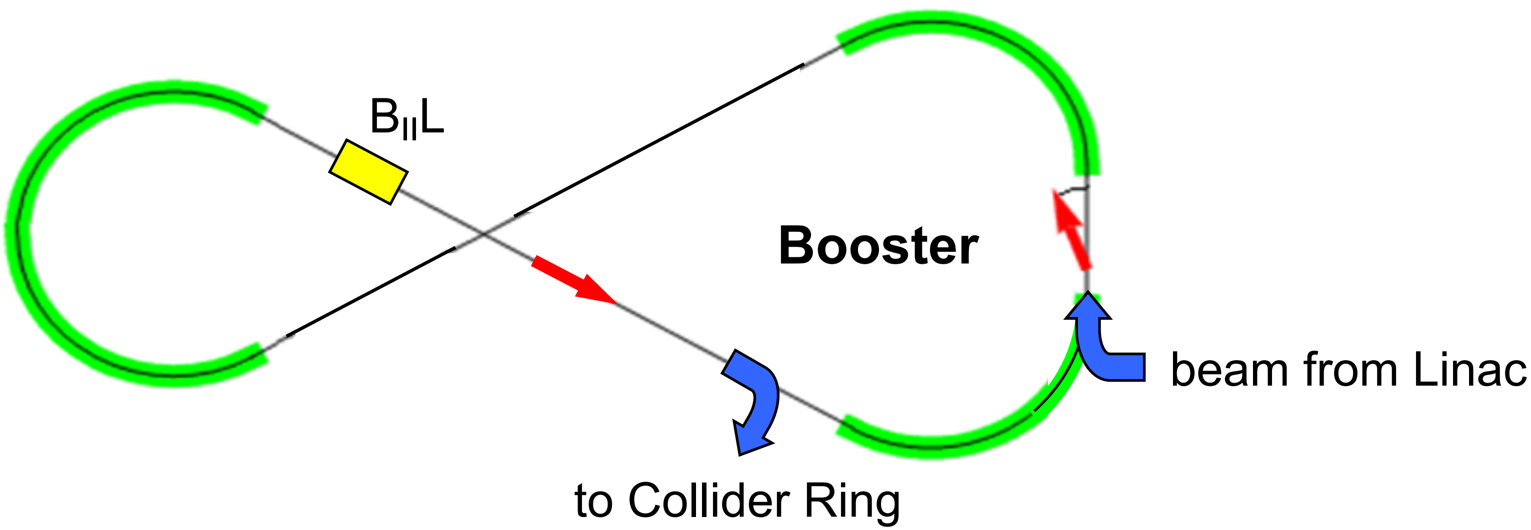
- The rms vertical excursion of the closed orbit

$$\overline{y^2(z)} = \frac{\pi^2 \beta_y(z)}{2\sin^2 \pi\nu_y} \sum_{k=1}^{Q} \left(\frac{l_k}{C}\right)^2 \overline{h_k^2}\, \beta_k$$

- Based on the expected closed orbit excursion, one can estimate the expected coherent component of the zero-integer spin resonance strength

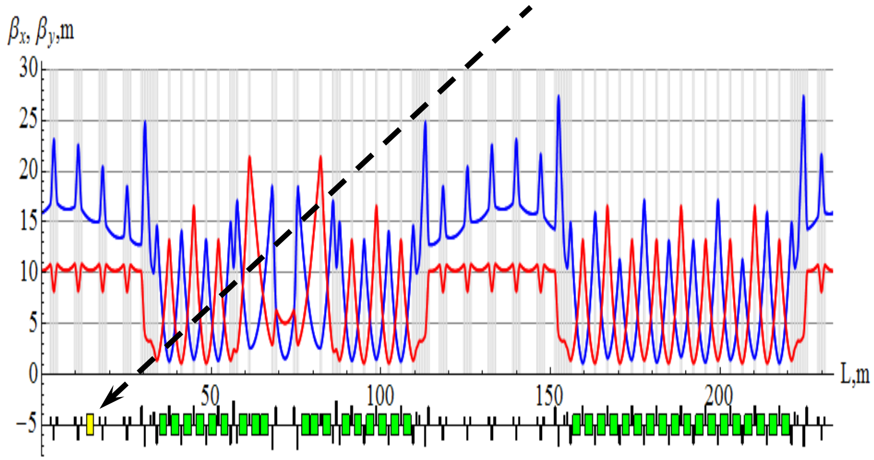
Ion Booster

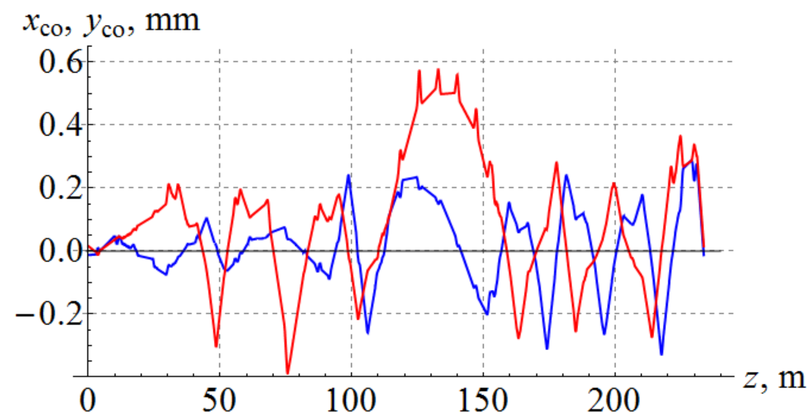
- Polarization in Booster stabilized and preserved by a single weak solenoid
  - **0.6 T·m** at 8 GeV/c
  - ν_d / ν_p = 0.003 / 0.01
- Longitudinal polarization in the straight with the solenoid
- Conventional 8 GeV accelerators require $B_{||}L$ of **~30 Tm** for protons and **~100 Tm** for deuterons



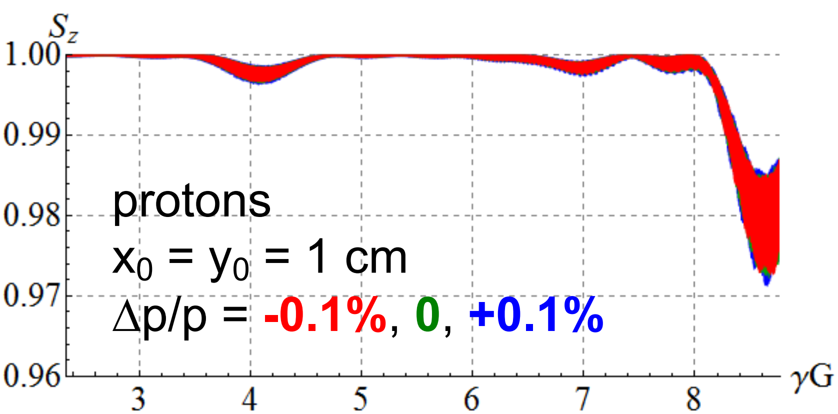
Spin Dynamics in Booster

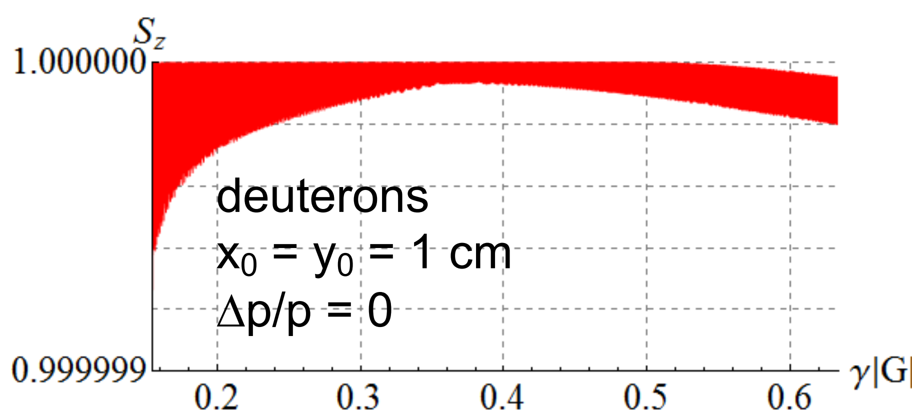
- Acceleration in figure-8 booster with transverse quadrupole misalignments
- 0.3 Tm (maximum) spin stabilizing solenoid





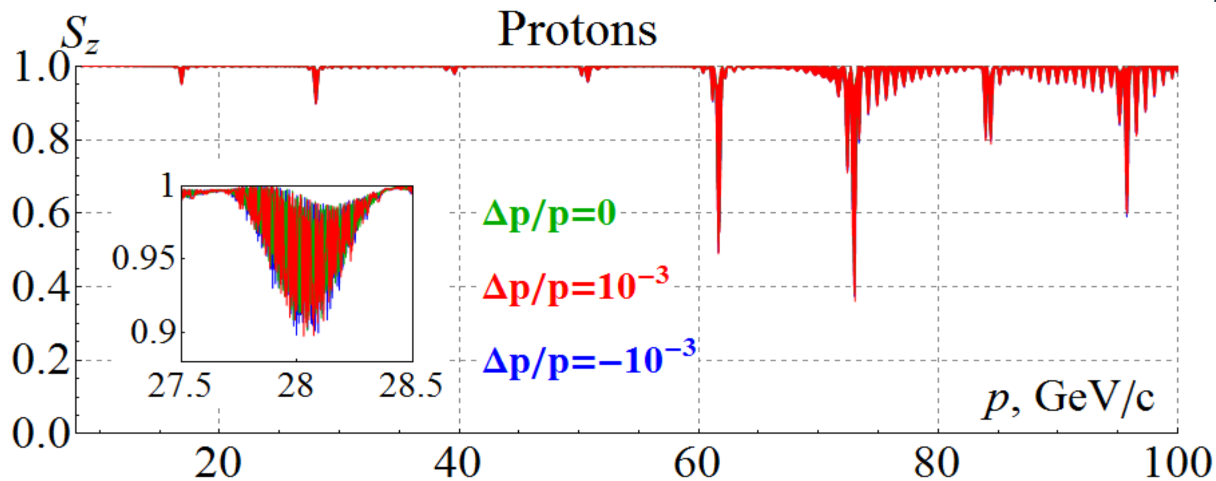
- Spin tracking simulation using Zgoubi





Start-to-End Proton Acceleration in Ion Collider Ring

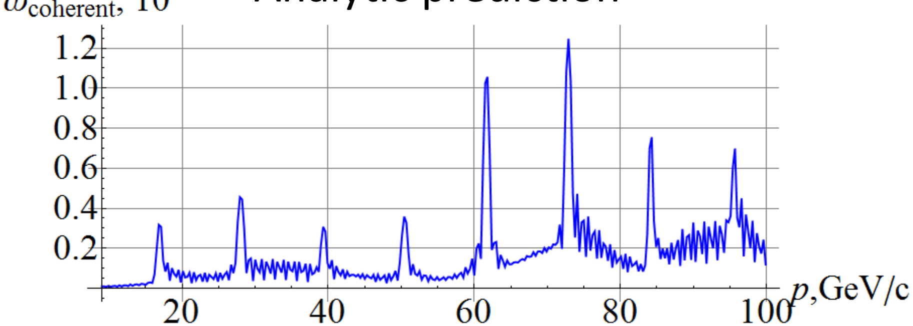
- Three protons with $\varepsilon_{x,y}^{N} = 1\ \mu m$ and $\Delta p/p = 0, \pm 1 \cdot 10^{-3}$ accelerated at ~3 T/min in lattice with 100 μm rms closed orbit excursion, $\nu_{sp} = 0.01$



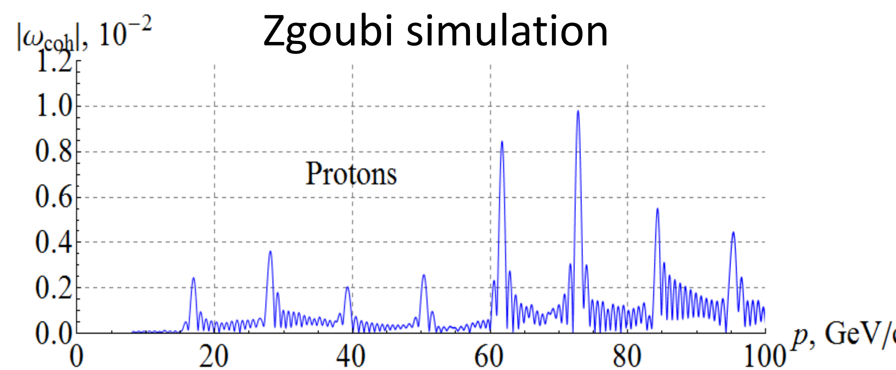
Zgoubi simulation

- Coherent resonance strength component

Analytic prediction



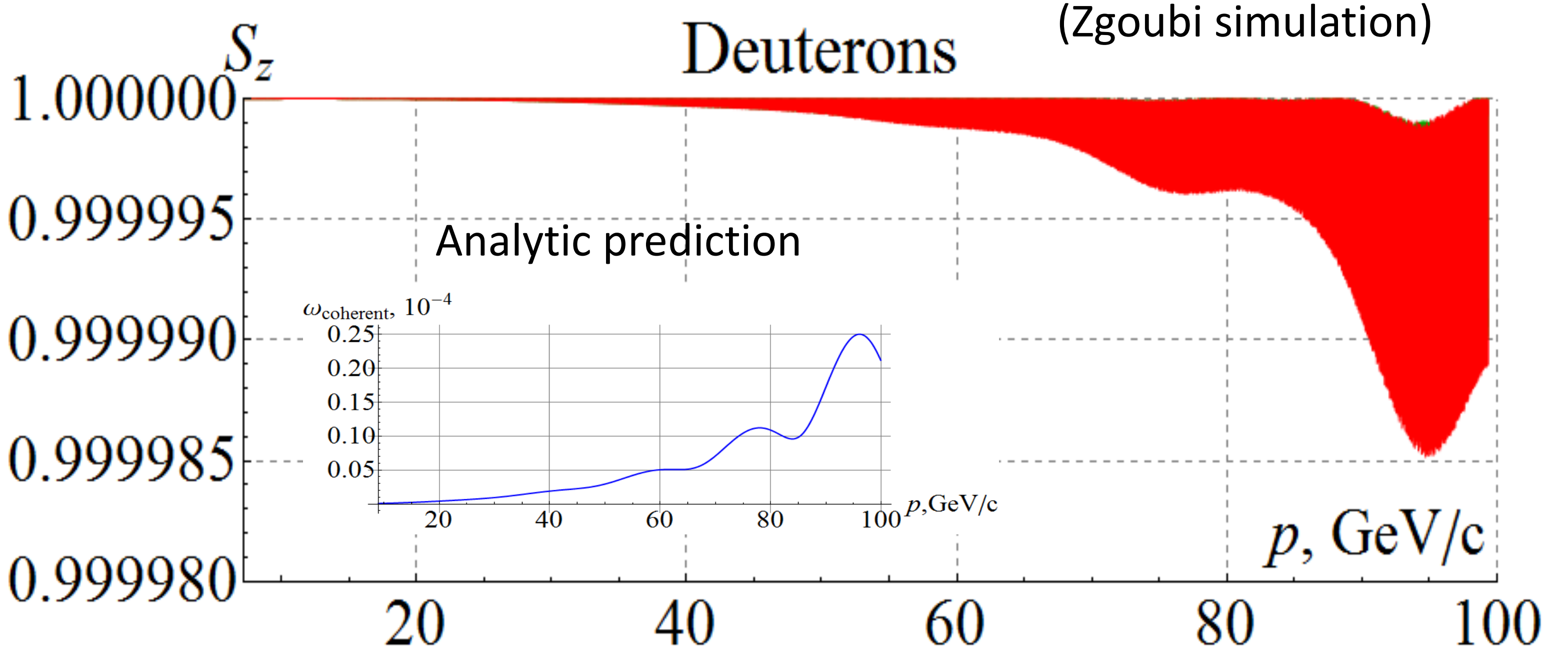
Zgoubi simulation



Start-to-End Deuteron Acceleration in Ion Collider Ring

- Three deuterons with $\varepsilon_{x,y}^{N} = 0.5\ \mu m$ and $\Delta p/p = 0, \pm 1 \cdot 10^{-3}$ accelerated at ~3 T/min in lattice with 100 μm rms closed orbit excursion, $\nu_{sp} = 3 \cdot 10^{-3}$

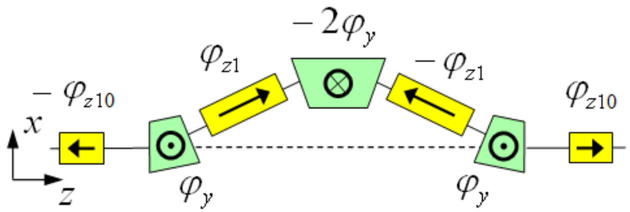
(Zgoubi simulation)



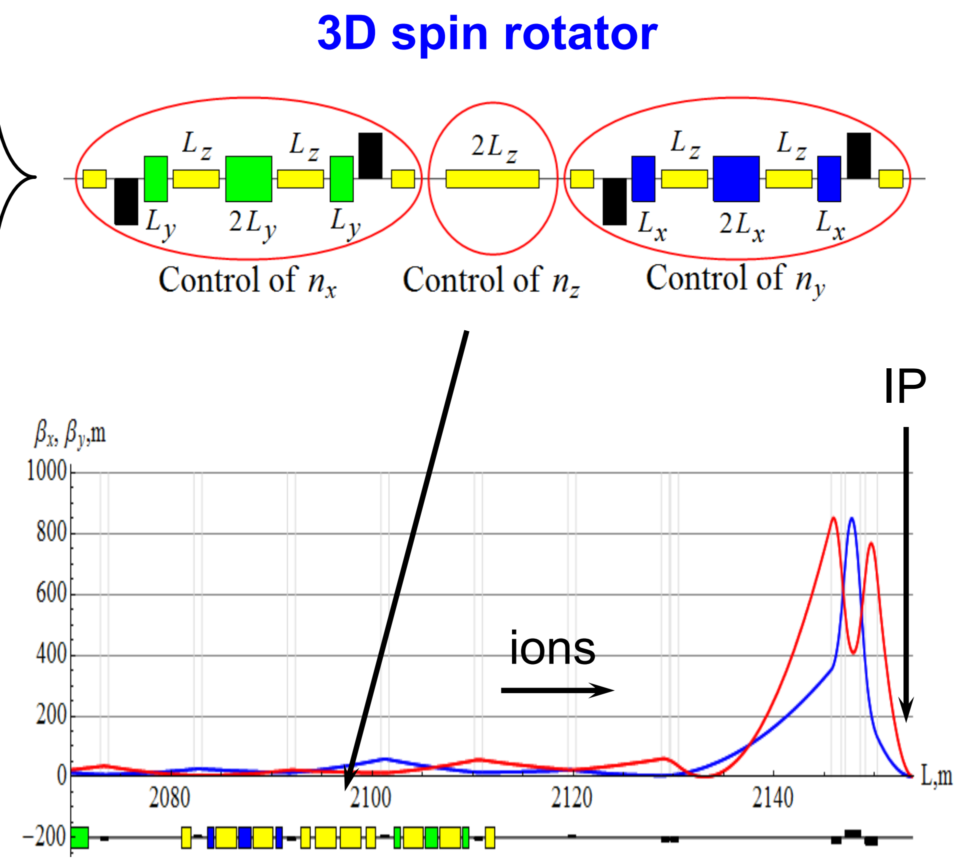
- Deuteron spin is highly stable in figure-8 rings, which can be used for high precision experiments

3D Spin Rotator in Ion Collider Ring

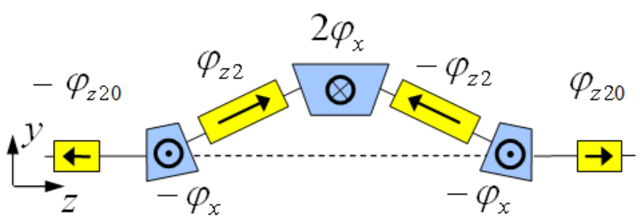
- Provides control of the radial, vertical, and longitudinal spin components
- Module for control of the radial component (fixed radial orbit bump)



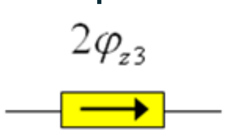
$L_{tot} = 7$ m, $\Delta x = 15$ mm, $B_{dip}^{max} = 3$ T, $B_{sol}^{max} = 3.6$ T



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



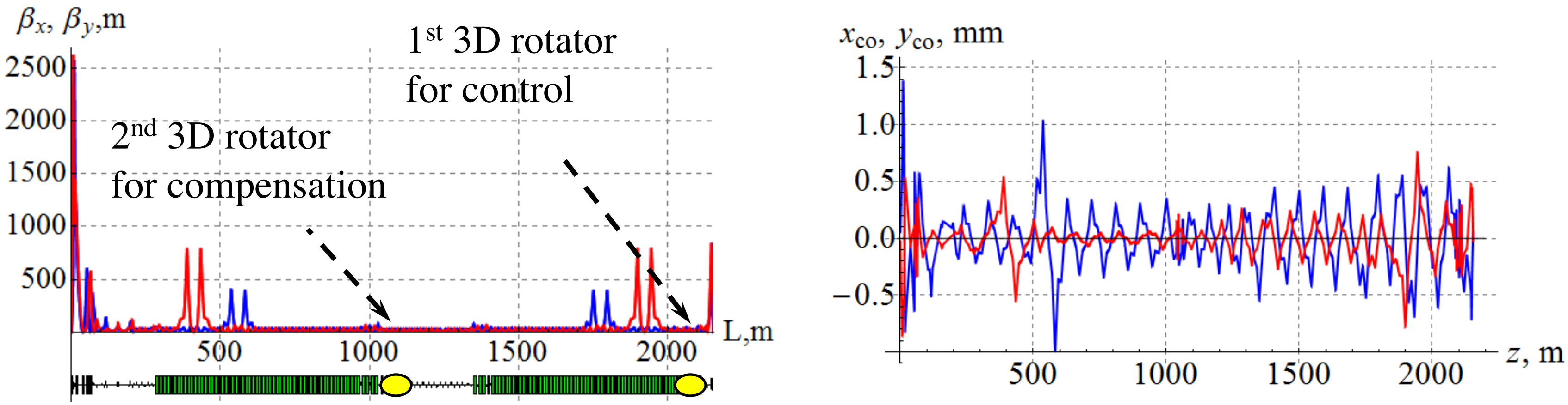
- Module for control of the longitudinal component



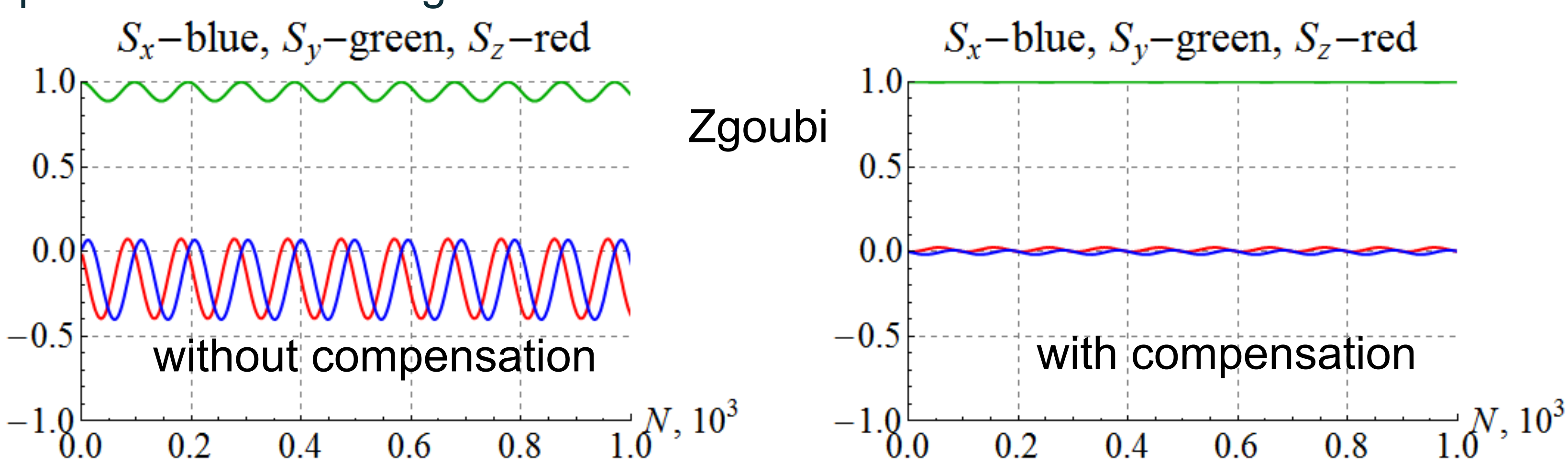
$L_x = L_y = 0.6$ m, $L_{zi} = 2$ m, $L_{zi0} = 1$ m, $\alpha_{orb} = 0.31^\circ$

Polarization Control in Ion Collider Ring

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

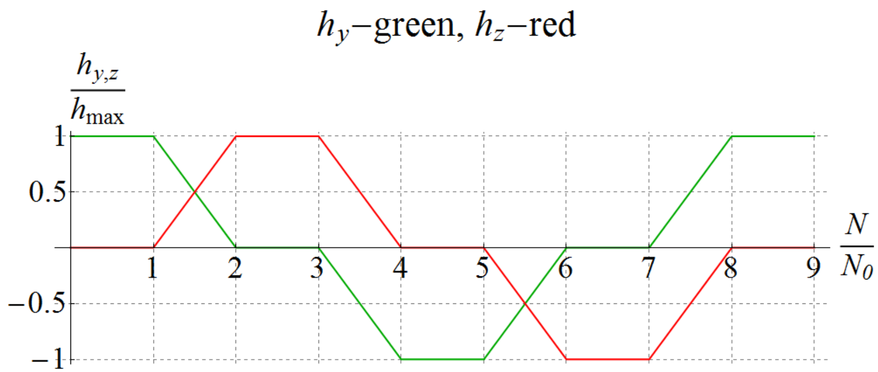


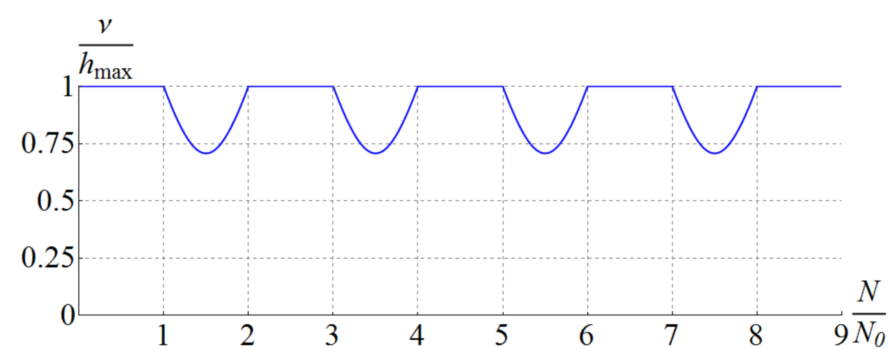
- Example of vertical proton polarization at IP. The 1st 3D rotator: $\nu = 10^{-2}$, n_y=1. The 2nd 3D rotator is used for compensation of coherent part of the zero-integer spin resonance strength



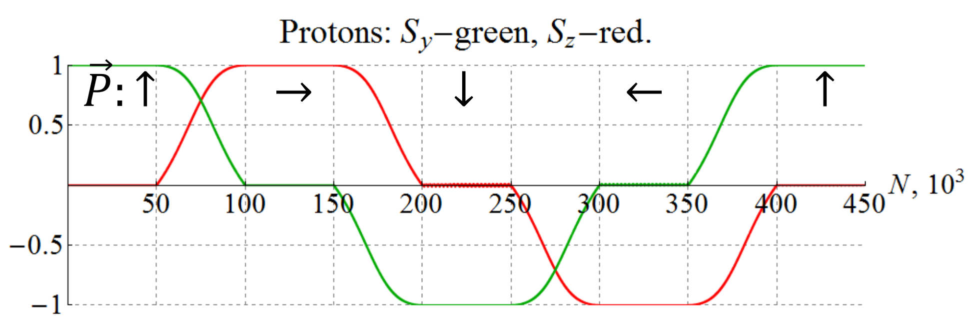
Spin Flipping

- Adiabaticity criterion: spin reversal time must be much longer than spin precession period $\Rightarrow \tau_{\text{flip}} >> 1$ 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)
- N is the number of particle turns





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



Zgoubi simulation

$N_0 = 50 \cdot 10^3$

Study of Spin Transparency Mode in RHIC

- This EIC R&D proposal is funded by the DOE in FY18-19 with the collaboration of Jlab and BNL
- RHIC is a perfect place for an experimental test of the spin transparency mode: no new hardware is needed, existing polarimeter
- Make snake axes parallel at $0°$ to set RHIC in the spin transparency mode
- 3D spin rotator
  - Small angle between the snake axes = vertical module
  - Small mismatch of the spin rotators = radial module
  - Small mismatch between the snake strengths = longitudinal module

Task	FY18 Q1	FY18 Q2	FY18 Q3	FY18 Q4	FY19 Q1	FY19 Q2	FY19 Q3	FY19 Q4
1. Analysis and simulation of the spin transparency mode in RHIC								
2. Evaluation of the technical capabilities of RHIC								
3. Development of an experimental program								
4. Preparation and submission of an experimental proposal								
5. Completion of an experimental test								
6. Analysis and publication of experimental data								

Radiative Polarization Effects

- Sokolov-Ternov polarization change rate

$$\tau_{ST}^{-1} = \frac{5\sqrt{3}}{8} \frac{r_e \gamma^5 h/2\pi}{m_e} \frac{1}{C} \oint ds \left\langle \frac{1 - \frac{2}{9}(\hat{n} \cdot \hat{s})^2}{|\rho(s)|^3} \right\rangle_s$$

$\hat{n}$ is the invariant spin field, a 1-turn periodic unit 3-vector field over the phase space satisfying the T-BMT equation along particle trajectories, $\hat{s}$ is a unit vector along the particle velocity, and $2\pi\hbar$ is Planck's constant.

- Depolarization rate due to spin diffusion

$$\tau_{SD}^{-1} = \frac{5\sqrt{3}}{8} \frac{r_e \gamma^5 h/2\pi}{m_e} \frac{1}{C} \oint ds \left\langle \frac{11(\partial\hat{n}/\partial\delta)^2}{18|\rho(s)|^3} \right\rangle_s$$

$\partial\hat{n}/\partial\delta$ is the spin-orbit coupling function

- Total polarization change rate

$$\tau_{DK}^{-1} = \tau_{ST}^{-1} + \tau_{SD}^{-1}$$

- Equilibrium polarization

$$P(t) = P_{ens,DK}\left(1 - e^{-t/\tau_{DK}}\right) + P_0 e^{-t/\tau_{DK}}$$

where $P_{ens,DK} = P_{DK}\langle\hat{n}\rangle_s$ is the value of ensemble average of P_{DK} independent of s and P_0 is the initial polarization

Spin Matching

- Spin matching
  - The optics and layout must be adjusted so that $(\partial\hat{n}/\partial\delta)^2$ is small where $1/|\rho(s)|^3$ is large
  - So far it is only possible to do this within the linear approximation for spin motion
  - In general, the rotators and the sections between them are the main source of depolarization and this is confirmed by calculations with SLICK. By suitable choice of optics, it may be possible to make the whole region spin transparent.
- Spin matching stages
  - *Strong synchro-betatron spin matching* is applied to the optics of a perfectly aligned ring, in particular to the interaction regions and the rotators.
  - *Harmonic closed orbit spin matching* is applied to soften the effect of misalignments by adjusting the closed orbit to reduce the tilt of $\hat{n}_0$ from the vertical in the arcs. Because the misalignments and the closed orbit are usually not known with a precision sufficient to predict the tilt of $\hat{n}_0$, the closed orbit is adjusted empirically while the polarization is measured.
- Spin matching effect
  - If successful, as for example at HERA, it reduces the strengths of the first order spin-orbit resonances and improves the polarization lifetime.

Spin Matching in e-Ring

- Tolerance to alignment errors of magnetic elements in the arcs
  - Depolarizing effect of synchrotron radiation is determined by the spin-orbit coupling function $(\partial\hat{n}/\partial\delta)^2$
    - Spin-orbit coupling is a periodic function of the electron ring and is determined by its magnetic lattice
  - When $\gamma G \gg 1$, the main depolarizing mechanism is diffusion of the spin rotation angle about the arcs' magnetic fields
    - When polarization is vertical in the arcs, diffusion of the spin rotation angle gives no contribution to the polarization decrement
    - Lattice errors give rise to a transverse polarization component in the arcs, which must be sufficiently small (where α_{arc} is the arc's orbital rotation angle)

$$|\Delta\vec{n}_{\perp}| \ll \sqrt{\frac{54}{11}\frac{1}{\gamma G \alpha_{arc}}}$$

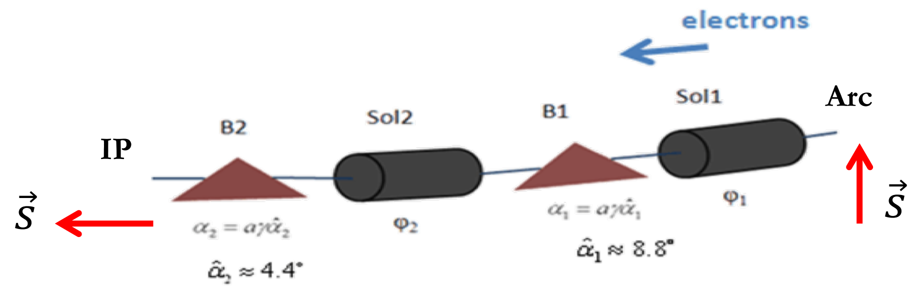
    - The greatest danger comes from roll and vertical misalignment of arc quadrupoles and final focusing quadrupoles

Spin Matching in e-Ring

- Requirements to the USR
  - To minimize additional contribution of the USR to the polarization decrement, it must meet the following requirements
    - The closed orbit must be restored
    - The rotator must provide vertical polarization in the arcs
    - There must be no vertical dispersion and betatron oscillation coupling in the arcs
    - The rotator must not excite the spin-orbit coupling function $\vec{d}$ at the arc's entrance
  - Increase in the radiative decrement in this case is related only to radiation in the USR
    - The additional contribution of radiation to the decrement has cubic dependence on the rotator's dipole fields and can be reduced by lengthening the dipole magnets
  - As a next step, one must optimize parameters of the USR with subsequent numerical verification including alignment errors of magnetic elements of the electron ring lattice

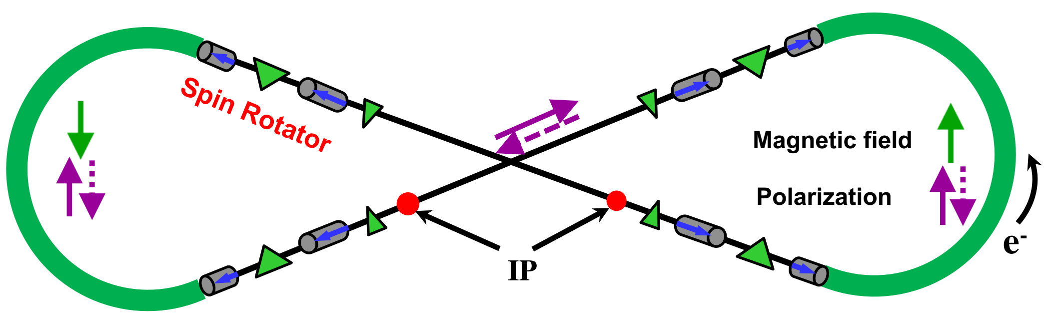
Universal Spin Rotator

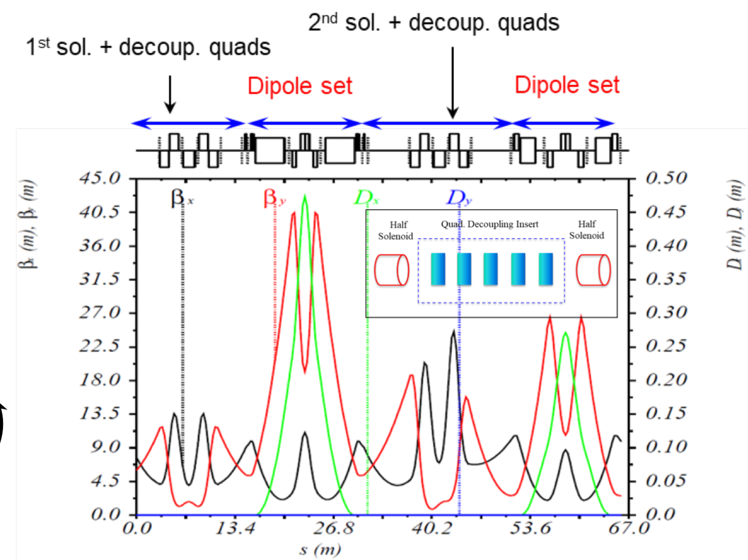
- Changes polarization from vertical in the arcs to longitudinal in the straights
- Sequence of solenoid and dipole sections
- Geometry independent of energy



E	Solenoid 1		Dipole set 1	Solenoid 2		Dipole set 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

- Dispersion suppressed in solenoids and each solenoid is individually decoupled
- Two polarization states with equal lifetimes





Polarization Lifetime and Continuous Injection

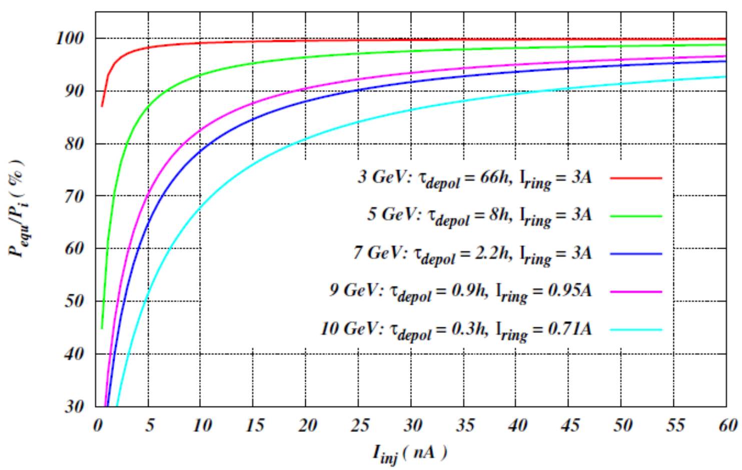
- Estimated polarization lifetime

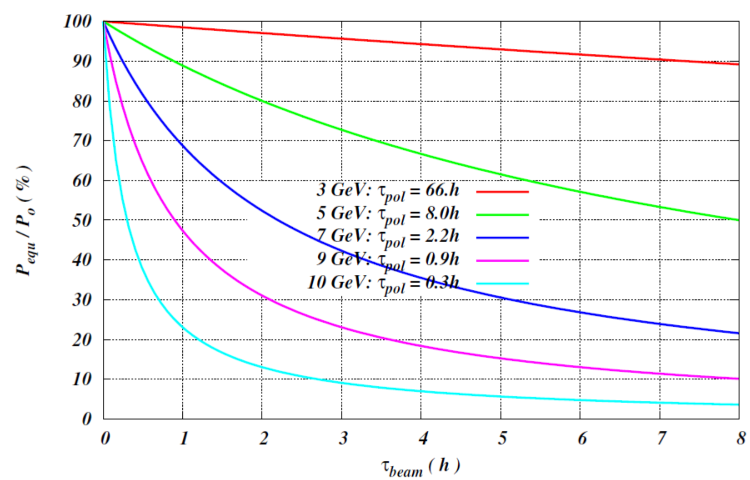
Energy (GeV)	3	5	7	9	12
Lifetime (hours)	116	9	1.7	0.5	0.1

- Constant polarization is maintained by continuous injection of highly polarized electron beam from CEBAF
- Equilibrium polarization

$$P_{equ} = P_0\left(1 + \frac{T_{rev} I_{ring}}{\tau_{DK} I_{inj}}\right)^{-1}$$

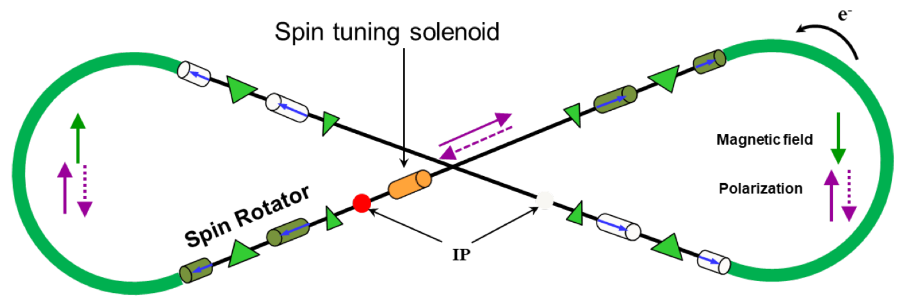
- A relatively low average injected beam current of tens-of-nA level can maintain a high equilibrium polarization in the whole energy range
- Beam lifetime must be balanced with the beam injection rate and $\tau_{beam} \ll \tau_{pol}$

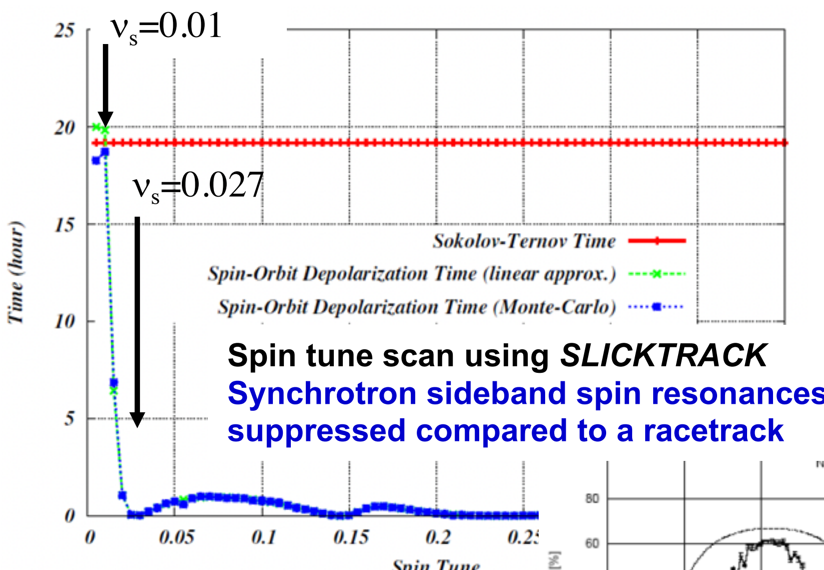


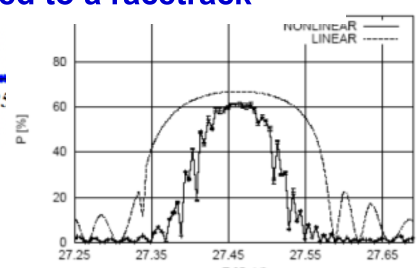


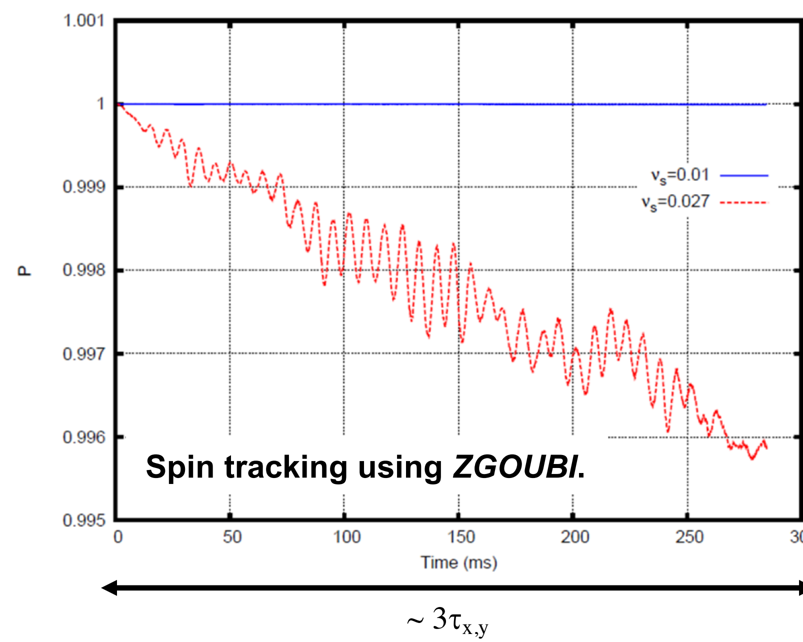
Spin Tracking

- Spin tune scan using a spin tuning solenoid in SLICK/SLICKTRACK
- Demonstrates suppression of synchrotron sideband spin resonances
- Verified by Zgoubi's Monte-Carlo spin tracking









Summary

- JLEIC rings adopt a figure-8 shape for better preservation and control of polarization by taking advantage of a spin transparency mode

- Both ion and electron polarization schemes have been designed

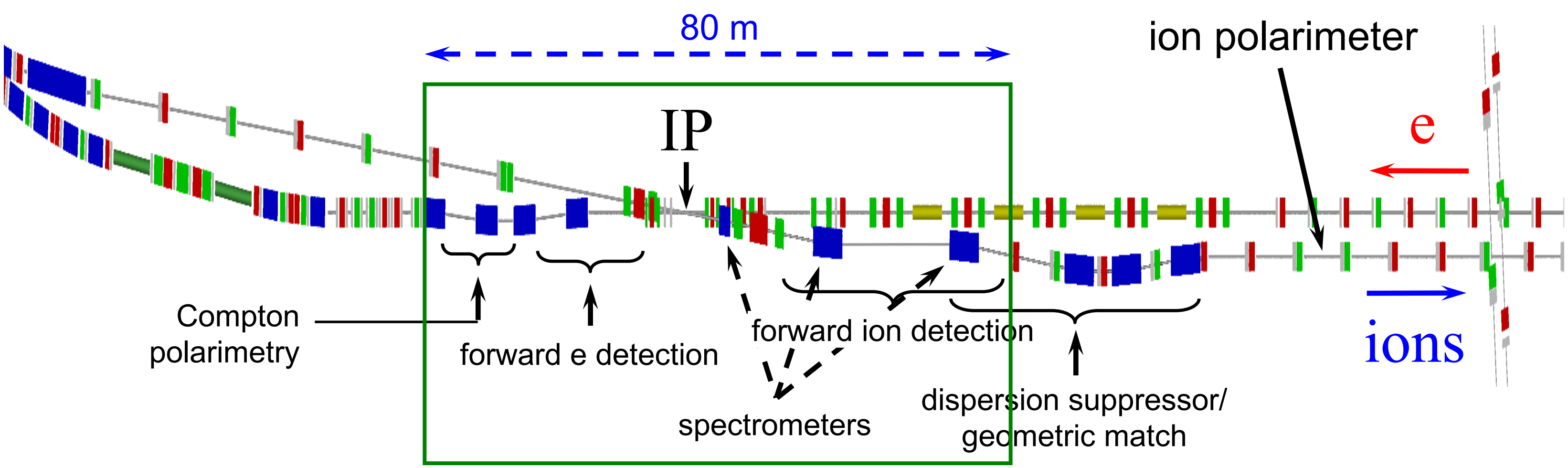
- Spin tracking numerically validated a figure-8 based polarization control schemes for the whole JLEIC complex

- Spin transparency mode will be studied in the RHIC

Back Up

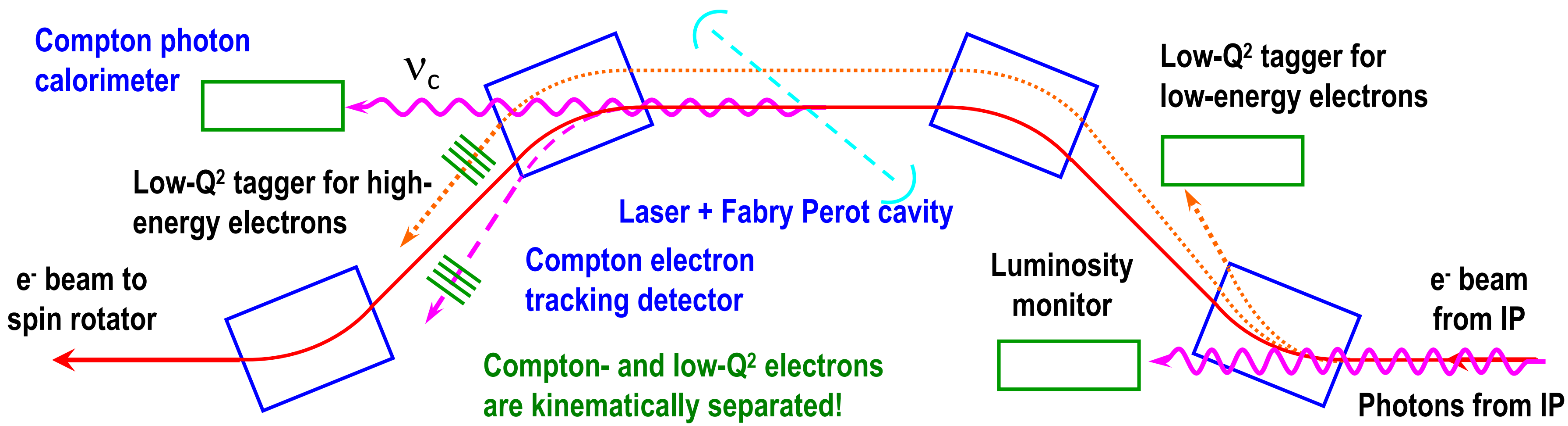
Polarization Measurement Strategy

- Polarimeter located downstream of IP
- Orbital bending angle between the IP and polarimeter should be as small as possible to minimize polarization measurement error
- Since ion polarimeter measures only transverse polarization component, complete “spin dance” to calibrate the polarization orientation at the polarimeter as a function of 3D spin rotator settings
- Measure polarization of bunch trains that have identical polarizations of individual bunches
- Calibrate fast polarimeter against absolute polarimeter



Compton Polarimeter

- Dipole chicane immediately downstream of the IP for detection of low-Q^2 electrons
- Compton polarimeter located in the middle of the chicane
  - same polarization at the laser as at the IP due to zero net bend
  - non-invasive continuous monitoring of electron polarization



Deuteron Tensor Polarization

- Preservation and control of vector polarization = preservation and control of tensor polarization
- Spin wave function of spin-j particle can be formally composed of spin wave functions of $2j$ independent spin-$1/2$ particles $\Rightarrow$
  - Description of spin-j dynamics in electric and magnetic fields reduces to description of spin-$1/2$
  - Demonstration of preservation and control of spin-$1/2$ polarization at the same time demonstrates preservation and control of spin-1 vector and tensor polarizations
- Polarization rotation

$$P_V(\theta) = Tr[\rho(\theta)S_z] = Tr\left[R^\dagger(\theta)\rho R(\theta)S_z\right] = P_V \cos\theta$$

$$P_T(\theta) = Tr[\rho(\theta)S_{zz}] = P_T\left\{\frac{3}{2}\cos^2\theta - \frac{1}{2}\right\}$$