Polarized Hadron and Electron Beams at JLEIC

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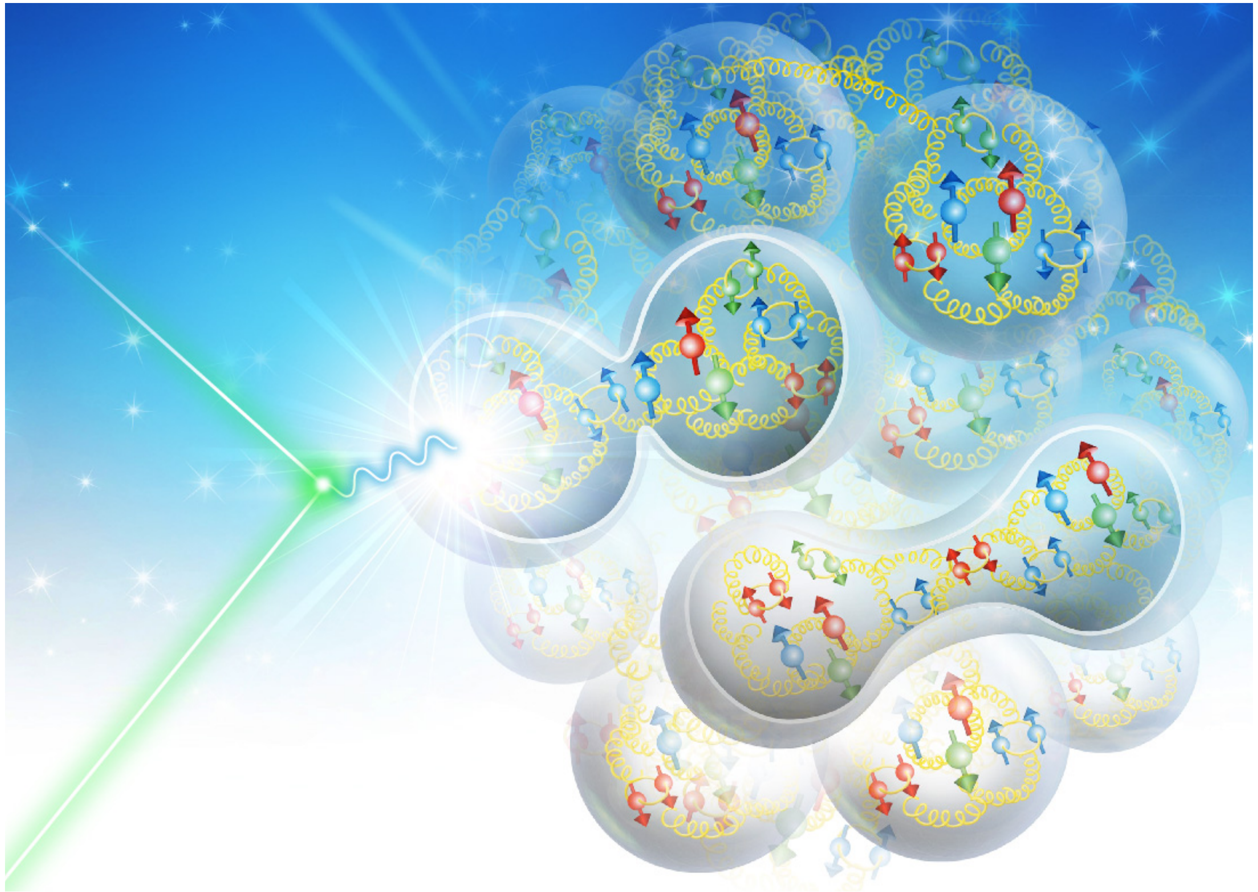
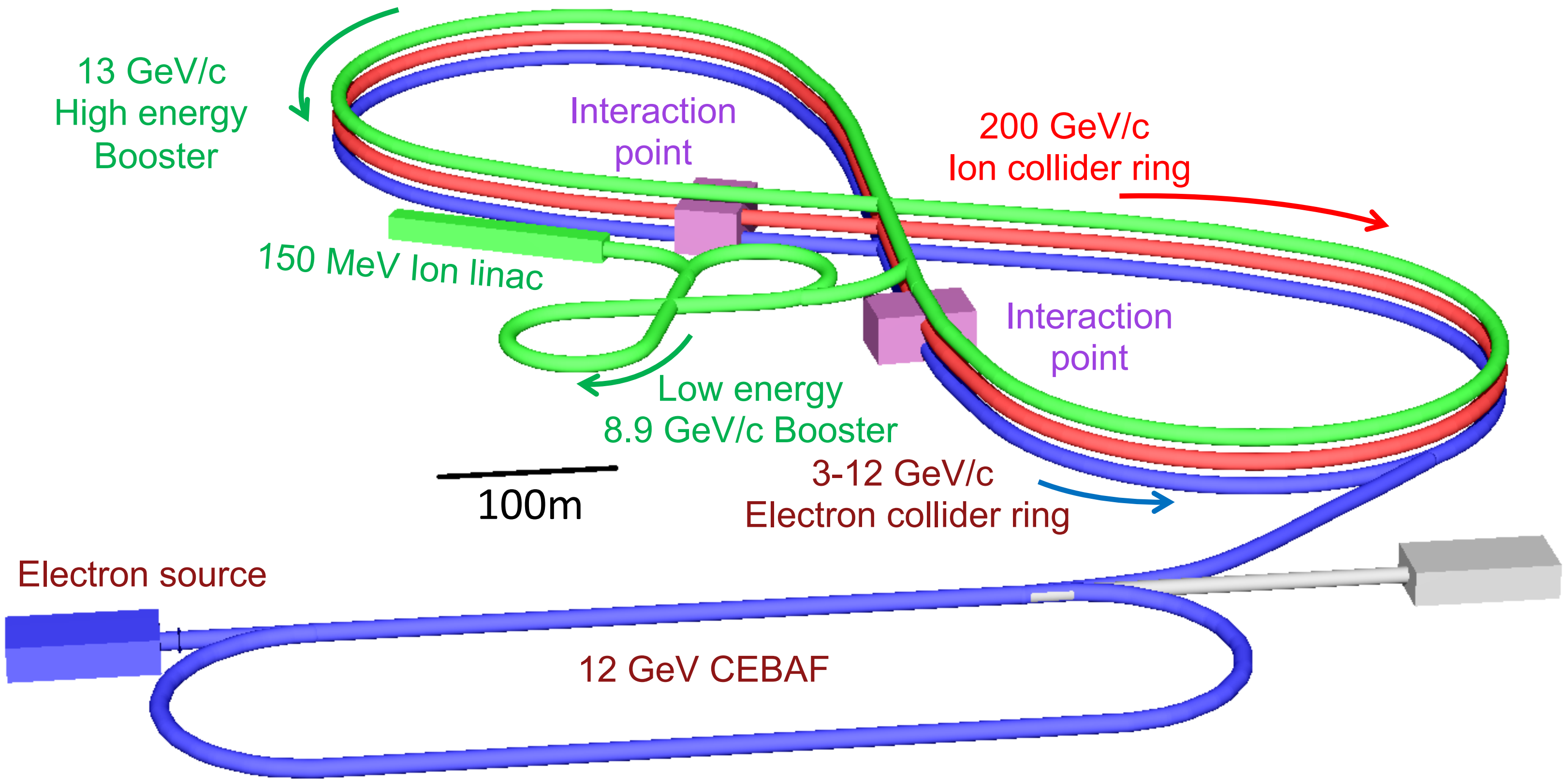


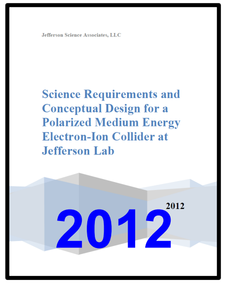
EIC Accelerator Collaboration Meeting 2019

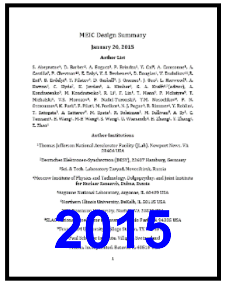
Argonne National Laboratory, Oct 9 -11, 2019

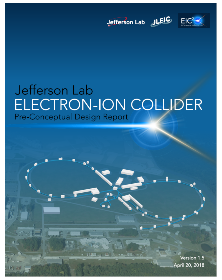
JLEIC Layout

- Electron complex
  - CEBAF
  - Electron collider ring: 3-12 GeV/c
- Ion complex
  - Ion source
  - SRF linac: 150 MeV for protons
  - Low Energy Booster: 8.9 GeV/c
  - High Energy Booster: 13 GeV/c
  - Ion collider ring: 200 GeV/c
- Up to two detectors at minimum background locations
- Upgradable to 140 GeV CM









arXiv:1209.0757
arXiv:1504.07961

pCDR
August 2019

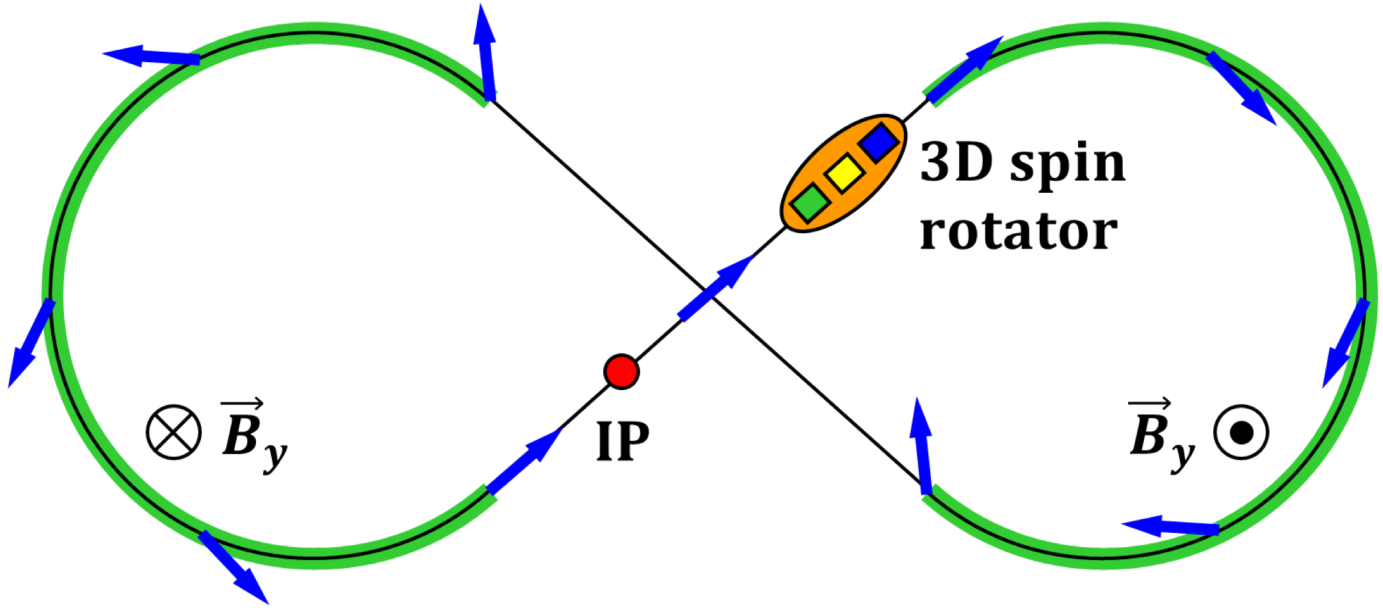
Polarization Requirements

- Ion polarization design requirements
  - High polarization (> 70%) 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 (> 70%)
  - Longitudinal polarization orientation at all IPs
  - Sufficiently long polarization lifetime
  - Opposite polarization states

High Ion Polarization

- Figure-8 concept: Spin precession in one arc is exactly cancelled in the other
- Spin stabilization by small fields: ~3 Tm vs. < 400 Tm for deuterons at 100 GeV
  - Criterion: induced spin rotation >> spin rotation due to orbit errors
- 3D spin rotator: combination of small rotations about different axes provides any polarization orientation at any point in the collider ring
- No effect on the orbit
- Polarized deuterons
- Frequent adiabatic spin flips



Spin Resonance and Spin Stability Criterion

- Total spin resonance strength

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

  is composed of
  - coherent part $\omega_{coherent}$ due to closed orbit excursion
  - incoherent part $\omega_{emittance}$ due to beam emittances

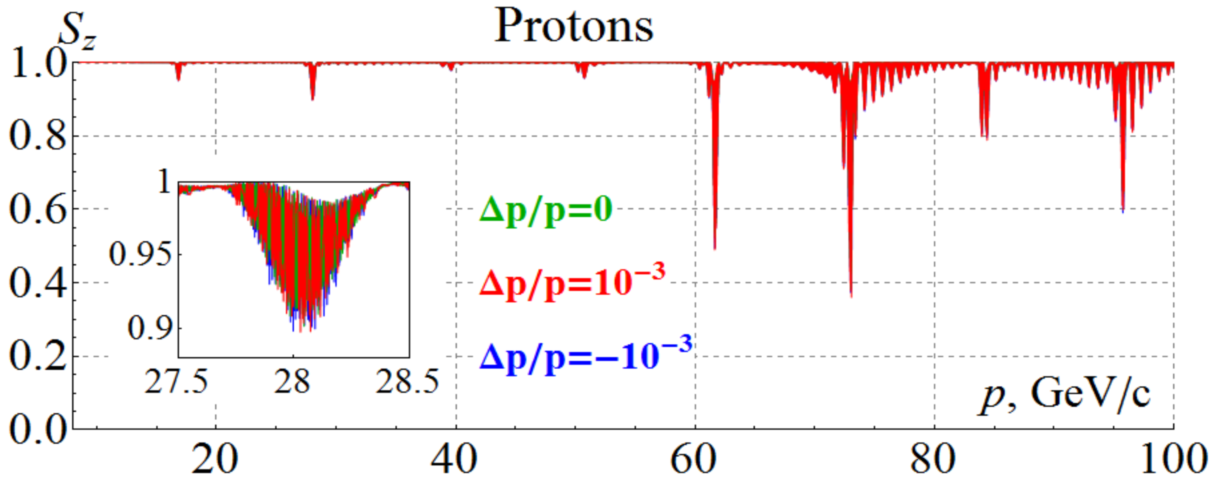
- Spin stability criterion
  - induced spin rotation must dominate over net rotation due to imperfections

$$\nu \gg |\vec{\omega}|$$

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

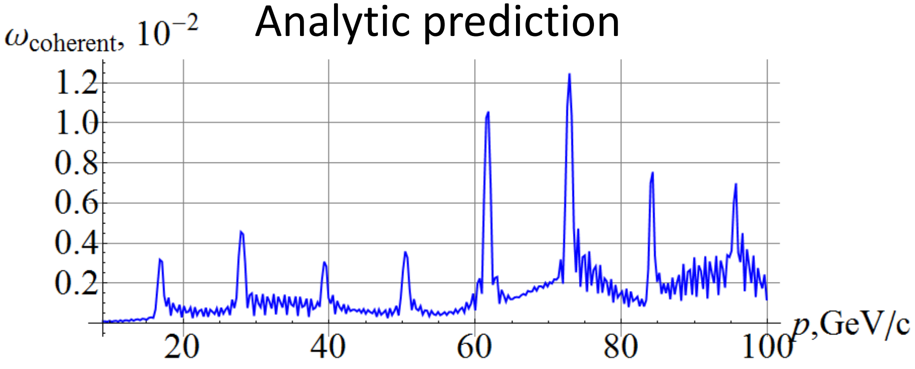
Start-to-End Proton Acceleration in Ion Collider Ring

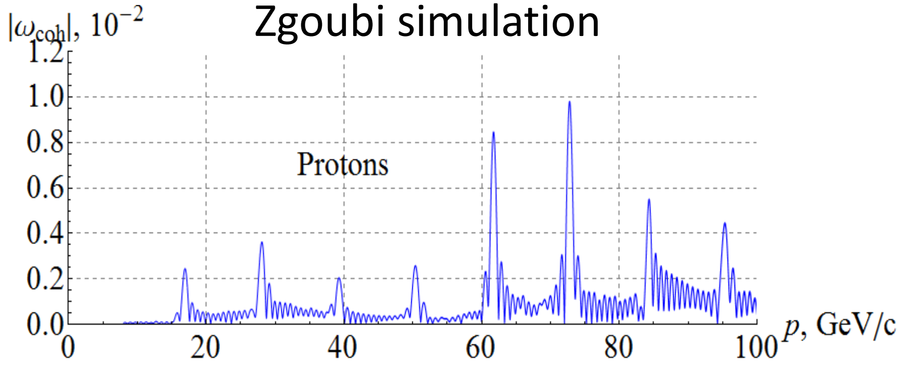
- Three protons with $\varepsilon_{x,y}^{N} = 1\ \mu m$ and $\Delta p/p = 0, \pm 1 \cdot 10^{-3}$ accelerated at ~3 T/min in lattice with 100 μm rms closed orbit excursion, $\nu_{sp} = 0.01$



Zgoubi simulation

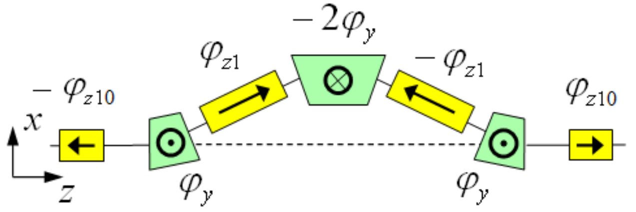
- Coherent resonance strength component





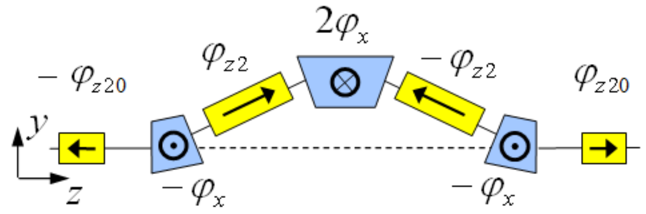
3D Spin Rotator in Ion Collider Ring

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

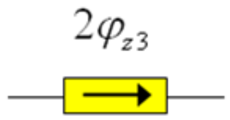


$L_{tot} = 7$ m, $\Delta x = 15$ mm, $B_{dip}^{max} = 3$ T, $B_{sol}^{max} = 3.6$ T

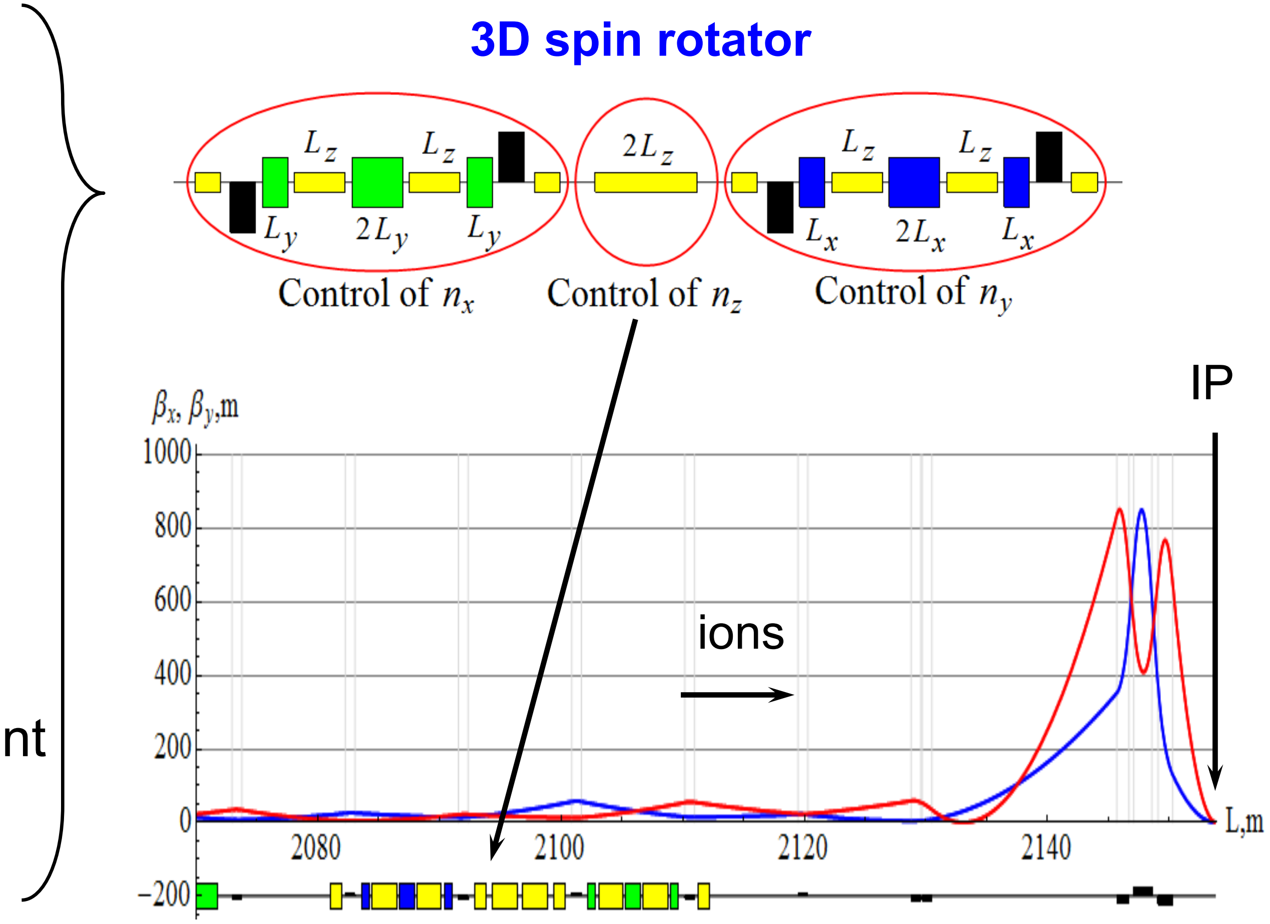
- Module for control of the vertical component (fixed vertical orbit bump)



- Module for control of the longitudinal component



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



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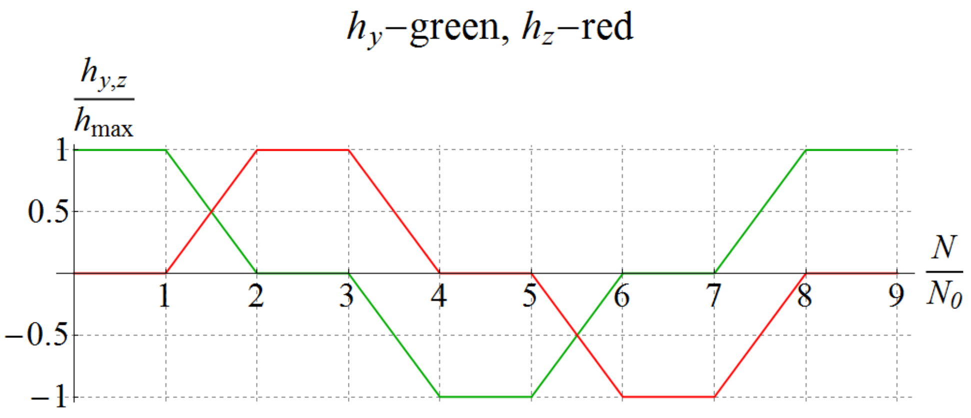
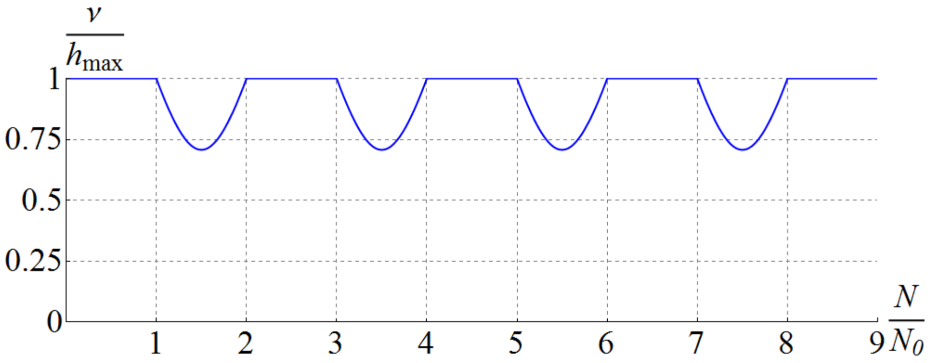
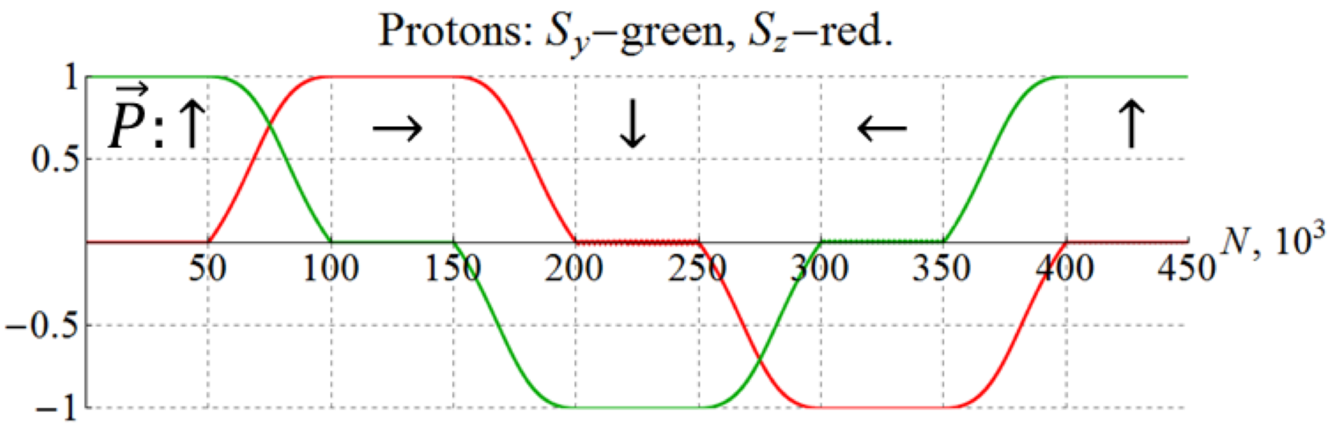
Spin Manipulation

- Spin axis change rate slow compared to spin precession rate
  - τ_{flip} >> 1 ms for protons and 0.1 s for deuterons
- Constant spin tune





Zgoubi simulation



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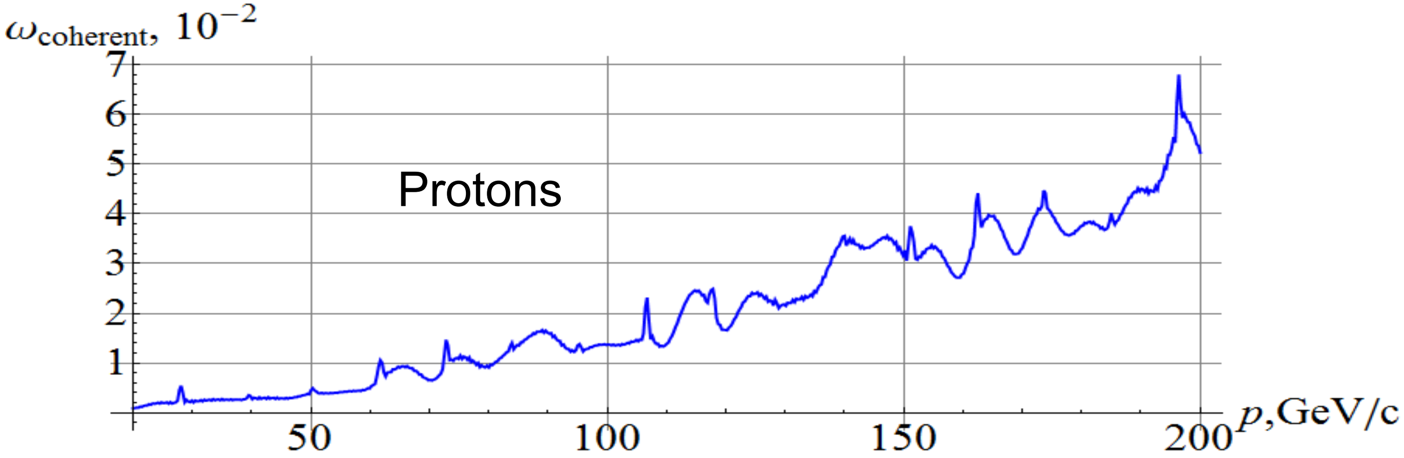
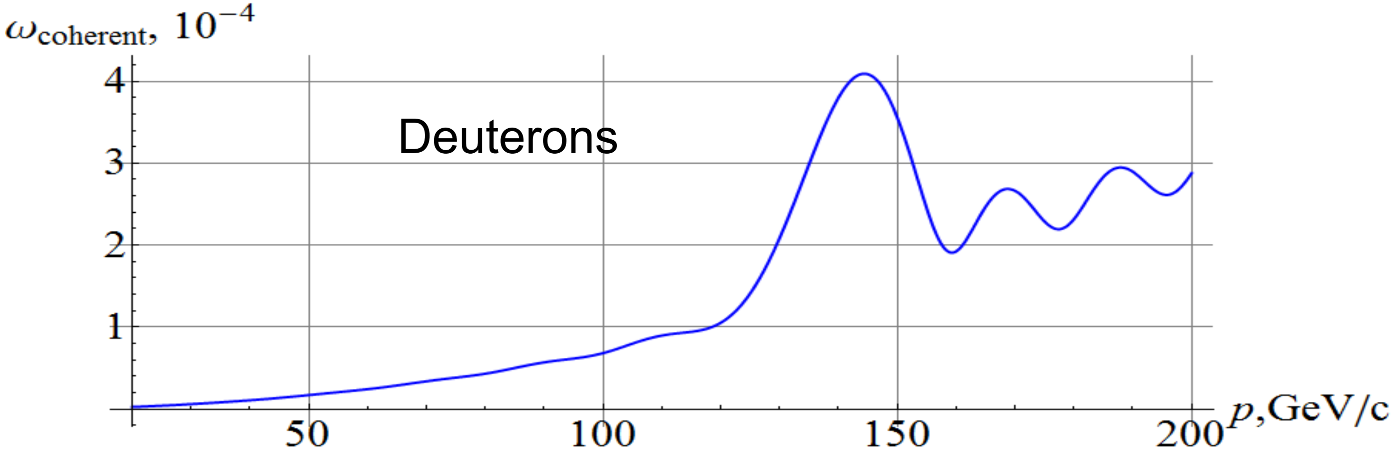
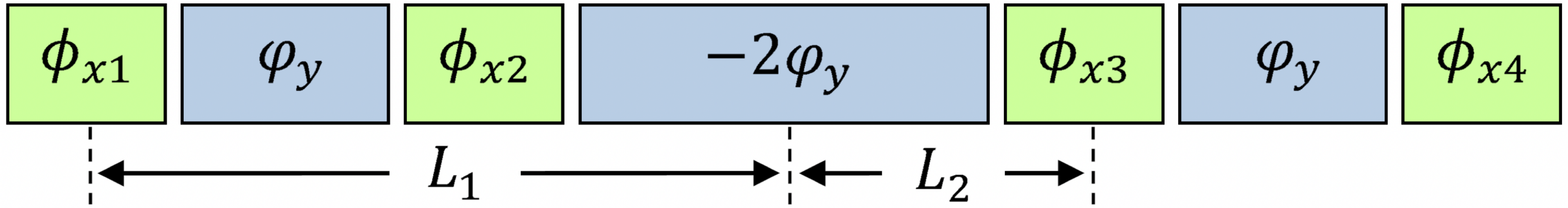
Spin Resonance Strength up to 200 GeV

- Assuming RMS closed orbit distortion of ~200 μm
- Above ~100 GeV/c, the 3D spin rotator strength may not be sufficient to control polarization ⇒ consider a 3D spin rotator based on transverse fields

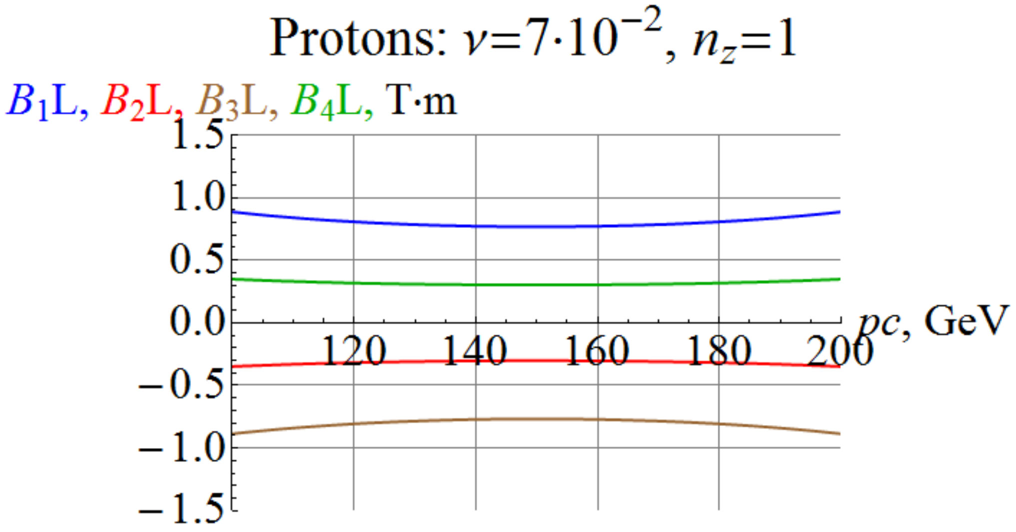




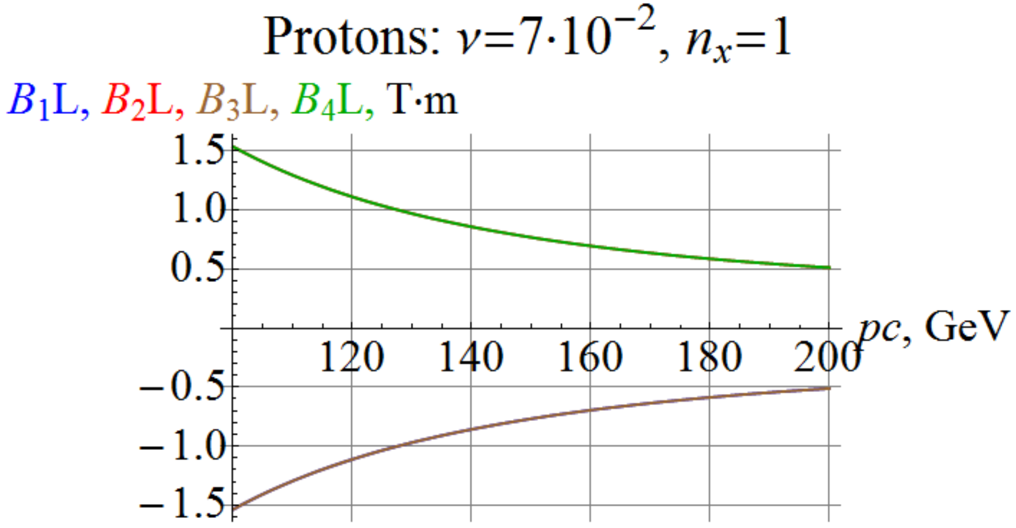
Proton Spin Rotator Utilizing Transverse Fields



Longitudinal Polarization at IP



Radial Polarization at IP



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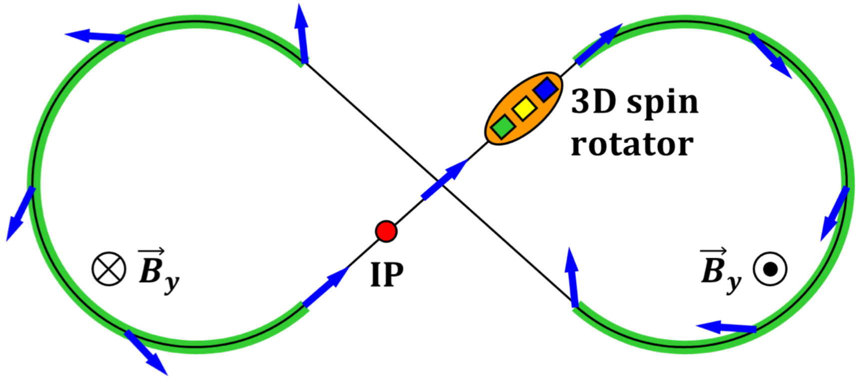
Concept of Transparent Spin Experiment (Funded FOA Proposal)

- A number of novel polarization preservation and control techniques have been developed for JLEIC
  - Transparent spin mode
    - Figure-8 ring
    - Racetrack with two identical Siberian snakes separated by 180° bend (practical for high energy protons)



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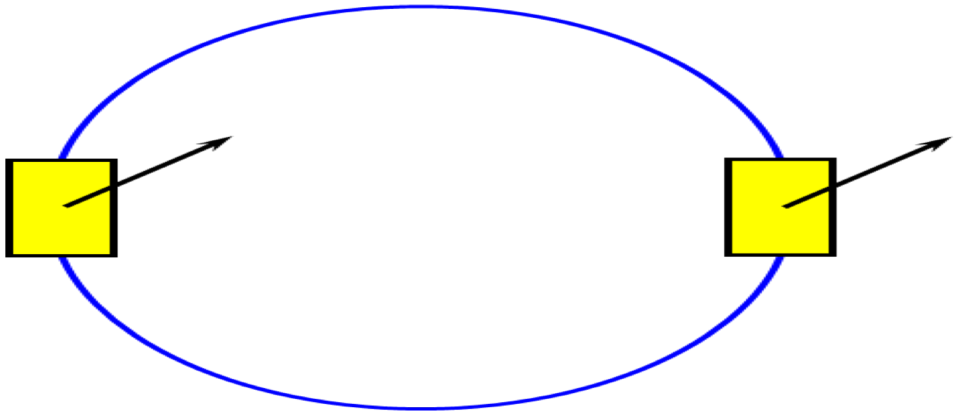
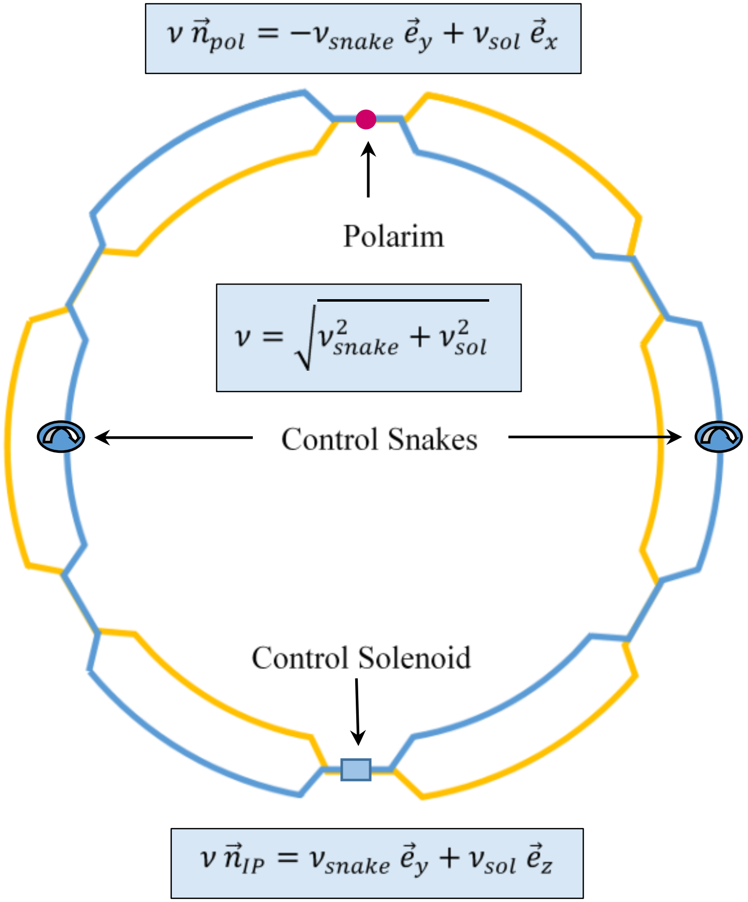


  - 3D spin rotator: small rations about three orthogonal axes = rotation about any direction
  - Polarized deuteron beam at higher than ever before energies
  - New spin dynamics theory and analytic and simulation tools
- Spin transparency mode is of interest to BNL for the eRHIC electron collider ring
- Plan experimental verification of theory and simulations

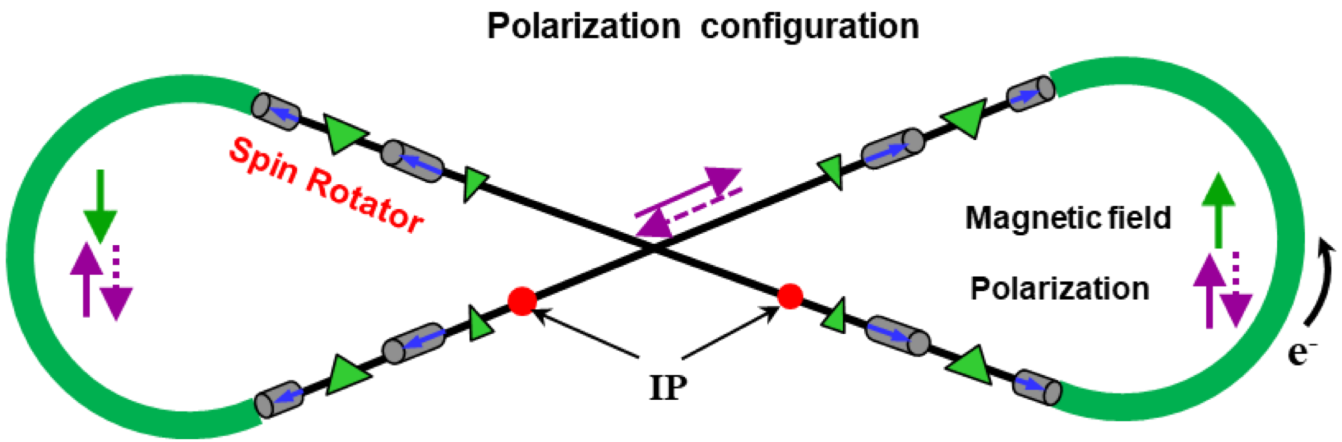
RHIC in Transparent Spin Mode

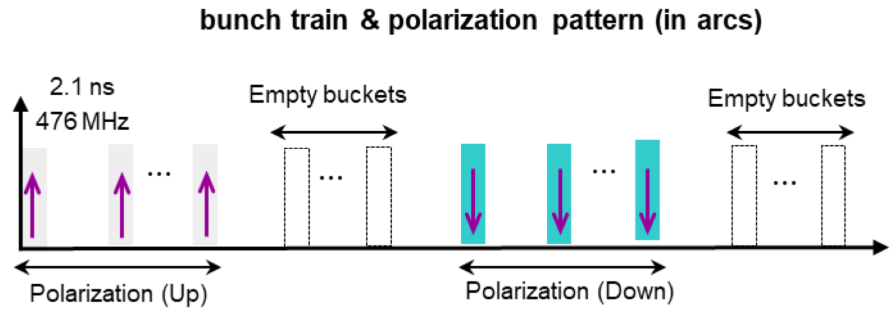
- RHIC already has all of the necessary technical capabilities
- Make snake axes parallel at $0°$
- 3D spin rotator
  - Small angle between the snake axes = vertical module
  - Mismatch of the snake strengths from π = longitudinal & radial modules
- Existing polarimeter with fast measurement time, primarily interested in relative measurement



Electron Polarization Strategies

- Highly vertically polarized electron beam from CEBAF
  - High equilibrium polarization maintained by continuous injection
  - Two oppositely polarized bunch trains
- Polarization vertical in the arc to avoid spin diffusion and longitudinal at collision points
  - Universal spin rotator with fixed orbit from 3 to 12 GeV
- Energy independent spin tune
- Spin matching considered
- Compton polarimeter





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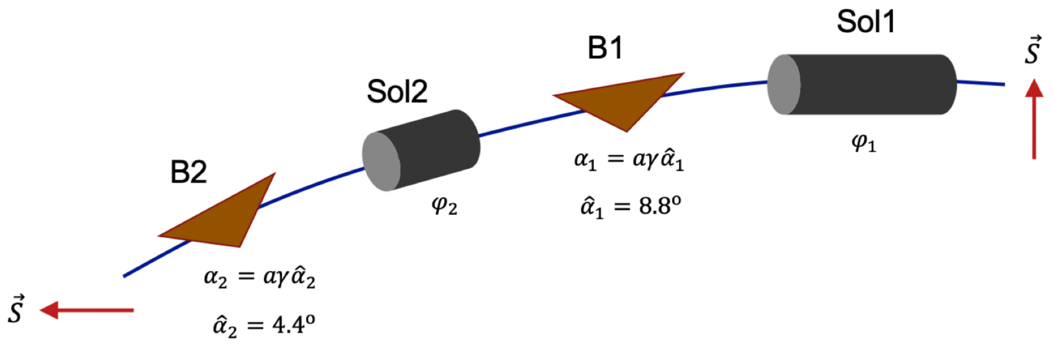
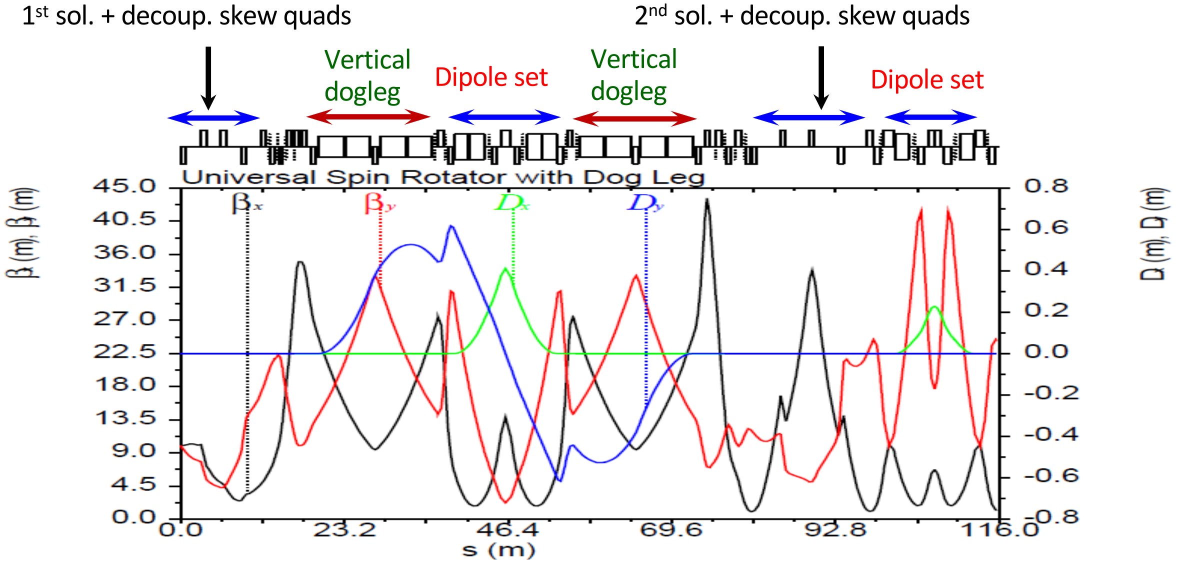
Universal Spin Rotator

- Vertical polarization ↔ longitudinal
- Sequence of solenoid and dipole sections



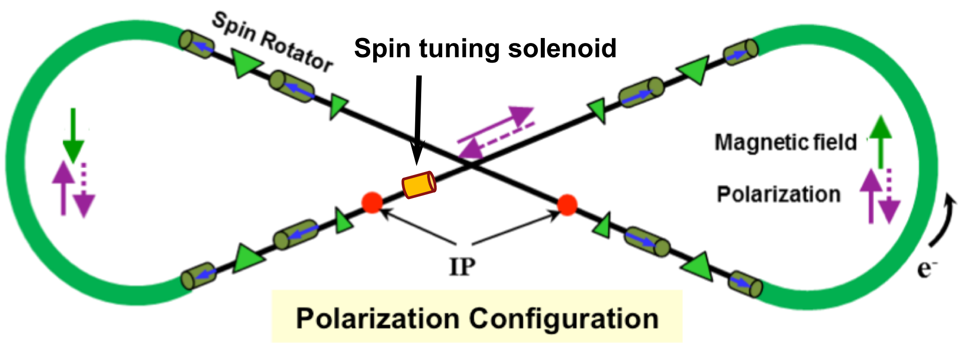
- Geometry independent of energy
- Dispersion-free individually-decoupled solenoids
- Two polarization states with equal lifetimes
- House vertical doglegs for stacking collider arcs

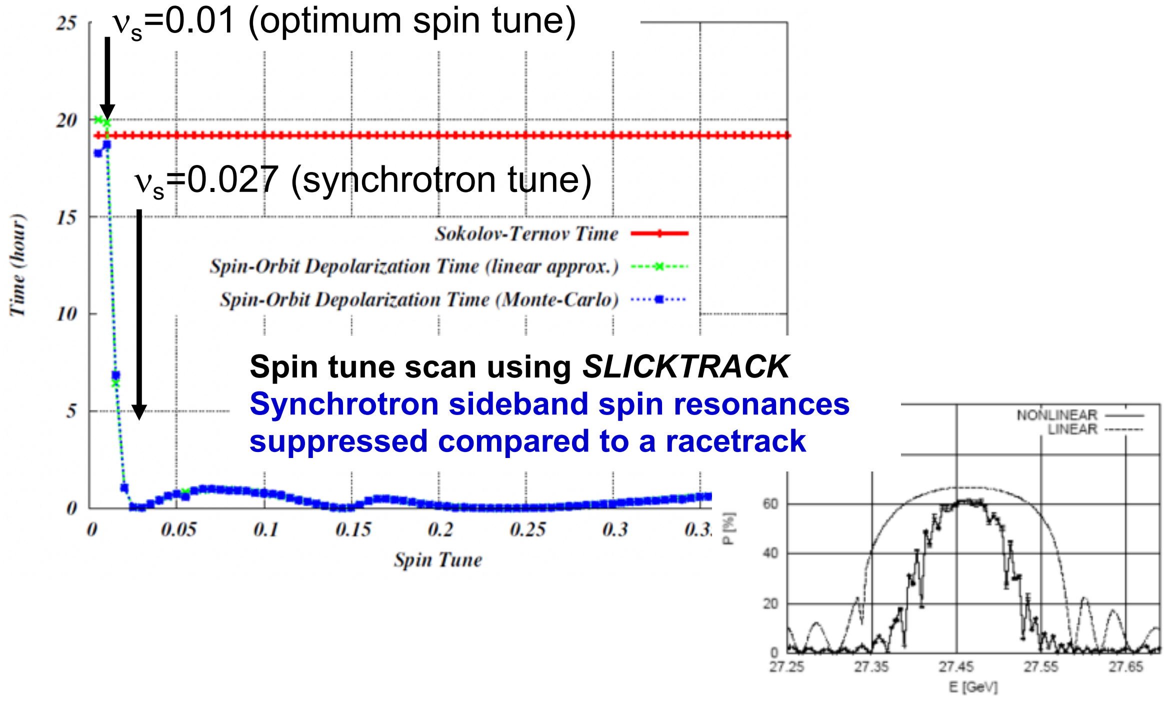
E	Solenoid 1		Dipole set 1	Solenoid 2		Dipole set 2
	Spin Rotation	BDL	Spin Rotation	Spin Rotation	BDL	Spin Rotation
GeV	rad	T·m	rad	rad	T·m	Rad
3	π/2	15.7	π/3	0	0	π/6
4.5	π/4	11.8	π/2	π/2	23.6	π/4
6	0.62	12.3	2π/3	1.91	38.2	π/3
9	π/6	15.7	π	2π/3	62.8	π/2
12	0.62	24.6	4π/3	1.91	76.4	2π/3



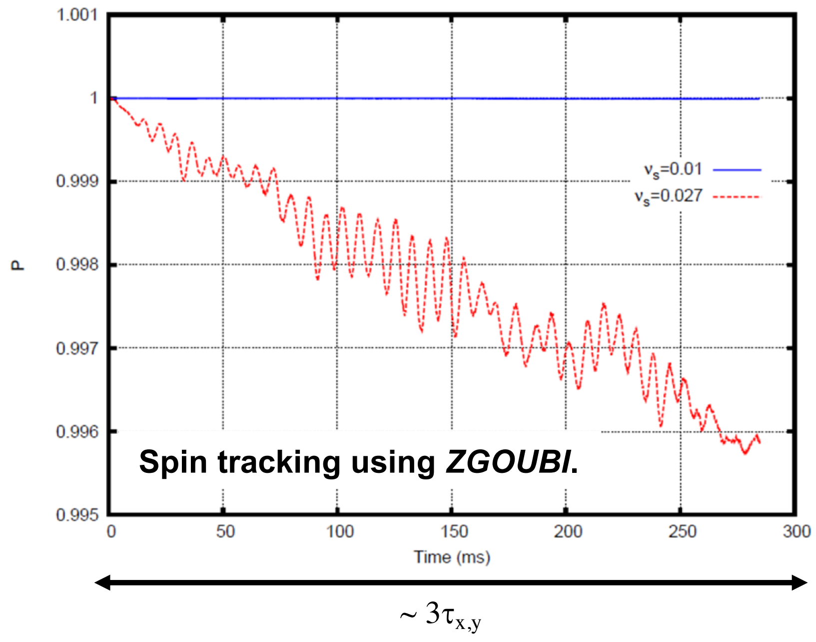
Spin Tracking

- 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





Spin tune scan using *SLICKTRACK*
Synchrotron sideband spin resonances suppressed compared to a racetrack



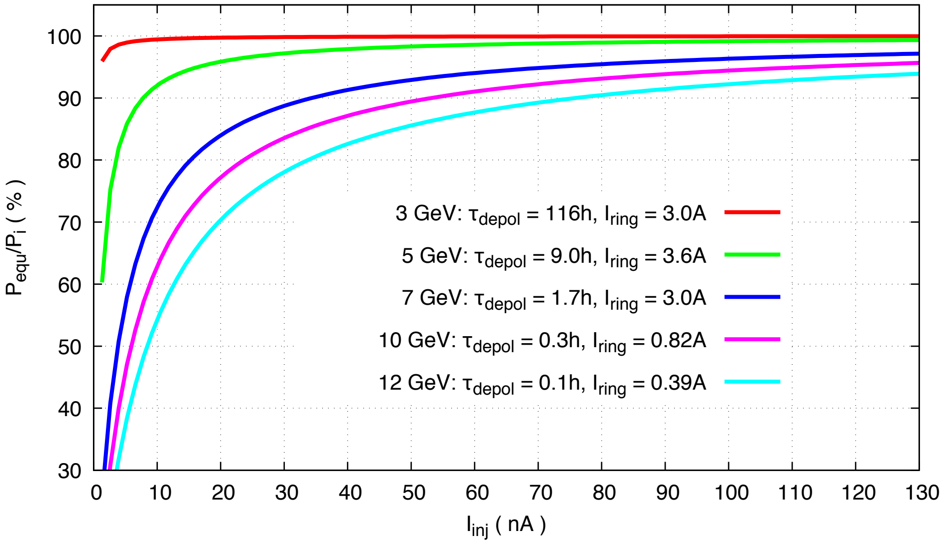
Spin tracking using *ZGOUBI*.

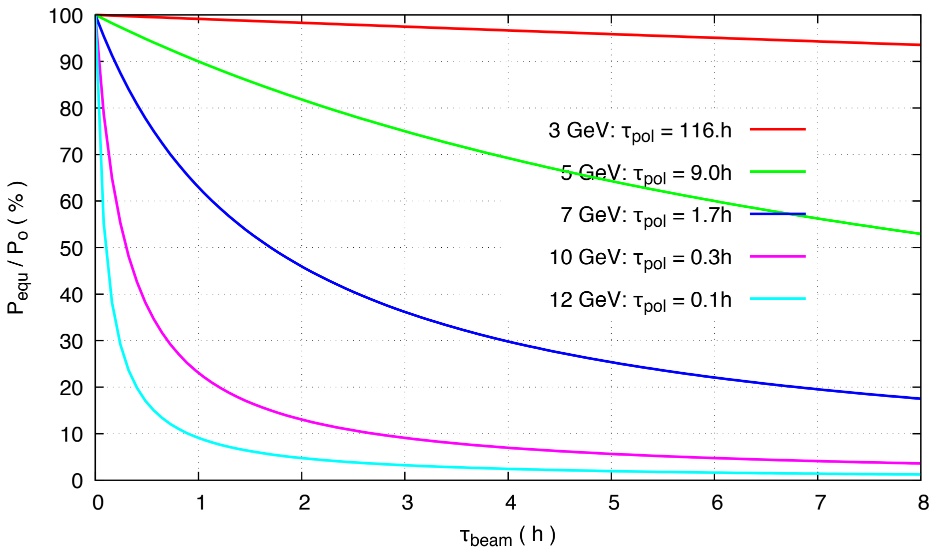
Polarization Lifetime and Continuous Injection

- Estimated polarization lifetime

Energy (GeV)	3	5	7	10	12
Lifetime (hours)	116	9	1.7	0.3	0.1

- Constant polarization maintained by continuous injection from CEBAF
- Equilibrium polarization $P_{equ} = P_0 \left(1 + \frac{T_{rev} I_{ring}}{\tau_{DK} I_{inj}}\right)^{-1}$
- Tens-of-nA level average injected current sufficient to maintain high equilibrium polarization
- Beam lifetime must match the beam injection rate and $\tau_{beam} \ll \tau_{pol}$





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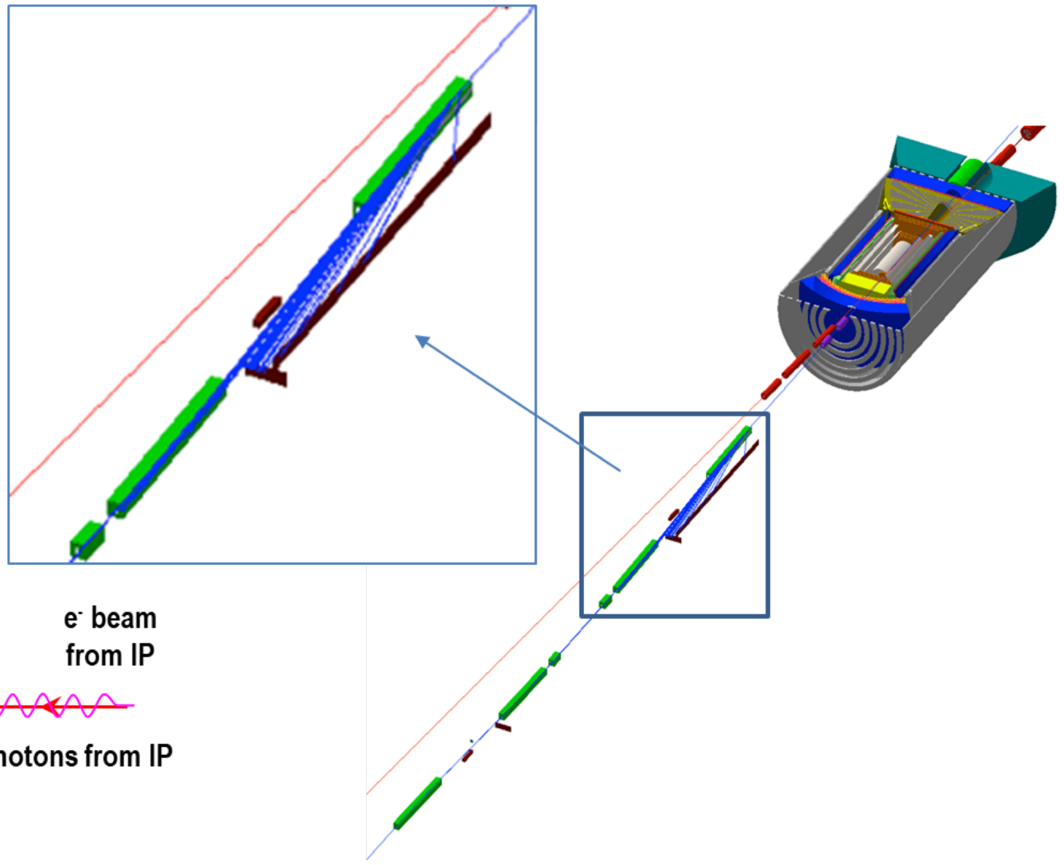
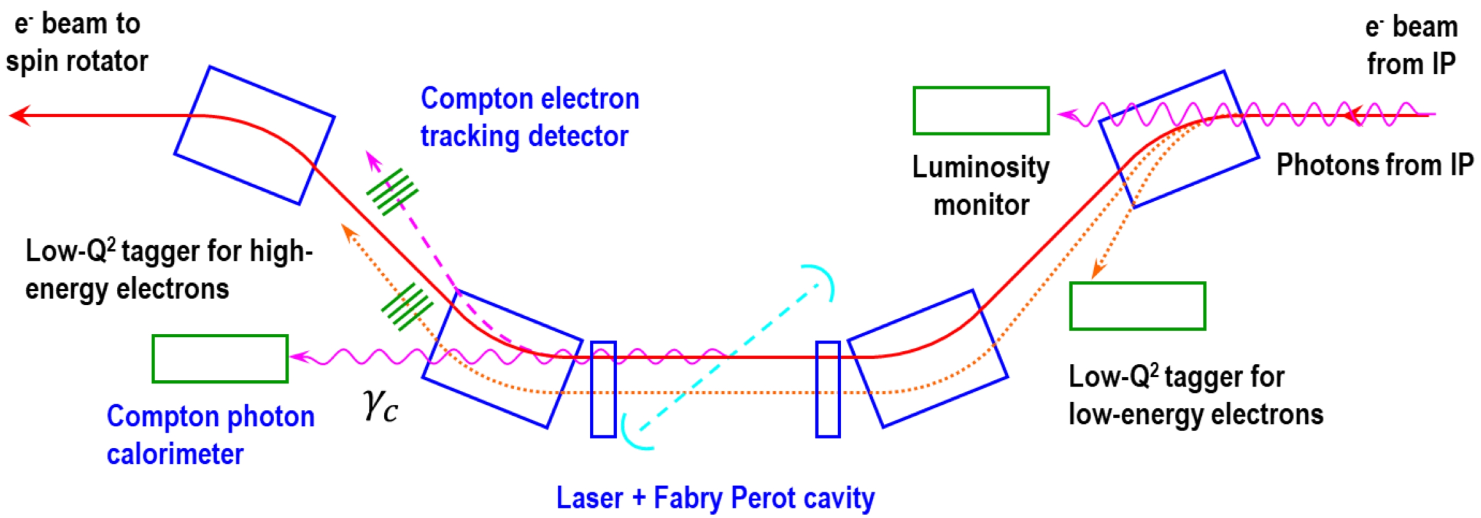
Low Q^2 Tagger in JLEIC

- Dipole chicane for high-resolution detection of low-Q^2 electrons
- Compton polarimetry has been integrated to the interaction region design
  - same polarization at laser as at IP due to zero net bend
  - non-invasive monitoring of electron polarization





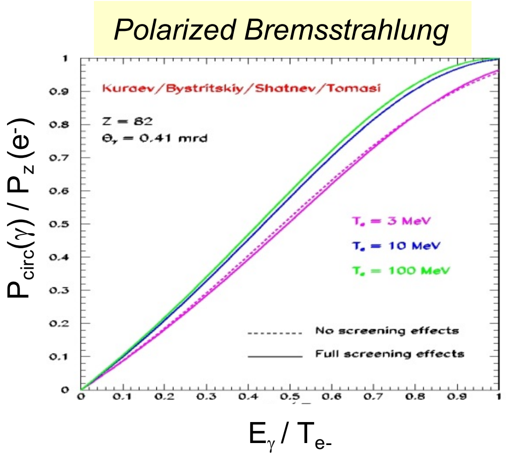
Generation of Polarized Positrons in CEBAF: PEPPo

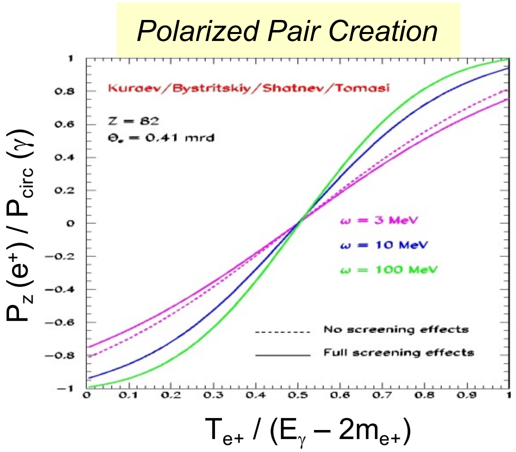
- Polarized Electrons for Polarized Positrons (PEPPo) Concept

$$\vec{e}^- \rightarrow \gamma \rightarrow \vec{e}^+ \; (+ \; \vec{e}^-)$$

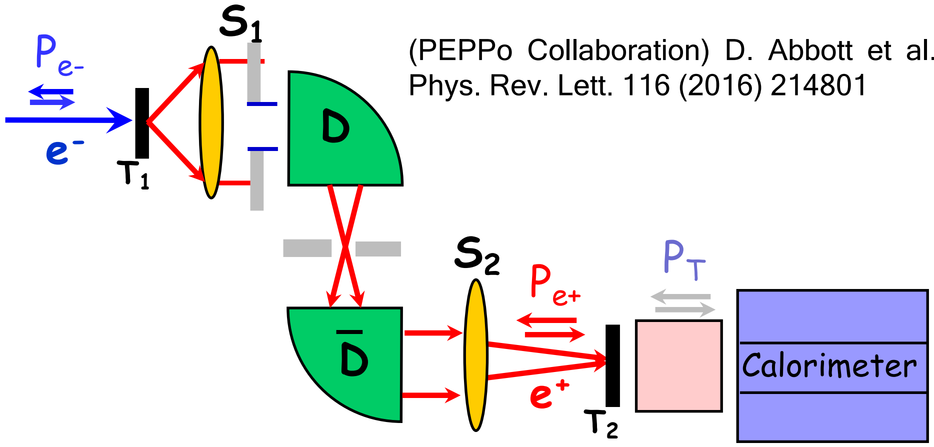
E.G. Bessonov, A.A. Mikhailichenko, EPAC (1996)
A.P. Potylitsin, NIM A398 (1997) 395

E.A. Kuraev, Y.M. Bystritskiy, M. Shatnev, E.Tomasi-Gustafsson, PRC 81 (2010) 055208

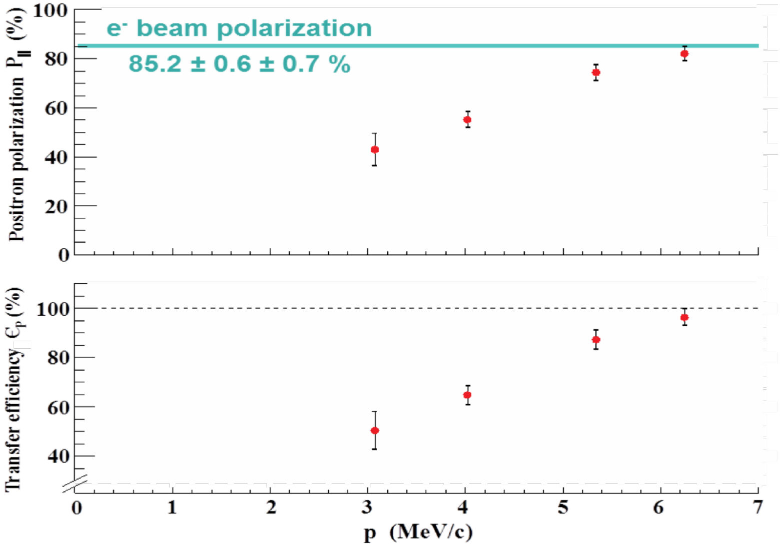




- PEPPo Experiment



(PEPPo Collaboration) D. Abbott et al., Phys. Rev. Lett. 116 (2016) 214801



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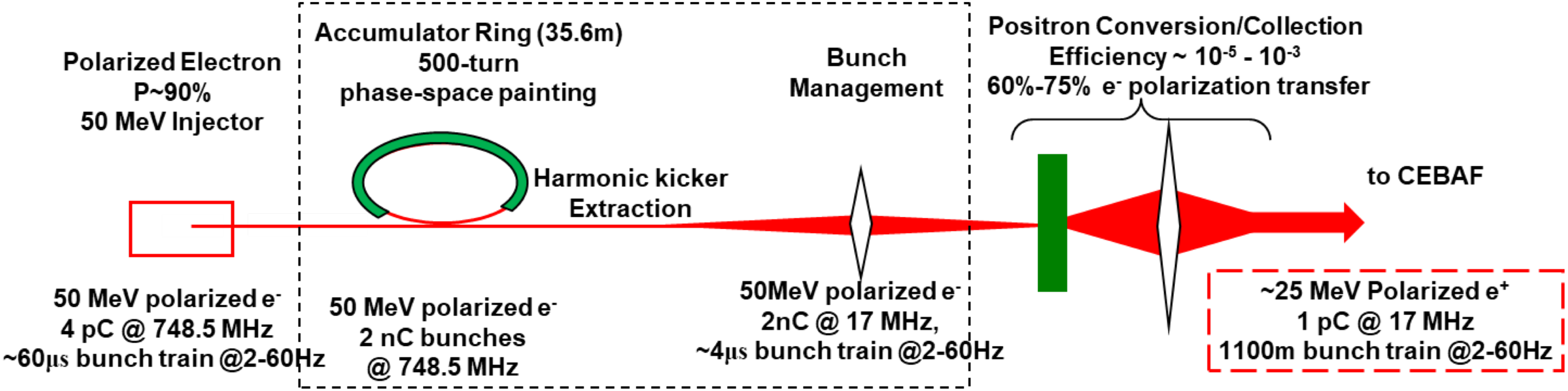
JLEIC Positron Production Scheme

- Assuming ~90% polarization from the e^- source, 60-75% e^- to e^+ polarization transfer, and 80% polarization retention by top-off, we get e^+ polarization of 43-54%
- Challenging accumulator section can be eliminated by developing a 17 MHZ polarized e^- gun with 2 nC bunches (34 mA)



Summary

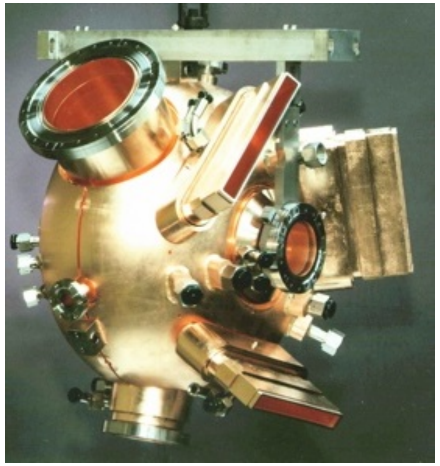
- Ion polarization scheme
  - Figure-8
    - Energy independent spin tune
    - Ease of spin preservation, control and manipulation by weak magnetic fields
  - 3D spin rotator designed
  - Verified by spin tracking
  - Extended to 200 GeV
  - Test experiment in preparation
- Electron polarization scheme
  - Full-energy injection of polarized beam from CEBAF
  - High equilibrium polarization maintained by top-off injection
  - Universal fixed-geometry spin rotators
    - Longitudinal polarization at the IPs
    - Vertical polarization in the arcs to minimize the spin diffusion
  - Figure-8
    - Equal lifetimes of the two polarization states
    - Energy-independent spin tune
  - Spin tracking in progress
    - Close collaboration with University of New Mexico and RadiaSoft LLC

Thank You for Your Attention !

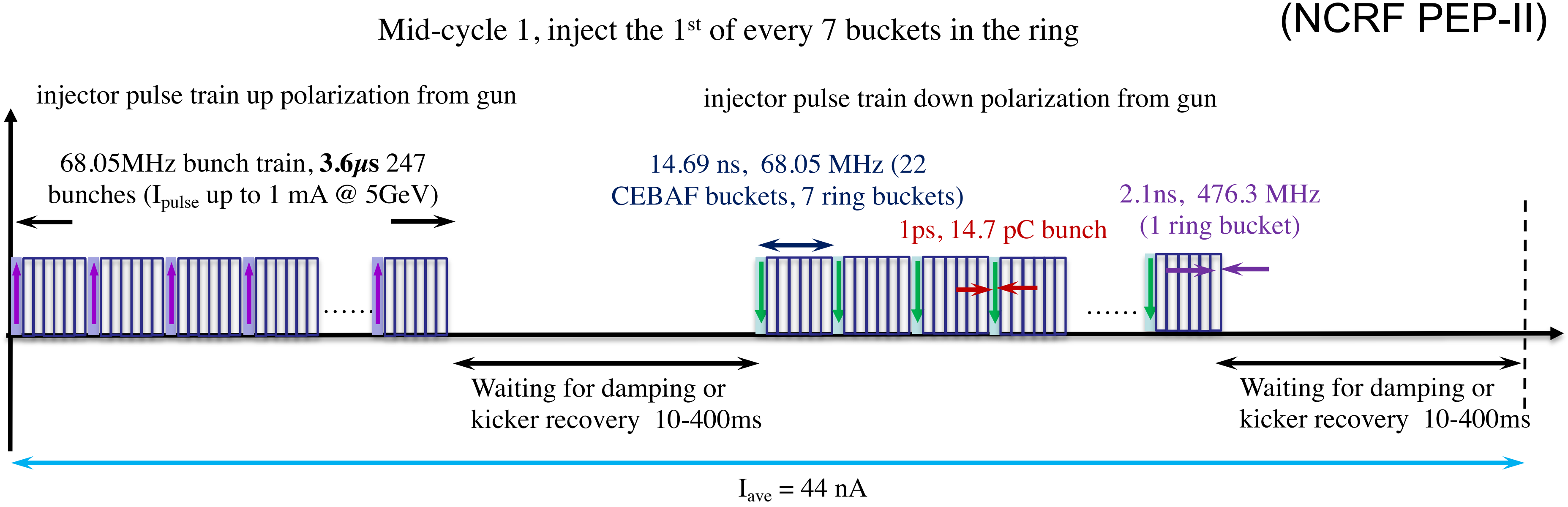
Back Up

Electron Injection

- Electron injection from CEBAF
  - Existing CEBAF electron gun
  - **Two polarization state** injection
  - f_{ring} / f_{CEBAF} = 476.3 MHz / 1497 MHz = 7 / 22
- Test of CEBAF in JLEIC injector mode completed

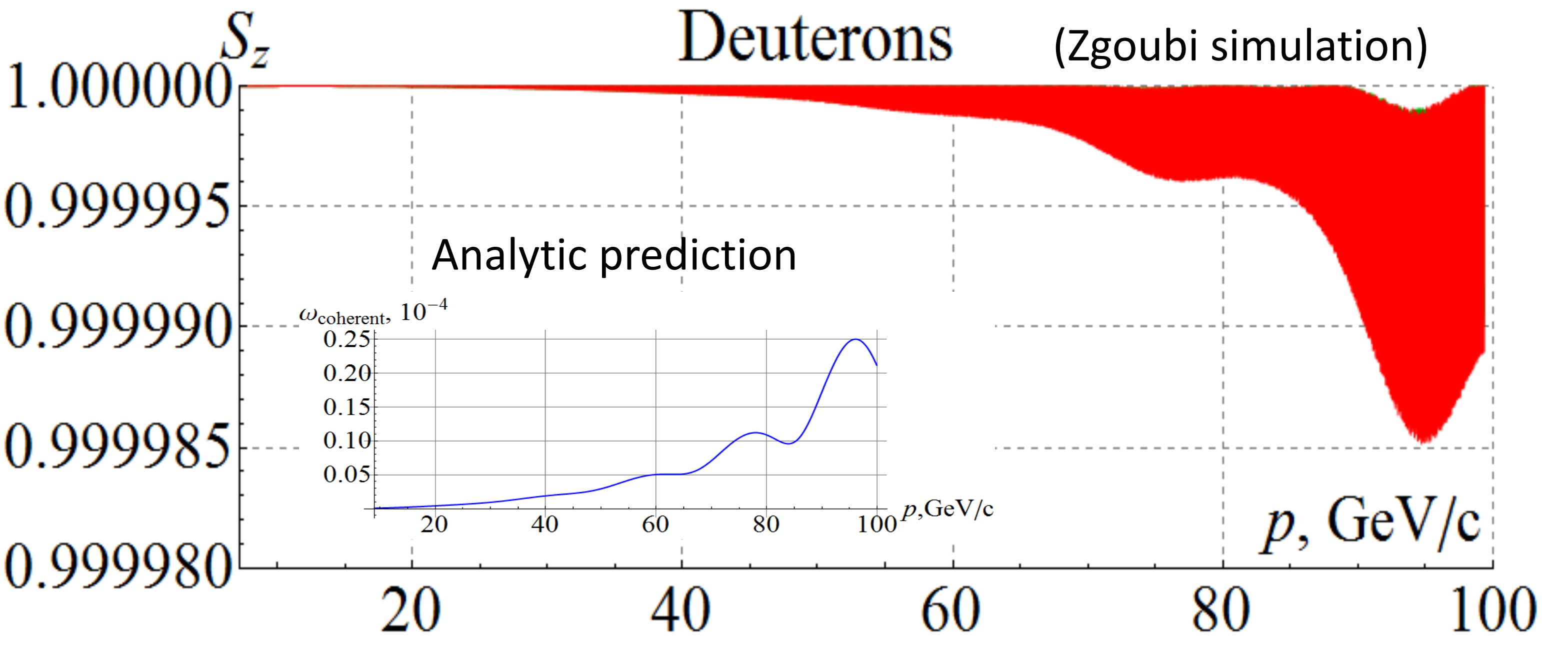


476.3 MHz e-ring (NCRF PEP-II)



Start-to-End Deuteron Acceleration in Ion Collider Ring

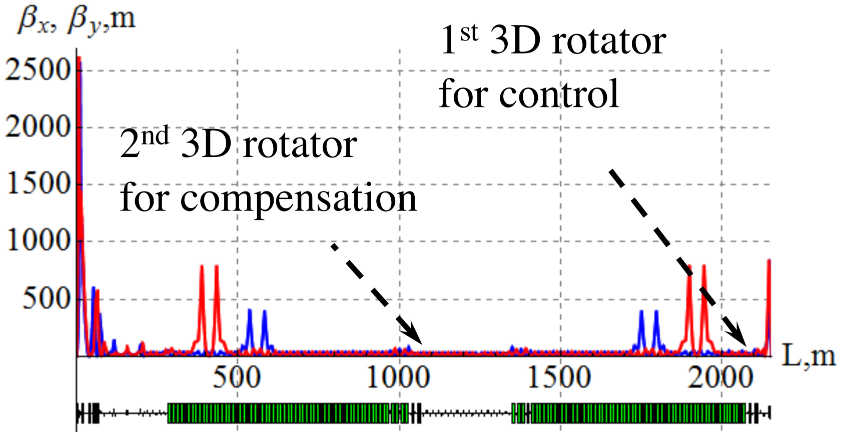
- Three deuterons with $\varepsilon_{x,y}^{N} = 0.5\ \mu m$ and $\Delta p/p = 0, \pm 1 \cdot 10^{-3}$ accelerated at ~3 T/min in lattice with 100 μm rms closed orbit excursion, $\nu_{sp} = 3 \cdot 10^{-3}$

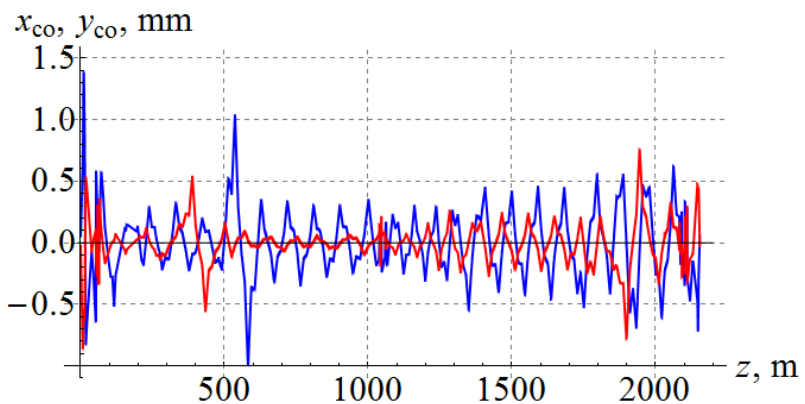


- Deuteron spin is highly stable in figure-8 rings, which can be used for high precision experiments

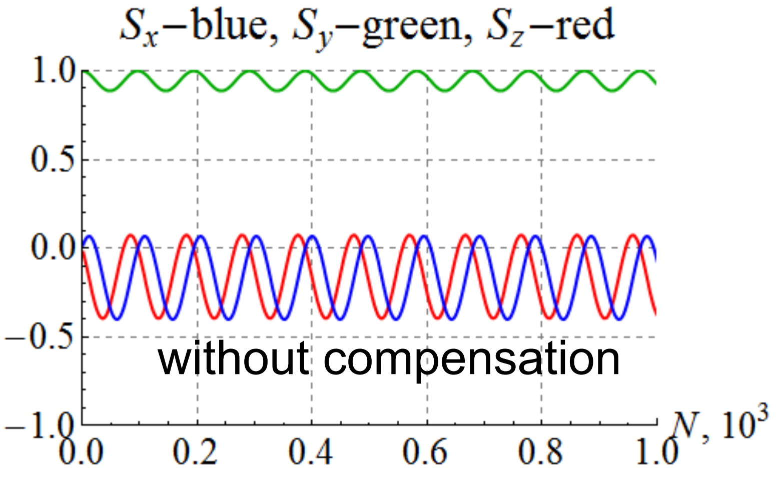
Polarization Control in Ion Collider Ring

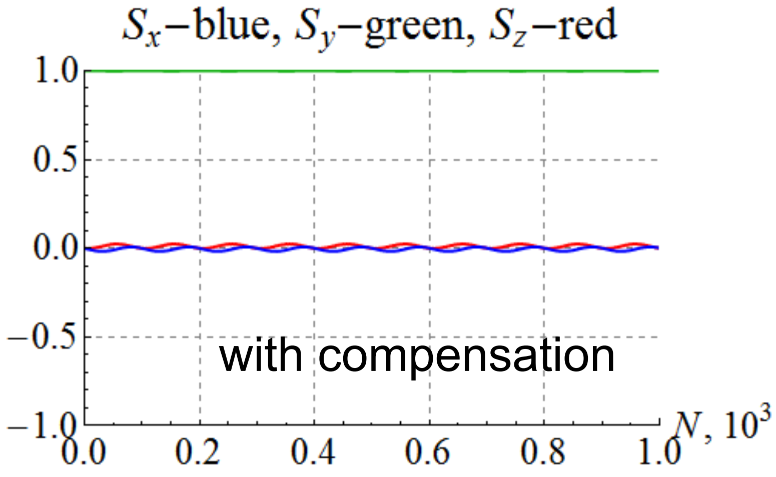
- 100 GeV/c figure-8 ion collider ring with transverse quadrupole misalignments





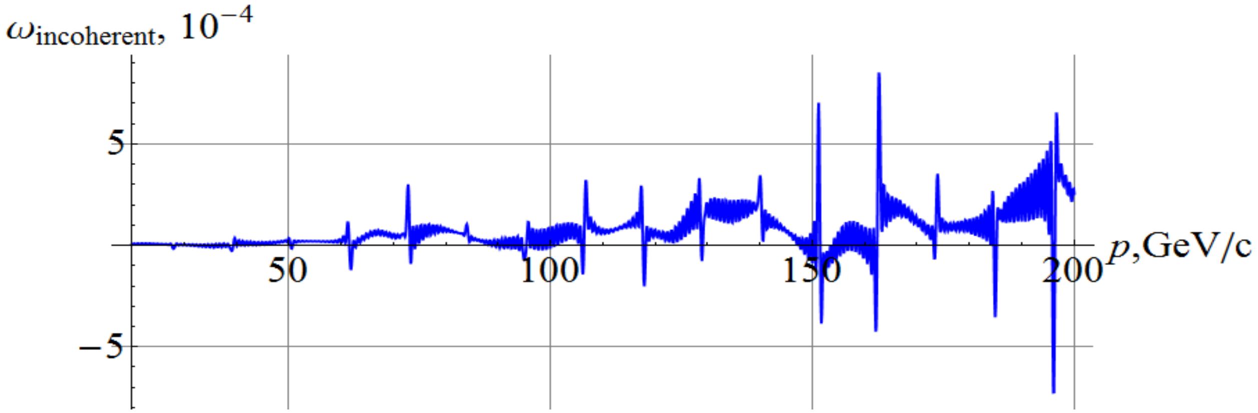
- Example of vertical proton polarization at IP. The 1st 3D rotator: $\nu = 10^{-2}$, n_y=1. The 2nd 3D rotator is used for compensation of coherent part of the zero-integer spin resonance strength



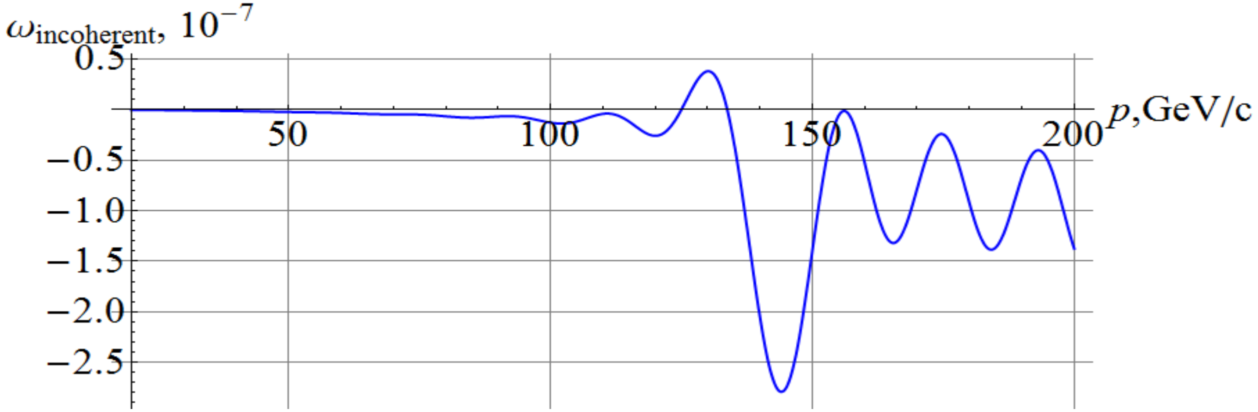


Incoherent Part of Zero-Integer Spin Resonance Strength

Protons



Deuterons



- Assuming normalized vertical beam emittance of 0.07 μm rad
- $\nu_p^{max} = 10^{-2}$, $\nu_d^{max} = 10^{-4}$ at **200 GeV/c** are sufficient to stabilize the polarization

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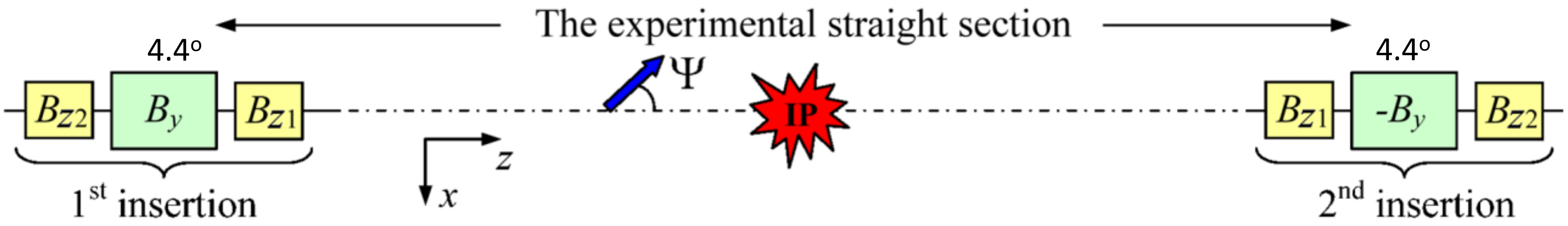
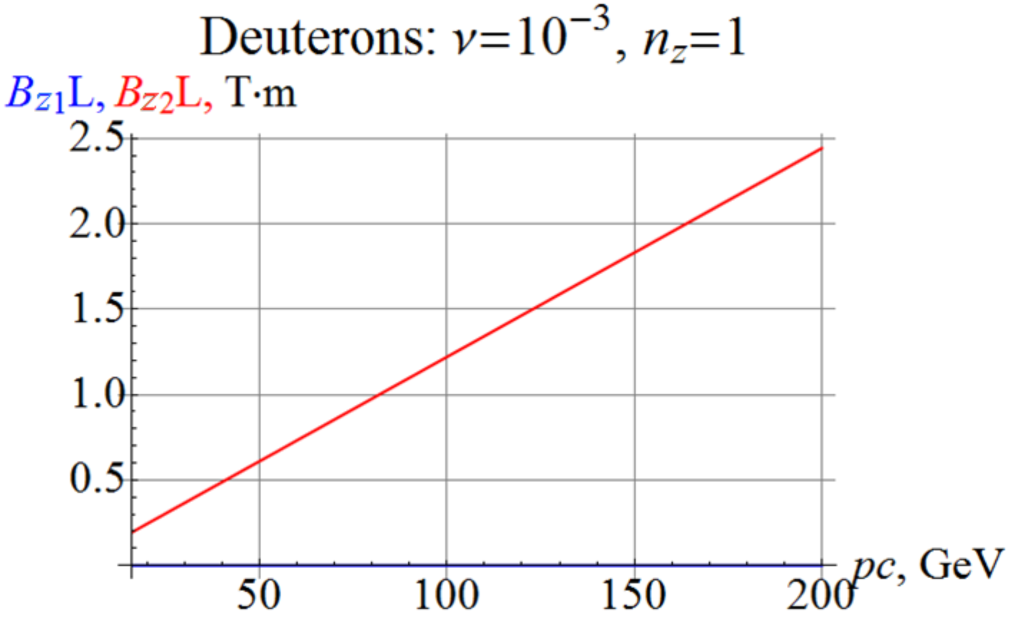
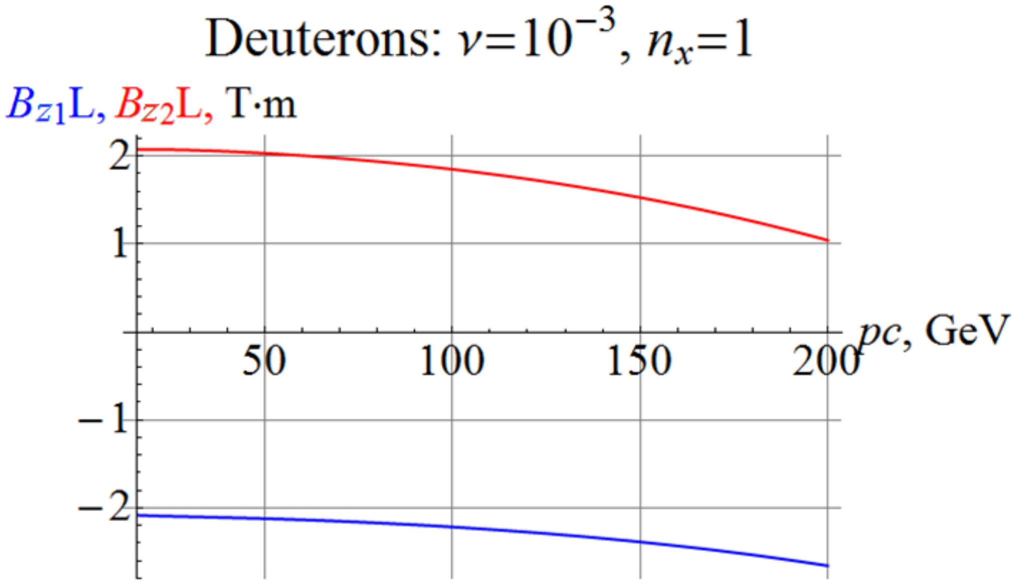
Deuteron Spin Rotator Utilizing Longitudinal Fields



Longitudinal Polarization at IP

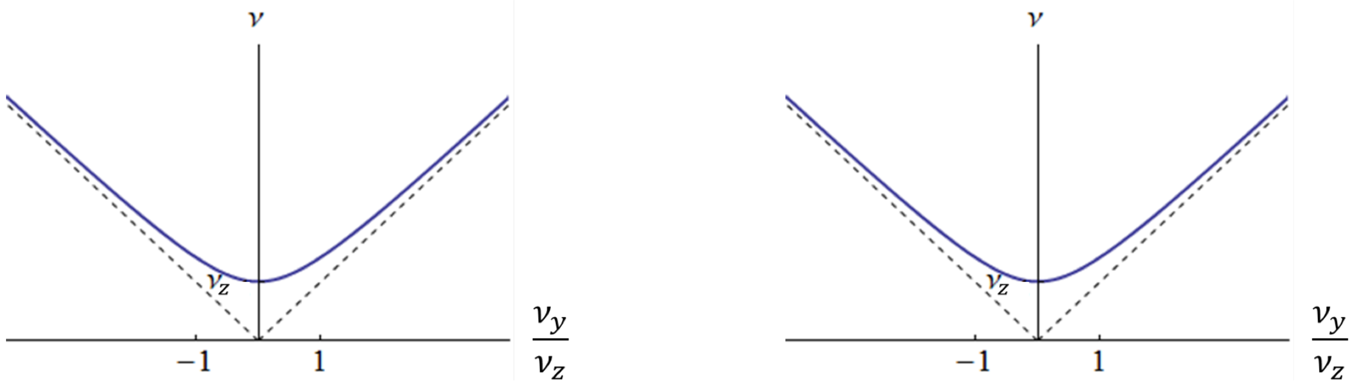


Radial Polarization at IP



Experimental Scenarios

- Injection and acceleration of polarized protons in the spin transparency mode in RHIC
  - Beam is injected vertically polarized
  - Stable vertical polarization in RHIC is set by adjusting the angle between the snake axes φ_{sn} to $\sim 10°$. The spin tune is $\nu_y \approx \varphi_{sn}/\pi \approx 0.05$
- Demonstration of polarization control in the collider
  - Demonstrate polarization reversal at the polarimeter
  - Adjust the snake strengths to set $\nu_z = 0.01$
  - Vertical polarization component at the polarimeter $n_y = -\nu_y/\sqrt{\nu_y^2 + \nu_z^2}$
  - Sweep the angle between the snakes from $-10°$ to $+10°$ thus changing ν_{sn} from -0.05 to $+0.05$



  - A similar test with the solenoid off can measure the zero-integer spin resonance strength

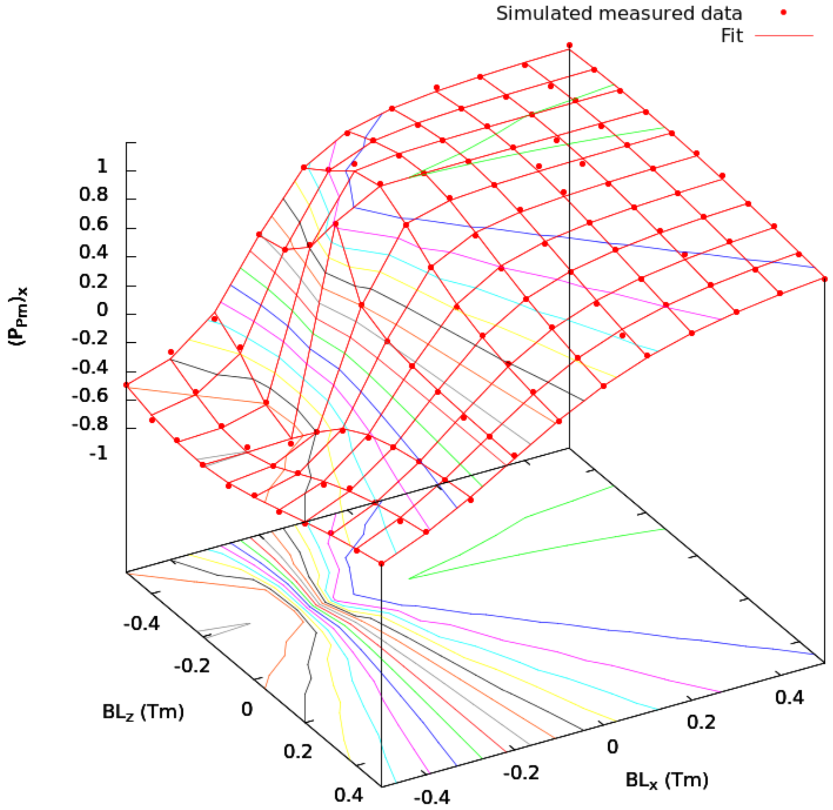
Spin Rotator Calibration

- Radial polarization at a polarimeter in terms of spin rotator solenoid field integrals

$$(P_{Pm})_x = P_0 \frac{BL_x + \omega_x/C_x}{\sqrt{(BL_x + \omega_x/C_x)^2 + (BL_z C_z/C_x + \omega_z/C_x)^2}}$$

- Assume typical parameters of a 100 GeV/c proton beam
- Assume that polarization is measured with a random error of 0.02 rms
- Fit randomly generated data to $(P_{Pm})_x$ formula and extract input parameters

Parameter	Input	Fit
P_0	0.8	0.803 ± 0.003 (0.35%)
ω_x/C_x (Tm)	0.2183	0.2185 ± 0.0007 (0.31%)
C_z/C_x	0.582	0.590 ± 0.007 (1.24%)
ω_z/C_x (Tm)	0.131	0.132 ± 0.002 (1.31%)



Jefferson Lab

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

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	X	X	X	X	X	X	X	
2. Evaluation of the technical capabilities of RHIC	X	X	X					
3. Development of an experimental program		X	X	X				
4. Preparation and submission of an experimental proposal		X	X	X				
5. Completion of an experimental test					X	X		
6. Analysis and publication of experimental data							X	X