Polarization Preservation and Control in a Figure-8 Ring

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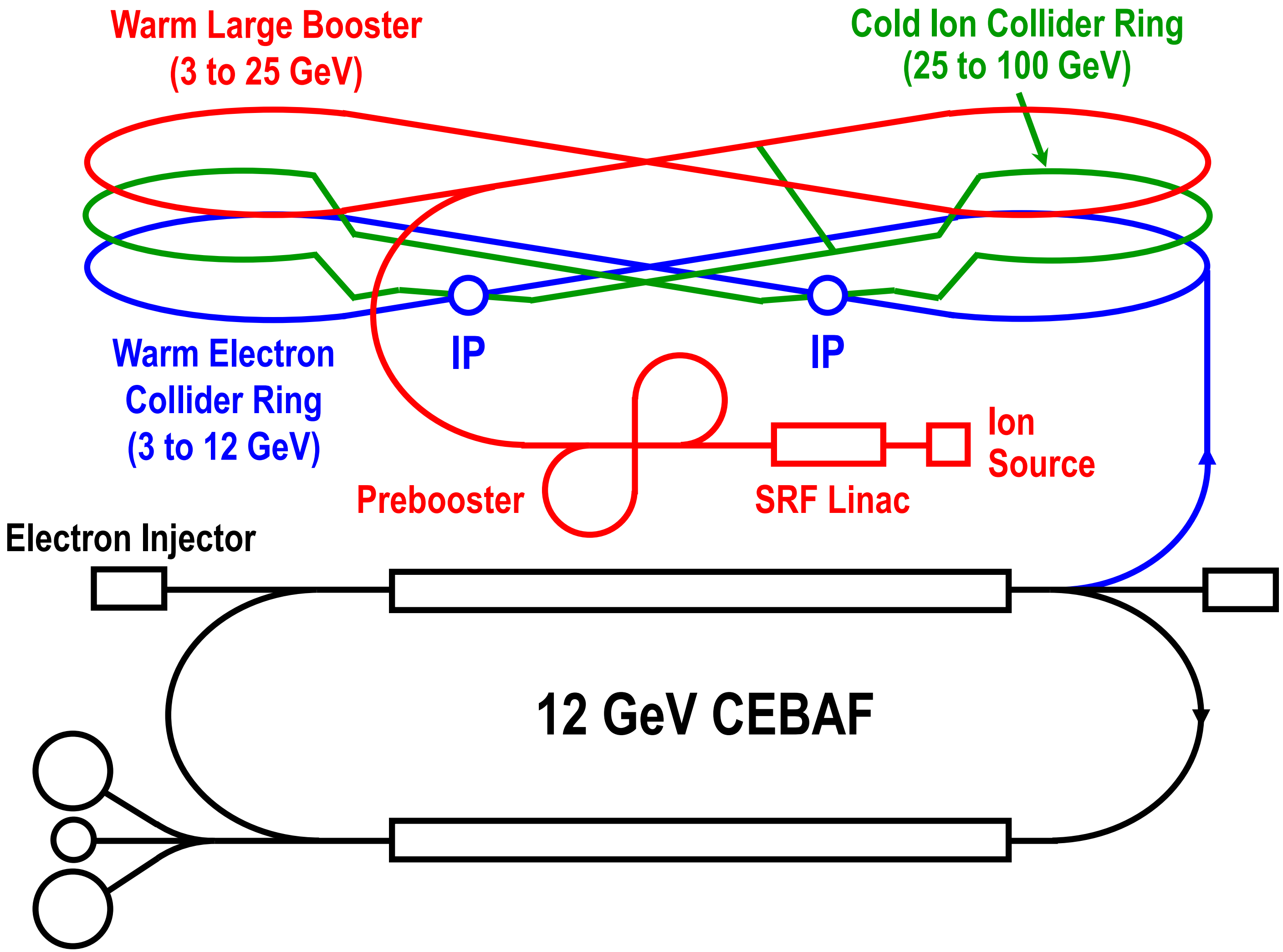
Outline

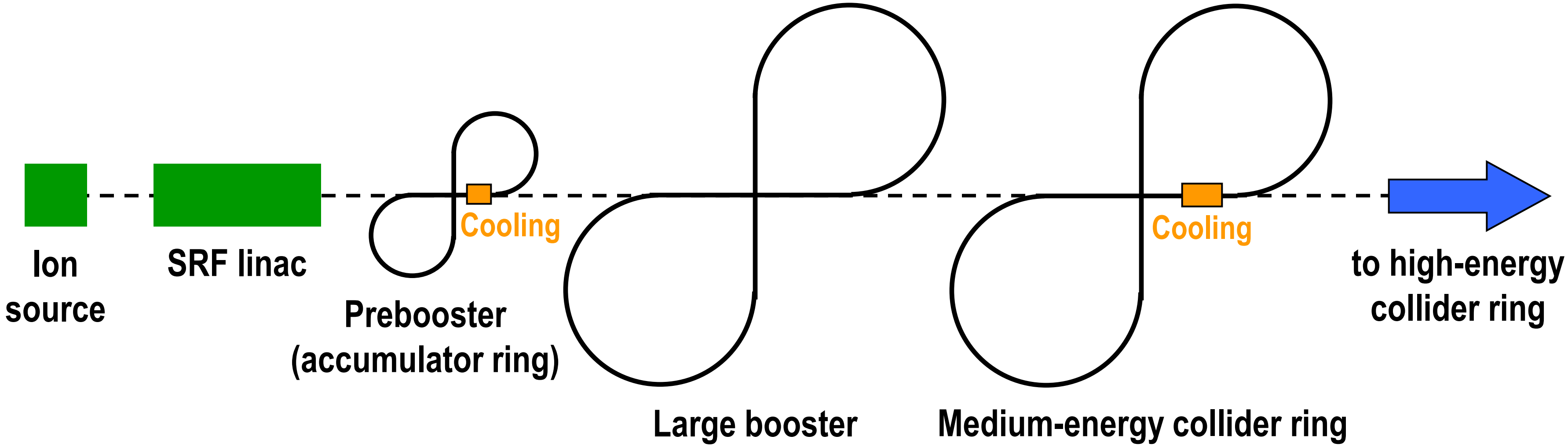
- Introduction
- Figure-8 versus circular accelerators with Siberian Snakes
- Polarization preservation during acceleration
- Polarization control in a storage or collider ring
- Compensation of zero-integer spin resonance strength
- Initial spin tracking results
- Conclusions

Medium-energy Electron Ion Collider (MEIC)



Ion Polarization Requirements

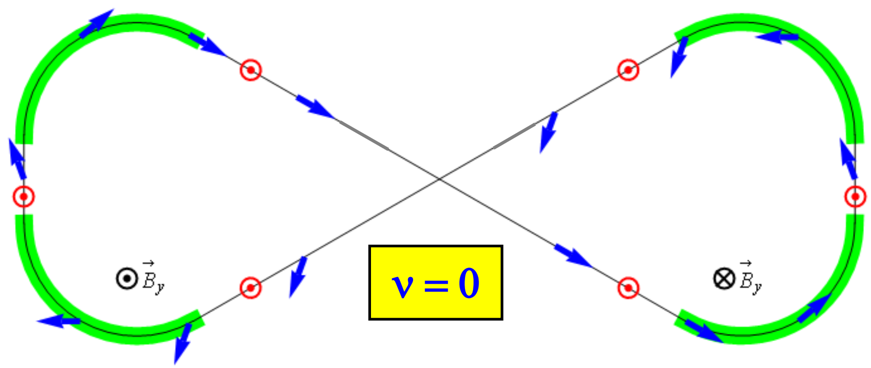
- Major MEIC ion complex components



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

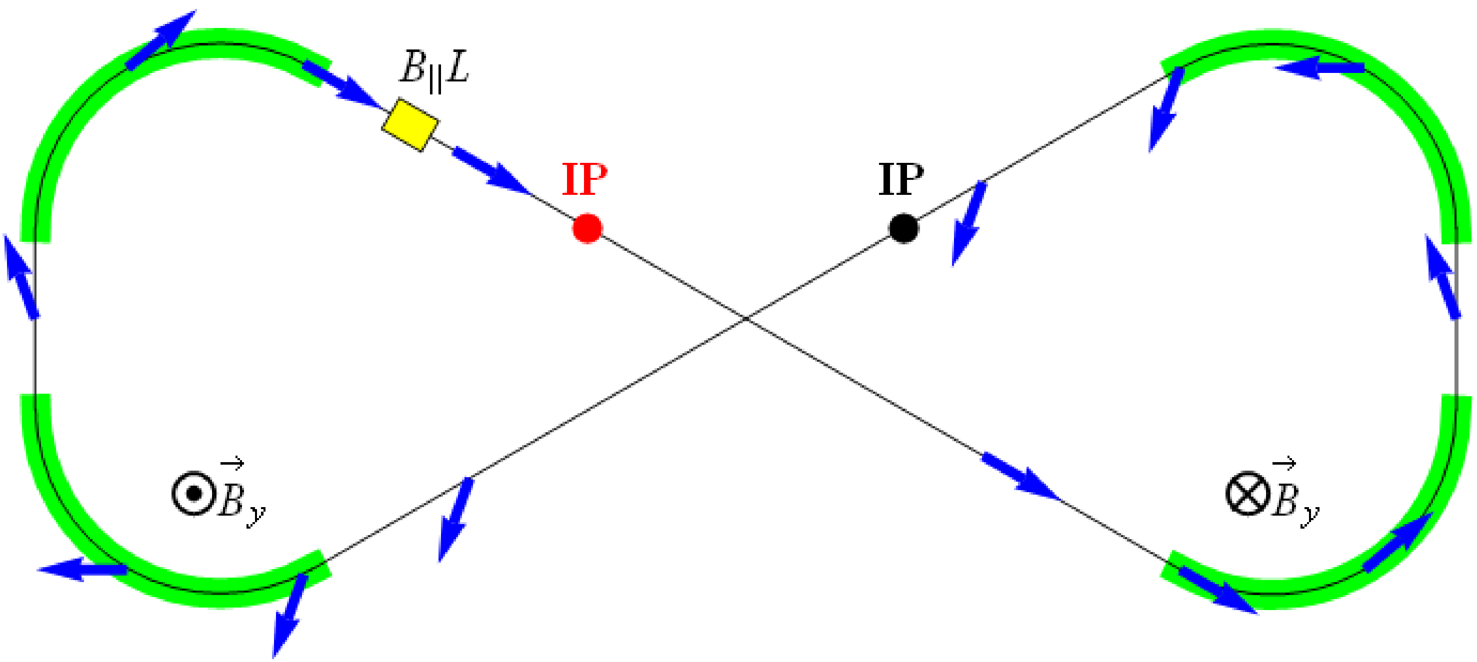
Spin Motion in a Figure-8 Ring

- Properties of a figure-8 structure
  - Spin precessions in the two arcs are exactly cancelled
  - In an ideal structure (without perturbations) all solutions are periodic
  - The spin tune is zero independent of energy
- A figure-8 ring provides unique capabilities for polarization control
  - It allows for stabilization and control of the polarization by small field integrals
  - Spin rotators are compact, easily rampable and have little or no orbit distortion
  - It eliminates depolarization problem during acceleration
    - Spin tune remains constant for all ion species avoiding spin resonance crossing
  - It provides efficient polarization control of any particles including deuterons
  - It is currently the only practical way to accommodate polarized deuterons
  - Electron quantum depolarization is reduced due to energy independent spin tune
  - It makes possible ultra-high precision experiments with polarized beams



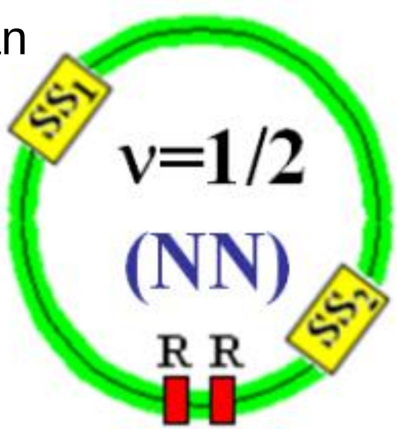
Polarization Control Concept

- Local spin rotator determines spin tune and local spin direction
- Polarization is stable if $\nu \gg w_0$
  - w_0 is the zero-integer spin resonance strength
  - $B_{||}L$ of only 3 Tm provides deuteron polarization stability up to 100 GeV
  - A conventional ring at 100 GeV would require $B_{||}L$ of 1200 Tm or $B_{\perp}L$ of 400 Tm



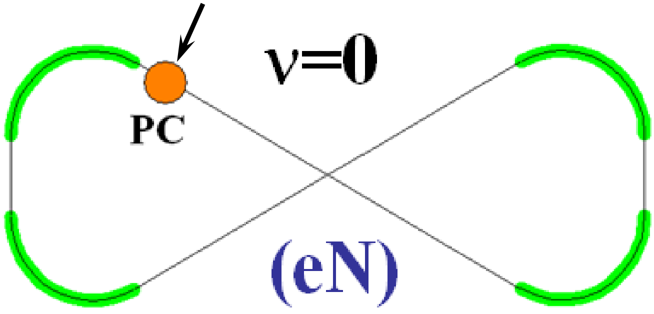
Circular Ring versus Figure-8

Siberian Snake (SS)



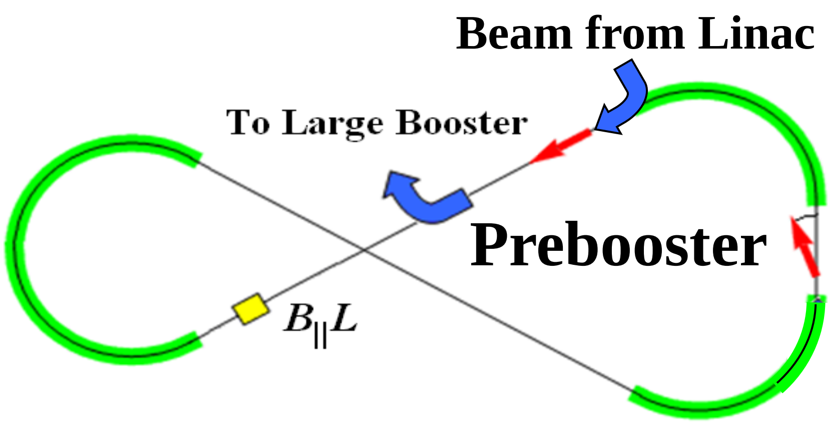
Spin Rotators (R)

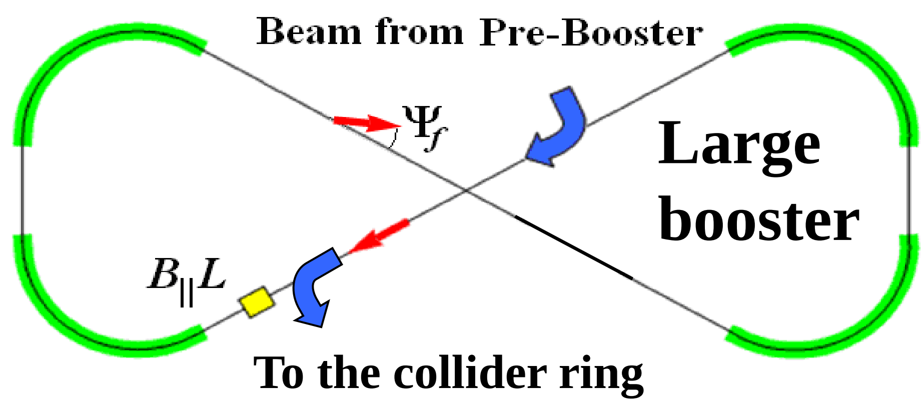
Weak-field Polarization Control (PC)



- Circular ring with Siberian Snakes
  - Adequate at high energies
  - Single stable polarization direction
  - Polarization control by strong-field spin rotators (R)
  - Orbital dynamics may be affected by polarization control
- Figure-8 ring
  - Adequate at low to medium energies
  - Any polarization direction is allowed
  - Polarization control by weak-field solenoids (PC)
  - Orbital dynamics is not affected

Acceleration and Spin Matching



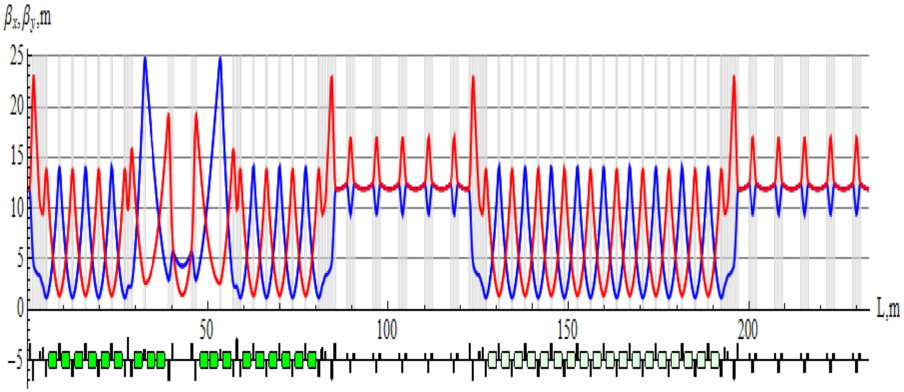


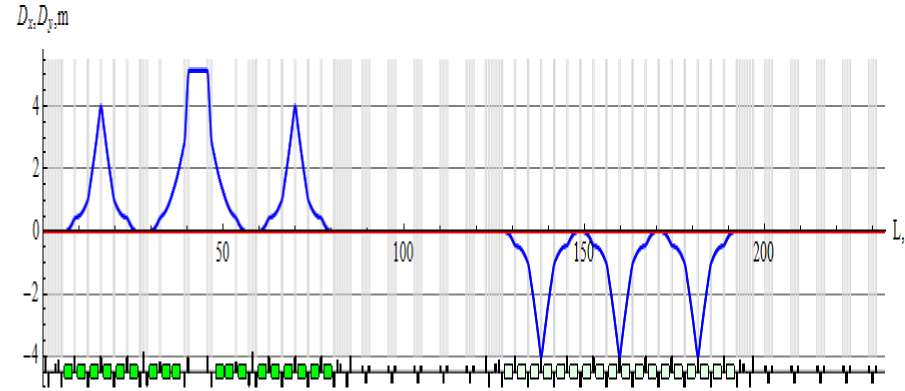
	p_{inj} / p_{ext} (GeV/c)	$(B_{sol}L_{sol})_{inj} / (B_{sol}L_{sol})_{ext}$ $(\mathrm{T \cdot m})$	L_{sol} (cm)	ν_{deut} / ν_{prot}
Pre-booster (1 solenoid)	0.785 / 3.83	0.06 / 0.28	60	0.003 / 0.01
Large booster (1 solenoid)	3.83 / 25	0.28 / 1.9	120	0.003 / 0.01

Conventional 20 GeV accelerators require $B_{||}L$ of ~70 Tm for protons and
~250 Tm for deuterons

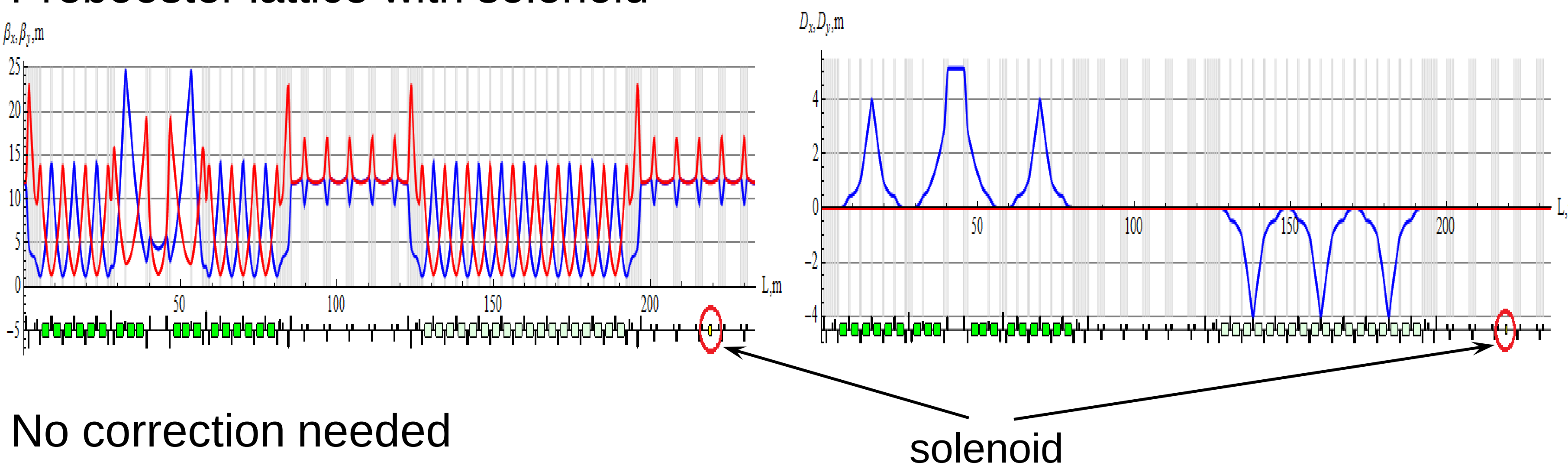
Solenoid Matching in Prebooster

- Prebooster lattice without solenoid





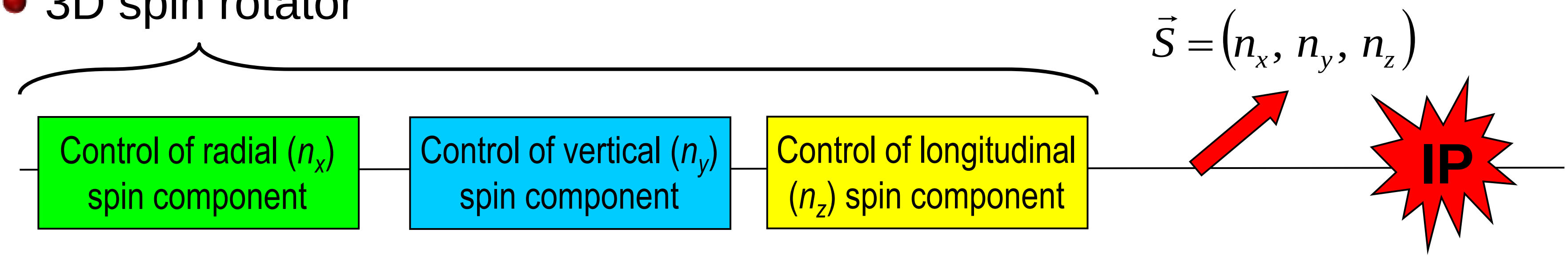
- Prebooster lattice with solenoid



- No correction needed

Polarization Control with 3D Spin Rotator

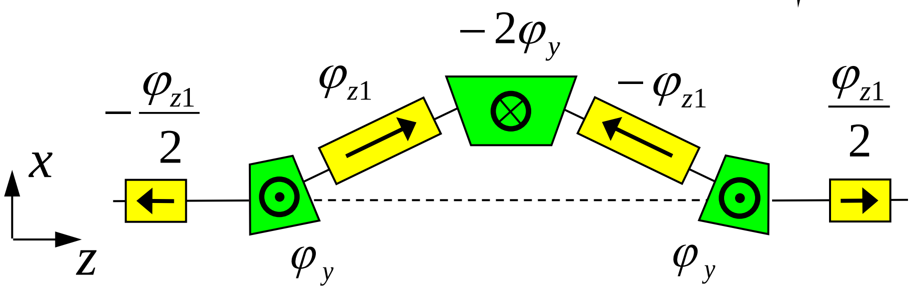
- 3D spin rotator



- n_x control module (constant radial orbit bump)

$$\varphi_{z1} = \pi\nu \frac{n_x}{\sin\varphi_y}$$

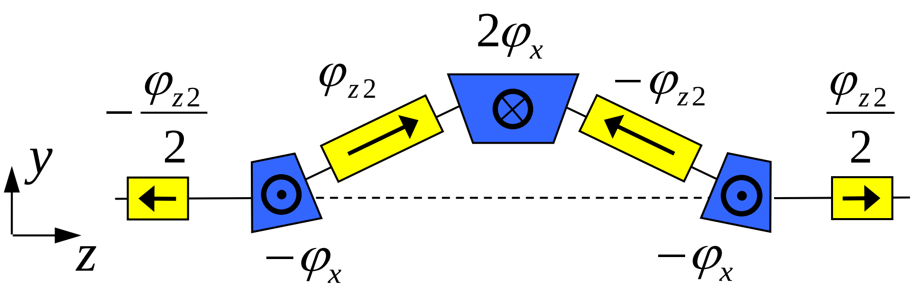
$$\alpha_y = 0.58^\circ \quad L \approx 5\text{m} \quad \Delta x \approx 1.8\text{ cm}$$



- n_y control module (constant vertical orbit bump)

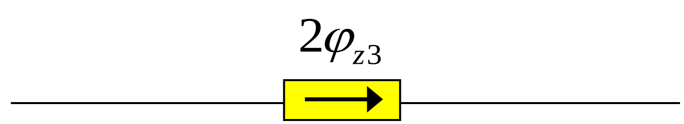
$$\varphi_{z2} = \pi\nu \frac{n_y}{\sin\varphi_x}$$

$$\alpha_x = 0.58^\circ \quad L \approx 5\text{m} \quad \Delta y \approx 1.8\text{ cm}$$



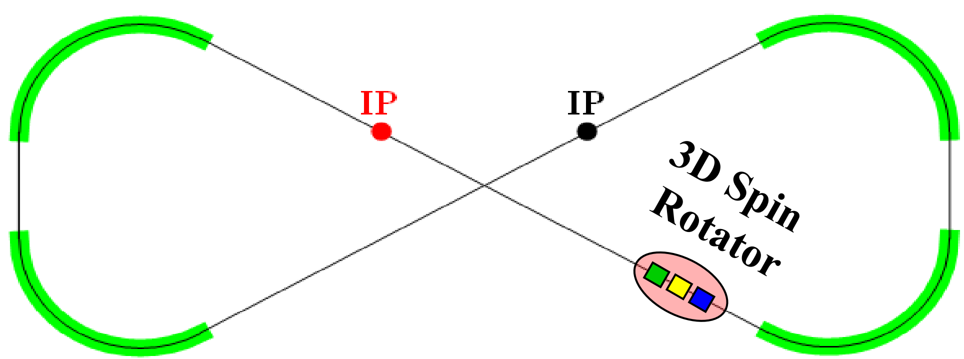
- n_z control module

$$\varphi_{z3} = \pi\nu\, n_z$$

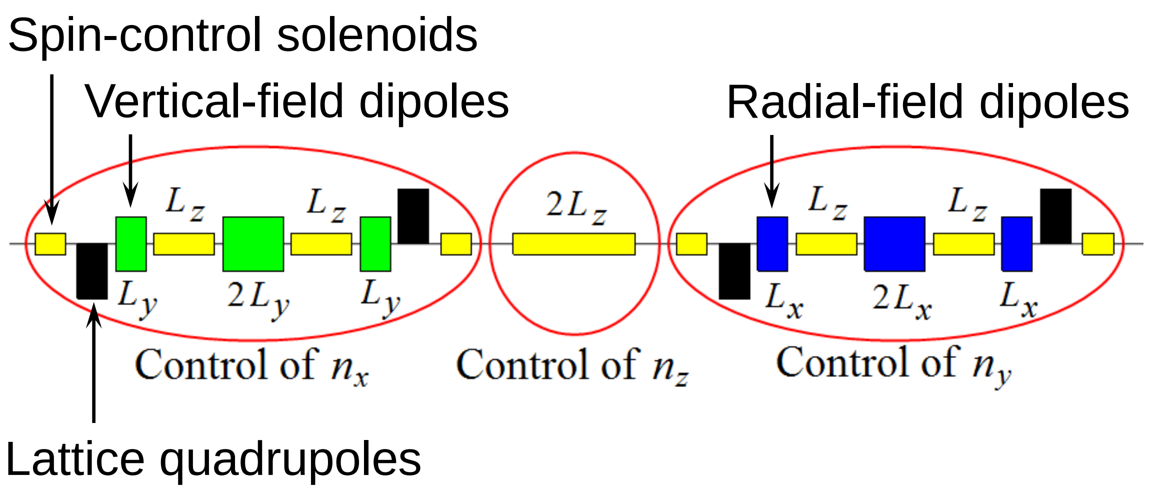


Polarization Control in the Collider Ring

- Placement of the 3D spin rotator in the collider ring



- Integration of the 3D spin rotator into the collider ring's lattice
  - Seamless integration into virtually any lattice



$$\alpha_x = \alpha_y = 0.58^\circ$$

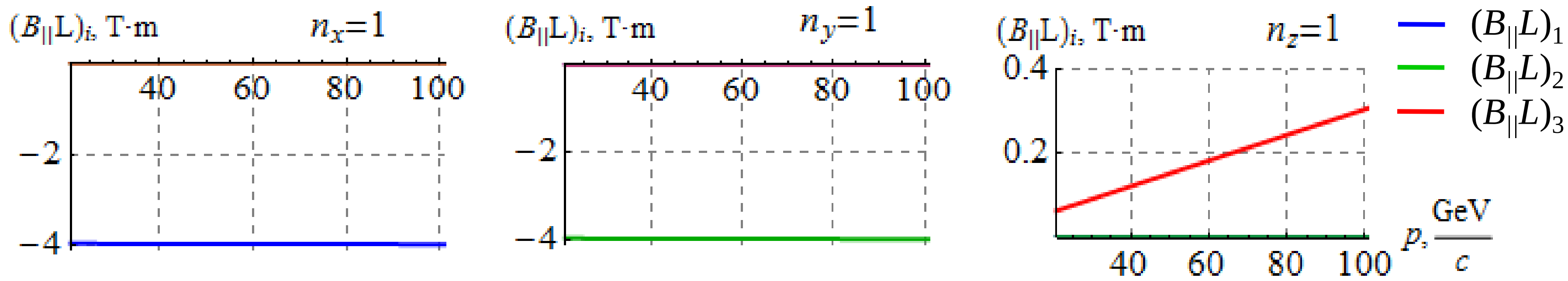
$$L_x = L_y = 0.5\,\text{m}$$

$$L_z = 1\,\text{m}$$

Solenoid Strengths

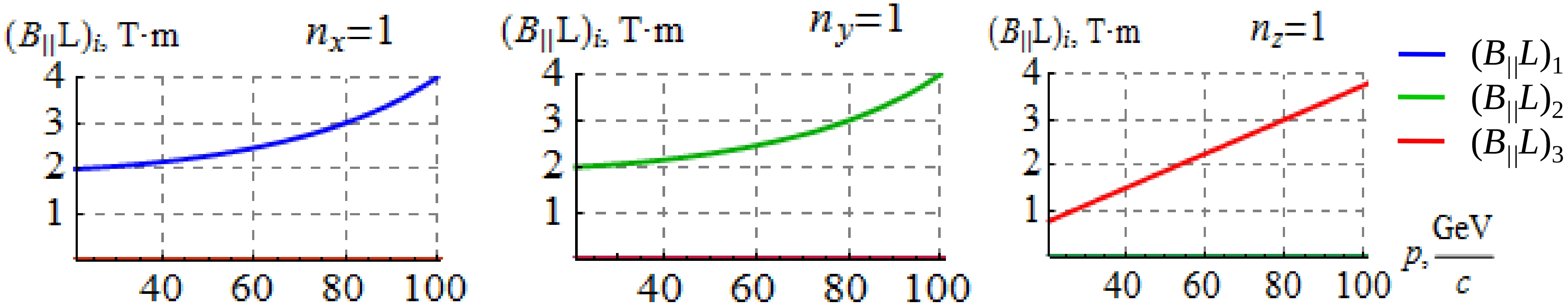
- Momentum dependence of $(B_{\parallel}L)_i = \varphi_{zi}\, B\rho/(1+G)$ for deuterons, ν = 2.5·10^-4

Radial | Vertical | Longitudinal



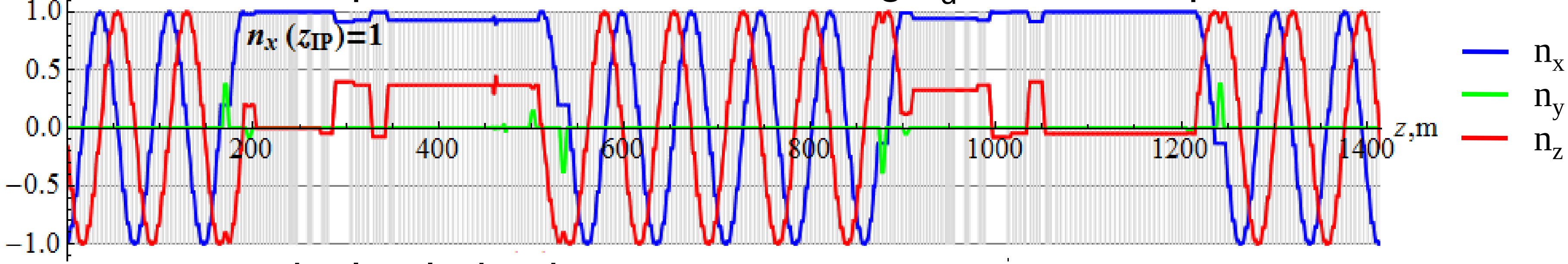
- Momentum dependence of the solenoid strengths for protons, ν = 0.01

Radial | Vertical | Longitudinal

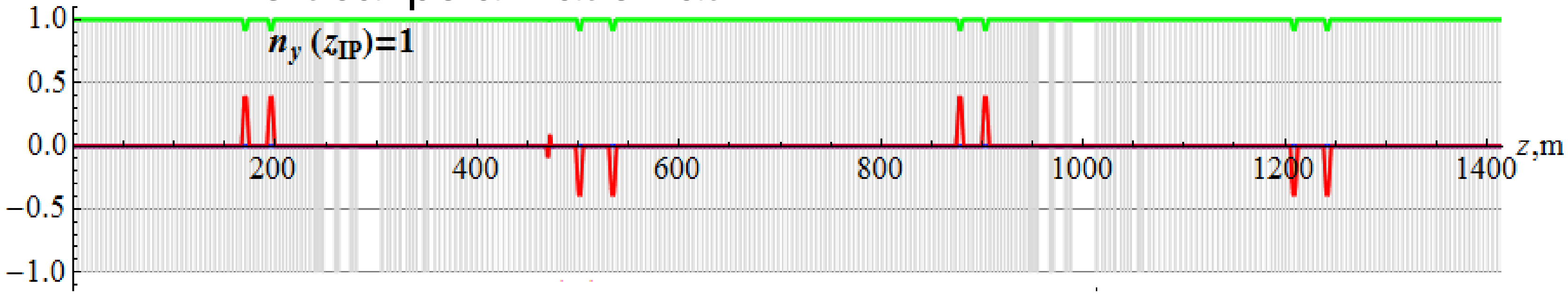


Deuteron Polarization Behavior

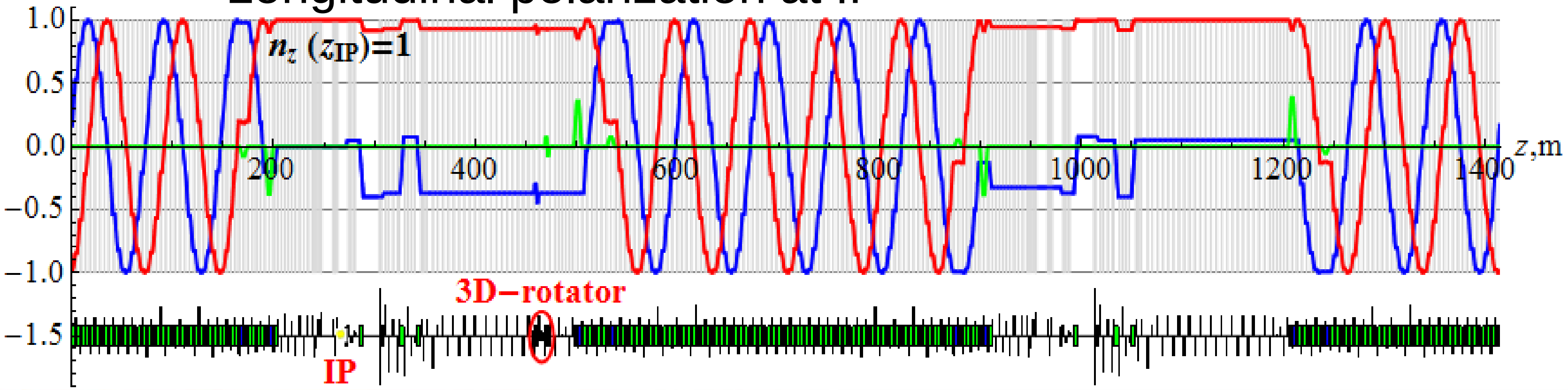
- Radial polarization at IP assuming $\nu_d = 2.5\cdot10^{-4}$, p = 100 GeV/c



- Vertical polarization at IP

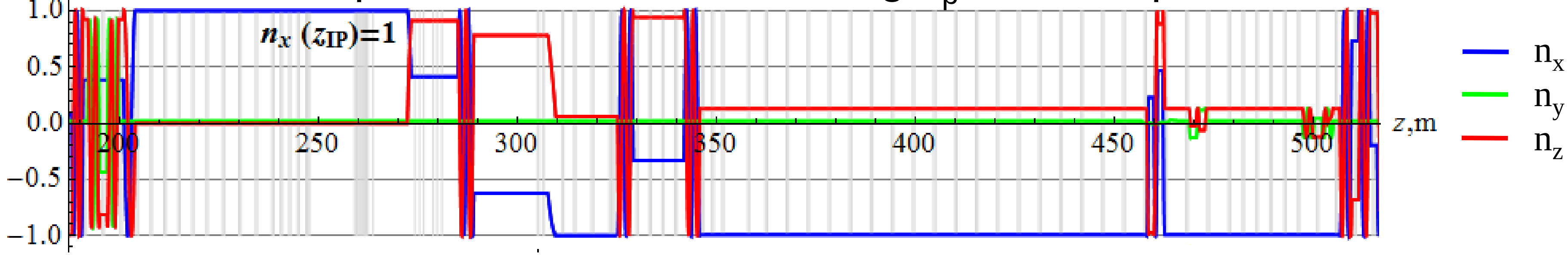


- Longitudinal polarization at IP

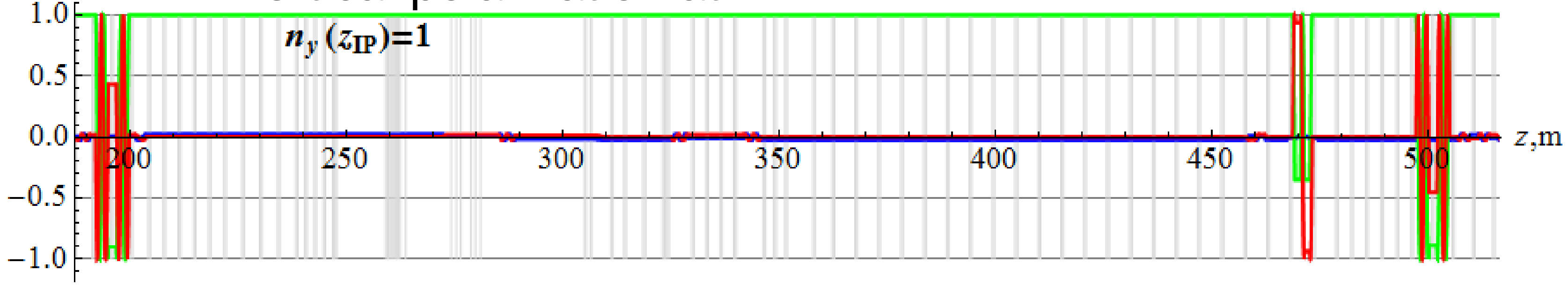


Proton Polarization Behavior

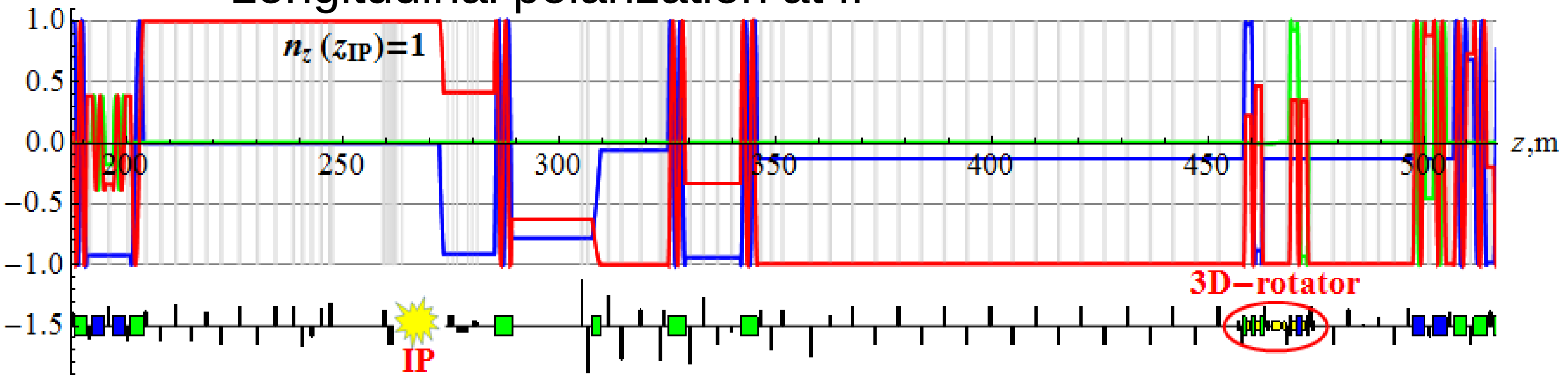
- Radial polarization at IP assuming $\nu_p = 1\cdot10^{-2}$, p = 100 GeV/c



- Vertical polarization at IP



- Longitudinal polarization at IP



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Zero-Integer Spin Resonance Strength

- The total zero-integer spin resonance strength

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

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

- The coherent part

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

  where $F(\theta)$ is the spin response function, arises due to radial fields from
  - dipole roll $\alpha_k = \alpha_{\text{orb}} \Delta\alpha$
  - vertical quadrupole misalignments $\alpha_k = \frac{\partial B_y}{\partial x} \frac{L}{B\rho} \Delta y$

- $\Delta\alpha_{\text{rms}} = 0.1\,\text{mrad},\ \Delta y_{\text{rms}} = 0.02\,\text{mm} \quad \Rightarrow \quad \left| w_0 \right|_p \sim 10^{-2}, \quad \left| w_0 \right|_d \sim 10^{-3}$

Compensation of Zero-Integer Resonance

- In linear approximation, the zero-integer spin resonance strength is determined by two components of spin perturbation lying in the ring's plane

  $$w_0 \approx w_{\text{coherent}} = w_x + i\, w_z$$

  and can be compensated by correcting devices whose spin rotation axis lies in the same plane

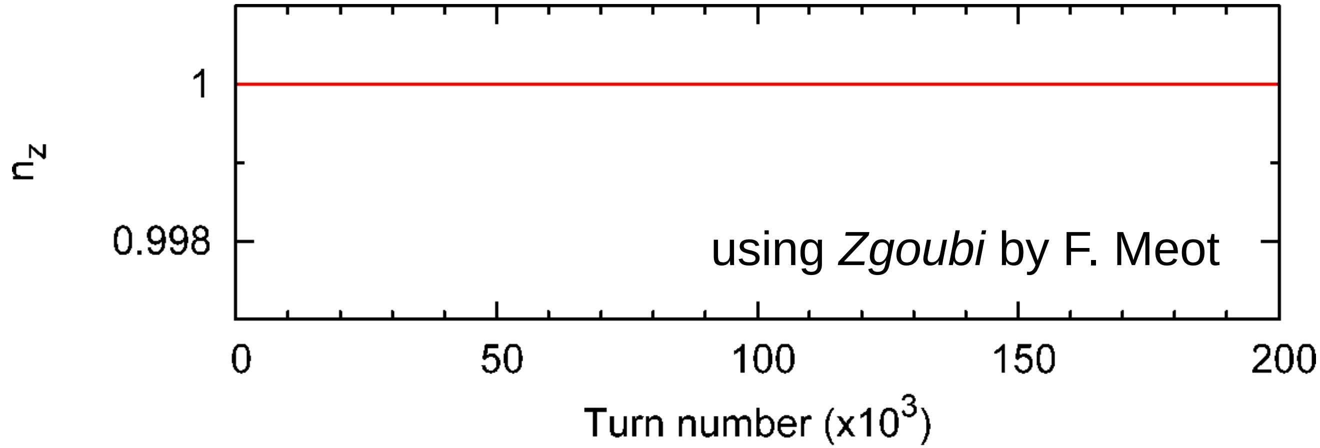
- Additional 3D spin rotators can be used to compensate the coherent part of the zero-integer spin resonance strength

- Spin resonance strength after compensation

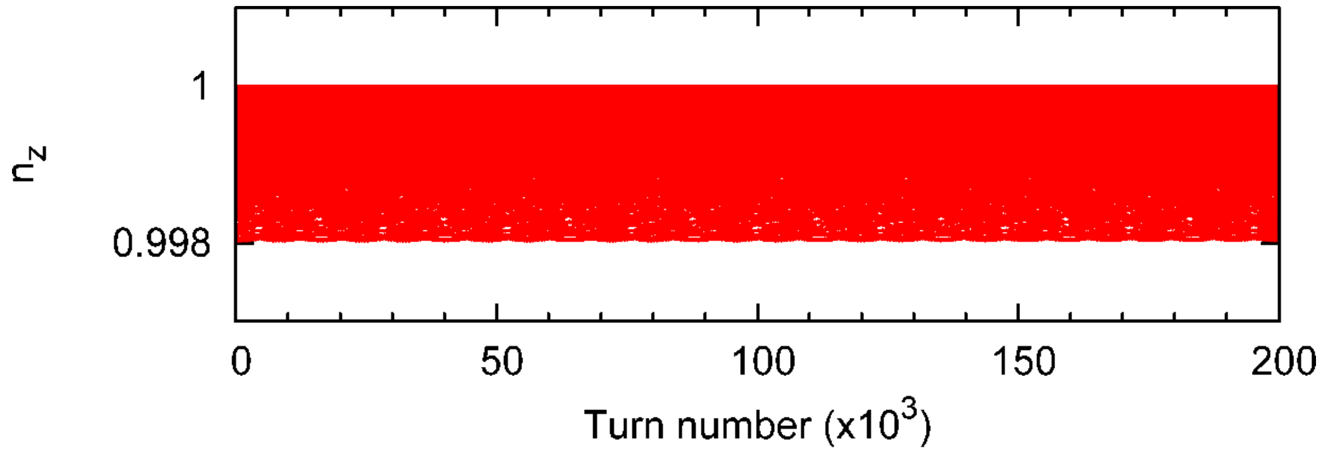
  $$w_0 \sim w_{\text{emittance}} \quad \Rightarrow \quad |w_0|_p < 10^{-3}, \quad |w_0|_d < 10^{-5}$$

Spin-Tracking Perfect Figure-8 Ring

- MEIC lattice, no errors, 60 GeV/c proton, initial spin n_z = 1, reference orbit

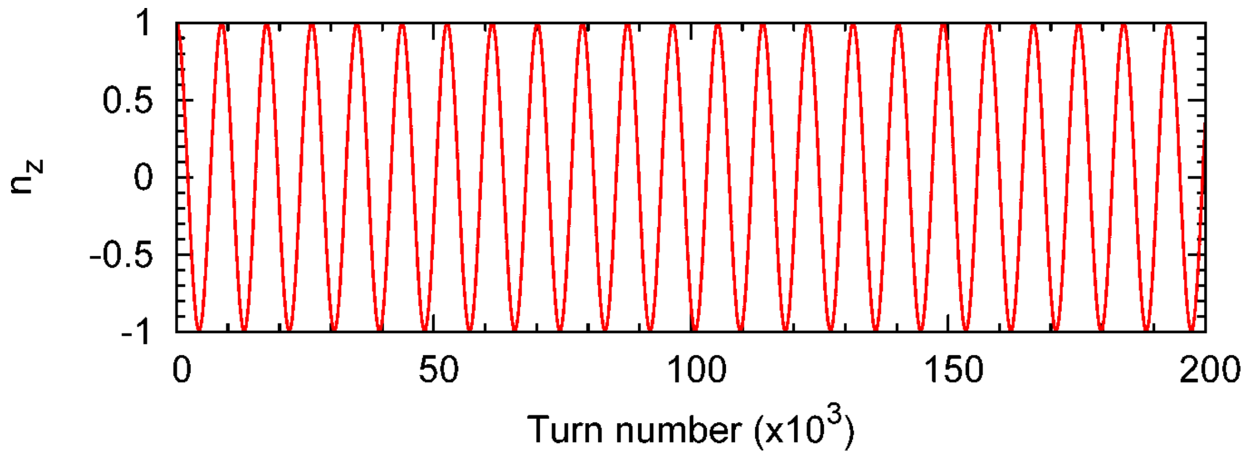


- Proton on one-sigma phase-space trajectories in both x and y

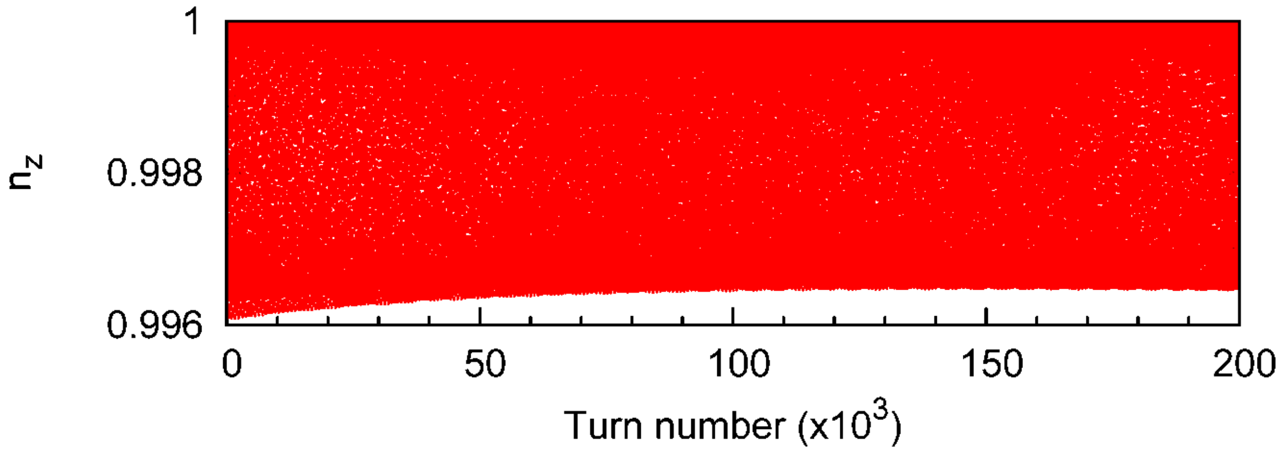


Error Effect and Correction

- One arc dipole rolled by 0.2 mrad, no closed orbit correction

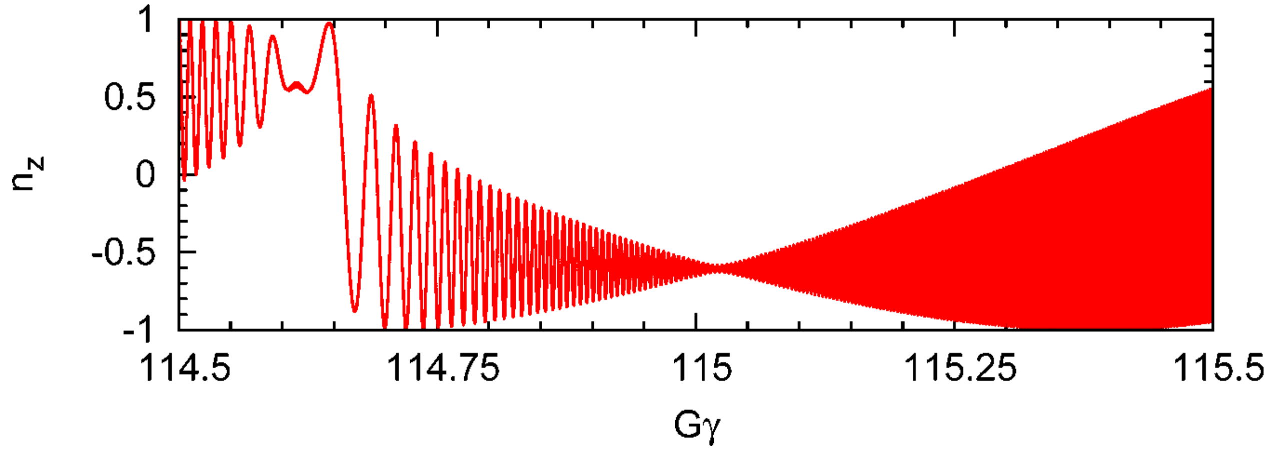


- After addition of a 1° spin rotator solenoid in the straight

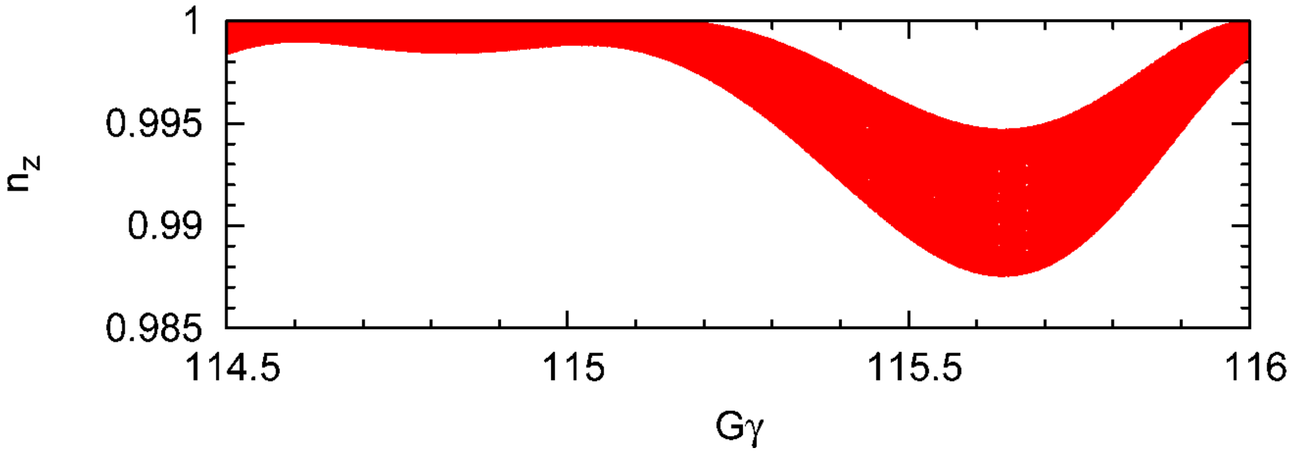


Acceleration

- With 0.2 mrad dipole roll, no orbit correction, no spin rotator, $200 \cdot 10^3$ turns



- After addition of a 5° spin rotator in the straight , $300 \cdot 10^3$ turns



Conclusions

- Schemes have been developed for MEIC based on the figure-8 design that
  - eliminate resonant depolarization problem during acceleration
  - allow polarization control by small fields without orbit perturbation
  - provide for seamless integration of the polarization control into the ring lattice
  - efficiently control the polarization of any particles including deuterons
  - allow adjustment of any polarization at any orbital location
  - allow spin manipulation during experiments
  - make possible ultra-high precision experiments with polarized beams
  - allow for straightforward adjustment of spin dynamics for any experimental needs
- Initial spin tracking results support the validity of the developed concepts