Beam Dynamics Issues at the High Luminosity Polarized Collider RHIC

- Polarized proton acceleration in the AGS
- Polarized proton acceleration and collisions in RHIC
- High luminosity and high polarization

BROOKHAVEN NATIONAL LABORATORY

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Spin Dynamics in Rings

Precession Equation in Laboratory Frame:
(Thomas [1927], Bargmann, Michel, Telegdi [1959])

$$d\mathbf{S}/dt = -(e/\gamma m)\,[(1+G\gamma)\mathbf{B}_\perp + (1+G)\,\mathbf{B}_{||}\quad] \times \mathbf{S}$$

Lorentz Force equation:

$$d\mathbf{v}/dt = -(e/\gamma m)\,[\quad \mathbf{B}_\perp \quad] \times \mathbf{v}$$

- For pure vertical field:
  Spin rotates $G\gamma$ times faster than motion, $\nu_{sp} = G\gamma$
- For spin manipulation:
  At low energy, use longitudinal fields
  At high energy, use transverse fields

Spin tune and Depolarizing Resonances

Depolarizing resonance condition:

Number of spin rotations per turn = Number of spin kicks per turn
Spin resonance strength ε = spin rotation per turn / 2π

Imperfection resonance (magnet errors and misalignments):

$\nu_{sp} = n$

Intrinsic resonance (Vertical focusing fields):

$\nu_{sp} = Pn \pm Q_y$

P : Superperiodicity [AGS: 12]
Q_y : Betatron tune [AGS: 8.75]

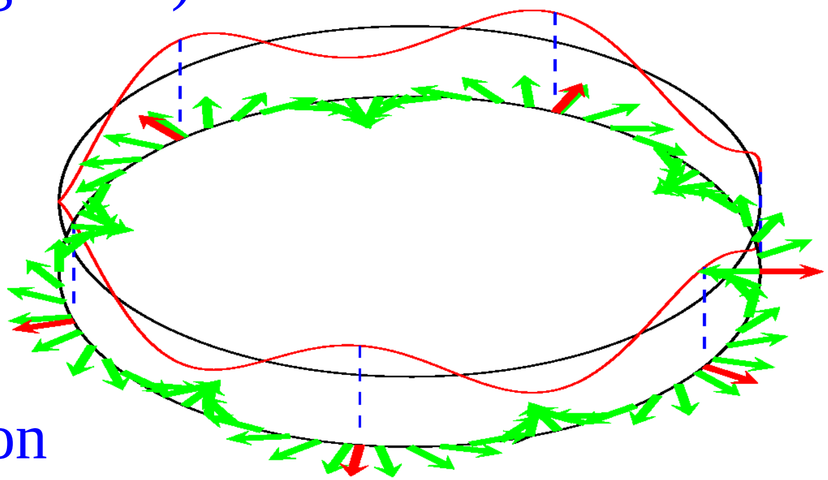


Illustration by W.W. MacKay

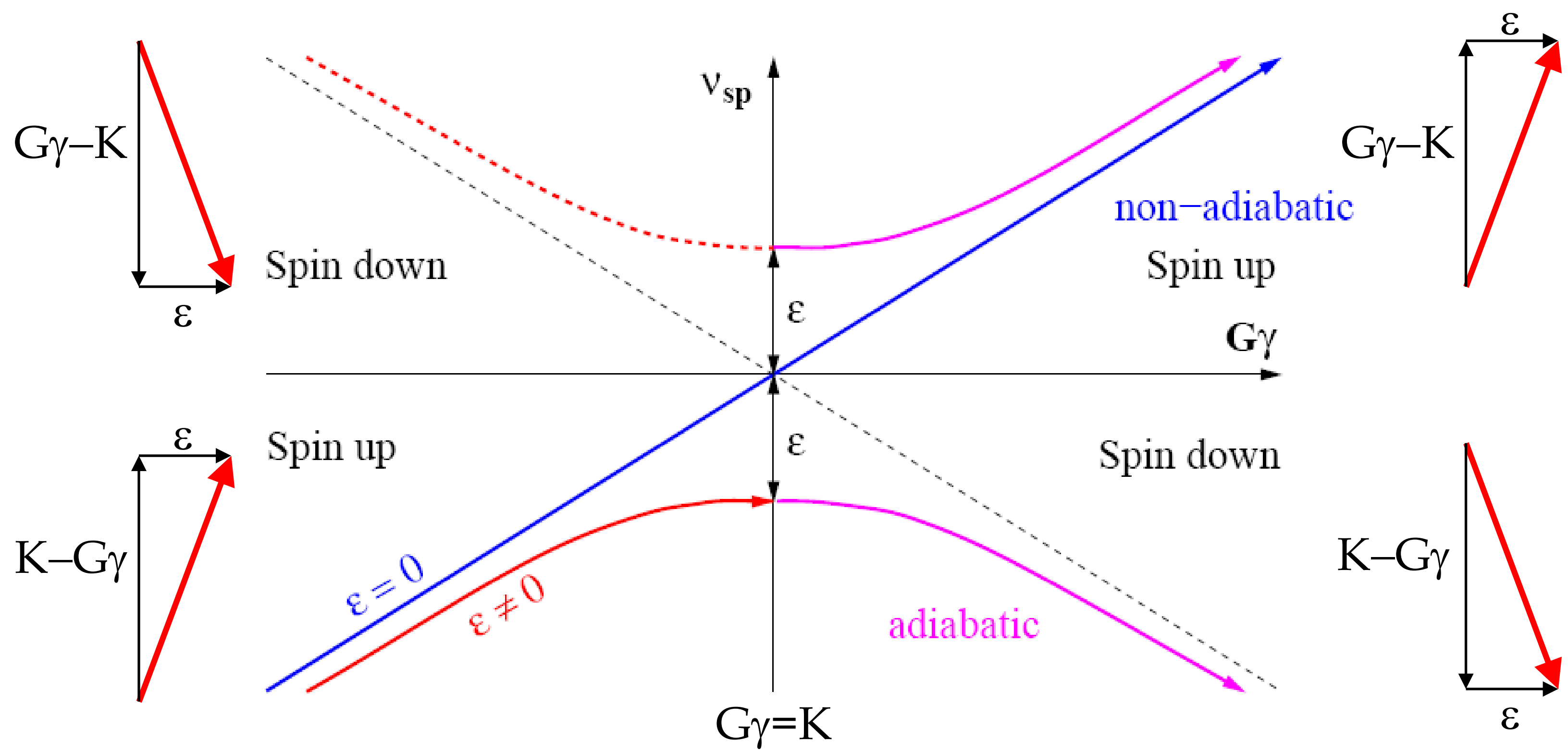
Weak resonances: some depolarization
Strong resonances: partial or complete spin flip

Spin Resonance Crossing

Froissart-Stora: $$\frac{P_f}{P_i} = 2\, e^{-\left(\frac{\pi \varepsilon^2}{2\alpha}\right)} - 1$$ [α: crossing speed]

Non-adiabatic ($\varepsilon^2/\alpha << 1$) ↔ Adiabatic ($\varepsilon^2/\alpha >> 1$)

$P_f / P_i = 1$ $P_f / P_i = -1$

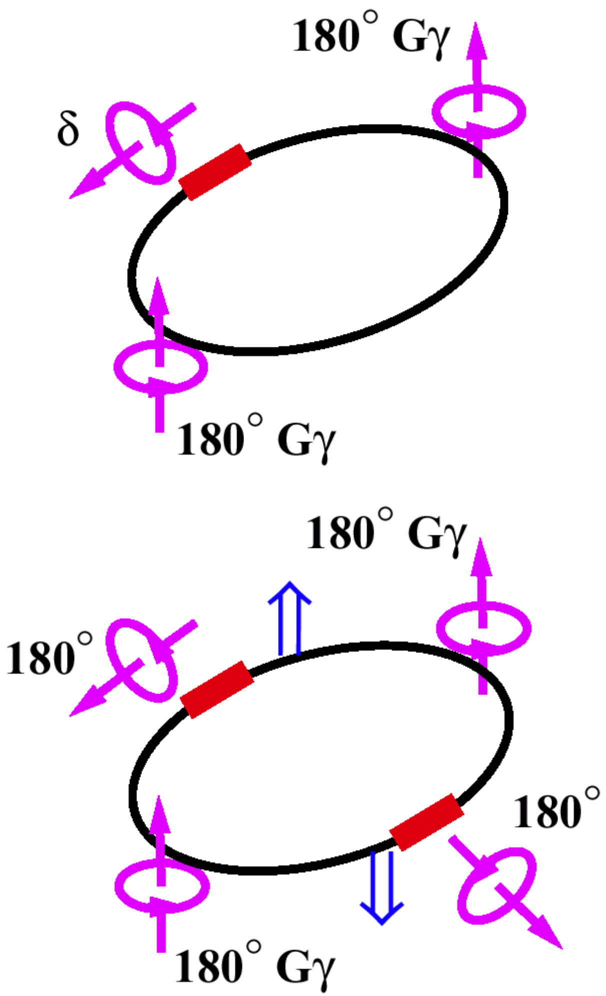


Spin Resonance Crossing

- Non-adiabatic ($\varepsilon^2/\alpha << 1$)
- $P_f / P_i = 1$
- Imperfection resonances:
  - Correction dipoles (ε small)
- Intrinsic resonances:
  - Pulsed quadrupoles (α large)
  - Lattice modifications (ε small)

- Adiabatic ($\varepsilon^2/\alpha >> 1$)
- $P_f / P_i = -1$
- Imperfection resonances:
  - Partial Siberian snake(s) (ε large)
- Intrinsic resonances:
  - RF Dipole (ε large)
  - Strong partial Siberian snake(s) (ε large)

Siberian Snakes (Local Spin Rotators)



$$\boxed{\cos(180^\circ \nu_{sp}) = \cos(\delta/2) \cdot \cos(180^\circ G\gamma)}$$

$\delta \neq 0^\circ \rightarrow \nu_{sp} \neq n$

No imperfection resonances

Partial Siberian snake (AGS)

$\delta = 180^\circ \rightarrow \nu_{sp} = ½$

No imperfection resonances and

No Intrinsic resonances

Full Siberian Snake

(Ya.S. Derbenev and A.M. Kondratenko)

Two Siberian Snakes (RHIC):

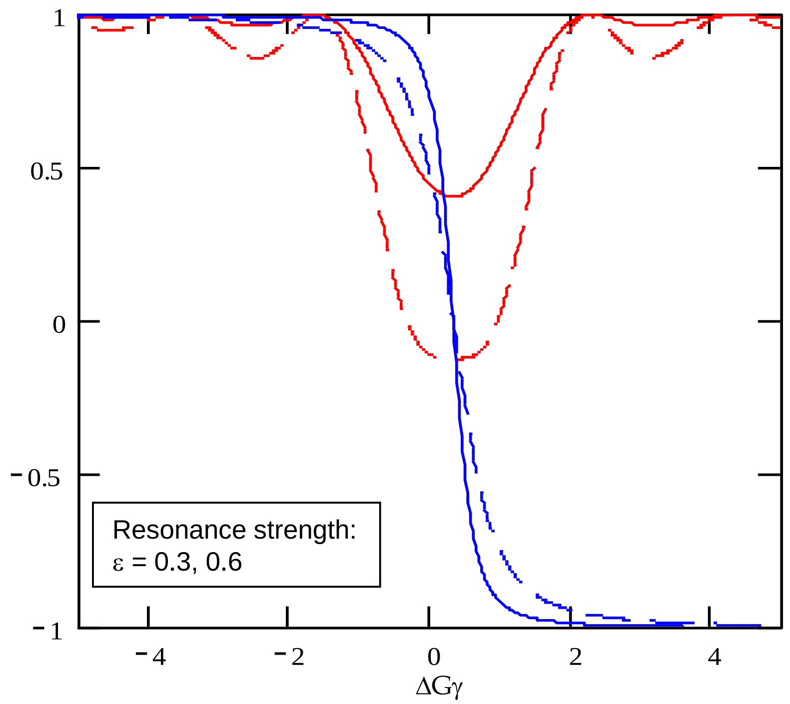
$\nu_{sp} = (\alpha_2 - \alpha_1)/180^\circ$ ($\alpha_{1,2}$: angles between snake axis and beam direction)

Orthogonal snake axis: ν_{sp} = ½ and independent of beam emittance (SRM, S. Mane)

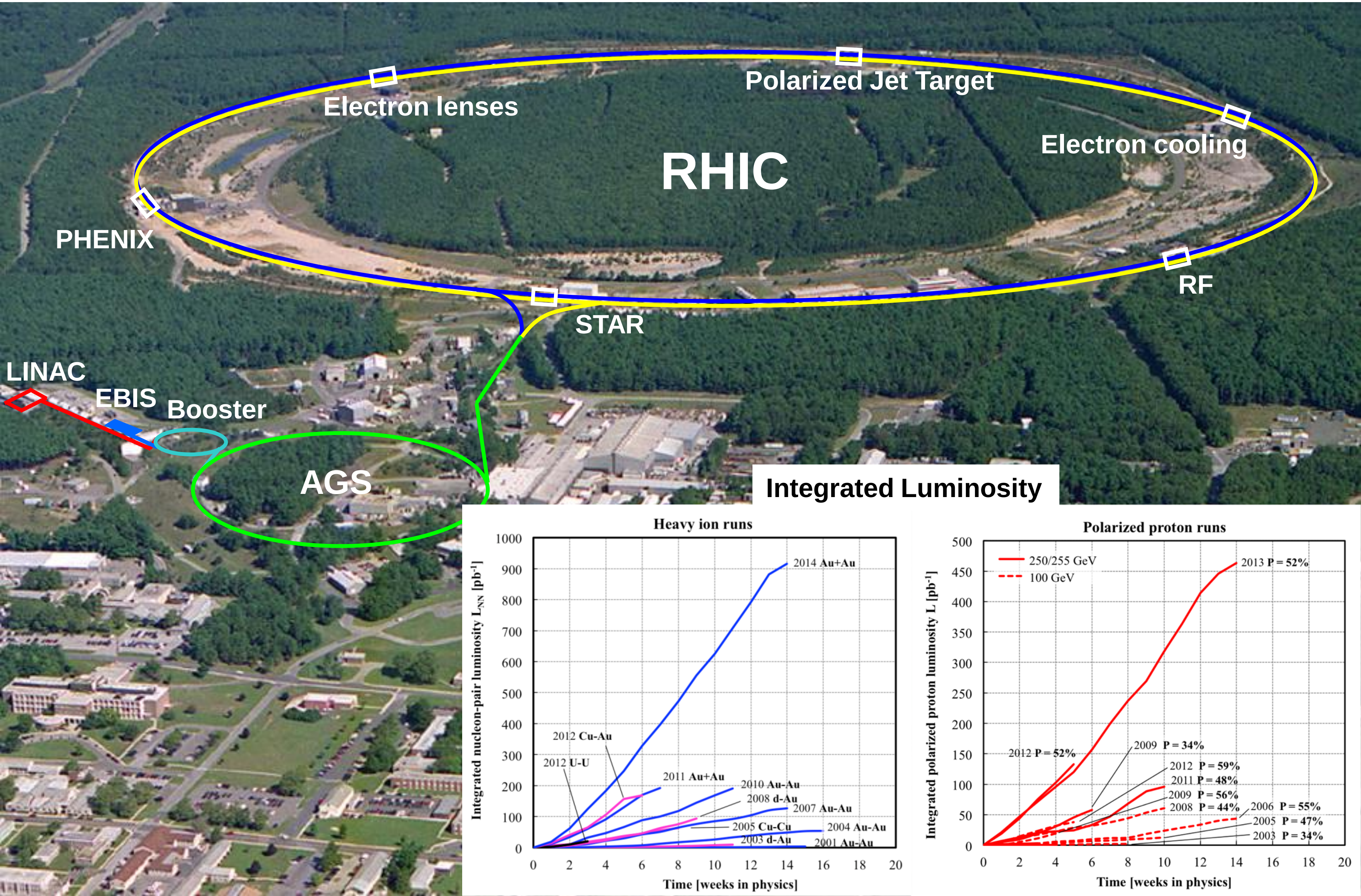
Beam Polarization Near a Single Strong Intrinsic Resonance

- Without snakes:
  - Full spin flip, width ~ ± 5ε

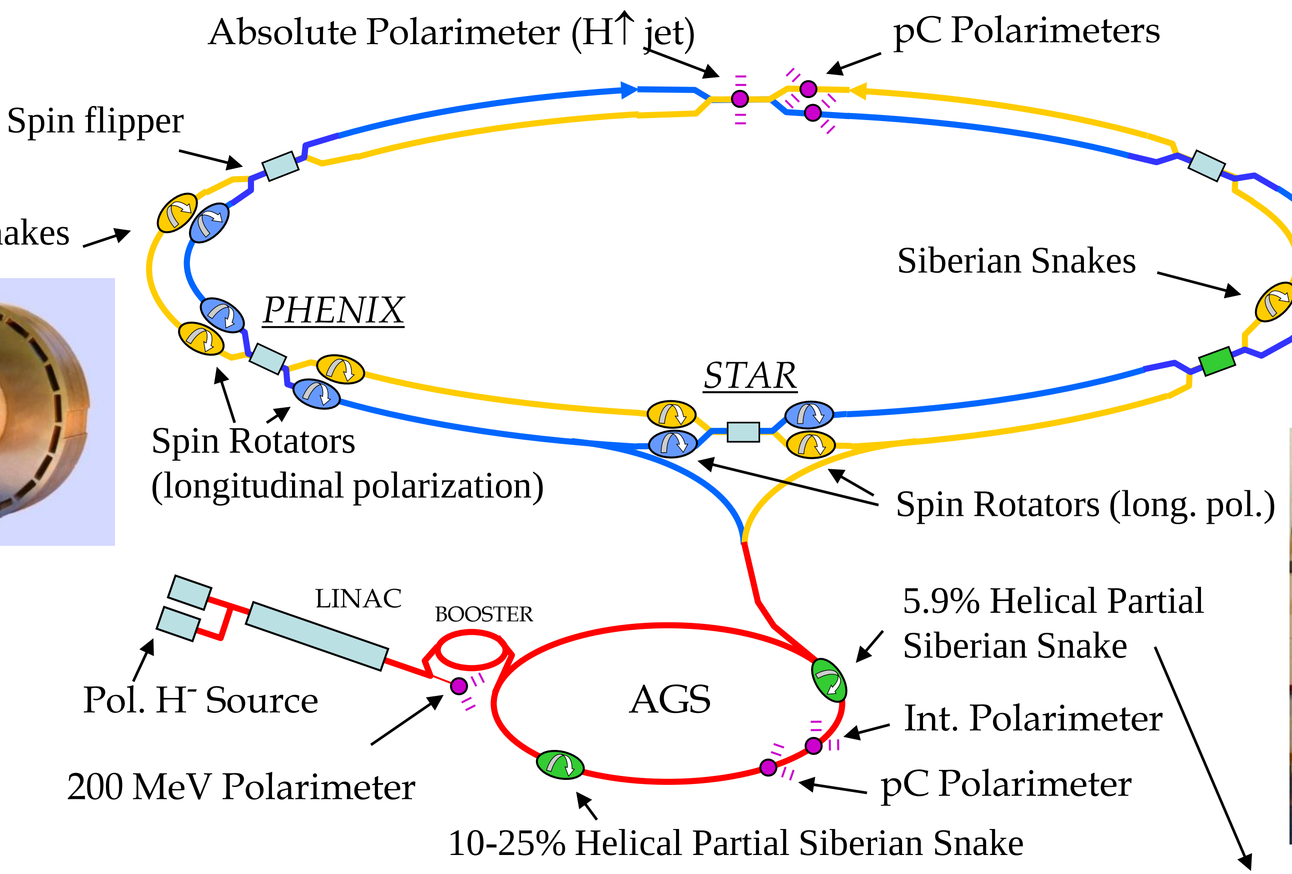
- With snakes:
  - Opening/closing of “spin cone”, nodes at ± 2
  - Resonance crossing during acceleration is adiabatic with no polarization loss.

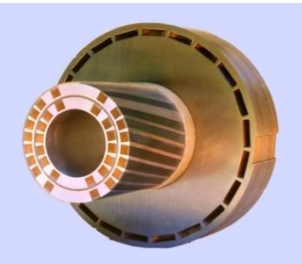


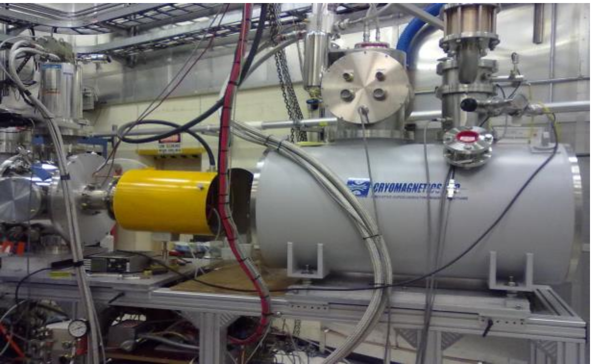
RHIC – a high luminosity polarized hadron collider

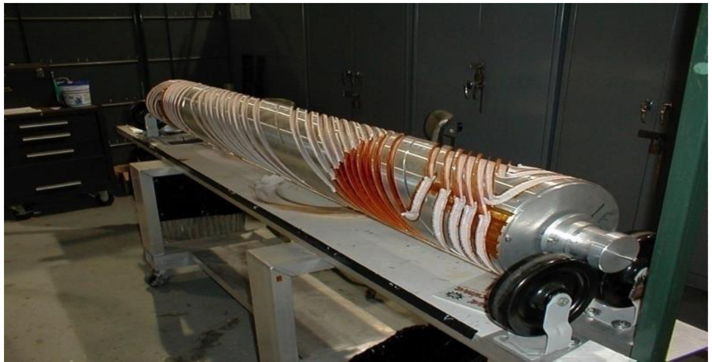


RHIC – First Polarized Hadron Collider



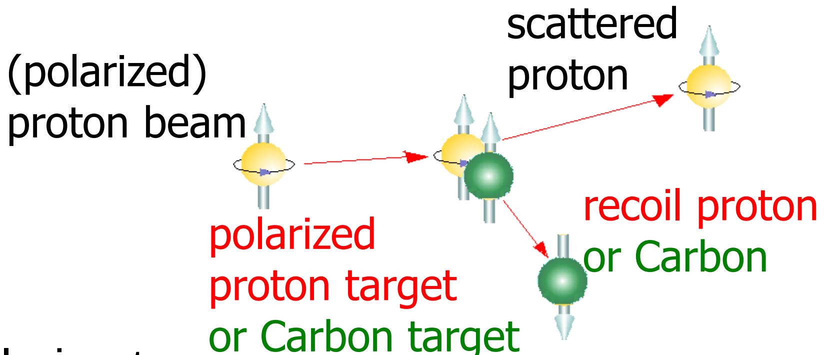




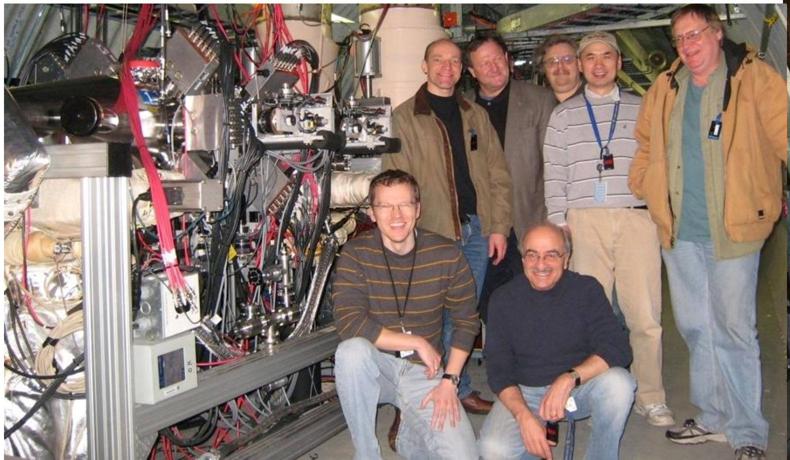


RHIC polarimetry

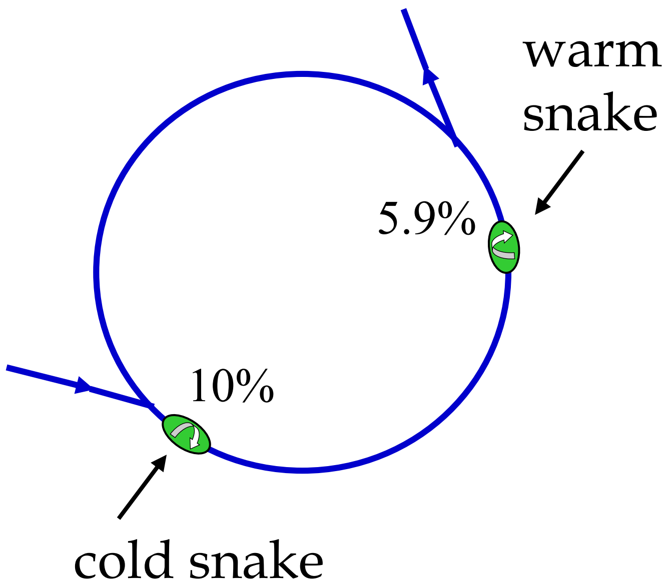
- Absolute polarimeter (Pol. Hjet)
  - Polarized hydrogen jet target allows for absolute beam polarization measurement:
    $$P_{\text{Beam}} = P_{\text{Target}} \frac{\varepsilon_{\text{Beam}}}{\varepsilon_{\text{Target}}}$$
  - Jet target thickness of ~ 1×10^{12} cm^{-2} achieved
  - Jet pol. 92 ± 2 % measured with Breit-Rabi polarimeter
  - Analyzing power A_N ~ 0.044 (24 – 255 GeV)



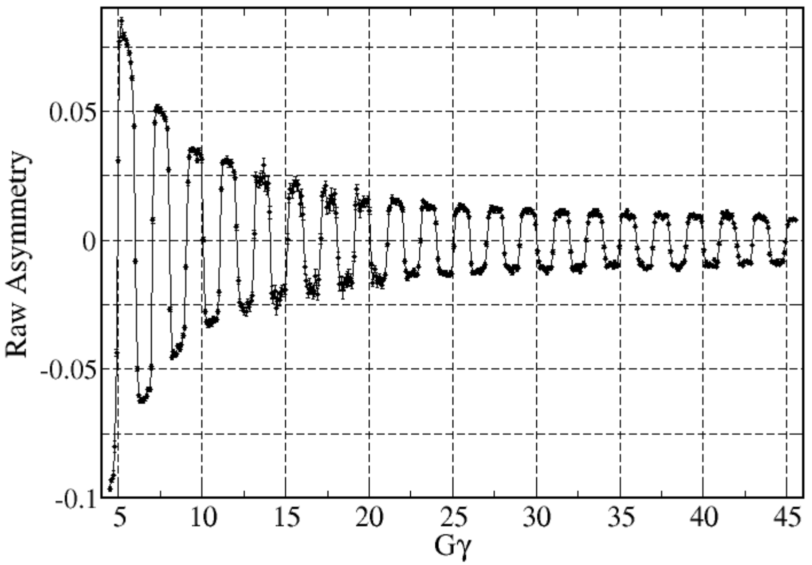
- Relative polarimeters (proton-carbon)
  - Measure horizontal and vertical polarization profiles
  - Fast measurements (~ 2 minutes)
- Local IP polarimeters (forward neutron production)
  - Significant asymmetry, calibrated with Hjet
  - Used to adjust transverse polarization component to zero

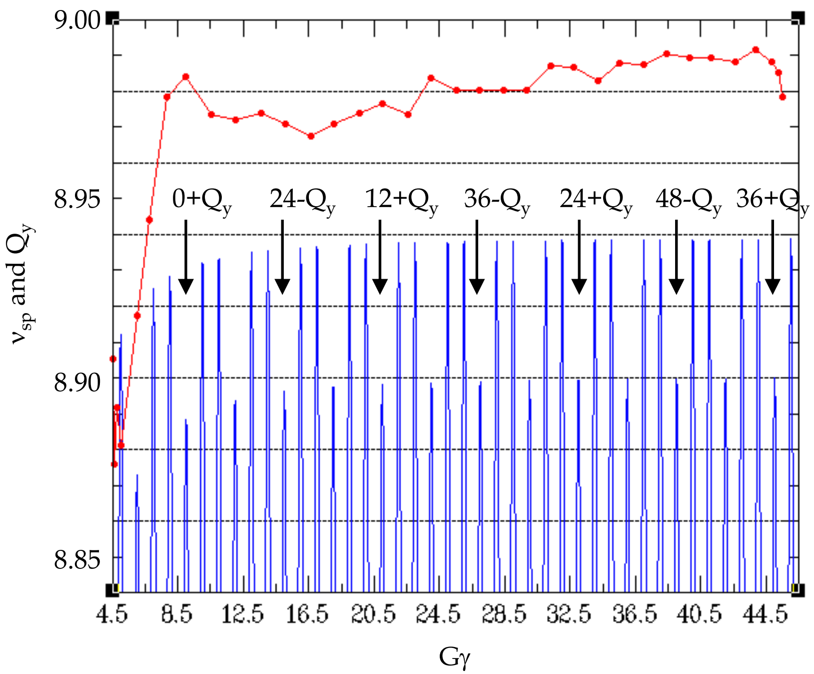


Polarized proton acceleration in the AGS



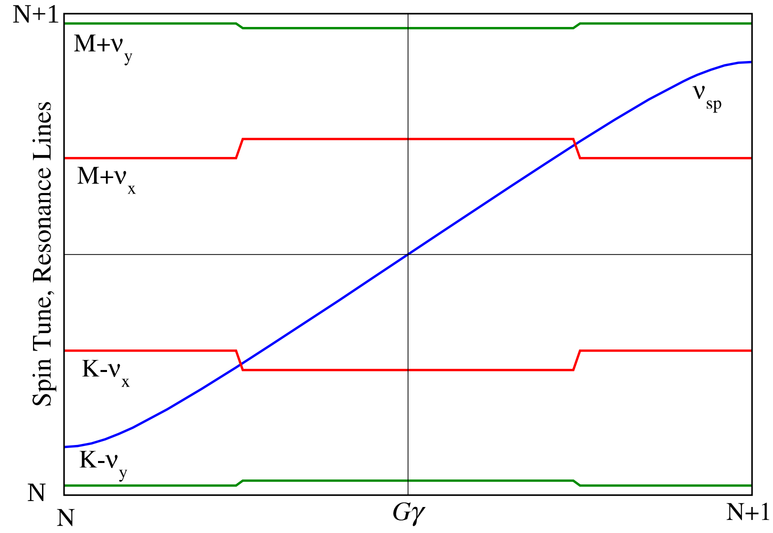
- During acceleration in AGS polarization flips 40 times
- To avoid intrinsic resonances vertical betatron tune is placed very close to 8.98!

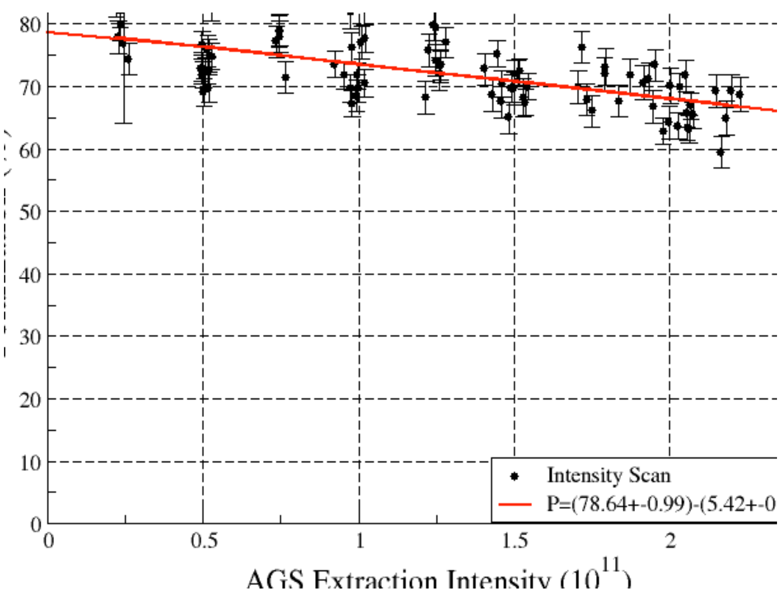


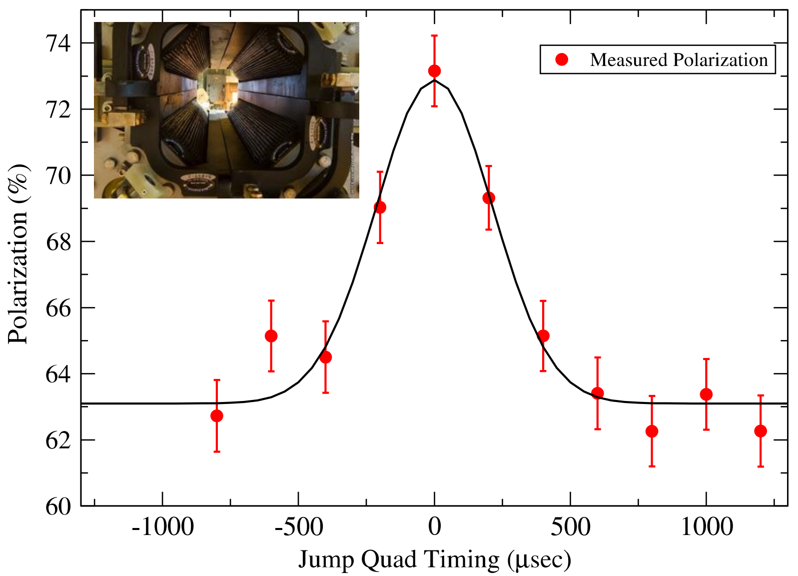


Horizontal spin resonances

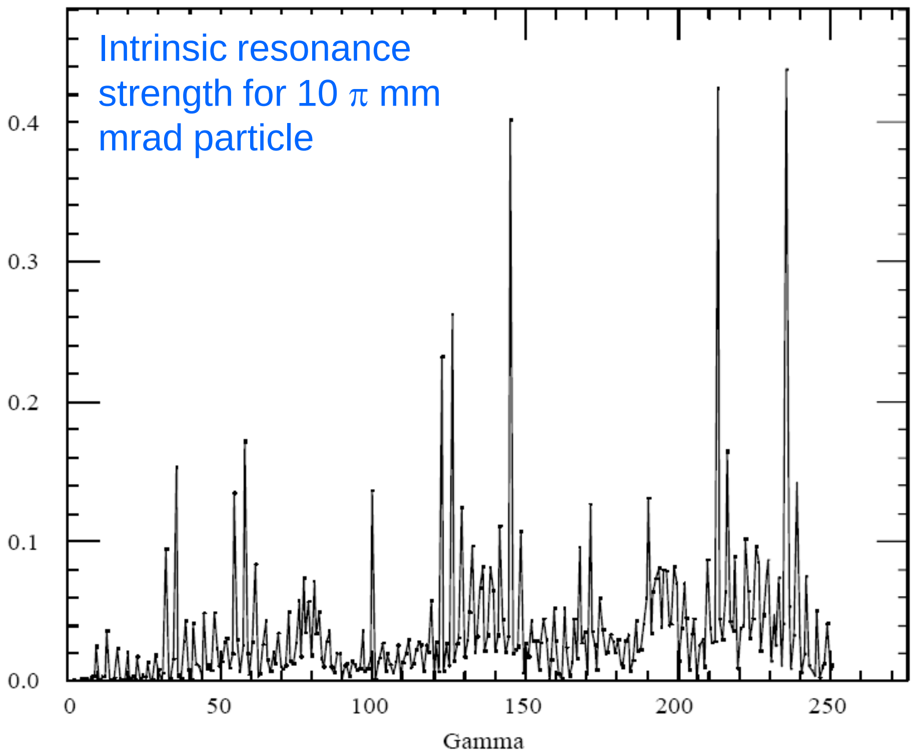
- Partial snakes generate ~ 80 weak horizontal spin resonances
- Use two fast quadrupoles, pulsing them 40 times during the half second ramp, to overcome all the horizontal resonances.
- Reached 90% polarization transmission and 70% polarization at high intensity (2 x 10^{11} ppb)

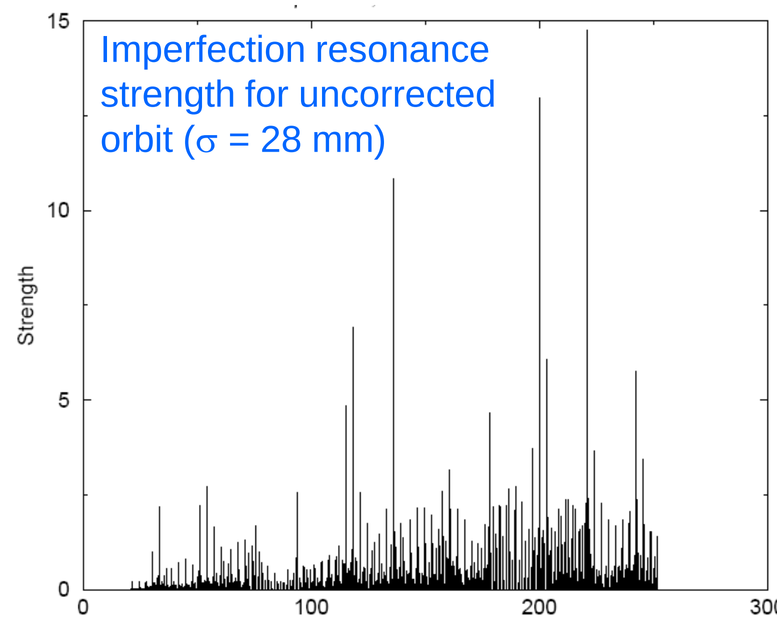


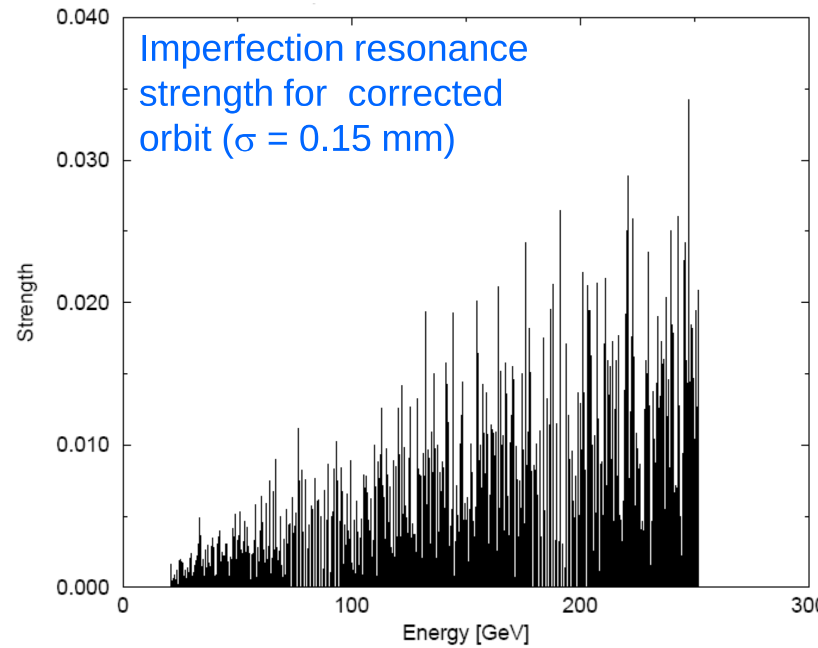




Spin Resonances in RHIC w/o Snakes



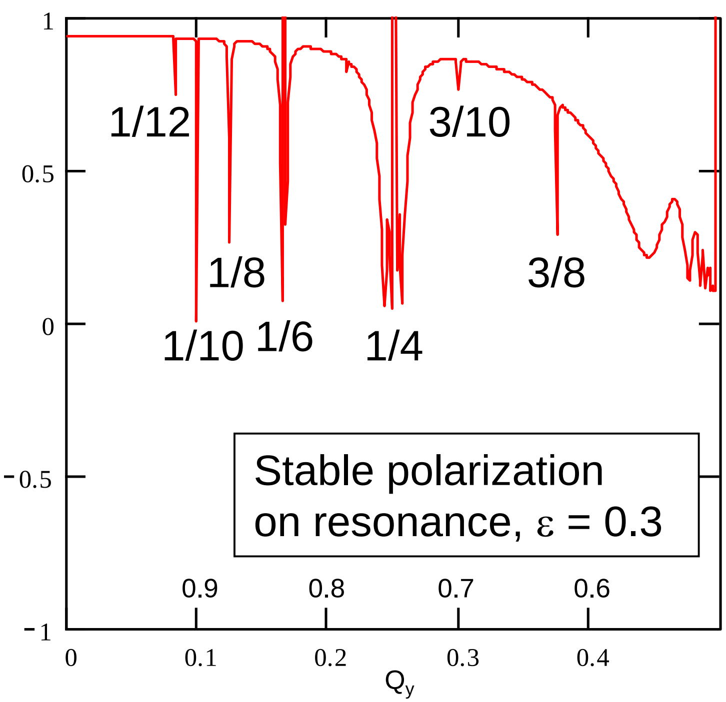




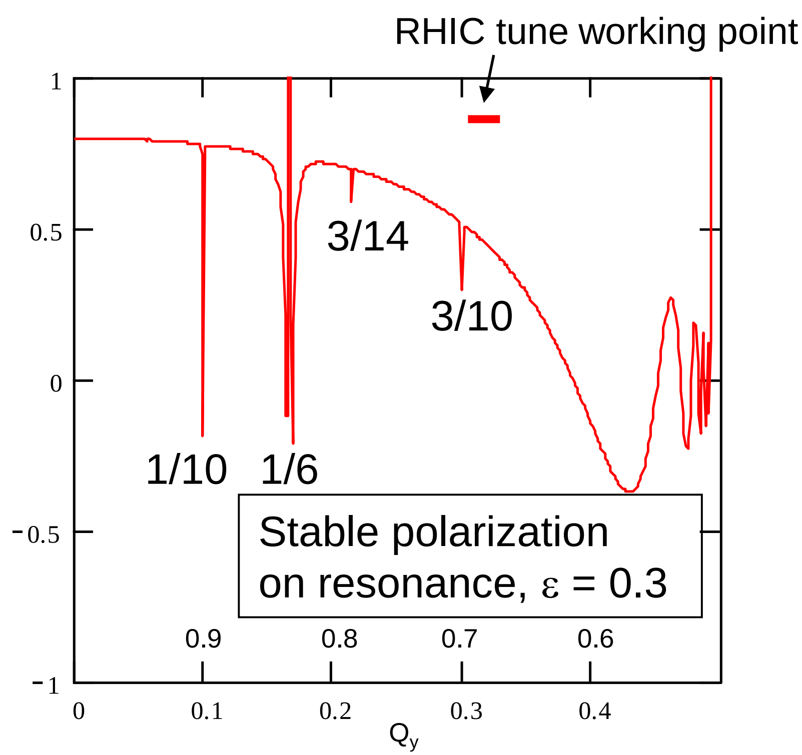
Snake Resonances

- Higher order resonance condition $\nu_{sp} + mQ_y = k$ (m, k = integer) driven by interaction of intrinsic resonance $G\gamma + Q_y = k$ with large spin rotations of dipoles and snakes.
- No non-linear drive term necessary – combination of rotations is already non-linear.
- "Snake resonance strength" depends on intrinsic resonance strength and therefore energy
- For $\nu_{sp}=1/2+\Delta\nu_{sp} \rightarrow Q_y = (2k-1)/2m-\Delta\nu_{sp}/m$
  - First analytical solution of isolated resonance with snakes by S.R. Mane, NIM A 498 (2003) 1

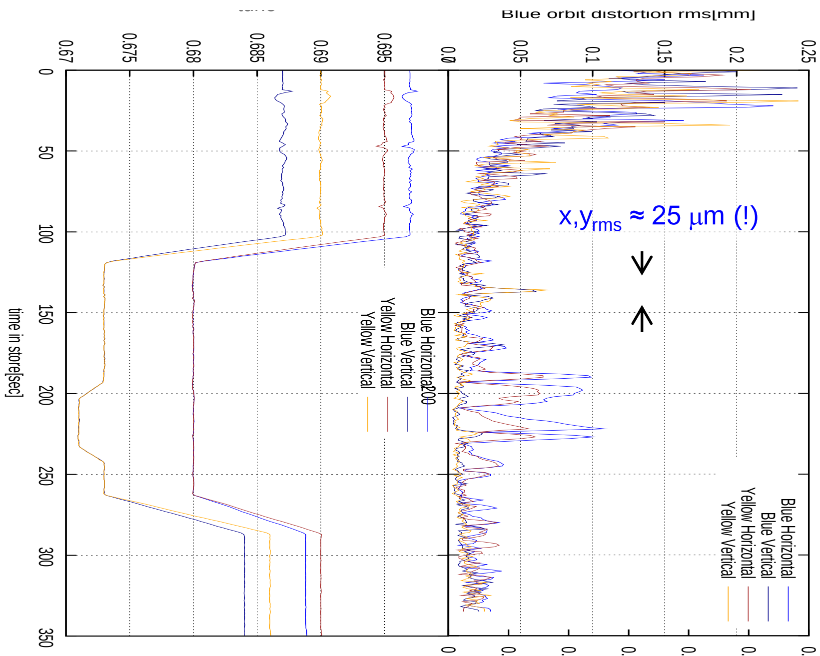
single snake
or two snakes with orbit errors

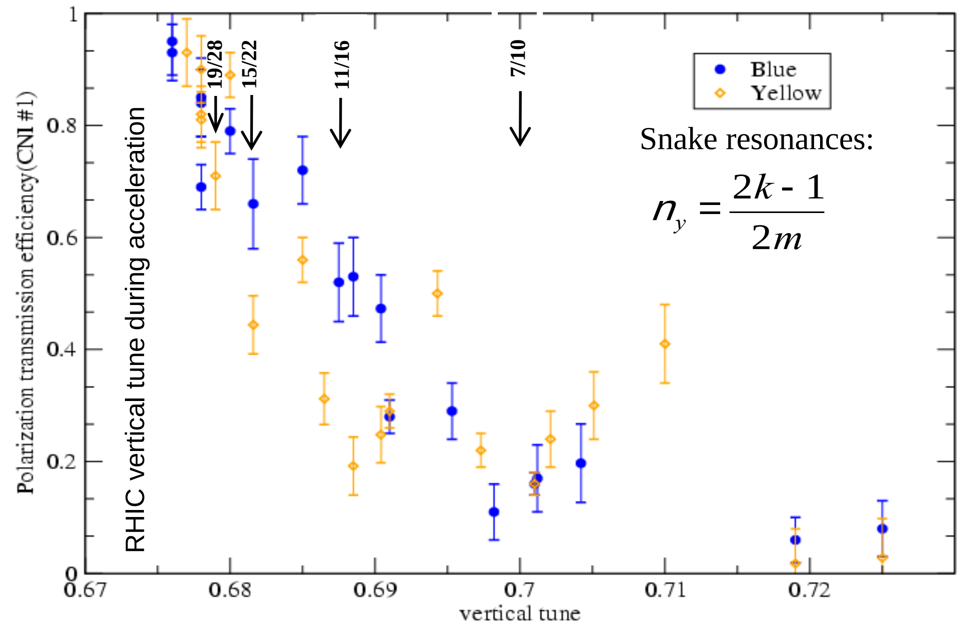


two snakes (m: odd)



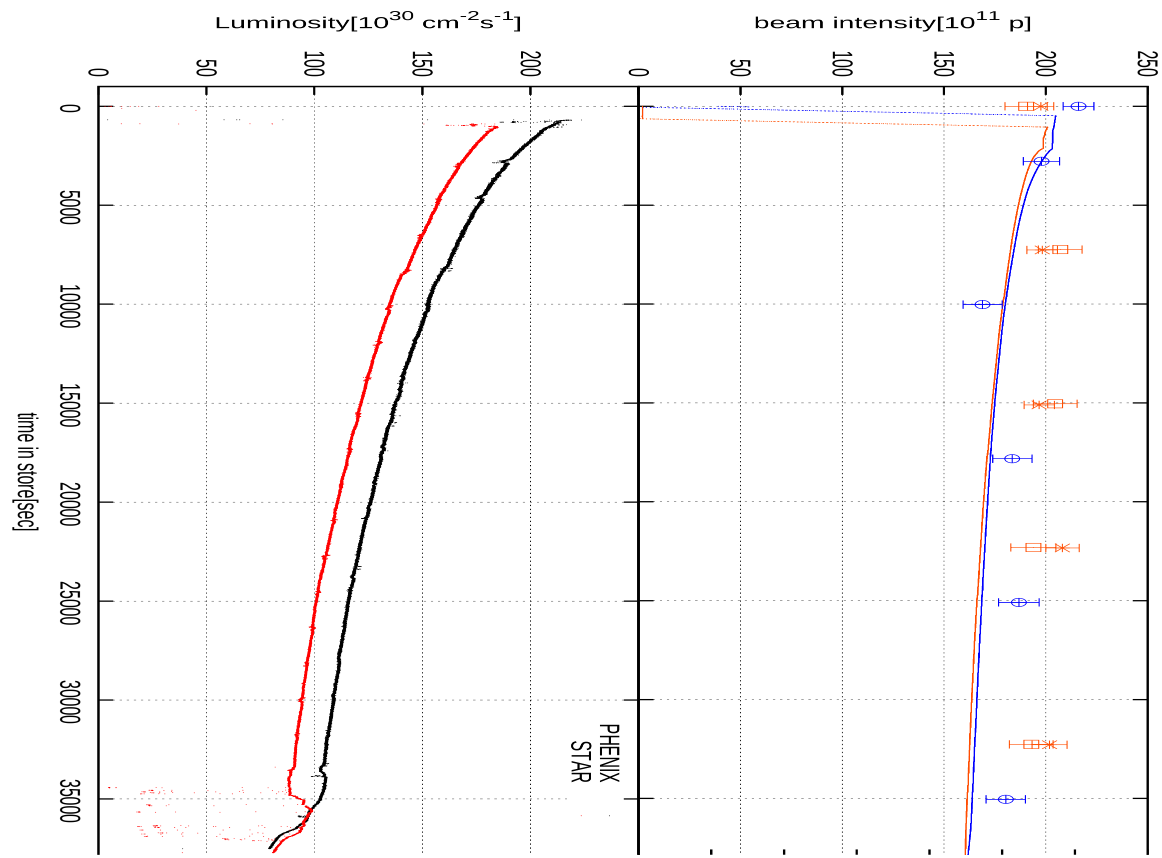
Accelerating polarized protons in RHIC





- Tune/coupling feedback on every ramp allows for:
  - Acceleration between Q_y = 0.667 and Q_y = 0.7 with best polarization transmission
- Slow orbit feedback on every ramp allows for:
  - Smaller y_{rms} (smaller imperfection resonance strength)
  - Ramp reproducibility (have 24 h orbit variation)
- Continuous fast 10 Hz orbit feedback eliminates effect of vibrating triplets

Polarized proton collisions at 255 GeV beam energy



- Reached ~57% average polarization in 14 best stores
- Little polarization loss on ramp and during store
- Peak luminosity: 2.5 × 10^{32} cm^{-2} s^{-1}
- Requires excellent control of orbit, tune and coupling

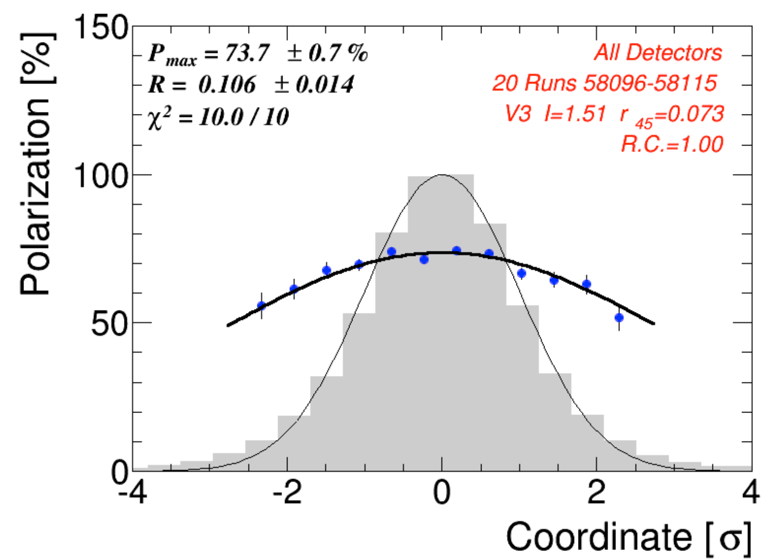
Depolarization and polarization profiles

- Polarization loss from intrinsic resonances: polarization lost at edge of beam → polarization profile
  - Impact of polarization profile on beam polarization at collisions $P_{coll.}$:

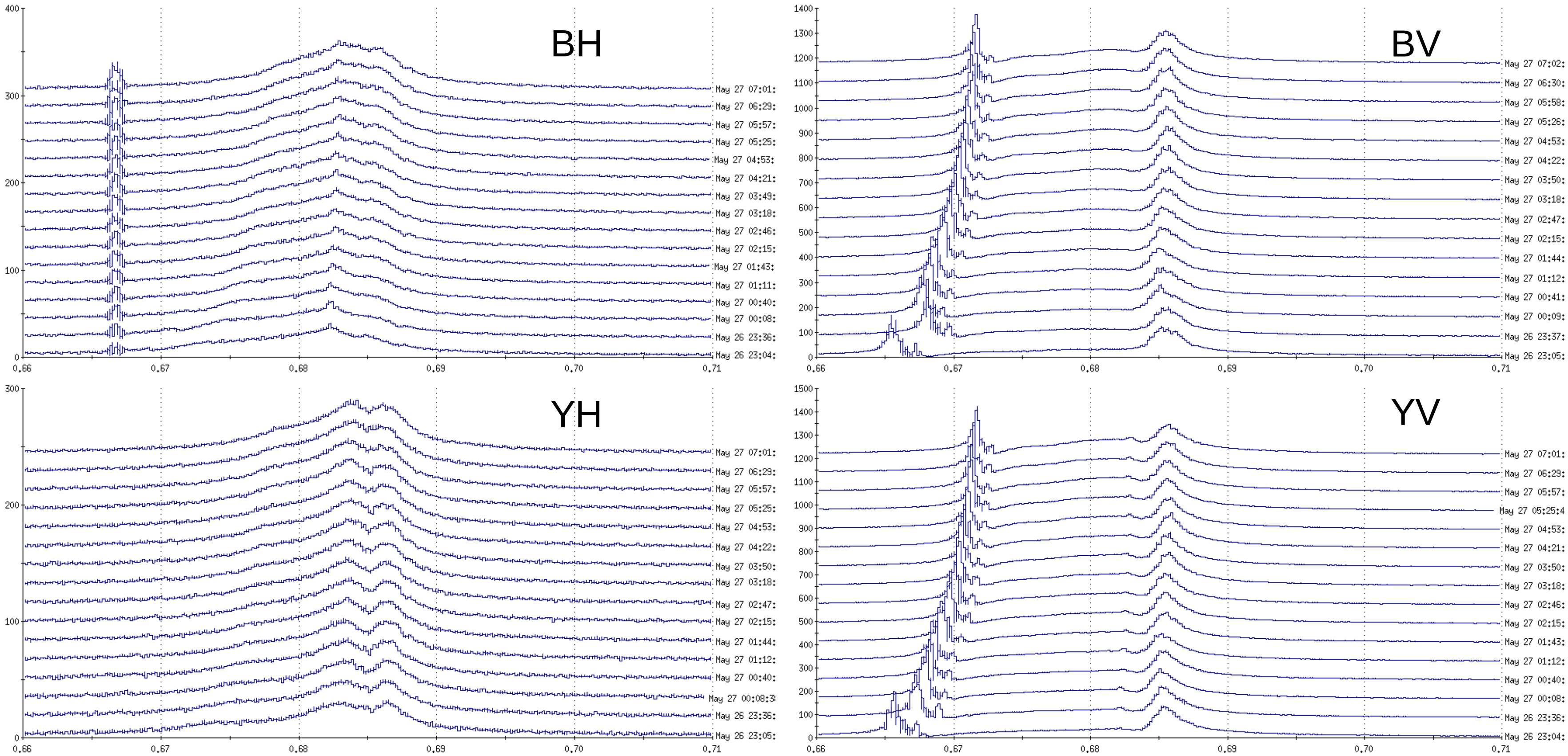
$$P(x,x',y,y') = P_0 e^{-\frac{x^2+x'^2}{2s_{x,P}^2}} e^{-\frac{y^2+y'^2}{2s_{y,P}^2}}; \quad I(x,x',y,y') = I_0 e^{-\frac{x^2+x'^2}{2s_{x,I}^2}} e^{-\frac{y^2+y'^2}{2s_{y,I}^2}}; \quad R_H = \frac{s_{x,I}^2}{s_{x,P}^2}; \quad R_V = \frac{s_{y,I}^2}{s_{y,P}^2}$$

$$\langle P \rangle = P_0 \frac{1}{(1+R_H)(1+R_V)}; \quad P_{coll.} = P_0 \frac{1}{\sqrt{1+\frac{1}{2}R_H}\sqrt{1+R_H}\sqrt{1+\frac{1}{2}R_V}\sqrt{1+R_V}} = \langle P \rangle \frac{\sqrt{1+R_H}\sqrt{1+R_V}}{\sqrt{1+\frac{1}{2}R_H}\sqrt{1+\frac{1}{2}R_V}}$$

  - For $R_H \approx R_V \approx R$ and small: $P_0 = \langle P \rangle (1+R)^2$; $P_{coll.} \approx \langle P \rangle (1+½R)$
  - <P> measured with H jet polarimeter; R measured with pC polarimeter
  - Typical values at RHIC 255 GeV: P_0= 80%; <P>=57%, R=0.18, $P_{coll.}$=62%
- Note that P_0, the polarization of the core particle, should be equal to the maximum achievable polarization.
- Loss of average polarization is compatible with development of polarization profiles → all remaining polarization loss in AGS and RHIC is due to intrinsic resonances. (no coherent polarization loss)



Transverse BTF measurements during RHIC store

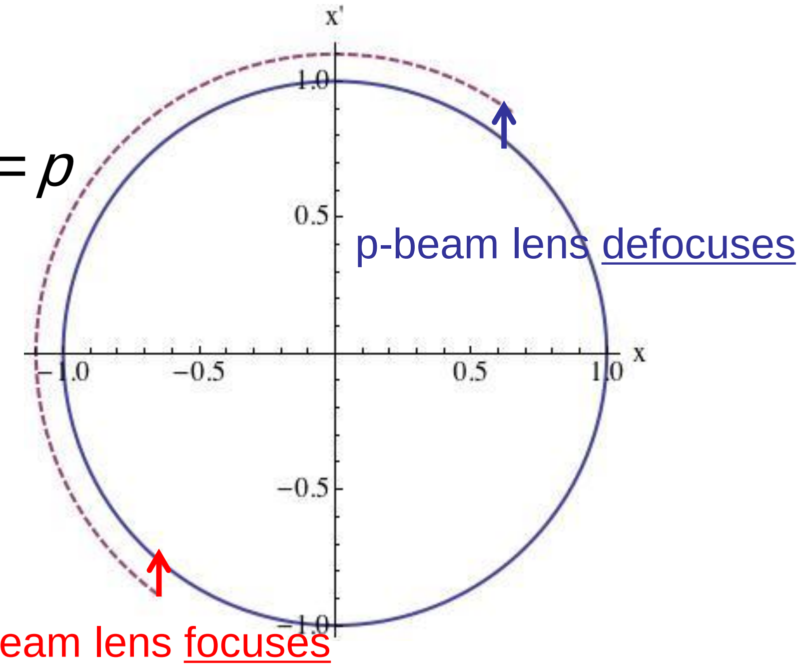


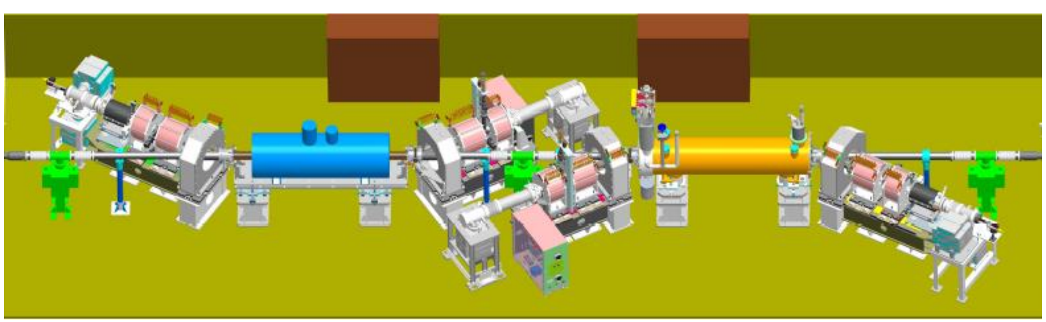
- BTF measurements give indication of tune distribution
- Orbit and spin resonances limit tunes to 0.667 – 0.700
- Clear signal of π and σ mode in vertical planes
- Indication of beam-beam tune spread in horizontal plane
- Beam-beam pushes π mode to 0.667
- Some particles in horizontal 2/3 resonance

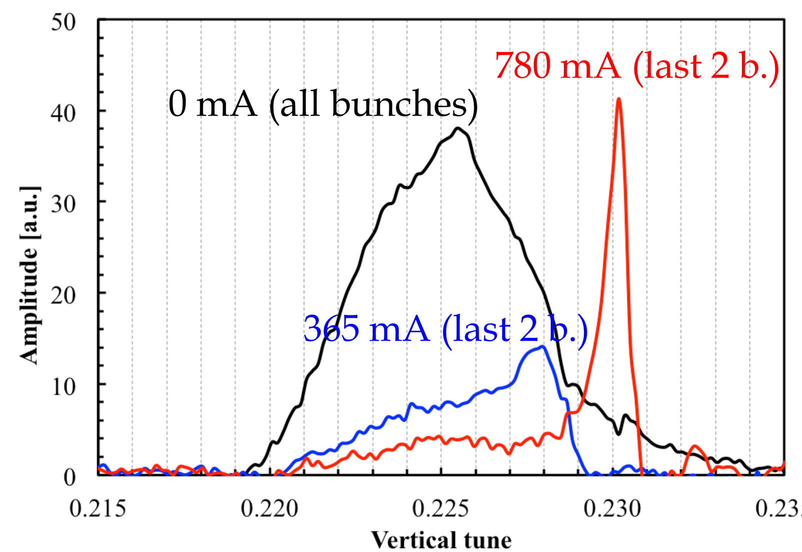
Head-on beam-beam compensation with electron lens

- Compensation of:
  - **Tune spread:** e-p has same amplitude dependent force as p-p
  - **Resonance driving terms:** phase advance between p-p and e-p is $\Delta\psi = k\pi$
- Two electron lenses installed in RHIC and test with Au beam successfully reduced beam-beam tune spread
- Correct phase advance between p-p collisions and electron lenses during upcoming polarized proton run

$Dy = p$



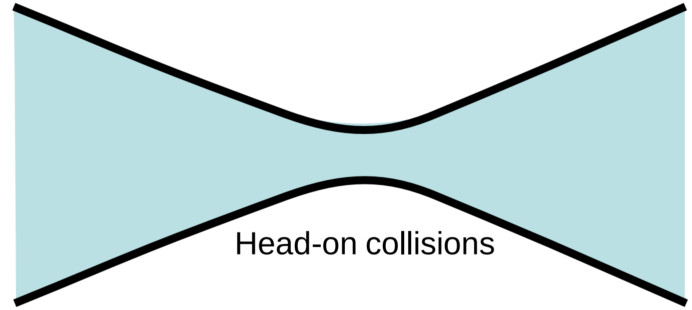




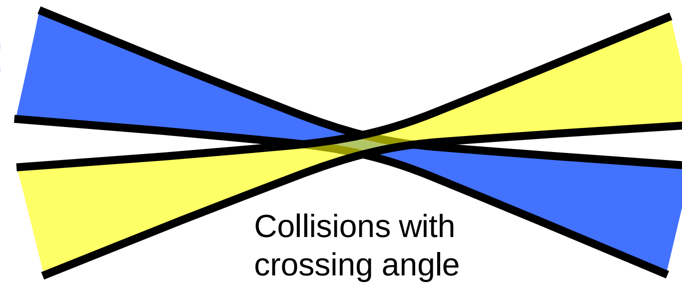
Summary

- Successful operation of RHIC as polarized proton collider with 255 GeV beam energy
- Reached 57 % beam polarization with residual polarization loss from intrinsic (amplitude dependent) spin resonances in AGS and RHIC
- Reached high luminosity up to beam-beam limit with no impact on beam polarization
- Head-on beam-beam compensation with electron lenses planned for next run.

Symmetric collisions with large crossing angle



- Head-on collisions:
  - Luminosity loss from hour-glass effect requires shorter bunch length for smaller beta-star
  - Reducing bunch length limited by peak current, momentum acceptance and/or instabilities
  - Difficult to reduce beta-star without reducing emittance and momentum spread



- Large crossing-angle collisions (Piwinski angle):
  - To be beneficial needs low emittance beams (strong cooling: synchrotron rad. or CeC)
  - Separate bunches outside high luminosity region to avoid beam-beam effect from low luminosity region.
  - Reducing beam emittance back to beam-beam limit
  - Smaller emittance and shorter overlap region allows for smaller beta-star
  - For reduced overlap (1/k) and reduced emittance $\varepsilon = \varepsilon^0/k$:

$$\frac{L}{\gamma} = \frac{1}{4\pi}\frac{N_b}{k\varepsilon}\frac{N_b}{\tau_b}\frac{R}{\beta^*} = \frac{1}{4\pi}\frac{N_b}{k\varepsilon}\frac{N_b}{\tau_b}\frac{R\gamma\sigma'^2}{\varepsilon} = \frac{1}{4\pi}\frac{N_b}{\varepsilon^0}\frac{N_b}{\tau_b}\frac{R\gamma\sigma'^2}{\varepsilon^0/k} = k\frac{L^0}{\gamma}$$