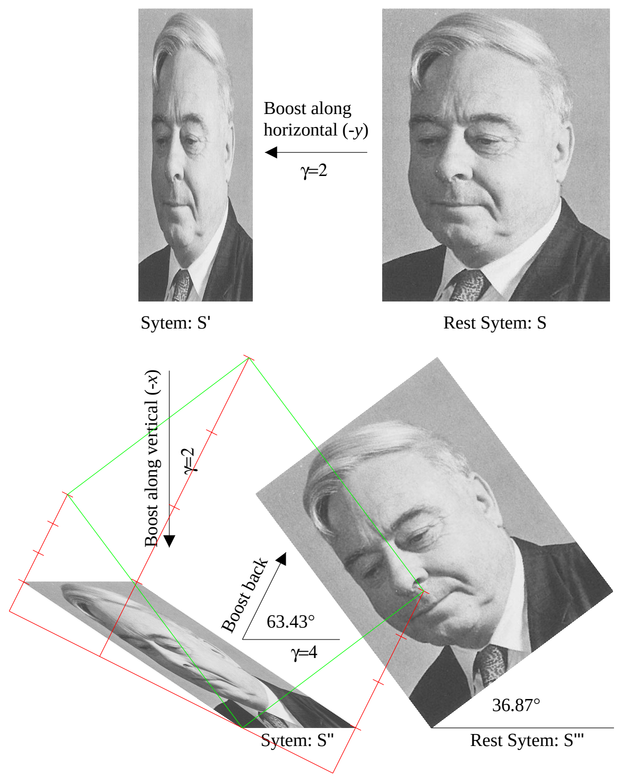
Status of Proton Polarization at RHIC and AGS

Waldo MacKay, BNL



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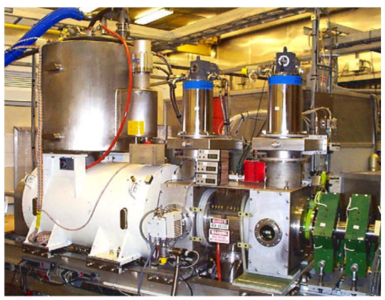
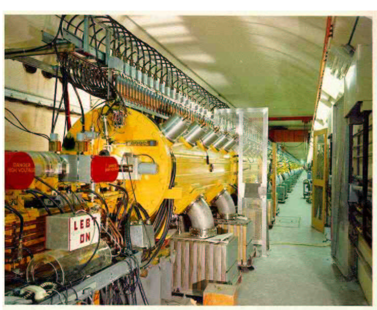
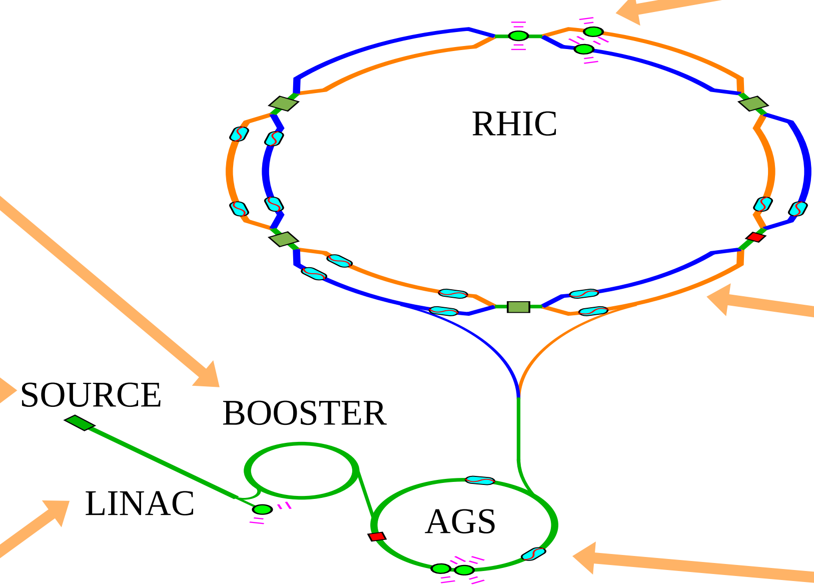
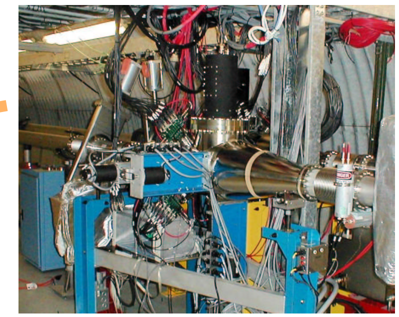
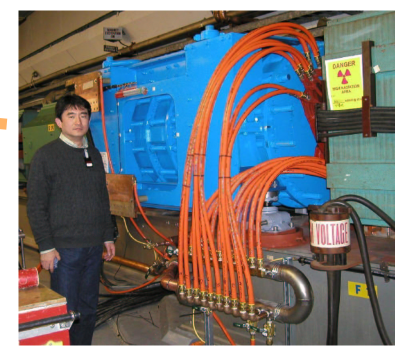
Accelerators with Polarized Protons





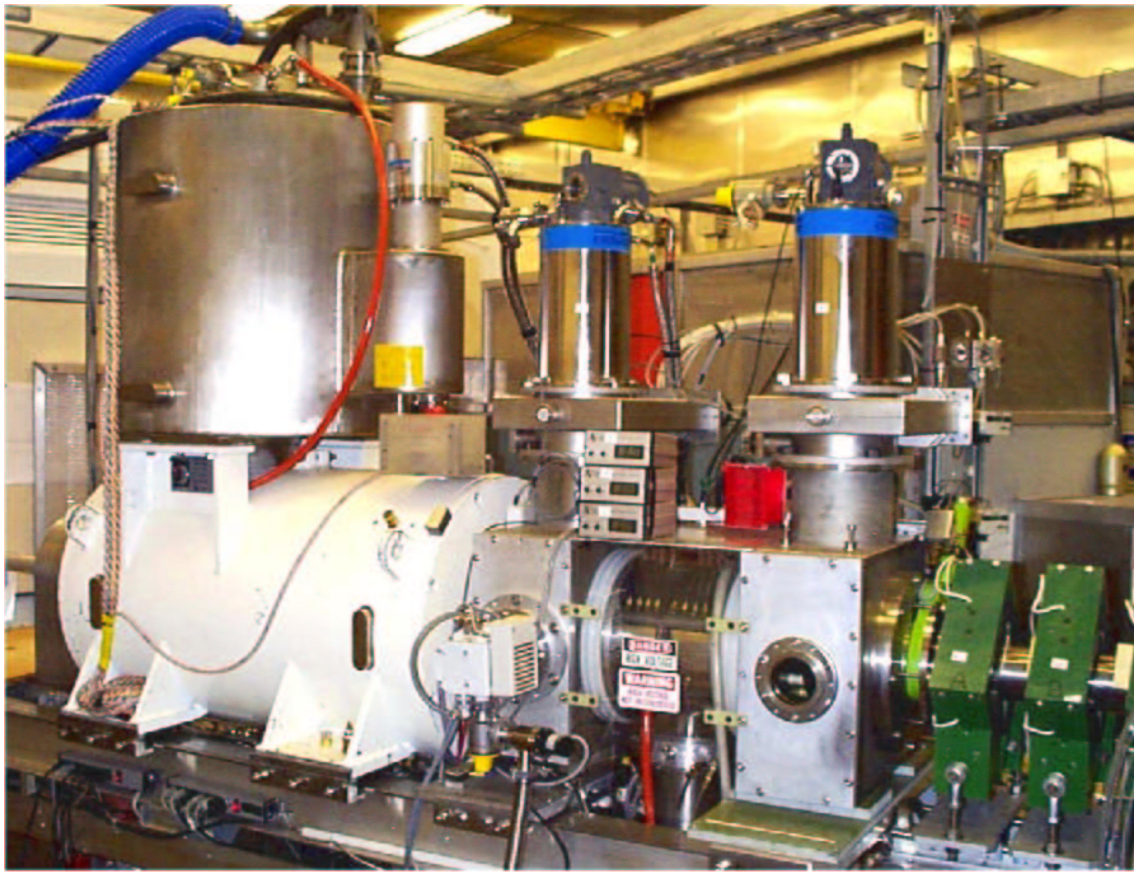






LINAC: Linear Accelerator
AGS: Alternating Gradient Synchrotron
RHIC: Relativistic Heavy Ion Collider

High Intensity Polarized H^- Source



KEK OPPIS*
upgraded at TRIUMF

$70 \rightarrow 80\%$ Polarization

15×10^{11} protons/pulse
at source

6×10^{11} protons/pulse
at end of LINAC

Coming soon: New solenoid from TRIUMF

*Optically Pumped Polarized Ion Source

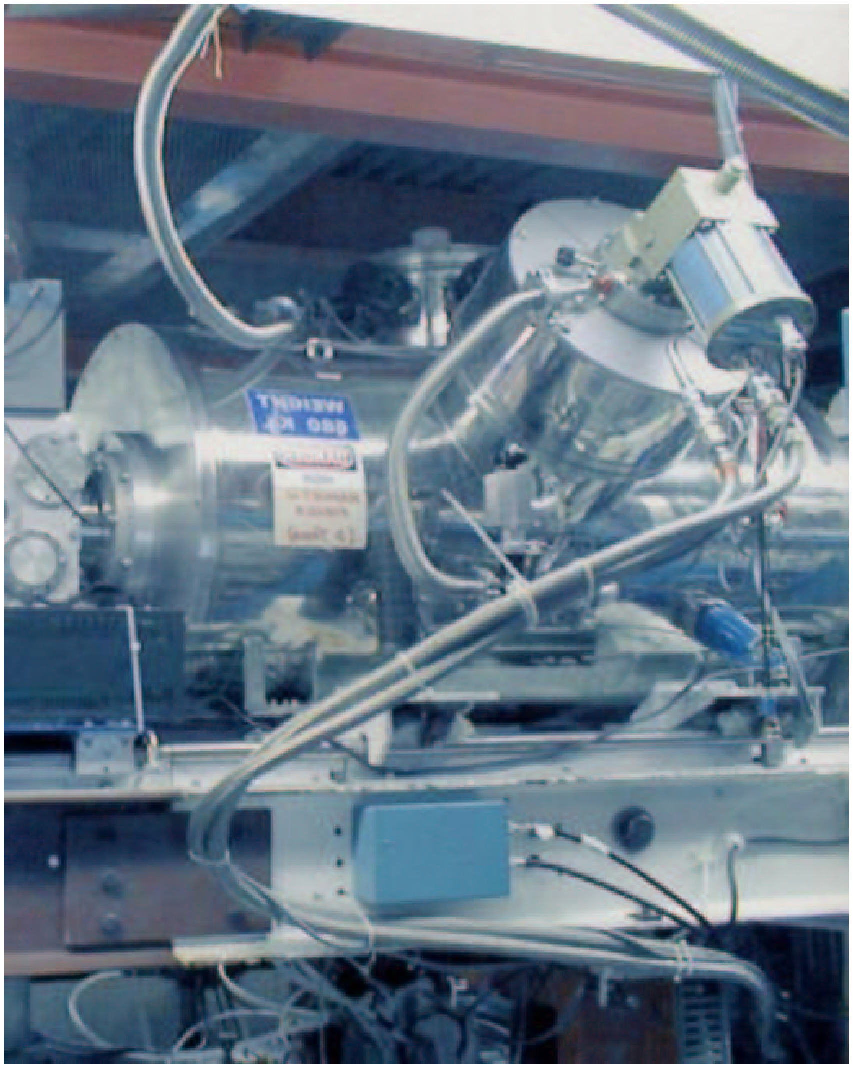
Oxford Inst. SC solenoid at TRIUMF

Solenoid has cold yoke:lower $B_\perp$

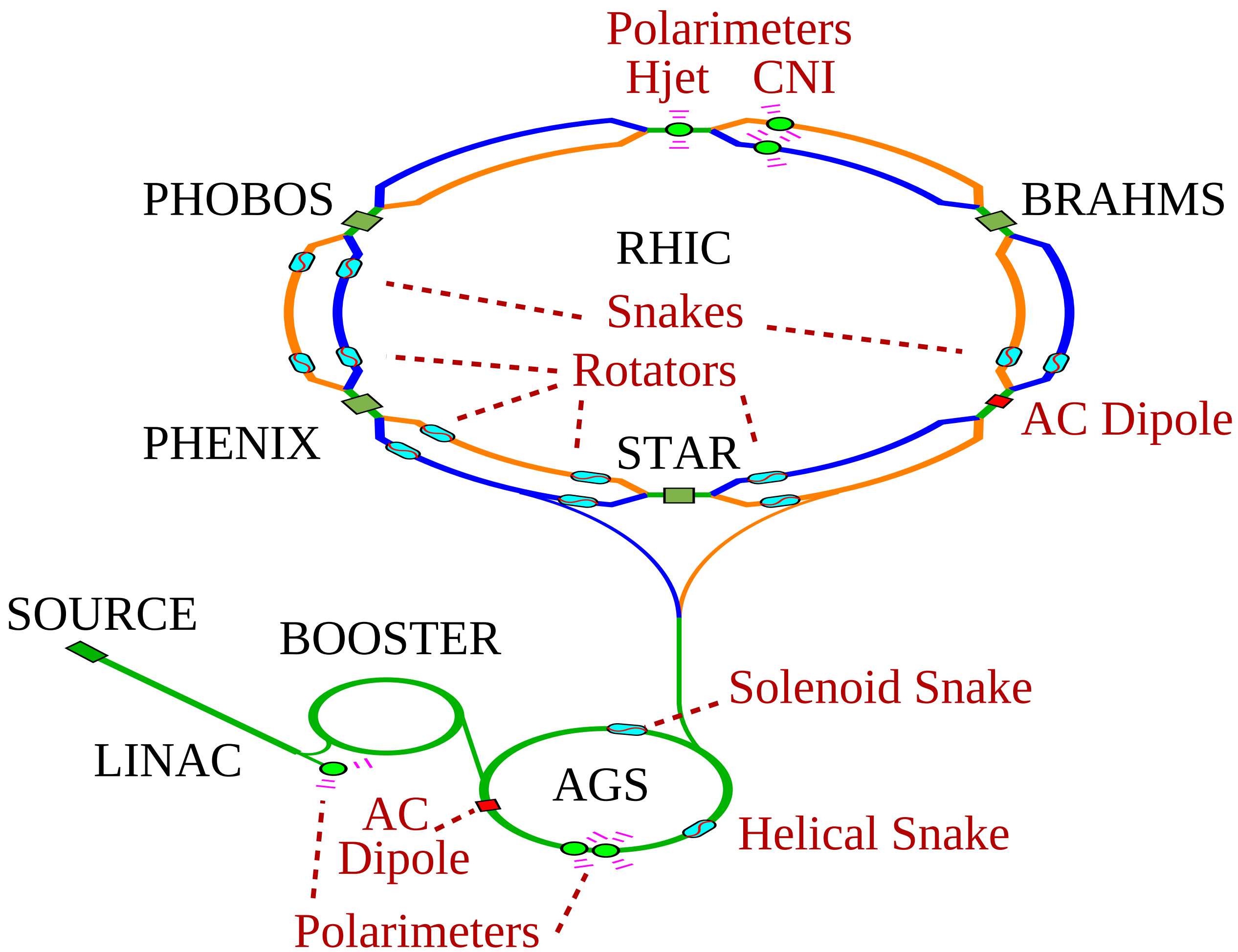
85% polarization and 1.6 mA was obtained during OPPIS tests with this at TRIUMF in 1999.

(80–82% and 0.8mA with original KEK solenoid)

Solenoid has been shipped to BNL and will be installed for the 2005 run.

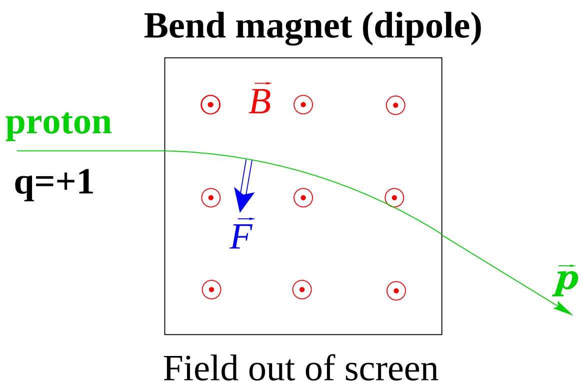


Accelerator Complex for Protons



Particle Trajectories in Magnetic Fields

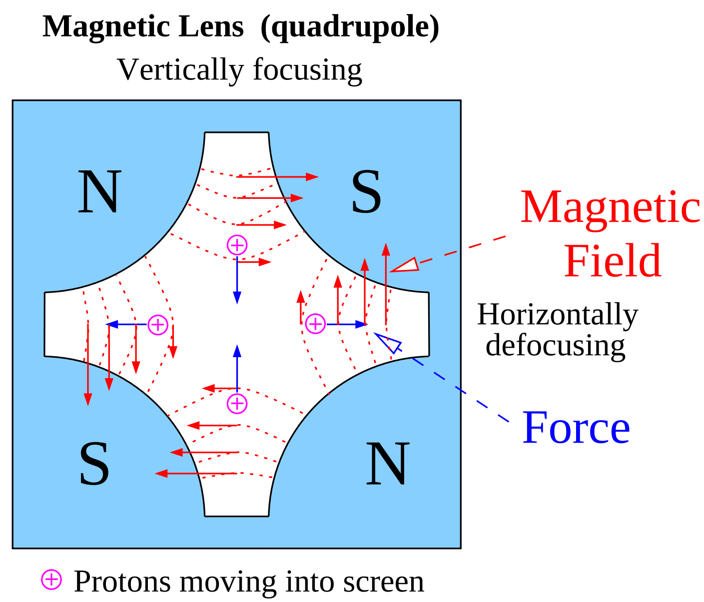
Dipole magnets bend the beam around the ring.



Charged particles are deflected by magnetic fields. Lorentz Force:

$$\vec{F} = \frac{q}{\gamma m} \vec{p} \times \vec{B}$$

Quadrupole magnets focus the beam for stability.



Hill's Equations

$$x'' + k_x(s)x = \frac{\delta}{\rho(s)},$$

$$y'' + k_y(s)y = 0,$$

$$\text{with} \quad \delta = \frac{\delta p}{p_0}.$$

For quadrupoles:

$$k_x = \frac{q}{p}\frac{\partial B_y}{\partial x}$$

$$k_y = -\frac{q}{p}\frac{\partial B_y}{\partial x}$$

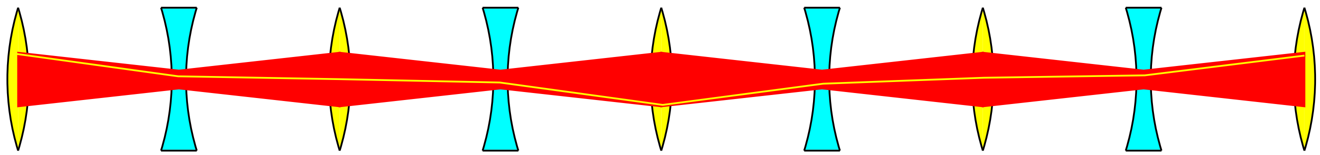
Harmonic oscillator with periodic spring constant.

Periodic conditions: $k_j(s+L) = k_j(s), \qquad \rho(s+L) = \rho(s)$

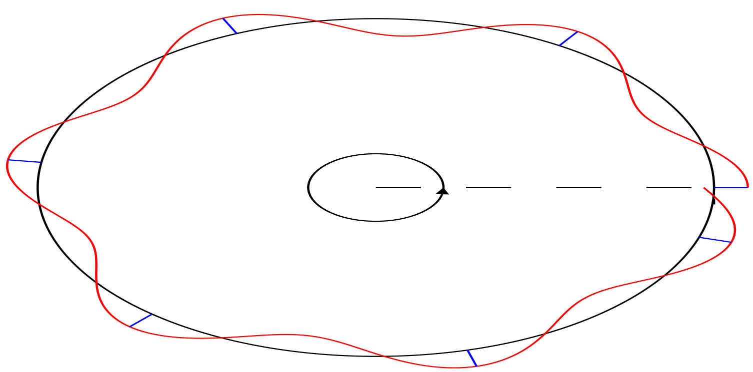
where L is length of periodic cell.

- Horizontal motion has inhomogeneous dispersion term.
  - Ignore it for now.

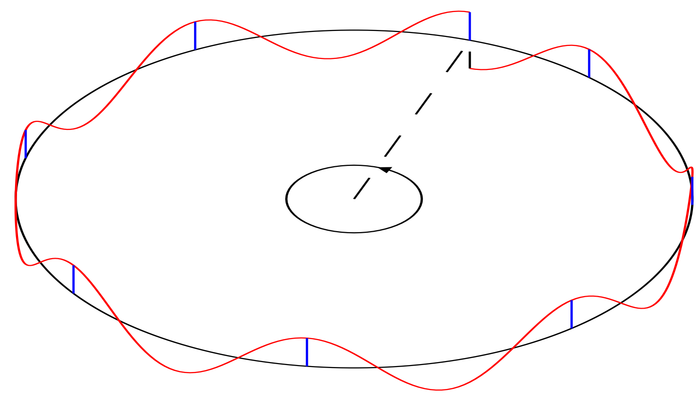
Transport and Betatron Oscillations



Alternate focusing and defocusing lenses for stability.



Horizontal Betatron Oscillation
with tune: $Q_h = 6.3$,
i.e., 6.3 oscillations per turn.



Vertical Betatron Oscillation
with tune: $Q_v = 7.5$,
i.e., 7.5 oscillations per turn.

Thomas—Frenkel (BMT) Equation

In the local rest frame of the proton, the spin precession of the proton obeys the Thomas-Frenkel equation:

$$\frac{d\vec{S}^{\diamond}}{dt} = \frac{q}{\gamma m}\vec{S}^{\diamond} \times \left[(1+G\gamma)\vec{B}_{\perp} + (1+G)\vec{B}_{\|} + \left(G\gamma + \frac{\gamma}{\gamma+1} \right) \frac{\vec{E}\times\vec{v}}{c^2} \right].$$

This is a mixed description: t, $\vec{B}$, and $\vec{E}$ in the lab frame, but spin $\vec{S}^{\diamond}$ in local rest frame of the particle:

Proton:	$G = \frac{g-2}{2} = 1.792847,$	523.34 MeV/unit $G\gamma$
Electron:	$a = G = \frac{g-2}{2} = 0.001159652,$	440.65 MeV/unit $a\gamma$

$$\gamma = \frac{\text{Energy}}{mc^2}.$$

Thomas—Frenkel (BMT) Equation

In the local rest frame of the proton, the spin precession of the proton obeys the Thomas-Frenkel equation:

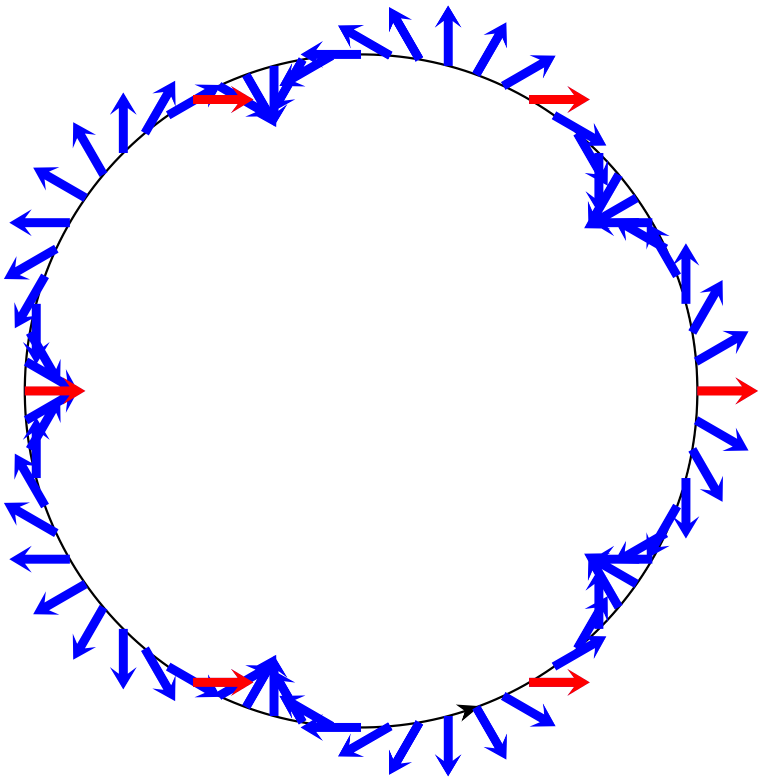
$$\text{Torque}: \quad \frac{d\vec{S}^\diamond}{dt} = \frac{q}{\gamma m}\vec{S}^\diamond \times \left[(1+G\gamma)\vec{B}_\perp + (1+G)\vec{B}_\parallel\right] \qquad \text{TF}$$

$$\text{Force}: \quad \frac{d\vec{p}}{dt} = \frac{q}{\gamma m}\vec{p} \times \vec{B}_\perp \qquad \text{Lorentz}$$

Polarization: Average spin of the ensemble of protons.

$$\vec{P} = \frac{1}{N}\sum_{j=1}^{N}\frac{\vec{S}}{|S|}$$

Spin Precession in a Ring



Example with 6 precessions of spin in one turn:

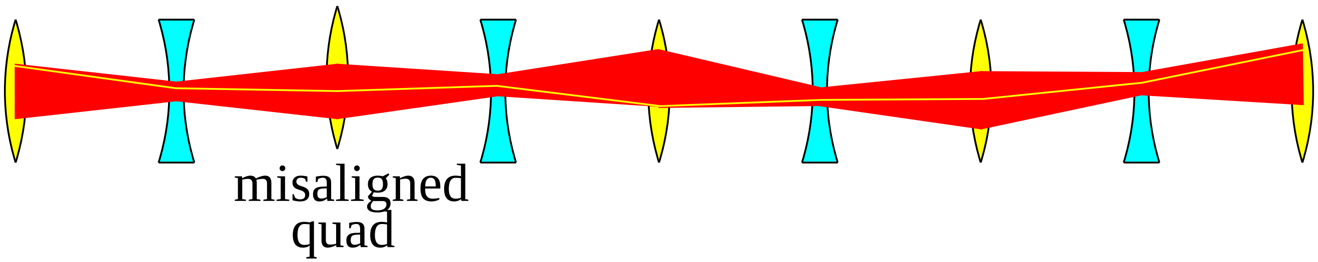
$$G\gamma + 1 = 6.$$

Spin tune: number of precessions per turn relative to beam's direction.
So we subtract one:

$$\nu_{\text{spin}} = G\gamma \quad \propto \quad \text{energy},$$

i.e., 5 in this example.

Misalignments or Imperfections



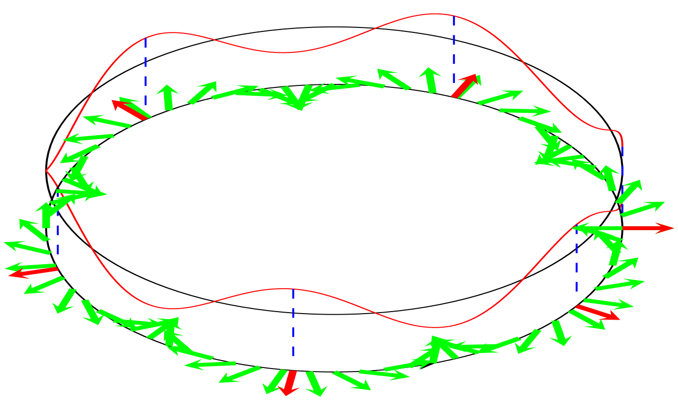
- A misaligned quadrupole creates a steering error which propagates through the lattice.
- For an accelerator ring, this shifts the closed orbit away from the design trajectory.
- If the misalignment is vertical, then the design trajectory will have a periodic set of small vertical bends interspersed with the normal horizontal bends of the bending magnets.
- This leads to an integer resonance condition for the spin tune.

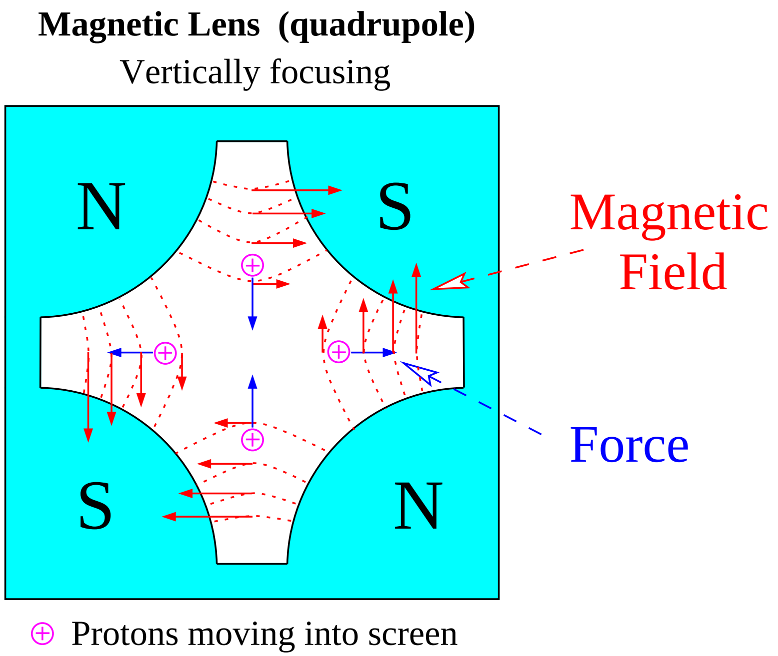
Depolarizing Resonances

Simple Resonance Condition:

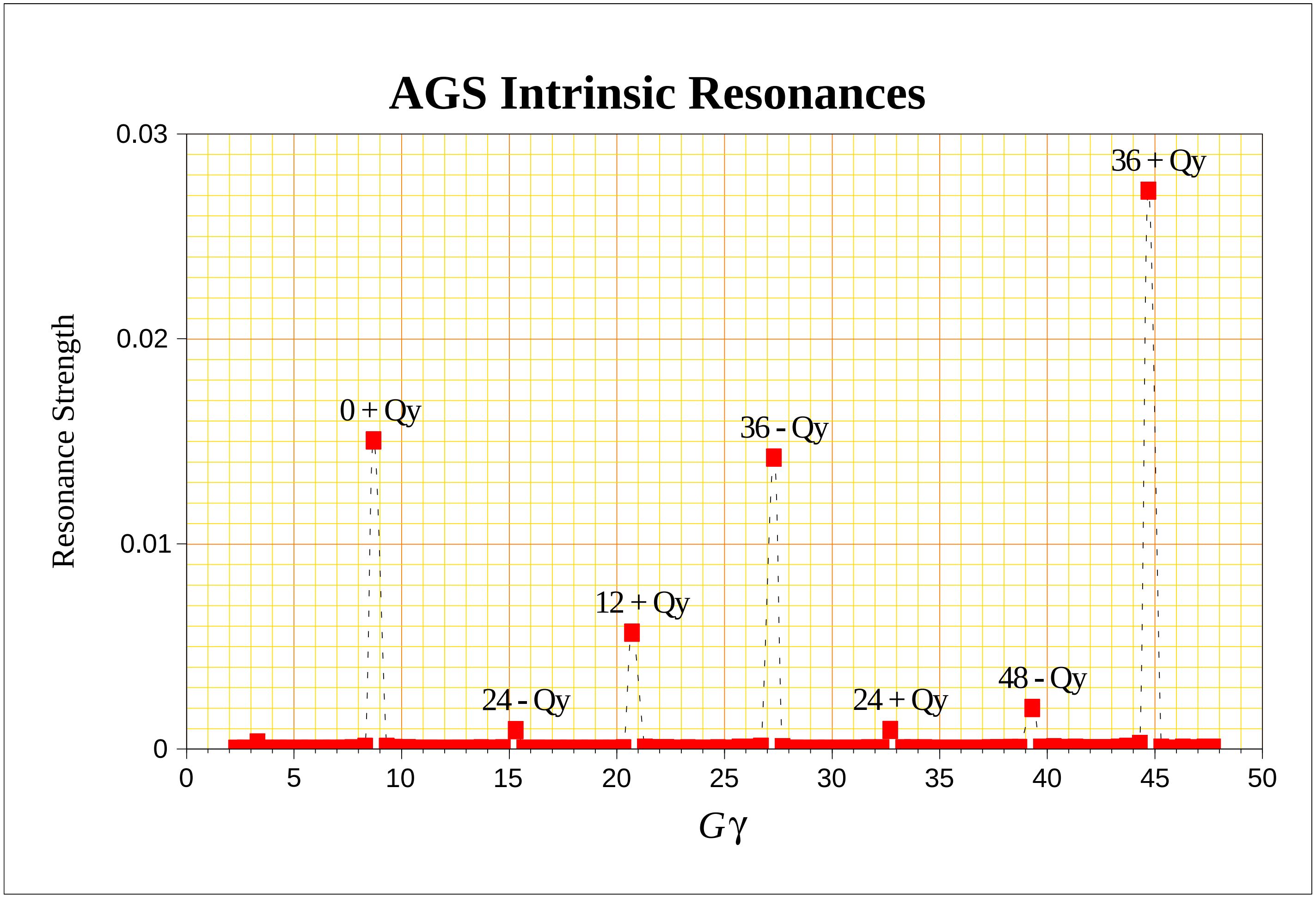
$$\nu_{\rm spin} = \underset{\text{(imperfection)}}{N} + \underset{\text{(intrinsic)}}{N_{\rm y} Q_{\rm y}},$$

where N and $N_{\rm y}$ are integers.





AGS Intrinsic Resonances



Crossing an Isolated Spin Resonance

Froissart—Stora Formula:

$$\frac{P_{\rm f}}{P_{\rm i}} = 2\exp\left(-\frac{\pi|\epsilon|^2}{2\alpha}\right) - 1.$$

Ramp rate: $\alpha = \frac{dG\gamma}{d\theta}$, $(\theta: \; 2\pi/\text{turn.})$

Resonance strength: $\epsilon =$Fourier amplitude.

Weak resonances:

- speed up crossing
- decrease strength (harmonic content of closed orbit)

Strong resonances:

- increase strength to cause total flip

Partial Snake in AGS

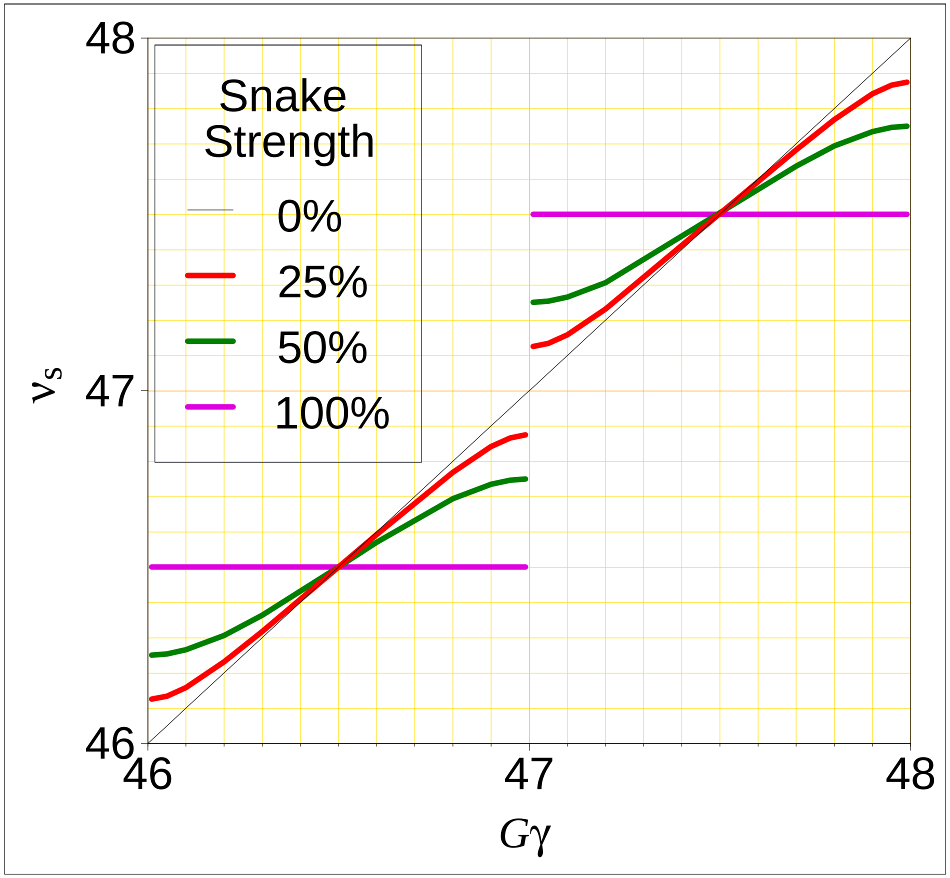
Adding a partial snake opens up stop bands around the integer imperfection resonances.

At the snake the stable spin direction points along the snake's rotation axis when $G\gamma =$ integer.

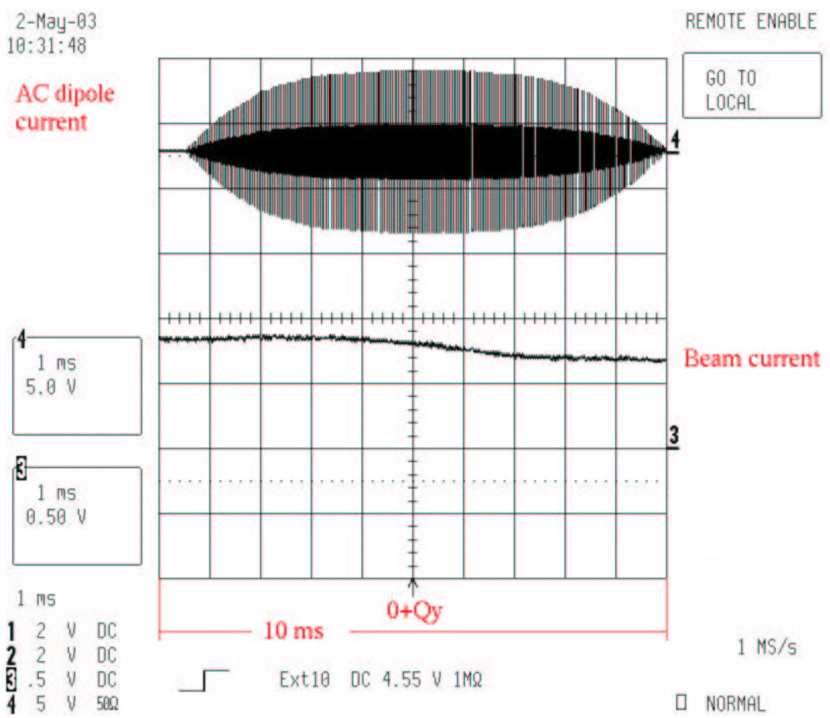
Partial snake strength: $\frac{\mu}{\pi}$

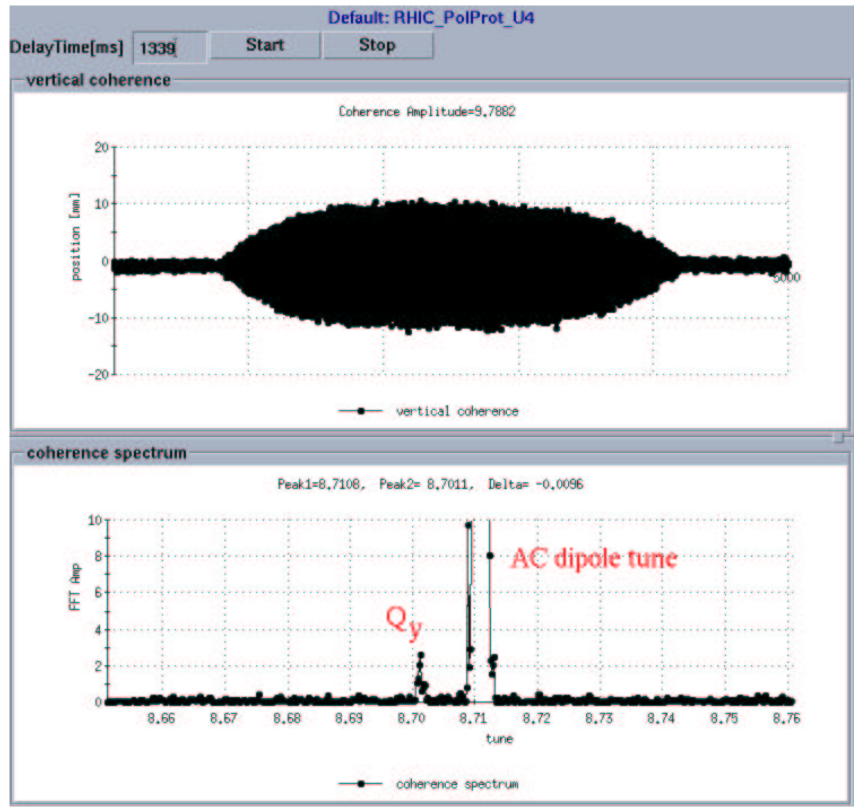
$$\cos \pi \nu_s = \cos(G\gamma\pi) \cos \frac{\mu}{2}$$

μ is the rotation angle the snake.



AC Dipole pulse at $G\gamma = 0 + Q_y$





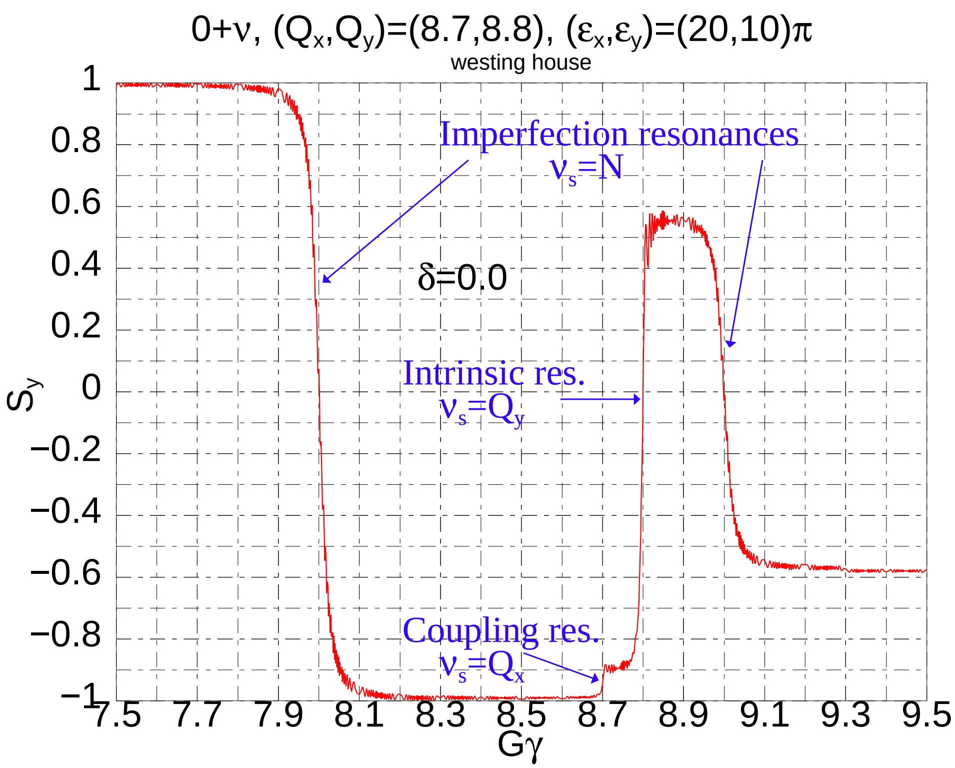
Top: AC dipole pulse amplitude (current)

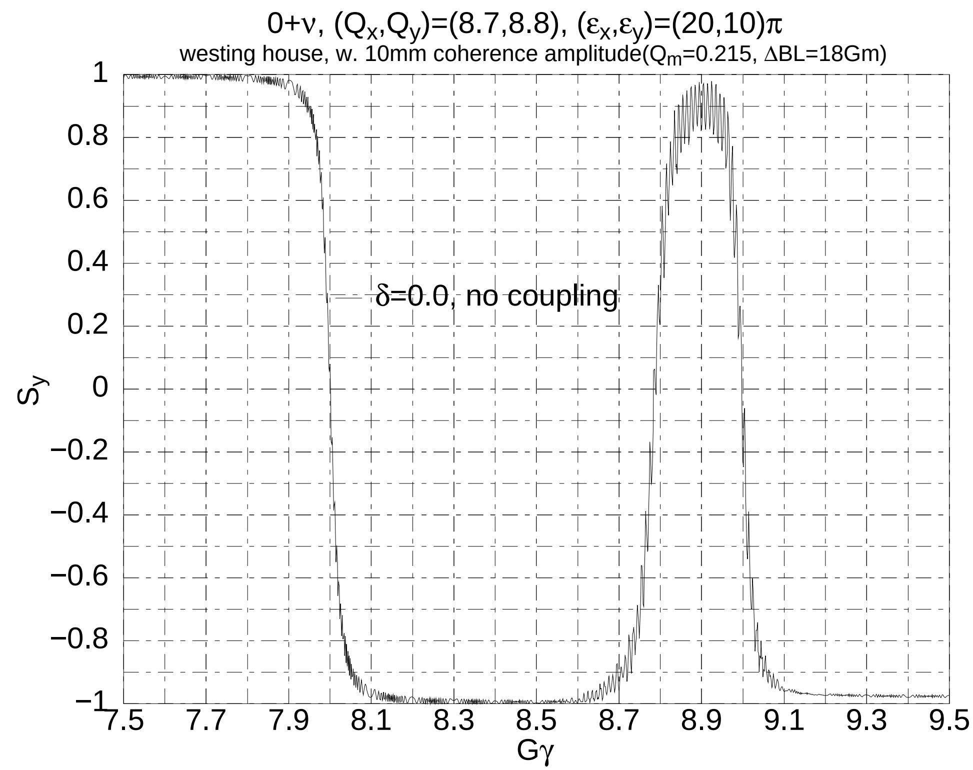
Bottom: Beam current. (Just scrapes the beam pipe.)

Top: Beam coherence

Bottom: Tune spectrum

Resonance Crossing in AGS

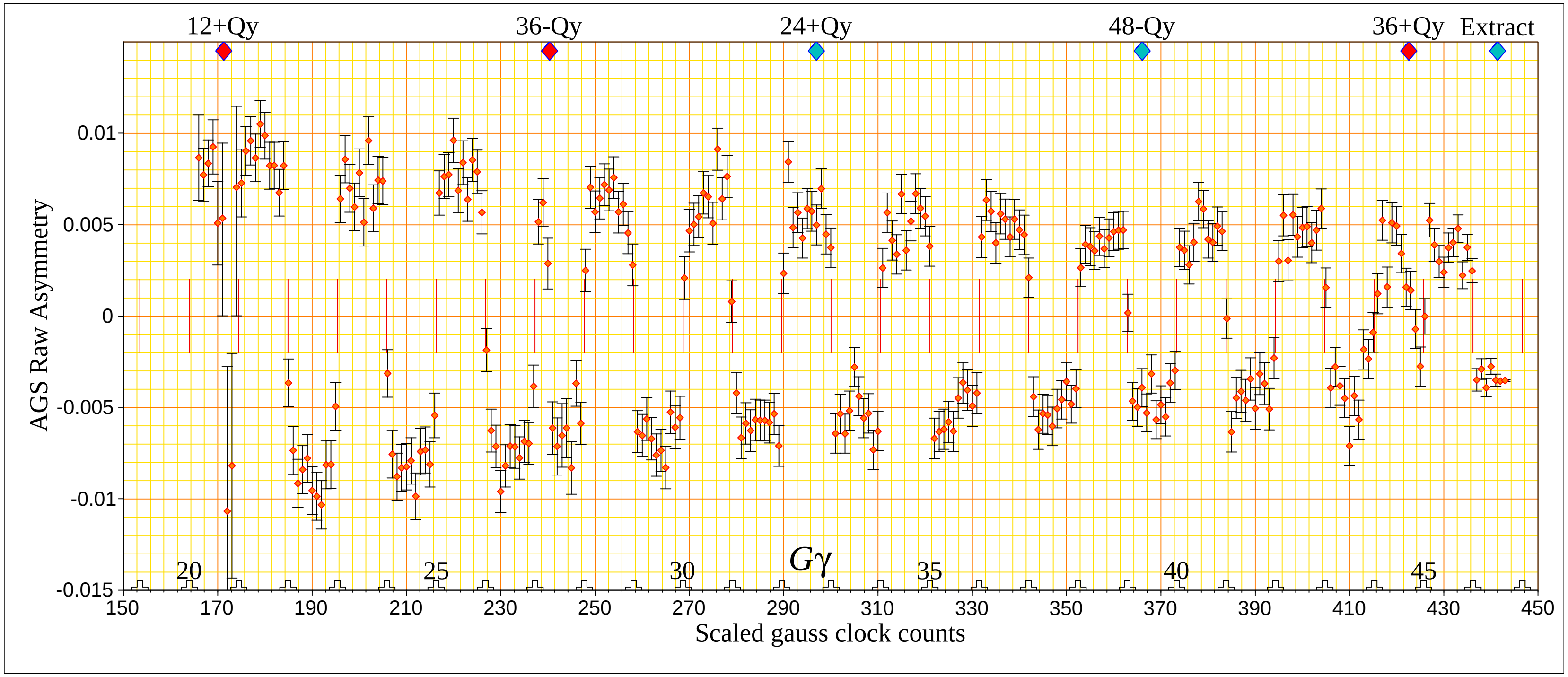




AC dipole used to increase strength of $\nu_{\mathrm{s}} = Q_y$ resonance.

(Simulations by Mei Bai)

AGS Raw Asymmetry during Ramp



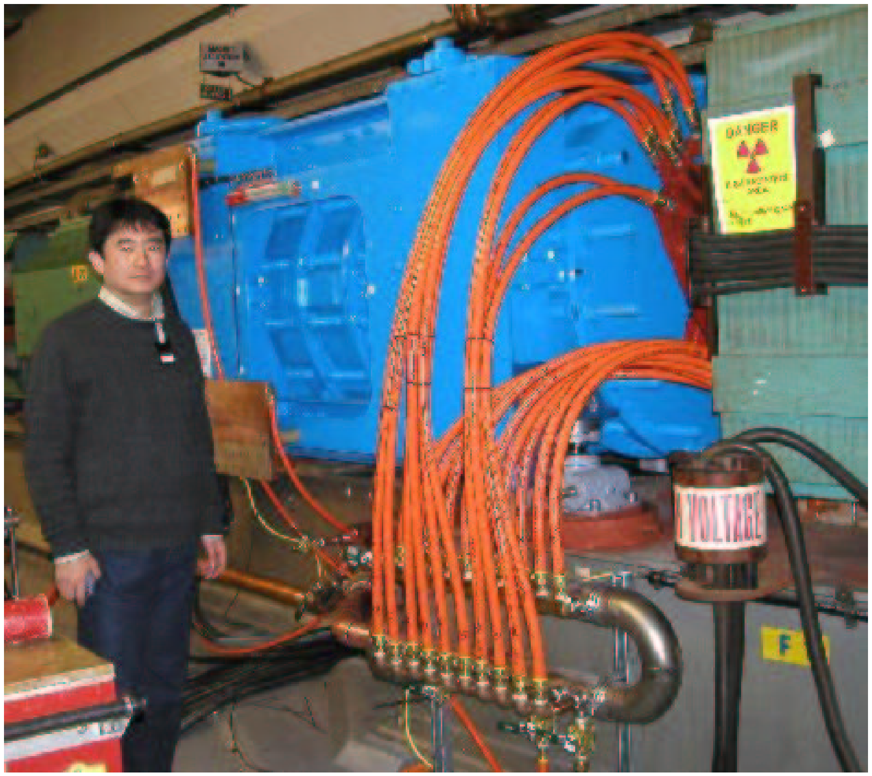
AGS has 12 superperiods.
Vertical betatron tune: 8.7
Snake strength: 5%

(From Jeff Woods)

AC dipole pulses at resonances:

- $0 + Q_y$
- $12 + Q_y$
- $36 - Q_y$
- $36 + Q_y$

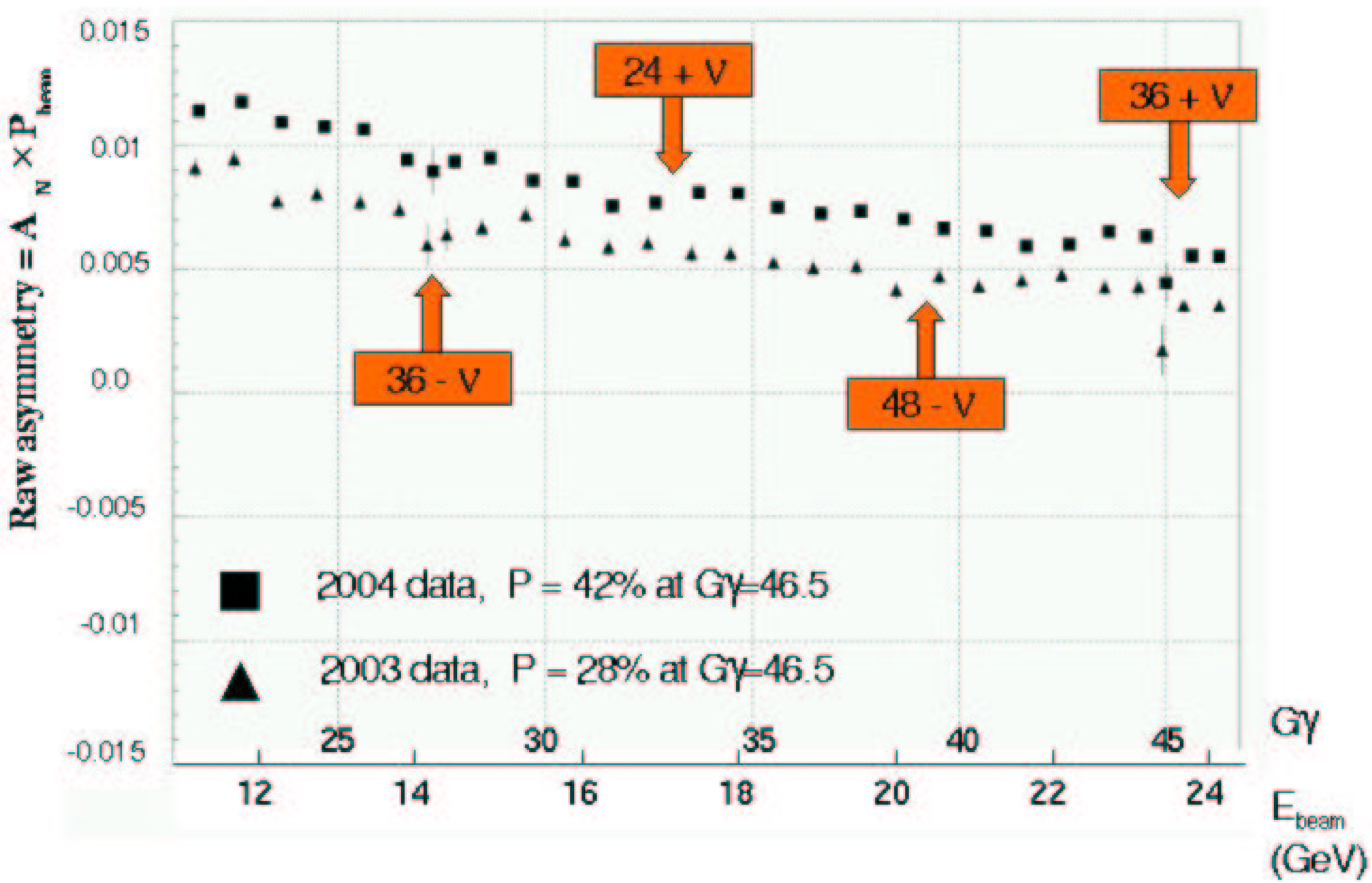
New Warm Helical Snake



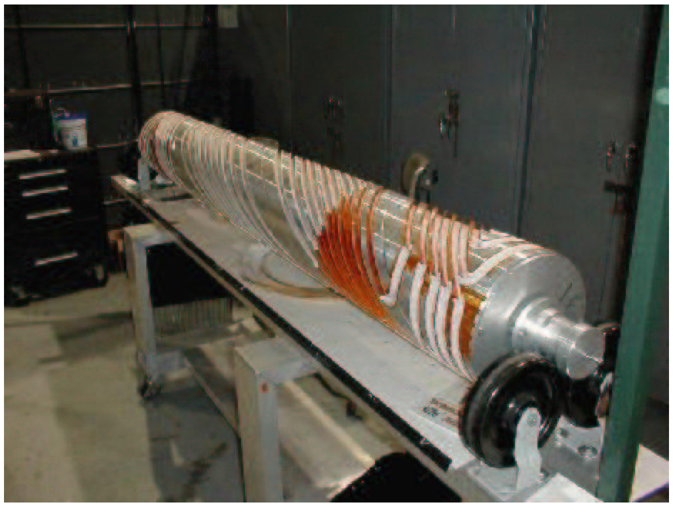
- $B = 1.53\text{T}$
- Strength:
  - Inject: 8.3% ($\mu = 15^\circ$)
  - Extract: 5.9% ($\mu = 10.6^\circ$)
- smaller coupling than solenoid

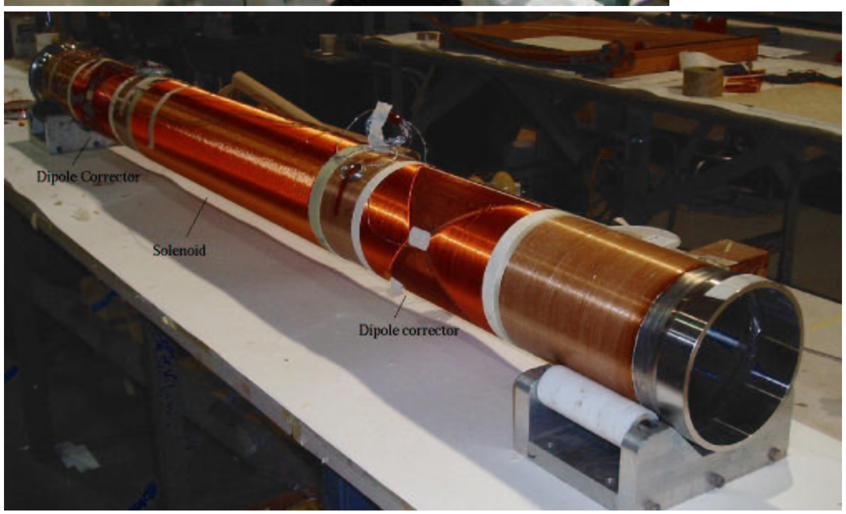
Provided by RIKEN; Designed by M. Okamura, J. Takano, and A. Luccio

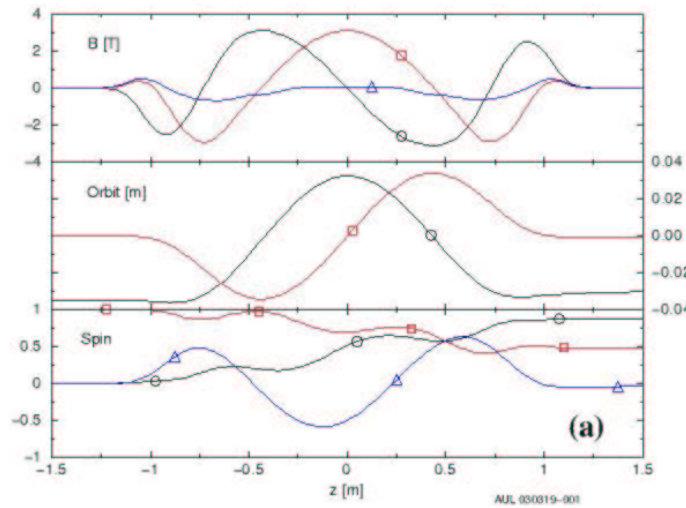
pC CNI Asymmetry during AGS Ramp

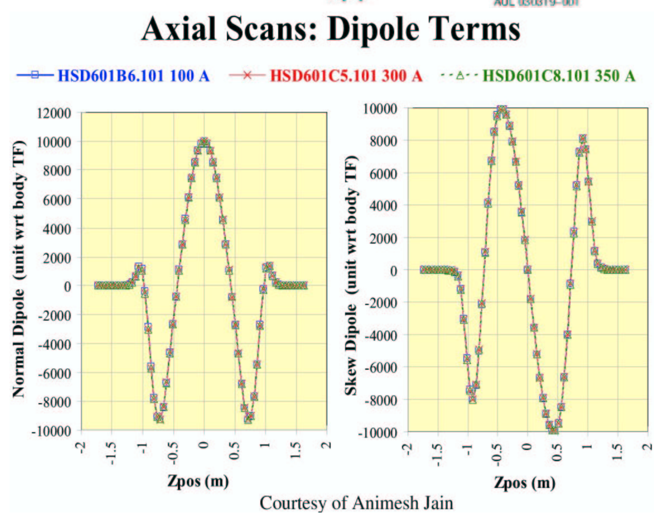


New AGS cryogenic snake

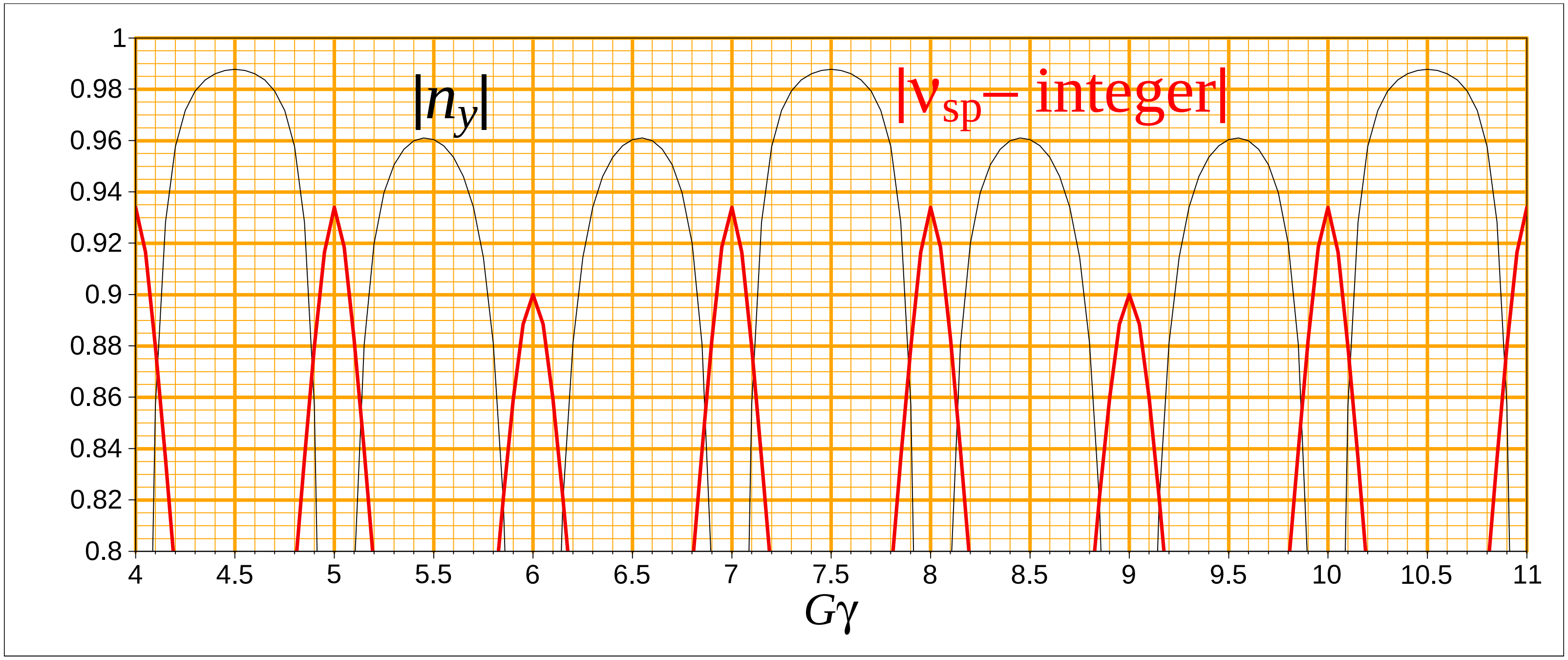








Two Helical Partial Snakes in AGS

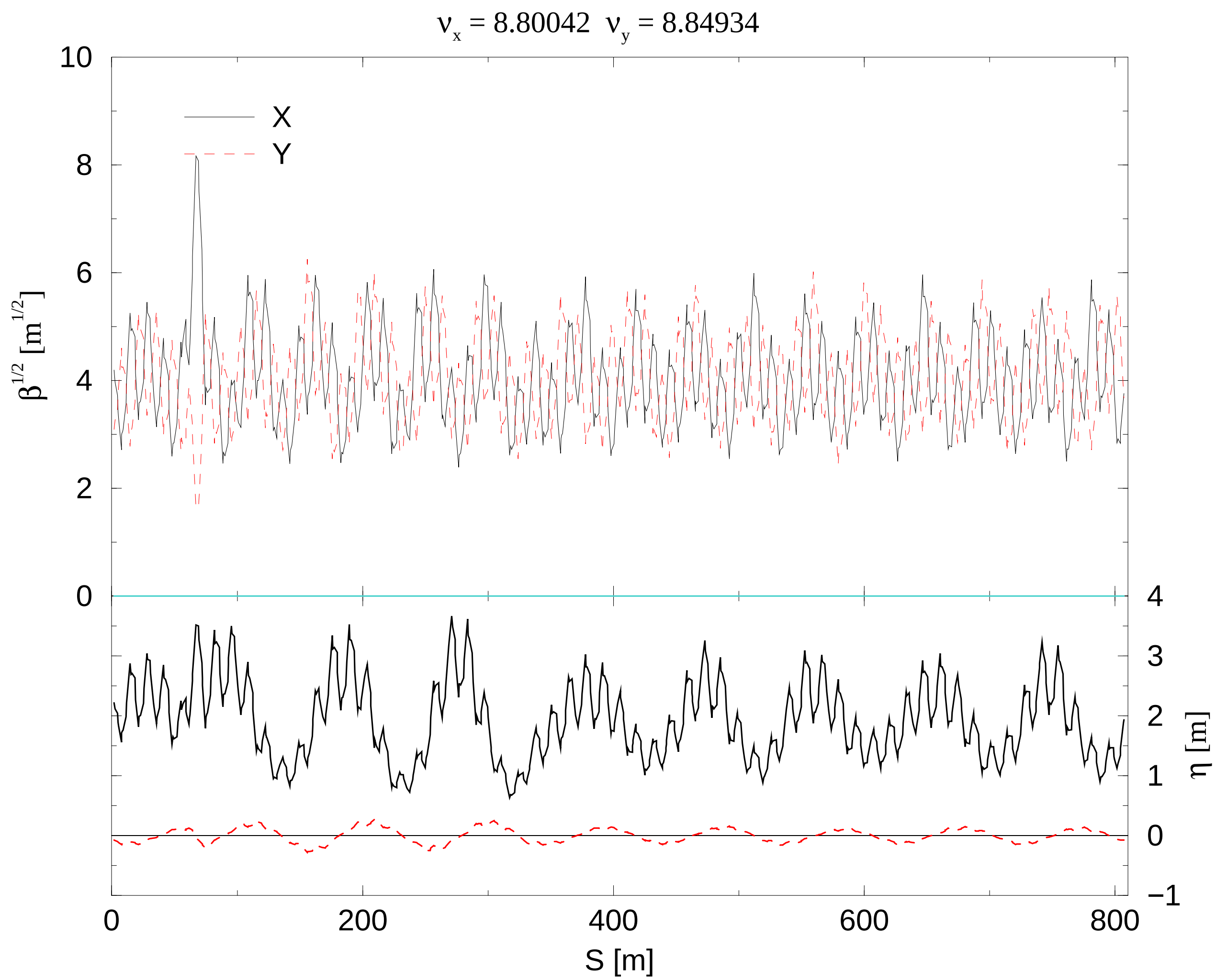


A20 Cold snake: 15%
E20 Warm snake: 5%
Superperiodicity: 12

Spin tune stop bands: integer$\pm$0.065
Putting $Q_y = 8.96$ eliminates intrinsic resonances.
Pattern repeats every 3 integers

Spin almost vertical at injection ($G\gamma = 4.5$) and extraction (46.5)

Two snakes 15% and 6.7% at injection



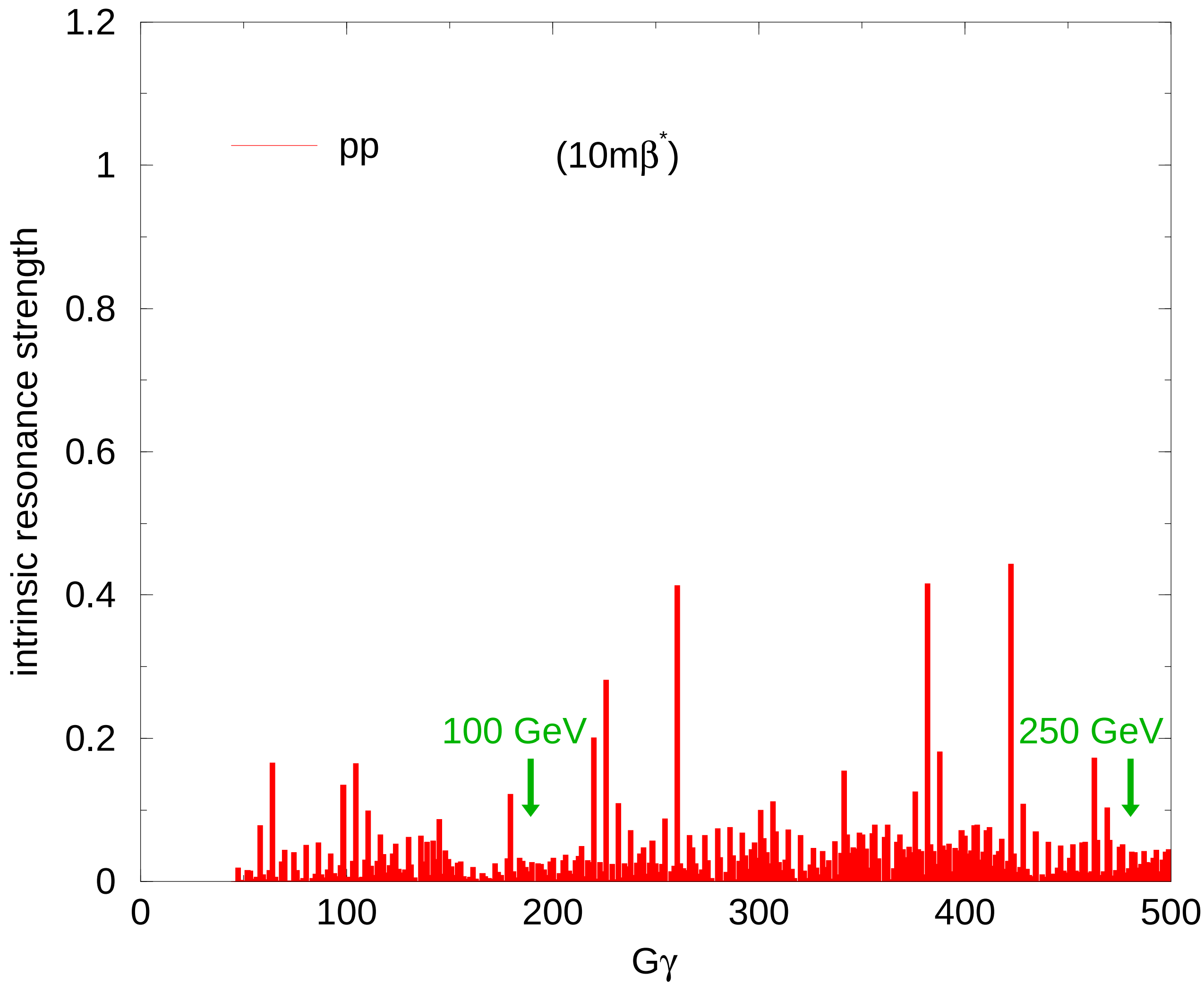
Cold snake:
A20

Warm snake:
E20

Extra Quads:
A17, A19,
B1, B3

Courtesy of
Mei Bai

Depolarizing Resonances in RHIC



$Q_x = 28.236$

$Q_y = 29.219$

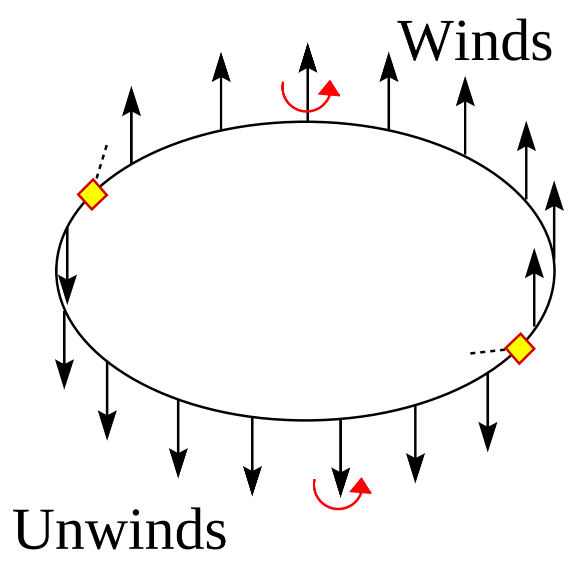
$\pi\epsilon_y = 10\pi\ \mu\text{m}$

Will depolarize beam during acceleration.

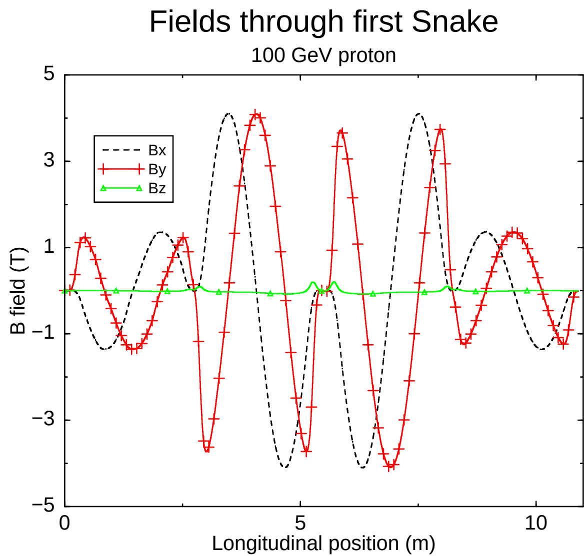
Solution: Snakes

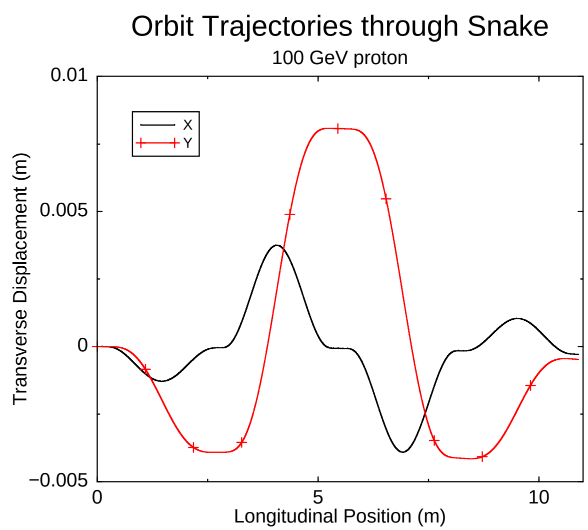
Snake Charming

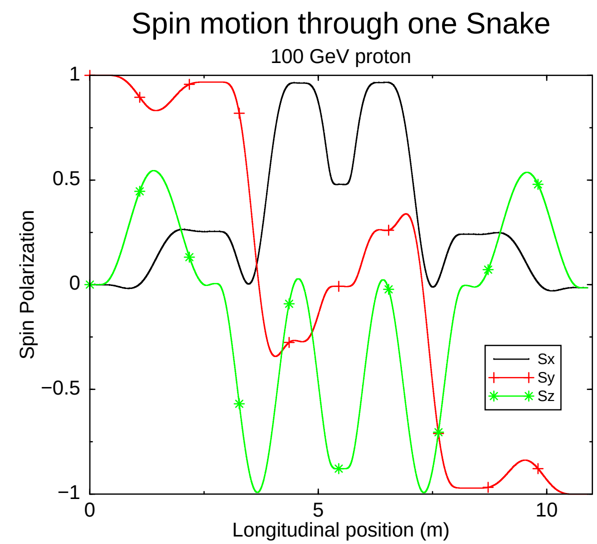
- 2 snakes: spin is up in one half of the ring, and down in the other half.
- Spin tune: $\nu_{\text{spin}} = \frac{1}{2}$
  (It's energy independent.)
- "The unwanted precession which happens to the spin in one half of the ring is unwound in the other half."

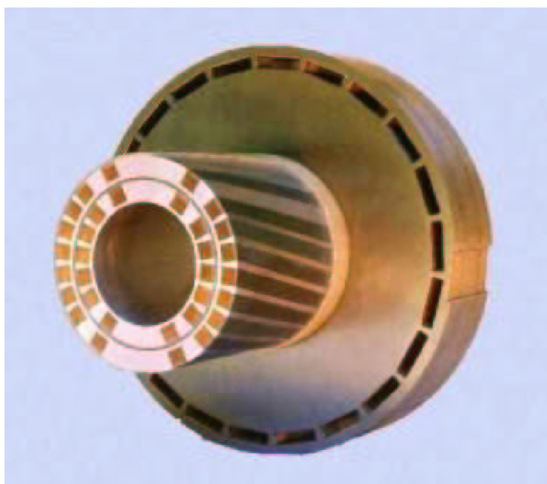


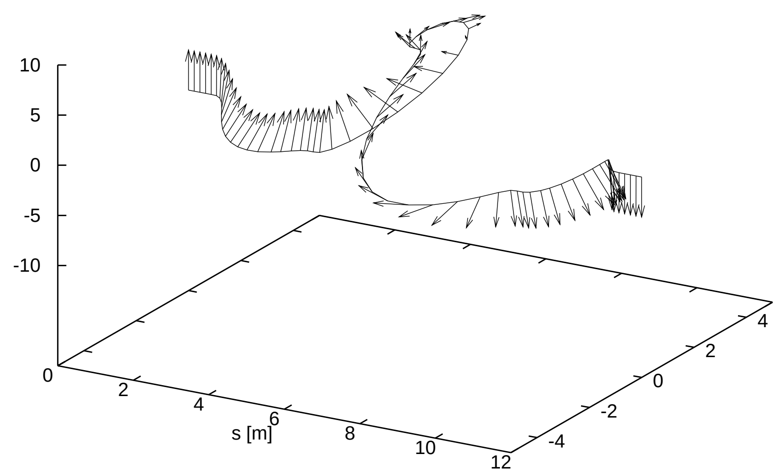
Trajectory and Spin through Snakes











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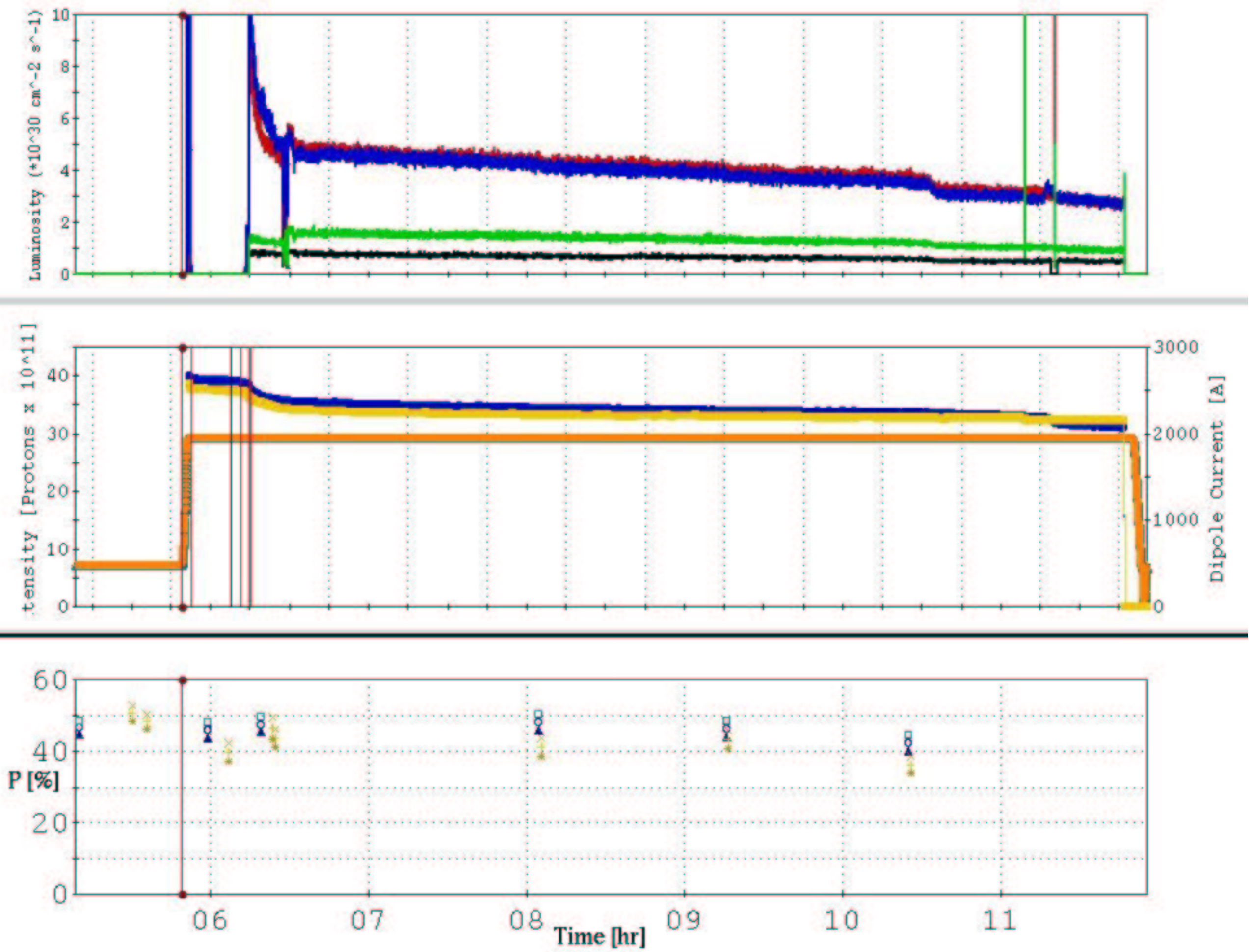
RHIC Beam Polarization



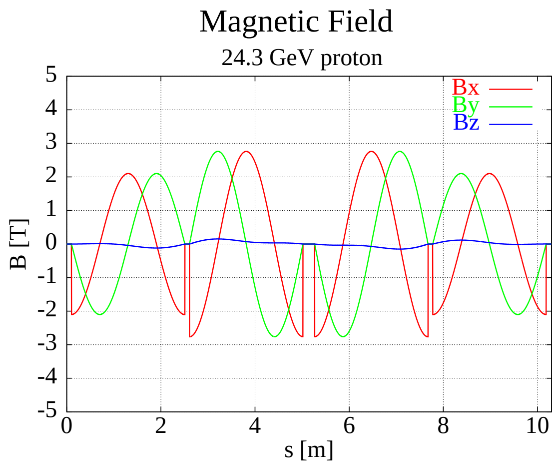
Luminosity

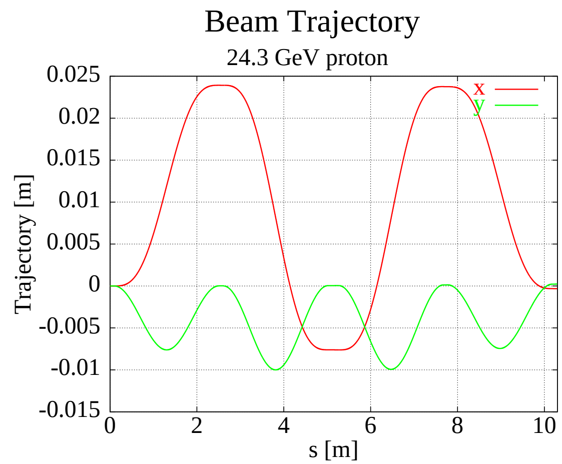
Beam current

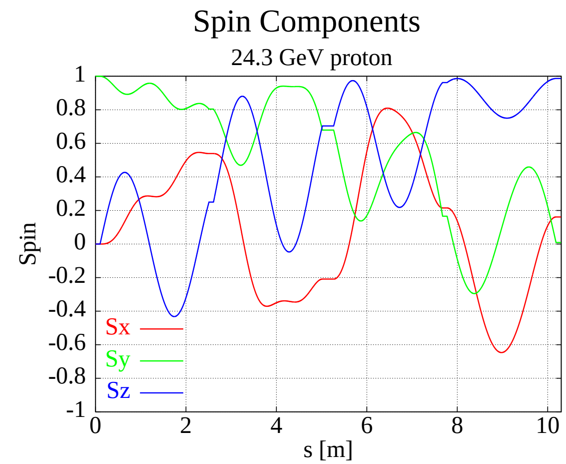
Dipole current

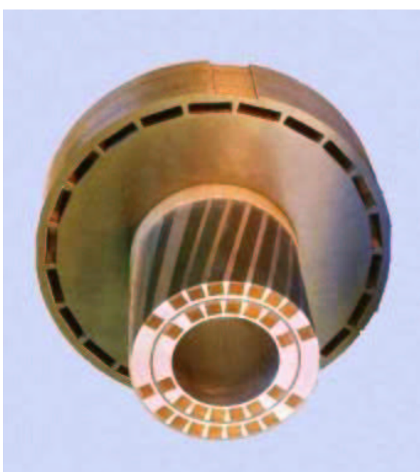
Polarization

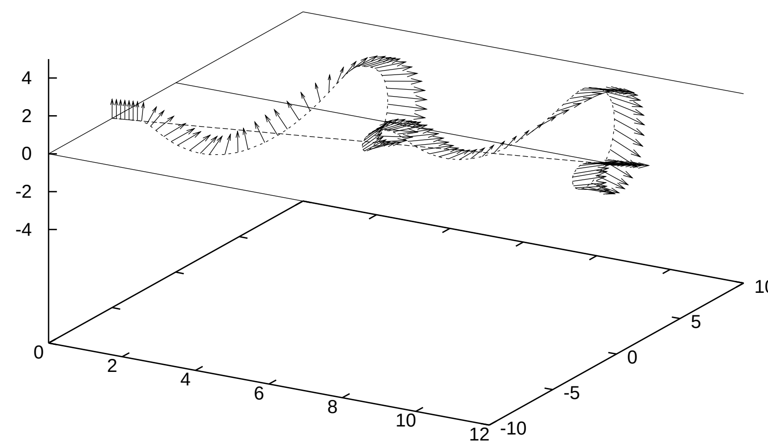
Helical Spin Rotators



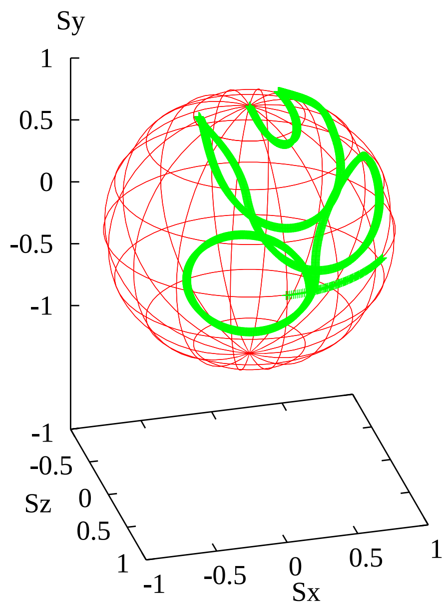




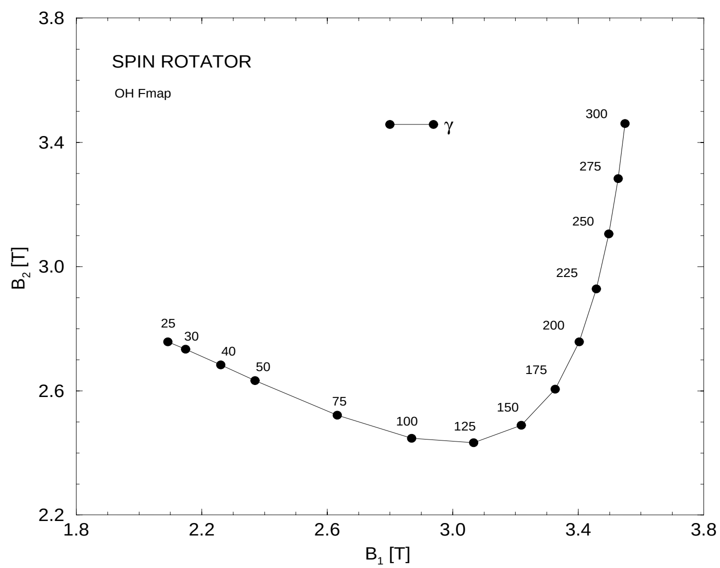


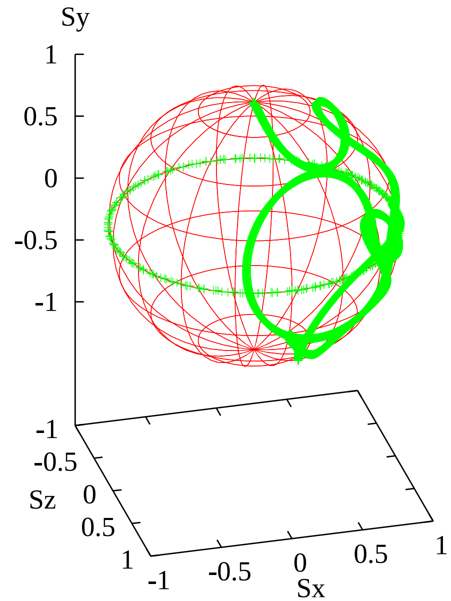


Compensation for D0-DX Bends

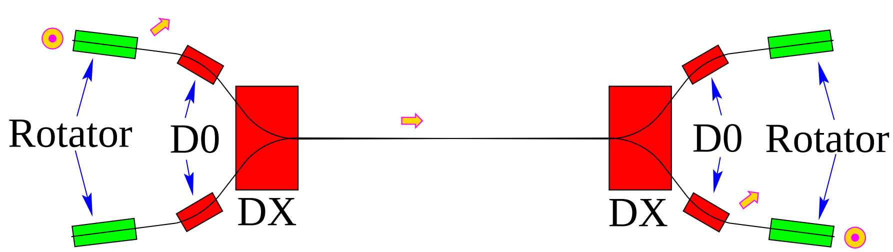


$E = 25$ GeV

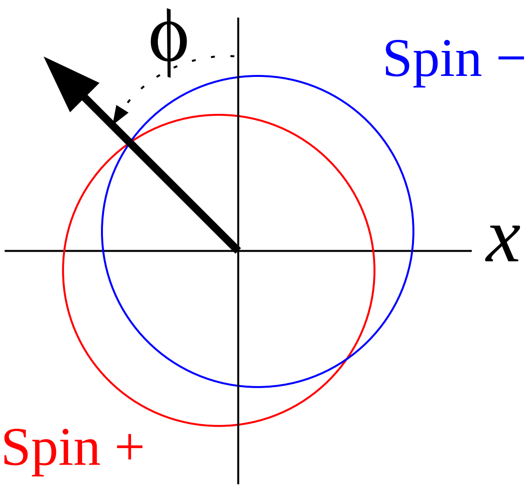




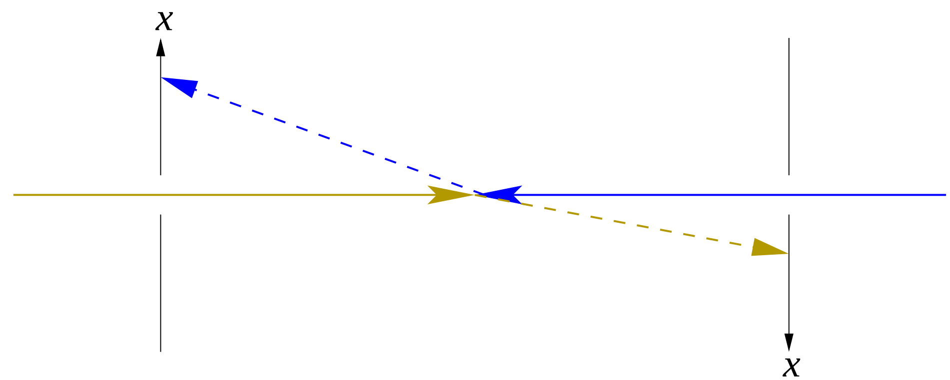
$E = 250$ GeV



Orientation of PHENIX Polarimeters



"Left−Right" Asymmetry
(Tilted at 45°)

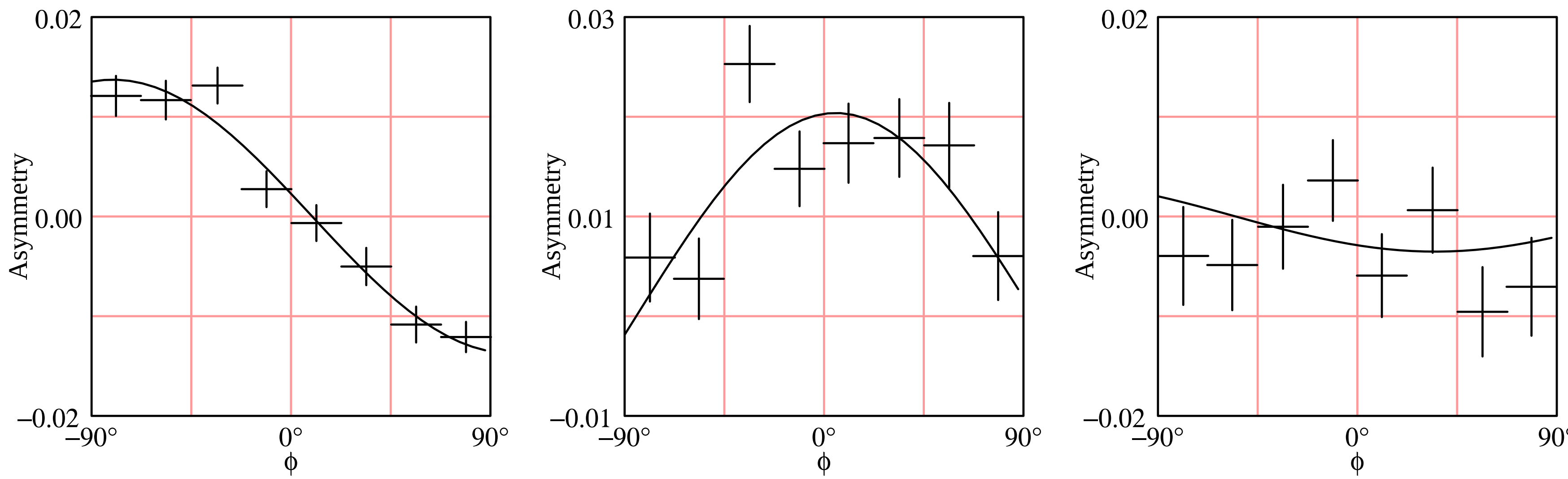


Schematic layout of PHENIX polarimeters
Yellow from left. Blue from right.

The PHENIX Local Polarimeter measures an asymmetry in small angle scattered neutrons which is proportional to transverse polarization.

$$A_{\mathrm{LR}} = \frac{\sqrt{L^+R^-} - \sqrt{L^-R^+}}{\sqrt{L^+R^-} + \sqrt{L^-R^+}} \propto P_y$$

Longitudinal Polarization at PHENIX



Vertical polarization with rotators off.

Spin is down.

Rotators on

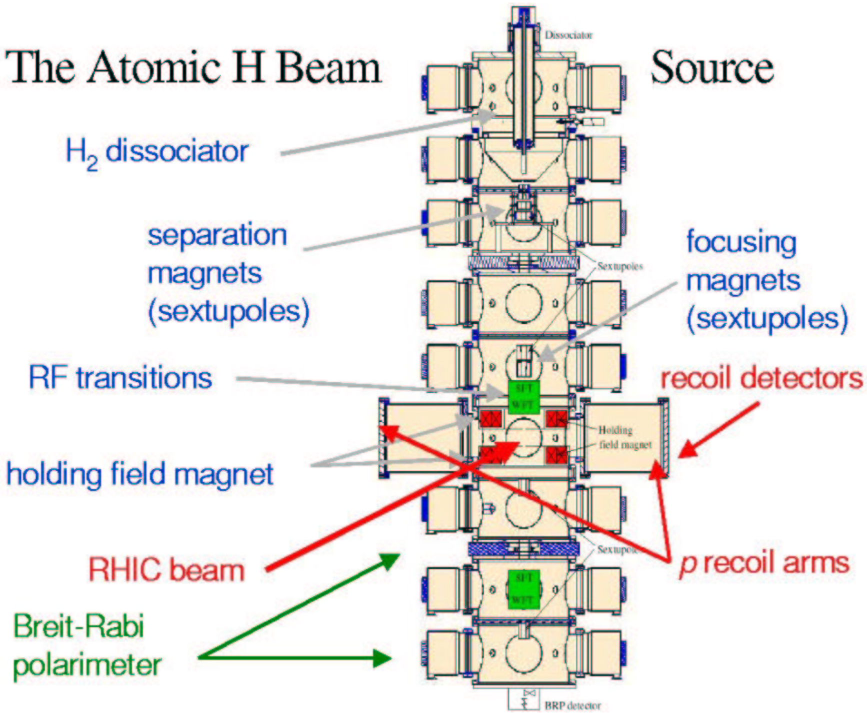
Spin is radially inwards!

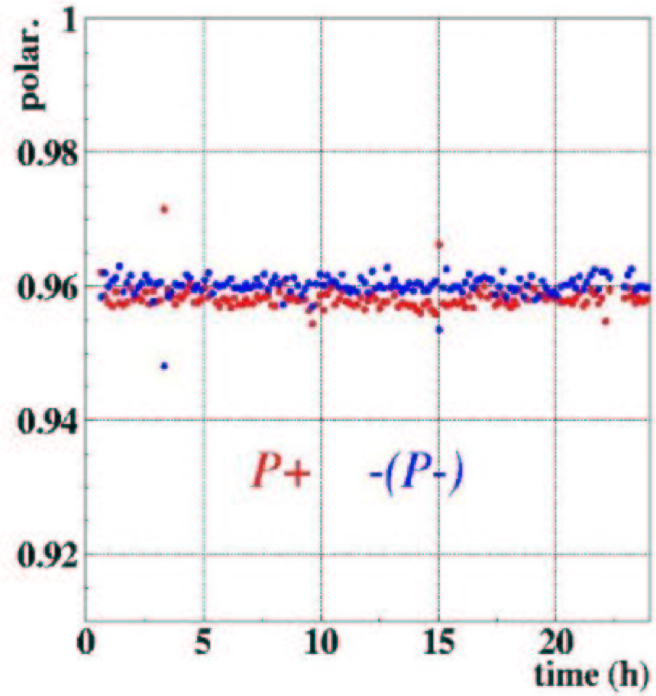
OOPS!

Reverse all rotator power supplies and try again.

YES!

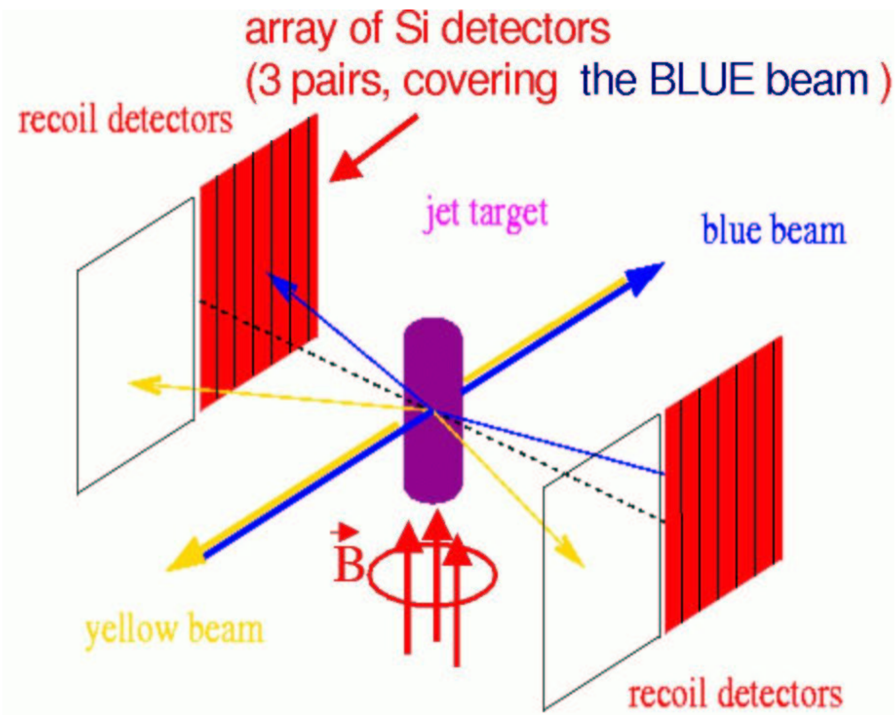
Hydrogen Jet Polarimeter

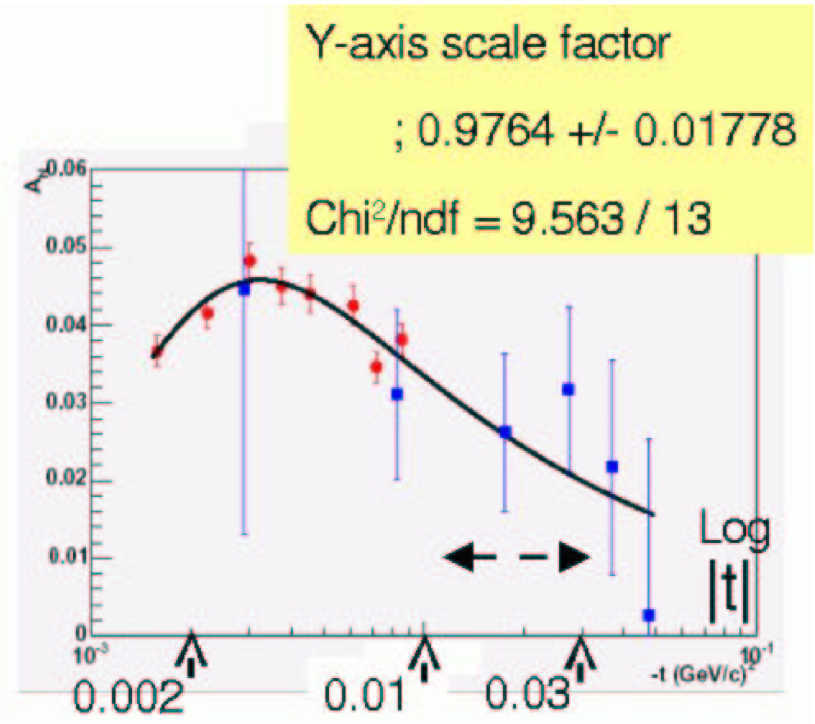




- Target density: 1.07×10^{12} atoms/cm^2

Hydrogen Jet: A_N for pp at 100 GeV

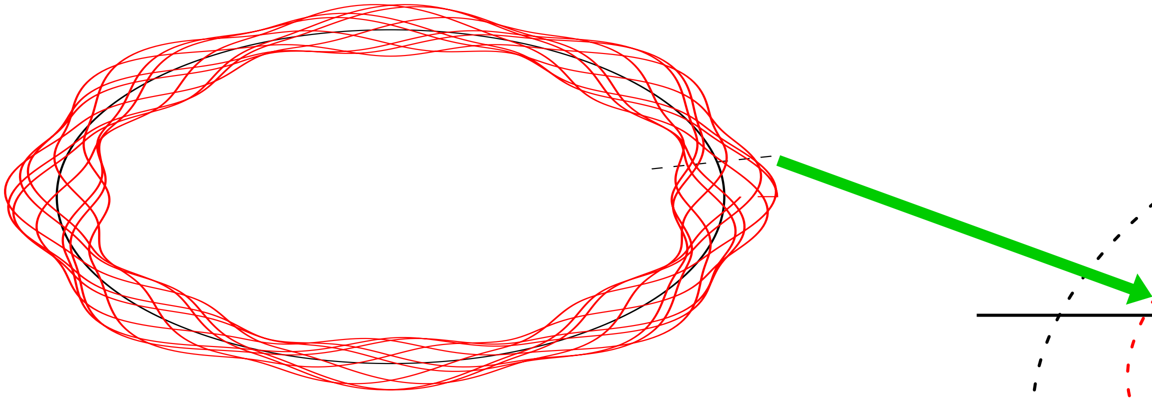




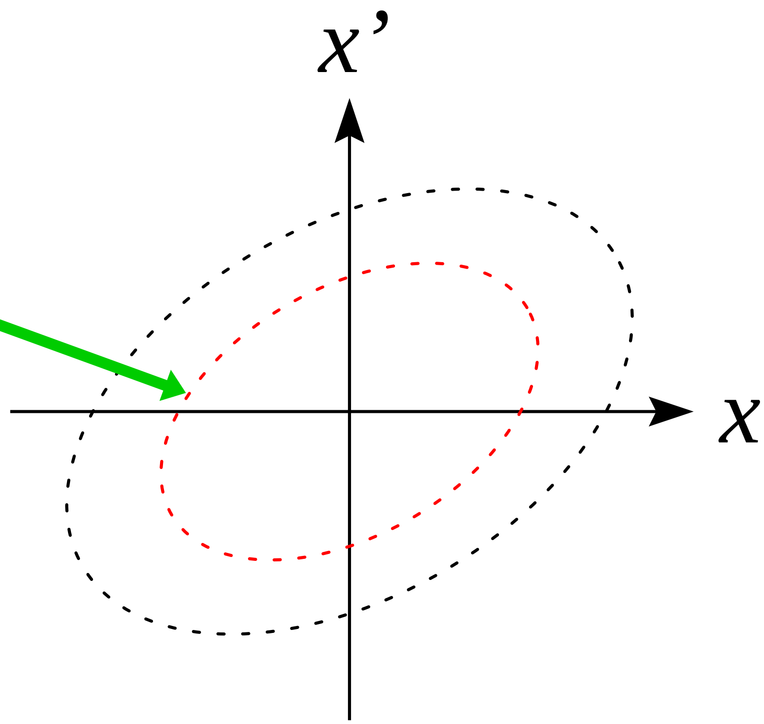
Figures from H. Okada's talk

- Blue points from FNAL E704
  Phys Rev D48, 3026 (1993)

2d Phase Space Plots

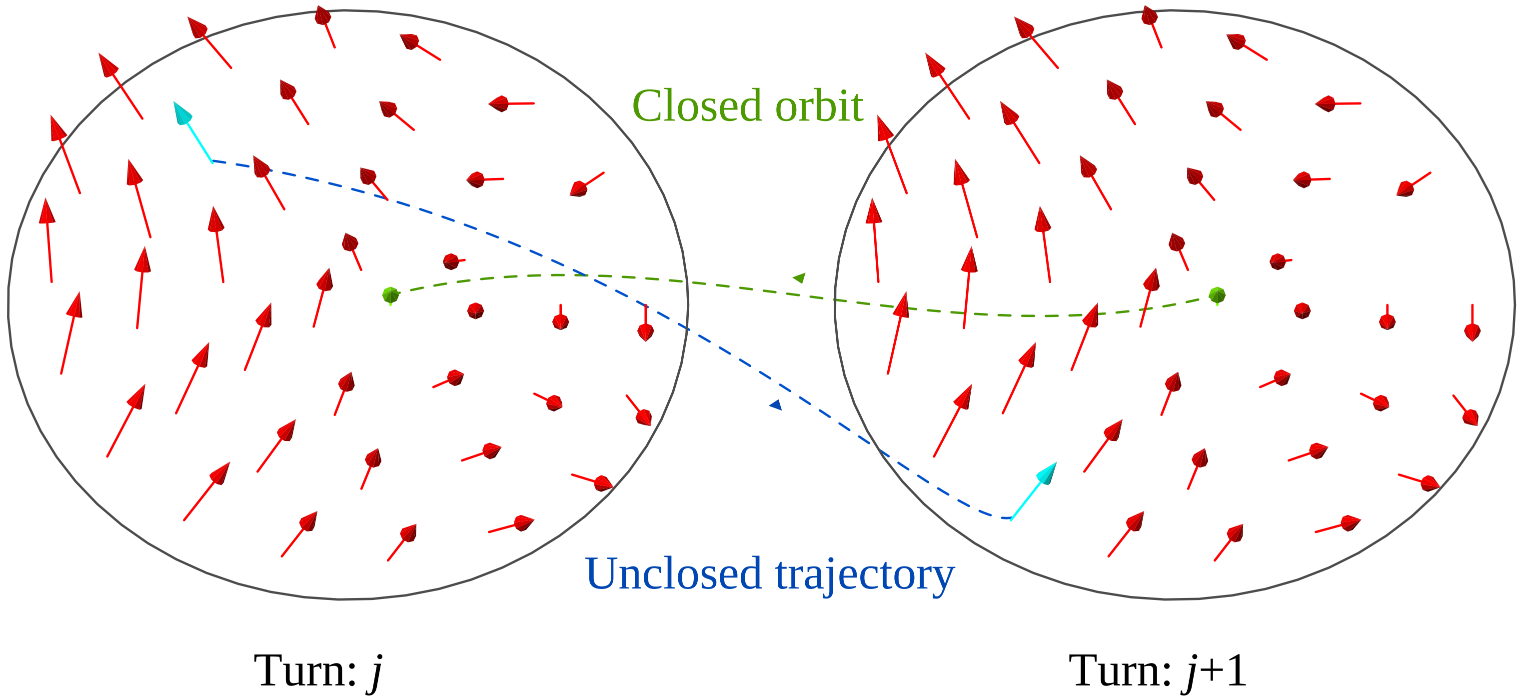


Horizontal Betatron Oscillation
with tune: $Q_x = 3.28$,
tracked through 10 turns
with 8 periodic cells.



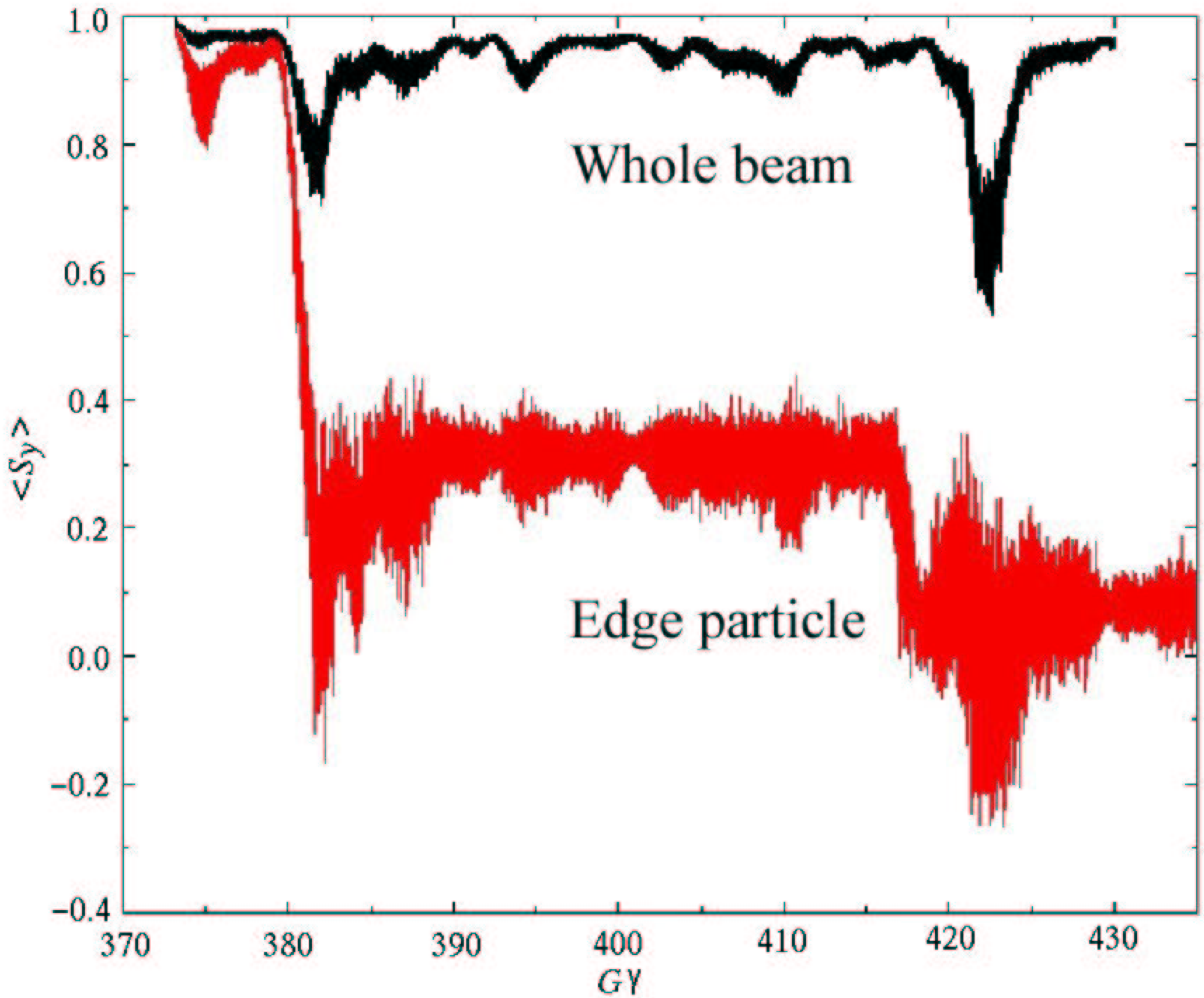
Poincaré plot of proton on successive turns for one location in the ring.

Invariant Spin Field



- For the closed orbit: $\vec{n}_0(s) = \vec{n}_0(s+L)$, with $\vec{q}_0(s) = \vec{q}_0(s+L)$ and $\vec{P}_0(s) = \vec{P}_0(s+L)$.
- For other locations in phase space: $\vec{n}(\vec{q}, \vec{P}, s) = \vec{n}(\vec{q}, \vec{P}, s+L)$, even though in general $q(s+L) \neq q(s)$ and $P(s+L) \neq P(s)$.

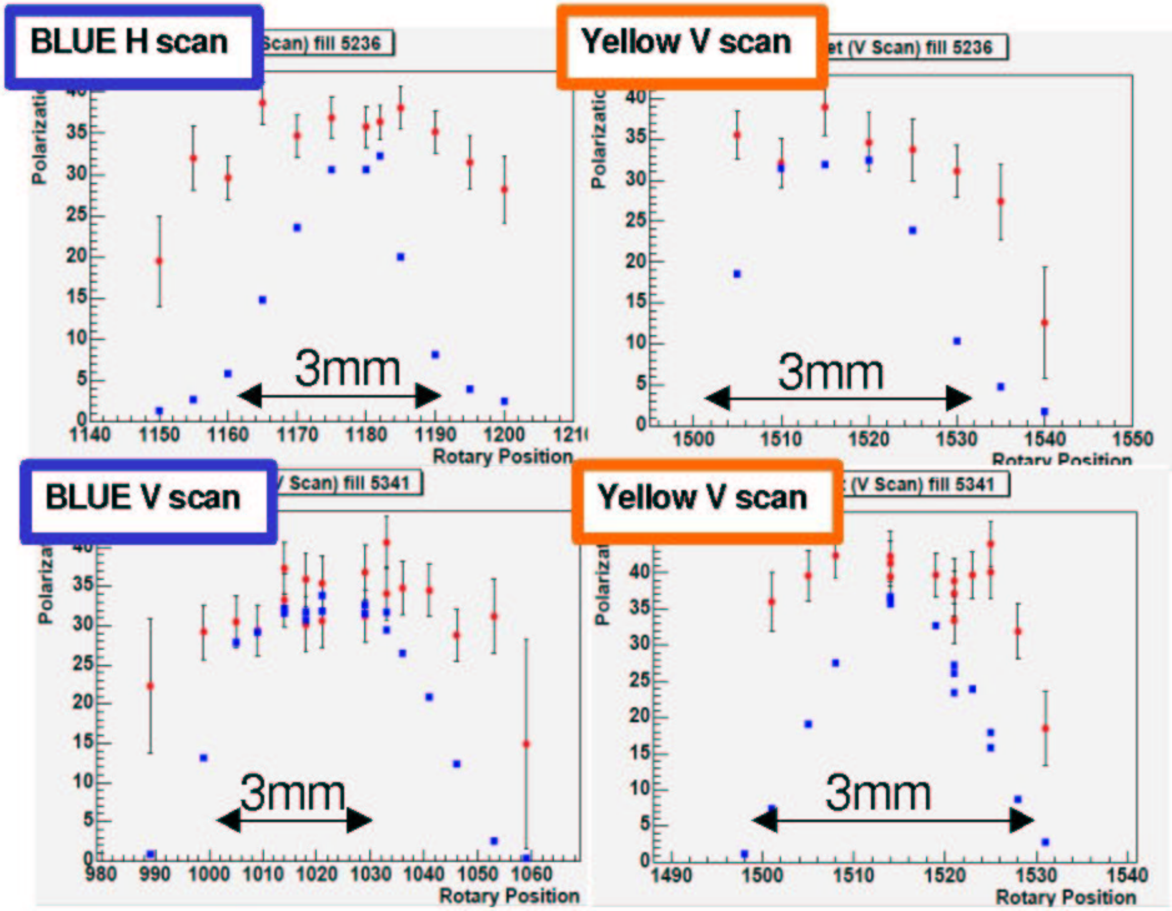
Spin Tracking in RHIC



Particles with larger amplitude betatron oscillations may have a larger tilt of $\vec{n}$ away from the stable spin direction $\vec{n}_0$ of the closed orbit

(Alfredo Luccio)

Transverse Profiles of Polarization



Data points:

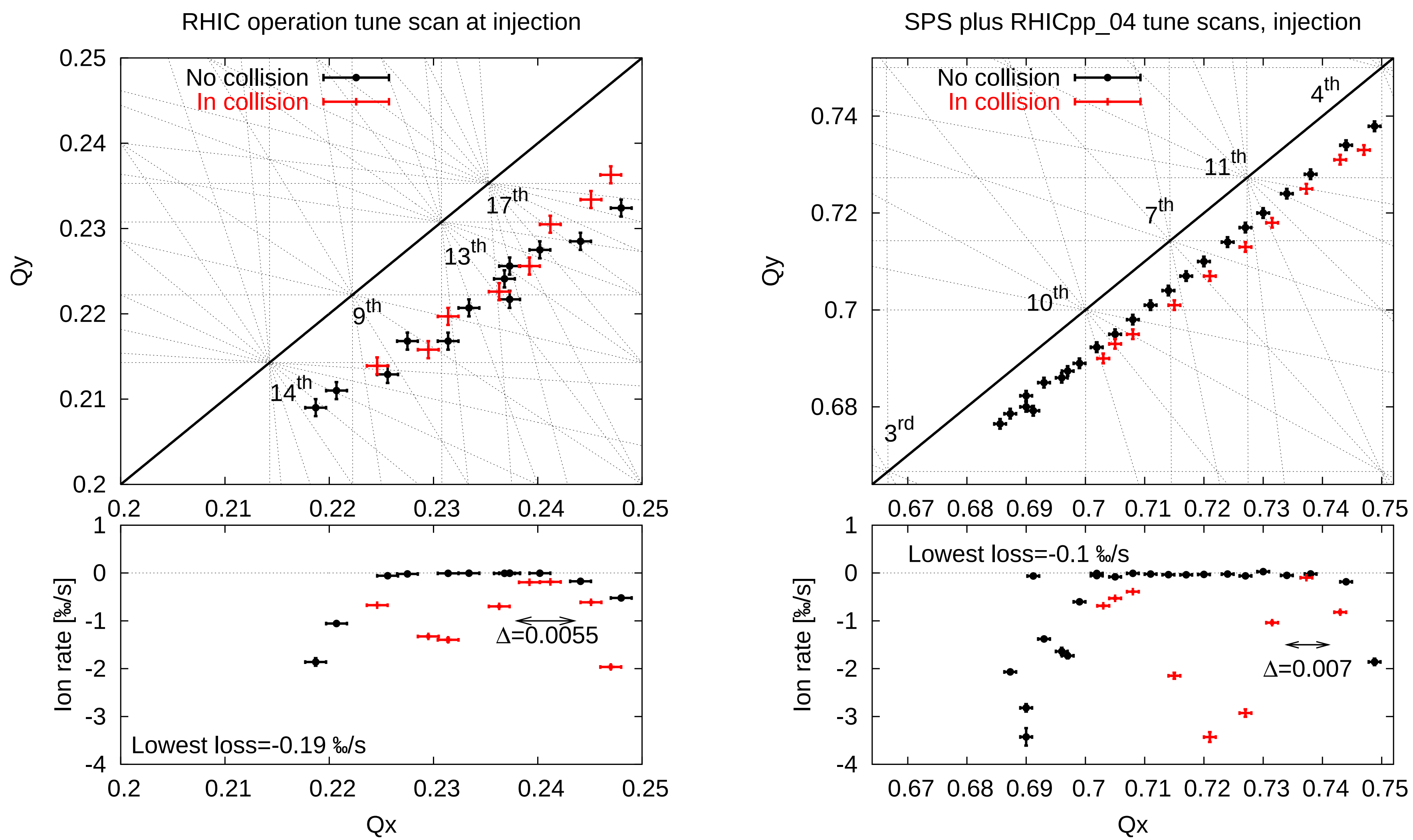
Blue: counting rate

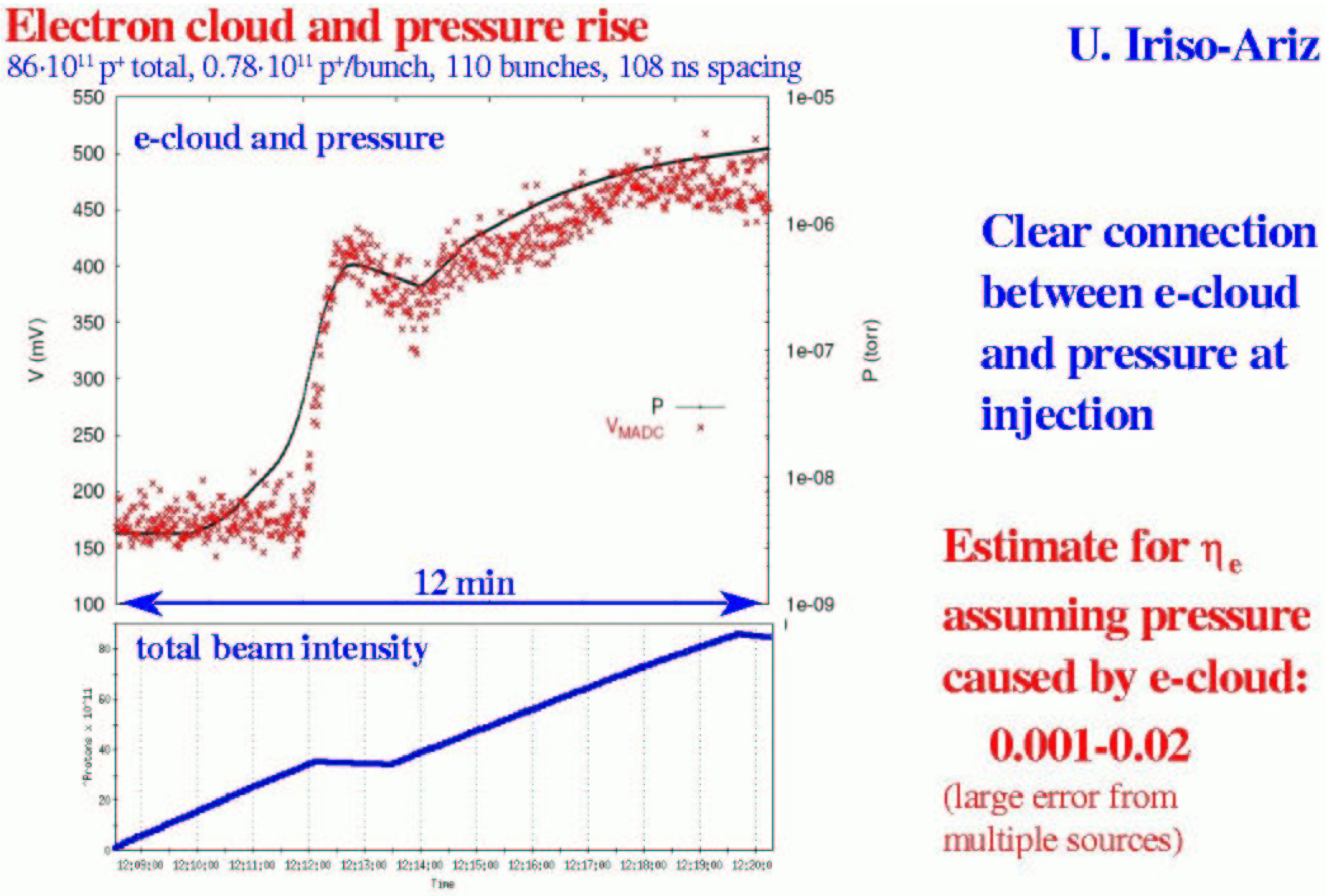
Orange: Polarization

BROOKHAVEN NATIONAL LABORATORY

Spin 2004, Trieste
Waldo MacKay 15 Oct., 2004

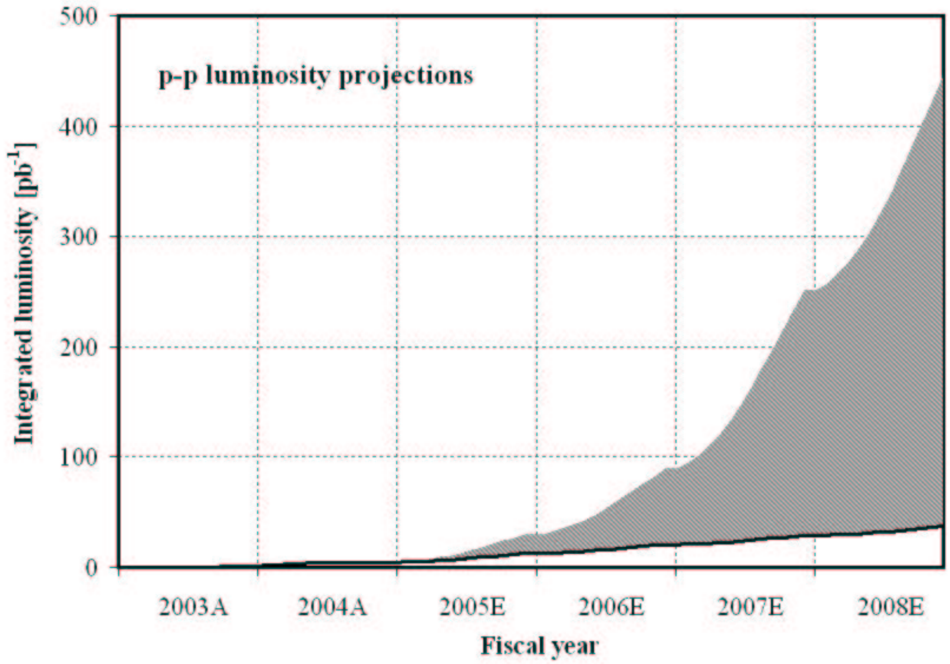
Tune Working Point for RHIC





Adding NEG-coating (getter) inside beam pipes in warm sections.

Luminosity Projections



Year	2004	2008
# of Bunches	56	112
Protons/bunch [$\times 10^{11}$]	0.7	2.0
$\langle \mathcal{L} \rangle$ [10^{30} cm^{-2}s^{-1}]	4	72
$\int \mathcal{L}$/week [pb^{-1}]	0.9	26.0
Store polarization	40%	70%
$\int \mathcal{L} P^4$/week [nb^{-1}]	24	6230

Assumed:

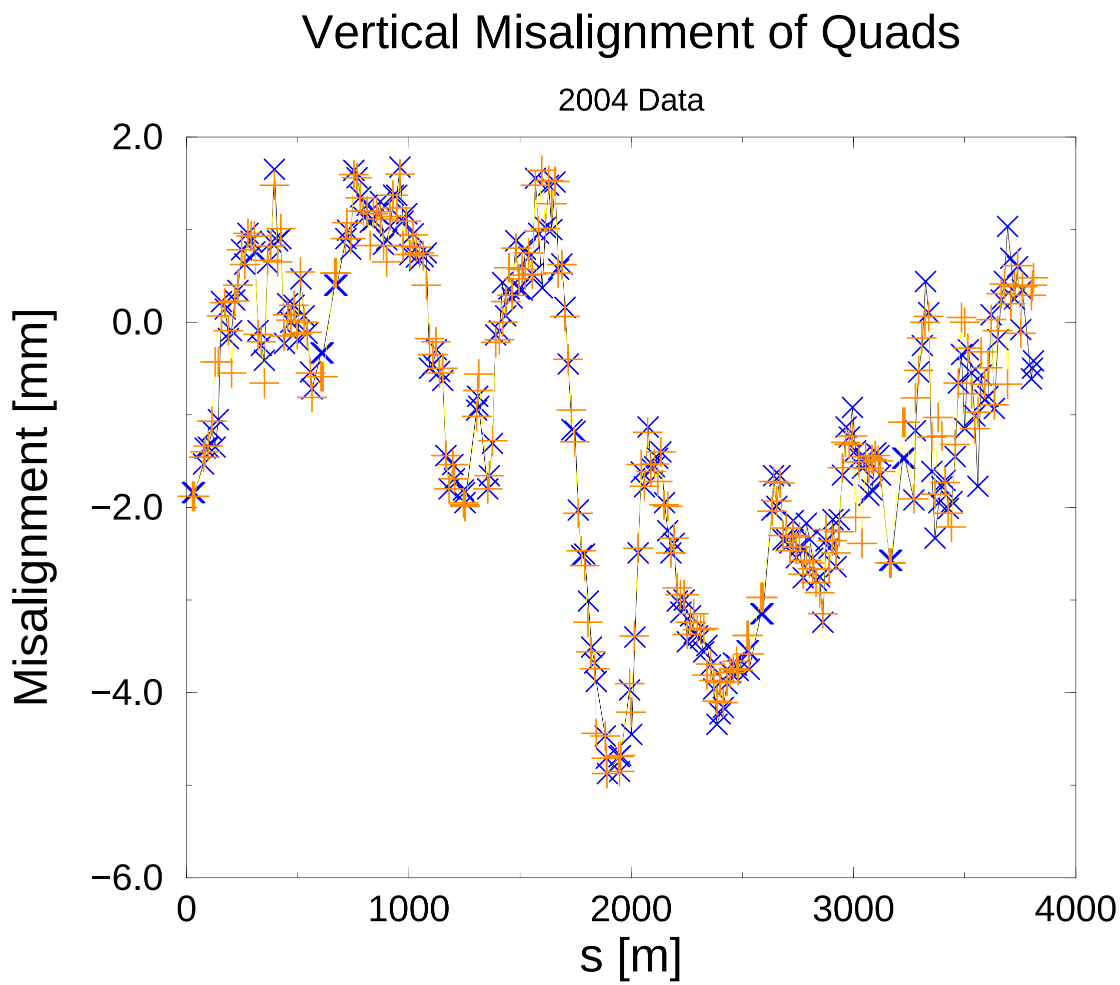
- 12 weeks of production per year
- 8 weeks of linear luminosity increase
- Only 2 experiments

Vertical Survey of RHIC Quadrupoles

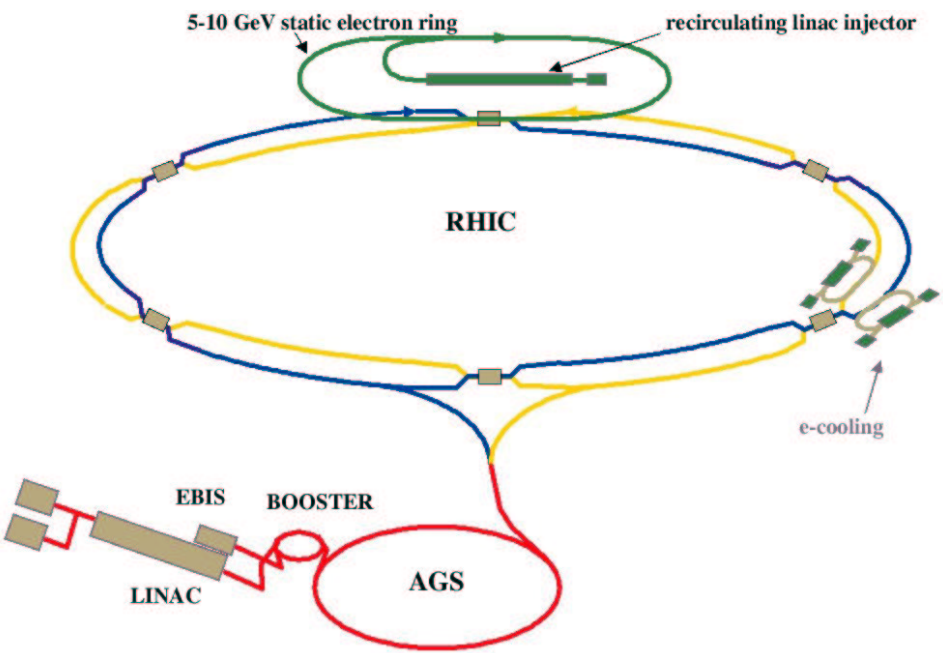
For higher energies vertical alignment becomes more important.

Realigning around IP12 (1800–2000 m) before next run

Flat but tilted ring corresponds to an approximate sine-wave.



eRHIC: polarized electrons and protons



$e^{\pm}$ Energy: 5–10 GeV
Polarization: $\gtrsim$70%
Luminosity: $\sim 10^{32} - 10^{33}$ cm^{-2}s^{-1}

Go to Abhay Deshpande's talk tomorrow.

L. Ahrens et al., "eRHIC Zero$^{\text{th}}$ Order Design Report", C-A/AP/142 (2004).
`http://www.rhichome.bnl.gov/AP/ap_notes/ap_note_142.pdf`

Summary (1)

- Achievments at 100 GeV
  - Ave. Luminosity: 4×10^{30} cm^{-2}s^{-1}
  - Ave. Polarization: 40% – transverse and longitudinal
  - Preliminary results from H jet polarimeter:
    - A_N consistent with theory without hadron spin-flip and with FNAL E704
  - p + C CNI polarimeters:
    - Polarization variation measured across beam distribution
- Injector plans
  - Replace solenoid in polarized source for 2005 run.
  - Add stronger AGS cryogenic snake – commission 2005 (will use warm helix only for 2005 production)
    - cold snake should allow $\geq 70\%$ polarization at 2×10^{11} per bunch

Summary (2)

- RHIC plans
  - NEG-coated vacuum chamber in warm sections: $\sim 50\%$ complete
    - Enhanced Luminosity goal: 1.5×10^{32} cm^{-2}s^{-1} at 250 GeV
  - Accelerate polarized beam to higher energy
  - Commission spin flipper
  - Calibrate snakes
  - Realign quadrupoles
  - Improve orbit correction (BPM upgrade)
  - Study polarization profile across beam distribution
  - Calibrate beam energy
- eRHIC: polarized electrons and protons
  (Abhay Deshpande's talk tomorrow)