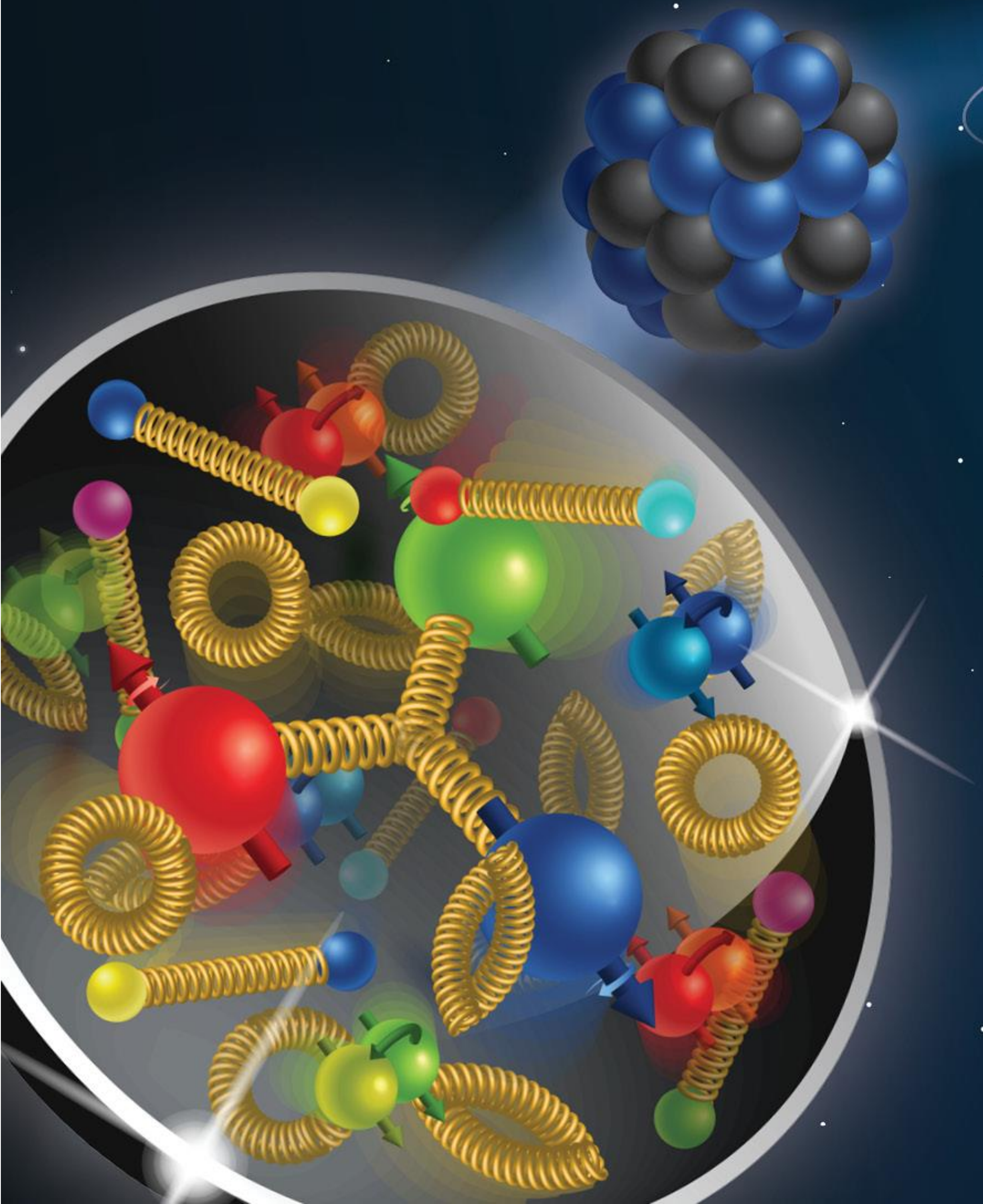


Preservation of electron polarization ramping in the EIC rapid cycling synchrotron

Vahid Ranjbar

FCC Optics Tuning and Corrections for Future Colliders workshop

June 27, 2023

Electron-Ion Collider

BROOKHAVEN NATIONAL LABORATORY Jefferson Lab U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

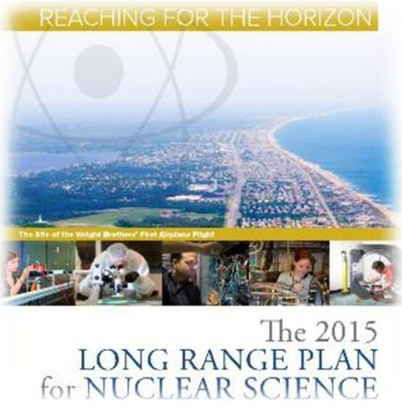
- EIC Requirements and Design Overview
- RCS Lattice Design Considerations
    - Spin Resonances Review
    - Periodicity and Tune
    - Arc Insert and bypass
- Managing Lattice Evolution
    - Spin Resonance Canceling Insertions
    - Current Lattice Twiss Parameters
- Polarization Performance
    - Spin imperfection correction scheme
- Generalization of EIC's RCS polarized approach
    - Intrinsic spin resonance cancelling cells.
- Summary

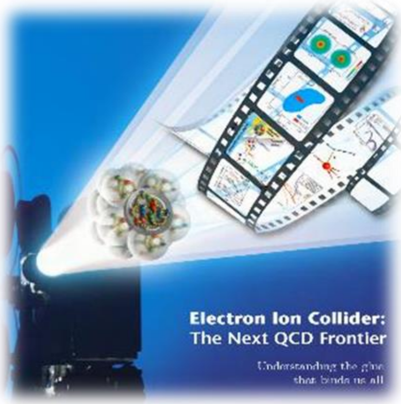
EIC Project Requirements

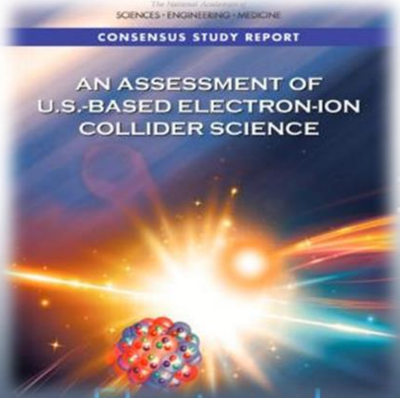
Project Design Goals

- High Luminosity: L= 10^{33} – 10^{34}cm^{-2}sec^{-1}, 10 – 100 fb^{-1}/year
- Highly Polarized Beams: 70%
- Large Center of Mass Energy Range: E_{cm} = 20 – 140 GeV
- Large Ion Species Range: protons – Uranium
- Large Detector Acceptance and
  Good Background Conditions
- Accommodate a Second Interaction Region (IR)

Conceptual design scope and expected performance meets or exceed NSAC Long Range Plan (2015) and the EIC White Paper requirements endorsed by NAS (2018).

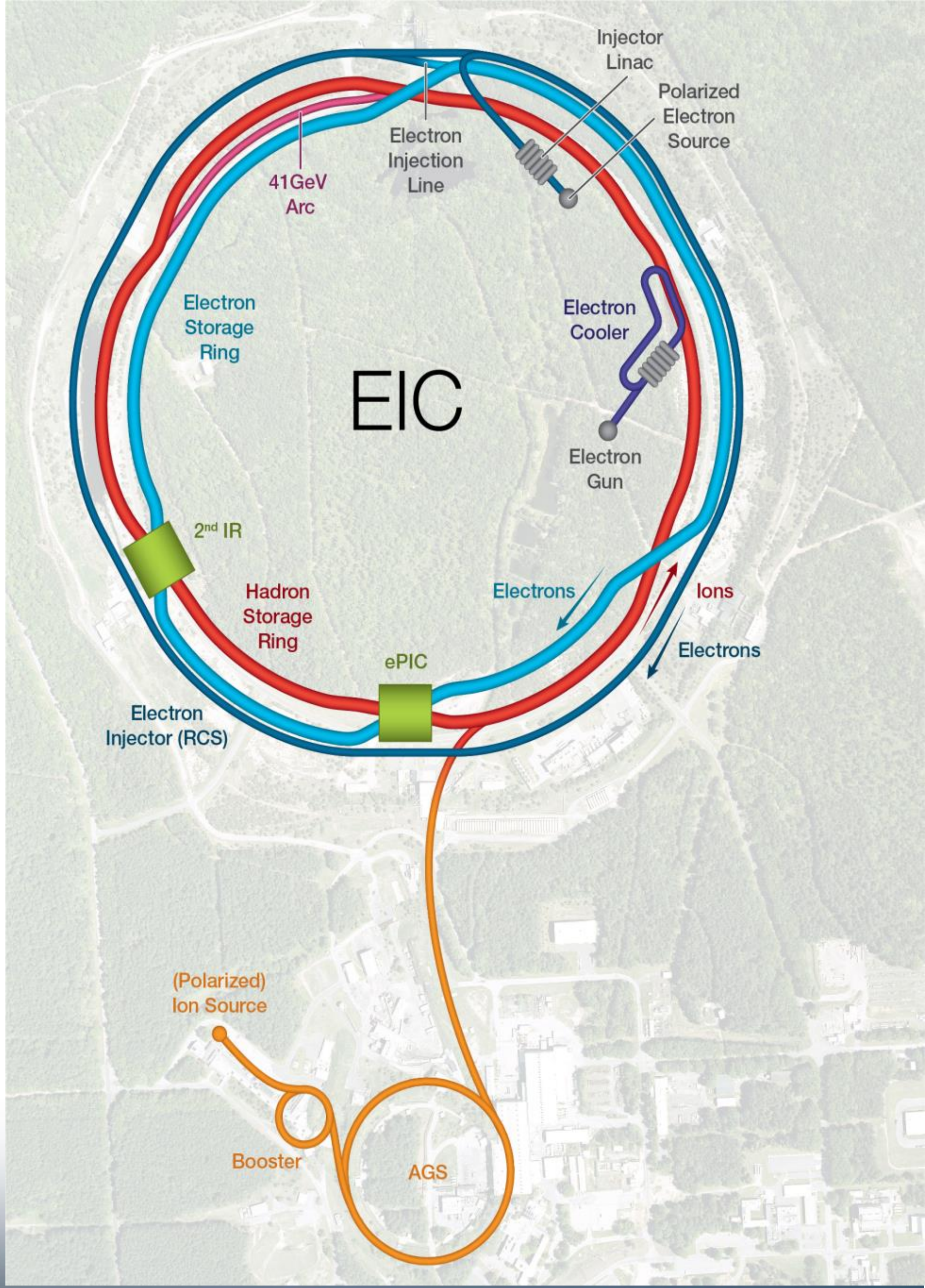






EIC Design Overview

- Design based on **existing RHIC Complex**
  - RHIC is well maintained, operating at its peak
  - RHIC accelerator chain will provide EIC hadrons
- High luminosity interaction region(s)
  - $L = 10^{34} cm^{-2} s^{-1}$
- Hadron storage Ring (RHIC Rings) 40-275 GeV
  - Suppled by AGS and Booster Injectors
- Electron storage ring 5–18 GeV
  - Need to Inject polarized bunches every second
- Rapid Cycling Synchrotron (RCS)
  - Designed to supply polarized bunches to the ESR every second
  - Supplied by 400 MeV LINAC



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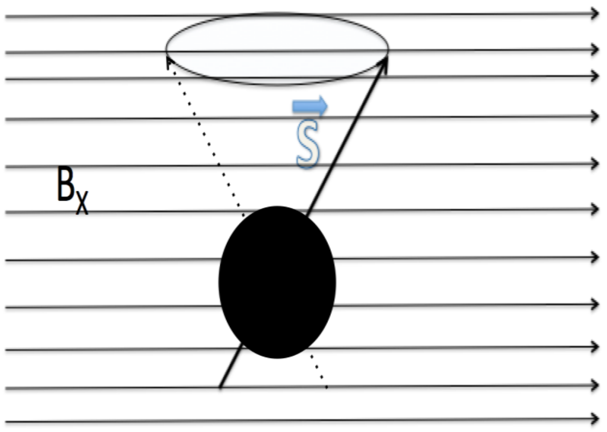
The EIC's Rapid Cycling Synchrotron (RCS)

- Will receive 7nC electrons polarized to ~90% from pre-injector at 400 MeV.
- The RCS Requirements:
  - needs to merge these bunches into one 28nC bunches for 5 and 10 GeV operations and 11nC for 18 GeV.
  - Preserve polarization during acceleration from 400 MeV to extraction at 5, 10 and 18 GeV. With losses less < 5%.

Spin Resonance Review

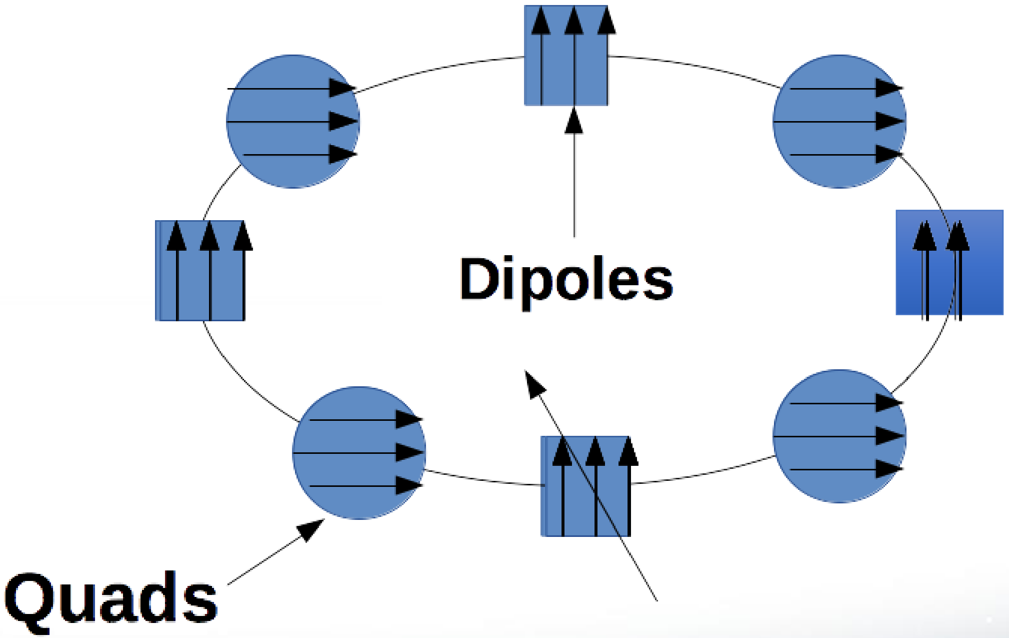
Spinor Form

T-BMT Equation: $\frac{d\vec{S}}{dt} = \frac{q}{\gamma m}\vec{S} \times \left((1+G\gamma)\vec{B}_{\perp} + (1+G)\vec{B}_{\parallel}\right) \longrightarrow \frac{d\Psi}{d\theta} = -\frac{i}{2}\begin{pmatrix} f_3 & -\xi \\ \xi^* & -f_3 \end{pmatrix}\Psi.$



Spin Resonance: Spin Tune = Rate of Horizontal field kicks
(vertical motion through Quads)

Gγ = N +/- Qz Intrinsic or **Gγ = N** Imperfection
Due to vertical betatron Due to vertical closed orbit error



Spin Resonance Driving terms

$$\mathrm{w}_K = \lim_{N_T \to \infty} \frac{-1}{2\pi N_T} \int_0^{LN_T} \left[(1+G\gamma)(z'' + \frac{iz'}{\rho}) - i(1+G)(\frac{z}{\rho})' \right] e^{iK\Theta(s)} \mathrm{d}s.$$

Spin Resonances come from vertical motion mostly. The z'' term dominates

$$z = z_\beta + z_{co}$$

Intrinsics Resonance

$$K = N \pm Q_z$$

Imperfection Resonance

$$G\gamma = K = N$$

$$\zeta_P(\frac{K \pm Q_z}{P})$$

$$\zeta_P(x) = \frac{\sin(P\pi x)}{\sin(\pi x)}.$$

Tell when they are significant

Concept Overview: Spin Resonance Free Lattice

- Both the strong intrinsic and imperfection resonances occur at:
  - K = nP +/- Qy
  - K = nP +/- [Qy] (integer part of tune)
- To accelerate from 400 MeV to 18 GeV requires the spin tune ramping from
  - **$0.907 < G\Upsilon < 41.$**
- If we use a periodicity of P=96 and a tune with an integer value of 50 then our first two intrinsic resonances will occur outside of the range of our spin tunes
  - $K1 = 50+\nu_y$ (ν_y is the fractional part of the tune)
  - $K2 = 96 – (50+\nu_y) =46-\nu_y$
  - Also our imperfection will follow suit with the first major one occurring at K2 = 96 – 50 = 46

How to make this work in the RHIC tunnel?

- It is easy to accomplish this with a perfectly circular ring. Just construct a series of FODO cells with bending magnets so that we have total periodicity of 96.
- The problem is that the RHIC tunnel is not circular and has an inherent six fold symmetry.
- The solution make the spin resonances integrals over the straight sections equal to zero. Or lattice insert where spin kicks between dipoles cancel.

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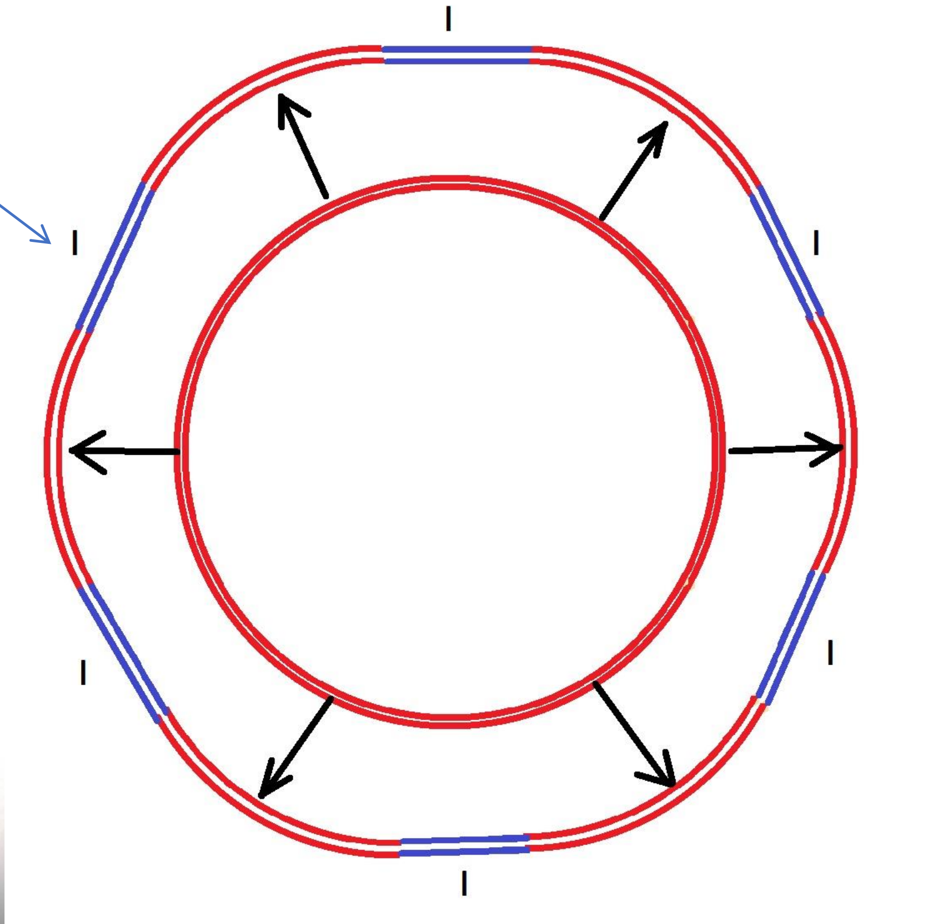
Project onto the RHIC tunnel

RHIC Tunnel

For all the insertion regions between arcs we forced the spin contribution to cancel between the dipoles.



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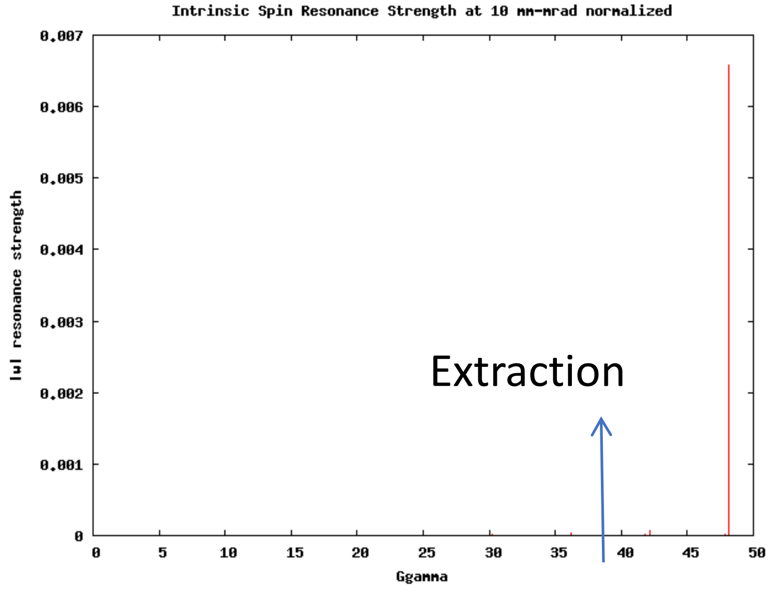
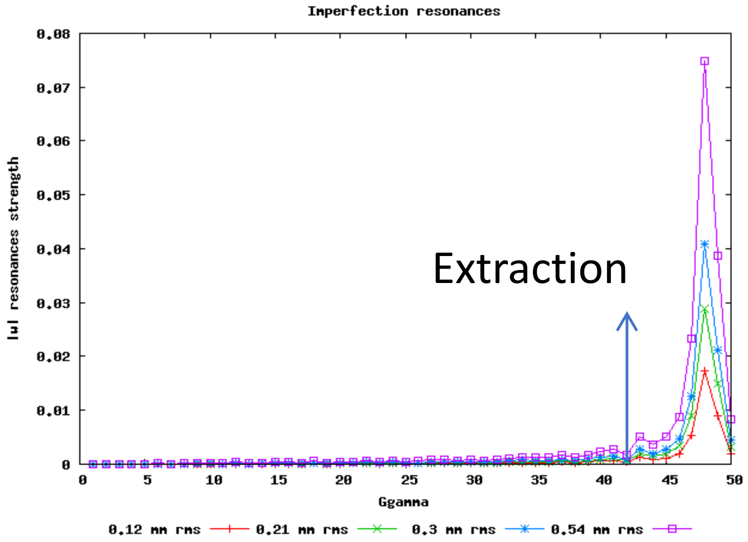
Calculating Spin Resonances





- No polarization loss from cumulative effective of intrinsic spin resonances for distributions over 100 msec ramp.
- Issue to control: Imperfection spin resonances ~ vertical rms orbit 0.5 mm to keep losses < 5%.

RCS Design Parameters

- Current Design accommodates detector bypasses and RF physical needs
- Two connecting arc designs
  - Detector→ IP6, IP8
  - RF, Extraction, Injection
    - IP10→ RF
    - IP12→ Extraction/injection
    - IP2
    - IP4
- Achieved bypass at the IP.
- Impacts symmetry of lattice.
  - However by optimizing the quad strengths in the bypass region we can recover low intrinsic losses.

❖ **Spin resonance free electron ring injector Phys. Rev. Accel. Beams 21, 111003 – Published 27 November 2018**

RCS lattice changes

- Since original design RCS lattice has undergone two major revisions and currently in middle of a third
  - Avoid obstructions of walls and other beamlines
  - Remove all RCS magnets from the detector hall
  - Maximum beta functions increased from 70m to 120m
  - Maintained zero polarization losses on ramp due to intrinsic spin resonances.
  - Improved off-momentum DA from 1% to 1.5%

Spin Resonance Canceling Lattice Insert:

The transport of spin polarized beam across a standard focusing and defocusing lattice (FODO) introduces transverse spin kicks which can accumulate between dipoles. These spin kicks will, for an appropriate spin tune, add up coherently and lead to beam depolarization marked by the presence of an intrinsic spin resonance. However if the quadrupole's location and strength can be organized correctly the transverse spin kicks can cancel for all spin tunes. This is somewhat similar to what is known as spin matching at a particular spin tune. However since the cancellation occurs between spin precessing dipoles, this makes the spin matching condition work for all energies and spin tunes.

$$\int z'' e^{iK\theta} ds = \sum_n k_n z_\beta$$
$$= \sum_n k_n \sqrt{\beta_n} \cos(\mu_n + \phi) e^{iK\theta_n}$$

→ 0 between dipoles

$$0 = \sum_n k_n \sqrt{\beta_n} \cos(\mu_n)$$
$$0 = \sum_n k_n \sqrt{\beta_n} \sin(\mu_n).$$

Spin resonance canceling lattice cell design principles

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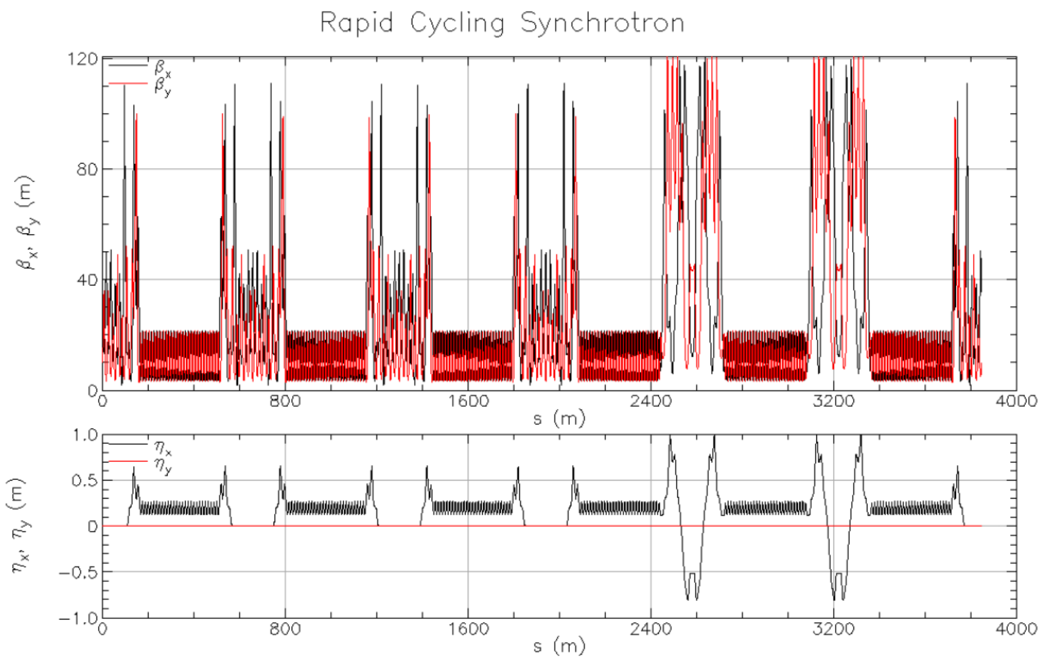
Baseline RCS optics

Thanks: Henry Lovelace III



- **β_{max}=120 m(both planes)**
- **Q_x = 58.8**
  - $\xi_x = 1$
- **Q_y = 64.2**
  - $\xi_y = 1$
- **5σ beam envelope does not exceed 16 mm**
  - 2/3 of the quadrupole radius is 13.3 mm

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Polarization Performance

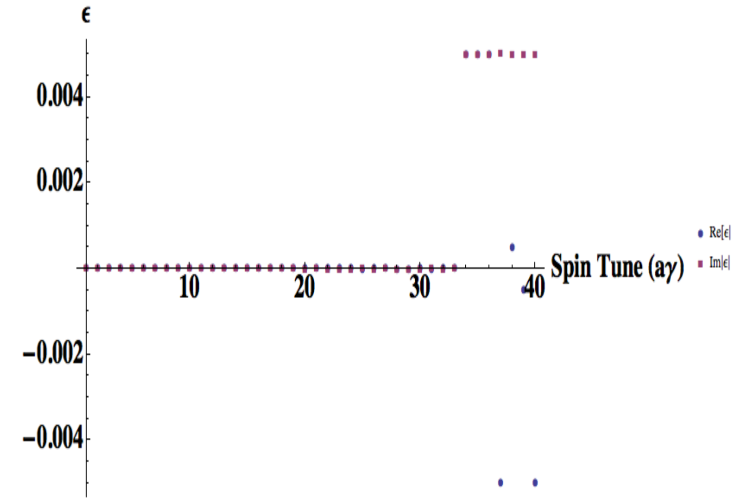
- Intrinsic resonance as calculated by DEPOL yield no cumulative depolarization loss for a beam with a vertical emittance of 40 mm-mrad rms normalized emittance (RCS's emittance at injection which falls to near zero by 18 GeV).
- Imperfections could however potentially cause greater than 5% losses during ramp.
- Due primarily to quadrupole misalignment and dipole rolls.
  - But these effects can be controlled to bring our losses below 5% on ramp.→ Orbit Smoothing and Imperfection bumps.

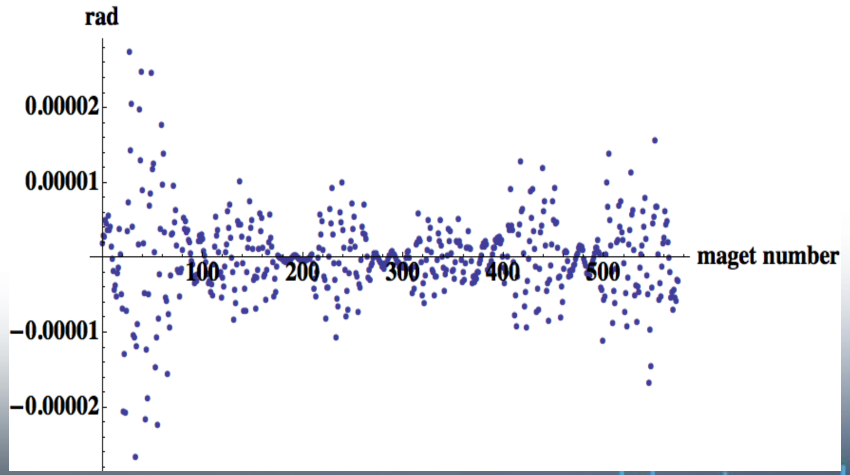
Analysis of Imperfections:

- Survey estimates are 0.2 mm rms with a 2 sigma cut off and +/- 1 mrad rolls. This yields an estimated rms orbit distortion of between 3-6 mm rms.
- Extracting at 10 GeV RCS can handle > 3 mm RMS orbit with < 5% pol. Loss and 2 mrad uncorrected rolls.
- With appropriate BPM and corrector pairs this can be corrected down to below 0.5 mm rms and push our polarization losses below 5% extracting at 18 GeV.
- Once corrected, dynamical changes of the relative field strength in the quads and dipoles of greater than 0.5% can be tolerated with little effect on polarization transmission.
- Orthogonal imperfection bump scheme to fix any remaining losses beyond SVD orbit smoothing.

Orthogonal Imperfection Bump

- **Static imperfection** bumps at any imperfection resonance location on the ramp.
- **Bumps are orthogonal** to each other and localized in energy space
  → no required bandwidth beyond what is needed to ramp the dipoles with the energy.
- **Example Shown on Right**: 10 to 15% (0.005 res.) Depolarization Kick Imaginary and Real no kicks anywhere else.





FCC-h Toy Lattice

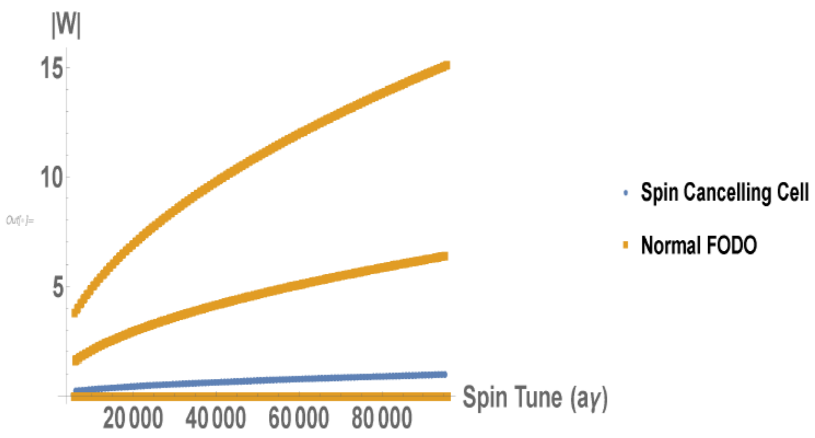


FIG. 9. DEPOL calculated spin resonances for a FCC-hh arc only (no insertions) lattice using standard FODO cell construction versus an FCC-hh like lattice with three quad arc cells which suppress the spin resonances.

TABLE V. FCC-h Arc only standard lattice

Bending Radius [km]	10.427
Peak Dipole Field [T]	16
Peak Possible $a\gamma$	95532
Circumference (arc only) [km]	83.081
Cell length [m]	213.03
Periodicity	390
Q_x	99.83
Q_y	100.57
C_x	-129.22
C_y	-130.03
BetaX MAX [m]	355.5
BetaY MAX [m]	354.99
Dx MAX [m]	2.22
Arc packing factor	0.78
Peak Quadrupole gradient [T/m]	320[a]

[a] CDR has 367 T/m

TABLE VI. FCC-h Arc only three quad optimized lattice

Bending Radius [km]	10.427
Peak Dipole Field [T]	16
Peak Possible $a\gamma$	95532
Circumference (arc only) [km]	99.239
Cell length [m]	254.46
Periodicity	780
Q_x	92.35
Q_y	33.71
C_x	-80.59
C_y	-74.91
BetaX MAX [m]	214.79
BetaY MAX [m]	485.60
Dx MAX [m]	2.05
packing factor	0.66
peak quadrupole gradient [T/m]	610[a]

[a] scaled value based on CDR peak quadrupole value would be 699 T/m

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Optical changes for FCC-h arcs:

Full Cell

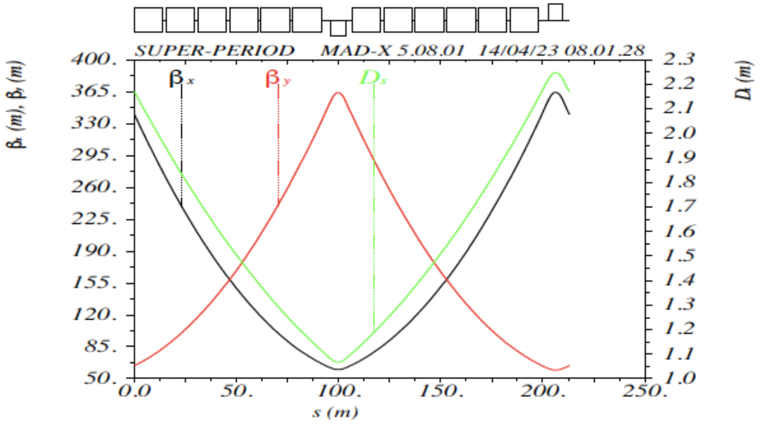

FIG. 7. Beta functions for horizontal and vertical planes and dispersion in the horizontal plane are shown for one FODO cell of the arc FCC-h lattice (per 2019 CDR)

Half Cell

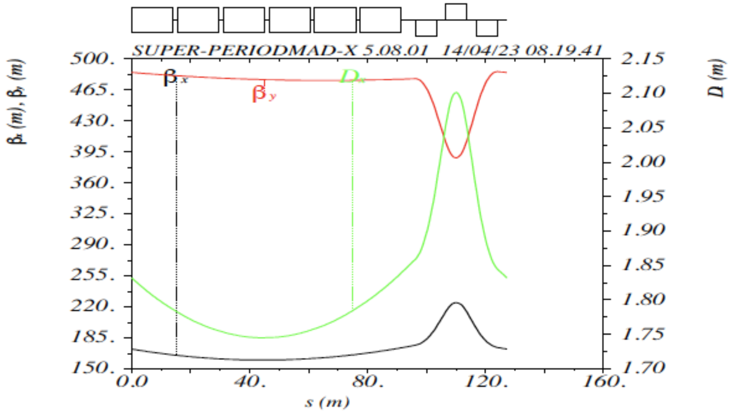

FIG. 8. Beta functions for horizontal and vertical planes and dispersion in the horizontal plane are shown for one Dipole to Dipole (similar to half standard FODO cell) of my Toy arc only FCC-h lattice.

Summary

- Resonances in RCS lattice are driven by imperfections
- Intrinsic resonances are so weak that even large field distortions don't hurt.
- Resilient to misalignments, dipole rolls and orbit distortions:

  - Up to 0.4 mm quadrupole misalignments and 2.5 mrad dipole rolls are tolerable provided the orbit is corrected to 0.5 mm RMS level.

  - Assume orbit correction using SVD algorithm with a corrector and a BPM next to each quadrupole.

  - within state-of-the art orbit control hard-and software
- This will result in > 95% polarization transmission.
- To provide additional margin we show that fixed orthogonal imperfection bumps are capable of removing any residual polarization losses.
- Using intrinsic resonance canceling arc cells one can build up a whole ring with all sorts of broken symmetry and still avoid strong intrinsic depolarization. One of the challenges is to build these cells in such a way that the beta functions and dispersion are controlled. Additionally, their natural dynamic aperture and chromatic features should be studied to better understand the optimal configuration.