JLEIC Electron and Ion Polarization

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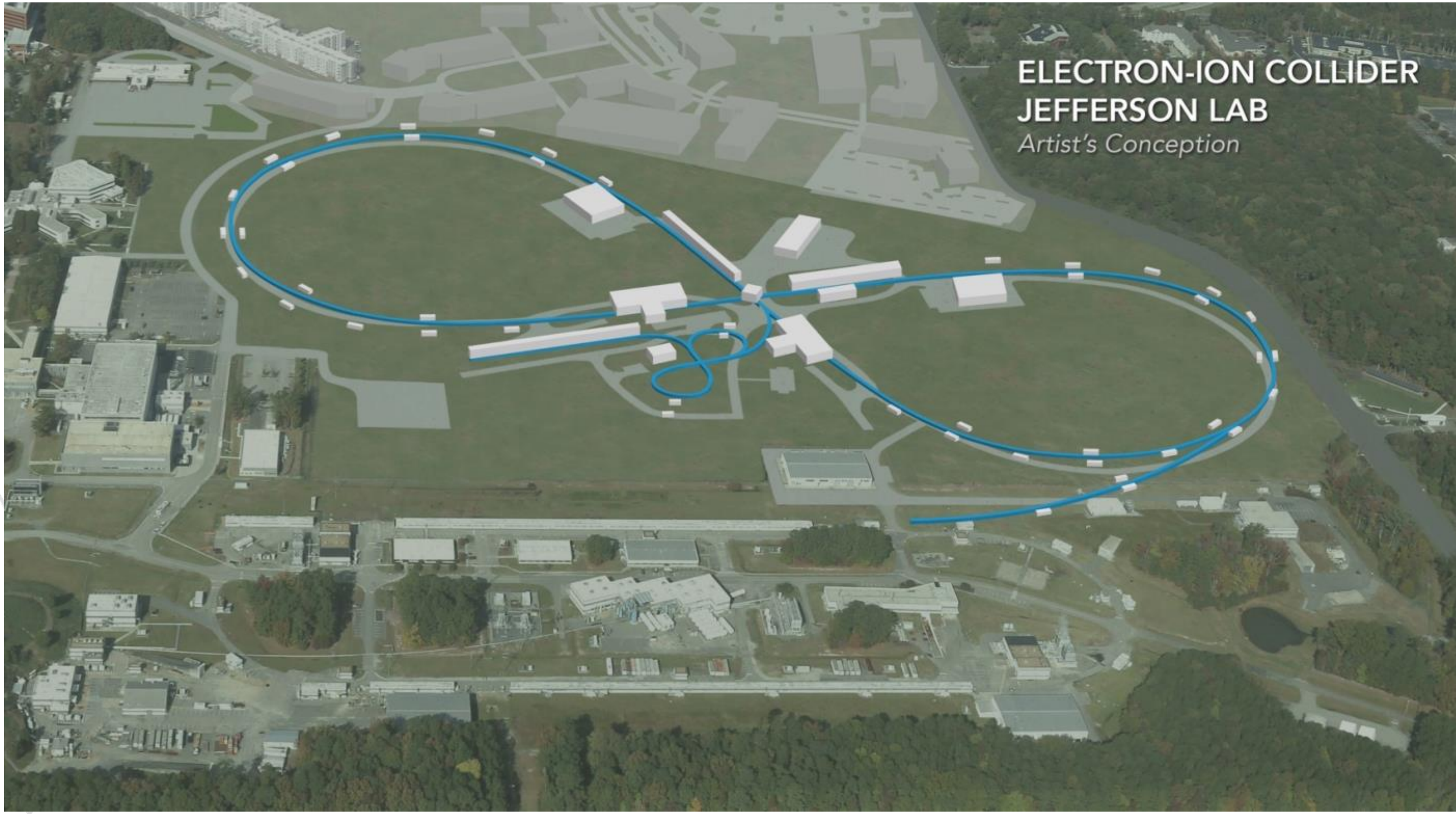
Jefferson Lab



Outline

- Introduction
- Overview of JLEIC
- JLEIC Figure-8 Ring Concept
- Proton/Light Ion Polarization
- Electron Polarization
- JLEIC with a Polarized Positron
- Spin Transparency Mode Test
- Summary

Acknowledgement

JLEIC Accelerator Collaboration, particularly

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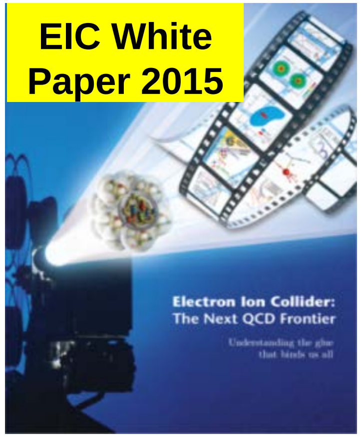
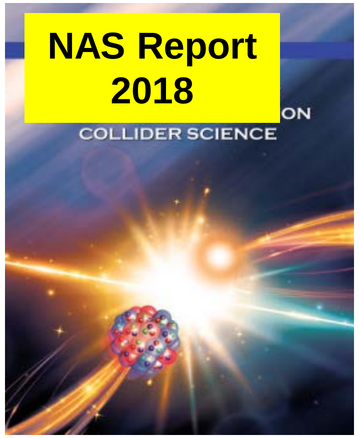
- A. Kondratenko, M. Kondratenko (Zaryad, Russia)
- Yu. Filatov (MIPT, Russia)

Introduction

- The nuclear science community envisions a high luminosity highly polarized EIC for exploring future QCD frontier
- JLEIC is a proposed Jefferson Lab Electron-Ion Collider to respond this science need
- JLEIC is designed for delivering high performance including ***high luminosity***, ***high polarization*** and ***full detector acceptance***



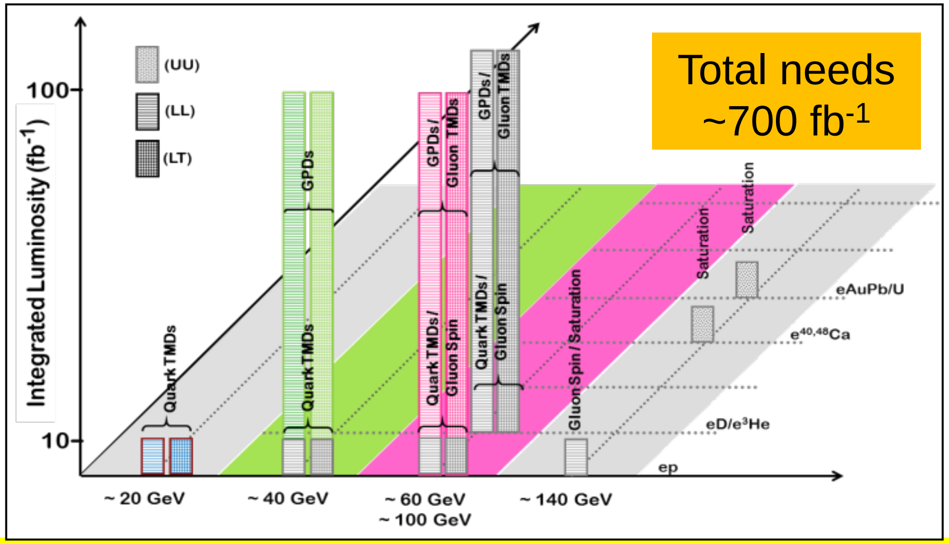


EIC Sciences

- ***Precisely image*** *sea quarks and gluons in nucleons & nuclei*
- Explore the ***new QCD frontier*** of strong color fields in nuclei
- Resolve outstanding issues in understanding nucleons & nuclei in terms of fundamental building blocks of QCD

Design Requirements

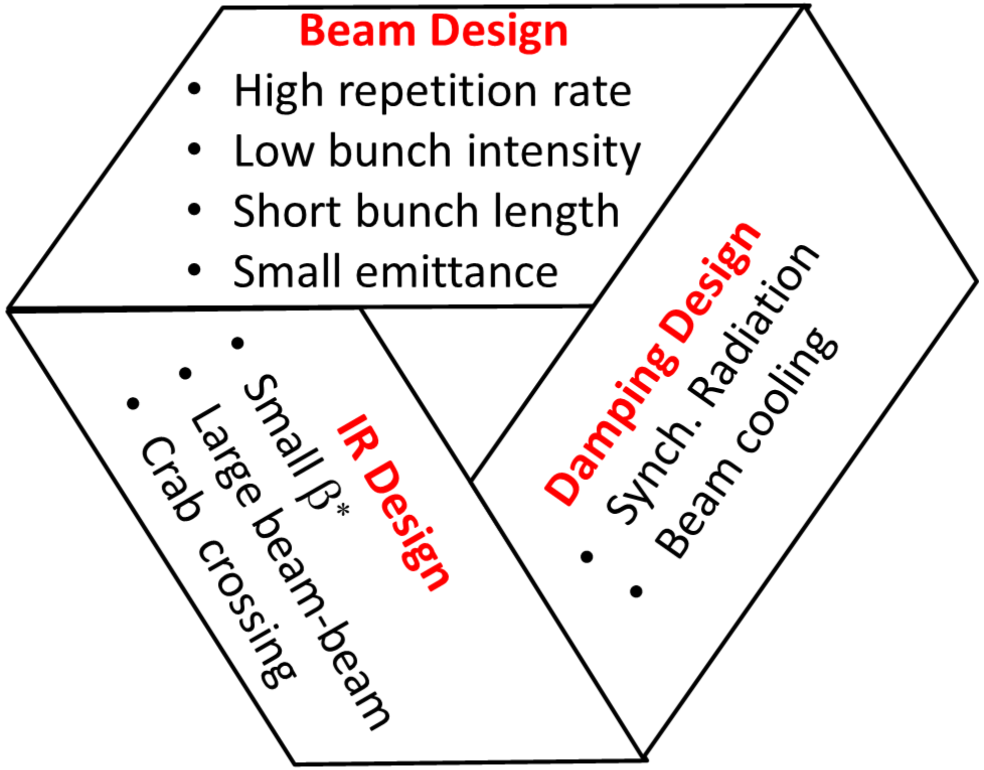
- Variable CM energy: ~20 to ~100 GeV, upgradable to ~140 GeV
- Ion beams from deuteron to the heaviest nuclei (lead)
- ***Highly polarized (~70%) electron and nucleon beams***
- High collision luminosity of ~10^{33-34} cm^{-2} s^{-1}
- Possibilities of having more than one interaction region

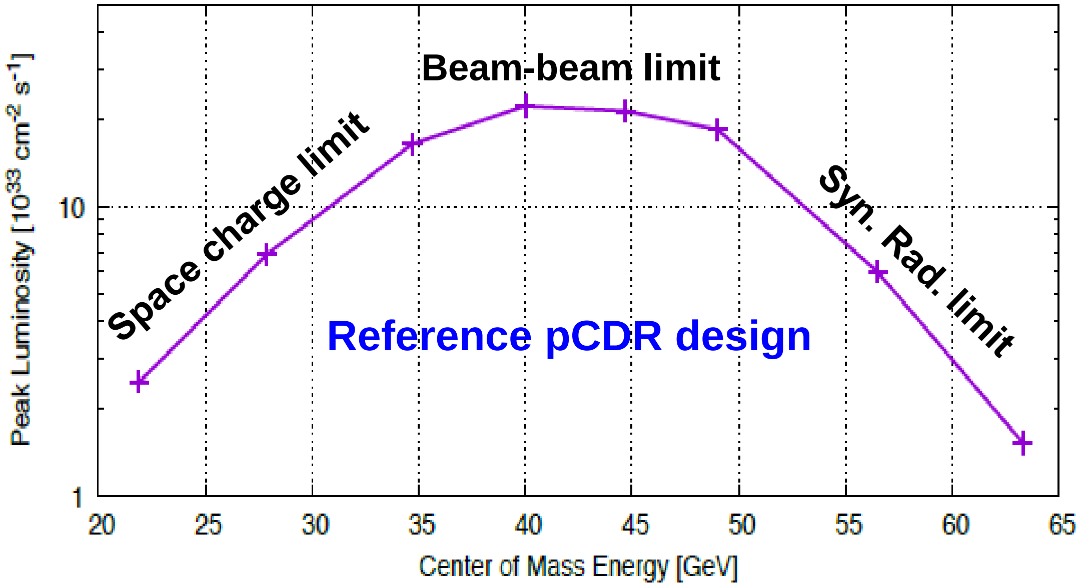


EIC integrated luminosity needs versus energy ranges and ion species for the White Paper Science program

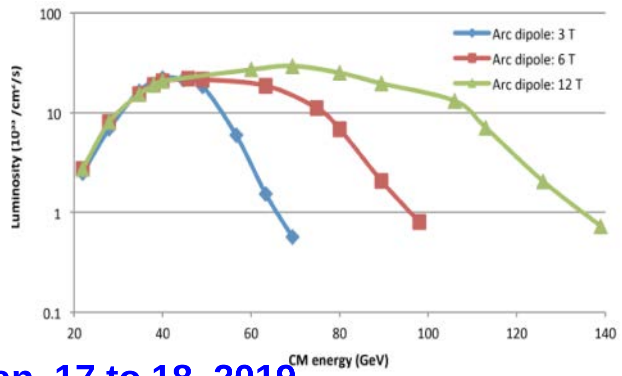
JLEIC Design Concept for High Luminosity

- *Conventional* approach for hadron colliders
  - Few colliding bunches ➔ low bunch frequency
  - High bunch intensity ➔ long bunch ➔ large β^*
- Approach: *high bunch rep-rate + short bunch beams* (standard for lepton colliders, KEK-B >2x10[34]/cm[2]/s)
- JLEIC is based on CEBAF, *already* up to 1.5 GHz
- *New green field* ion complex can be designed to deliver high bunch repetition rate
- Electron cooling of ion beam





Options for future upgrade



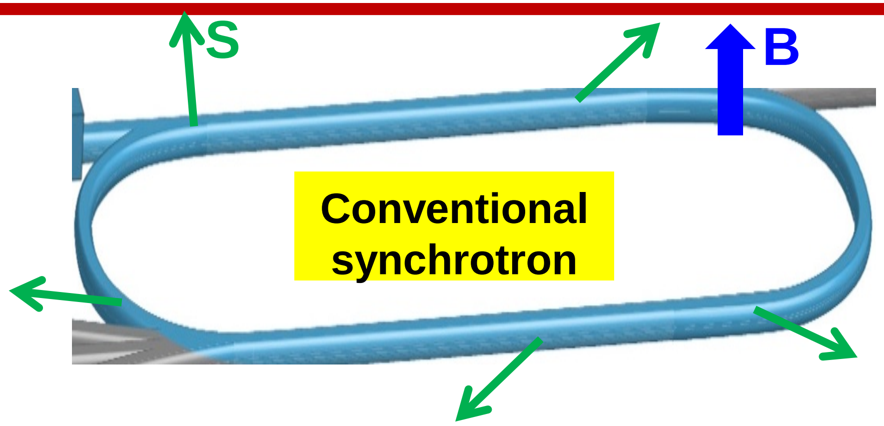
Role of cooling of ion beams

- Damping is critical for beam formation, emittance reduction and preservation
- No SR for ions in JLEIC medium energy range
- JLEIC relies on *electron cooling*

JLEIC Design Concepts for High Polarization

Requirements

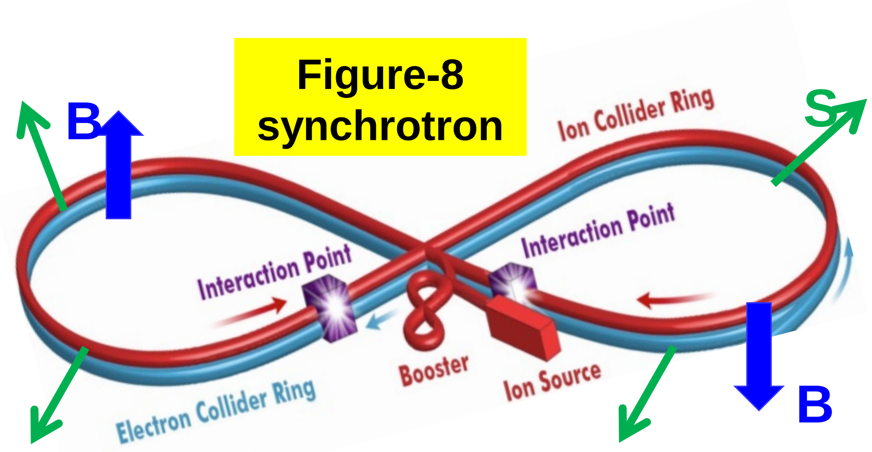
- High polarization (> 70%) of electrons, protons and light ions (d, $^3He^{++}$)
- *Proton/ions*: both longitudinal and transverse polarization at all IPs
- *Electrons*: longitudinal polarization at all IPs
- Sufficiently long polarization lifetime
- Spin flipping
- Polarimetry, 1% accuracy



- Spin precession/tune is energy dependent
- Cross spin resonances during acceleration
- Siberian Snake may help, but still difficult

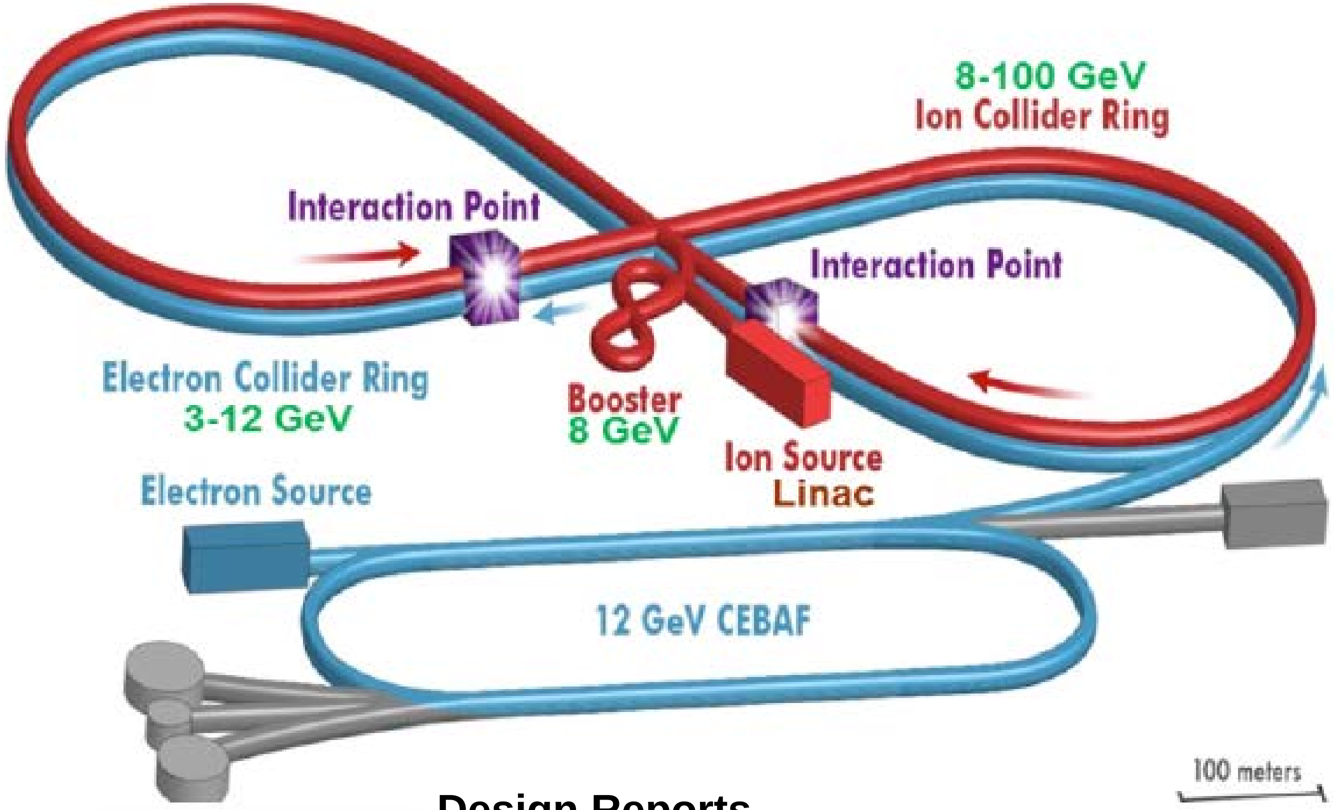
Design concepts

- Figure-8 topology ➔ *Enabled by a green field collider ring design*
- Spin precessions in the left & right parts of a figure-8 ring *exactly cancelled* ➔ spin tune is *zero*
- Does not cross spin resonance during energy ramp
- Spin can be controlled and stabilized by compact spin rotators, no need of Siberian Snakes
- The *only way* to accelerate/store polarized deuterons in medium energy range (gyromagnetic ratio *g-2* too small)



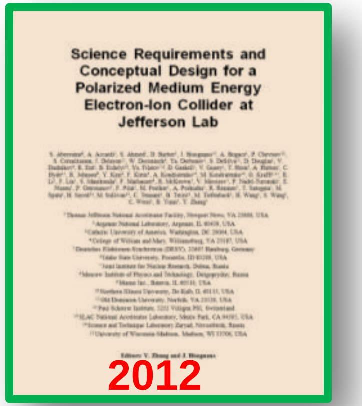
Invented by Ya. Derbenev

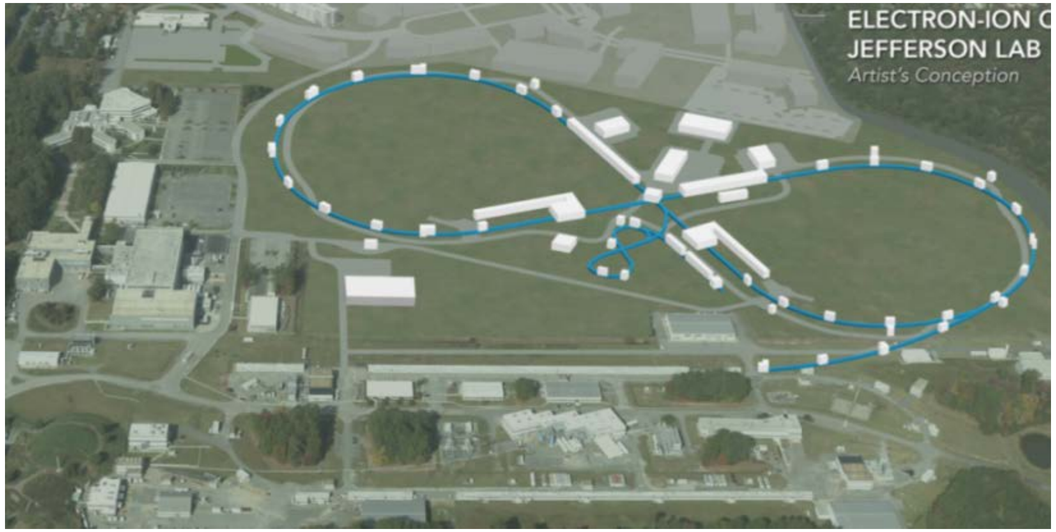
JLEIC Layout



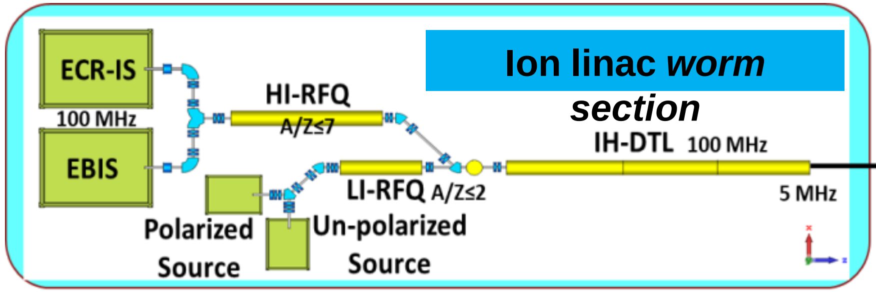
- Electron complex
  - CEBAF as a full energy injector
  - Collider ring
- Ion complex
  - Ion sources and linac
  - Booster (8 GeV, figure-8)
  - Collider ring (100 GeV, figure-8)
- Detectors
  - At least two, full acceptance
  - Horizontal crossing, with crab cavities

Design Reports



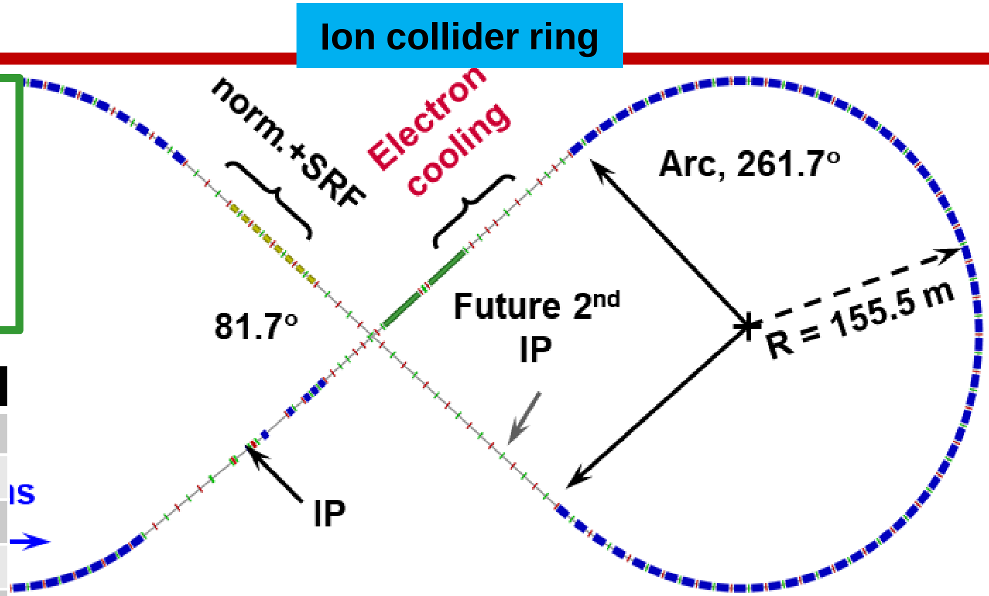


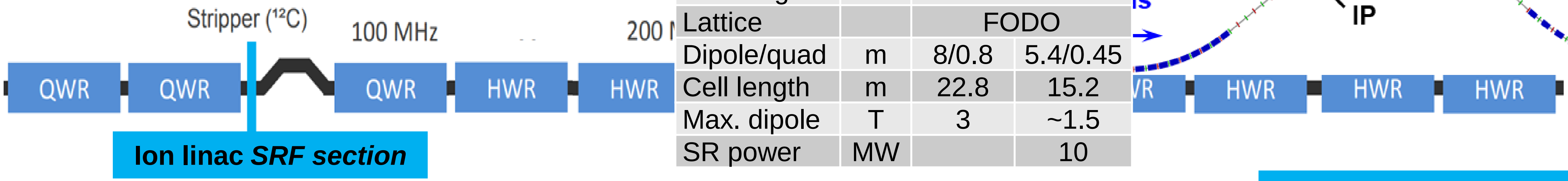
JLEIC Accelerator Design

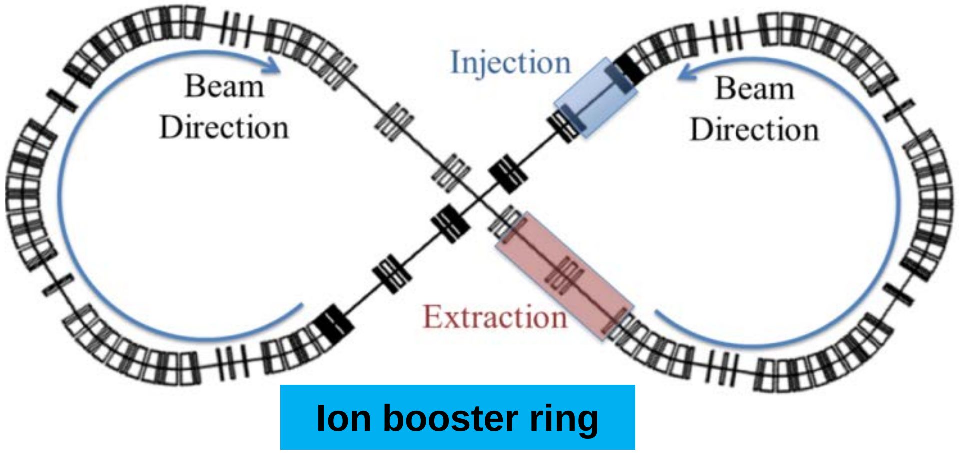


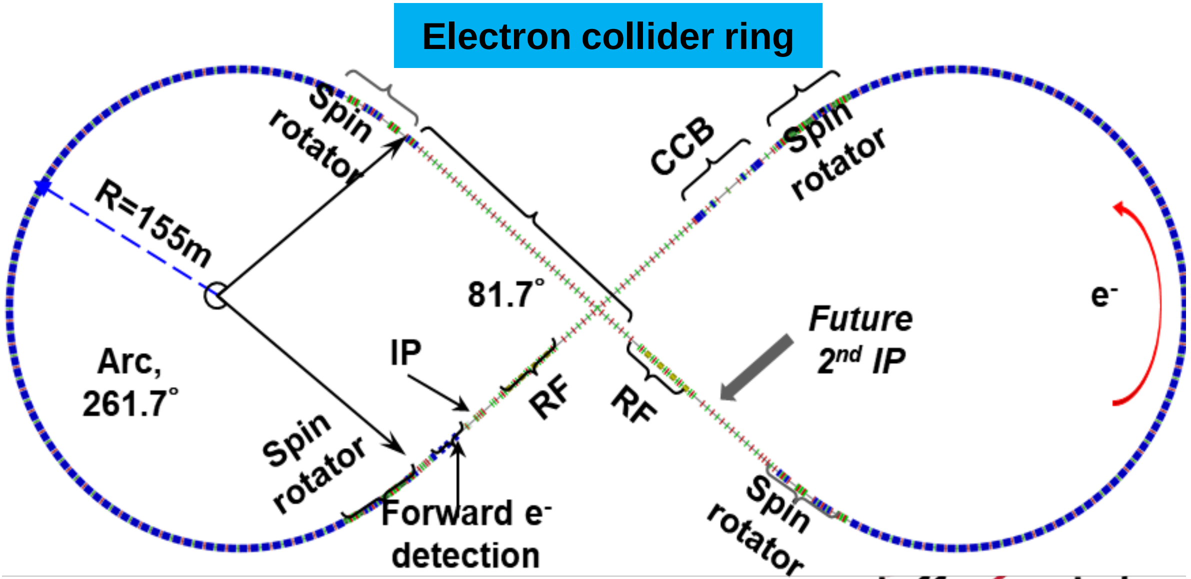
- Two rings stack vertically
- Horizontal crab crossing at IPs
- Electron vertical chicane
- Two IPs, fit to JLab site

		p	e
Circum.	m	~2257	
Crossing		77.4º	
Lattice		FODO	
Dipole/quad	m	8/0.8	5.4/0.45
Cell length	m	22.8	15.2
Max. dipole	T	3	~1.5
SR power	MW		10

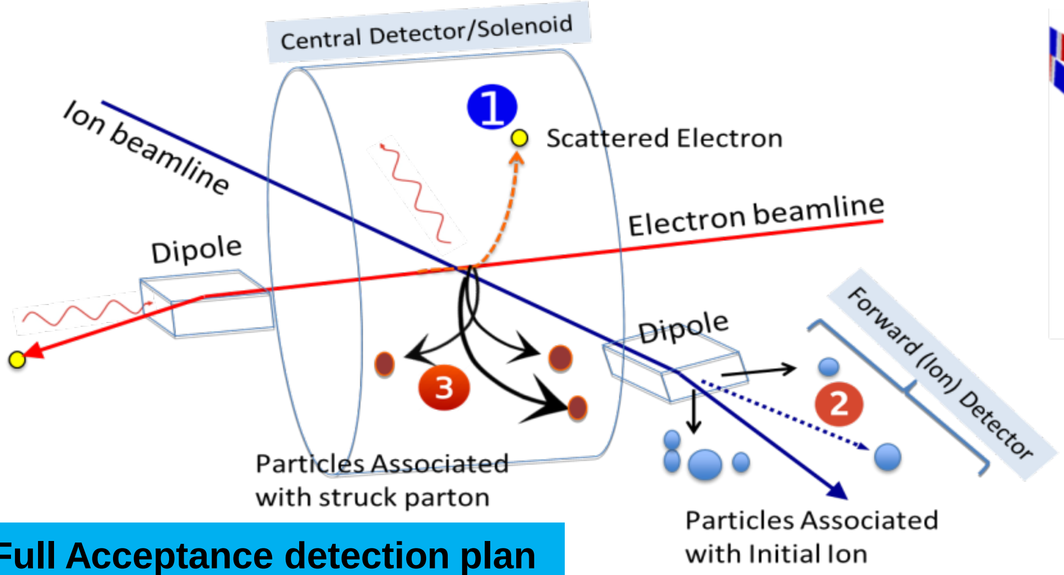






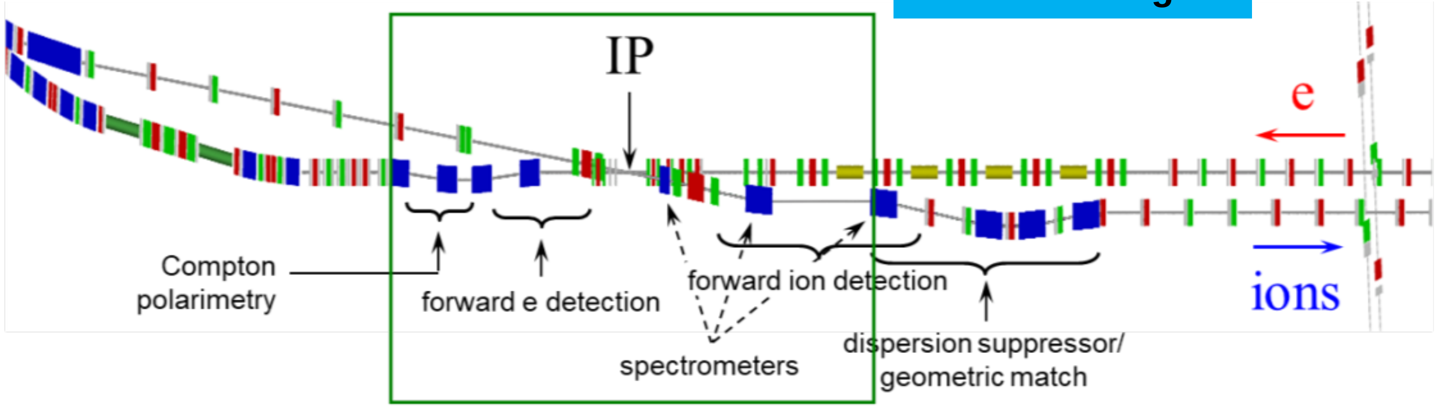


JLEIC Interaction Region

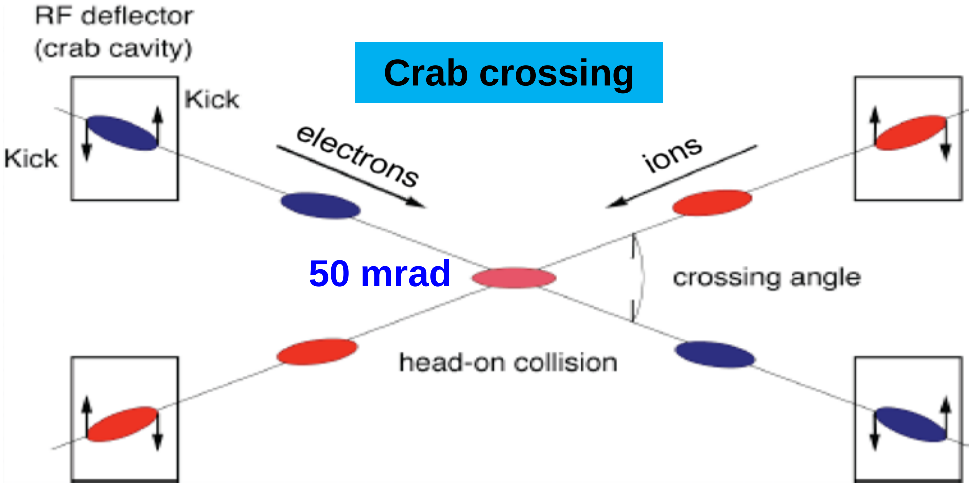


Full Acceptance detection plan

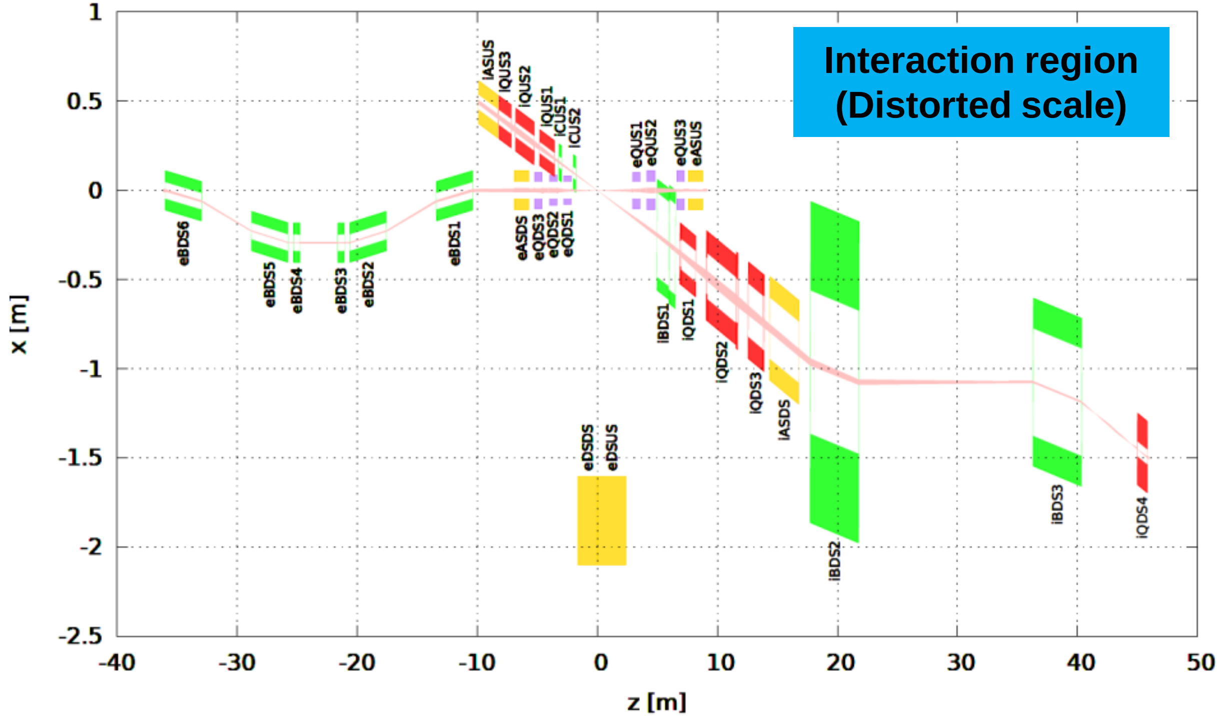
Interaction region



Crab crossing



Interaction region (Distorted scale)



Spin Resonances

- Spin tune in a conventional ring

$$\nu_s = G\gamma, \quad G_d \approx -0.143$$

- 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

$$\nu_s = k, \qquad E_d = 13.12k \text{ GeV}$$

  - 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 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

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

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

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

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

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

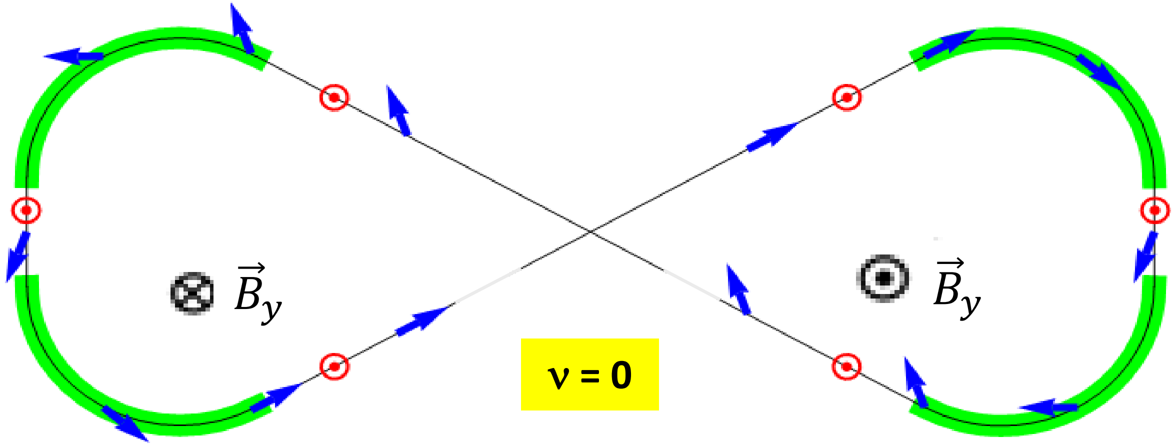
In reality, orbit control requirements lead to an increase of the field integral by a factor of ~3 or so

- Medium energies are still a problem
- Full snake is not practical for deuterons in medium to high energy range

Principle and Advantage of A Figure-8 Ring

- Figure-8 ring is transparent to 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

Invented by Ya. Derbenev



Zero-Integer Spin Resonance and Stability Criterion

- **Zero-integer spin resonance strength**

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

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 emittance), it causes spin tune spread potentially leading to depolarization

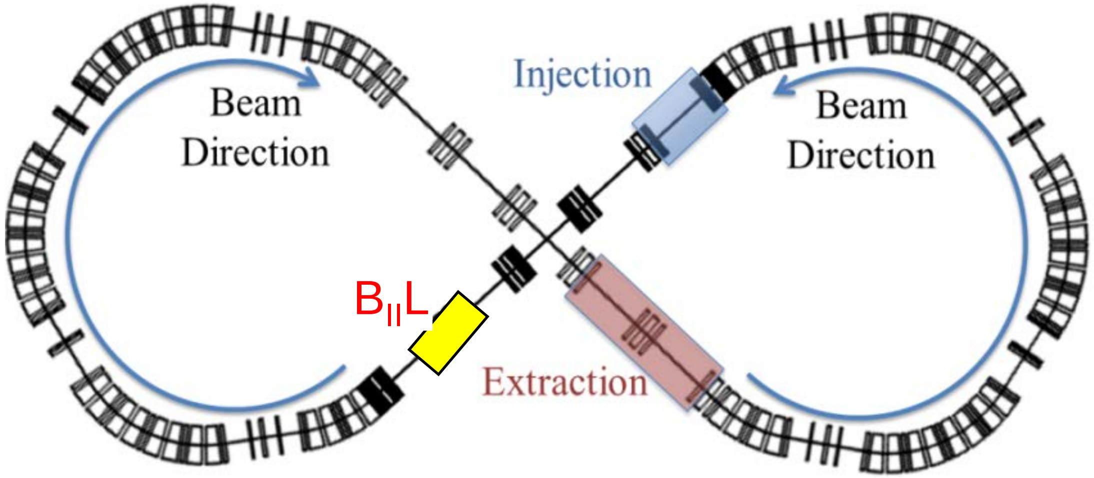
- **Spin stability criterion**
  - the spin tune induced by a spin rotator must significantly exceed the strength of the incoherent part of the zero-integer spin resonance

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

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

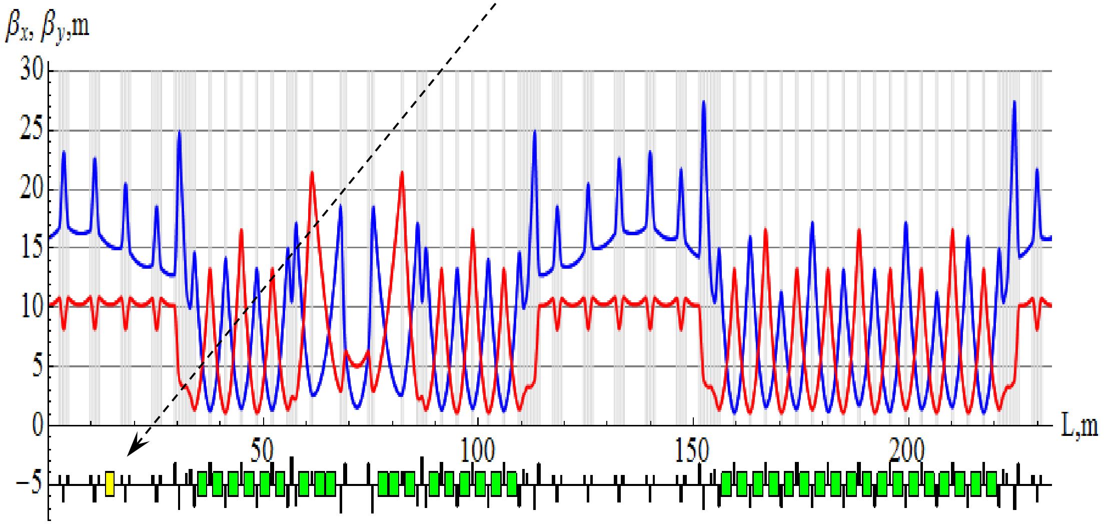
Booster

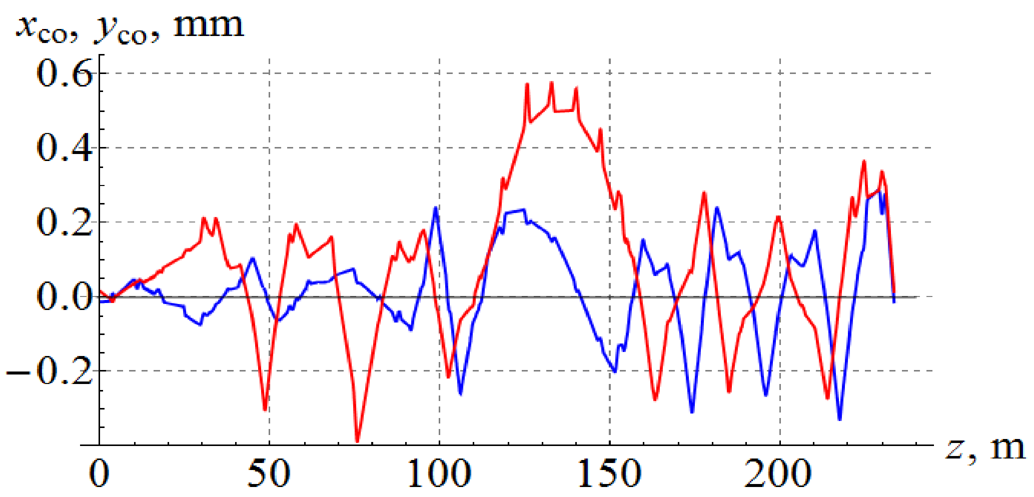
- Polarization in Booster stabilized and preserved by a single weak solenoid
  - **0.6 T·m** at 8 GeV/c
  - ν_d / ν_p = 0.003 / 0.01
- Longitudinal polarization in the straight with the solenoid
- Conventional 8 GeV accelerators require $B_{||}L$ of **~30 Tm** for protons and **~100 Tm** for deuterons



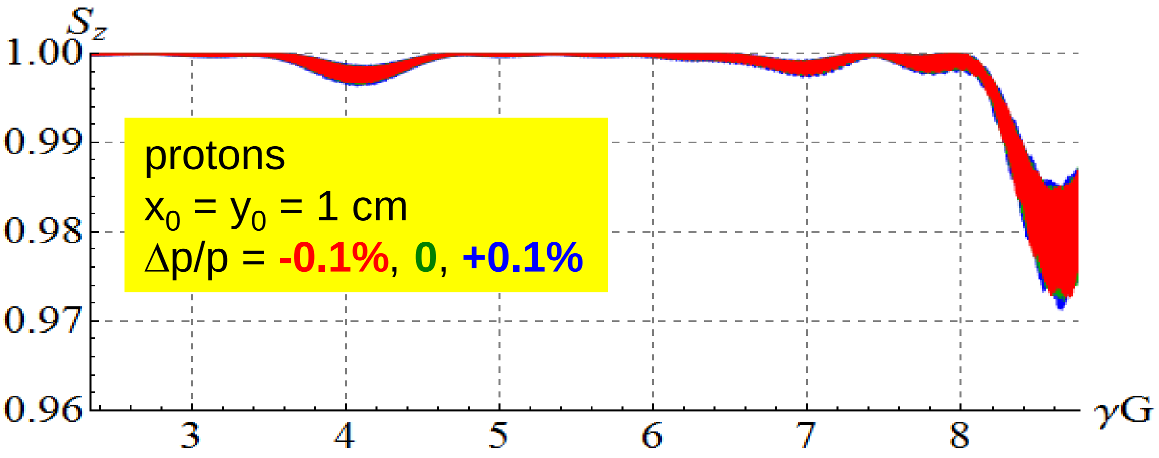
Spin Dynamics in Ion Booster

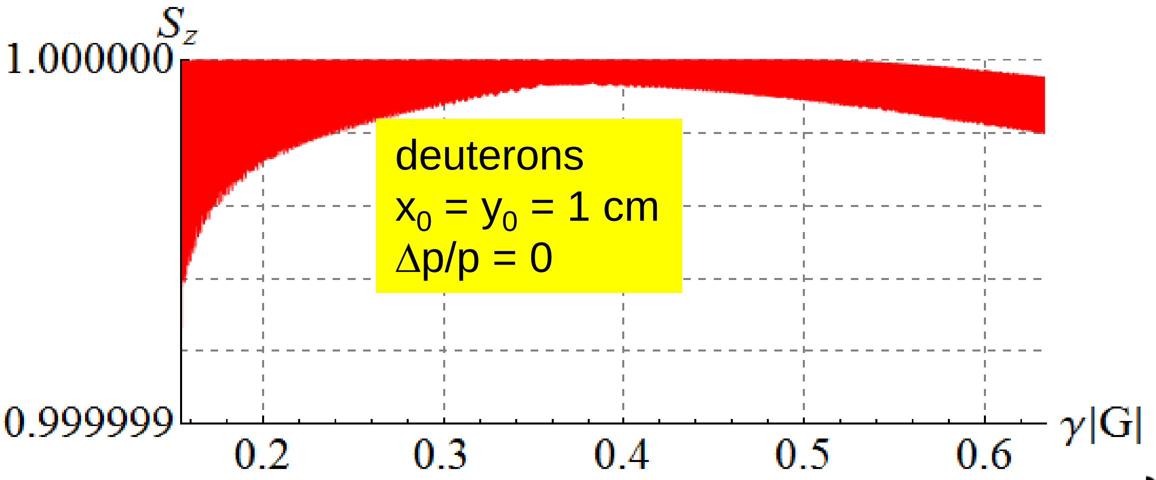
- Acceleration in figure-8 booster with transverse quadrupole misalignments
- 0.3 Tm (maximum) spin stabilizing solenoid





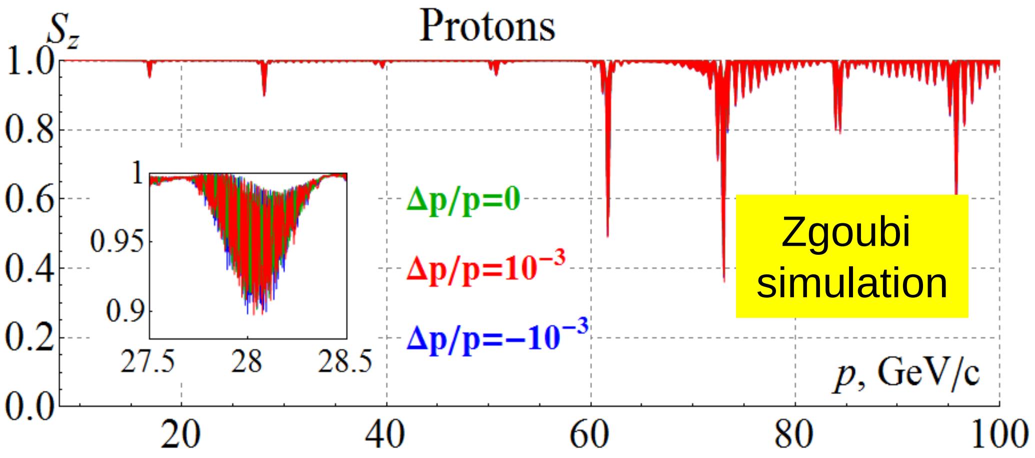
- Spin tracking simulation using Zgoubi



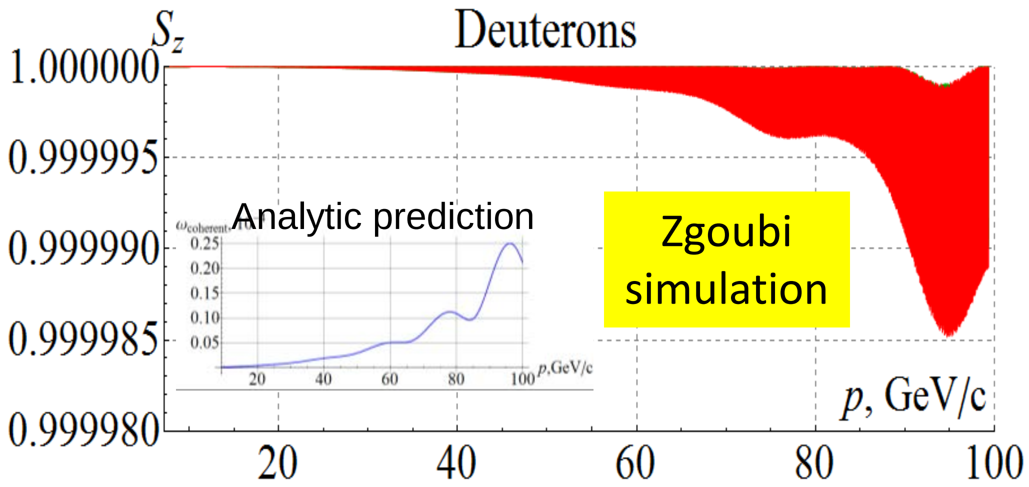


Start-to-End Acceleration in Ion Collider Ring

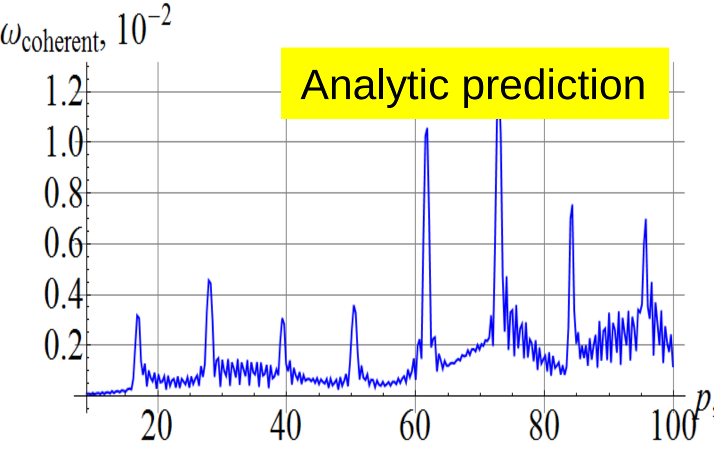
- 3 protons with $\varepsilon_{x,y}^{N} = 1\ \mu m$ and $\Delta p/p = 0, \pm 0.001$ accelerated at ~3 T/min in lattice with 100 μm rms closed orbit excursion, $\nu_{sp} = 0.01$

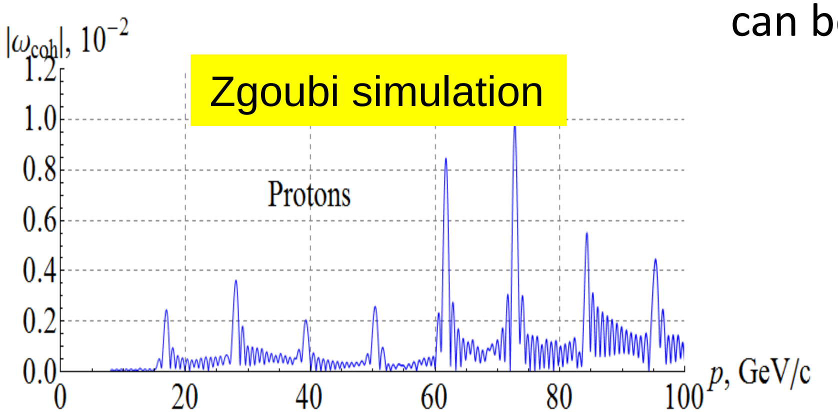


- 3 deuterons with $\varepsilon_{x,y}^{N} = 0.5\ \mu m$ and $\Delta p/p = 0, \pm 0.001$, accelerated at ~3 T/min in lattice with 100 μm rms closed orbit excursion, $\nu_{sp} = 3 \cdot 10^{-3}$



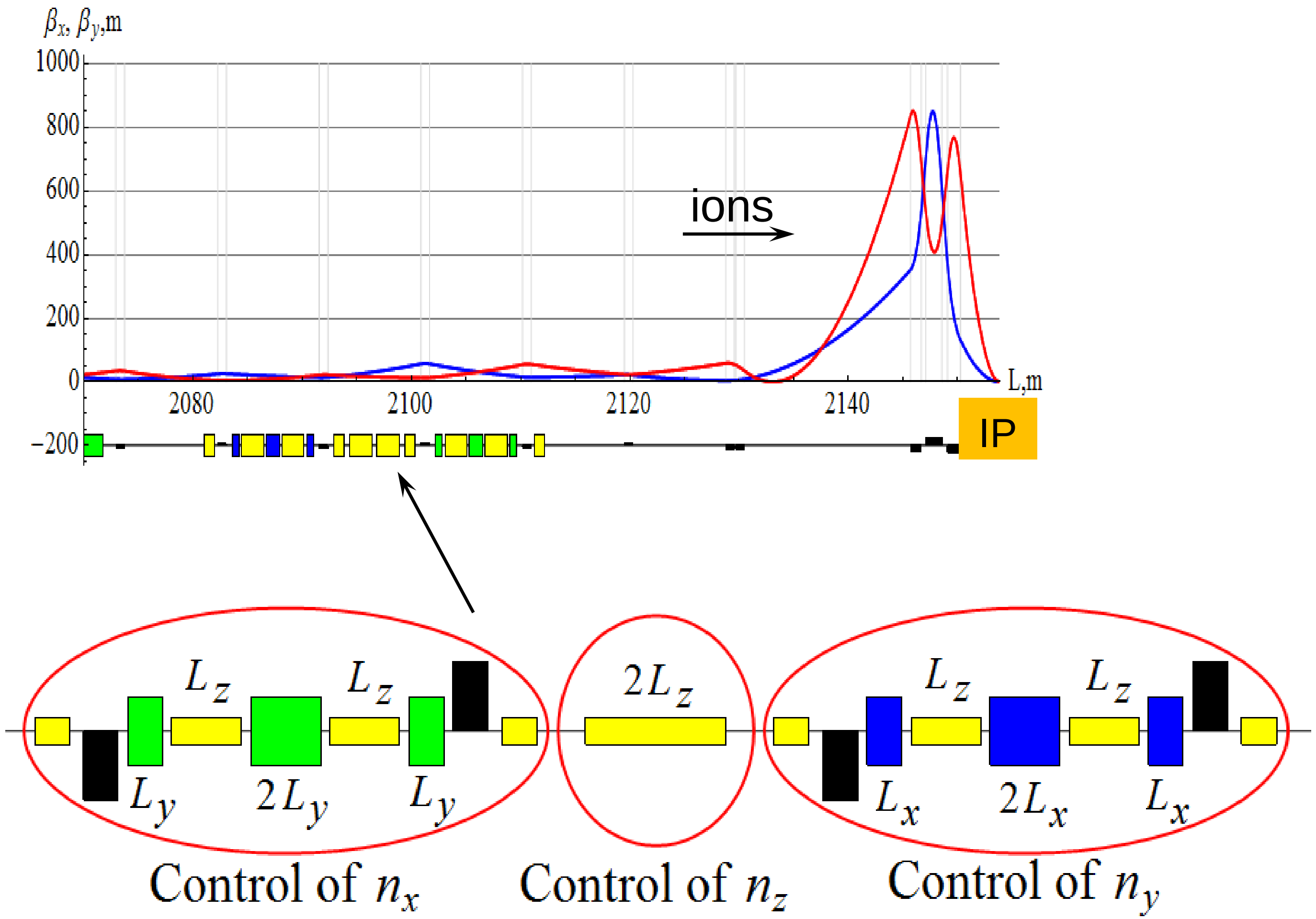
- Coherent resonance strength component





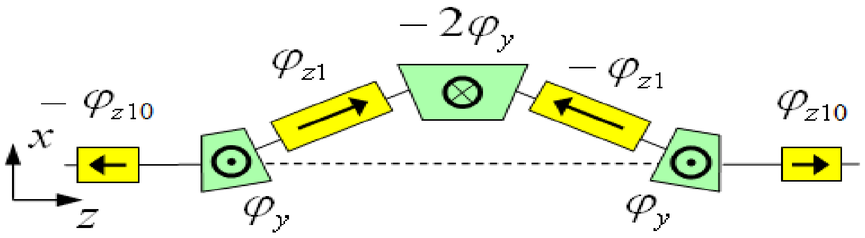
- Deuteron spin is highly stable in figure-8 rings, which can be used for high precision experiments

3D Spin Rotator in Ion Collider Ring



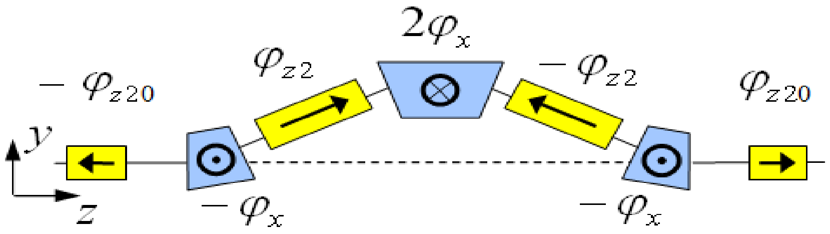
3D spin rotator

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

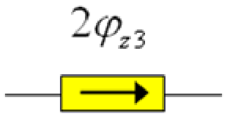


$L_{tot} = 7$ m, $\Delta x = 15$ mm, $B_{dip}^{max} = 3$ T, $B_{sol}^{max} = 3.6$ T

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



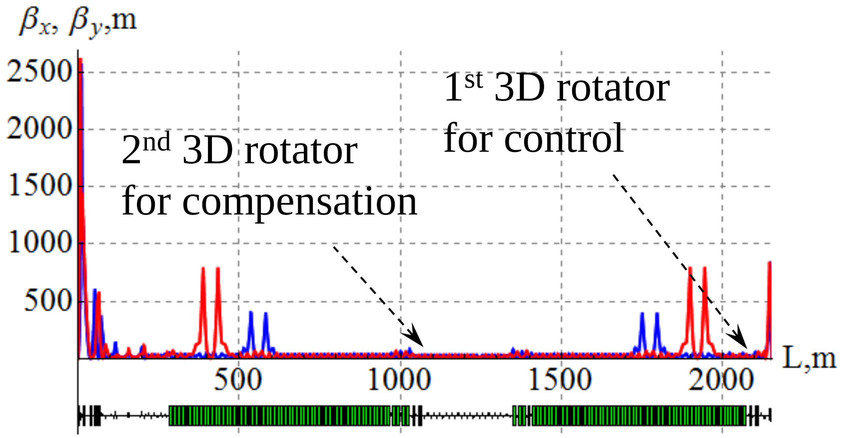
- Module for control of the longitudinal component

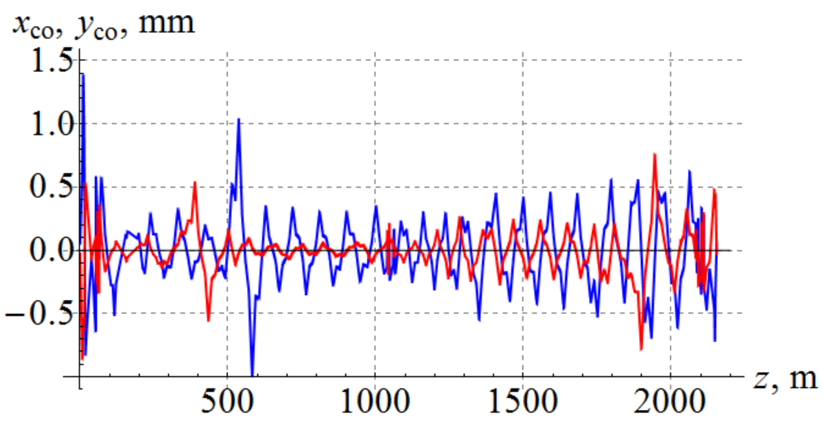


$L_x = L_y = 0.6$ m, $L_{zi} = 2$ m, $L_{zi0} = 1$ m, $\alpha_{orb} = 0.31^\circ$

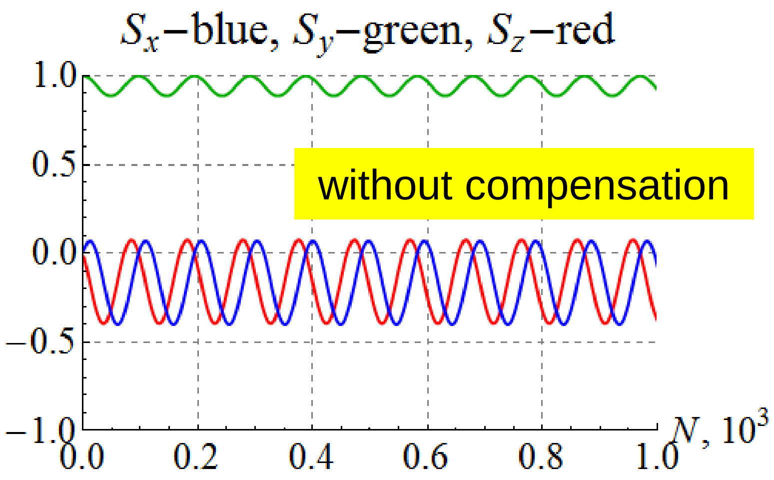
Polarization Control in Ion Collider Ring

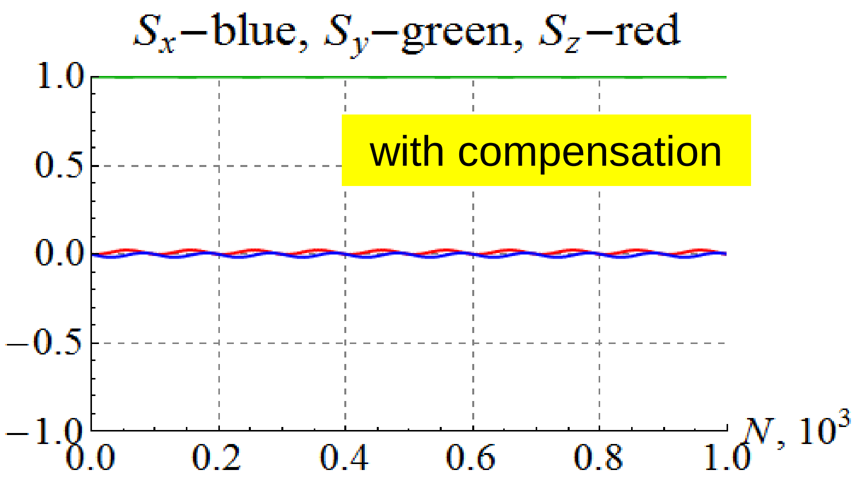
- 100 GeV/c figure-8 ion collider ring with transverse quadrupole misalignments





- 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





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, $\hat{s}$ 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

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

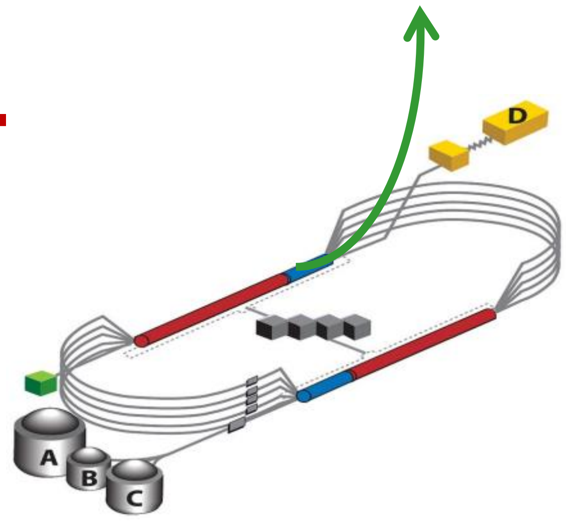
where $P_{ens,DK} = P_{DK}\langle\hat{n}\rangle_s$ is the value of ensemble average of P_{DK} independent of s and P_0 is the initial polarization

I. Ternov, D. Ivanenko, A. Sokolov

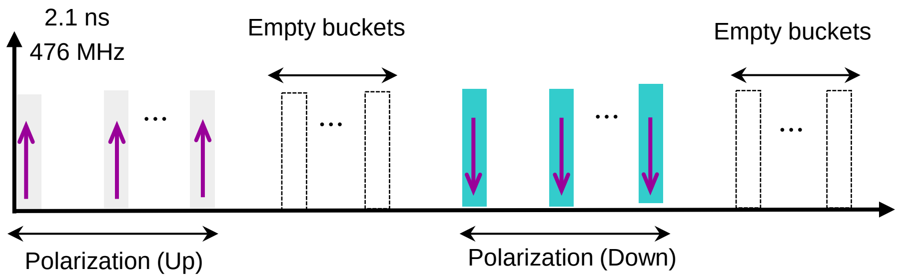
Invariant spin field: a 1-turn periodic unit 3-vector field over the phase space satisfying the T-BMT equation along particle trajectories

Electron Polarization Design Strategy

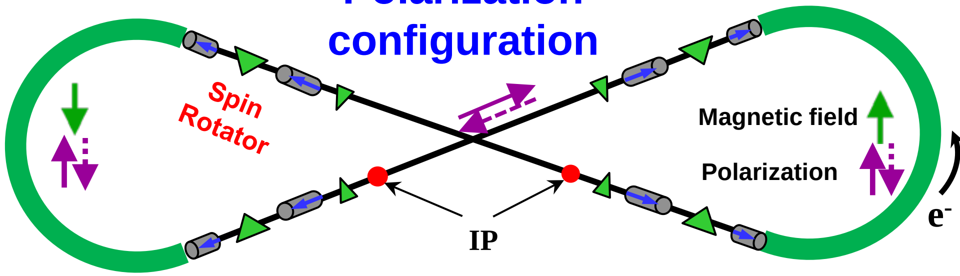
- **Polarized electron injector: 12 GeV CEBAF SRF linac**
  - Polarized electron source, providing superior polarization (>90%)
  - Full energy injection, with top-off/continuous injection capability
  - No polarization loss in linac and in transport line from linac to collider ring
- **Electron collider Ring**
  - Spin in vertical direction in arcs to avoid spin diffusion
  - ***Anti-parallel*** to arc dipole field in one half-ring, ***parallel*** in the other half-ring
    - ➔ net self-polarization is zero
    - ➔ polarization lifetime same for two spin states
  - Injected vertically to avoid spin decoherence, alleviate detector background
  - Rotate spin to longitudinal direction in straights using spin rotators
  - Figure-8 geometry removes electron spin tune energy dependence, significantly suppress the synchrotron sideband resonance
- **Universal spin rotator**
  - Covers 3 to 12 GeV, use arc dipoles and vertical doglegs
  - Fixed orbit, energy independent, optics independent
- **Advanced schemes**
  - Spin flip Implemented by changing the source polarization
  - Continuous injection highly-polarized electrons from CEBAF to maintain high equilibrium polarization
  - Spin matching in some key regions to improve polarization lifetime
  - Compton polarimeter provides non-invasive polarization measurements



bunch train & polarization pattern (in arcs)

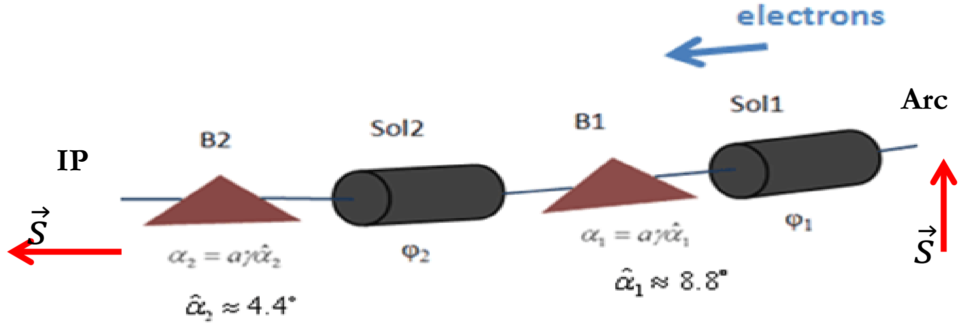


Polarization configuration



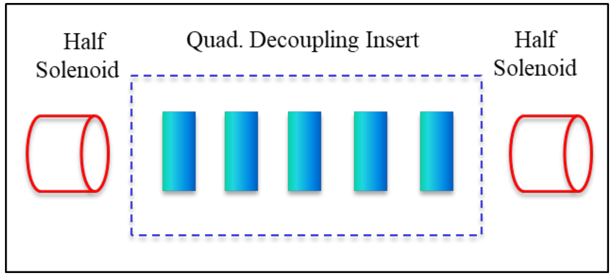
Universal Spin Rotator

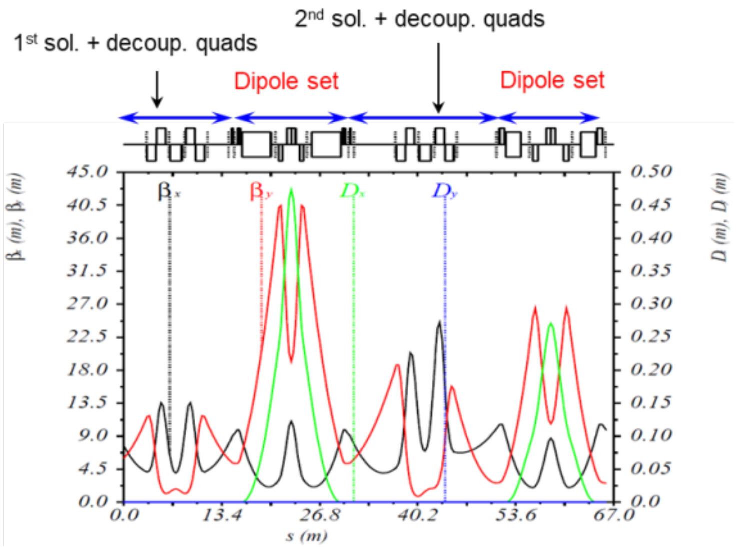
- Rotate spin from vertical in arcs to longitudinal in straights
- It consists of two solenoids and tow sets of arc dipoles (also optional dipoles of vertical chicane)
- Fixed geometry and optics, independent of energy

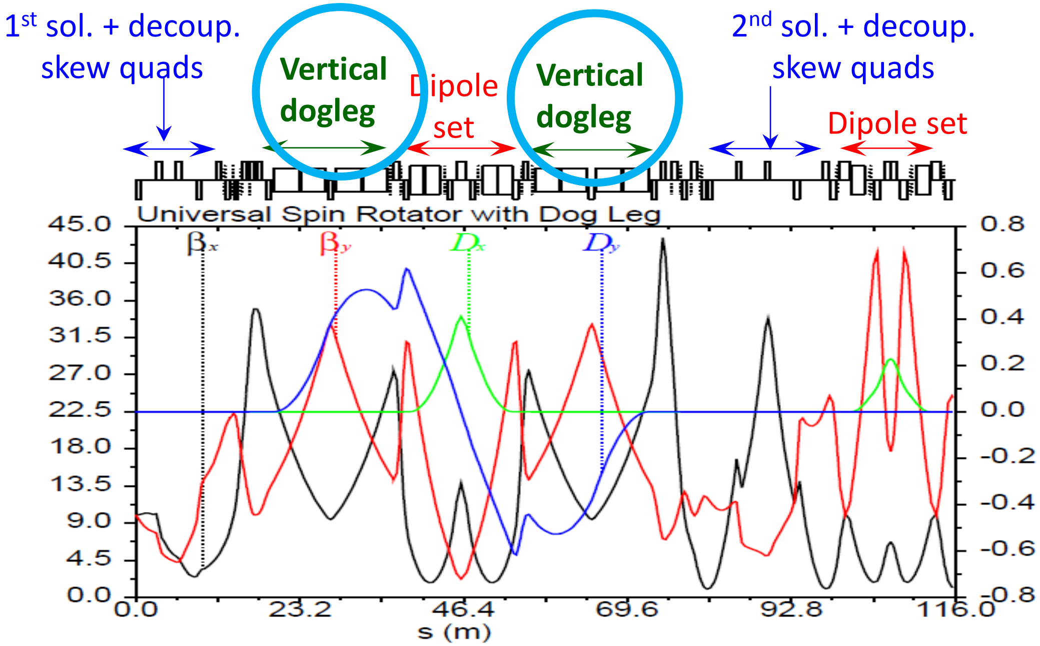


E	Solenoid 1		Dipole set 1	Solenoid 2		Dipole set 2
	Spin Rotation	BDL	Spin Rotation	Spin Rotation	BDL	Spin Rotation
GeV	rad	T·m	rad	rad	T·m	Rad
3	π/2	15.7	π/3	0	0	π/6
4.5	π/4	11.8	π/2	π/2	23.6	π/4
6	0.62	12.3	2π/3	1.91	38.2	π/3
9	π/6	15.7	π	2π/3	62.8	π/2
12	0.62	24.6	4π/3	1.91	76.4	2π/3

Dispersion suppressed in solenoids
Each solenoid individually decoupled

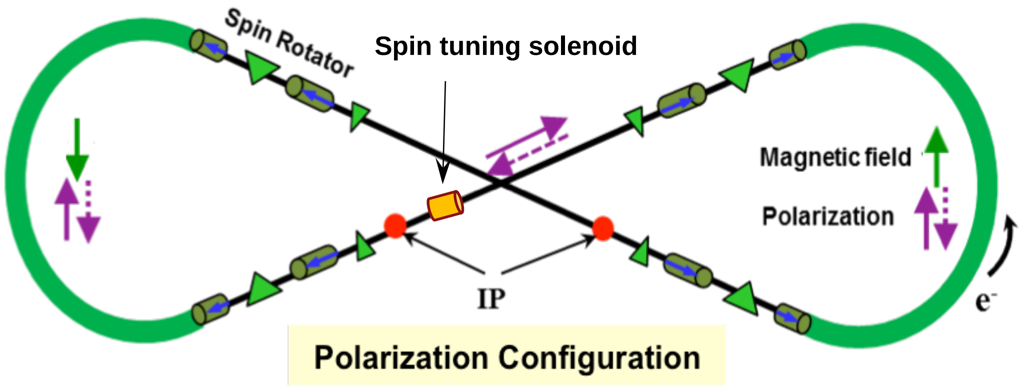


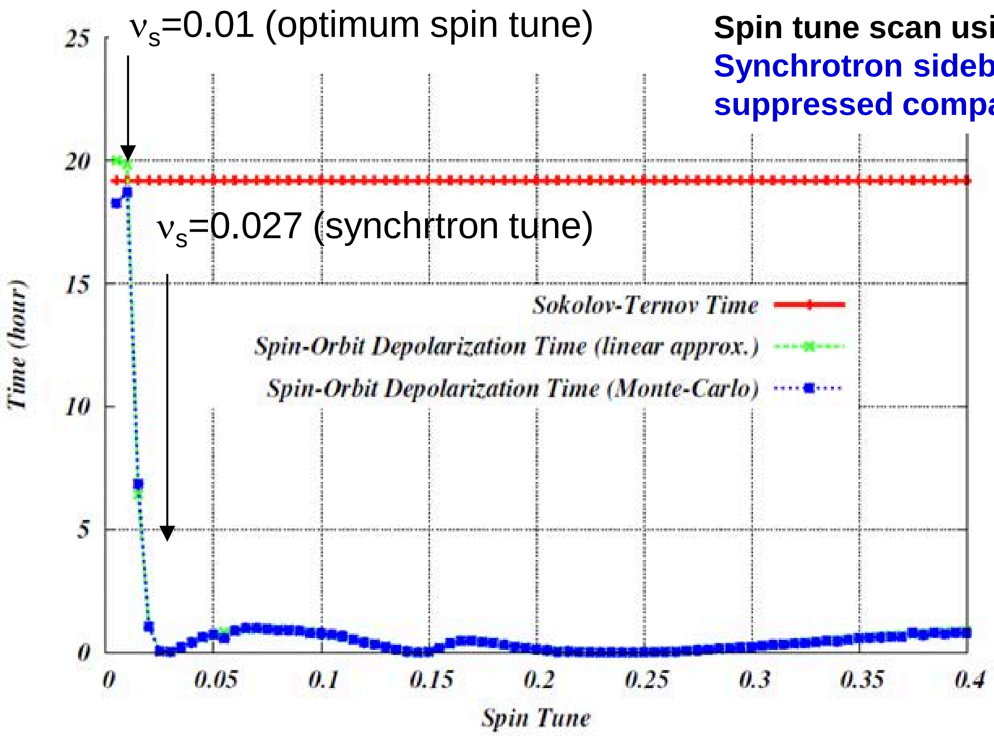




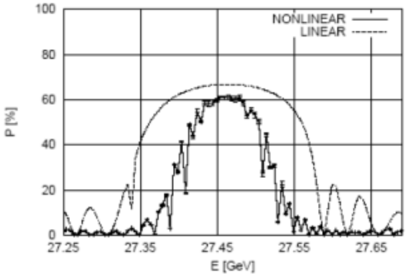
Electron Spin Tracking

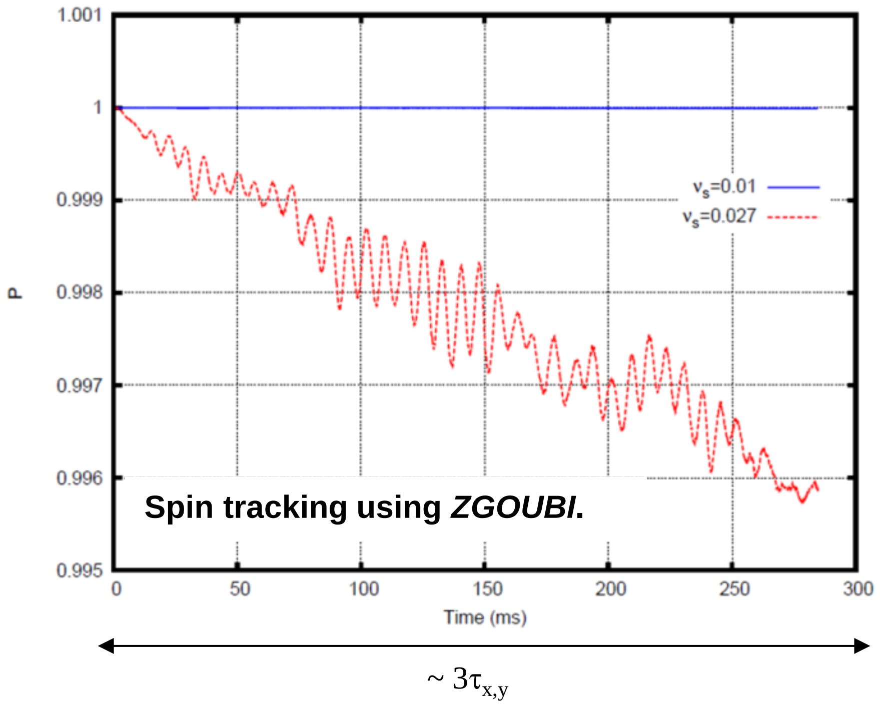
- Spin tune scan using a spin tuning solenoid inserted in one straight (the polarization is longitudinal)
- Monte-Carlo simulation using SLICKTRACK (developed by D. Barber)
- Included main field errors, quads vertical misalignment and dipole role
- Demonstrated suppression of synchrotron sideband spin resonances
- Verified by Zgoubi's Monte-Carlo spin tracking





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





Polarization Lifetime and Continuous Injection

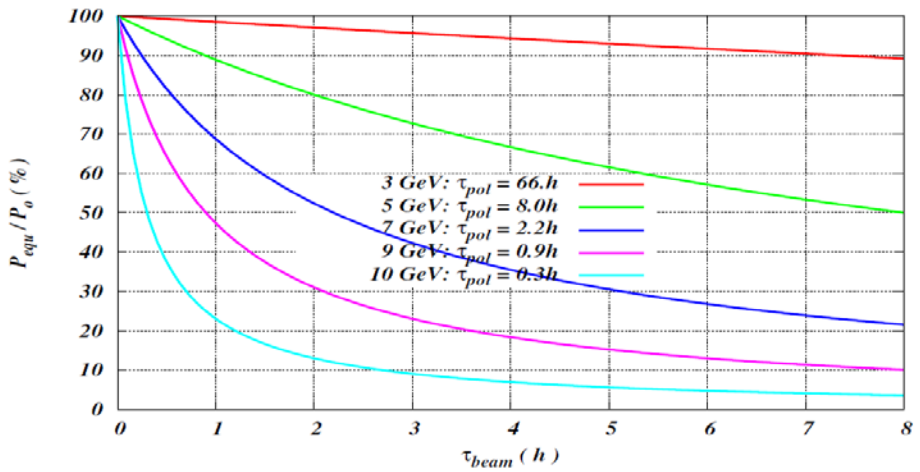
Estimated polarization lifetime

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

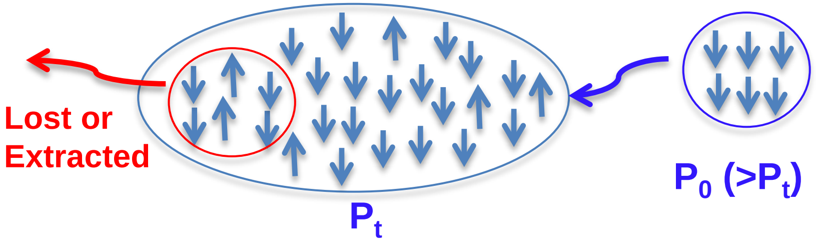
Mitigation: continuous injection

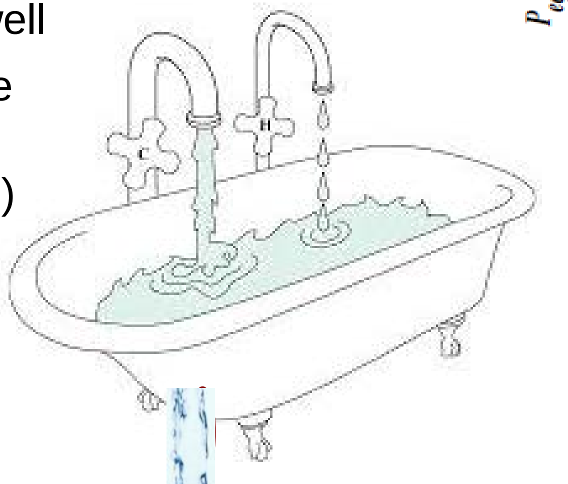
- Continuous injection of a relatively low average beam (tens of nA averaged current) from CEBAF can maintain a high equilibrium polarization in the whole energy range

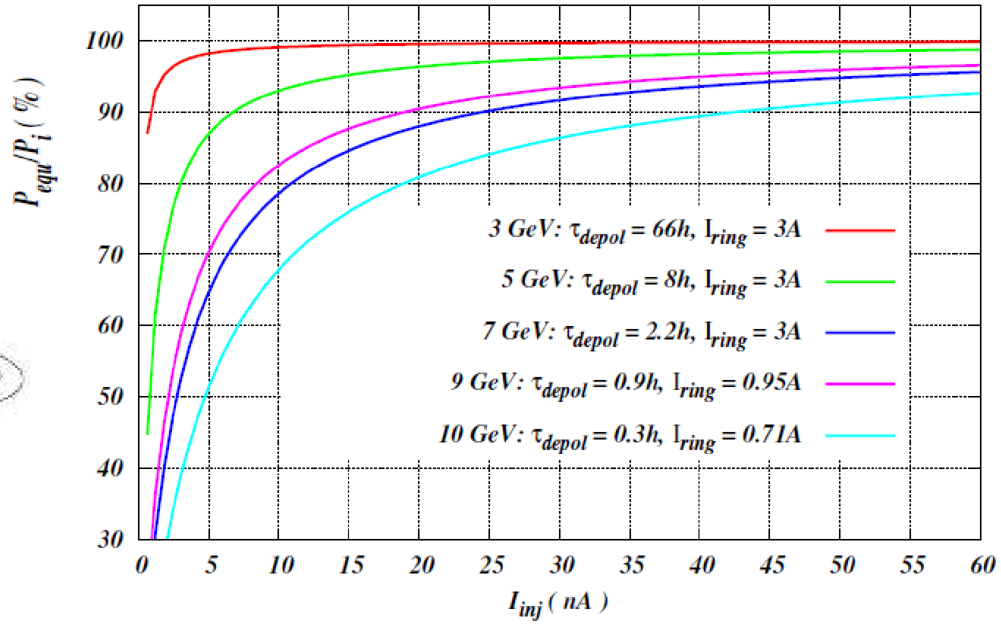
Equilibrium polarization $$P_{equ} = P_0 \left(1 + \frac{T_{rev} I_{ring}}{\tau_{DK} I_{inj}}\right)^{-1}$$



- Beam lifetime must be balanced with beam injection rate
  - $\boldsymbol{\tau_{beam} \ll \tau_{pol}}$: the beam lifetime is shorter than the polarization lifetime, continuous injection maintains the beam current and improves the polarization as well
  - $\boldsymbol{\tau_{beam} \gg \tau_{pol}}$: the beam lifetime is longer than the polarization lifetime, it has to been shorten (collimation, scraping, reducing dynamic aperture)







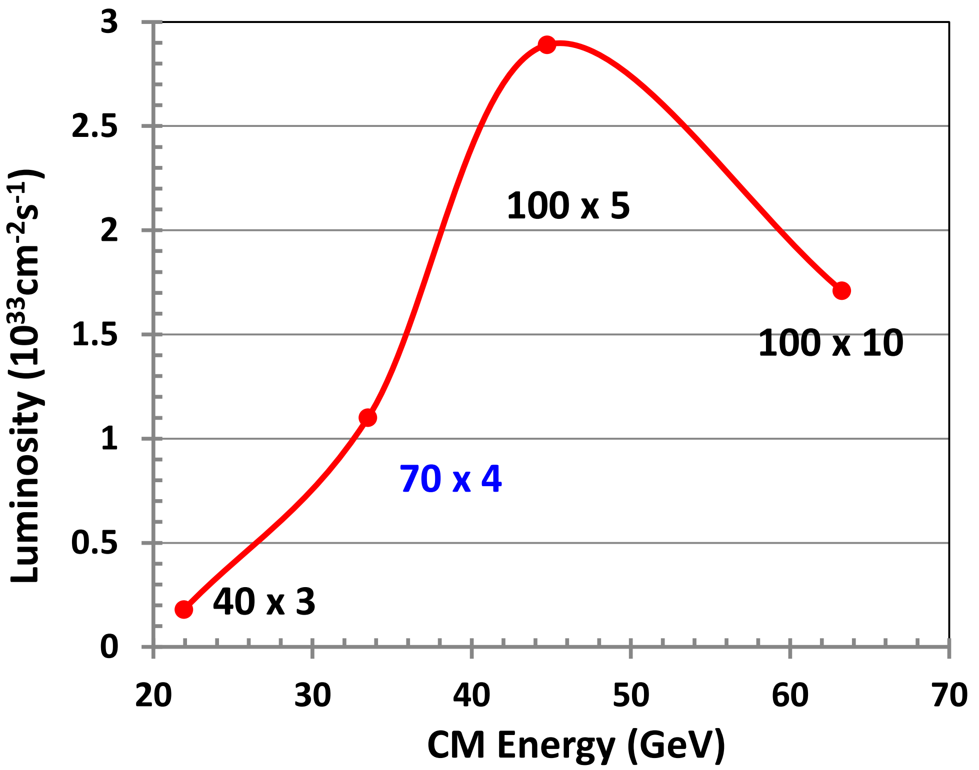
JLEIC + JL*E*+IC ?

- The question always comes up "*what about positron beams at an EIC*"
- High valuable science with polarized positron beams:
  - Luminosity > 10^{33}
  - Polarization > 40%

CM energy	GeV	21.9		44.7		63.3	
		p	e^+	p	e^+	p	e^+
Beam energy	GeV	**40**	**3**	**100**	**5**	**100**	**10**
Collision frequency	MHz	476/4=119		476/4=119		476/4=119	
Particles per bunch	10^{10}	1.1	1.1	2.1	1.1	3.9	1.1
Beam current	A	0.2	0.2	0.4	0.2	0.75	0.2
Polarization	%	80	**>40**	80	**>40**	80	**>40**
Bunch length, RMS	cm	3	1	2	1	2	1
Norm. emitt., h./v.	µm	0.3	24/24	0.5/0.1	54/10.8	0.9/0.18	432/86.4
Horiz. & vert. β*	cm	8	13.5	6/1.2	5./1	10.5/2.1	4/0.8
Vert. beam-beam		0.004	0.091	0.004	0.144	0.002	0.034
Laslett tune-shift		0.059	$3x10^{-4}$	0.059	$2x10^{-4}$	0.061	$6x10^{-6}$
Detector space, u/d	m	3.6/7	3.2/3	3.6/7	3.2/3	3.6/7	3.2/3
Hourglass reduction		0.98		0.77		0.77	
Lumi/IP, w/HG, 10^{33}	$cm^{-2}s^{-1}$	**0.18**		**2.9**		**1.7**	

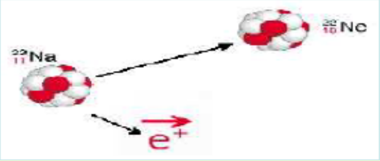
JLEIC polarized lepton beam design goal

- Electron: up to 3 A, > 80% polarization
- **Position: 0.2 A, > 40%** polarization



Generation of Polarized Positrons: The *PEPPo* Way

Polarized β⁺ Decay
L.A. Page & M. Heinberg. Phys. Rev. 106(6):1220-1224 (1957)



Polarization is low

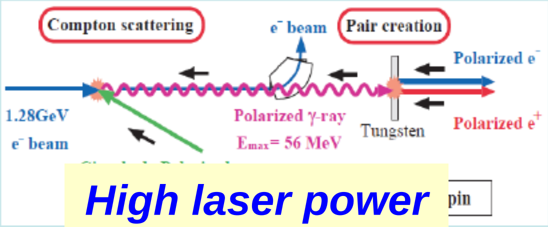
$P(e^+) \sim 40\ \%$

Sokolov-Ternov Effect
D. Barber , AIP Conf. Proc. 588, 338 (2001)

Not for continuous injection facilities

$P(e^+) \sim 70\ \%$

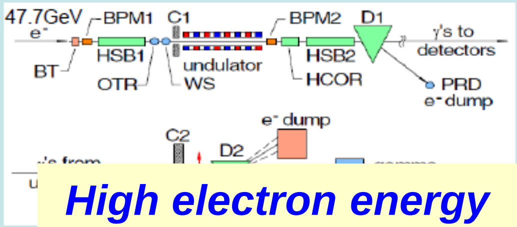
Inverse Compton Backscattering (KEK)
T. Omori et al, PRL 96 (2006) 114801



High laser power

$P(e^+) = 73 \pm 15_{(stat)} \pm 19_{(syst)}\ \%$

Helical Undulator (SLAC E166)
G. Alexander et al, PRL 100 (2008) 210801



High electron energy

$P(e^+) = 80 \pm 7_{(stat)} \pm 9_{(syst)}\ \%$

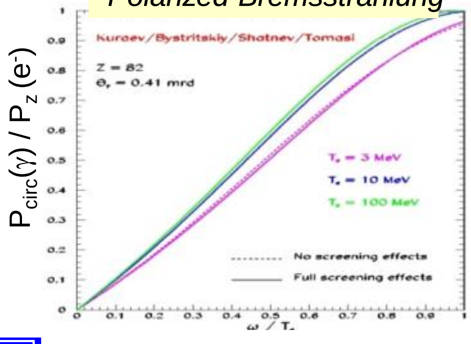
Polarized Electrons for Polarized Positrons (PEPPo) Concept

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

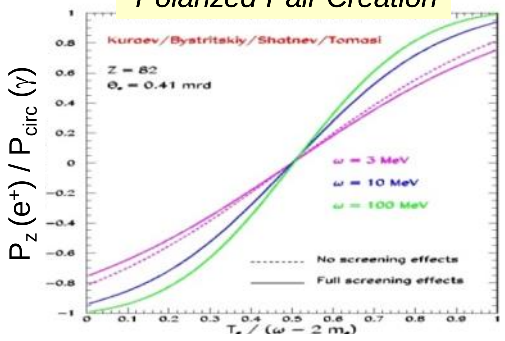
E.G. Bessonov, A.A. Mikhailichenko, EPAC (1996)
A.P. Potylitsin, NIM A398 (1997) 395

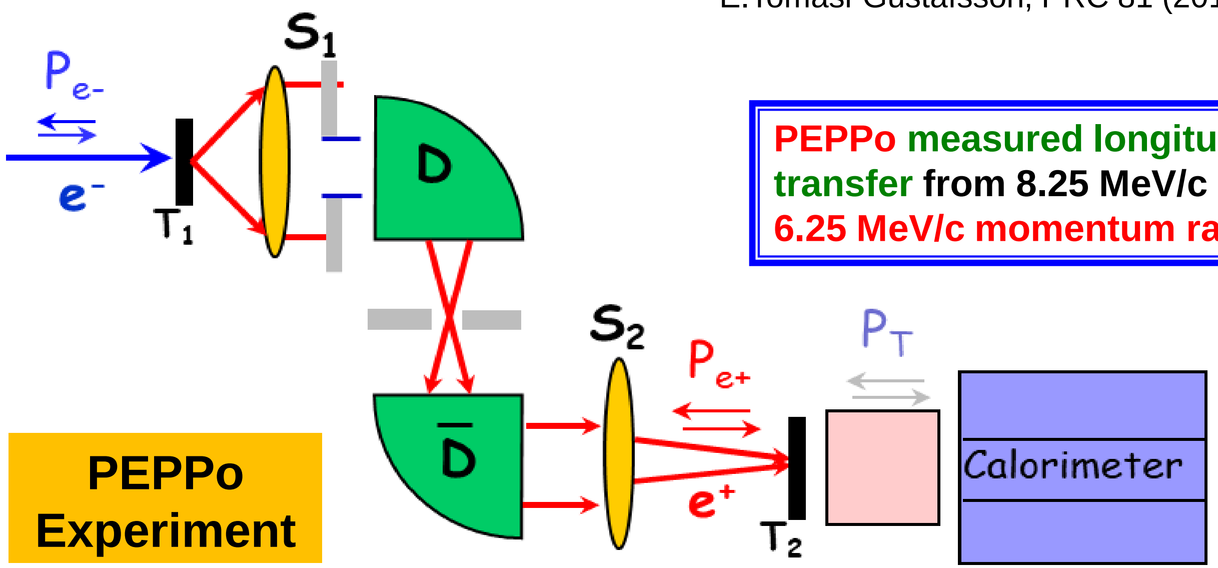
E.A. Kuraev, Y.M. Bystritskiy, M. Shatnev, E.Tomasi-Gustafsson, PRC 81 (2010) 055208

Polarized Bremsstrahlung

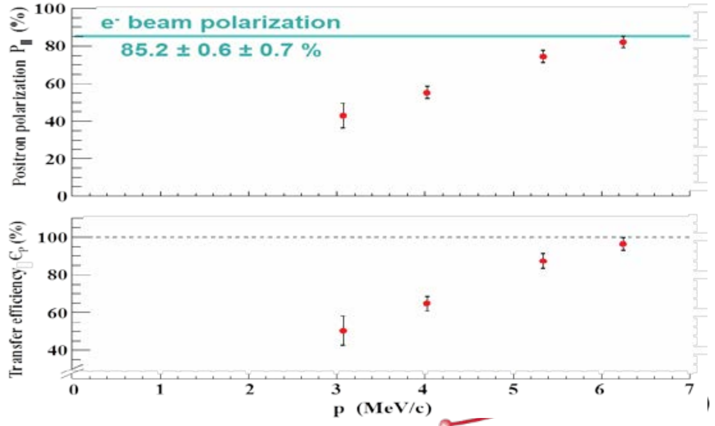


Polarized Pair Creation





PEPPo measured longitudinal polarization transfer from 8.25 MeV/c e⁻ to e⁺ in the 3.07-6.25 MeV/c momentum range.



PEPPo Experiment

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

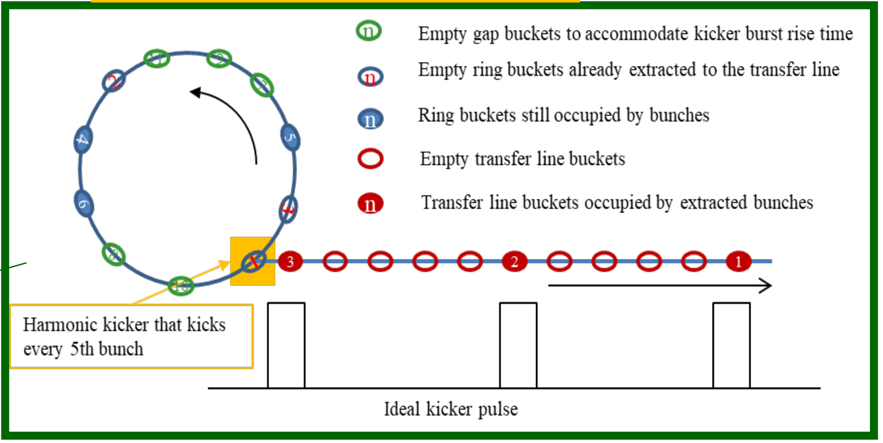
Polarized Position Injector for JLEIC

- PEPPo provides a new option for polarized positrons in a 10-100 MeV range
  - Pro: low neutron radiation
  - Con: low position yield (10^{-5} to 10^{-3})
- Mitigation of low current: Accumulation
  - "hot" positrons after conversion: hard to accumulate with large phase space distribution
  - "cold" electrons before conversion: easy to accumulate

- Design of the polarized positron injector should
  - reach averaged injected positron current (in a pulse mode) around ~3 nA in order to have reasonably short injection time and high equilibrium polarization
  - Base on the state-of-the-art technology in each major step, or with modest R&D effort.

Polarized electron source → Accumulation of polarized electrons → Hitting the target to get positrons → CEBAF (JLEIC)

Extraction by RF Kicker



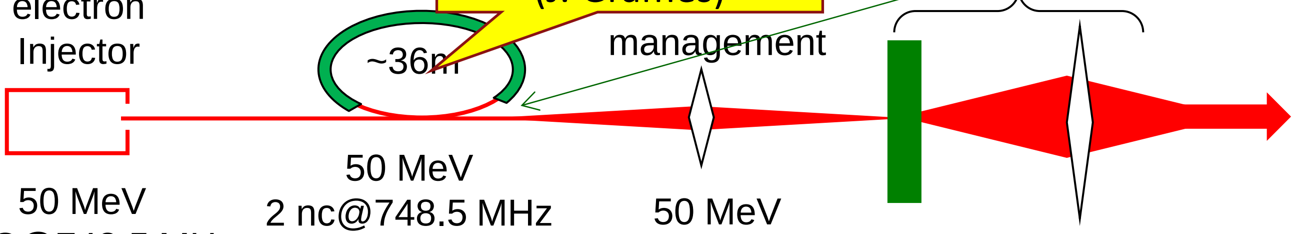
Polarized electron Injector

Compact accu[mulator] w/ 500-turn p[hase] painting i[njection]

Alternately, a high intensity gun (2 nC) (J. Grames)

Positron conversion and collection

management



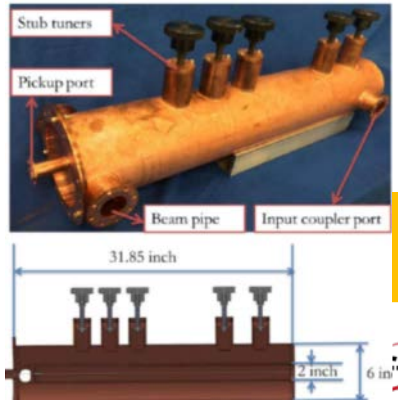
50 MeV
4 pC@748.5 MHz
85% polarization

50 MeV
2 nc@748.5 MHz
85% polarization

50 MeV
2 nC@17 MHz
80% polarization

10^{-5} - 10^{-3} efficiency
>60% in polarization

~30 MeV e^+
1 pC @ 17 MHz
> 60% polarization



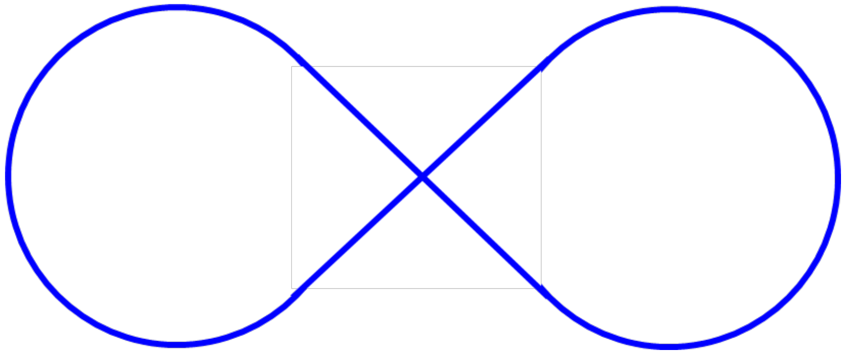
Harmonic RF Kicker

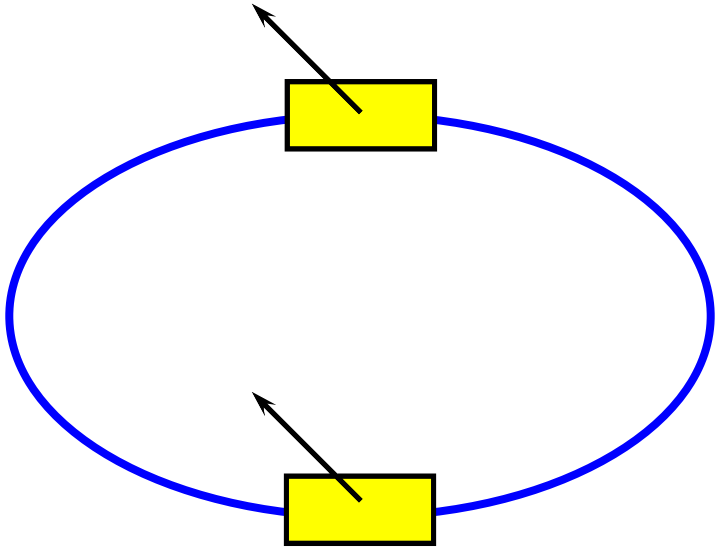
Spin Transparency Study and Experimental Test

- The spin motion is degenerate, any spin direction is periodic
- The spin tune is zero
- In an ideal case, any polarization direction is preserved
- Examples of spin transparent accelerators
  - Figure-8 accelerator
  - Racetrack accelerator with two full Siberian snakes located opposite to each other and their axes **parallel** to each other

- V. Morozov (Lead PI), Y. Derbenev, R. Huang, F. Lin (JLab)
- H. Huang (Co-PI), F. Meot, V. Ptitsyn (BNL)
- A. Kondratenko, M. Kondratenko (Novosibirsk)
- Y. Filatov (MIPT)

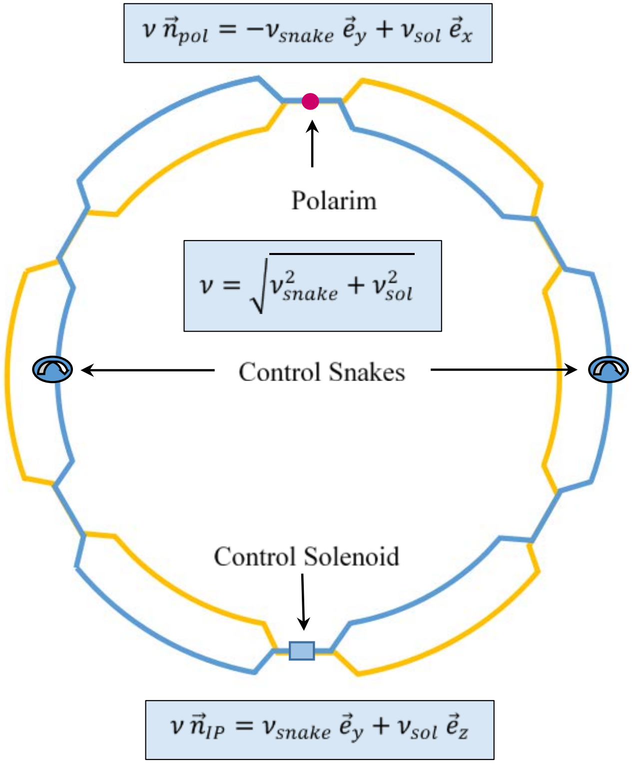
Supported by US DoE NP EIC R&D FOA funds





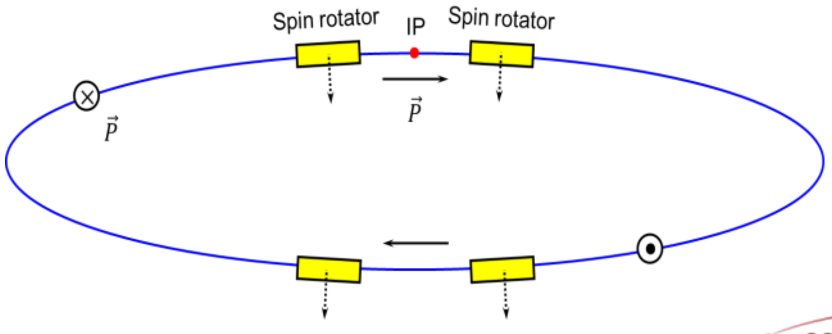
Setup of Spin Transparency Mode Test at RHIC

- RHIC is a perfect place for an experimental test of the spin transparency mode
- 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
  — Spin rotator = radial module
  — Spin rotator or small mismatch between snake strengths = longitudinal module
- Existing polarimeter
- Can test many features of the spin transparency mode and 3D spin rotator



Potential Benefit to eRHIC Electron Ring

- Configure the electron ring in the spin transparency mode
- Two spin rotators around an IP serve as a full Siberian snake
- Benefits
  — Same lifetimes of the two spin states
  — Simplified spin matching



Experimental Scenarios

- **Injection and acceleration** of polarized protons in the spin transparency mode in RHIC
  - Beam is injected vertically polarized
  - Stabilizing vertical polarization by adjusting the angle between the snake axes φ_{sn} to ~10º. The spin tune is $\nu_s \approx \varphi_{sn}/\pi \approx 0.05$

- **Demonstration** of polarization control in the collider
  - Demonstrate polarization reversal at the polarimeter
  - Turn the solenoid on to set $\nu_{sol} = 0.01$ (or ~2% snake strength mismatch)
  - Vertical polarization component at the polarimeter $n_y = -\nu_{sn}/\sqrt{\nu_{sn}^2 + \nu_{sol}^2}$
  - Sweep the angle between the snakes from -10º to 10º thus changing spin tune from -0.05 to 0.05
  - A similar test with the solenoid off can measure the zero-integer spin resonance strength

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							■	■

Summary

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

- Ion and electron polarization schemes have been designed.

- Spin tracking validated figure-8 based polarization control schemes for the whole JLEIC complex
  - Both ion and electron polarizations > 80% can be reached

- Spin transparency mode will be studied in RHIC

Back Up

Spin Matching

- **Spin matching**
  - Optics and layout must be adjusted so that $(\partial \tilde{n}/\partial \delta)^2$ is small where $1/|\rho(s)|^3$ is large
  - So far it is only possible with linear approximation for spin motion
  - In general, the rotators and the sections between them are the main source of depolarization
  - By suitable choice of optics, it may be possible to make 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.

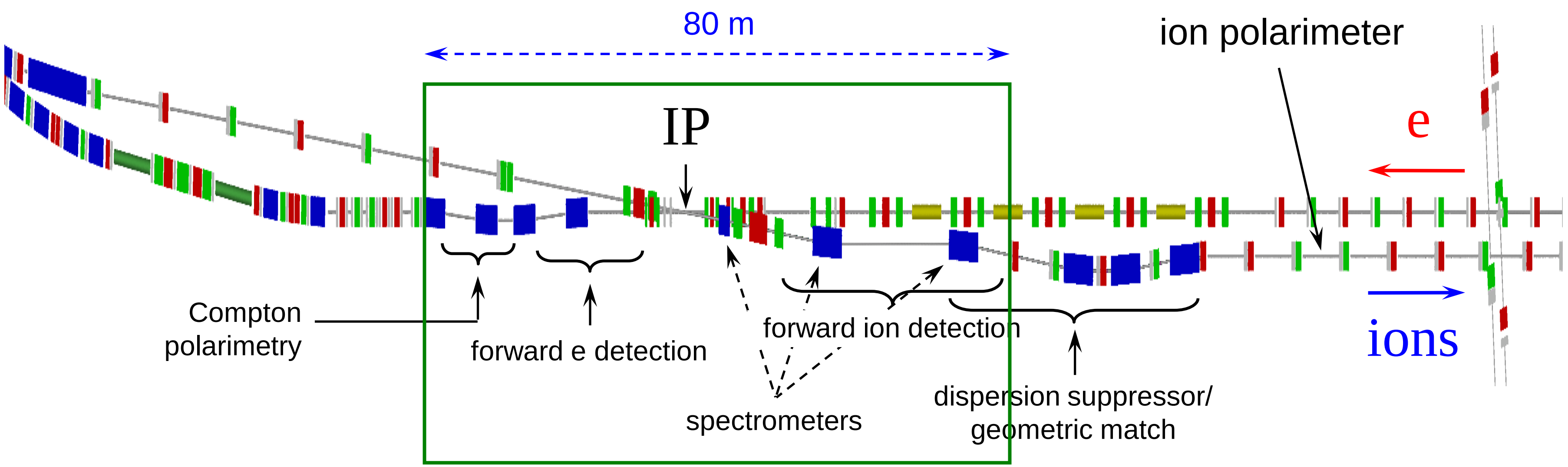
- **Spin matching effect**
  - As for example at HERA, it reduces the strengths of 1st spin-orbit resonances and improves the polarization lifetime.

Electron Spin Matching

- **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 dipole magnetic fields
    - For vertical polarization 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)
    - The greatest danger comes from roll and vertical misalignment of arc quadrupoles and final focusing quadrupoles
- **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

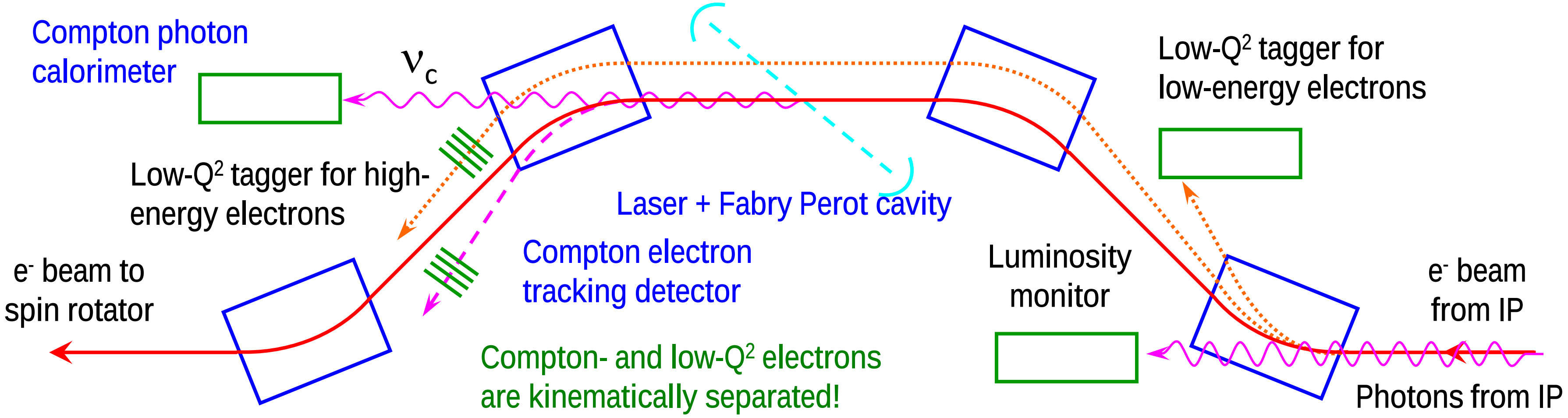
Ion Polarization Measurement Strategy

- Ion 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



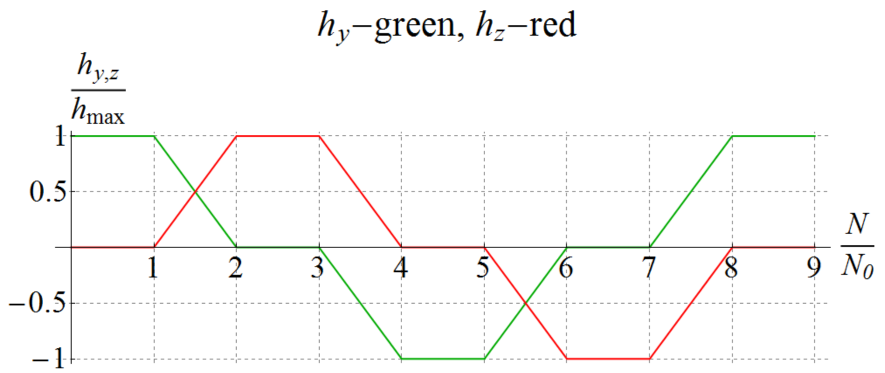
Compton Polarimeter

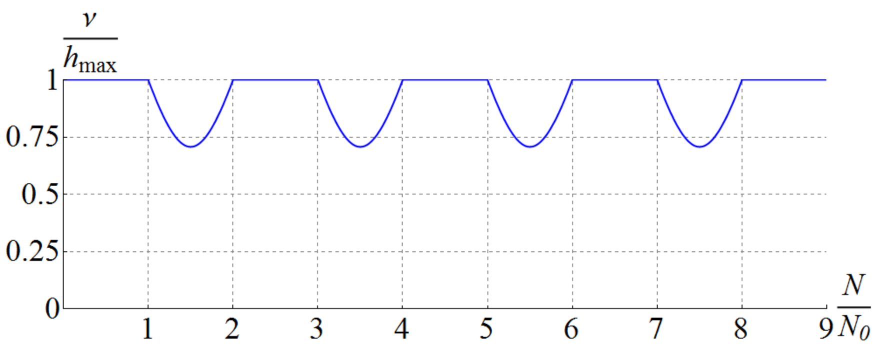
- Dipole chicane immediately downstream of the IP for detection of low-Q^2 electrons
- Compton polarimeter located in the middle of the chicane
  - same polarization at the laser as at the IP due to zero net bend
  - non-invasive continuous monitoring of electron polarization



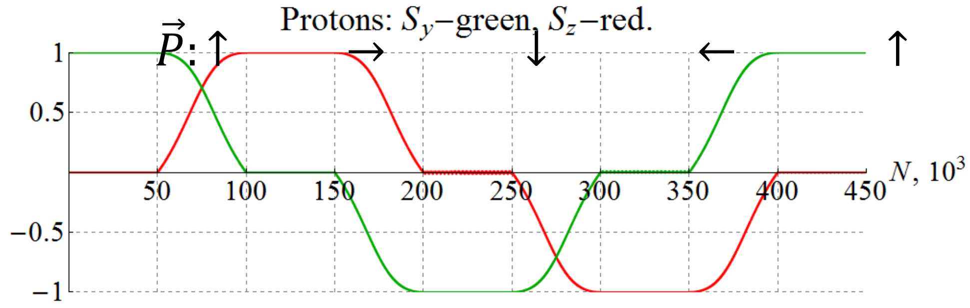
Spin Flipping

- Adiabaticity criterion: spin reversal time must be much longer than spin precession period $\Rightarrow$ 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 $\Rightarrow$ 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

$N_0 = 50 \cdot 10^3$