Brookhaven National Laboratory

Jefferson Lab

U.S. DEPARTMENT OF ENERGY

Electron Synchrotron for EIC

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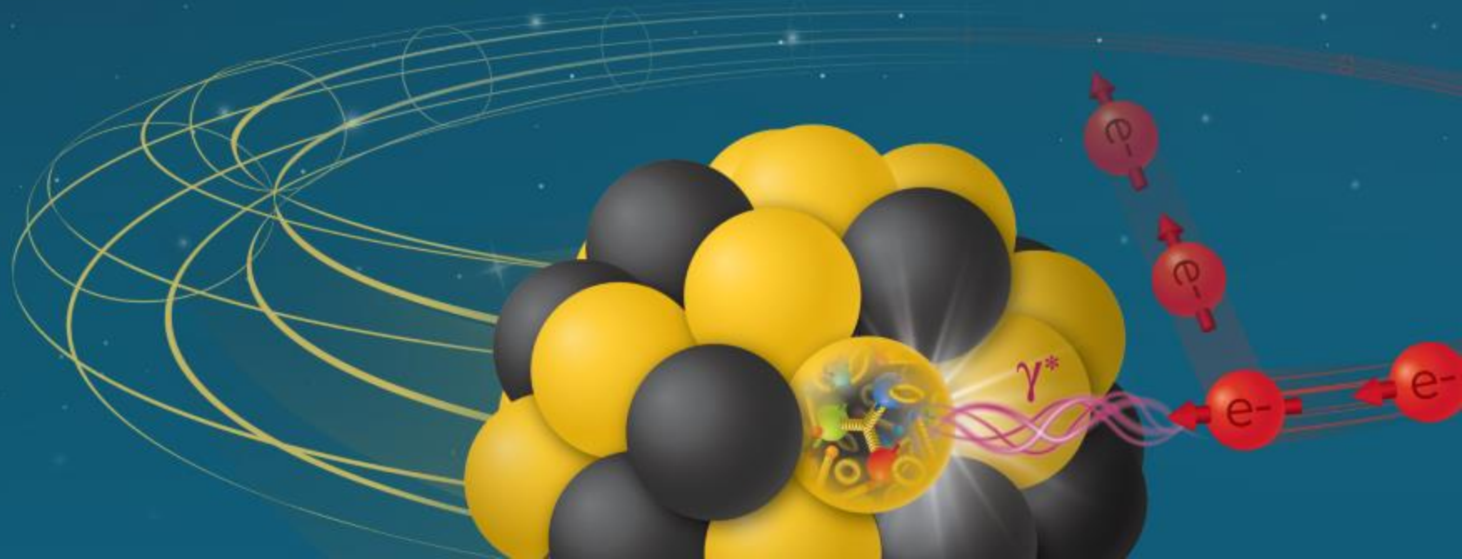
Accelerator Physics/Engineering Seminar at MSU/FRIB

Feb. 23rd 2024

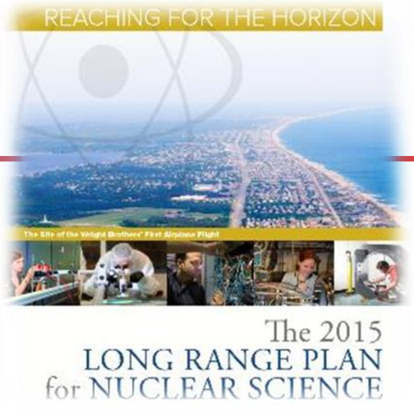
Electron-Ion Collider



Outline

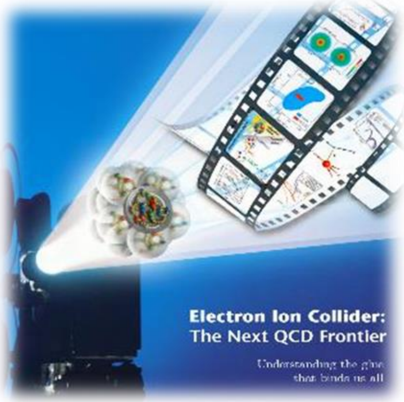
- EIC Requirements and Design Overview
- RCS Charge Accumulation Scheme
  - RF Injection
  - Bunch Merging
- RCS Lattice Design Considerations
  - Spin Resonances Review
  - Periodicity and Tune
  - Arc Insert and bypass
- Managing Lattice Evolution
  - Spin Resonance Canceling Insertions
  - Current Lattice Twiss Parameters
  - Dynamic Aperture
- Polarization Performance
  - Spin imperfection correction scheme
- Summary

EIC Project Requirements

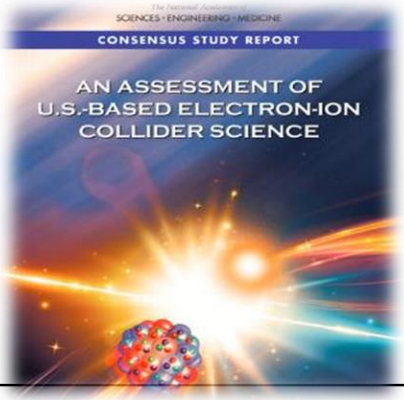


Project Design Goals

- 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)

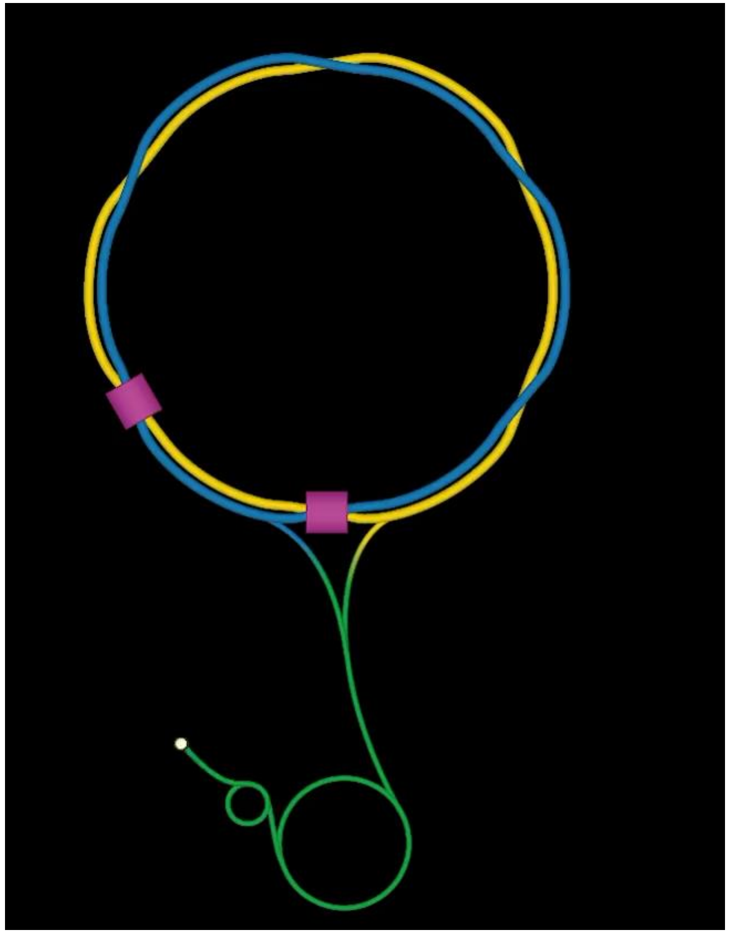


Conceptual design scope and expected performance meets or exceed NSAC Long Range Plan (2015) and the EIC White Paper requirements endorsed by NAS (2018).

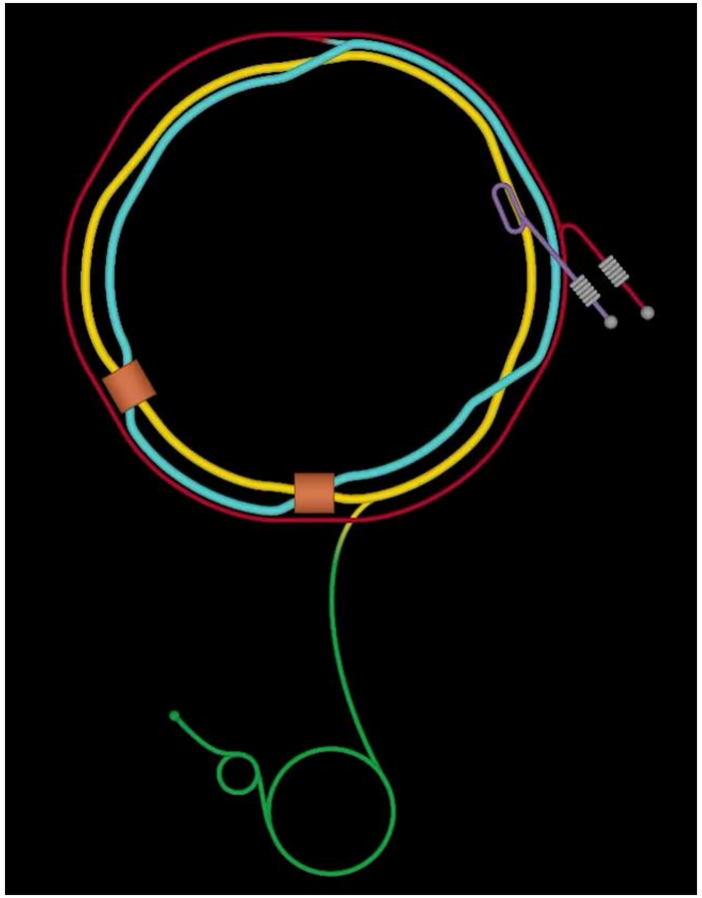


From RHIC to EIC:

RHIC Complex



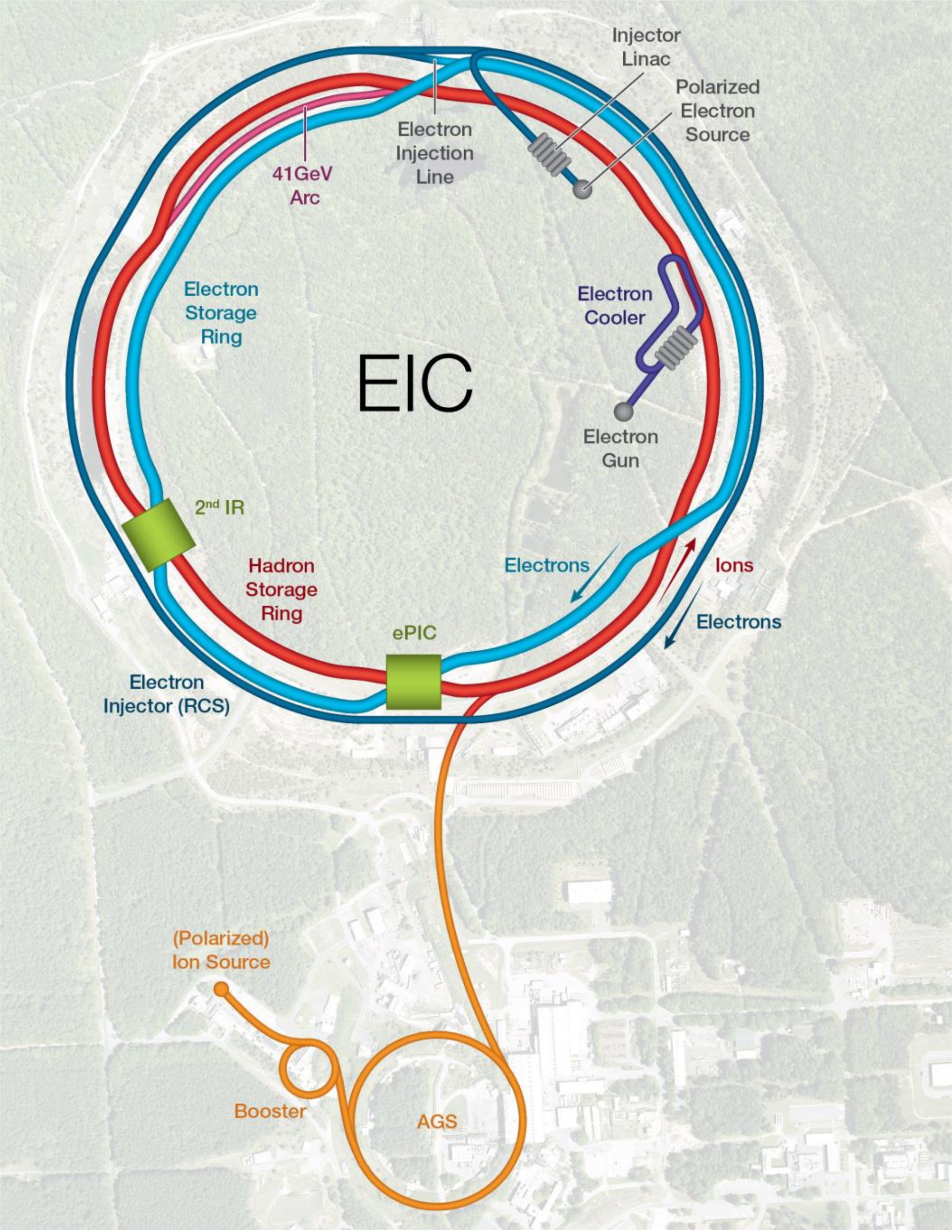
New EIC Complex



Note: Source
Moved from IP2 to IP12

EIC Design Overview

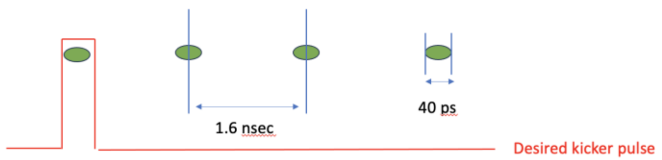
- Design based on **existing RHIC Complex**
  - RHIC is well maintained, operating at its peak
  - RHIC accelerator chain will provide EIC hadrons
- High luminosity interaction region(s)
  - $L = 10^{34} cm^{-2} s^{-1}$
- Hadron storage Ring (RHIC Rings) 40-275 GeV
  - Suppled by AGS and Booster Injectors
- 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



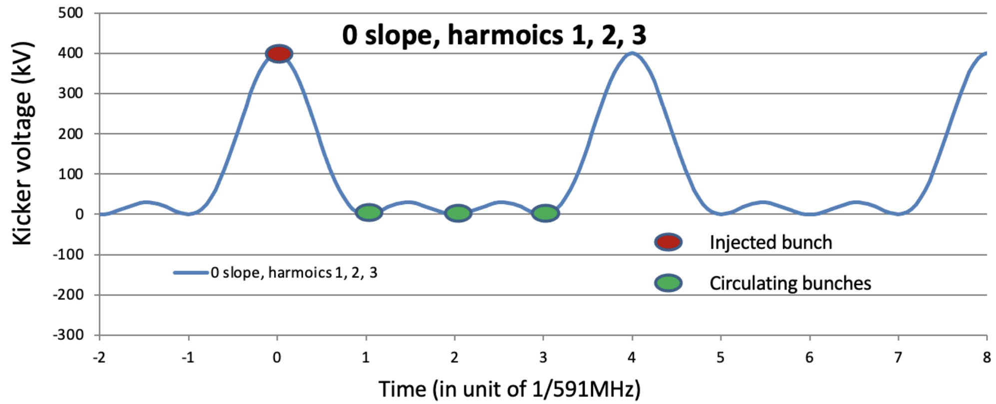
The EIC's Rapid Cycling Synchrotron (RCS)

- 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%.

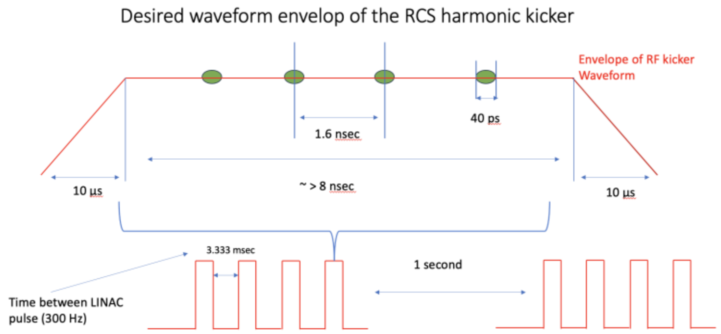
RF Injection Kicker



RCS RF injection HK micro-pulse: 0-slope scheme



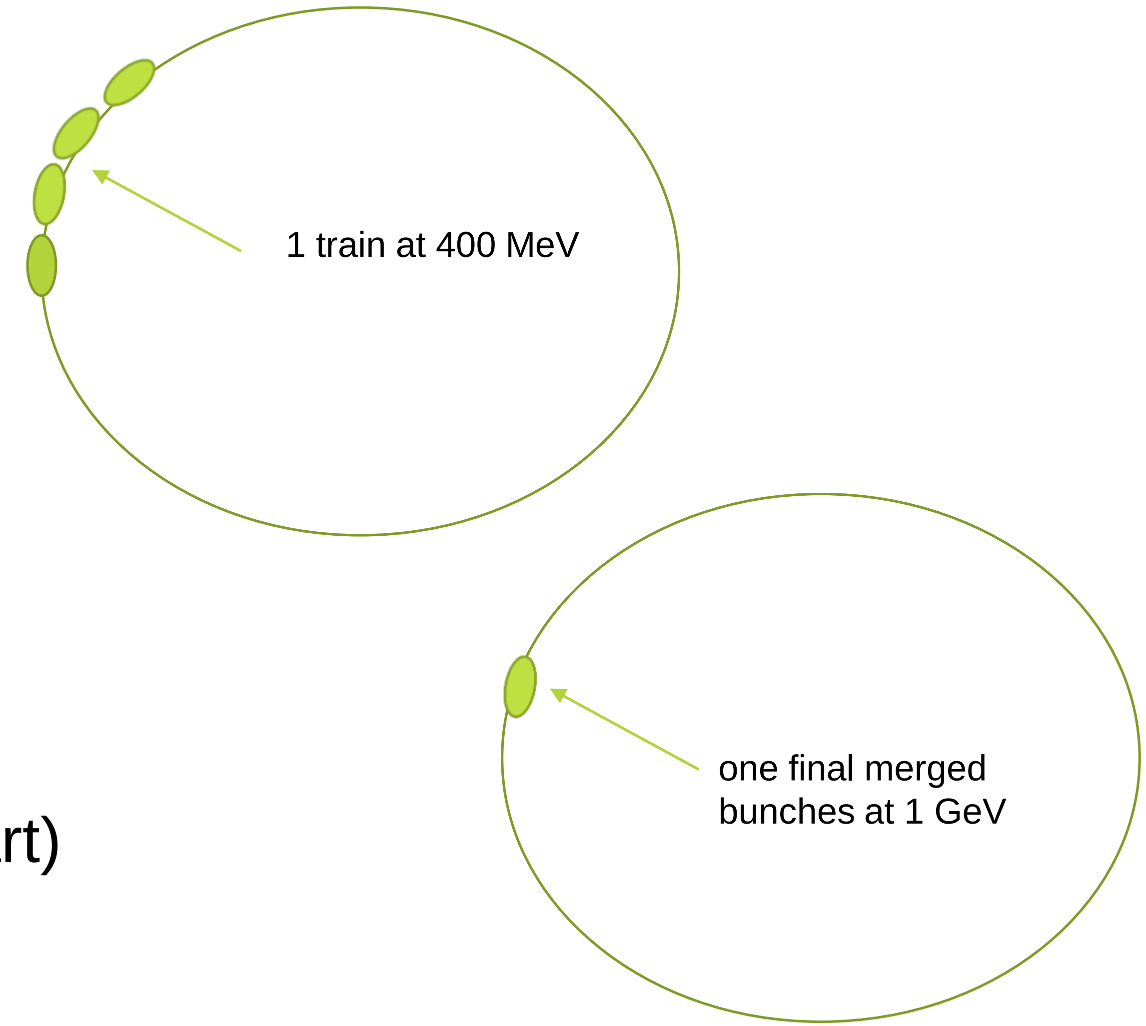
- Composed of two RF crab-like cavities (C1, C2)
  - C2: 147.8 MHz→ 150 kV
  - C1: 295.5 MHz → 100 kV
  - C2: 443.3 MHz→ 50 kV
- Kick of 0.5 mrad
  - Rise and fall in under one turn ~ 10 usec
- Slow bump of 2.5 mrad
  - Gives a total of 3 mrad necessary to kick bunch into RCS



Bunch Merge Scheme:

LINAC Pulse Pattern

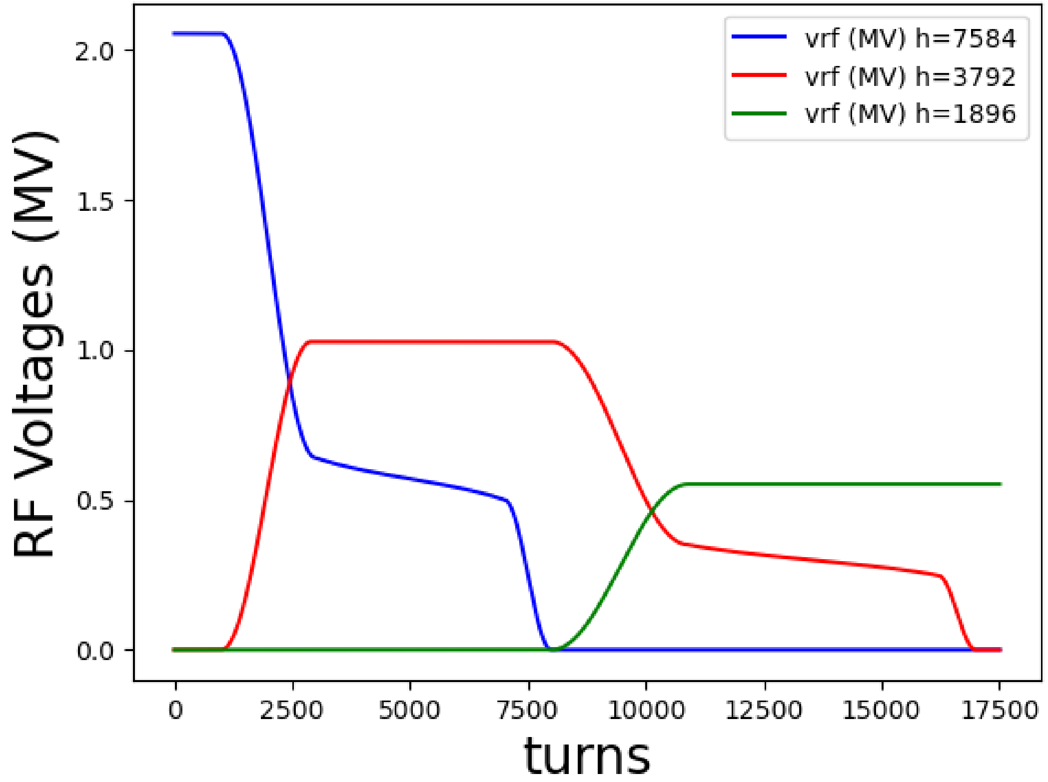
- Linac energy: 400 MeV
- One 7-nC bunch per pulse
- Pulsed 4 times per sec at ~300Hz
- Total fill time: 10 msec
- Bunch length: 40 ps RMS
- dp/p = 2.5×10^{-3} RMS
- $\sigma_t \times \sigma_E = 4\times10^{-5}$ eV-s
- Bunches filled in the RCS in neighboring rf buckets (1.69ns apart)
    - RF Injection kicker (next slide)



1 GeV merge general scheme:

Thanks: B. Lepore

RF Harmonic (Frequency)	H=7584 (591 MHz)	H=3792 (295.5 MHz)	H=1896 (147.8 MHz)
Max Voltage In MV:	2.054 MV	1.027 MV	.552 MV

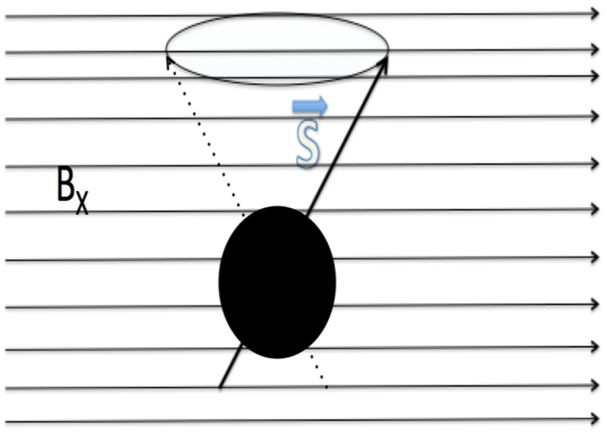


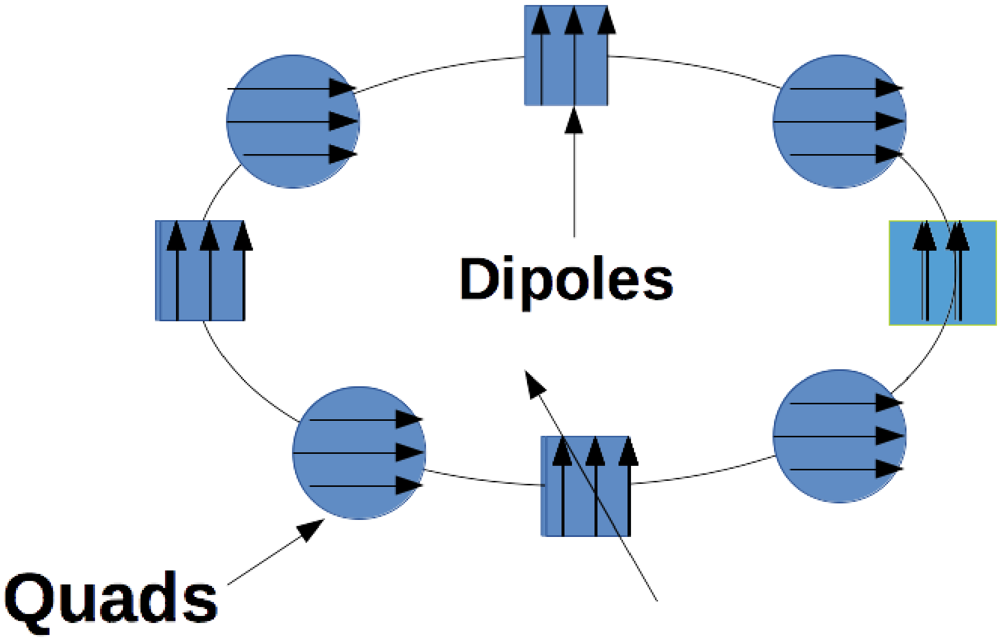
- This keeps us at just under 80% of the listed RF voltage on the lower harmonic cavities.
- Without collective forces this merge scheme yields a final rms emittance of <1.23e-4 eV-s (so, around a 1% longitudinal Emittance growth).
- With Collective Forces and a general phase offset to combat the potential well distortion the longitudinal rms emittance is <=2.6e-4 eV-s at the end of the merge.

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

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

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

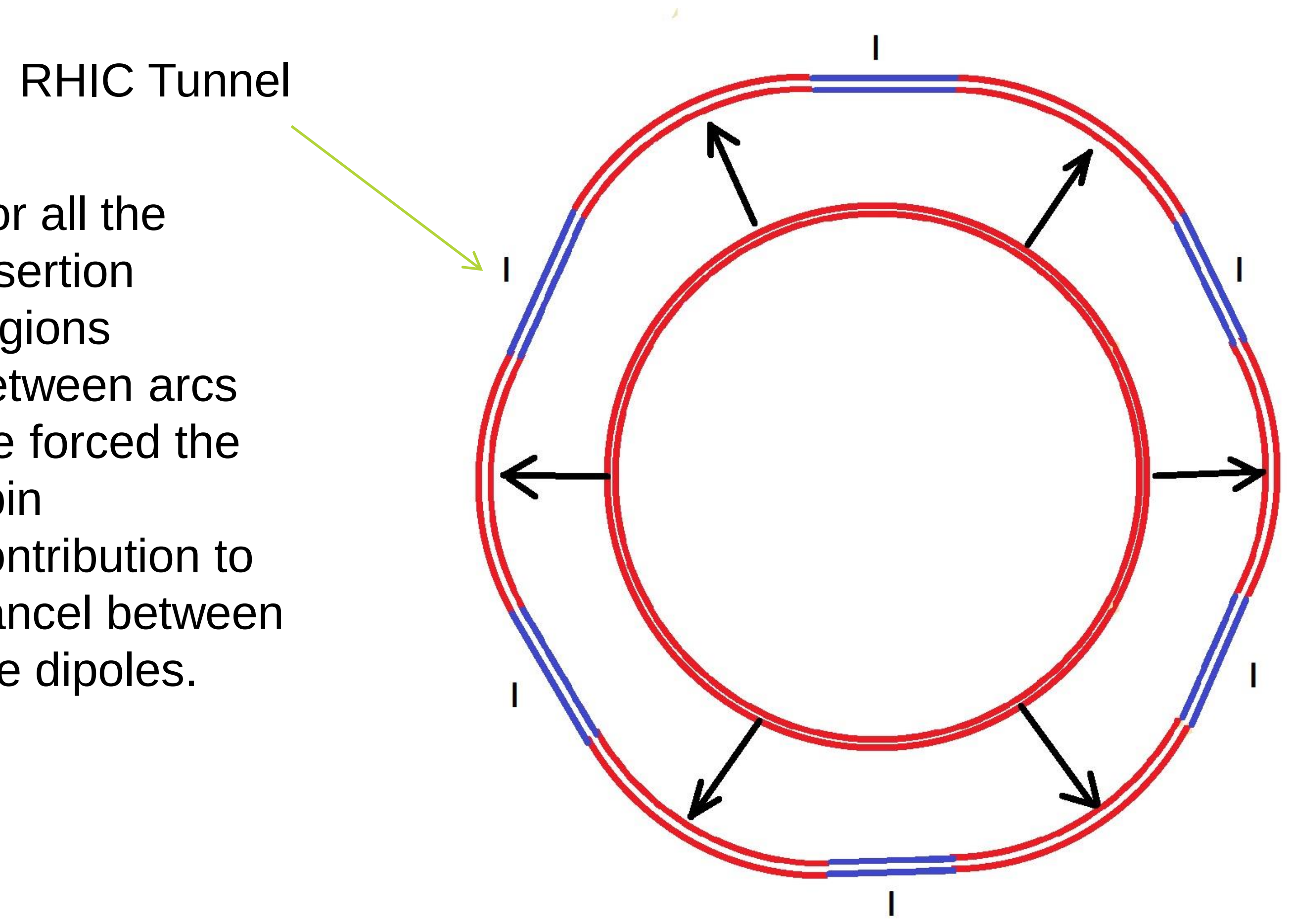
Concept Overview: Spin Resonance Free Lattice

- 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
  - **$0.907 < G\gamma < 41.$**
- 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
  - $K1 = 50+v_y$ (v_y is the fractional part of the tune)
  - $K2 = 96 – (50+v_y) =46-v_y$
  - 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?

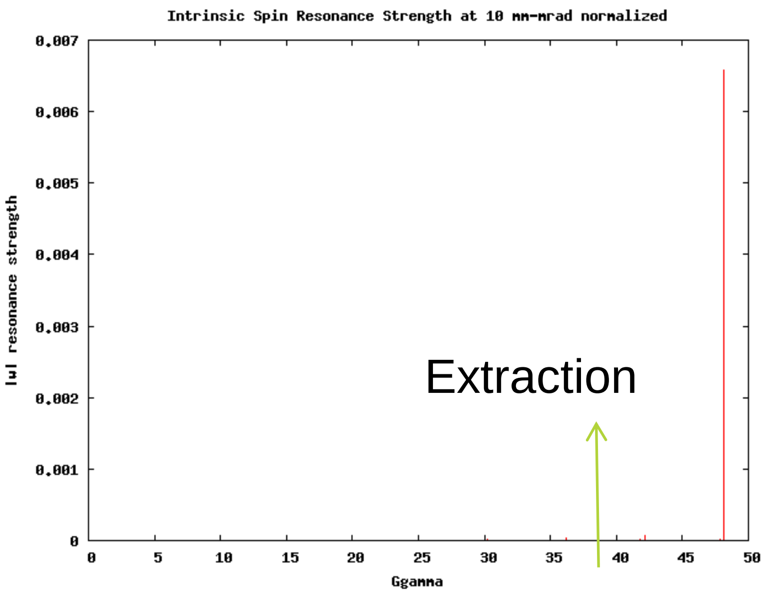
- It is easy to accomplish this with a perfectly circular ring. Just construct a series of FODO cells with bending magnets so that we have total periodicity of 96.
- The problem is that the RHIC tunnel is not circular and has an inherent six-fold symmetry.
- The solution make the spin resonances integrals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

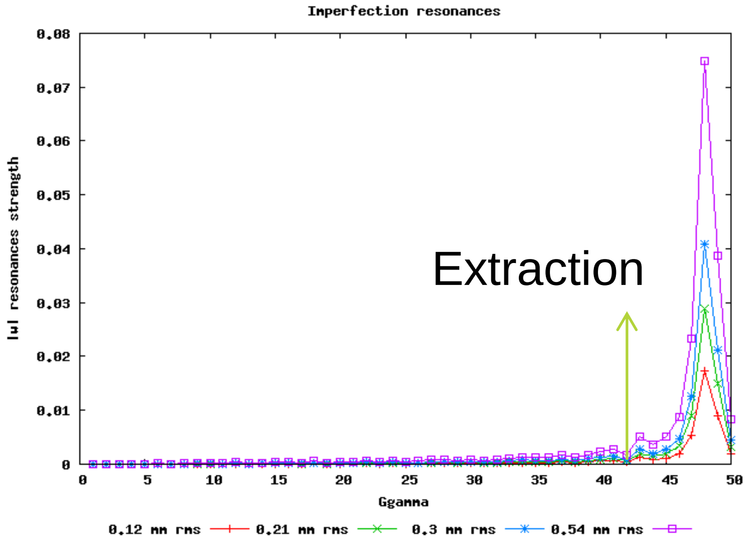
Project onto the RHIC tunnel



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

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 using principles of spin resonances canceling insertion

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

Principles of Spin Resonance Canceling Lattice Insertion

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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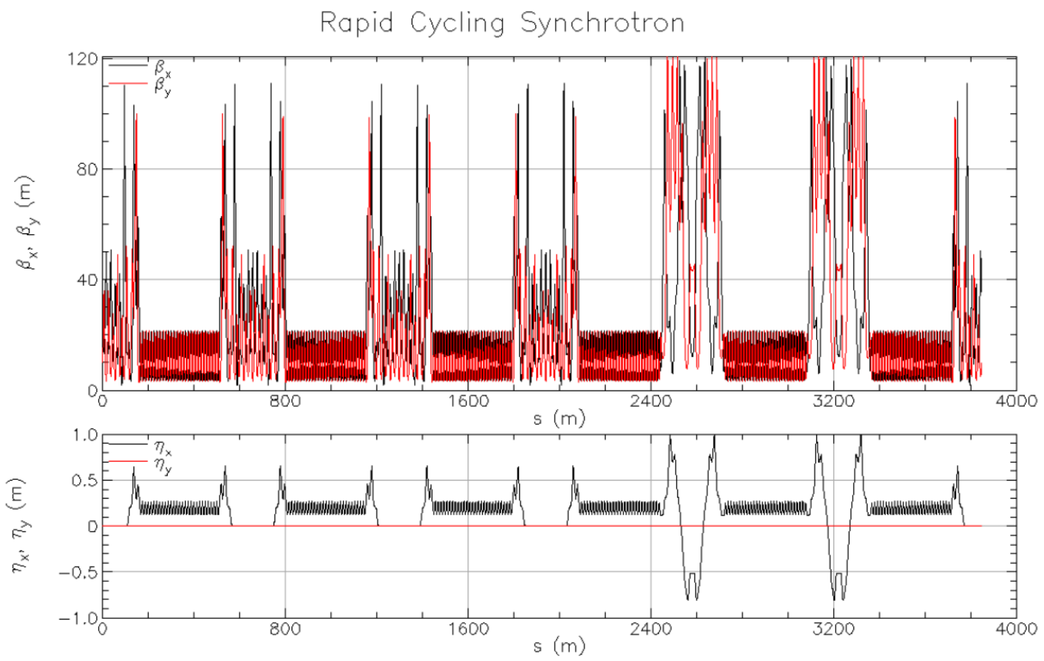
Phys. Rev. Accel. Beams **26**, 061001 – Published 5 June 2023

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%

Baseline RCS optics

Thanks: H. 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

Dynamic Aperture

Thanks: H. Lovelace III

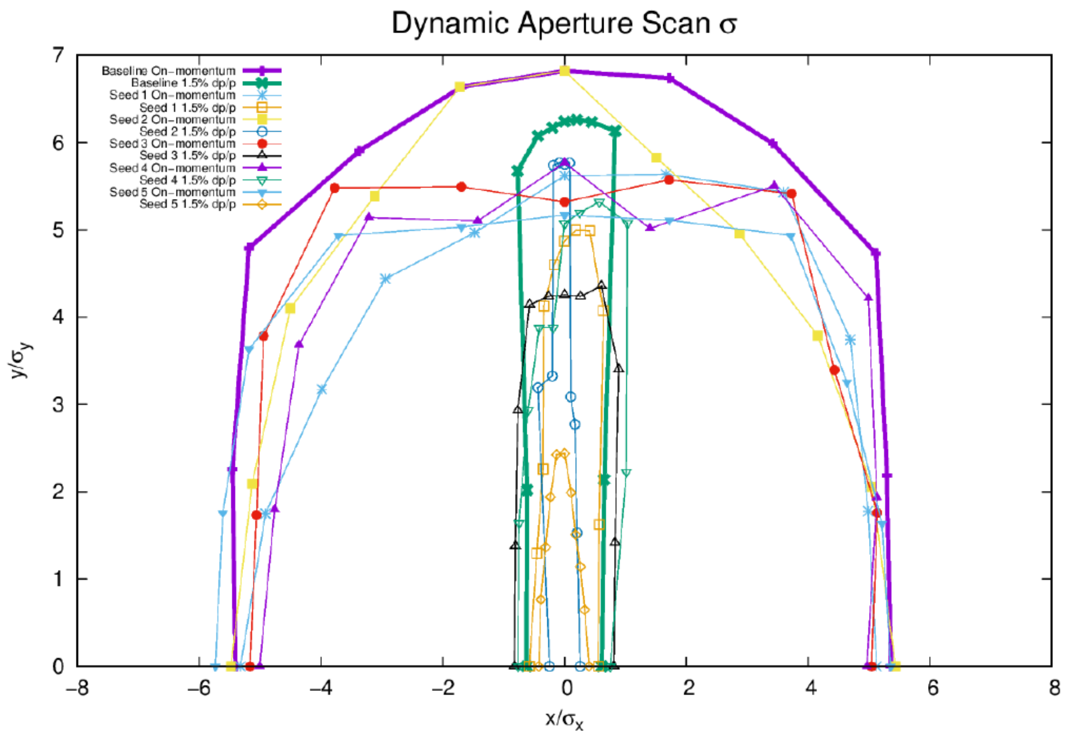


Figure 6: Dynamic Aperture scan of 5 seeds. Seed 3 of the scan did not find a closed orbit at 1.5% dp/p

Table 4: Magnet misalignment given to magnetic elements.

Element	Dip.	Quad.	Sext.
Field Error (%)	1	0.5	0.5
Tilt (mrad)	0.1	0.1	0.1
x-offset (mm)	0.15	0.15	0.15
y-offset (mm)	0.15	0.15	0.15

Polarization Performance

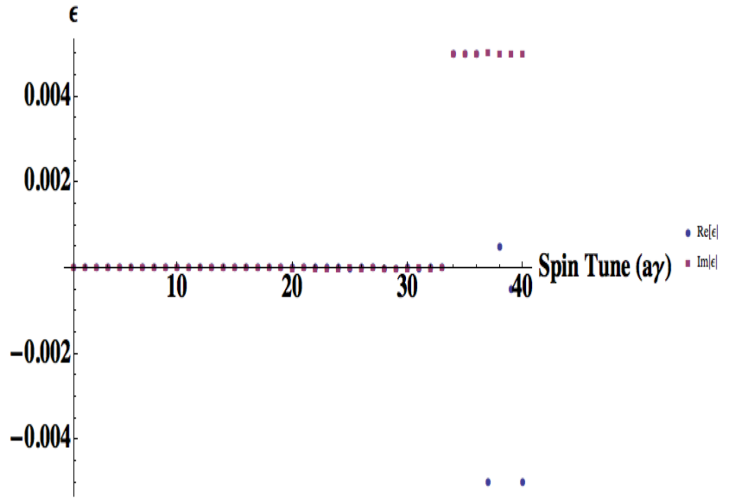
- Intrinsic resonance as calculated by DEPOL yield no cumulative depolarization loss for a beam with a vertical emittance of 40 mm-mrad rms normalized emittance (RCS's emittance at injection which falls to near zero by 18 GeV).
- Imperfections could however potentially cause greater than 5% losses during 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.

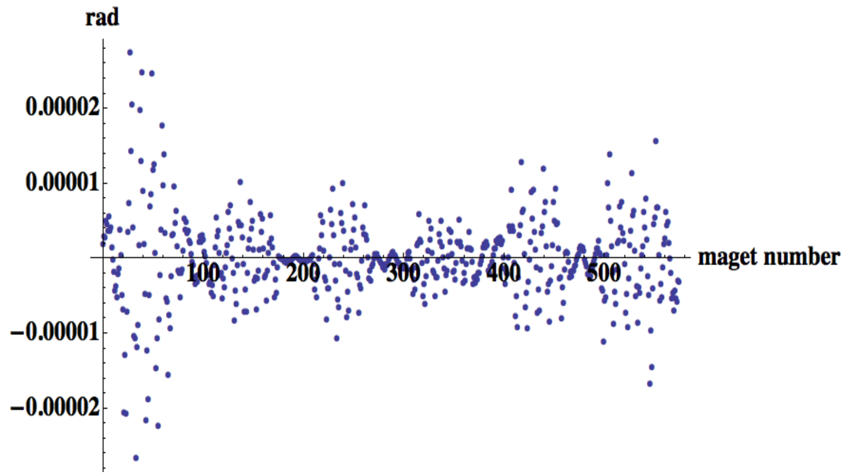
Analysis of Imperfections:

- 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.





Summary

- The future EIC complex will include two polarized electron synchrotrons the ESR and the RCS.
- The RCS will accelerate and inject polarized electrons using a unique lattice designed to avoid the effects of depolarizing spin resonances.
  - The design has evolved to accommodate the requirements for the EIC complex, but we have maintained its performance in terms of polarization transmission and dynamic aperture.
- The RCS is also designed to accumulate up to 28nC of bunch charge using a combination of a novel RF kicker to inject bunches into neighboring buckets and a four to one merge.