Polarized Electron and Hadron Beams at JLEIC

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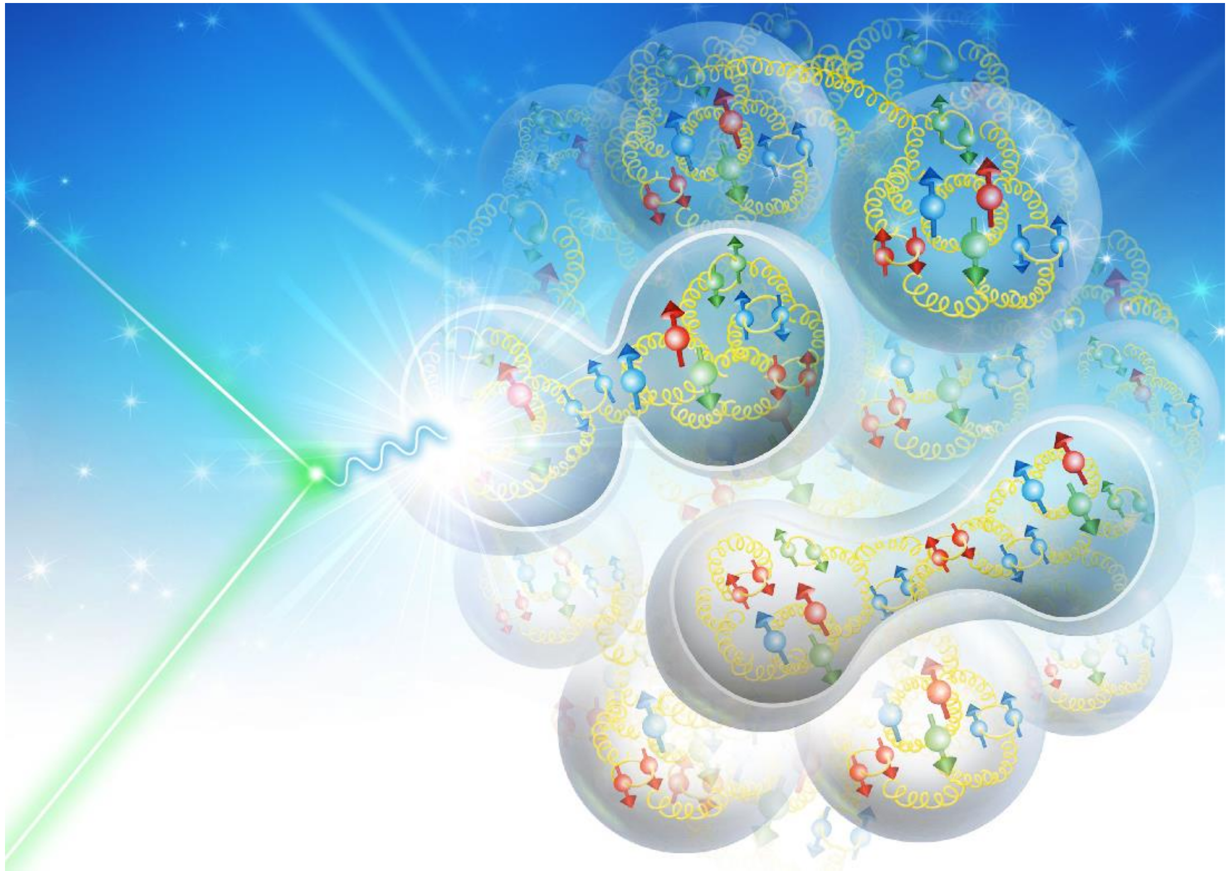
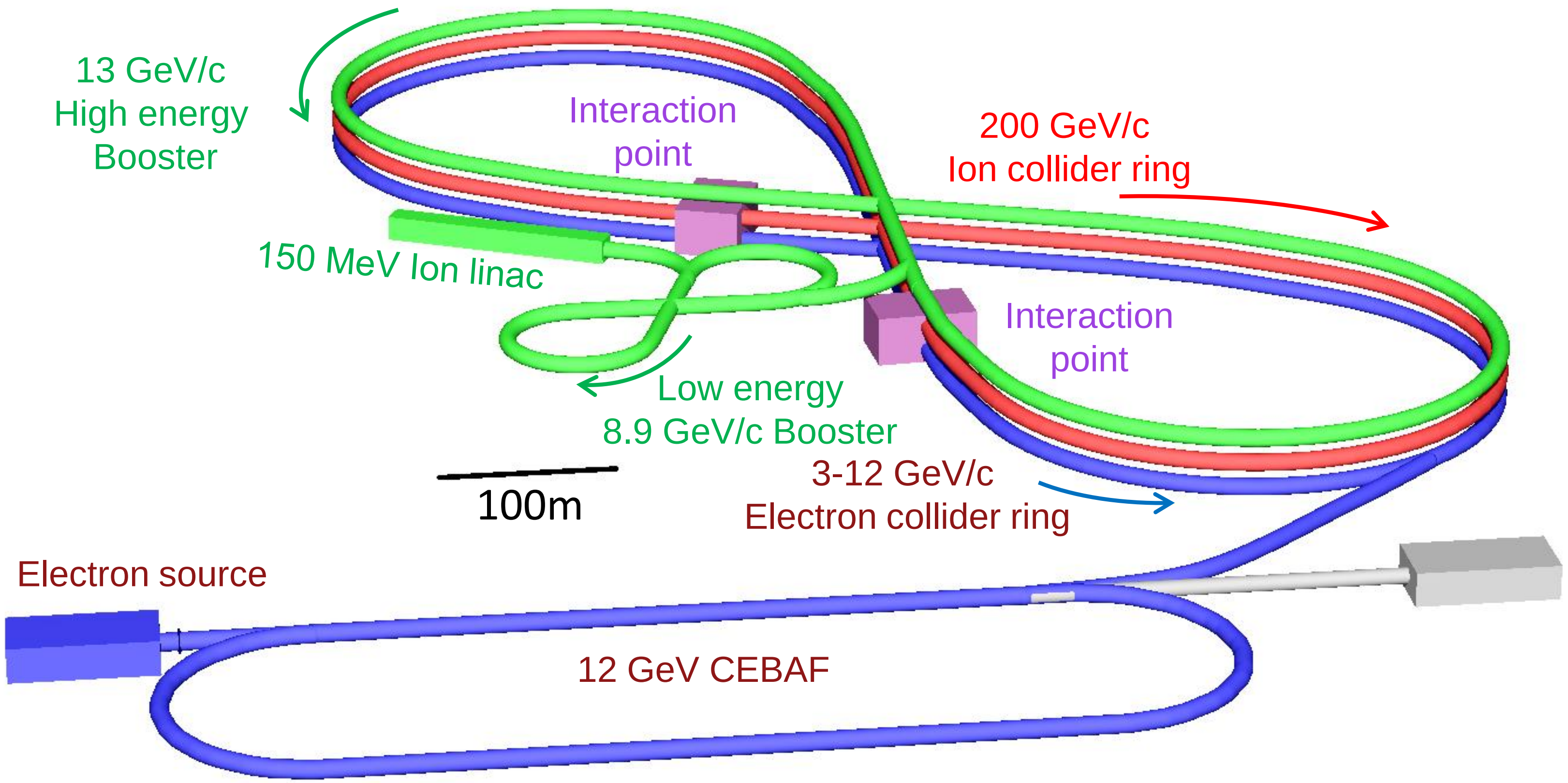
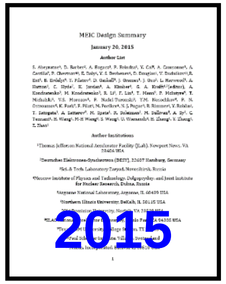


PSTP2019, Knoxville, TN
September 26, 2019

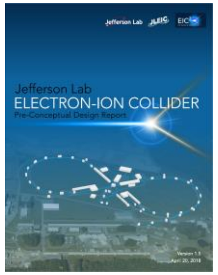
JLEIC Layout

- 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 by doubling ion energy





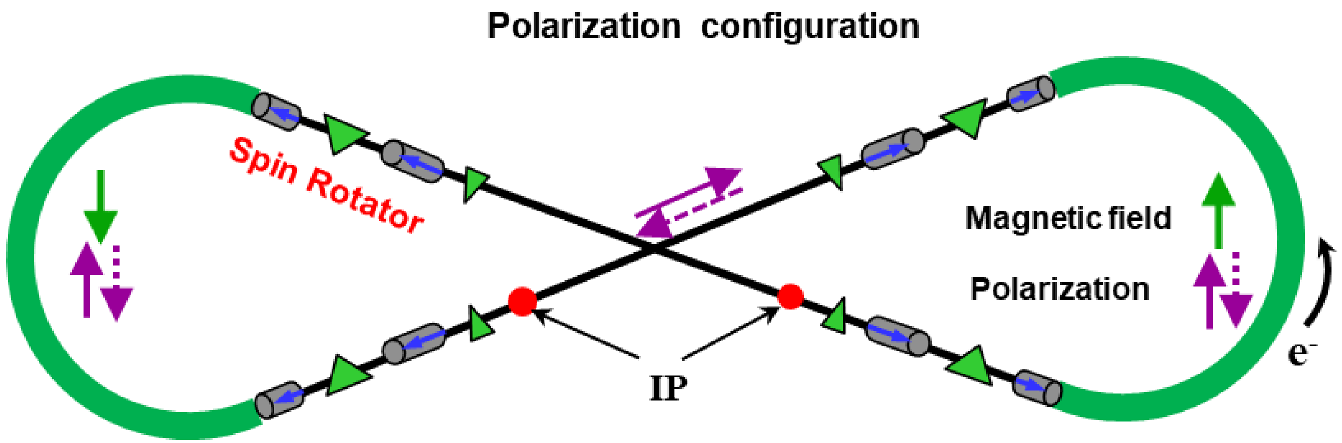
arXiv:1209.0757
arXiv:1504.07961

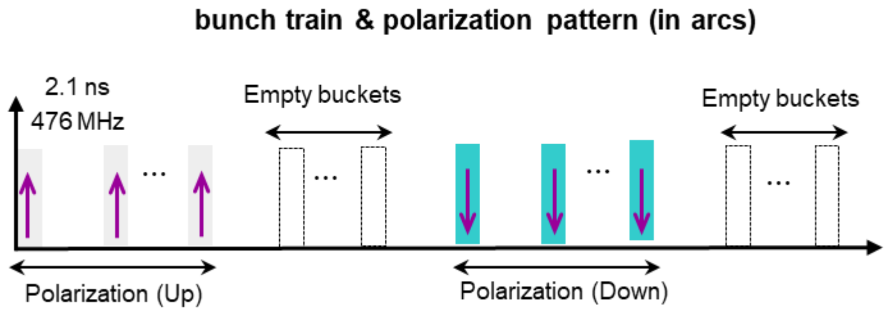


pCDR
August 2019

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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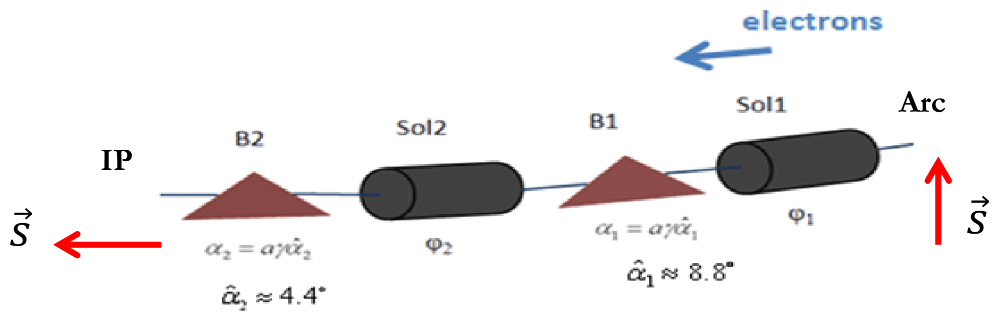
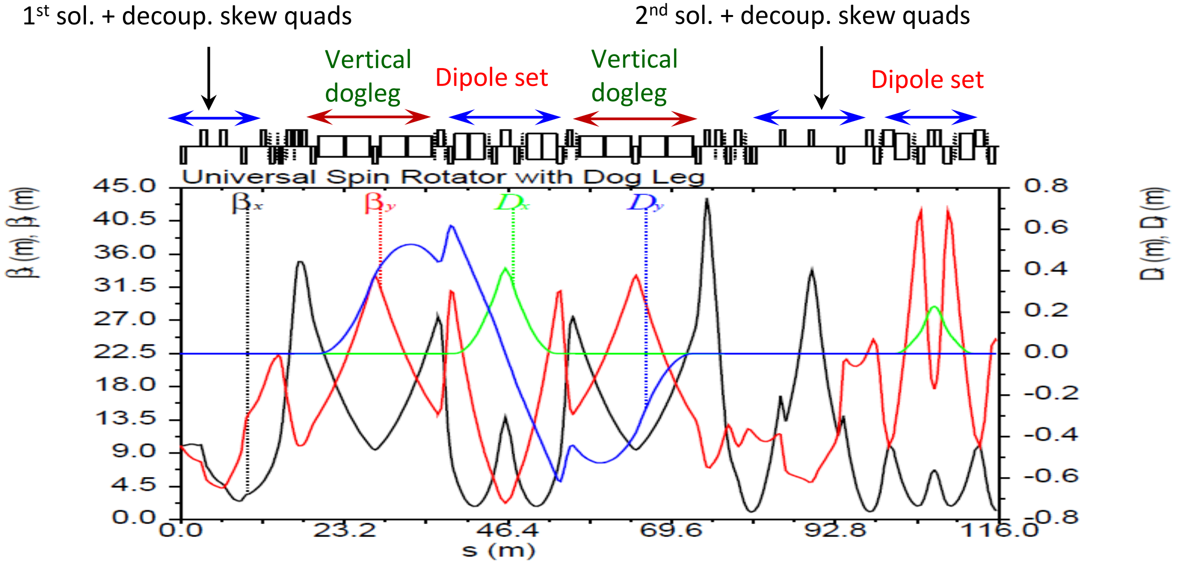
Universal Spin Rotator

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



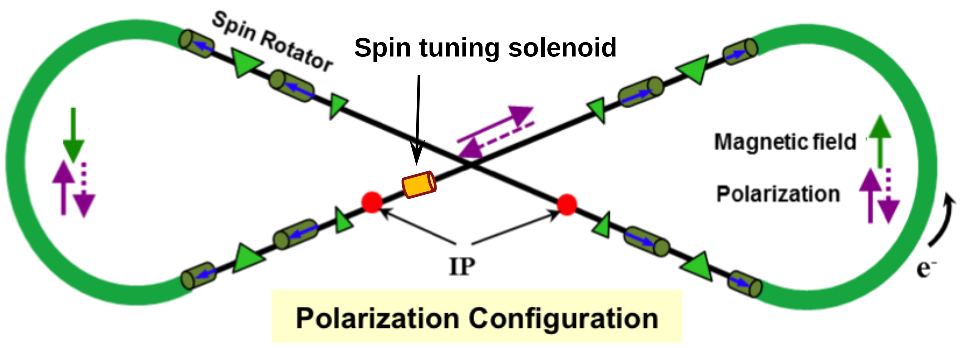
- Geometry independent of energy
- Dispersion-free individually-decoupled solenoids
- Two polarization states with equal lifetimes
- House vertical doglegs for stacking collider arcs

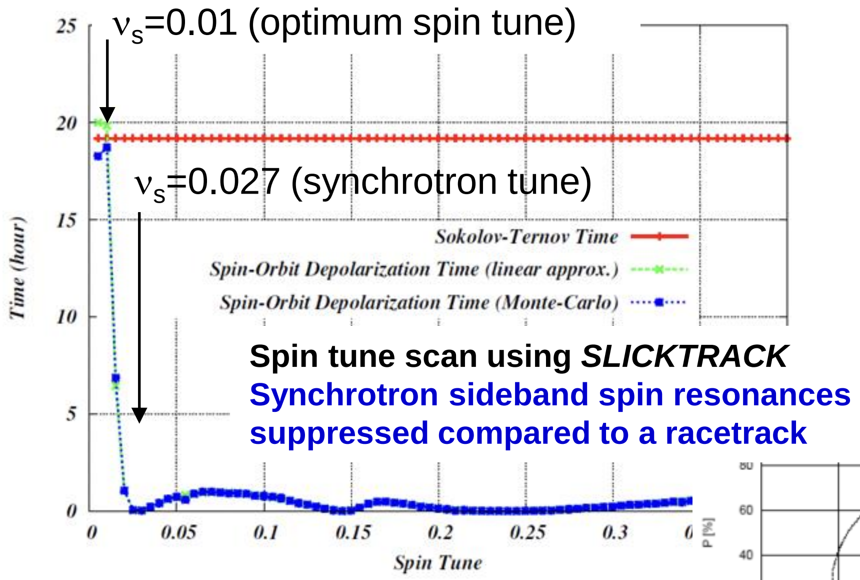
E	Solenoid 1		Dipole set 1	Solenoid 2		Dipole set 2
	Spin Rotation	BDL	Spin Rotation	Spin Rotation	BDL	Spin Rotation
GeV	rad	T·m	rad	rad	T·m	Rad
3	π/2	15.7	π/3	0	0	π/6
4.5	π/4	11.8	π/2	π/2	23.6	π/4
6	0.62	12.3	2π/3	1.91	38.2	π/3
9	π/6	15.7	π	2π/3	62.8	π/2
12	0.62	24.6	4π/3	1.91	76.4	2π/3



Spin Tracking

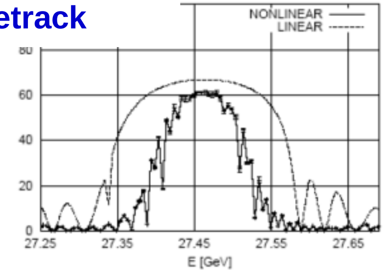
- Spin tune scan using a spin tuning solenoid in SLICK/SLICKTRACK
- Demonstrates suppression of synchrotron sideband spin resonances
- Verified by Zgoubi's Monte-Carlo spin tracking

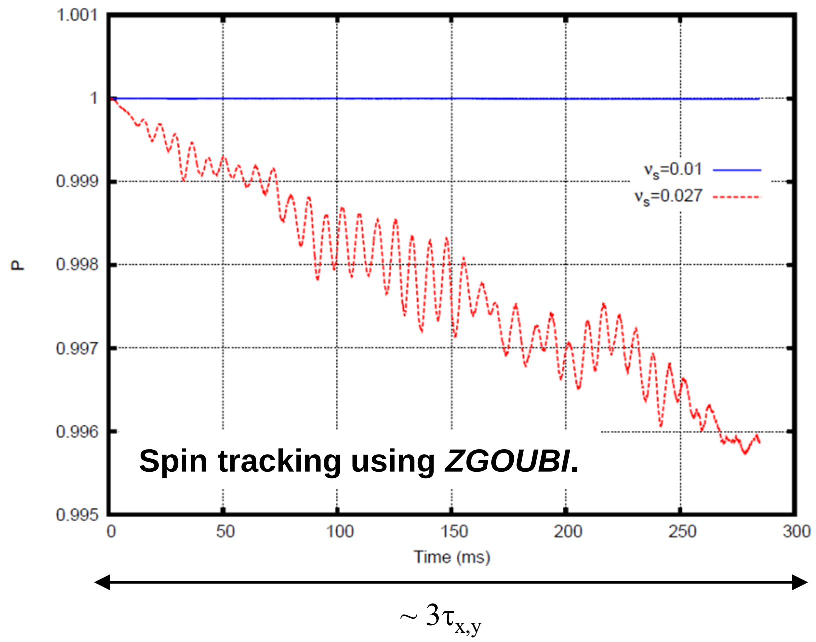




Spin tune scan using *SLICKTRACK*

Synchrotron sideband spin resonances suppressed compared to a racetrack





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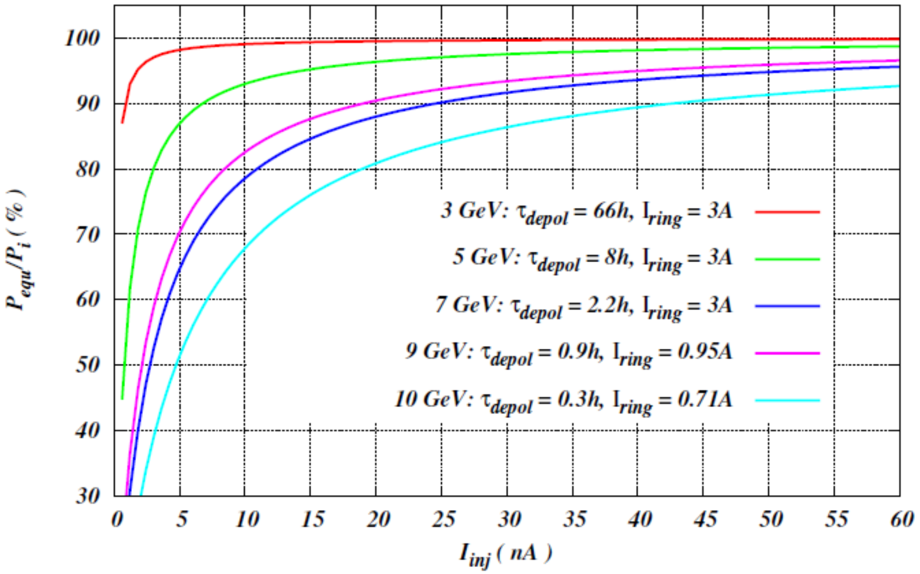
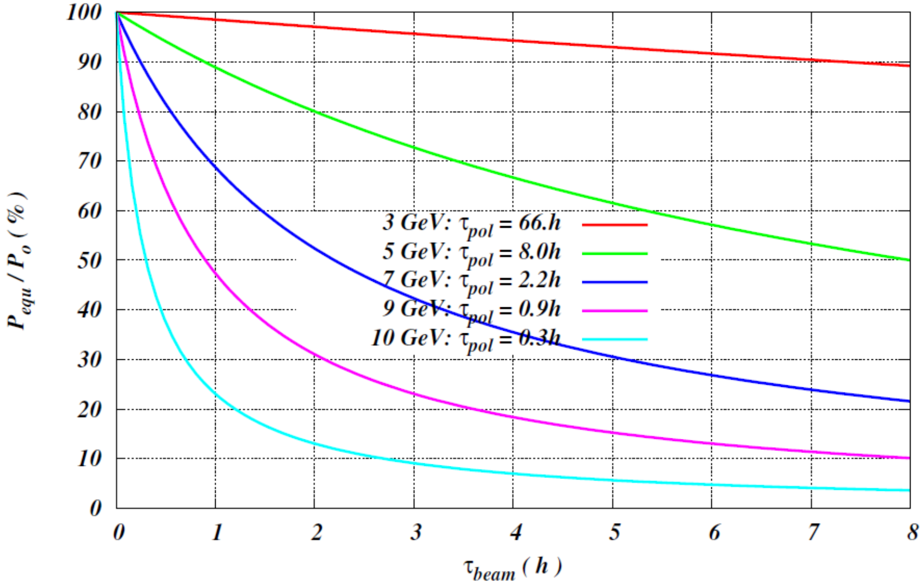
Polarization Lifetime and Continuous Injection

- Estimated polarization lifetime

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

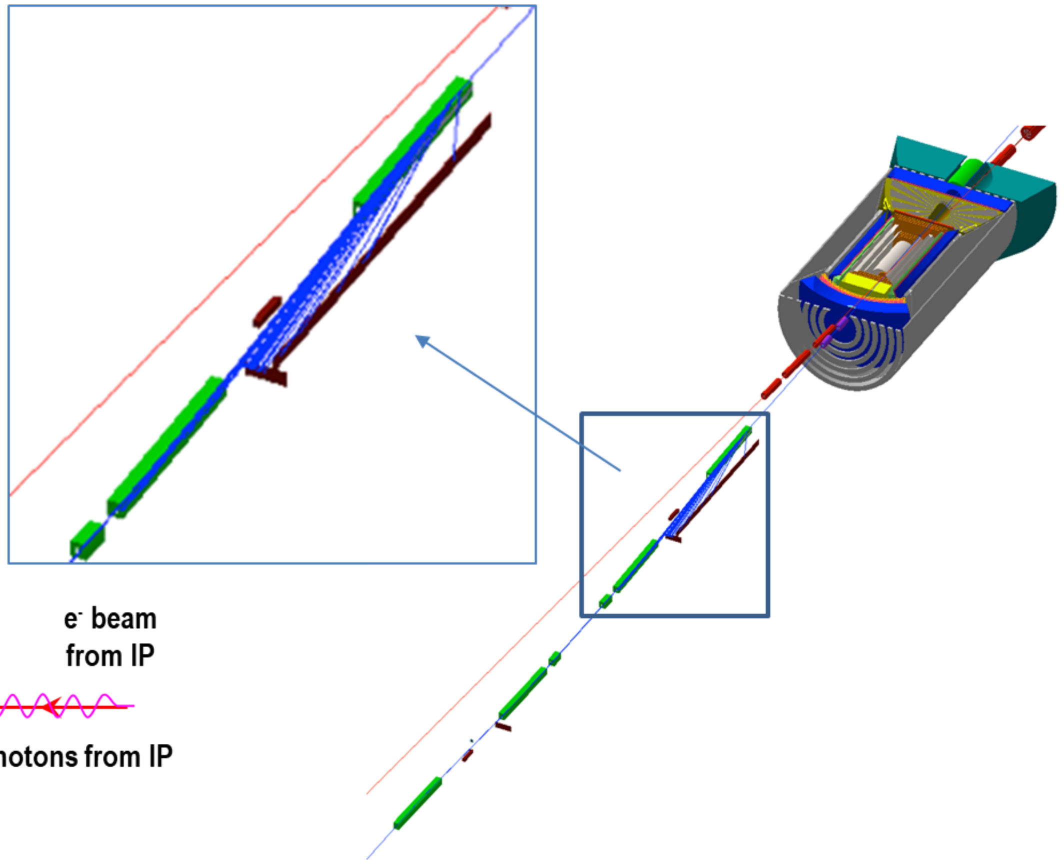
- Constant polarization maintained by continuous injection from CEBAF
- Equilibrium polarization $$P_{equ} = P_0 \left(1 + \frac{T_{rev} I_{ring}}{\tau_{DK} I_{inj}}\right)^{-1}$$
- Tens-of-nA level average injected current sufficient to maintain high equilibrium polarization
- Beam lifetime must match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

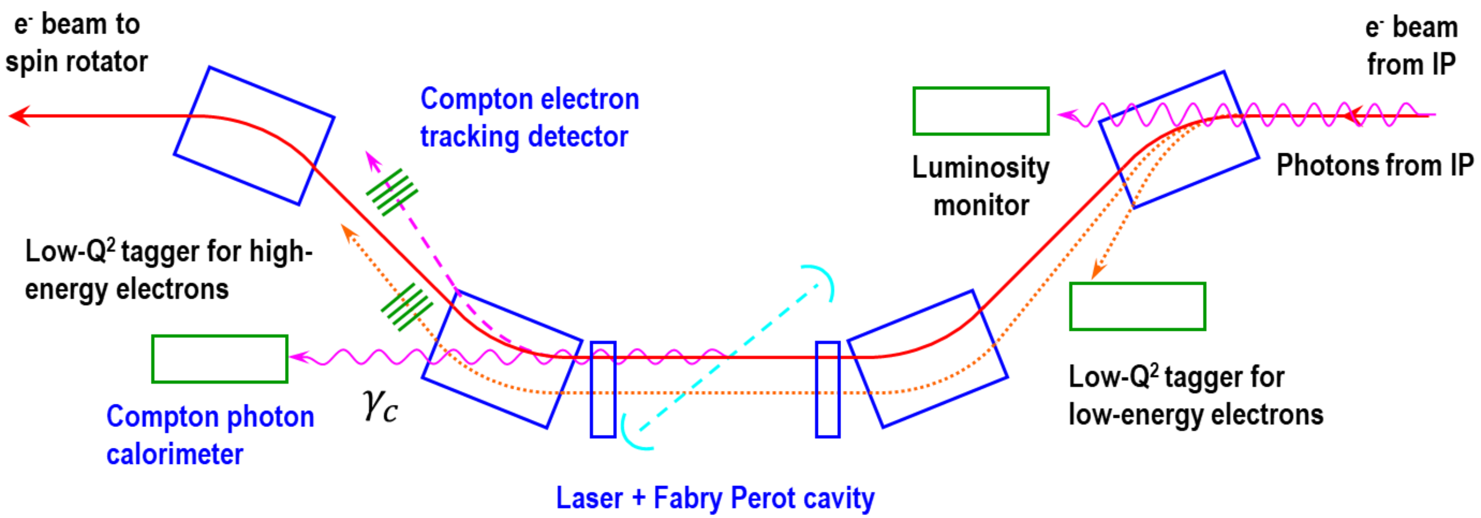




Low Q^2 Tagger in JLEIC

- 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

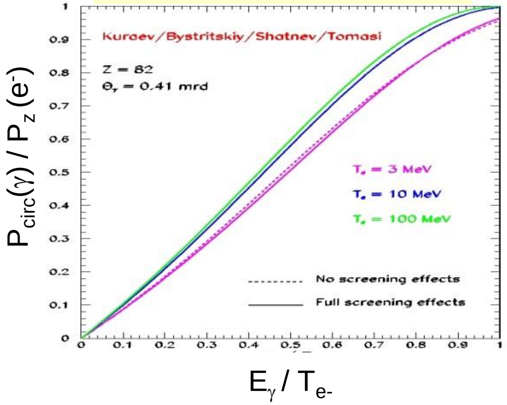
- Polarized Electrons for Polarized Positrons (PEPPo) Concept

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

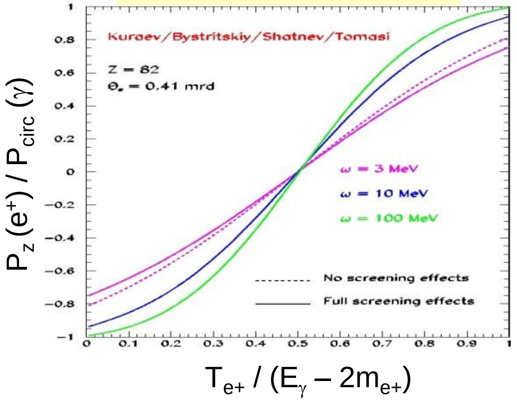
E.G. Bessonov, A.A. Mikhailichenko, EPAC (1996)
A.P. Potylitsin, NIM A398 (1997) 395

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

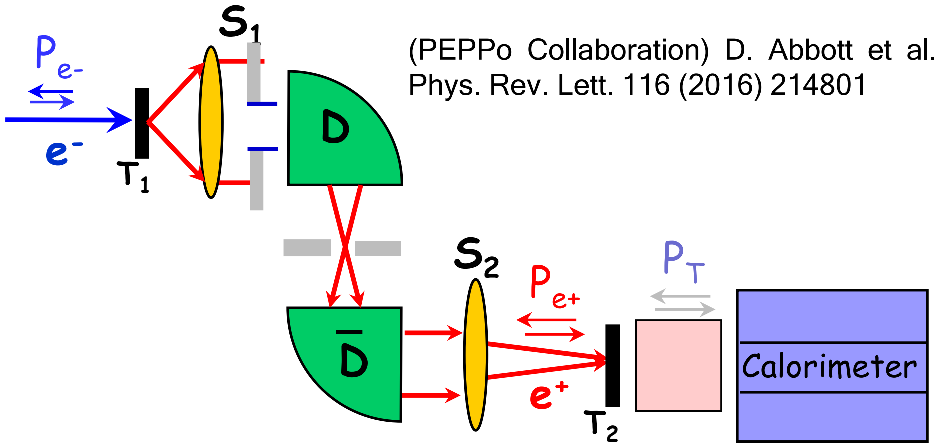
Polarized Bremsstrahlung



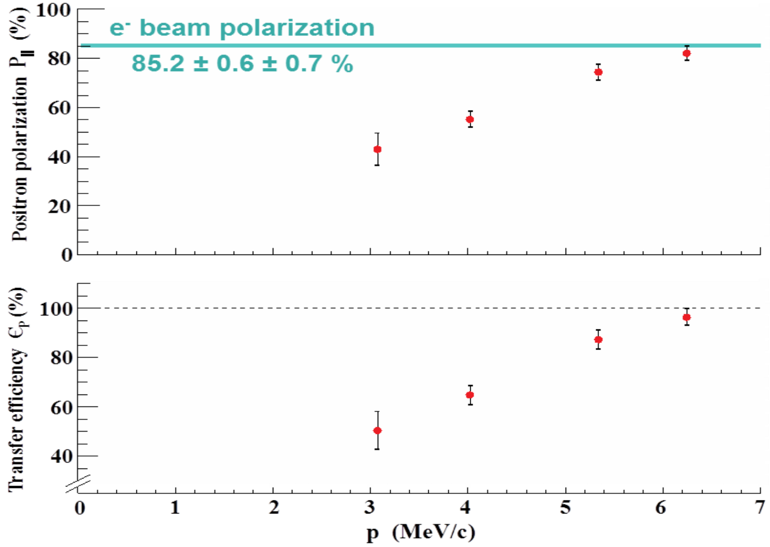
Polarized Pair Creation



- PEPPo Experiment



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



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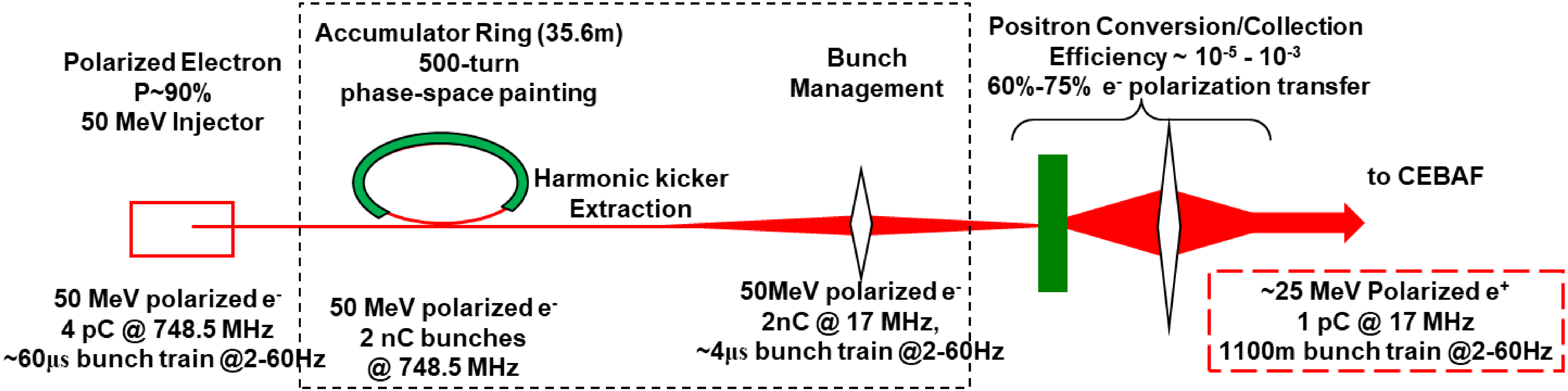
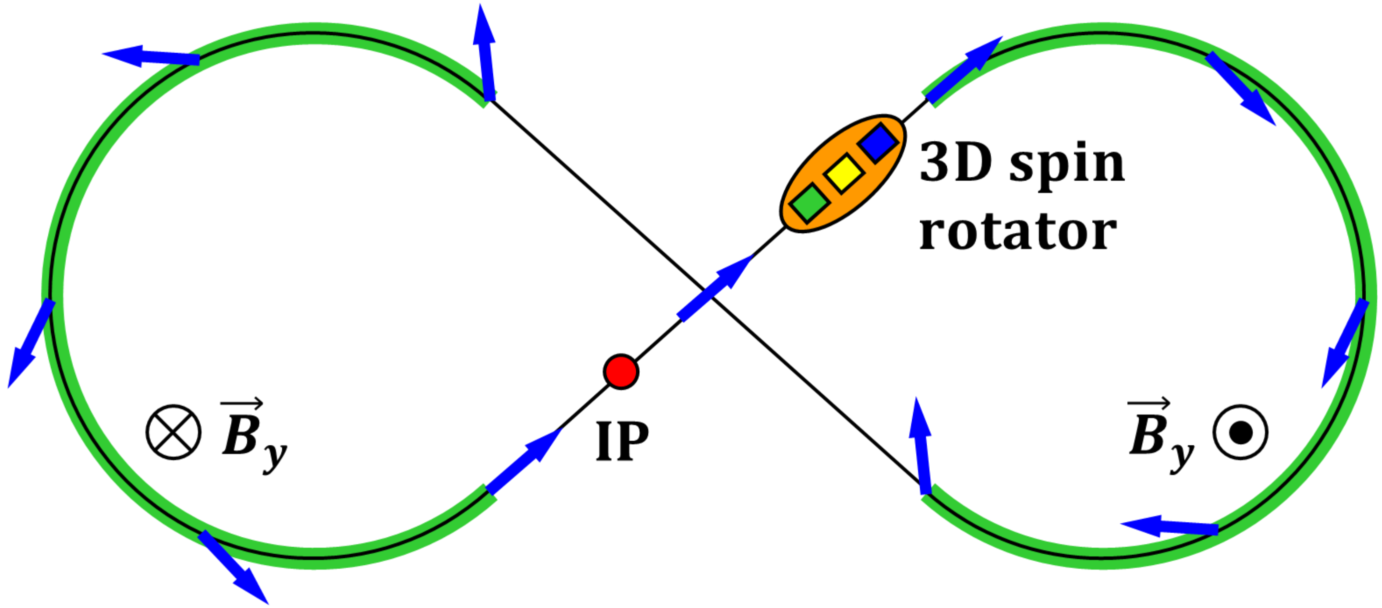
JLEIC Positron Production Scheme

- 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)



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



Transparent Spin Resonance and Spin Stability Criterion

- Total transparent 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

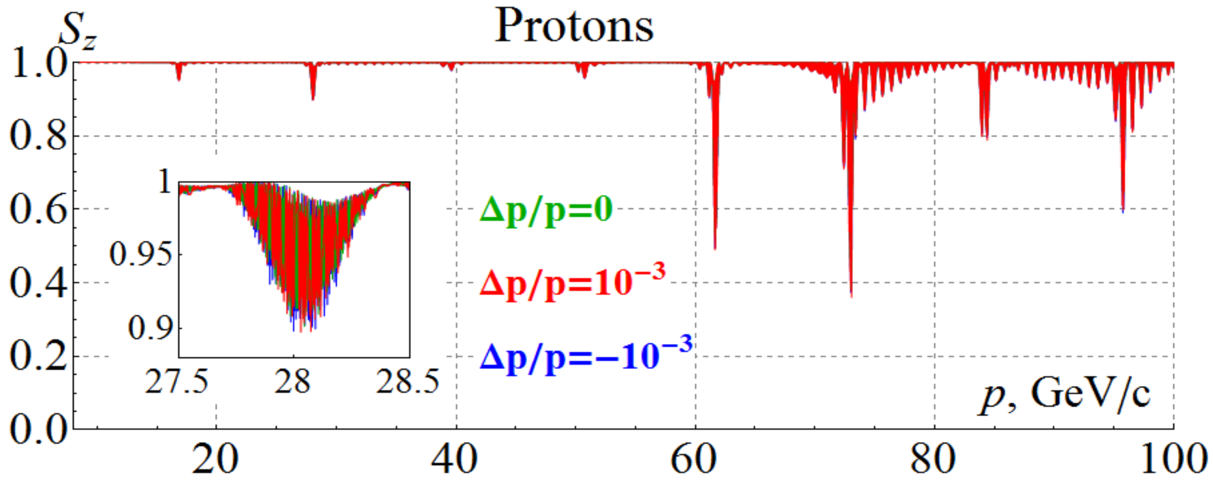
- Spin stability criterion
  - induced spin rotation must dominate over net rotation due to imperfections

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

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

Start-to-End Proton Acceleration in Ion Collider Ring

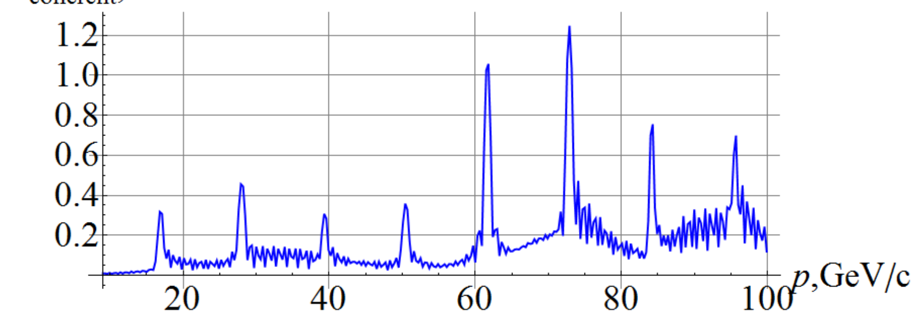
- Three protons with $\varepsilon_{x,y}^{N} = 1\ \mu m$ and $\Delta p/p = 0, \pm 1 \cdot 10^{-3}$ accelerated at ~3 T/min in lattice with 100 μm rms closed orbit excursion, $\nu_{sp} = 0.01$



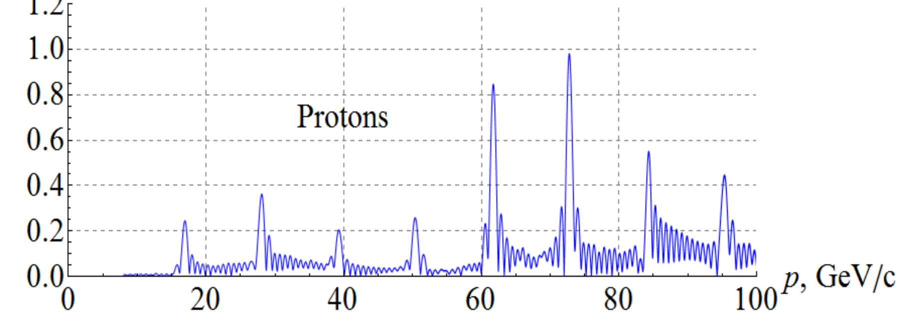
Zgoubi simulation

- Coherent resonance strength component

Analytic prediction



Zgoubi simulation



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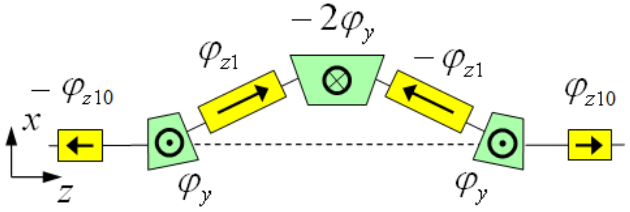
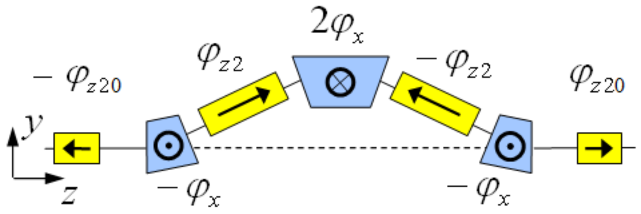
3D Spin Rotator in Ion Collider Ring

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

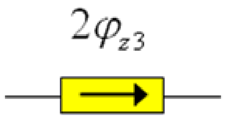


$L_{tot} = 7$ m, $\Delta x = 15$ mm, $B_{dip}^{max} = 3$ T, $B_{sol}^{max} = 3.6$ T

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

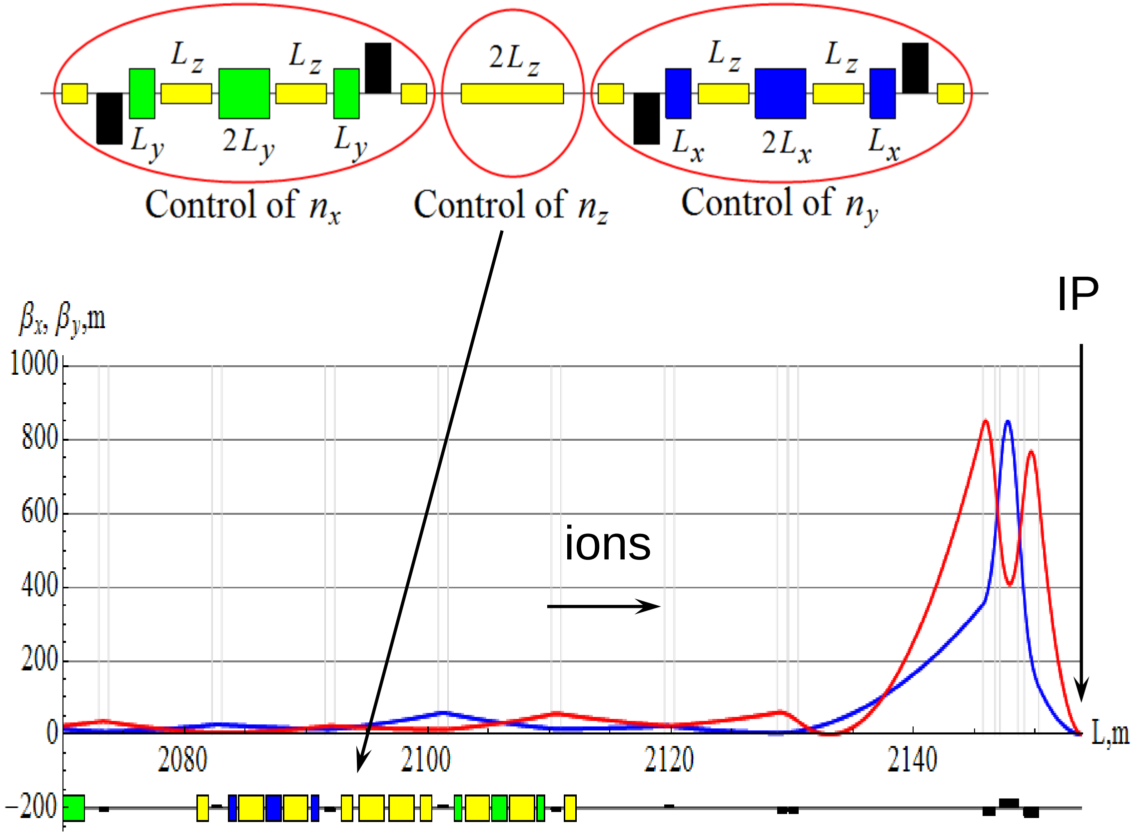


- Module for control of the longitudinal component



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

3D spin rotator



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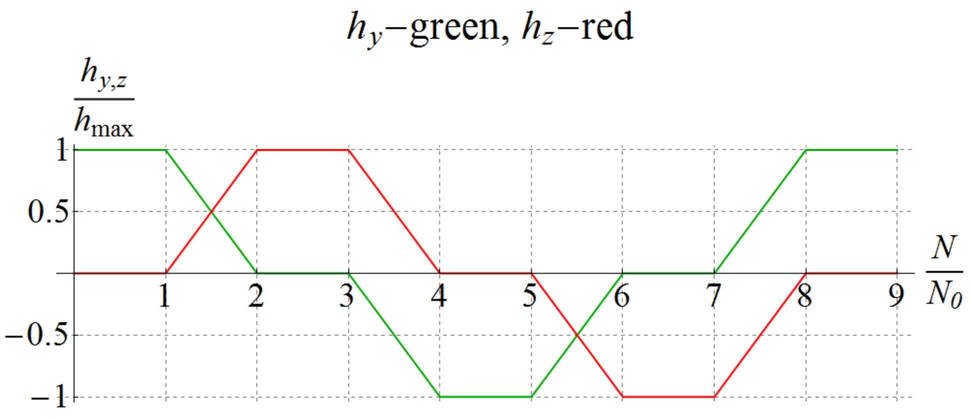
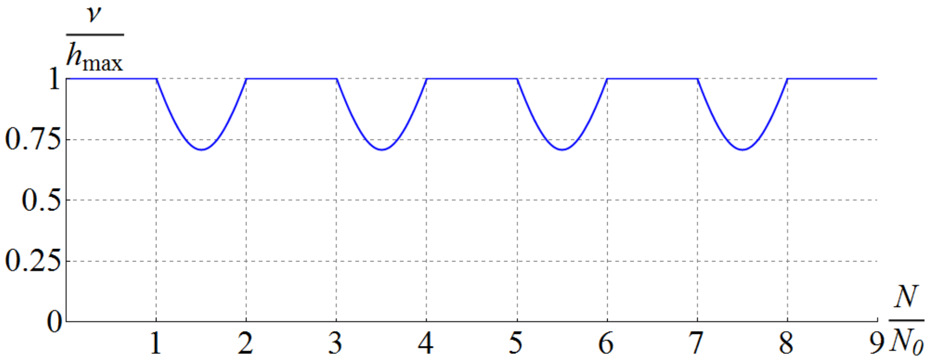
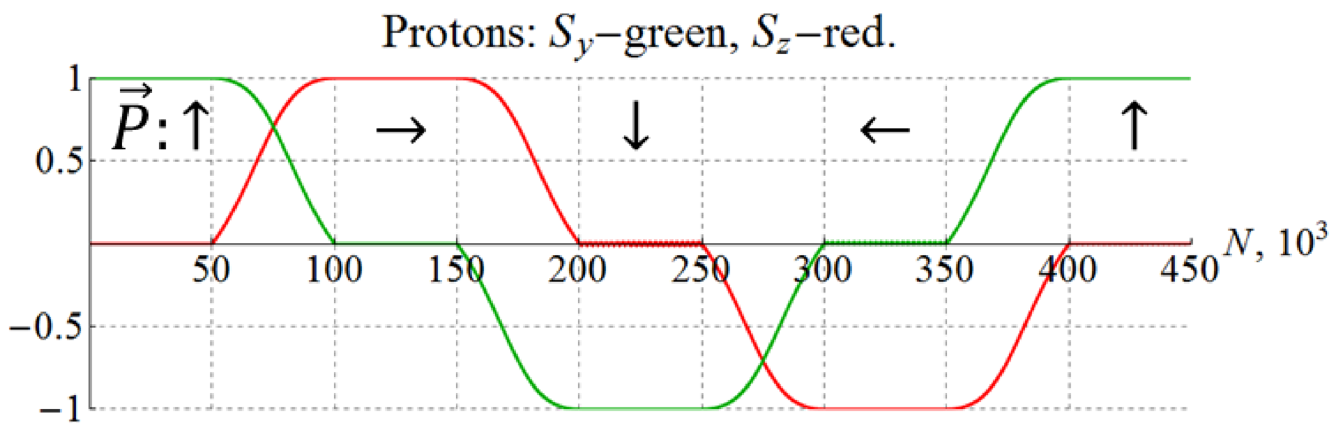
Spin Manipulation

- 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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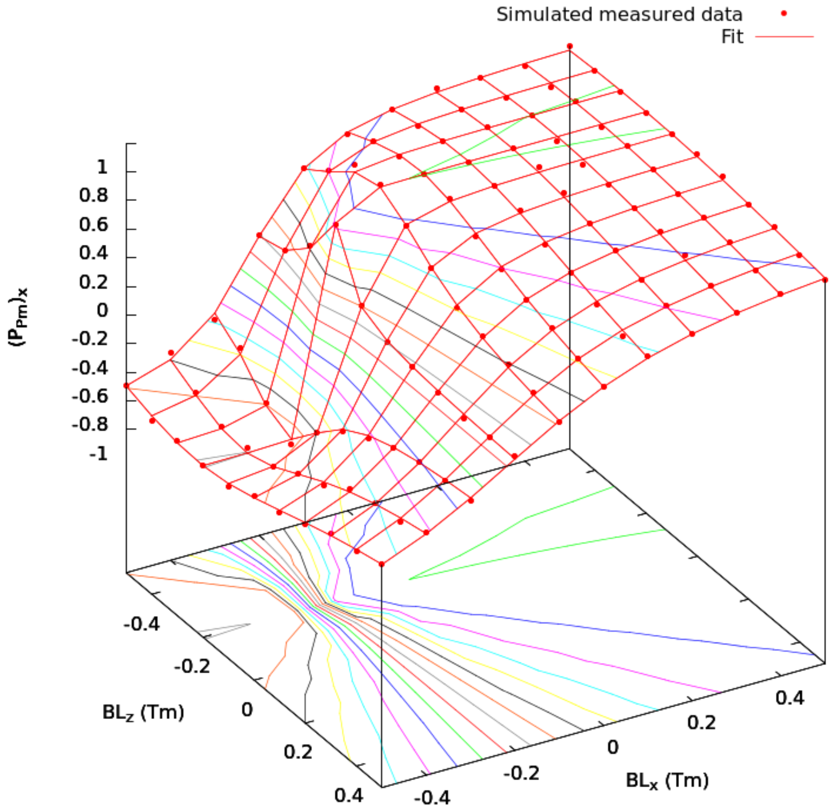
Spin Rotator Calibration

- 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%)



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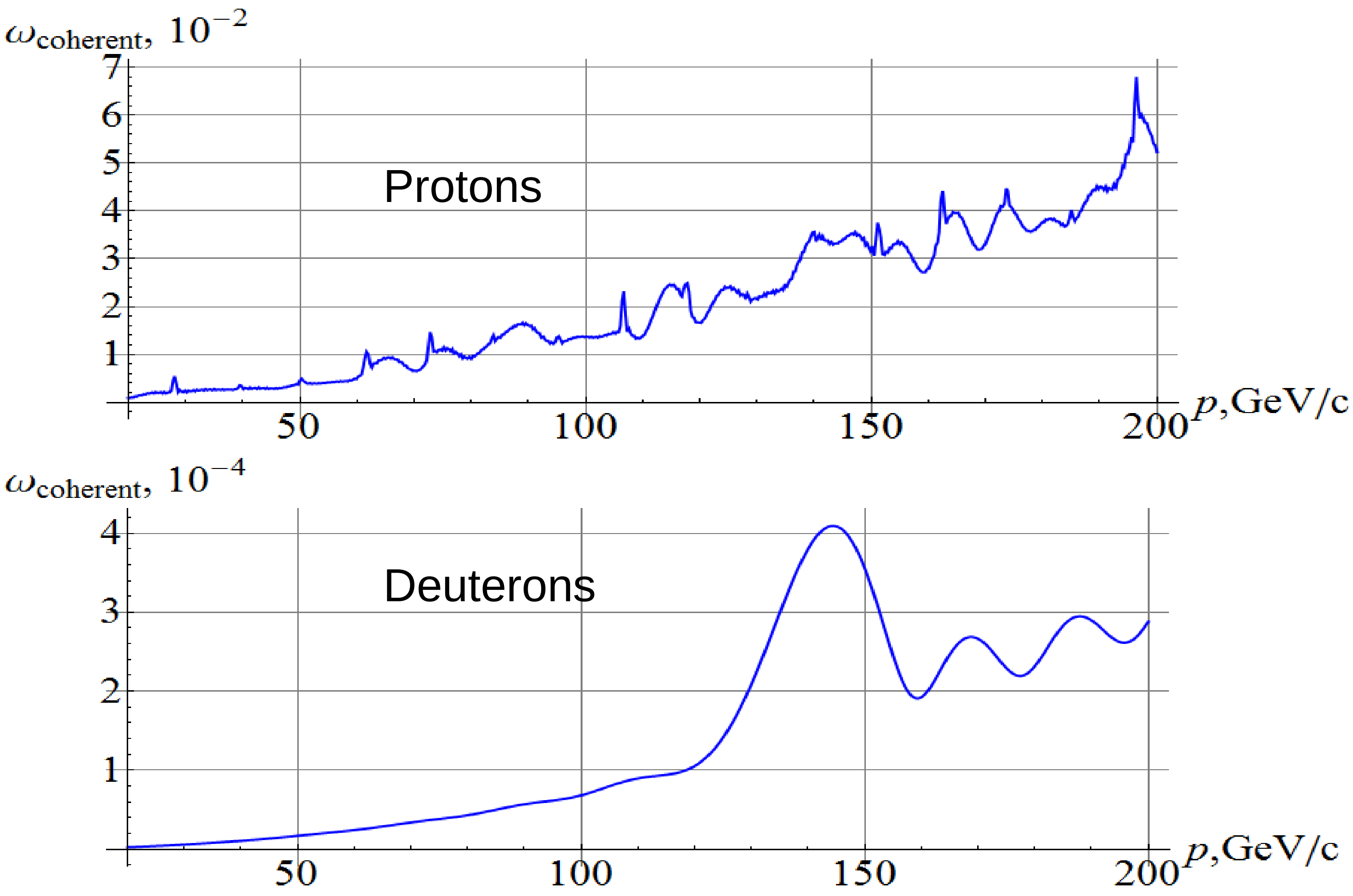
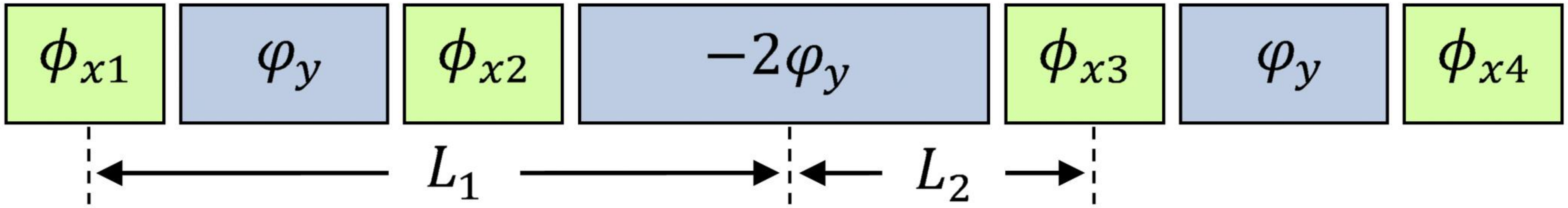
Transparent Spin Resonance Strength up to 200 GeV

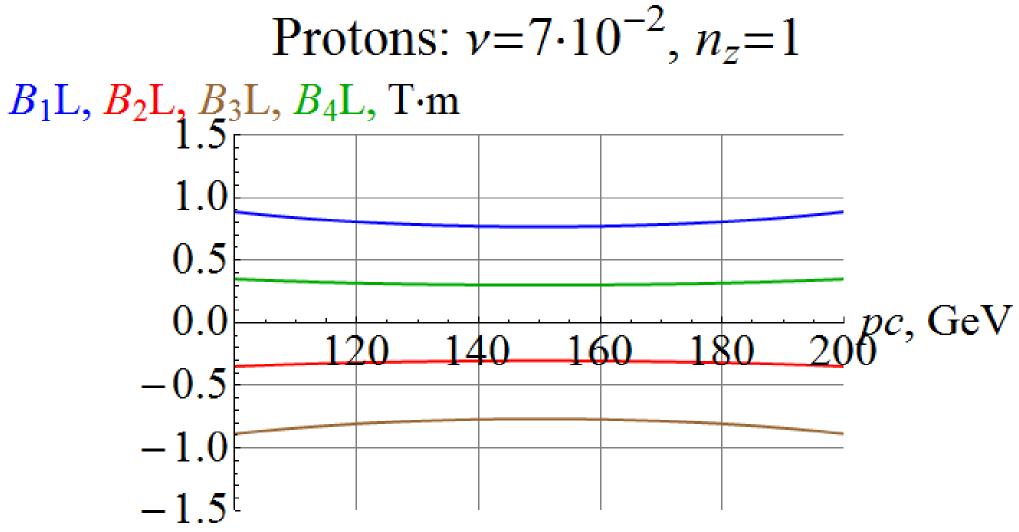
- Assuming RMS closed orbit distortion of ~200 μm
- Above ~100 GeV/c, the 3D spin rotator strength may not be sufficient to control polarization $\Rightarrow$ consider a 3D spin rotator based on transverse fields



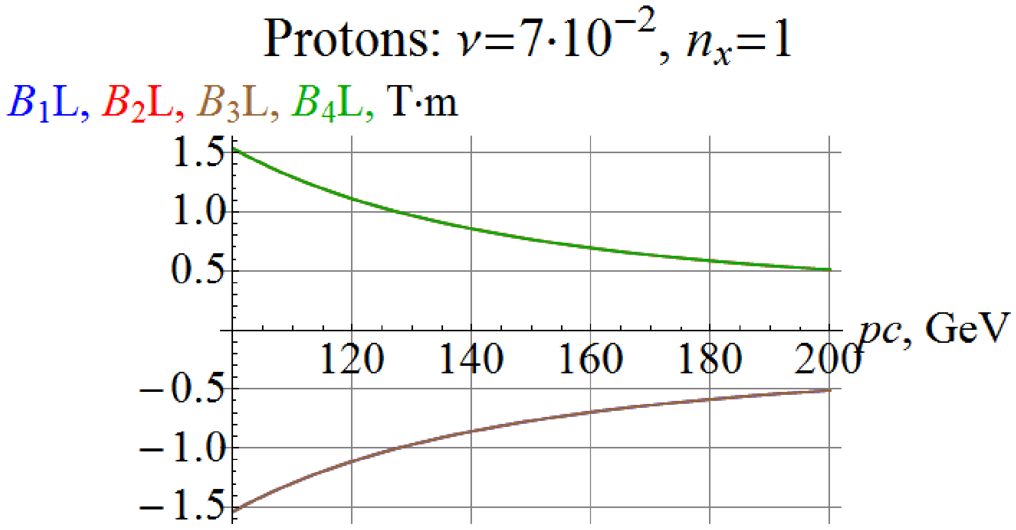
Proton Spin Rotator Utilizing Transverse Fields



Longitudinal Polarization at IP



Radial Polarization at IP



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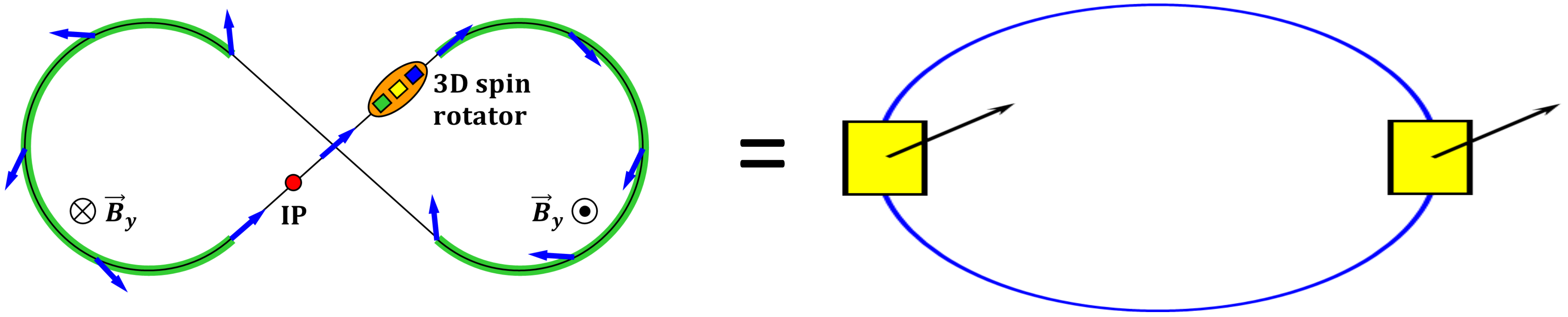
Concept of Transparent Spin Experiment

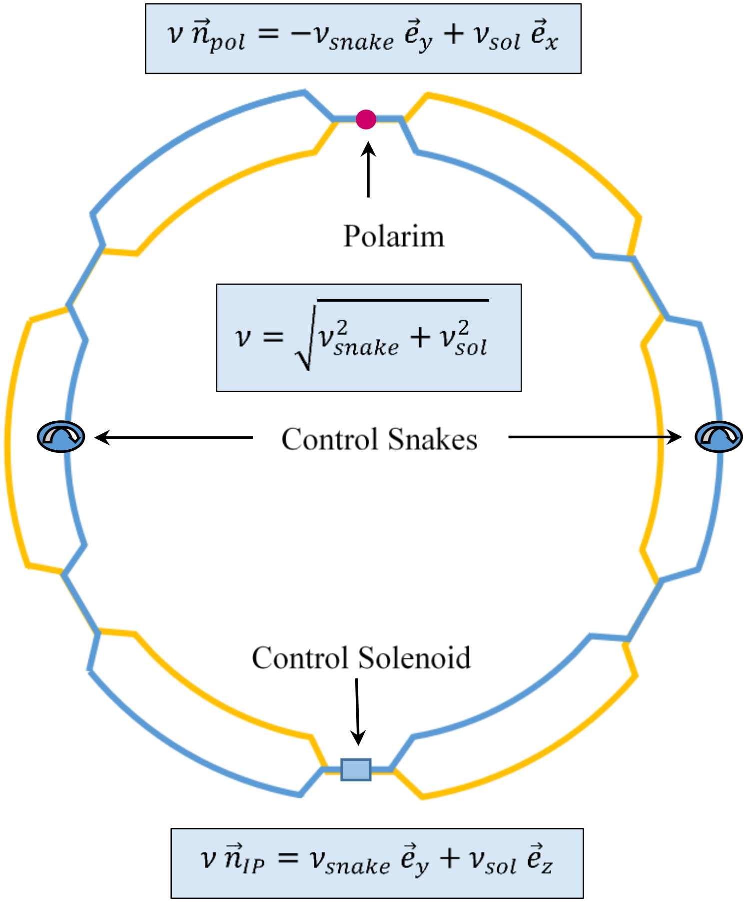
- A number of novel polarization preservation and control techniques have been developed for JLEIC
  - Transparent spin mode
    - Figure-8 ring
    - Racetrack with two identical Siberian snakes separated by 180° bend



  - 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



Summary

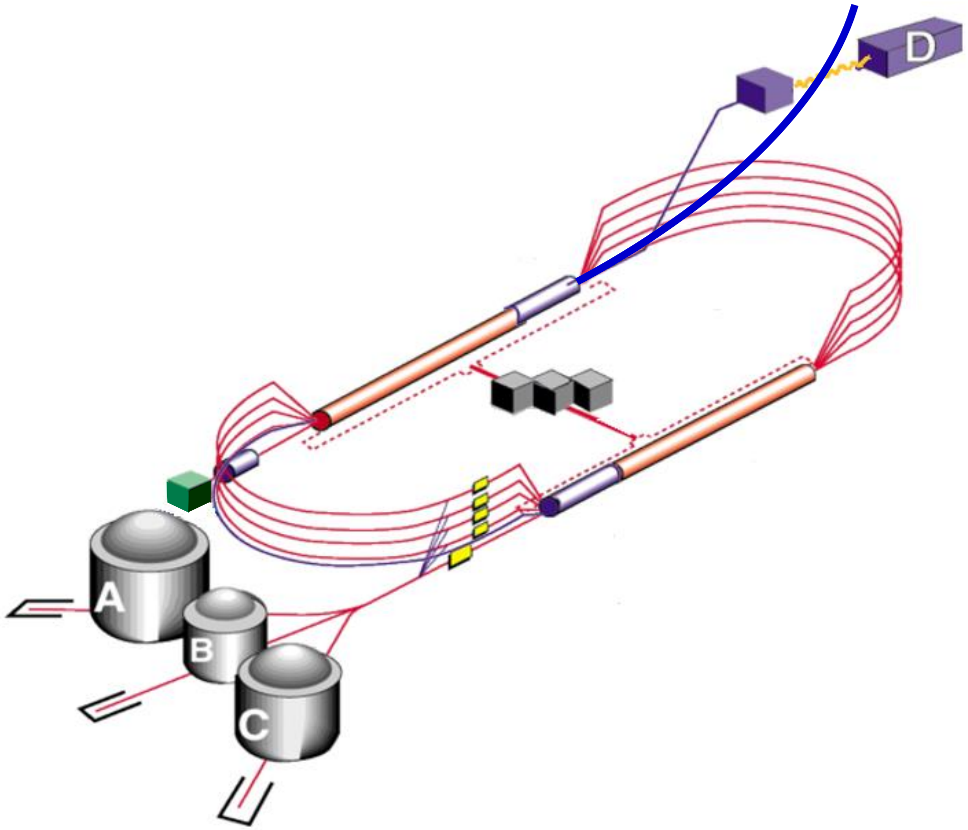
- Electron polarization scheme
  - Full-energy injection of polarized beam from CEBAF
  - High equilibrium polarization maintained by top-off injection
  - Universal fixed-geometry spin rotators
    - Longitudinal polarization at the IPs
    - Vertical polarization in the arcs to minimize the spin diffusion
  - Figure-8
    - Equal lifetimes of the two polarization states
    - Energy-independent spin tune
  - Spin tracking in progress
  - Compton polarimetry
- 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

Backup

12 GeV CEBAF as Injector

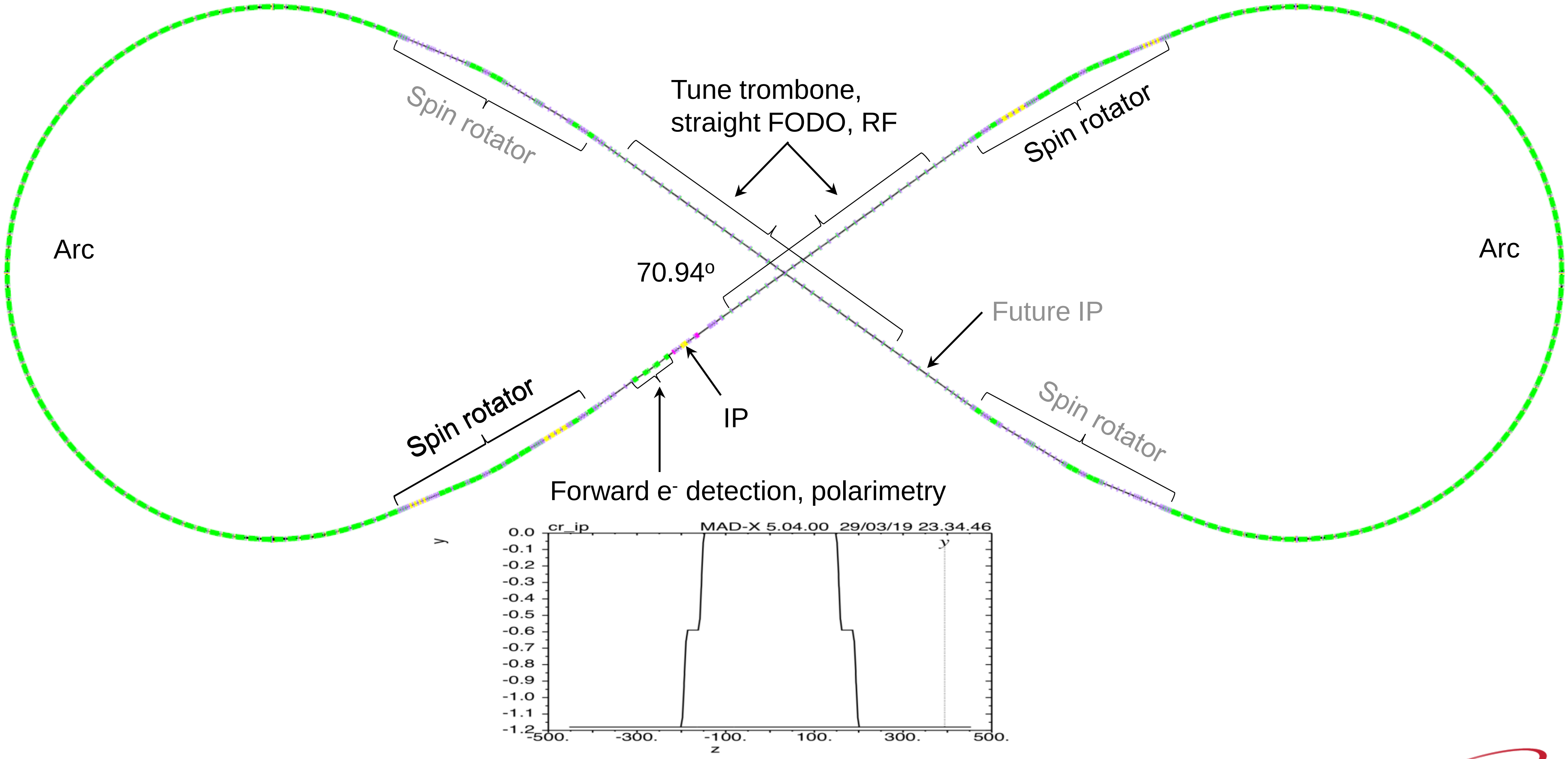
- Extensive fixed-target science program
  - Fixed-target program compatible with concurrent JLEIC operations
- JLEIC injector
  - Fast fill of collider ring
  - Full energy
  - ~85% polarization
  - Enables top-off
- New operation mode but no hardware modifications

Up to 12 GeV
to JLEIC



Electron Collider Ring Layout

- Cost reduction by reusing PEP-II magnets, RF and vacuum pipe in the electron ring



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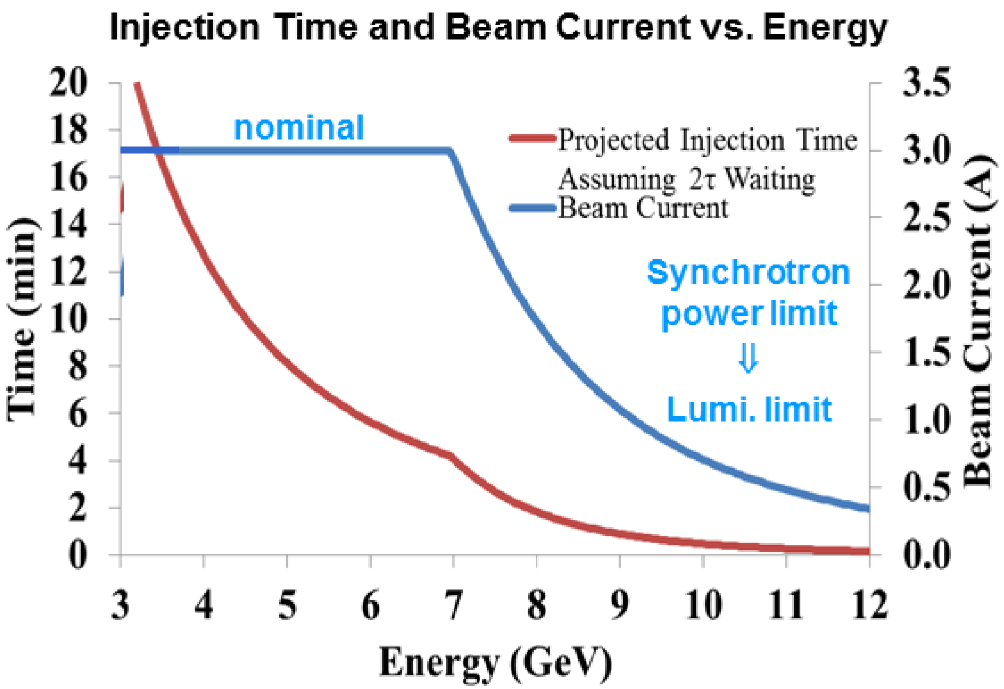
Electron Beam

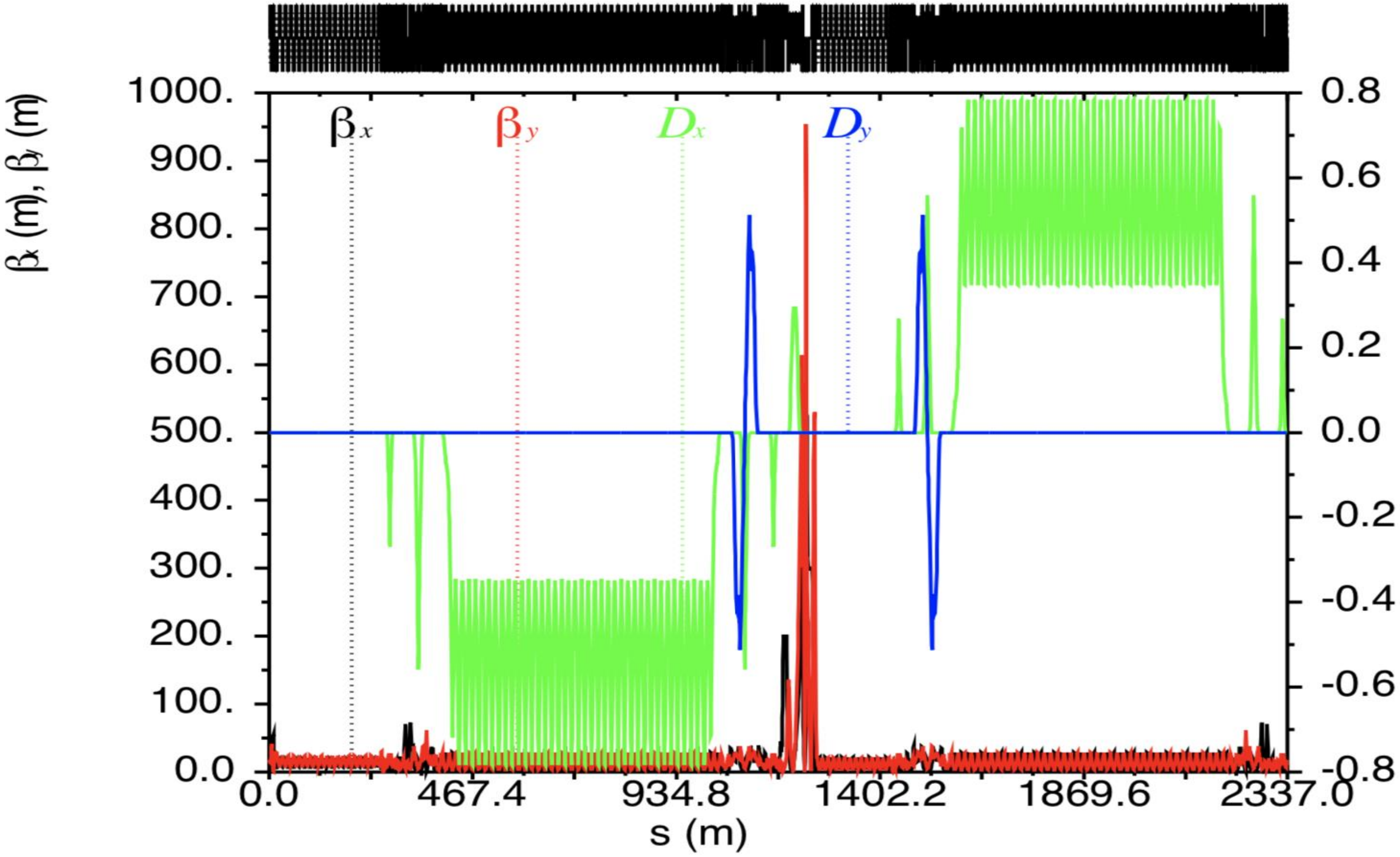
- Electron beam
  - **3 A** at up to 7 GeV
  - Normalized emittance **85 µm** @ 5 GeV
  - Synchrotron power density < **10 kW/m**
  - Total power up to **10 MW**



Parameter	Units					
Energy	GeV	3	5	7	10	12
Beam current	A	3	3	3	0.8	0.39
Total SR power	MW	0.30	2.28	8.76	9.73	9.84
Energy loss per turn	MeV	0.10	0.76	2.92	12.17	25.23
Energy spread	10^{-4}	2.5	4.1	5.8	8.2	9.9
Transverse damping time	ms	474	102	37	13	7
Longitudinal damping time	ms	237	51	19	6	4
Normalized horizontal emittance	um	18	85	234	683	1180
Normalized vertical emittance	um	1.3	6.0	16.6	48.3	83.5
Bunch length	cm	1	1	1	1	1.32

Electron Collider Ring Optics: Complete Ring

- Global chromaticity compensation scheme



Beam size

$\sigma = \sqrt{\beta\varepsilon + (D\Delta p/p)\text{^}2}$

$\varepsilon p/mc^2$ is a constant

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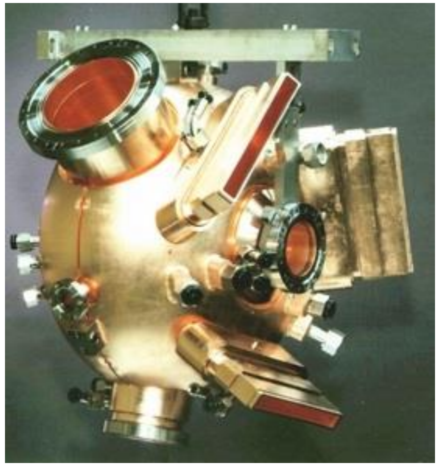
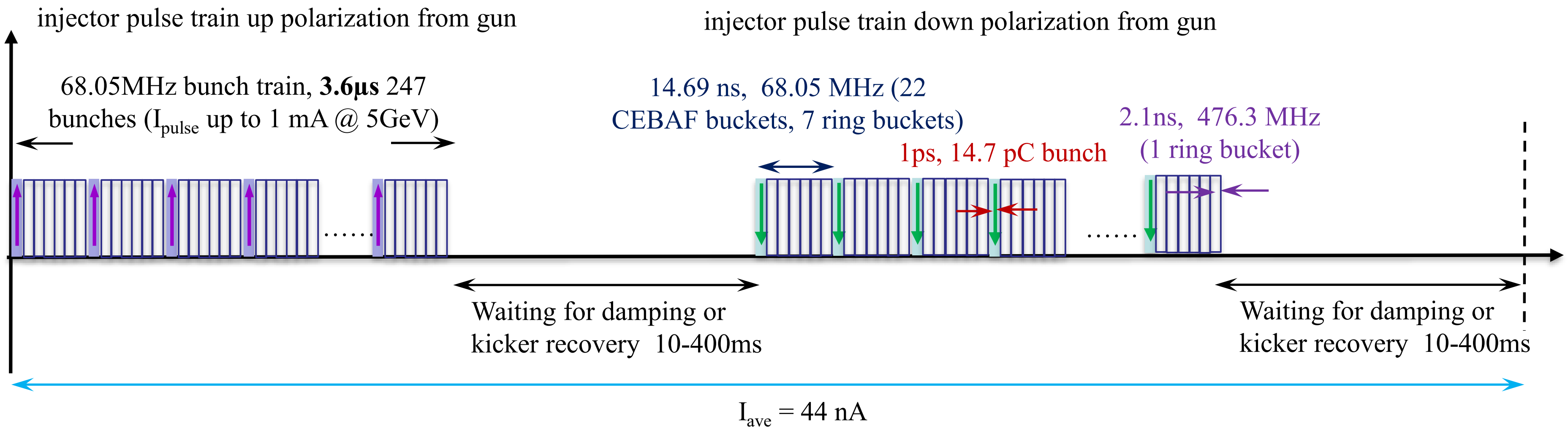
Electron Injection

- 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)

Mid-cycle 1, inject the 1st of every 7 buckets in the ring



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

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

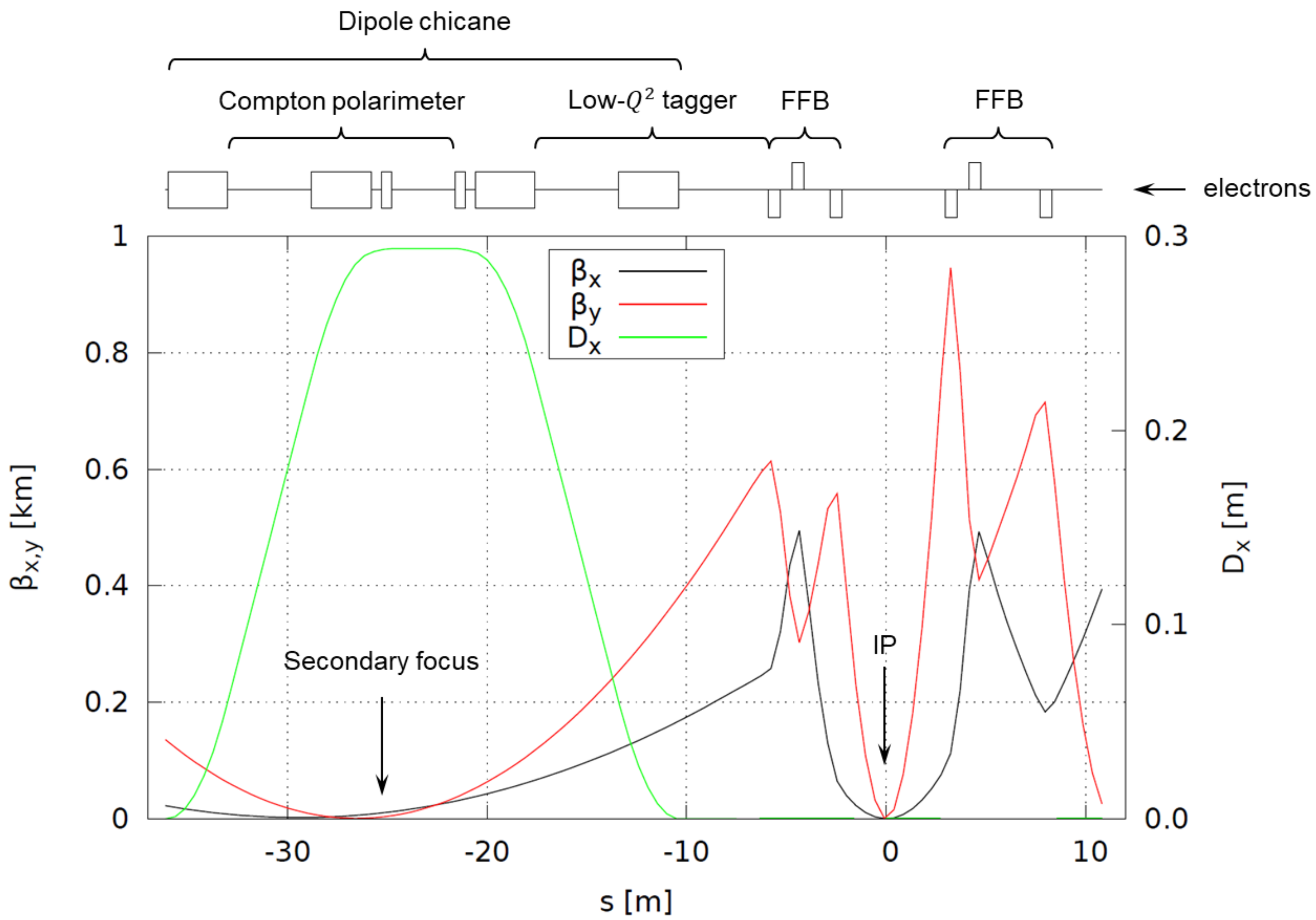
- Equilibrium polarization

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

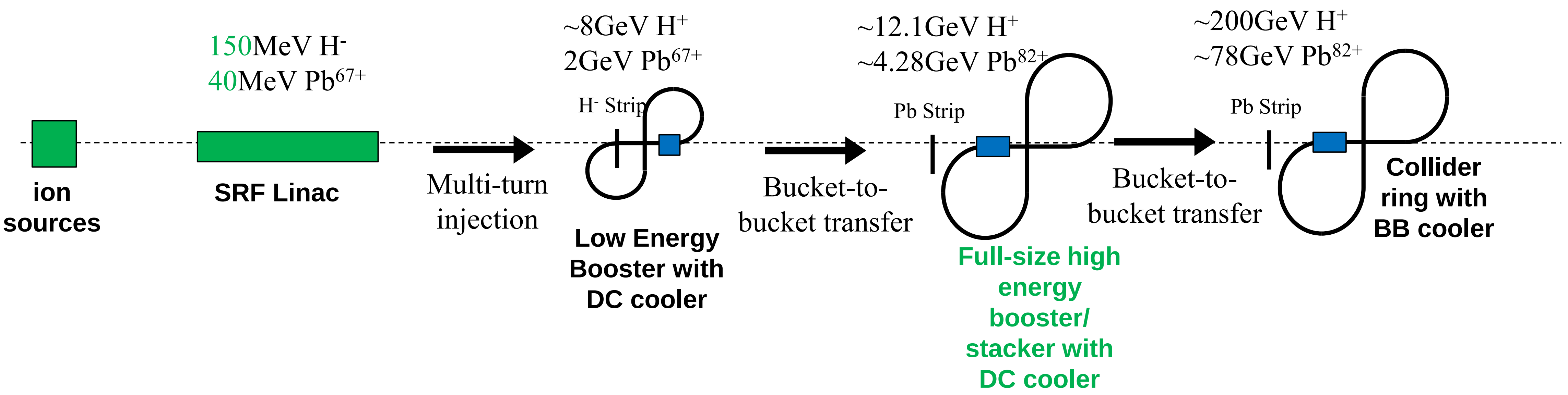
where $P_{ens,DK} = P_{DK}\langle\hat{n}\rangle_s$ is the value of ensemble average of P_{DK} independent of s and P_0 is the initial polarization

Electron Interaction Region

- Downstream chicane for low-Q^2 tagging and polarimetry



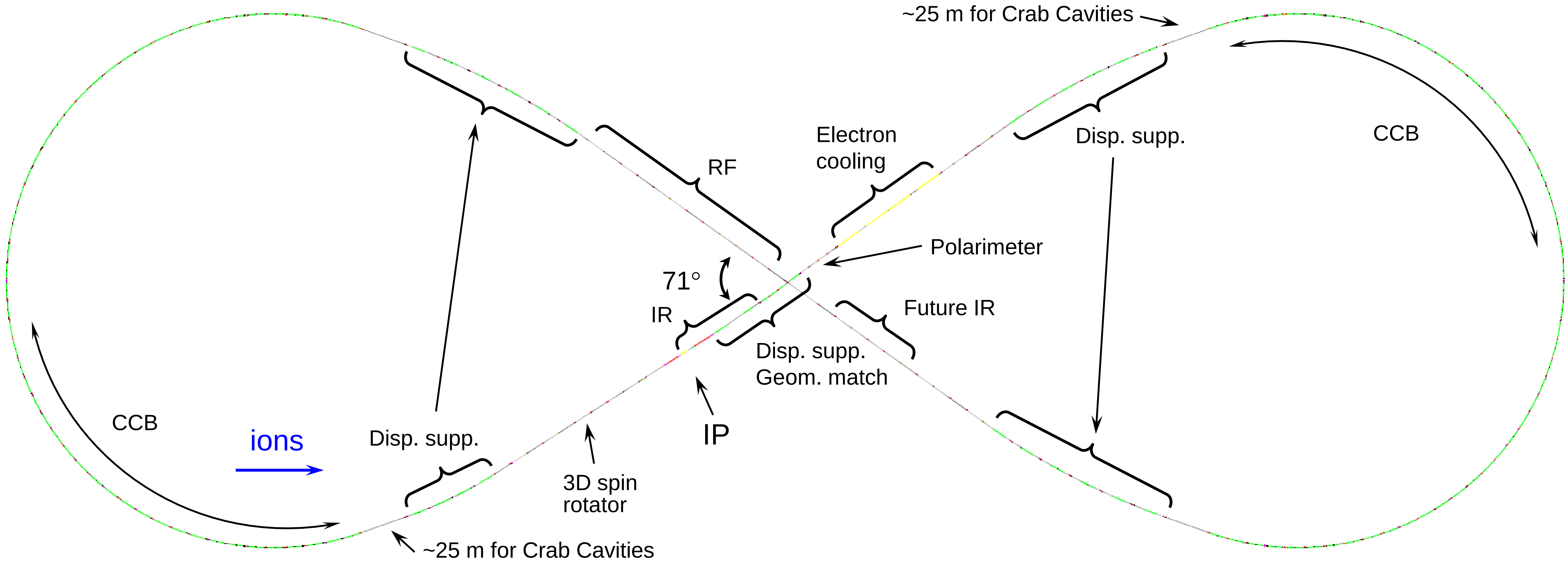
JLEIC Ion Injector Chain



- ~150 MeV linac energy
- Warm low energy booster (LEB)
  - 54-56 LEB cycles
- Full-size high energy booster (HEB), also functioning as a stacker
  - Most of the bunch formation process can be done in the HEB, increasing the collider duty factor and time averaged luminosity

Ion Collider Ring

- Circumference of 2335.975 m optimized for synchronization
- 200 GeV/c protons
- 6 T $\cos\theta$ dipoles and $\cos 2\theta$ quadrupoles



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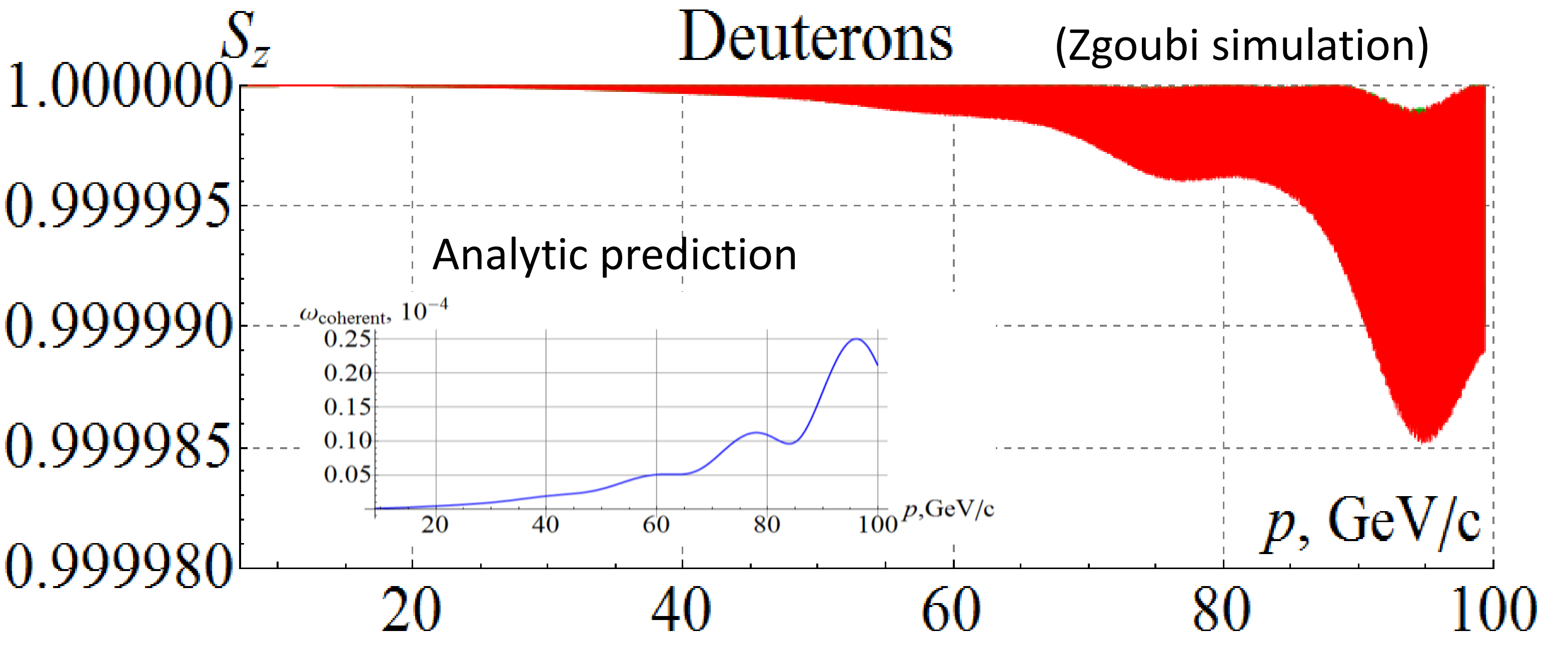
Start-to-End Deuteron Acceleration in Ion Collider Ring

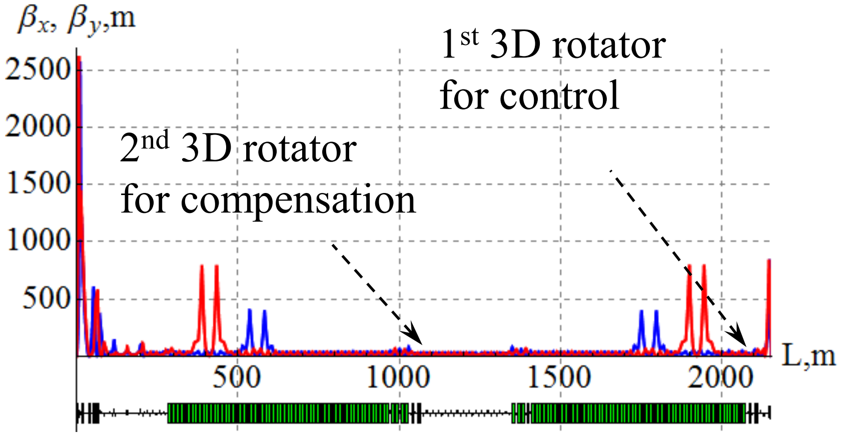
- Three deuterons with $\varepsilon^N_{x,y} = 0.5\ \mu m$ and $\Delta p/p = 0, \pm 1 \cdot 10^{-3}$ accelerated at ~3 T/min in lattice with 100 μm rms closed orbit excursion, $\nu_{sp} = 3 \cdot 10^{-3}$

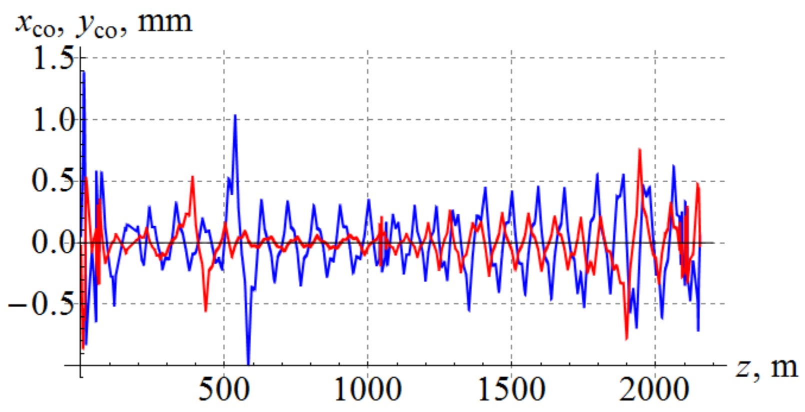


- Deuteron spin is highly stable in figure-8 rings, which can be used for high precision experiments

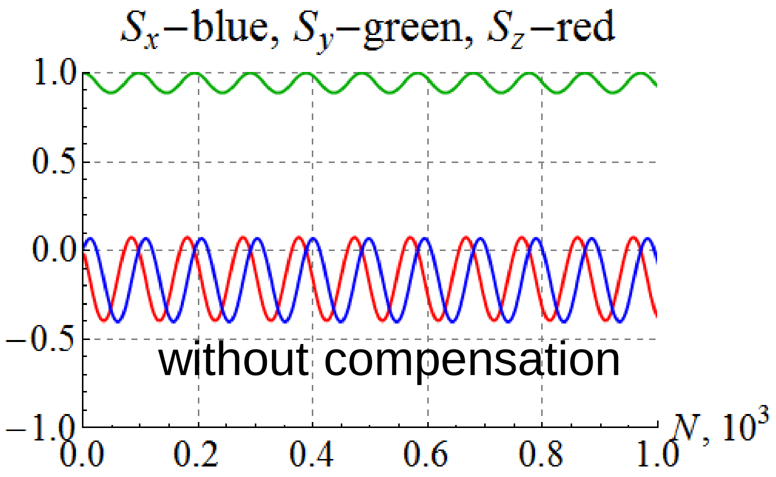
Polarization Control in Ion Collider Ring

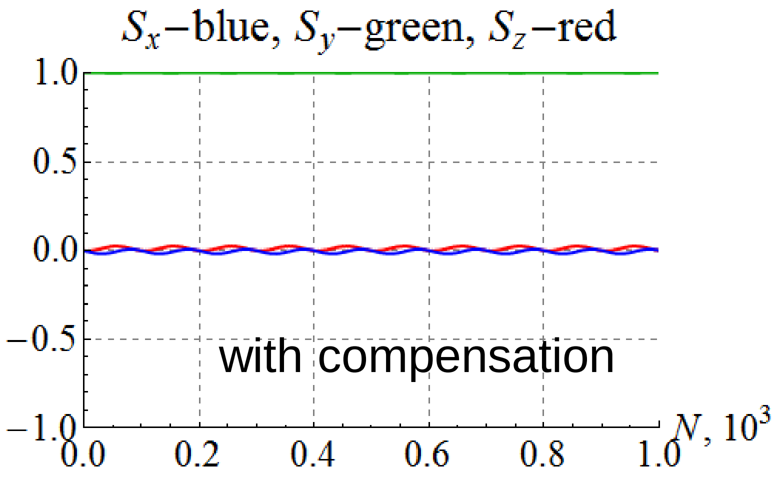
- 100 GeV/c figure-8 ion collider ring with transverse quadrupole misalignments





- 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

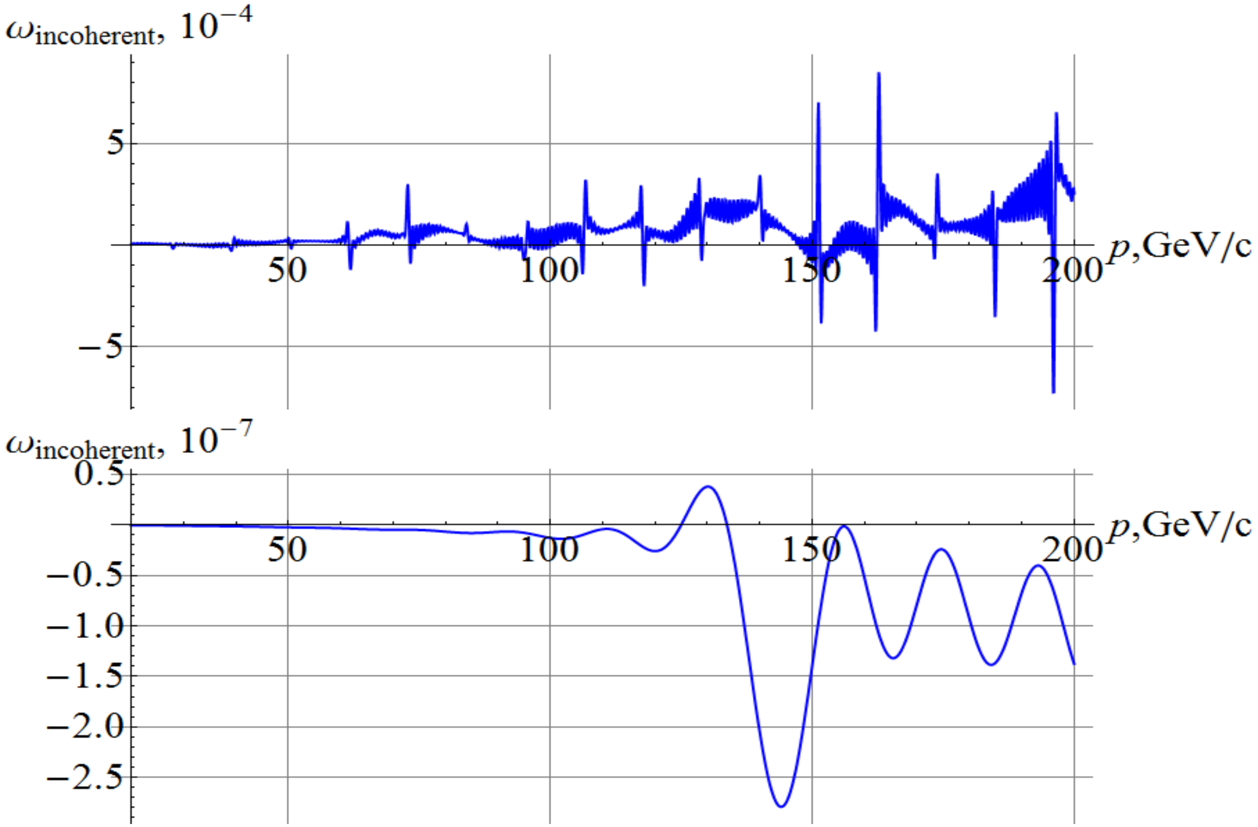




Incoherent Part of Zero-Integer Spin Resonance Strength

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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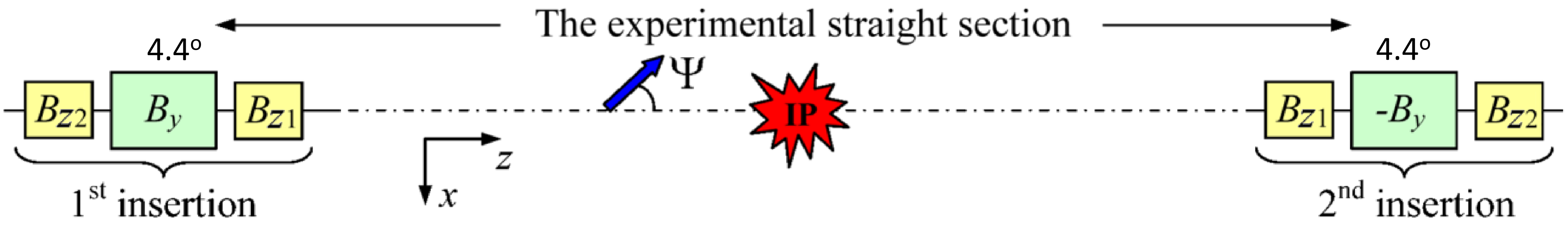
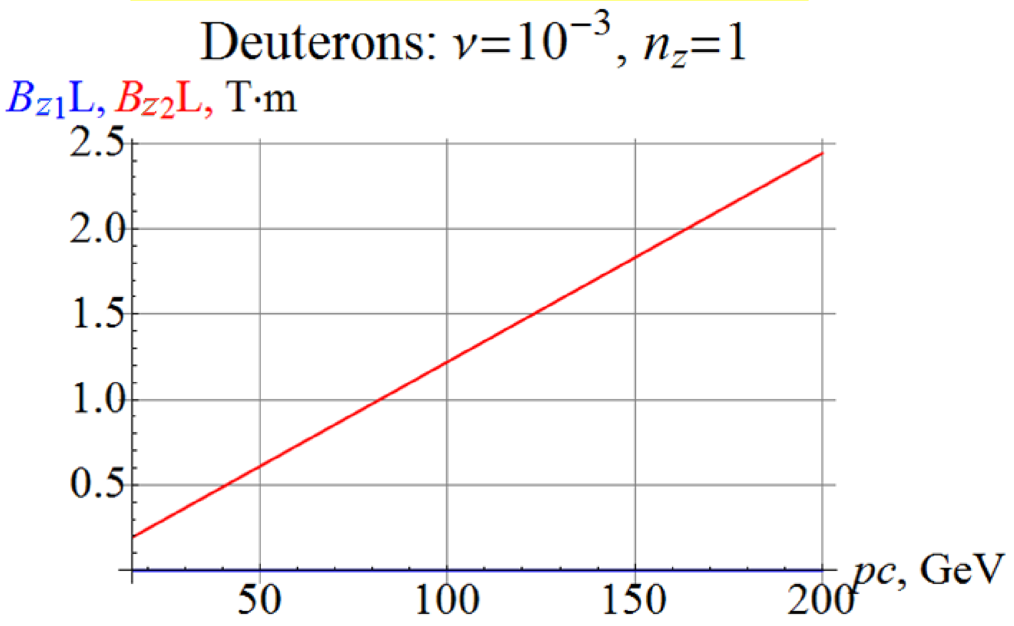
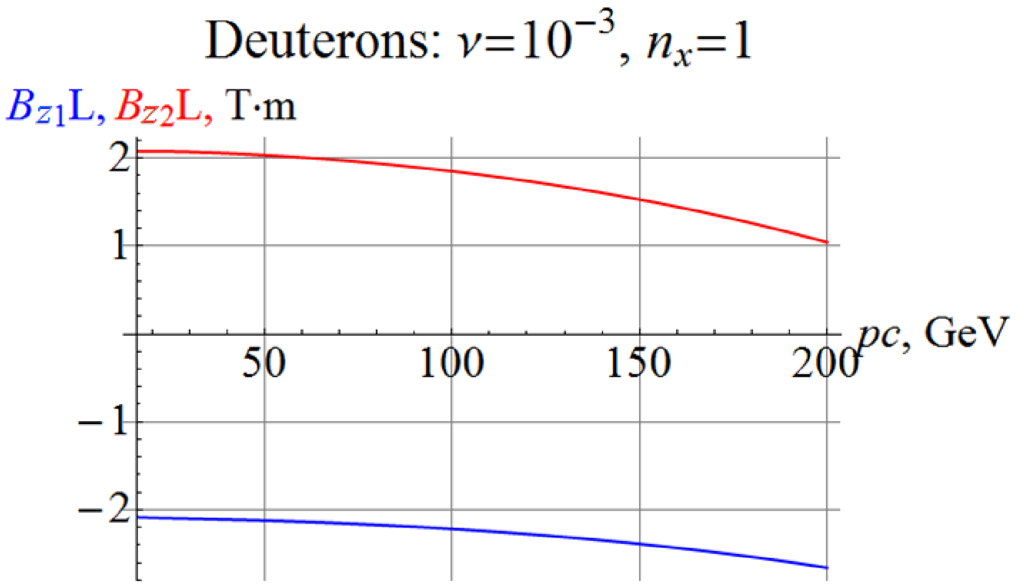
Deuteron Spin Rotator Utilizing Longitudinal Fields



Longitudinal Polarization at IP



Radial Polarization at IP



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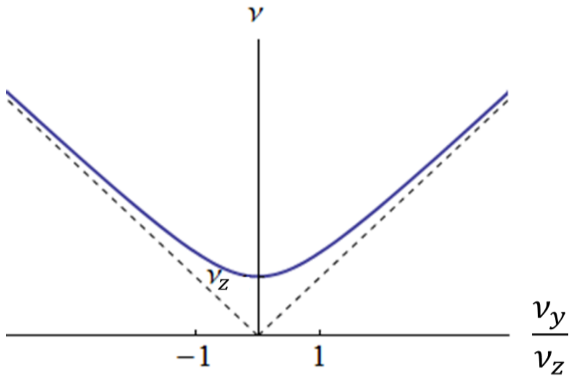
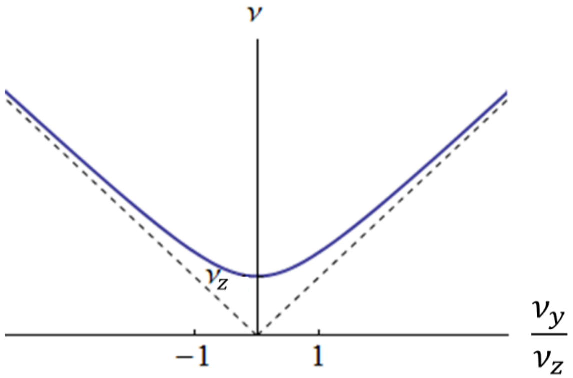
Experimental Scenarios

- 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