Spin Tracking in Ion and Electron Rings

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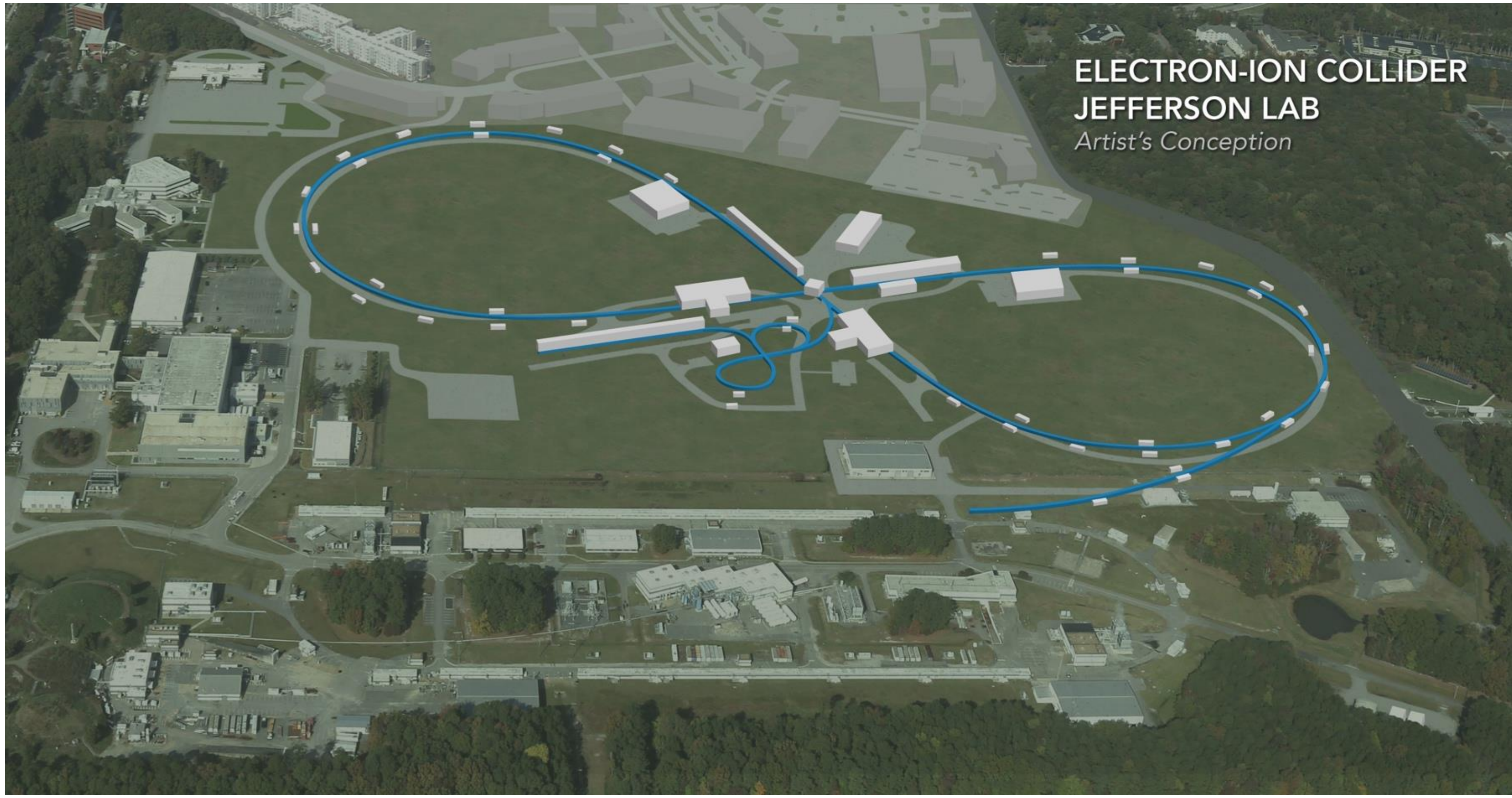


Supported by FY'17 DoE NP Base Funding

2018 NP Accelerator R&D PI Exchange Meeting

November 13-14, 2018

Outline

- Project on spin tracking in ion and electron rings
- Ion polarization scheme
- Polarized ion beam acceleration with transition energy crossing
- Polarization control in the ion collider ring
- Study of potential problems with polarization preservation and control
  - Detector solenoid
  - Betatron coupling
  - Higher-order resonances
- Electron polarization scheme
- Monte-Carlo electron spin tracking

Project on Spin Tracking in Ion and Electron Rings

- Description
  - Figure-8 ring design possesses a number of beneficial spin dynamics features. While intuitively simple, it is a novel approach. It requires development of new polarization preservation and control techniques and verification in spin tracking simulations of both electron and ion beams. We developed schemes for both electron and ion polarizations. We are currently in the process of validating these schemes in simulations.
- Status
  - Completed
- Main goals
  - Proton and deuteron polarization control at 100 GeV/c.
  - Acceleration of polarized protons and deuterons from 8 to 100 GeV/c.
  - Study of polarization effect of transition energy crossing.
  - Evaluation and compensation of the spin effect of the detector solenoid.
  - Study of betatron coupling effect on the polarization.
  - Study of higher-order spin resonances.
  - Monte-Carlo simulation of electron spin dynamics.

Project on Spin Tracking in Ion and Electron Rings

- Supported by JLab’s Base DoE NP funding
- The project’s funding is not continued by the FY’18 NP Accelerator R&D FOA. However, one funded FY’18 project benefits from this project’s results
  - Theoretical and Experimental Study of the Spin Transparency Mode in an EIC
- Budget

	FY’16-FY’17	Totals
a) Funds allocated	$104,000	$104,000
b) Actual costs to date	$104,000	$104,000

Project on Spin Tracking in Ion and Electron Rings

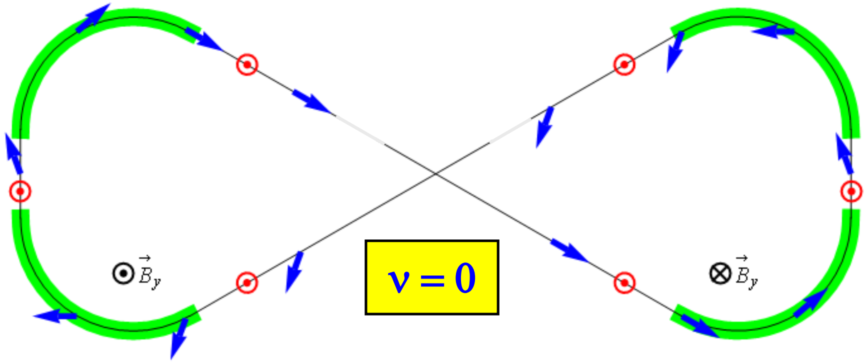
- Deliverables and schedule

Task	FY'17 Q1	FY'17 Q2	FY'17 Q3	FY'17 Q4
Proton and deuteron polarization control at 100 GeV/c.	×			
Acceleration of polarized protons and deuterons from 8 to 100 GeV/c.	×			
Study of polarization effect of transition energy crossing.		×		
Evaluation and compensation of the spin effect of the detector solenoid.		×		
Study of betatron coupling effect on the polarization.			×	
Study of higher-order spin resonances.			×	
Monte-Carlo simulation of electron spin dynamics.			×	×

- The project corresponds to Line 4, “Benchmarking of realistic EIC simulation tools against available data”, Priority High-A of the Jones' Panel report

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



Zero-Integer Spin Resonance and Spin Stability Criterion

- Total zero-integer spin resonance strength

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

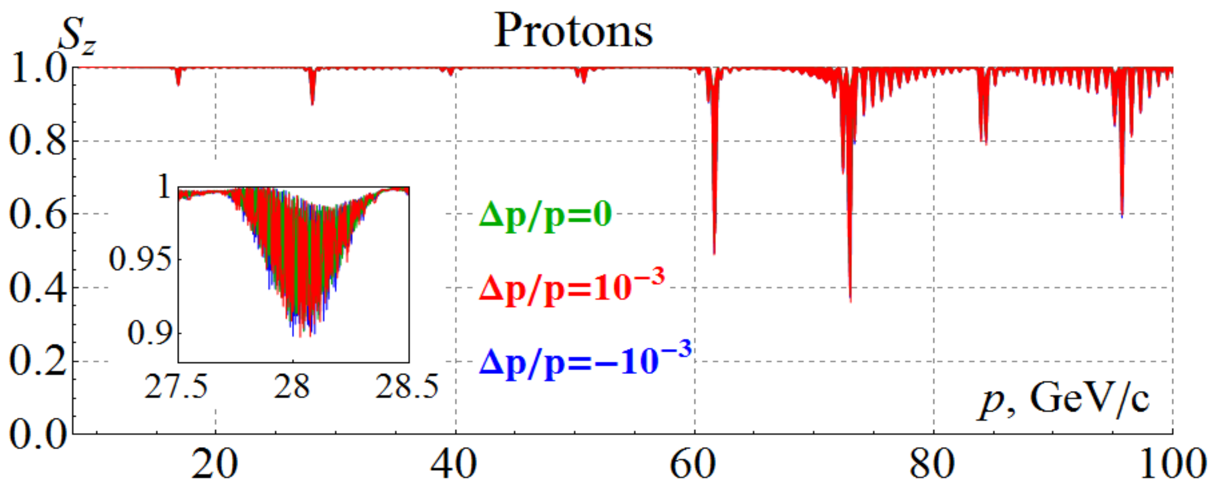
  is composed of
  - coherent part $w_{coherent}$ due to closed orbit excursions (due to imperfections); it does not lead to depolarization but causes coherent spin rotation about a priori unknown direction
  - incoherent part $w_{emittance}$ due to transverse and longitudinal emittances (proportional 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 $\nu_d = 10^{-4}$

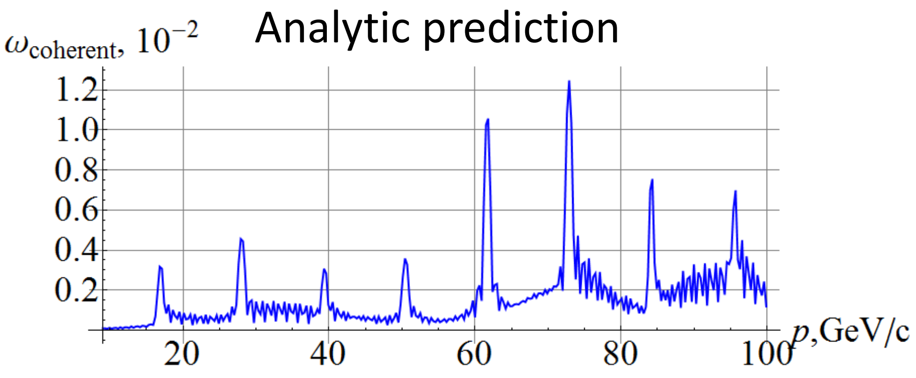
Start-to-End Proton Acceleration in Ion Collider Ring

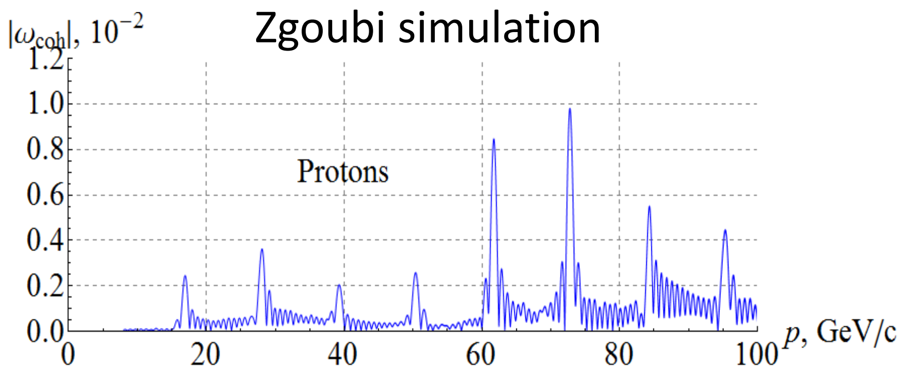
- Three protons with $\varepsilon_{x,y}^{N} = 1\ \mu m$ and $\Delta p/p = 0, \pm 1 \cdot 10^{-3}$ accelerated at ~3 T/min in lattice with 100 μm rms closed orbit excursion, $\nu_{sp} = 0.01$



Zgoubi simulation

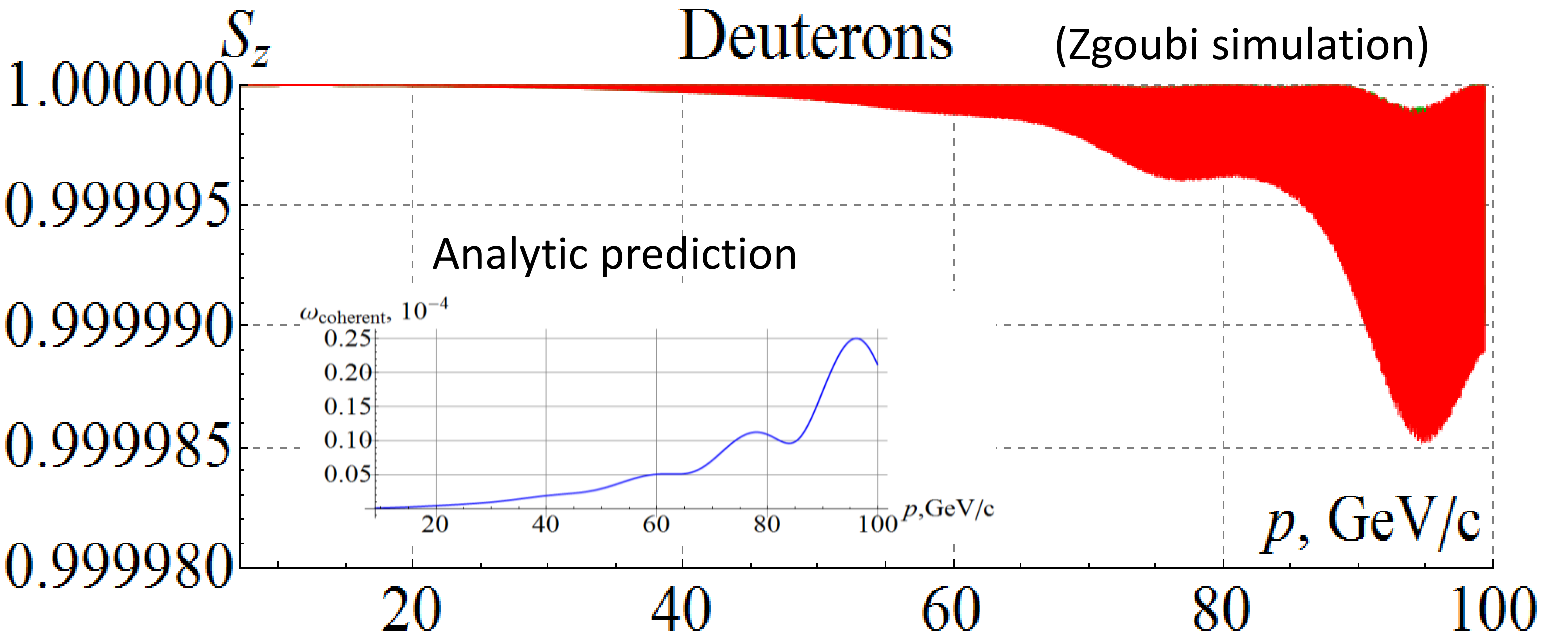
- Coherent resonance strength component


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, $\nu_{sp} = 3 \cdot 10^{-3}$



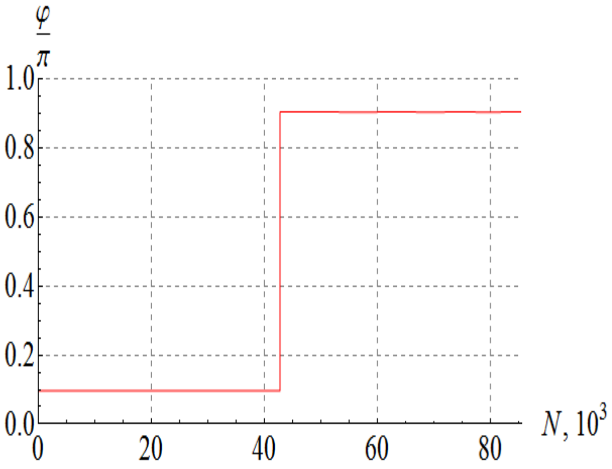
(Zgoubi simulation)

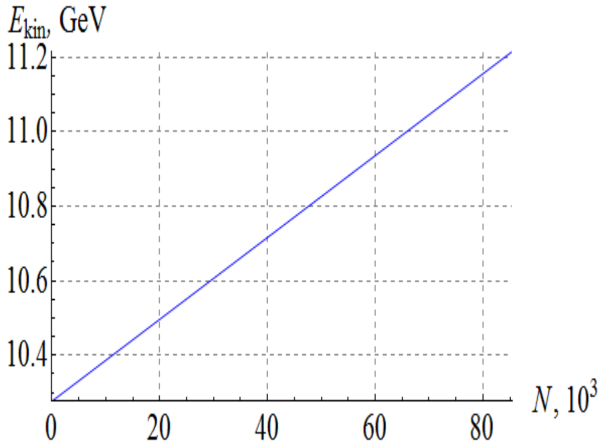
Analytic prediction

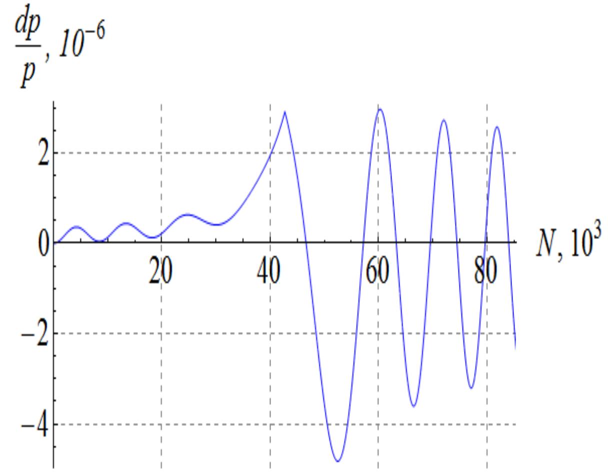
- Deuteron spin is highly stable in figure-8 rings, which can be used for high precision experiments

Transition Energy Crossing by RF Phase Jump

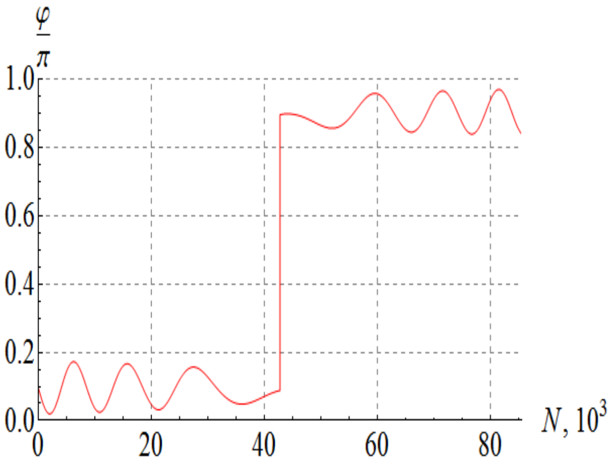
- On-momentum particle

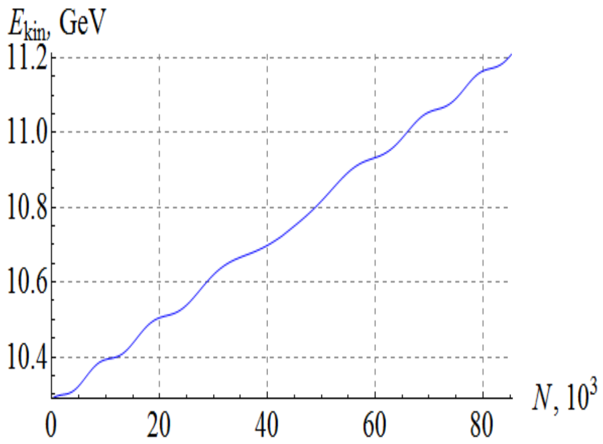


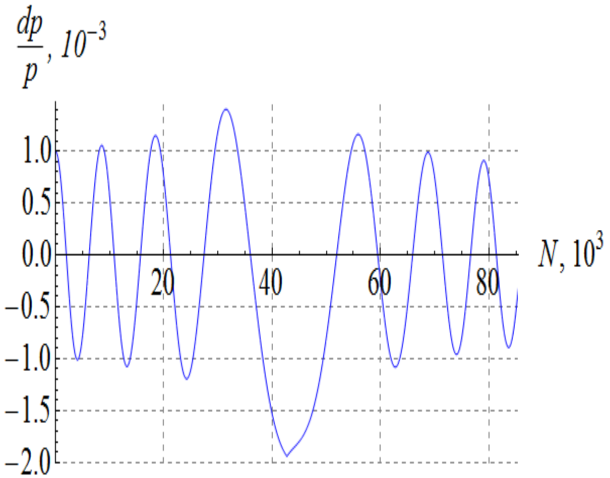




- Particle with $\Delta p/p = 1 \cdot 10^{-3}$

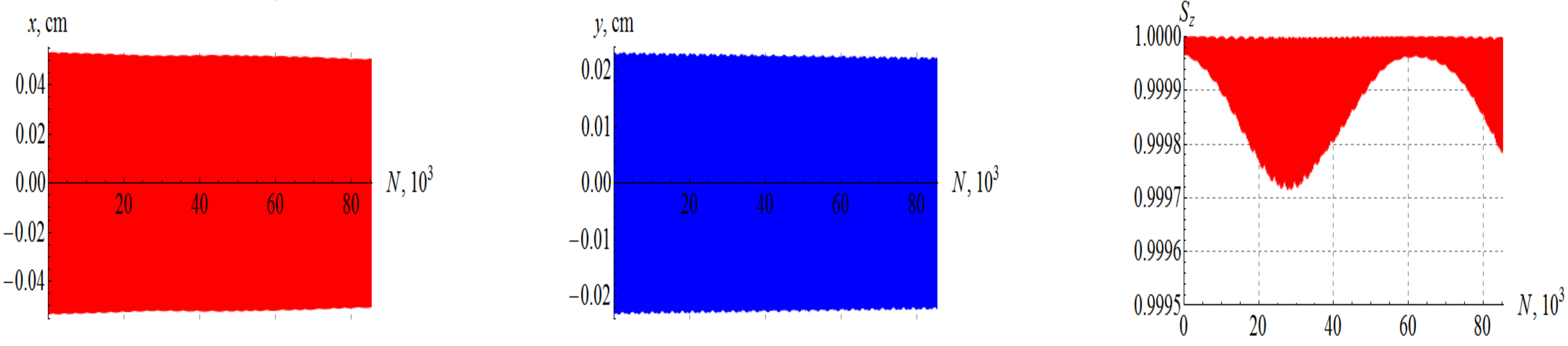




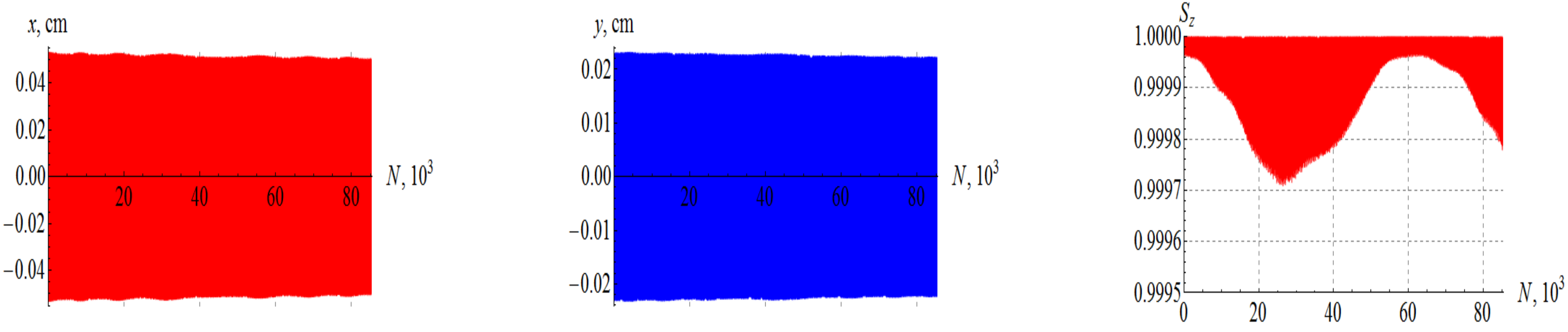


Proton Orbital and Spin Motion

- On-momentum particle

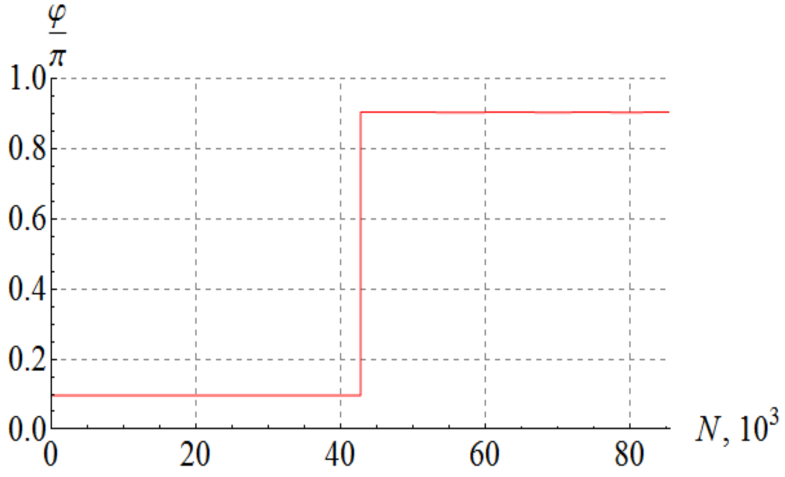


- Particle with $\Delta p/p = 1 \cdot 10^{-3}$

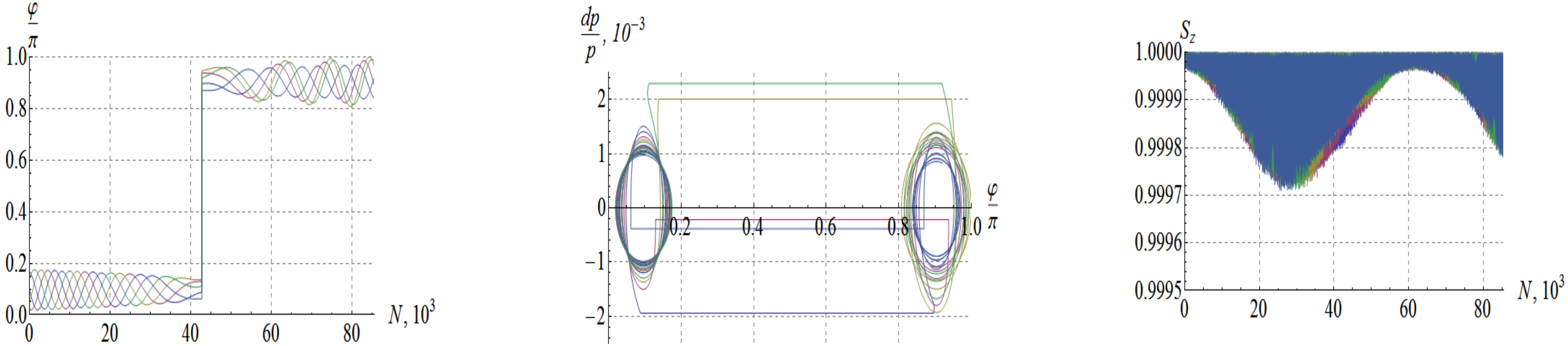


Impact of Synchrotron Phase

- On-momentum particle

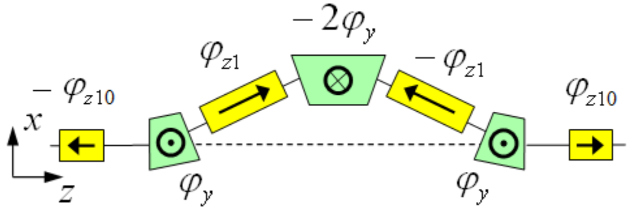


- Five particles uniformly distributed on an ellipse with $\Delta p/p = 1 \cdot 10^{-3}$



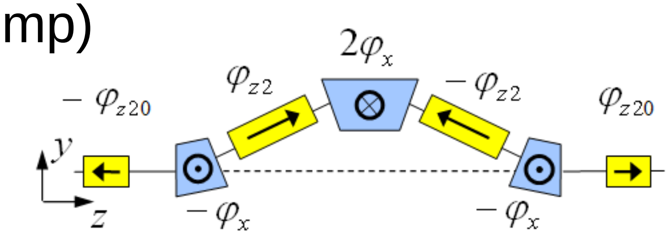
3D Spin Rotator in Ion Collider Ring

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

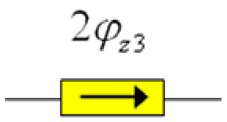


$$L_{tot} = 7\ m,\ \Delta x = 16\ mm,\ B_{dip}^{max} = 3\ T,\ B_{sol}^{max} = 2\ T$$

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



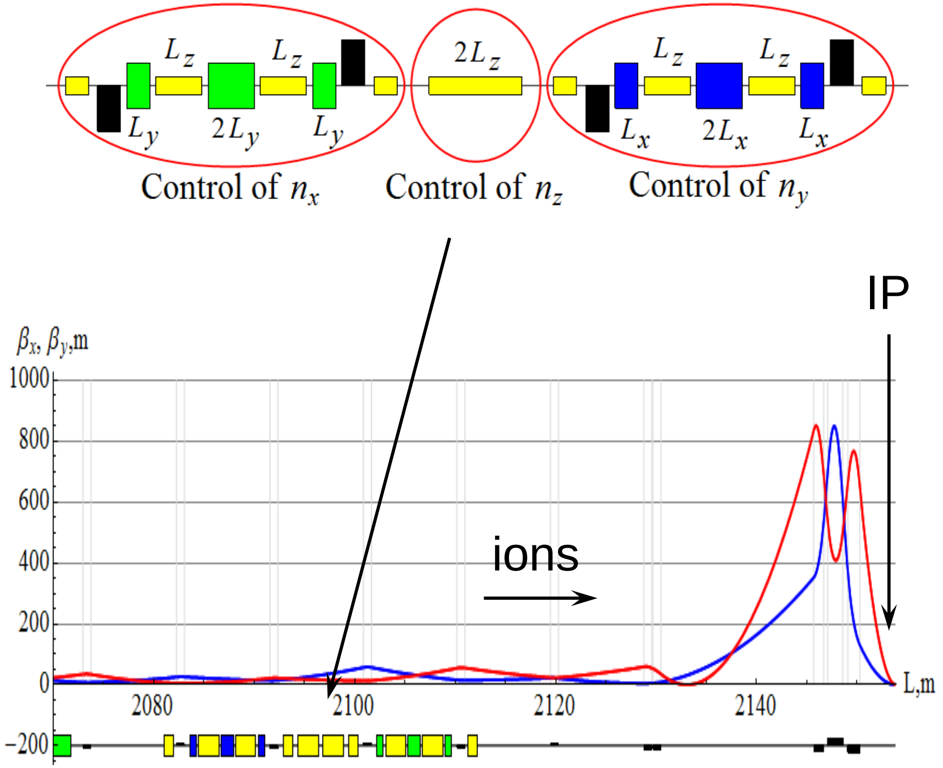
- Module for control of longitudinal component



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

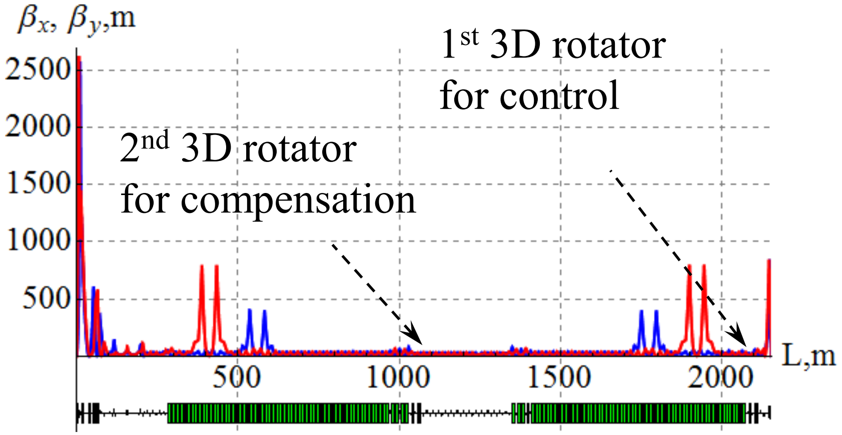
- Can be placed anywhere and has no effect on optics

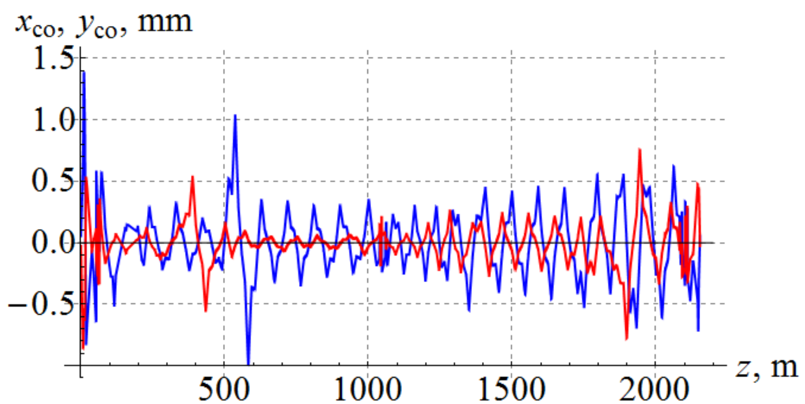
3D spin rotator



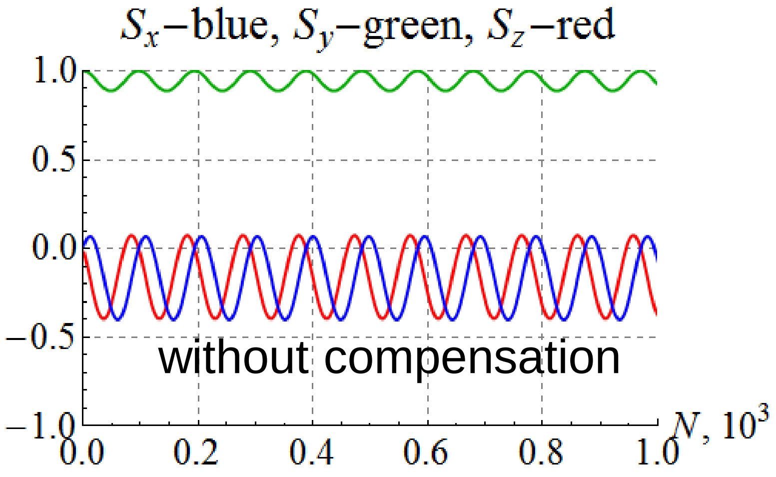
Polarization Control in Ion Collider Ring

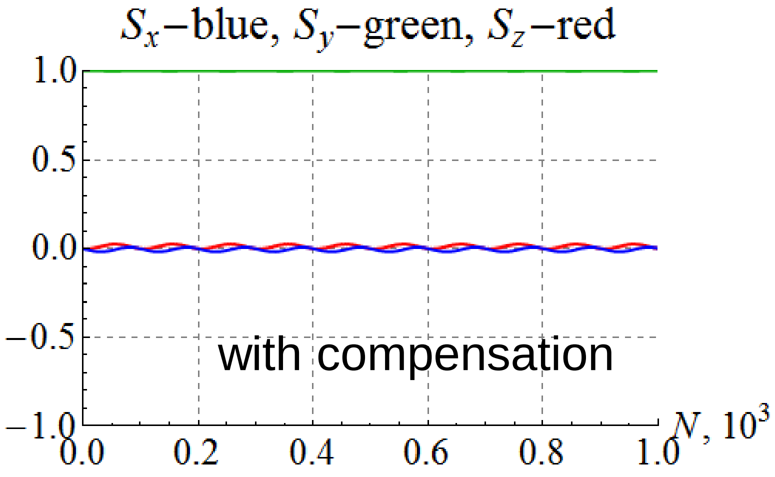
- 100 GeV/c figure-8 ion collider ring with transverse quadrupole misalignments





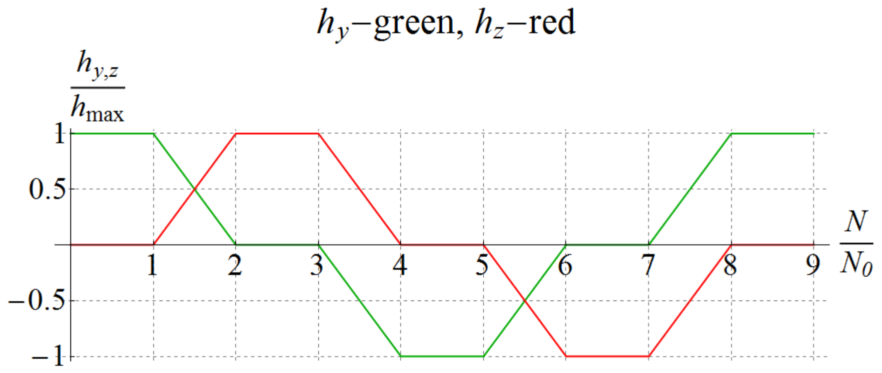
- Example of vertical proton polarization at IP. The 1st 3D rotator: $\nu = 10^{-2}$, n_y=1. The 2nd 3D rotator is used for compensation of coherent part of the zero-integer spin resonance strength

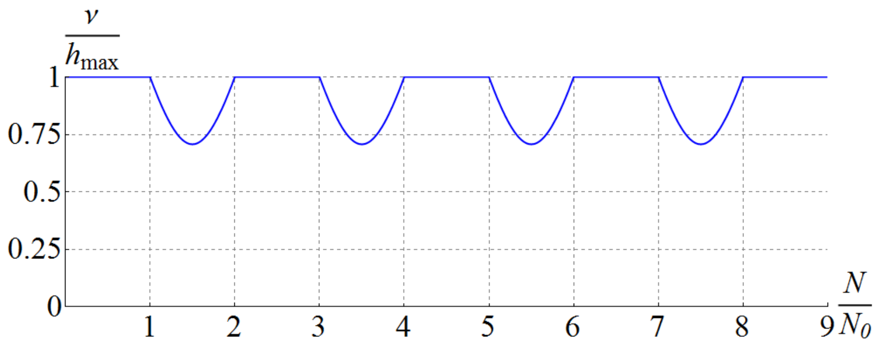




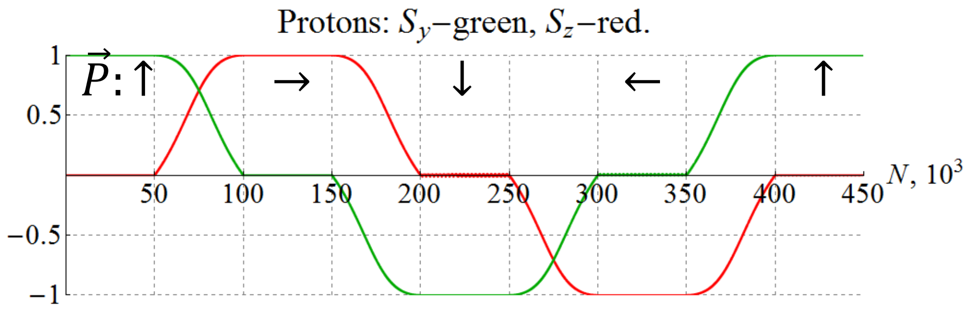
Spin Flipping

- Adiabaticity criterion: spin reversal time must be much longer than spin precession period ⇒ τ_{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 ⇒ 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

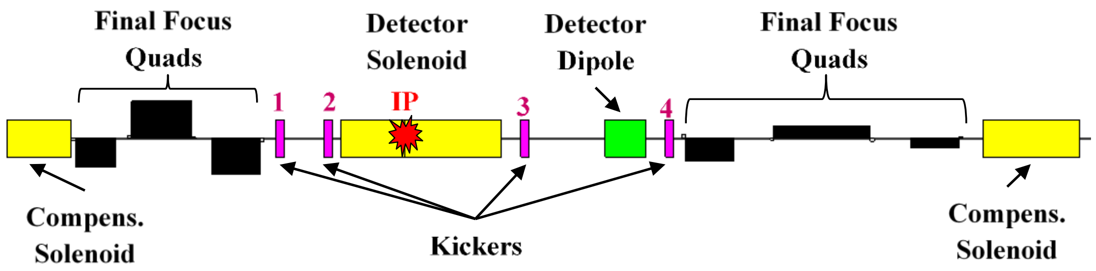


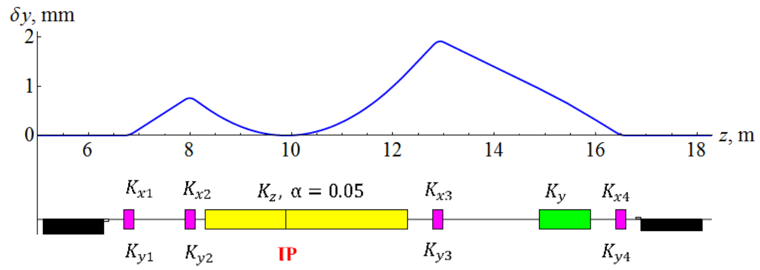
Zgoubi simulation

$N_0 = 50 \cdot 10^3$

Spin Effect of Detector Solenoid

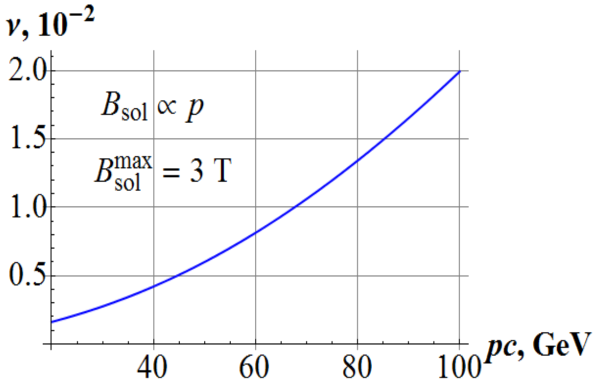
- Solenoid compensation scheme



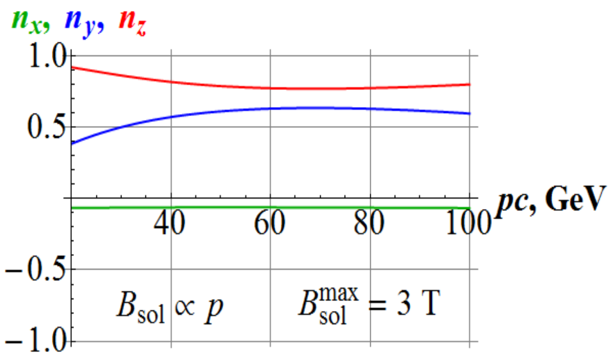


- Solenoid effect on the spin tune and stable polarization components

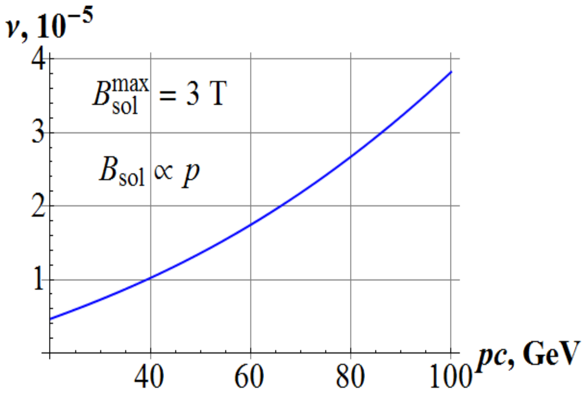
Protons



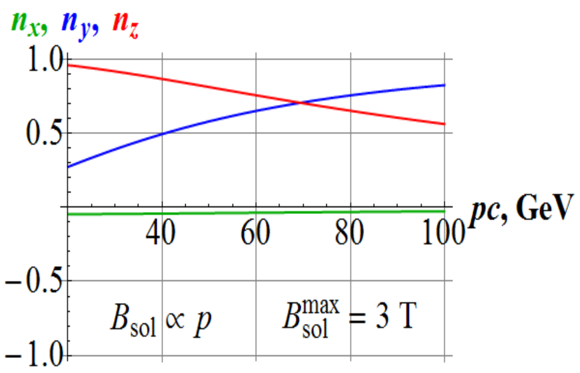
Protons



Deuterons



Deuterons



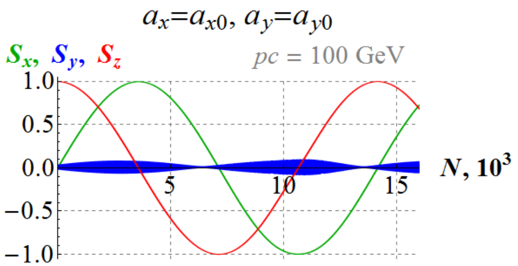
- Additional spin rotator is needed for compensation of detector solenoid

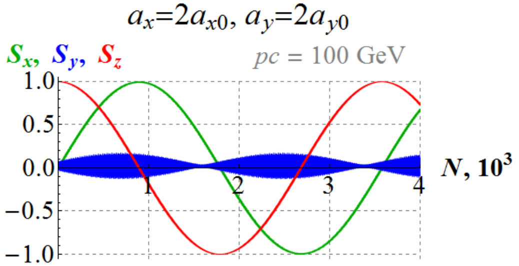
Spin Effect of Betatron Coupling

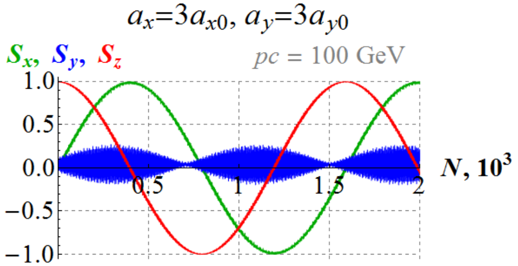
- Without coupling, the incoherent part of zero-integer spin resonance strength is
  - vertical
  - determined by the vertical emittance
- In the presence of coupling, the incoherent part
  - has horizontal component
  - depends on both horizontal and vertical emittances
    - makes little difference for round beams
    - for flat beams, the incoherent part may increase by up to emittance ratio and may require larger spin tune for stabilization

Spin Effect of Betatron Coupling

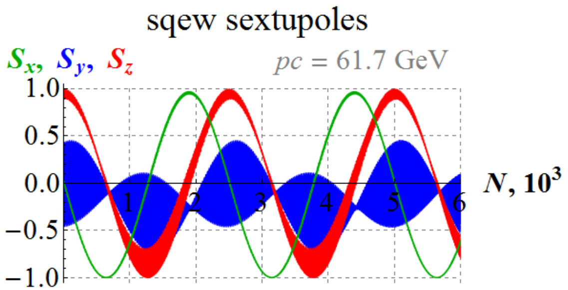
- Nonlinearity of orbital motion
  - Described by the incoherent part of the zero-integer spin resonance
  - Proportional to the vertical emittance

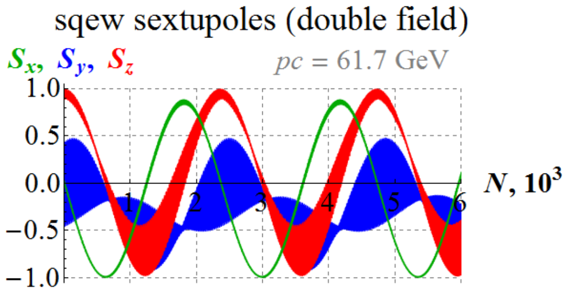






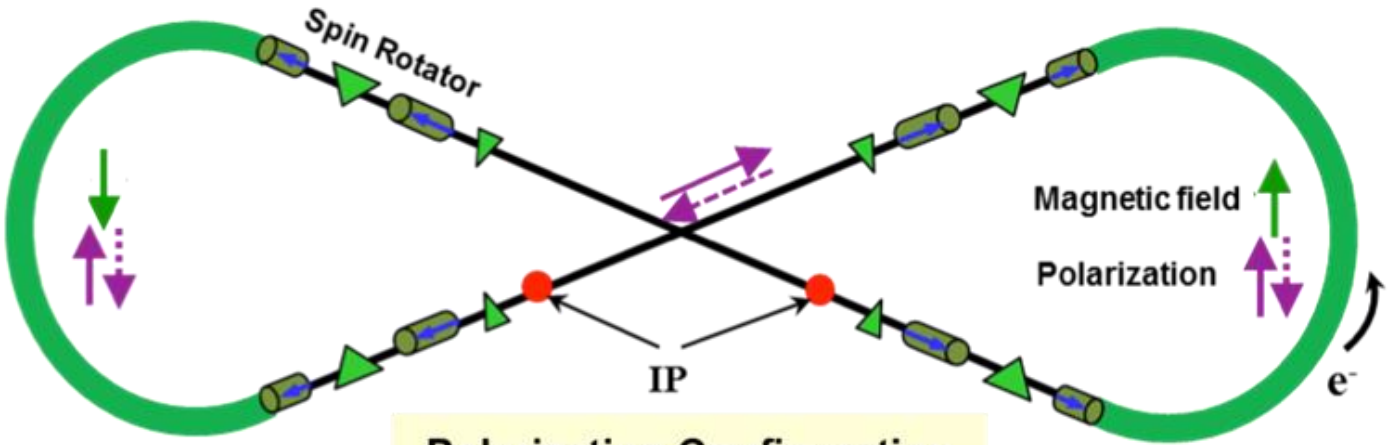
- Nonlinear magnetic fields
  - Straight sextupoles and octupoles do not contribute to spin resonances
  - Contribution to the incoherent part comes from skew sextupoles



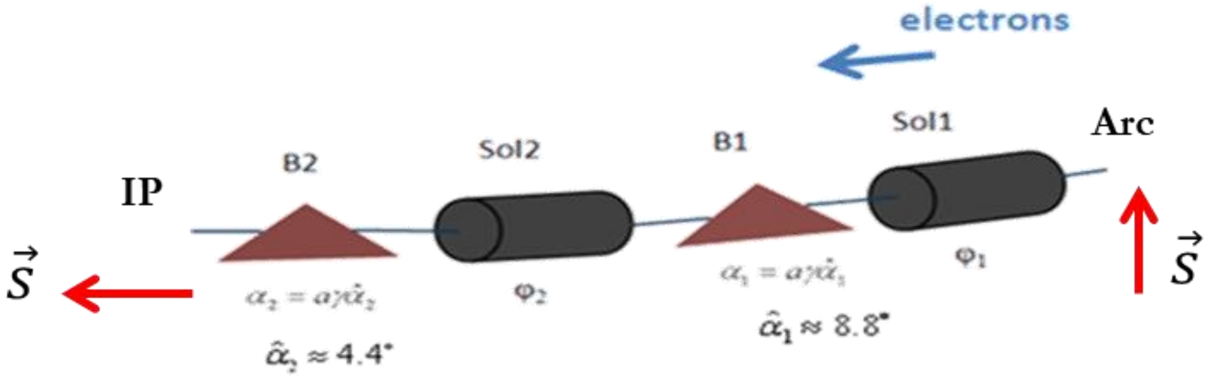


Electron Polarization

- Two highly polarized bunch trains maintained by top-off
- Universal spin rotator
  - Minimizes spin diffusion by switching polarization between vertical in arcs and longitudinal in straights
  - Two polarization states with equal lifetimes
  - Basic spin match

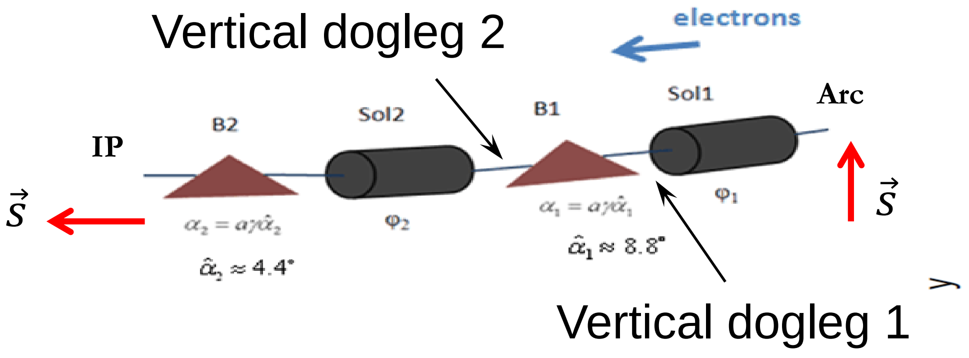


Polarization Configuration

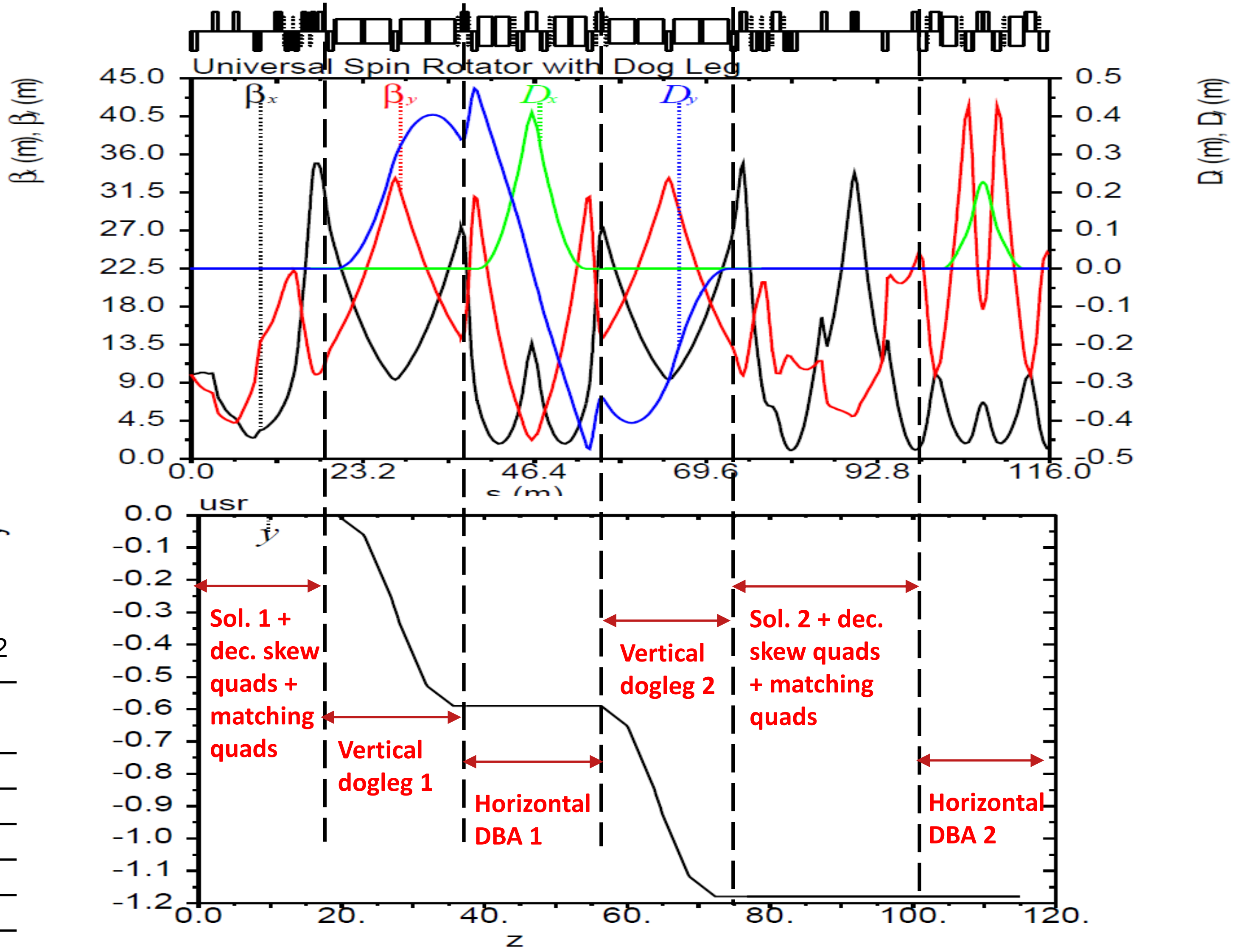


Electron Spin Rotators with Doglegs

- Universal spin rotator
  - Sequence of solenoid and dipole sections
  - Geometry independent of energy

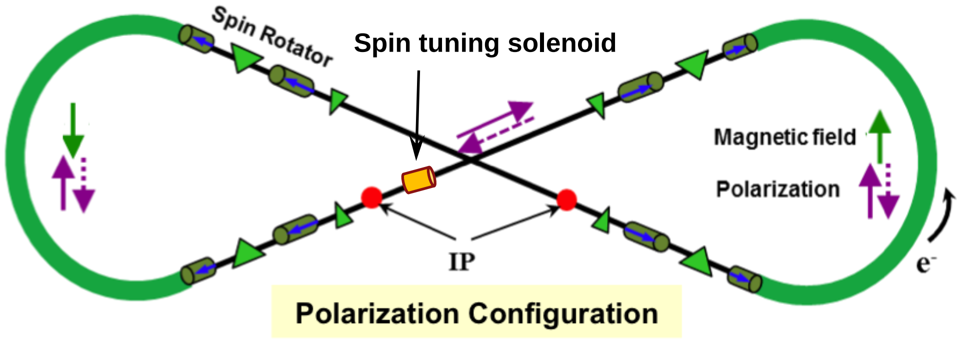


E	Solenoid 1		Dipole set 1	Solenoid 2		Dipole set 2
	Spin Rotation	BDL	Spin Rotation	Spin Rotation	BDL	Spin Rotation
GeV	rad	T·m	rad	rad	T·m	rad
3	π/2	15.7	π/3	0	0	π/6
4.5	π/4	11.8	π/2	π/2	23.6	π/4
6	0.62	12.3	2π/3	1.91	38.2	π/3
9	π/6	15.7	π	2π/3	62.8	π/2
12	0.62	24.6	4π/3	1.91	76.4	2π/3

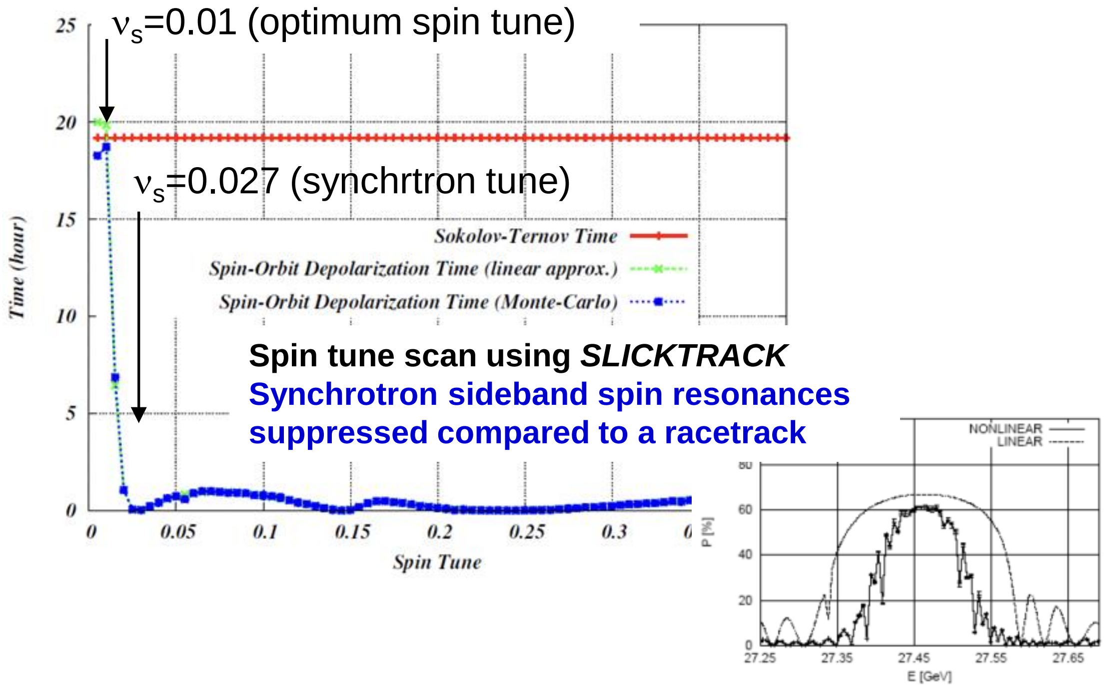


Spin Tracking

- 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

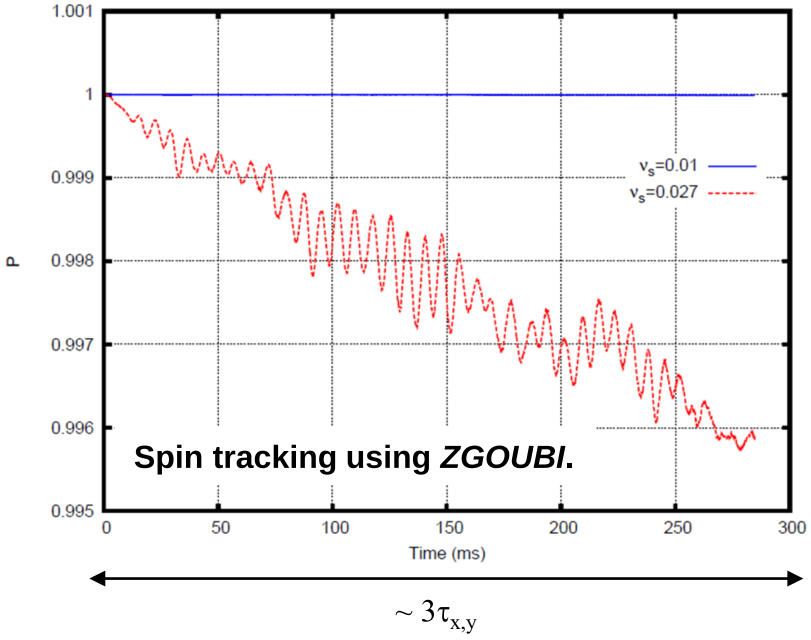


Polarization Configuration


ν_s=0.01 (optimum spin tune)

ν_s=0.027 (synchrtron tune)

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


Spin tracking using *ZGOUBI*.

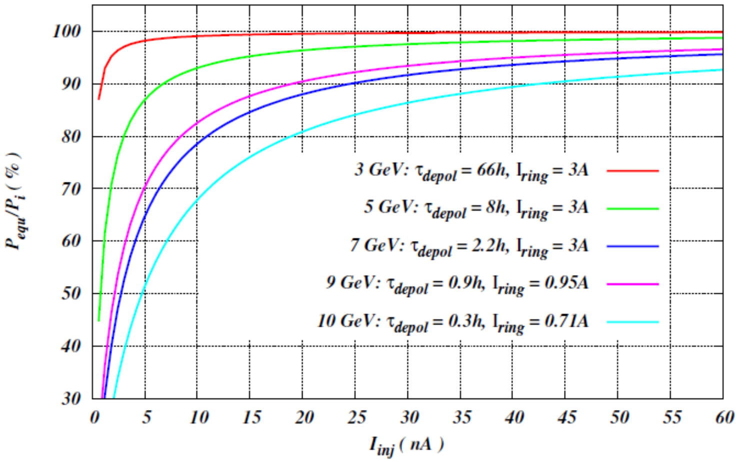
$\sim 3\tau_{x,y}$

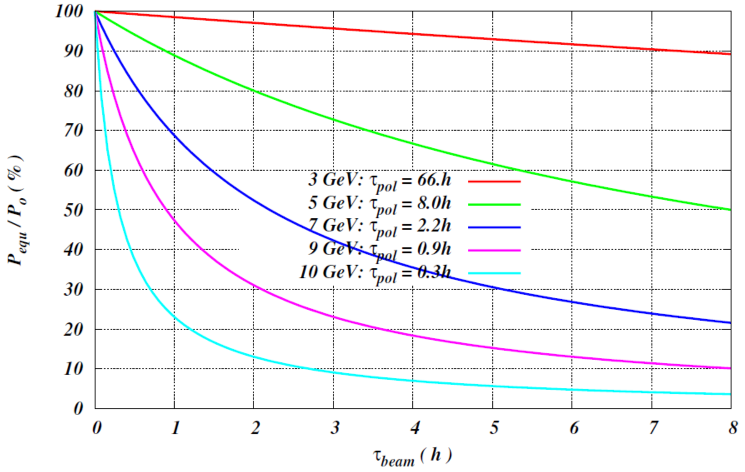
Polarization Lifetime and Continuous Injection

- 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 $\tau_{beam} \ll \tau_{pol}$





Summary

- JLEIC rings adopt the figure-8 shape for better preservation and control of polarization by taking advantage of the spin transparency mode.
- Ion and electron polarization preservation and control schemes have been designed.
- Acceleration and polarization control schemes have been validated numerically.
- Both ion and electron polarizations > 80% can be reached.
- We demonstrated that the following effects do not cause polarization loss
    - Transition energy crossing
    - Detector solenoid
    - Betatron coupling
    - Higher-order resonances
- Spin transparency mode will be tested experimentally in RHIC