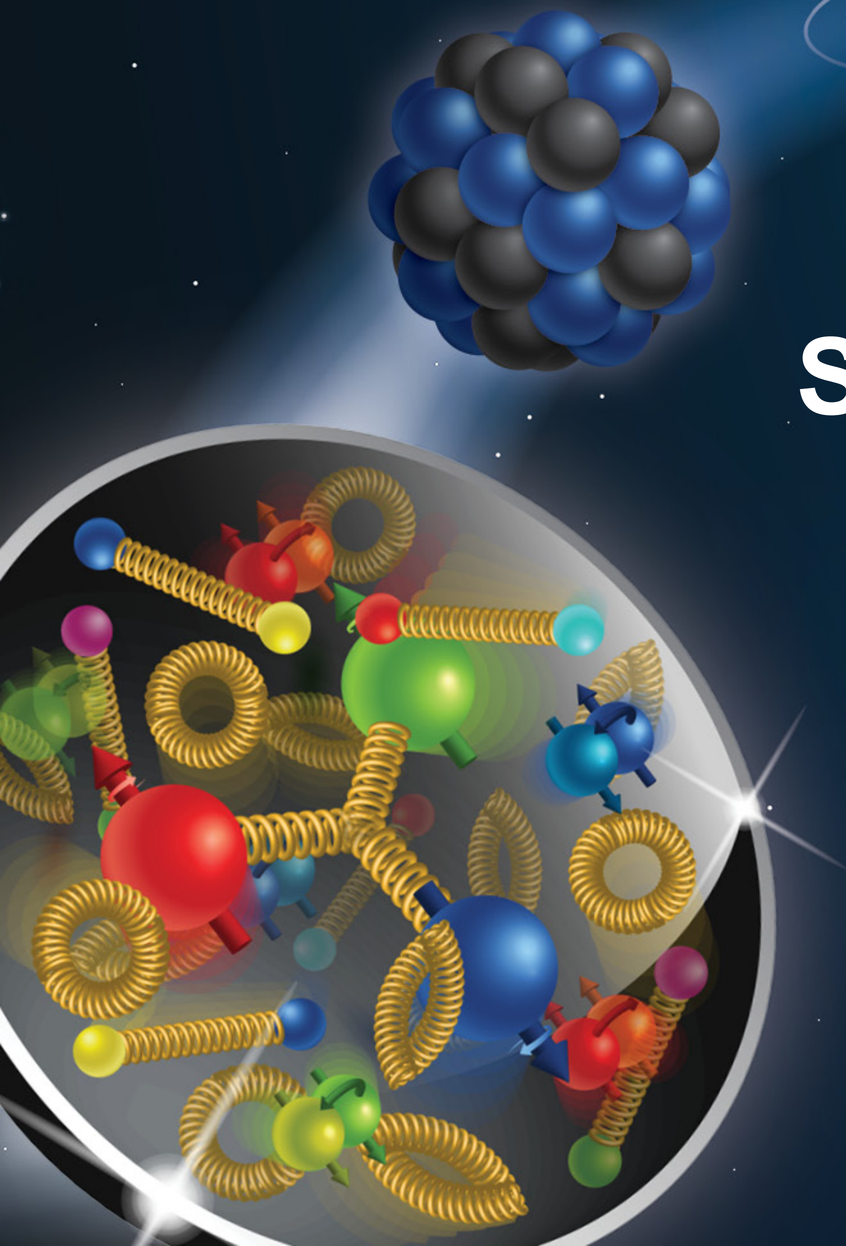

Status of RCS eRHIC Injector Design

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Electron Ion Collider – eRHIC

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U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

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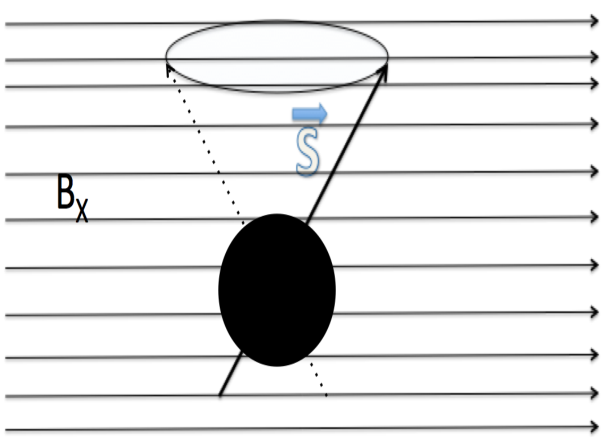
eRHIC Injector Requirements

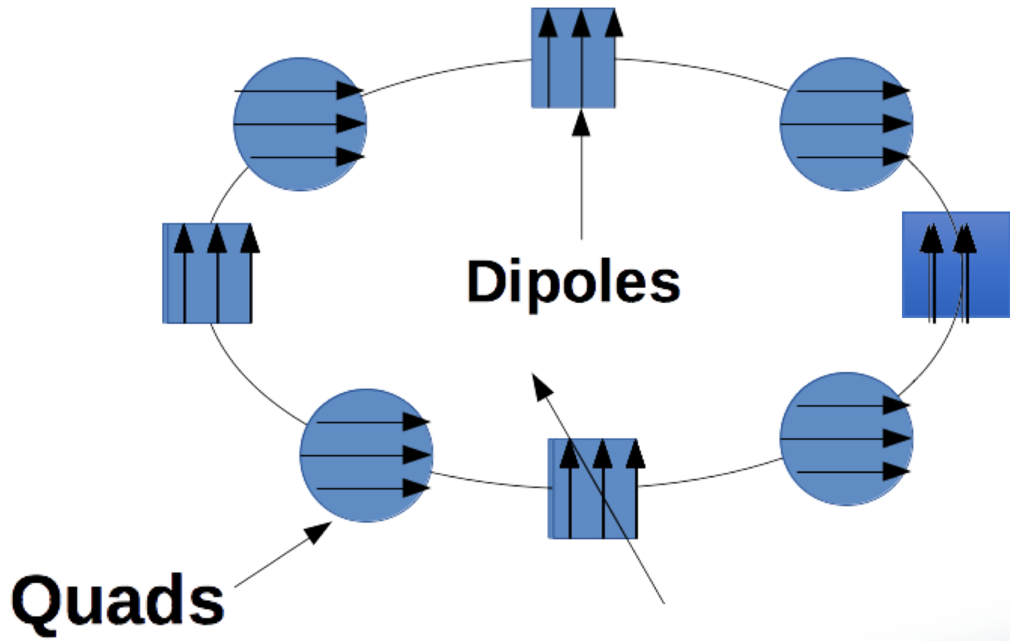
- A cost effective design to accelerate polarized electrons from 400 MeV → 18 GeV
  - For injection of 10 nC bunches into storage ring
  - Injection rate once per sec. (1Hz)
  - Maintain polarization transmission losses < 5%
  - Has to fit inside existing RHIC tunnel with bypass for detectors
  - Field effects on Storage Ring must be negligible
  - Use existing cost effective technologies.
- The Rapid Cycling Synchrotron (RCS) design meets these design requirements.

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

$$\xi(\theta) = F_1 - iF_2 = \sum_K \varepsilon_K e^{-iK\theta}$$

$$\varepsilon_K = -\frac{1}{2\pi}\oint \left[(1+G\gamma)(\rho z'' + iz') - i\rho(1+G)\left(\frac{z}{\rho}\right)'\right] e^{iK\theta} d\theta$$

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

$$G\gamma = K = N$$

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

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

Tell when they are significant

Concept Overview: Spin Resonance Free Lattice

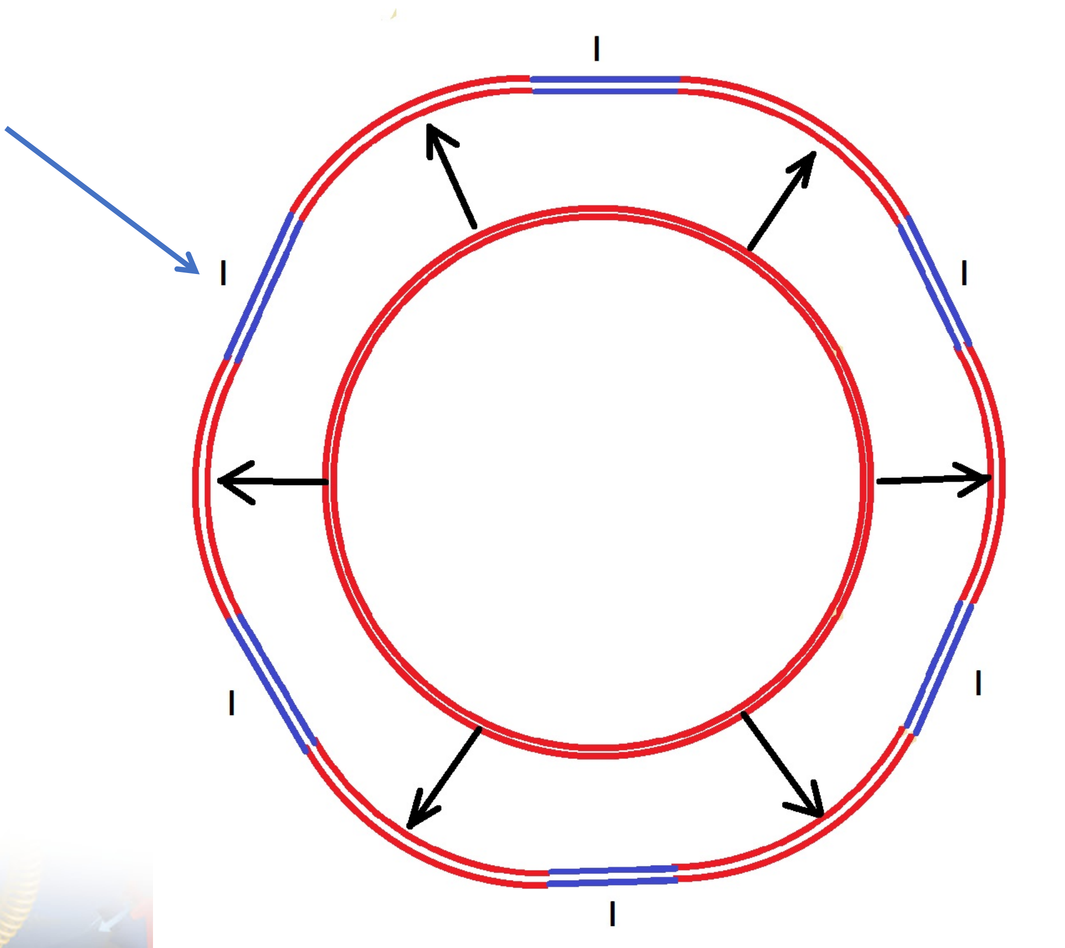
- Both the strong intrinsic and imperfection resonances occur at:
  - K = nP +/- Qy
  - K = nP +/- [Qy] (integer part of tune)
- To accelerate from 400 MeV to 18 GeV requires the spin tune ramping from
  - **$0.907 < G\Upsilon < 41.$**
- If we use a periodicity of P=96 and a tune with an integer value 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?

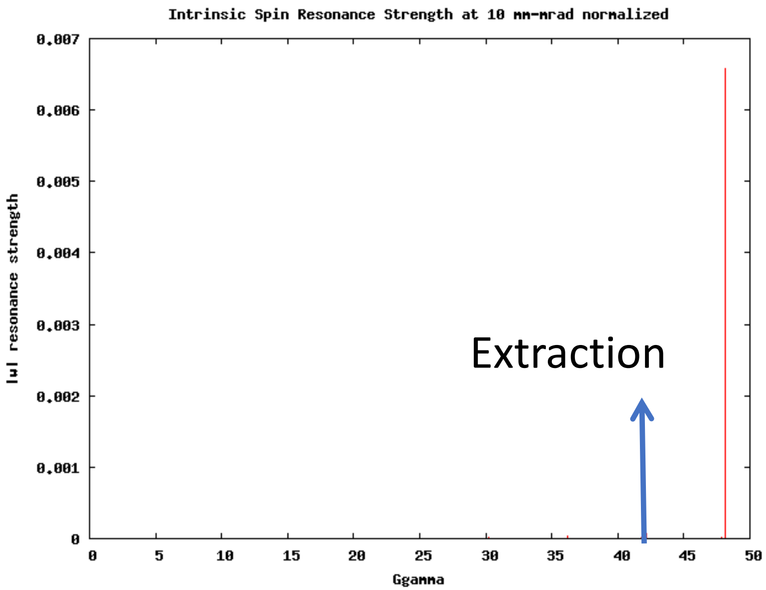
- It is easy to accomplish this with a perfectly circular ring. Just construct a series of FODO cells with bending magnets so that we have total periodicity of 96.
- The problem is that the RHIC tunnel is not circular and has an inherent six fold symmetry.
- The solution make the spin resonances integrals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

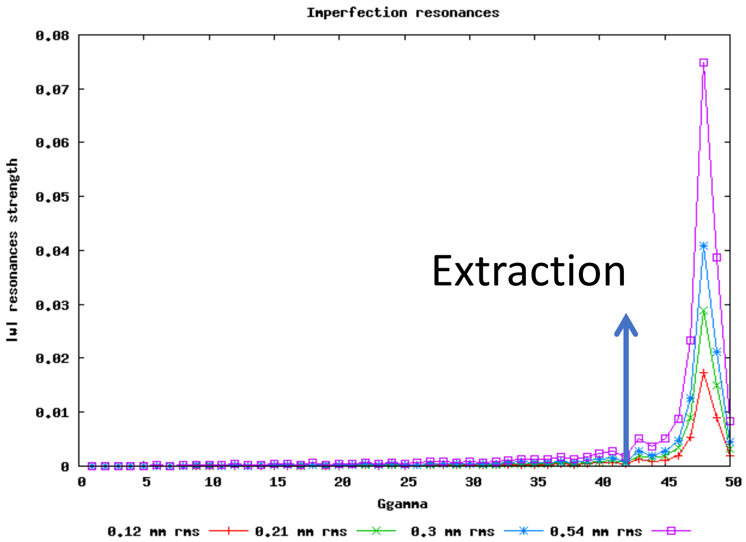
Project onto the RHIC tunnel

RHIC Tunnel



Calculating Spin Resonances



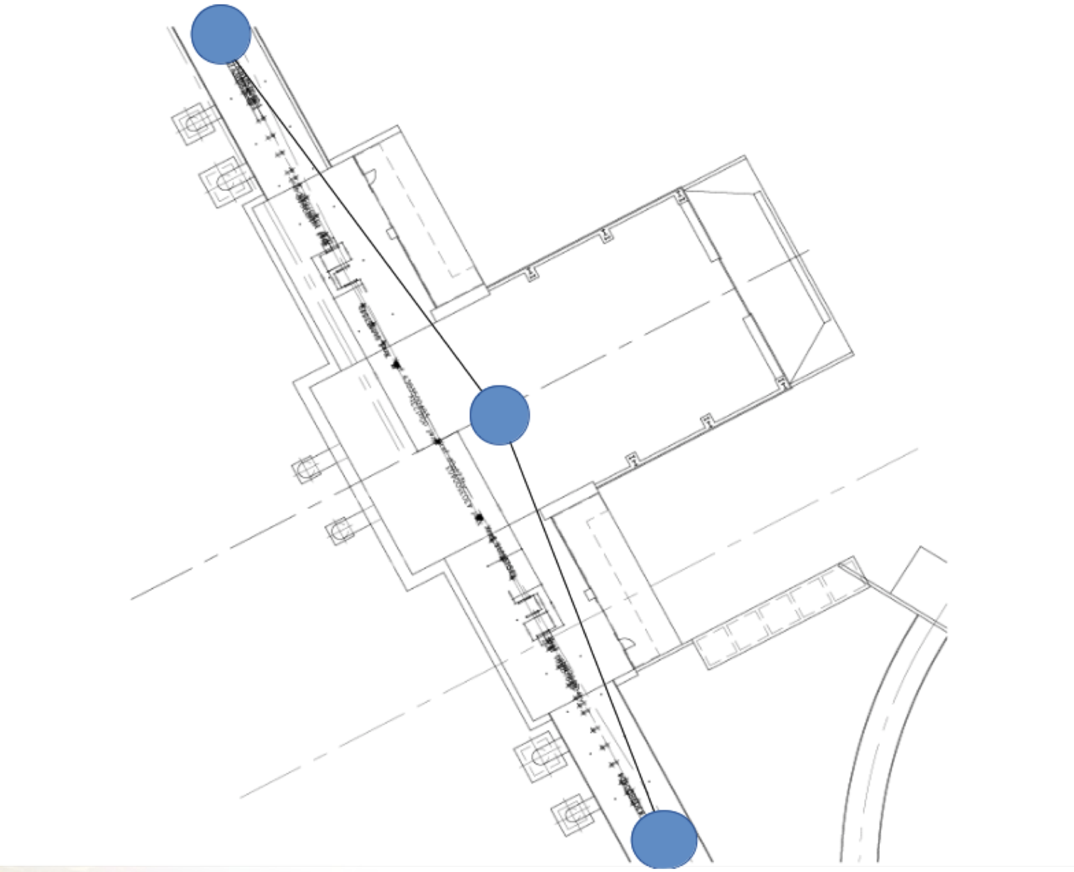


- No polarization loss from cumulative effective of intrinsic spin resonances for distributions with rms normalized emittance > 1000 mm-rad (100 msec ramp rate).
- At 200 mm-mrad rms normalized emittance, we can tolerate beyond 2% field errors and still maintain above 95% polarization transmission.
- Issue to control: Imperfection spin resonances ~ vertical rms orbit 0.5 mm to keep losses < 5%.

RCS Design Parameters

Injection Energy [MeV]	400
Top Energy [GeV]	18
α_c momentum compaction	0.000372959119
Max Relative Pol. loss [%]	5
Circumference [m]	3842.14227
Ramping repetition rate [Hz]	1
Acceleration time [msec], [turns]	100-200, 8000-16000
Total number of 'spin effective' superperiods	96
Integer Horizontal Tune	57
Integer Vertical Tune	61
Max vertical orbit rms [mm]	0.5
Number of Arc Cells	192
Number of straights	6
Number of dipoles	386
Number of quadrupoles	576
Number of sextupoles	420
Round Beam pipe diameter [mm]	40
Number of bunches	1
Charge per bunch [nC]	1-10
Radio frequency 1st	563 [MHz]
Cavity peak Voltage 1st [MV]	60
bunch length [mm], [ps]	1.8, 6
Hor. and Ver. emittance normalized [mm-mrad] inj	55,55
Hor. and Ver. emttiance normalized [mm-mrad] ext	775, 115
Max energy deviation dp/p	7.8e-04
U_0 Energy radiated per electron at 18 GeV [MeV/turn]	35.71
Hor. damping time (18 GeV) [s]	0.0129

Bypass: Detector and other



We have added a bypass option to the straight sections.

- Consists of moving last bend magnets in arc to center of straight section
- Achieves 3-4 meter bypass at the IP.
- Impacts symmetry of lattice.
    - However by optimizing the quad strengths in the bypass region we can recover low intrinsic losses

Polarization Performance

- Intrinsic resonance as calculated by DEPOL yield no cumulative depolarization loss for a beam with below 1,000 mm-mrad rms normalized emittance.
- Imperfections could however potentially cause greater than 5% losses during ramp.
  - Due primarily to quadrupole misalignment and dipole rolls.
  - Survey estimates are 0.2 mm rms with a 2 sigma cut off and +/- 1 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.

Studies with SVD orbit correction: Quadrupole Misalignments

Polarization Transmission to 18 GeV for random gaussian quadrupole misalignments with SVD orbit correction for 4 different random seeds. * indicates tests with bpm misalignments of 0.2 mm rms

rms quad misalignment	random seed	100 msec transmission [%]	200 msec transmission [%]
0.4	100000	97	95
0.4	12001	99	98.2
0.4	1200	99	98.7
0.4	120033	99.0	99.0
0.3	100000	99	98.
0.3	12001	99	98
0.3	1200	99	97.5
0.3	120033	99	98.6
0.2*	100000	99	99
0.2	12001	99	99
0.2	1200	99	99
0.2*	120033	99	98

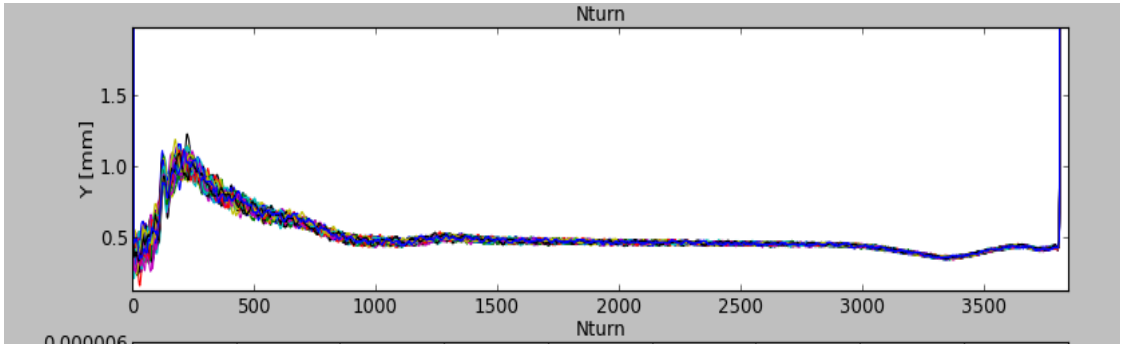
Studies with SVD orbit correction: Dipole Rolls

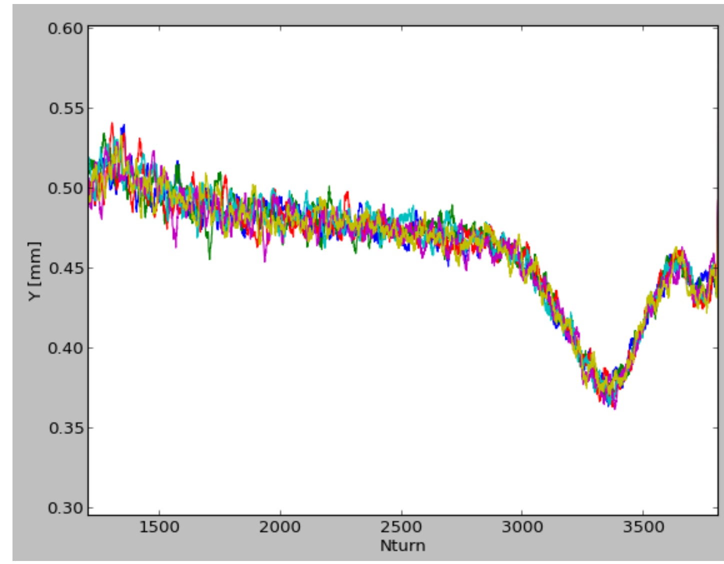
Polarization Transmission to 18 GeV for random gaussian dipole rolls with SVD orbit correction for 2 different random seeds. (calculated using spin tracking in Zgoubi)

RMS dipole roll misalignment (mrad)	random seed	100 msec transmission [%]	200 msec transmission [%]
2.0	100001	99.4	99.0
2.0	12001	99.5	99.0
2.5	12001	99.0	98.0
2.5	100001	99.0	98.2

Dynamical Orbit Effects Example: NSLS-II Booster

Thanks :Wang, Guimei

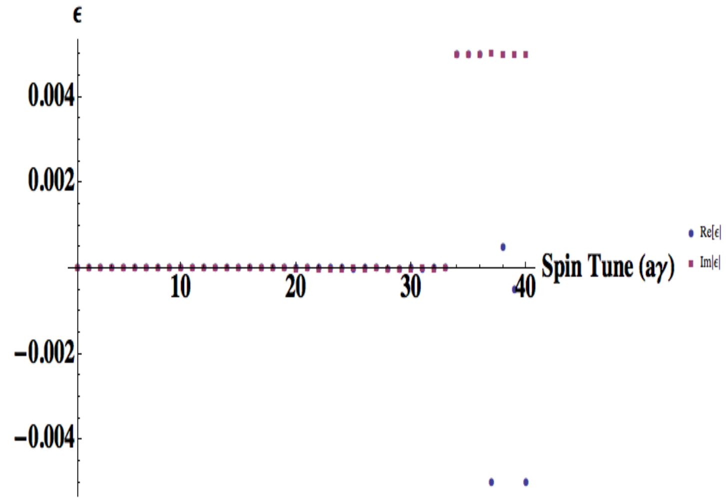


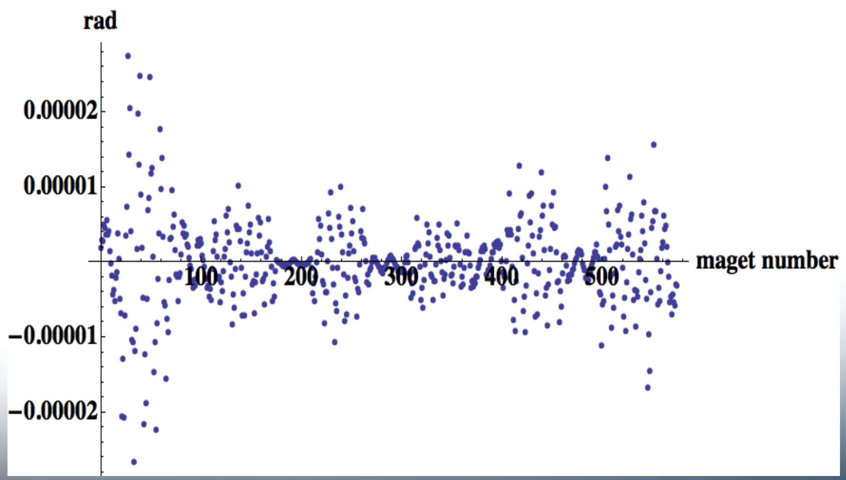


- 400 msec Ramp, 8M Turns to 3 GeV
- Randomly collected 50 shots over 1 hr.
- Shot to shot variation ~ 70 microns.
- Transient dynamics die after 1st 50 msec :
  - Equivalent to below 10 GeV in RCS
  - In RCS tolerate > 3 mm RMS orbit below 10 GeV
- After 50 msec variation on ramp peak swing 0.1 mm over 50 msec.
  - → 0.02 mrad kick at quads. This is well within the existing bandwidth of our corrector system (swing +/- 1 Amp 20Hz) Possible to achieve 200 Hz ~ 5 msec

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

- Resonances in this 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.