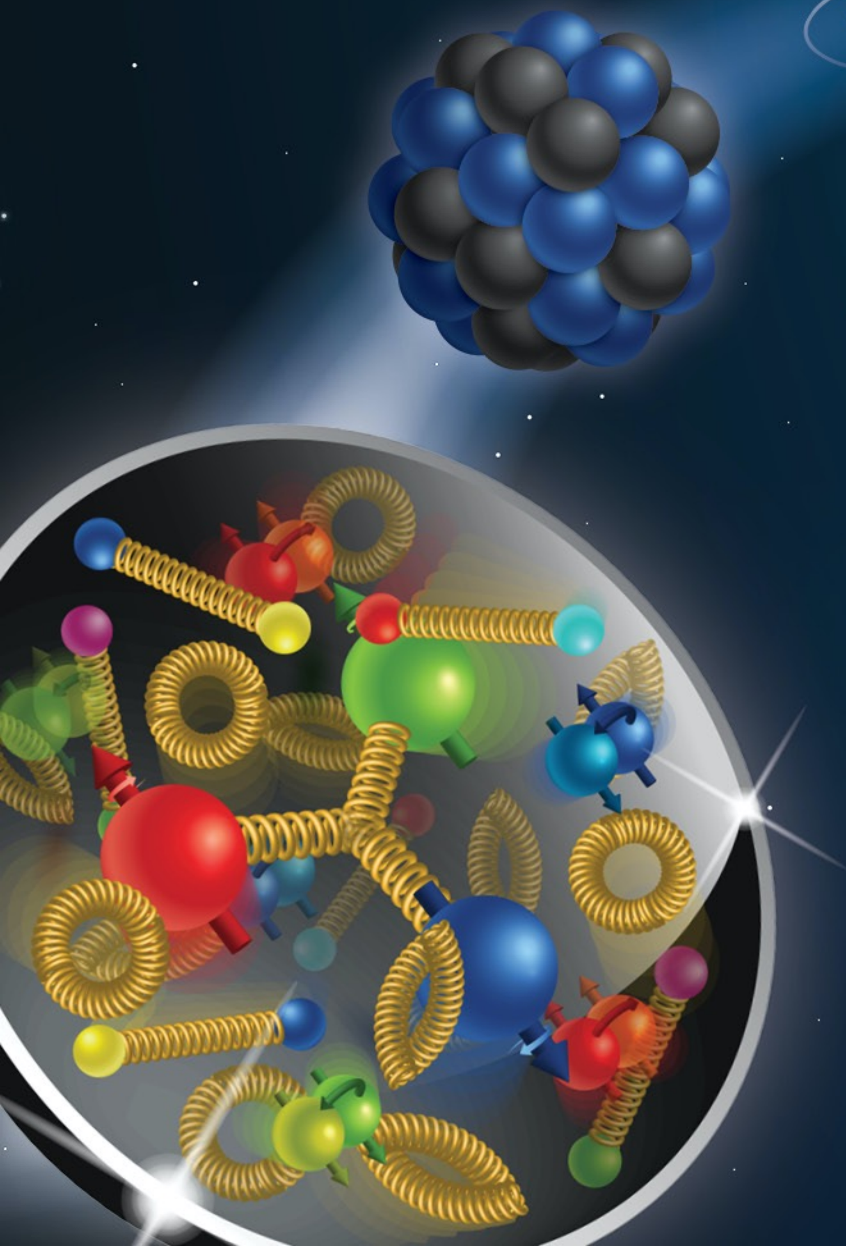


Progress in EIC Polarization Studies for the Injectors and Storage Ring

Vahid Ranjbar, BNL

eeFACT2022

12–15 Sep 2022

Frascati

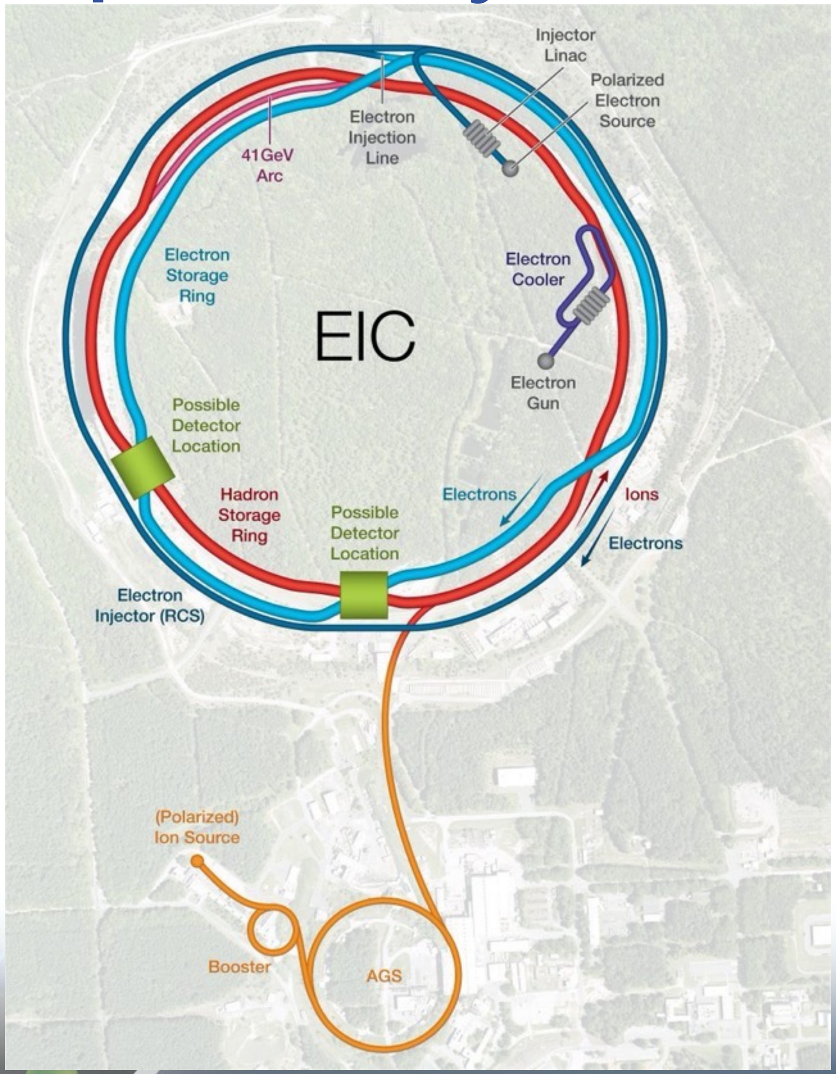
Electron Ion Collider

U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- Polarization Requirements in the ESR (work by Eliana Gianfelice)
  - Radiative polarization and asymptotic polarization
  - Optics and Misalignments
  - Matching e/p emittance
- Injector Polarization
  - Concept Overview and Design
    - Geometry
    - Spin resonance strengths
  - Polarization Performance
    - Tolerances for vertical misalignments
    - vertical orbit
    - Spin imperfection correction scheme
- Summary

EIC Complex Layout

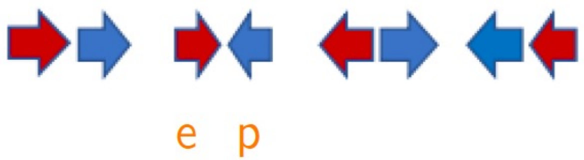


Radiative polarization and the EIC electron storage ring

Thanks: Eliana GIANFELICE

Experiments require

- Large electron (and proton) polarization
  - $< P >_t \geq 70\%$
- Longitudinal polarization at the IP with *both* helicities within the *same* store
- Energy
  - protons: between 41 and 275 GeV
  - electrons: 5 (or 6), 10 and 18 GeV



While high proton polarization is routinely achieved in RHIC, electron beam polarization is a new field at BNL.

Thanks: Eliana GIANFELICE

In storage rings lepton beams may become spin polarized through the Sokolov-Ternov effect. In an ideal planar and w/o rotators ring the periodic solution to Thomas-BMT equation, $\hat{n}_0$, is vertical and the polarization builds up in the vertical direction.

- asymptotic polarization: P_∞=92.4%
- polarization build-up rate:

$$\tau_p^{-1} = \frac{5\sqrt{3}}{8} \frac{r_e \hbar \gamma^5}{m_0 C} \oint \frac{ds}{|\rho|^3}$$

In actual rings, $\hat{n}_0(s)$ is not vertical and the beam has finite vertical size: photon emission leads to spin diffusion which lowers P_∞ (and τ_p).

Because experiments call for simultaneous storage of electron bunches with *both* spin helicity, Sokolov-Ternov effect is not an option.

- A full energy polarized electron injector is needed: electron bunches are injected from the RCS into the storage ring with high *vertical* polarization ($\approx$ 85%) and the desired spin direction (up/down).
- In the storage ring the polarization is brought into the longitudinal direction at the IP by solenoidal spin rotators left and right of the IP.

Assessing the needed asymptotic polarization

Thanks: Eliana GIANFELICE

Depending on equilibrium polarization, Sokolov-Ternov effect may have a strong impact on the initial high beam polarization.
Polarization vs. time

$$P(t) = P_\infty(1 - \mathrm{e}^{-t/\tau_p}) + P(0)\mathrm{e}^{-t/\tau_p}$$

In presence of depolarizing effects

asymptotic polarization (unknown)

$$\frac{1}{\tau_p} \simeq \frac{1}{\tau_{\mathrm{BKS}}} + \frac{1}{\tau_{\mathrm{d}}} \quad \text{and} \quad P_\infty \simeq \frac{\tau_p}{\tau_{\mathrm{BKS}}} P_{\mathrm{BKS}}$$

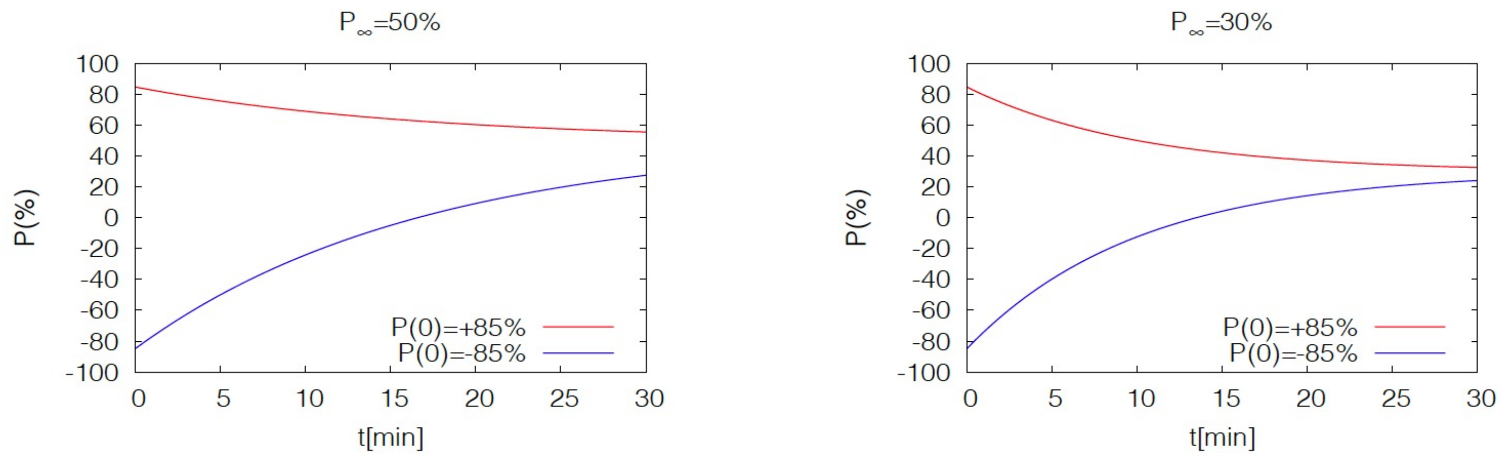
diffusion time (unknown)

- P_{BKS} and τ_{BKS} (Baier-Katkov-Strakhovenko generalization of Sokolov-Ternov quantities when $\hat{n}_0$ is not everywhere perpendicular to the velocity) are known for the *nominal* lattice.
- τ_d and thus P_∞ depend on the *actual* machine.

Once we fix a value for P_∞, also τ_p and τ_d are fixed.

Thanks: Eliana GIANFELICE

P for bunches polarized parallel or anti-parallel to the bending field

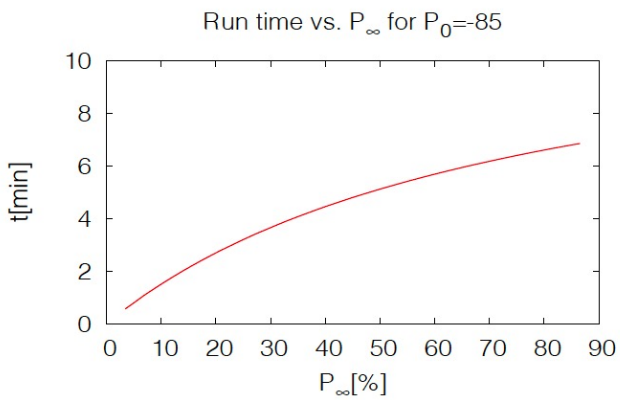


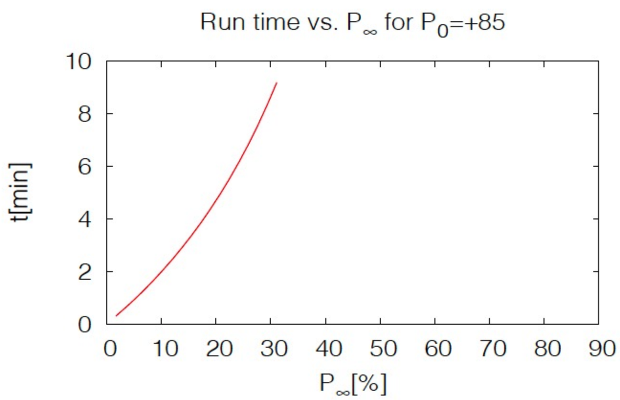
- If P_∞ <85% also the up-polarized bunches will suffer depolarization.
- Lower the P_∞, faster the depolarization.

Thanks: Eliana GIANFELICE

Run time vs. P_∞ for $< P >$=70%

for bunches polarized parallel or anti-parallel to the bending field





Thanks: Eliana GIANFELICE

Simulation Approach

- Use MADX for managing optics and misalignments
- Spin tracking codes
  - SITF (part of SITROS package) for computing polarization in linear spin motion approximation (as SLIM, but it digests thick lenses).
  - SITROS Monte Carlo tracking of particles with stochastic photons emission at user chosen dipoles
- First $\widehat{n_0}$ is calculated and then spins are initialized parallel to it and tracked for several thousand turns. From this the diffusion time τ_d and the asymptotic polarization P_∞ is determined using:

$$\frac{1}{\tau_p} \simeq \frac{1}{\tau_{\mathrm{BKS}}} + \frac{1}{\tau_{\mathrm{d}}} \quad \text{and} \quad P_\infty \simeq \frac{\tau_p}{\tau_{\mathrm{BKS}}} P_{\mathrm{BKS}}$$

Thanks: Eliana GIANFELICE

Optics

Since starting back in 2017 the storage ring optics is still undergoing some adjustments. We will consider only the 18 GeV case, the most challenging, and 2 quite different optics:

- EIC storage ring (esr) optics from 2019 (Version-5.2), 1 IP, β_y^*=0.048 m
  - $P_{bks} \simeq 82.7$ %
  - $\tau_{bks} \simeq 35.5$ min
- esr optics from 2022 (Version-5.6), 1 IP, β_y^*=0.057 m
  - $P_{bks} \simeq 86.5$ %
  - $\tau_{bks} \simeq 36.8$ min

In both cases

- fractional tunes q_x=0.12 and q_y=.10, close to the integer and to the difference linear coupling resonances;
- e-beam vertical size $\sigma_y^* \approx 12$ mm for matching p-beam size.

Thanks: Eliana GIANFELICE

Misalignment and Correction Studies for Lattice v5.2

Machine misalignments

Assumed quadrupole RMS misalignments

horizontal offset	δx^Q	200 μm
vertical offset	δy^Q	200 μm
roll angle	$\delta \psi^Q$	200 μrad

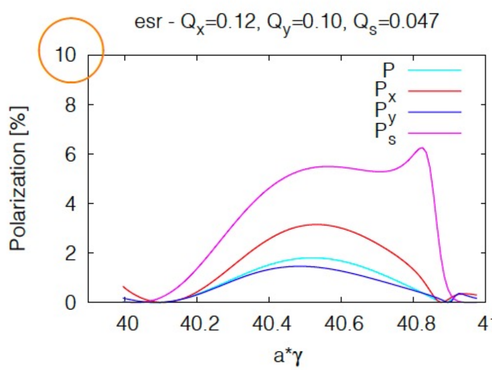
Correcting to ~ 0.4 mm rms

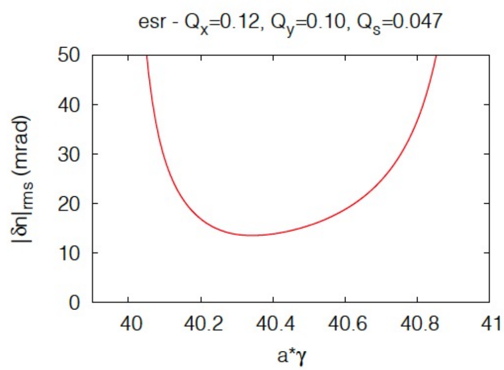
	q_x	q_y	x_{rms} (mm)	y_{rms} (mm)	$D_{y,rms}$ (m)	ϵ_x (μm)	ϵ_y (μm)
Bare	.3	.2	4.80	11.6	2.057		
SVD	.3	.2	0.25	0.20	0.036	0.0288	0.0003
	.12	.10	0.35	0.36	0.089	0.025	0.0073
SITF	.12	.10	0.41	0.38	-	0.024	0.0068

$P_{x,y,s}$ → Polarization with x,y and s orbital motion only

P → Polarization including all orbital motion.

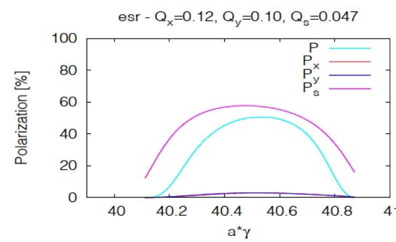
Resulting Polarization.

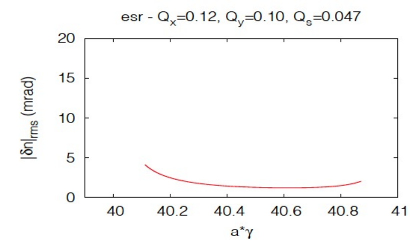




- Correcting lattice 5.2v to 0.04 mm rms
  - The small Px and Py may be a consequence of strong higher order resonances
  - Including Betatron coupling correction restored the 40% polarization level
  - But the beam size is about 6 times too small for matching proton beam.

	q_x	q_y	x_{rms} (mm)	y_{rms} (mm)	$D_{y,rms}$ (m)	ϵ_x (μm)	ϵ_y (μm)
1th SVD	.3	.2	0.25	0.20	0.036	0.0288	0.0003
2d SVD	.3	.2	0.09	0.08	0.024	0.0280	0.0002
lumi	.12	.10	0.19	0.15	0.044	0.0245	0.0048
3th SVD	.12	.10	0.05	0.05	0.025	0.0244	0.0053
+MICADO	.12	.10	0.05	0.04	0.024	0.0245	0.0050

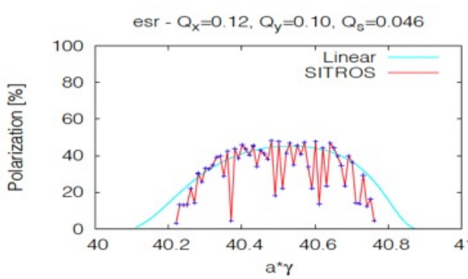




SITROS tracking after coupling correction.

Beam size at IP

	σ_x (mm)	σ_y (μm)	σ_ℓ (mm)
Analytic	0.111	1.758	8.543
Tracking	0.107	2.044	8.357



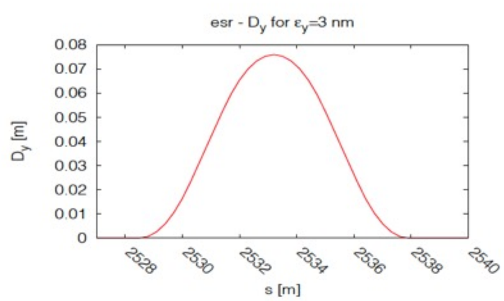
Thanks: Eliana GIANFELICE

Thanks: Eliana GIANFELICE

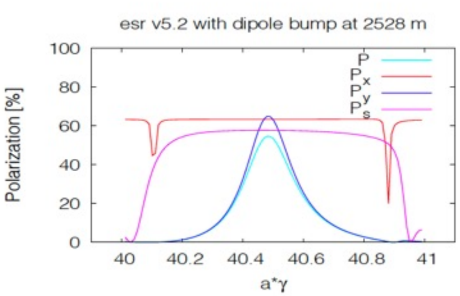
Approaches to match beam size at IP

- Introducing local coupling at the IP by 2 pairs of skew quads:
    - ruled out by beam-beam simulations.
- Increasing vertical emittance by adding
    a) a long vertical bump trough the arc sextupoles
        - Ruled out due to poor polarization performance
    b) a vertical orbit bump in a straight section without quadrupoles.
        - Possible if dispersion knob placed in “correct” location in lattice. Using location at 2528 m in the lattice increased vertical emittance to 3nm

Dispersion bump



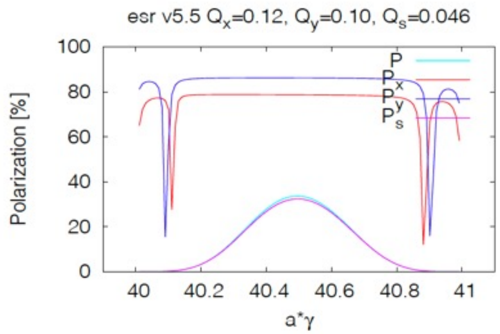
New location

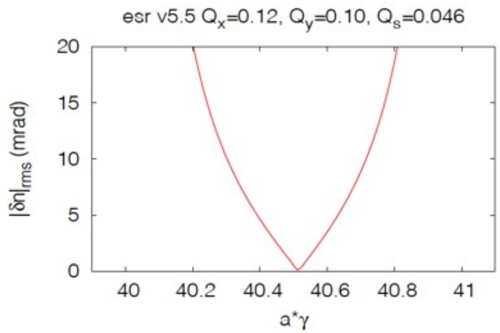


Thanks: Eliana GIANFELICE

Studies of lattice v5.5

Polarization for the *unperturbed* v5.5 optics.





- Large $\delta\hat{n}_0$ limits P_s:
  - maximum polarization is 34% even in linear approximation and w/o errors, still sufficient by tailoring the bunch replacement time.

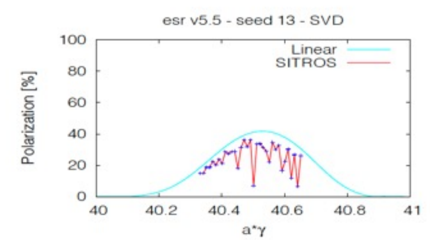
Results after orbit correction only:

- similar to 5.2v orbit corrections.

Also studied usefulness of harmonic Bumps:

- flattened $\delta\widehat{n_0}$ response to a*ɣ which resulted in higher polarization

	σ_x (μm)	σ_y (μm)	σ_ℓ (mm)
Analytic	124.05	11.09	8.335
Tracking	89.11	10.25	8.336



The beam size at IP is almost as required with sufficient polarization.

EIC Injector Requirements

- To meet the ESR requirements a polarized injector delivering electrons polarized to at least 85%
- To achieve the average polarization and luminosity requirements. The injector will need to inject two 28nC bunches once a second for energies of 5 and 10 GeV. At 18 GeV the intensity drops to two bunches at 11nC.

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 two 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%.

Concept Overview: Spin Resonance Free Lattice

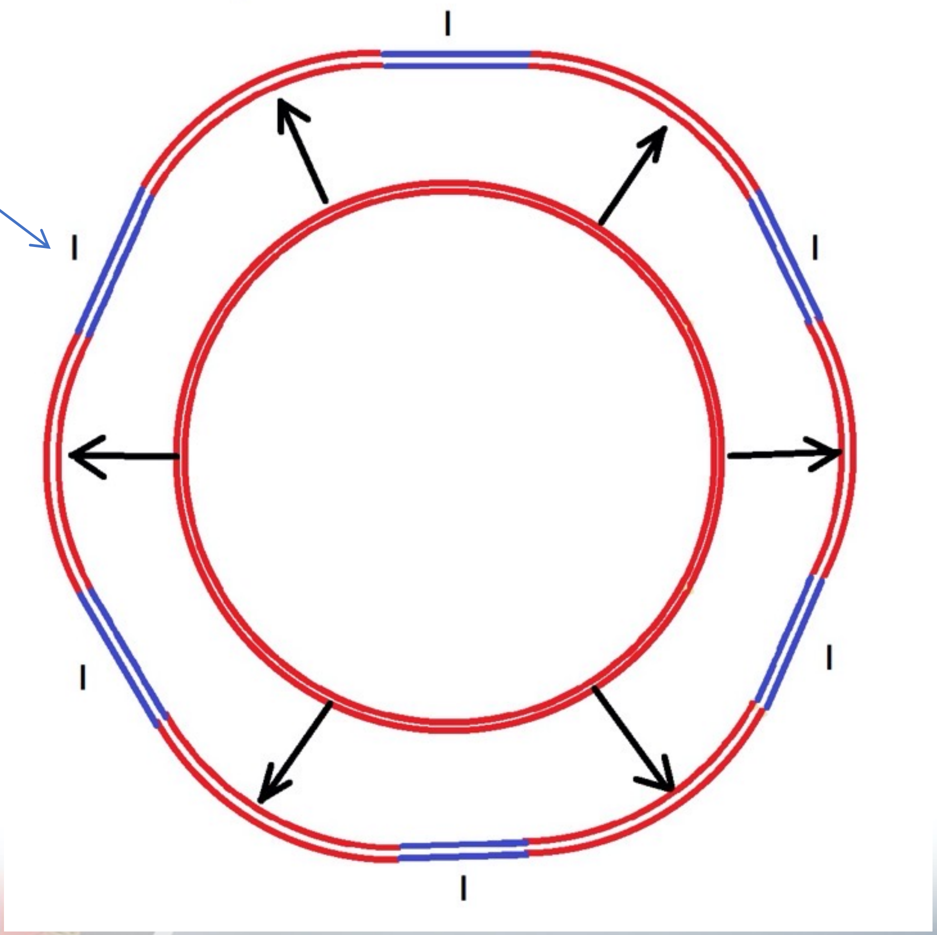
- Both the strong intrinsic and imperfection resonances occur at:
  - K = nP +/- Qy
  - K = nP +/- [Qy] (integer part of tune)
- To accelerate from 400 MeV to 18 GeV requires the spin tune ramping from
  - **$0.907 < G\Upsilon < 41$.**
- If we use a periodicity of P=96 and a tune with an integer value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

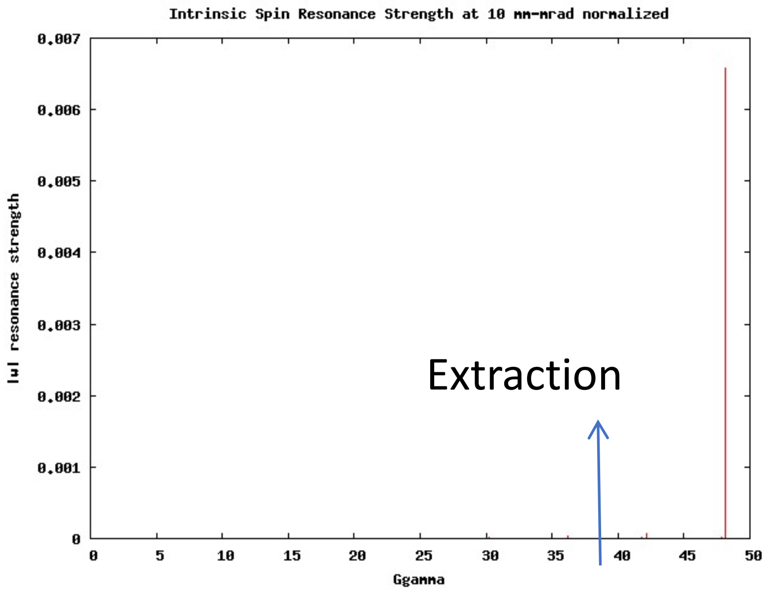
- It is easy to accomplish this with a perfectly circular ring. Just construct a series of FODO cells with bending magnets so that we have total periodicity of 96.
- The problem is that the RHIC tunnel is not circular and has an inherent six fold symmetry.
- The solution make the spin resonances integrals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

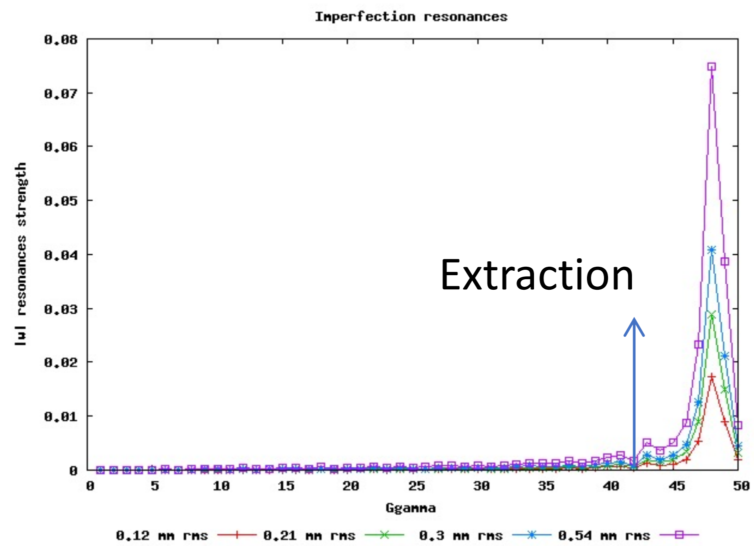
Project onto the RHIC tunnel

RHIC Tunnel



Calculating Spin Resonances





- No polarization loss from cumulative effective of intrinsic spin resonances for distributions 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 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.

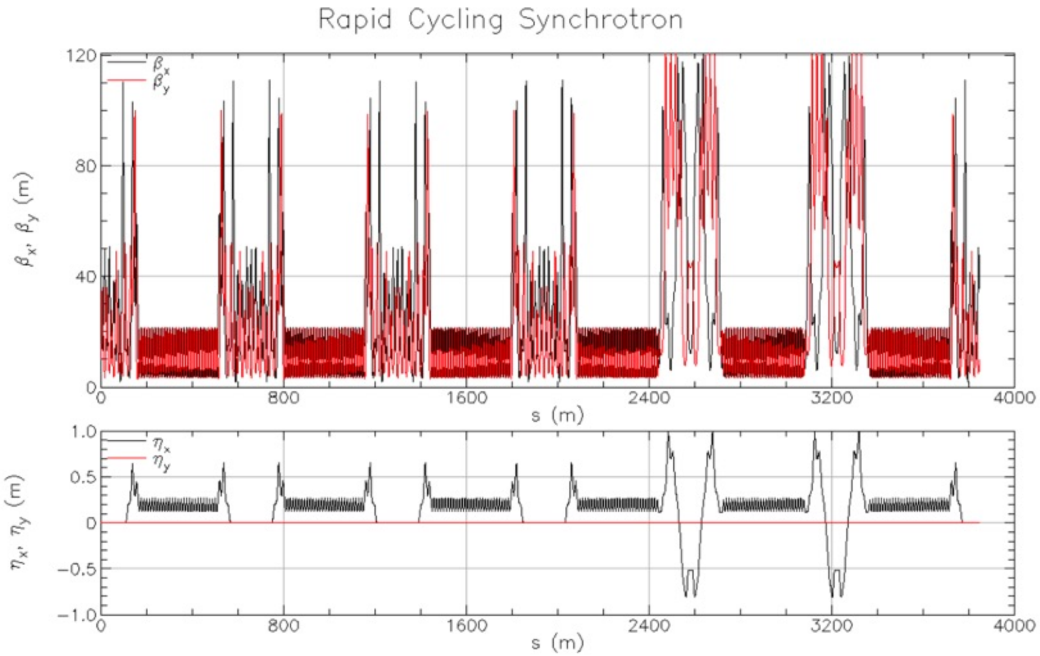
❖ **Spin resonance free electron ring injector Phys. Rev. Accel. Beams 21, 111003 – Published 27 November 2018**

RCS lattice changes

- Since original design RCS lattice has undergone two major revisions
  - 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%

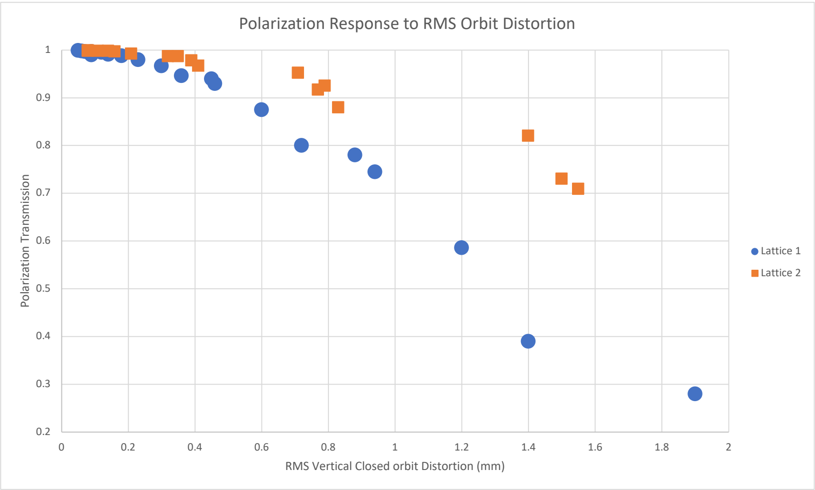
Baseline RCS optics

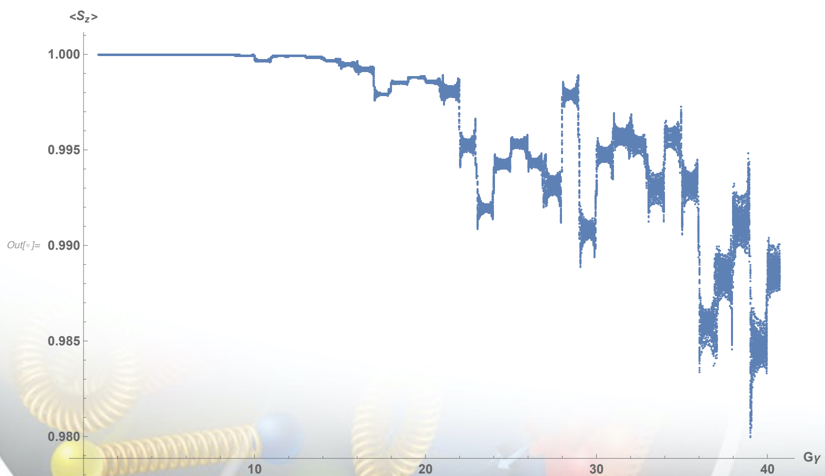
Thanks: Henry Lovelace III



- **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

Lattice response to orbit errors





Effect on Imperfections from Intrinsic suppression

Comparison of polarization transmission due to imperfection spin resonances as function of RMS orbit distortion. Lattice 1, was our first RCS optics attempt with 15% intrinsic resonance induced losses at RMS emittance of 1000 mm-mrad. Lattice 2 was our second and last RCS optics configuration with 8% losses at the same RMS emittance. This reduced imperfection spin resonance sensitivity as can be seen in the plot.

Lattice 2: 13 particle tracking with 0.6 mm RMS vertical and 0.3 mm RMS horizontal closed orbit distortion.

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.

$$\gamma \frac{\partial \hat{n}}{\partial \gamma}.$$

Summary

- ESR studies show that the sensitivity to errors for different optics are a result of different $\gamma \frac{d\hat{n}}{d\gamma}$
  - With the current rotator scheme the unperturbed polarization is much lower but the machine being less sensitive to errors it does not need an aggressive correction approach
  - Currently a scheme less aggressive than in HERAe is being considered.
  - Beam σ_y knobs may be not needed.
- RCS studies show that Polarization losses in this lattice are driven by imperfections
  - Intrinsic resonances are so weak that even large field distortions don't hurt.
  - Correction down to < 0.5 mm rms should be good enough to keep losses < 5% on 18 GeV Ramp.