EIC e-Injector polarization

Vahid Ranjbar, BNL
EPOL2022
21 Sep 2022
CERN

Electron Ion Collider

U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

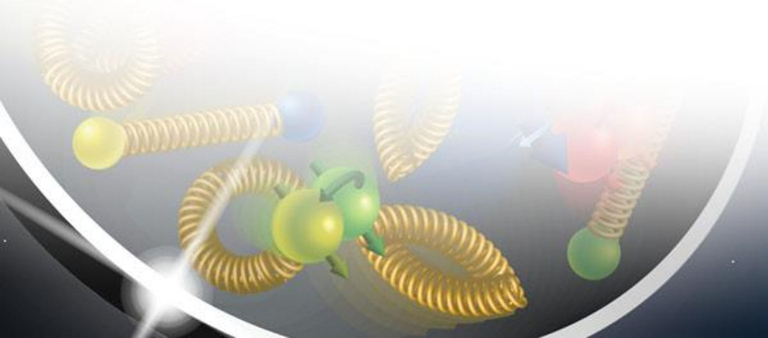
- Polarization Requirements
- Injector Polarization
  - Concept Overview and Design
    - Geometry
    - Spin resonance strengths
  - Polarization Performance
    - Tolerances for vertical misalignments
    - vertical orbit
    - Spin imperfection correction scheme
- Generalization of EIC's RCS polarized approach
  - Intrinsic spin resonance cancelling cells.
- Summary

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)

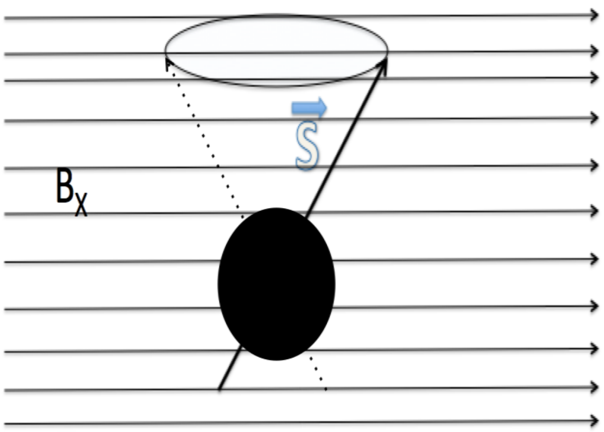
- Will receive 7nC electrons polarized to ~90% from pre-injector at 400 MeV.
- The RCS Requirements:
  - needs to merge these bunches into two 28nC bunches for 5 and 10 GeV operations and 11nC for 18 GeV.
  - Preserve polarization during acceleration from 400 MeV to extraction at 5, 10 and 18 GeV. With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

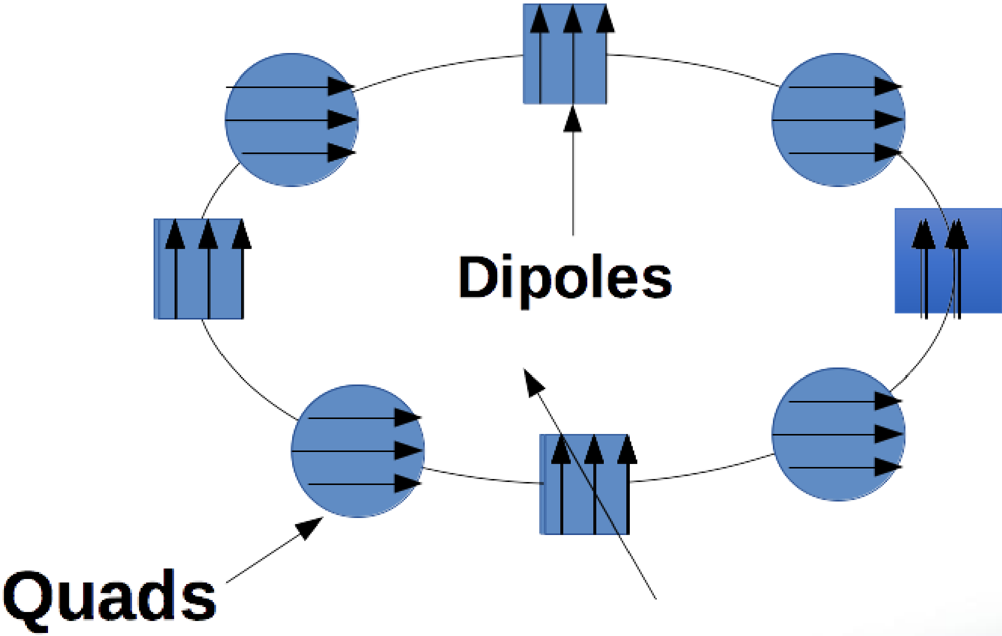


Spin Resonance Review

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)

$G\gamma$ = N +/- Q_z Intrinsic or **$G\gamma$ = N** Imperfection
Due to vertical betatron Due to vertical closed orbit error

Spin Resonance Driving terms

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

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

$$G\gamma = K = N$$

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

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

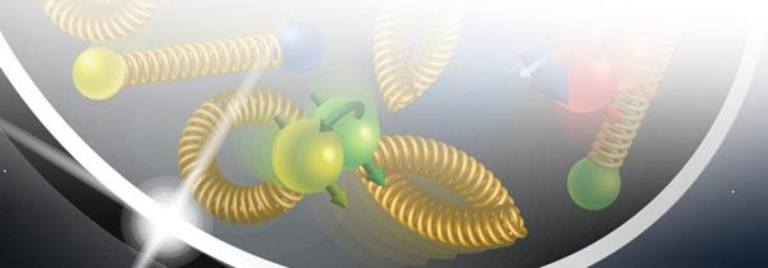
Tell when they are significant

Concept Overview: Spin Resonance Free Lattice

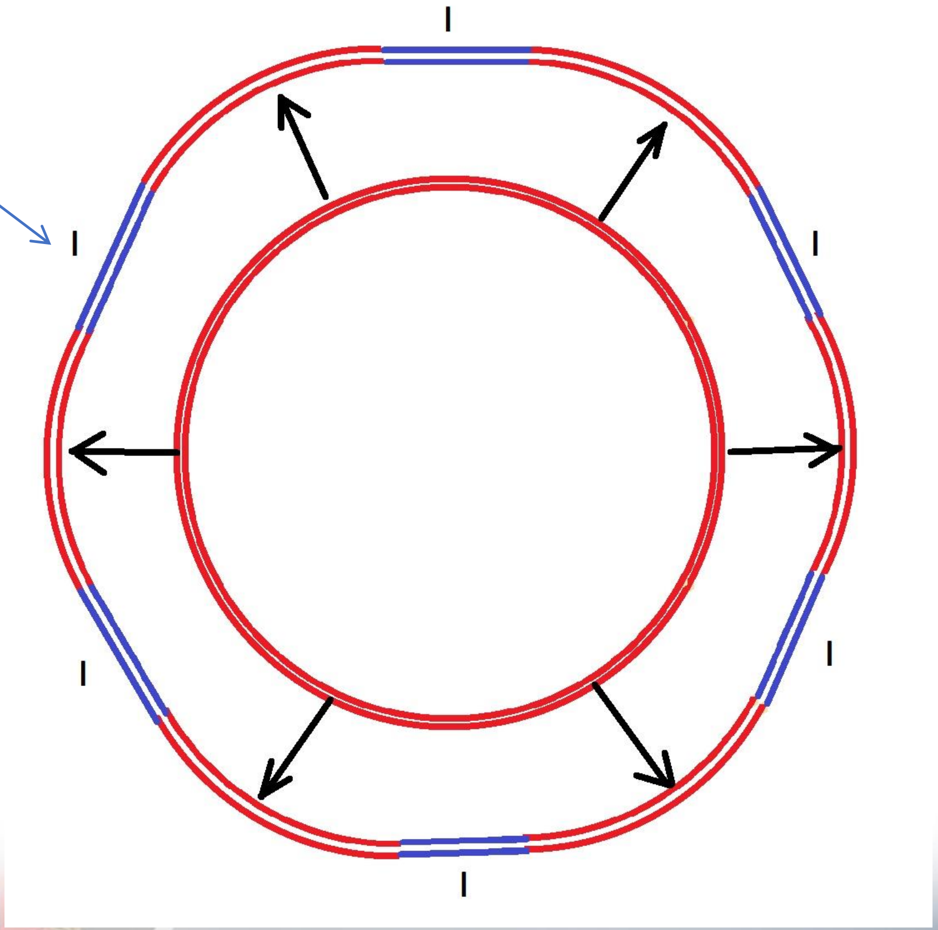
- Both the strong intrinsic and imperfection resonances occur at:
    - K = nP +/- Qy
    - K = nP +/- [Qy] (integer part of tune)
- To accelerate from 400 MeV to 18 GeV requires the spin tune ramping from
    - **$0.907 < G\Upsilon < 41.$**
- If we use a periodicity of P=96 and a tune with an integer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

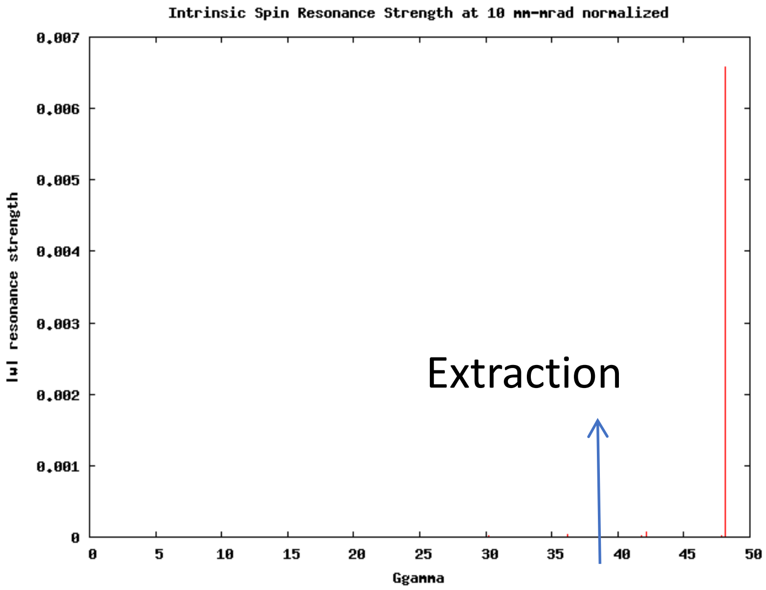


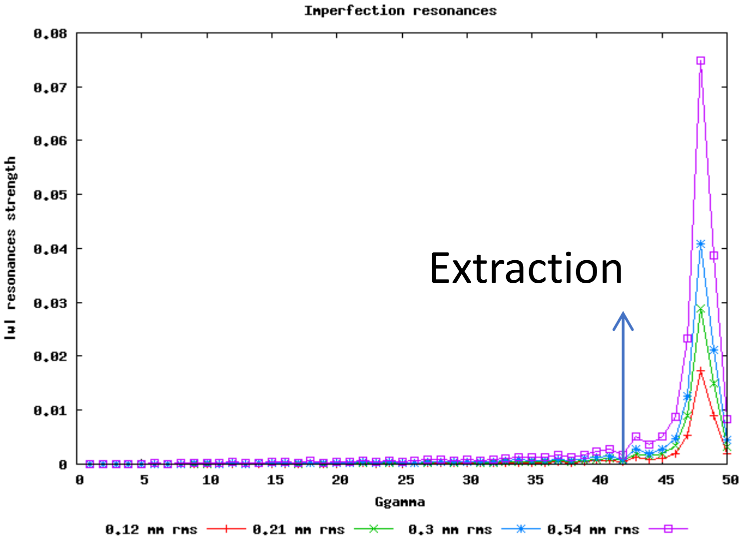
Project onto the RHIC tunnel



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.

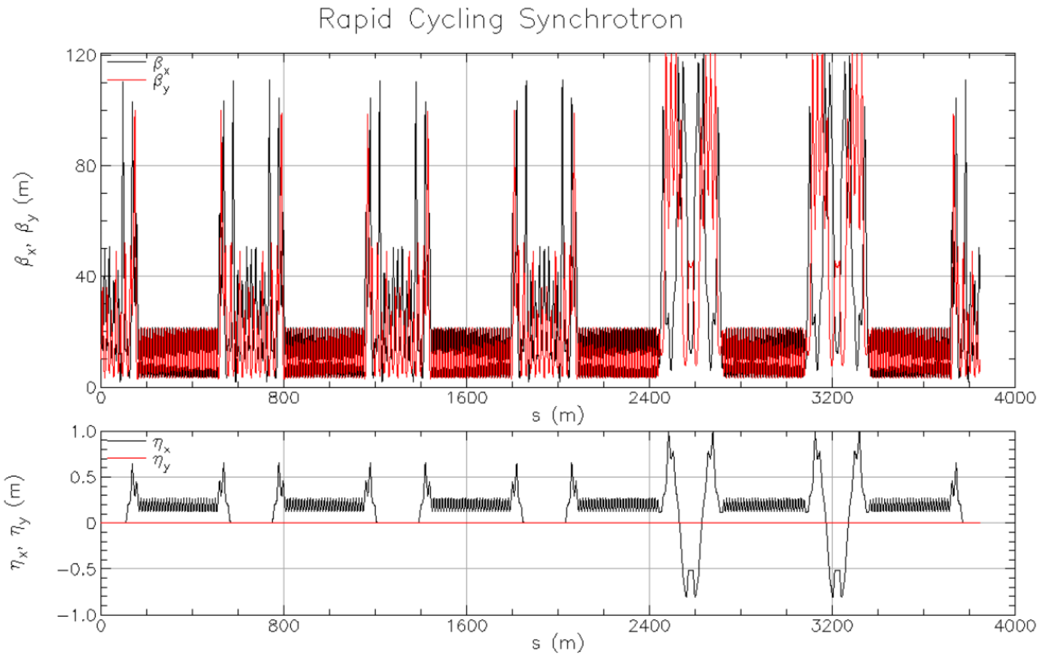
❖ **Spin resonance free electron ring injector Phys. Rev. Accel. Beams 21, 111003 – Published 27 November 2018**

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

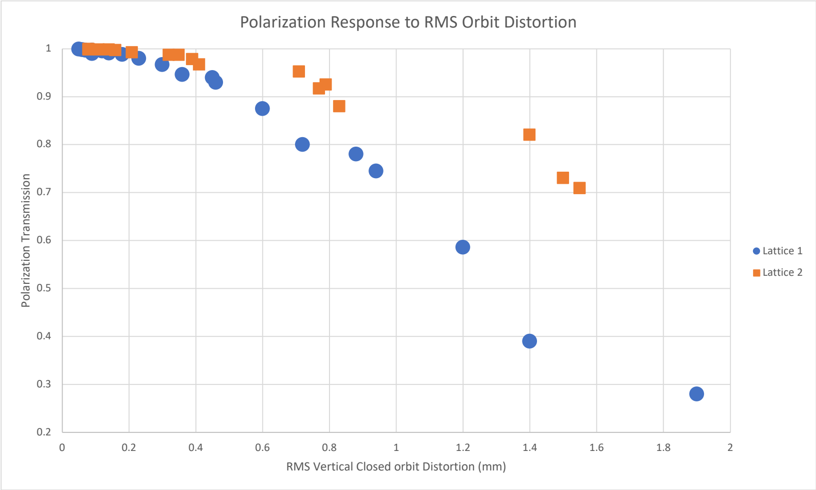
Polarization Performance

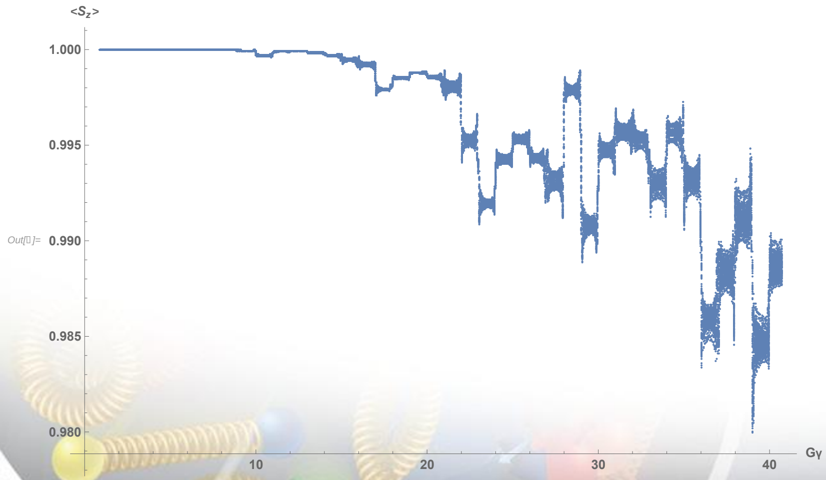
- Intrinsic resonance as calculated by DEPOL yield no cumulative depolarization loss for a beam with a vertical emittance of 40 mm-mrad rms normalized emittance (RCS’s emittance at injection which falls to near zero by 18 GeV).
- Imperfections could however potentially cause greater than 5% losses during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

Lattice response to orbit errors





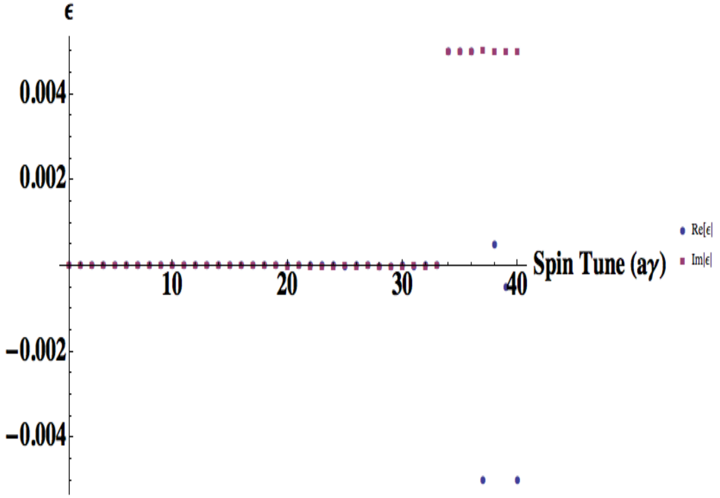
Effect on Imperfections from Intrinsic suppression

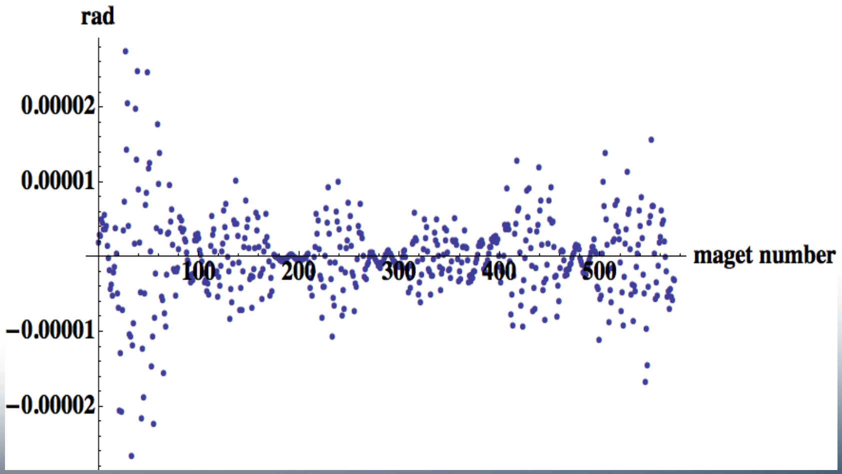
Comparison of polarization transmission due to imperfection spin resonances as function of RMS orbit distortion. Lattice 1, was our first RCS optics attempt with 15% intrinsic resonance induced losses at RMS emittance of 1000 mm-mrad. Lattice 2 was our second and last RCS optics configuration with 8%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

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.





Spin Resonance Canceling Lattice Cell for Future Polarized Machine Designs.

- **Generalization of approaches developed for the RCS lattice applied to individual lattice cells: arcs, straights FODO lattices.**

The transport of spin polarized beam across a standard arc 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.

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

→ 0 between dipoles

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

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

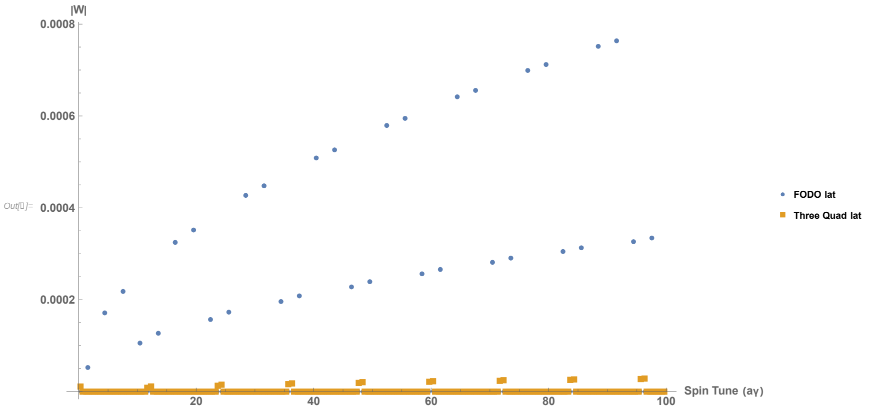
See BNL tech Note: https://technotes.bnl.gov/PDF?publicationId=223243

Cell construction

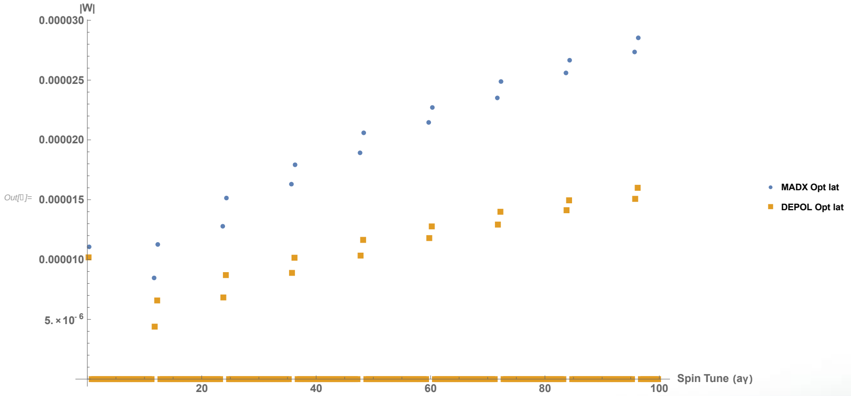
- Minimum number of quads → 3 e.g.:

$$M = \mathrm{QF}_1\ \ \mathrm{O}\ \ \mathrm{QD}\ \ \mathrm{O}\ \ \mathrm{QF}_2\ \ \mathrm{O}$$

$$0 = k_1\sqrt{\beta_1}\cos(\mu_1) + k_2\sqrt{\beta_2}\cos(\mu_2) + k_3\sqrt{\beta_3}\cos(\mu_3)$$
$$0 = k_1\sqrt{\beta_1}\sin(\mu_1) + k_2\sqrt{\beta_2}\sin(\mu_2) + k_3\sqrt{\beta_3}\sin(\mu_3)$$



Depol calculated spin resonances using special intrinsic spin resonance suppressing cell compared to a standard FODO cell with dipoles in-between



Depol calculated spin resonances using special intrinsic spin resonance suppressing cell optimized using DEPOL algorithm compared to approximate resonance suppression.

Study of two toy lattices

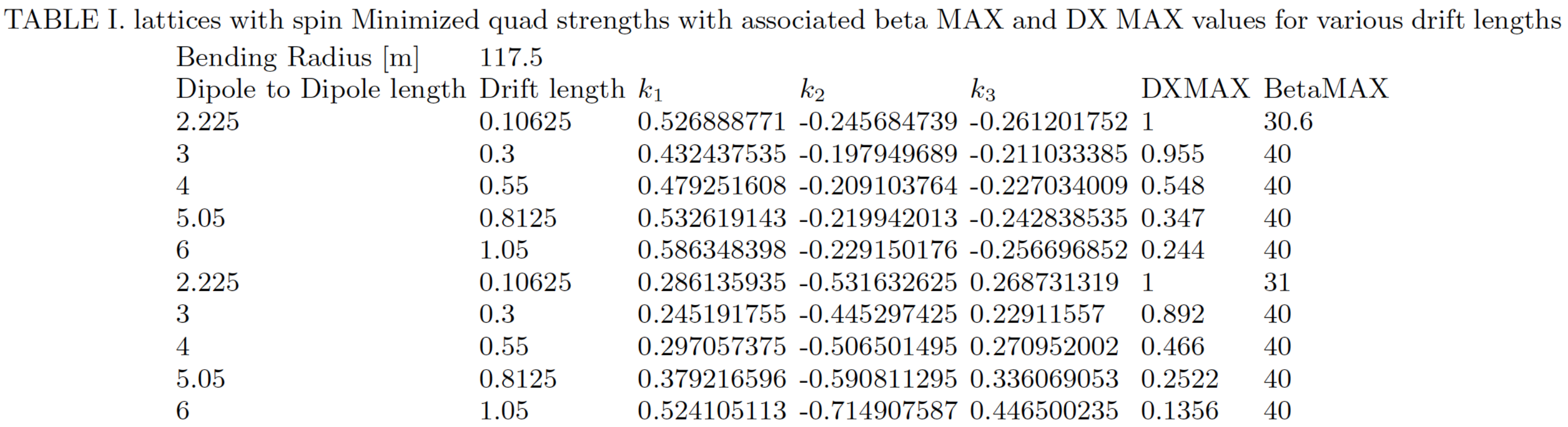


TABLE I. lattices with spin Minimized quad strengths with associated beta MAX and DX MAX values for various drift lengths

Bending Radius [m]	117.5					
Dipole to Dipole length	Drift length	k_1	k_2	k_3	DXMAX	BetaMAX
2.225	0.10625	0.526888771	-0.245684739	-0.261201752	1	30.6
3	0.3	0.432437535	-0.197949689	-0.211033385	0.955	40
4	0.55	0.479251608	-0.209103764	-0.227034009	0.548	40
5.05	0.8125	0.532619143	-0.219942013	-0.242838535	0.347	40
6	1.05	0.586348398	-0.229150176	-0.256696852	0.244	40
2.225	0.10625	0.286135935	-0.531632625	0.268731319	1	31
3	0.3	0.245191755	-0.445297425	0.22911557	0.892	40
4	0.55	0.297057375	-0.506501495	0.270952002	0.466	40
5.05	0.8125	0.379216596	-0.590811295	0.336069053	0.2522	40
6	1.05	0.524105113	-0.714907587	0.446500235	0.1356	40

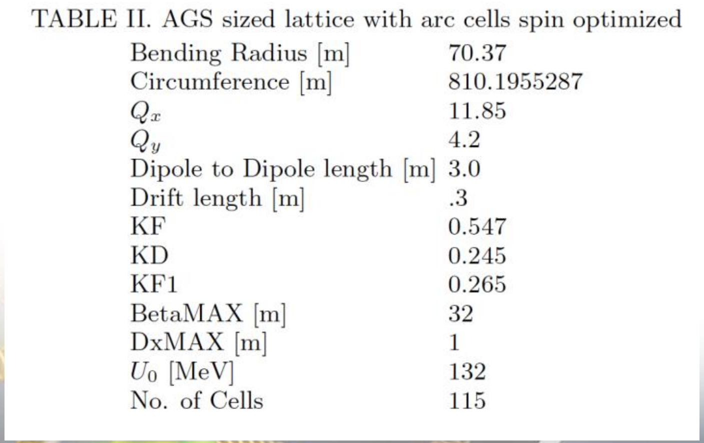


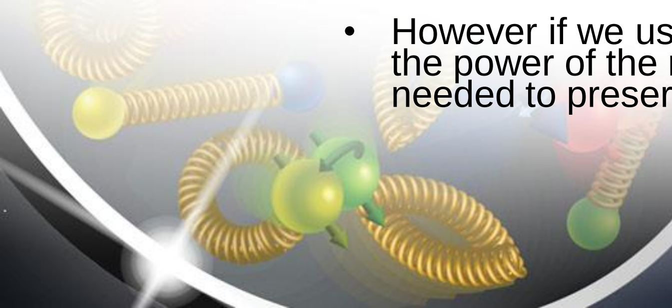
TABLE II. AGS sized lattice with arc cells spin optimized

Bending Radius [m]	70.37
Circumference [m]	810.1955287
Q_x	11.85
Q_y	4.2
Dipole to Dipole length [m]	3.0
Drift length [m]	.3
KF	0.547
KD	0.245
KF1	0.265
BetaMAX [m]	32
DxMAX [m]	1
U_0 [MeV]	132
No. of Cells	115

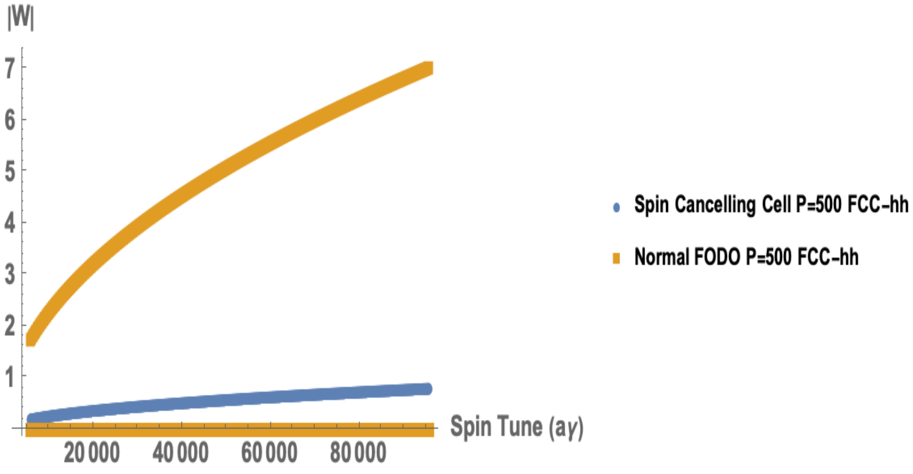
We also explored the possible construction of an AGS sized machine using this approach. In this case the lower tunes permits the appearance of the 0+ spin resonance in the energy range for electrons accelerating to 18 GeV. However since the cells are designed to minimize the spin resonance contribution, its effect is negligible under an acceleration rate comparable to the RCS's (100 msecs). The strengths are detailed in Table. II. The radiated energy per turn of 115 MeV makes the RF power requirements challenging for such a machine. However a proton machine or one with a lower energy or higher bending radius appears possible.

Accelerating Polarized beam in FCC/CEPC sized toy lattice

- Circumference ~ 97 km
- Number of arc Cells = 500
- Cell length ~ 195m
- Energy Range FCC-ee Booster: (20 to 182.5 GeV)
  - Electron → 45 – 414 Gɣ
    - At a Periodicity of 500 we can avoid all intrinsics using a vertical tune of less than 45:
    - Above tune of 45 we can suppress the 0+nu resonance using spin canceling cell design
    - Of course we must also take care of straights like we do in RCS
      - Regain good DA like we have done in RCS: easier if we don't have too many dipoles in straight (i.e. don't have to bend around experimental hall)
- Energy Range FCC-hh: (3 to 50 TeV)
  - Proton→ 5732 – 95532 Gɣ
    - Can't be done unless we go to probably unrealistically high periodicity.
    - However if we use the spin resonance cancelling arc cell approach, we can drop the power of the resonances that do appear significantly thus reduce # or snakes needed to preserve polarization during acceleration.

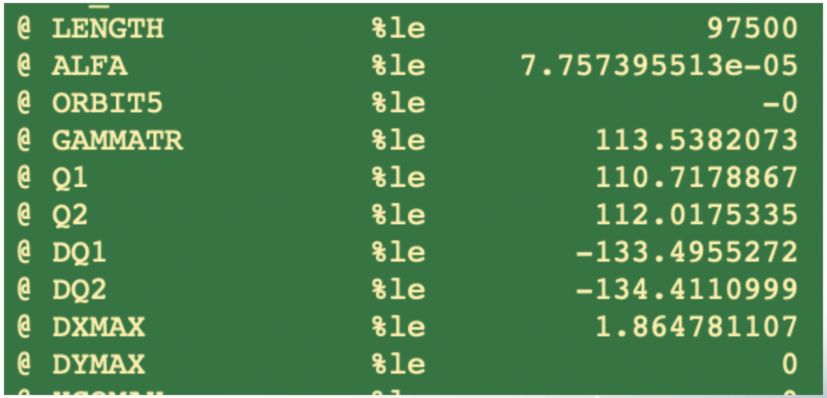


Toy FCC-hh Spin Resonance Strength

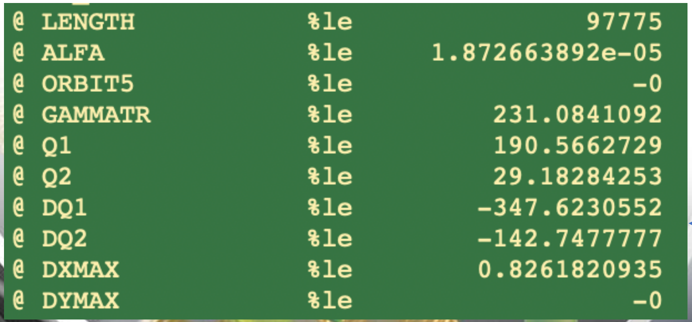


In this case we can potentially reduce max intrinsics from ~ 7 to 0.79. This means that we will need many fewer snakes to accelerate.

FODO Optics



```
@ LENGTH              %le                 97500
@ ALFA                %le      7.757395513e-05
@ ORBIT5              %le                    -0
@ GAMMATR             %le           113.5382073
@ Q1                  %le           110.7178867
@ Q2                  %le           112.0175335
@ DQ1                 %le          -133.4955272
@ DQ2                 %le          -134.4110999
@ DXMAX               %le           1.864781107
@ DYMAX               %le                     0
```



```
@ LENGTH              %le                 97775
@ ALFA                %le      1.872663892e-05
@ ORBIT5              %le                    -0
@ GAMMATR             %le           231.0841092
@ Q1                  %le           190.5662729
@ Q2                  %le           29.18284253
@ DQ1                 %le          -347.6230552
@ DQ2                 %le          -142.7477777
@ DXMAX               %le          0.8261820935
@ DYMAX               %le                    -0
```

Spin canceling cell optics

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.