

First Polarized Proton Collisions at RHIC

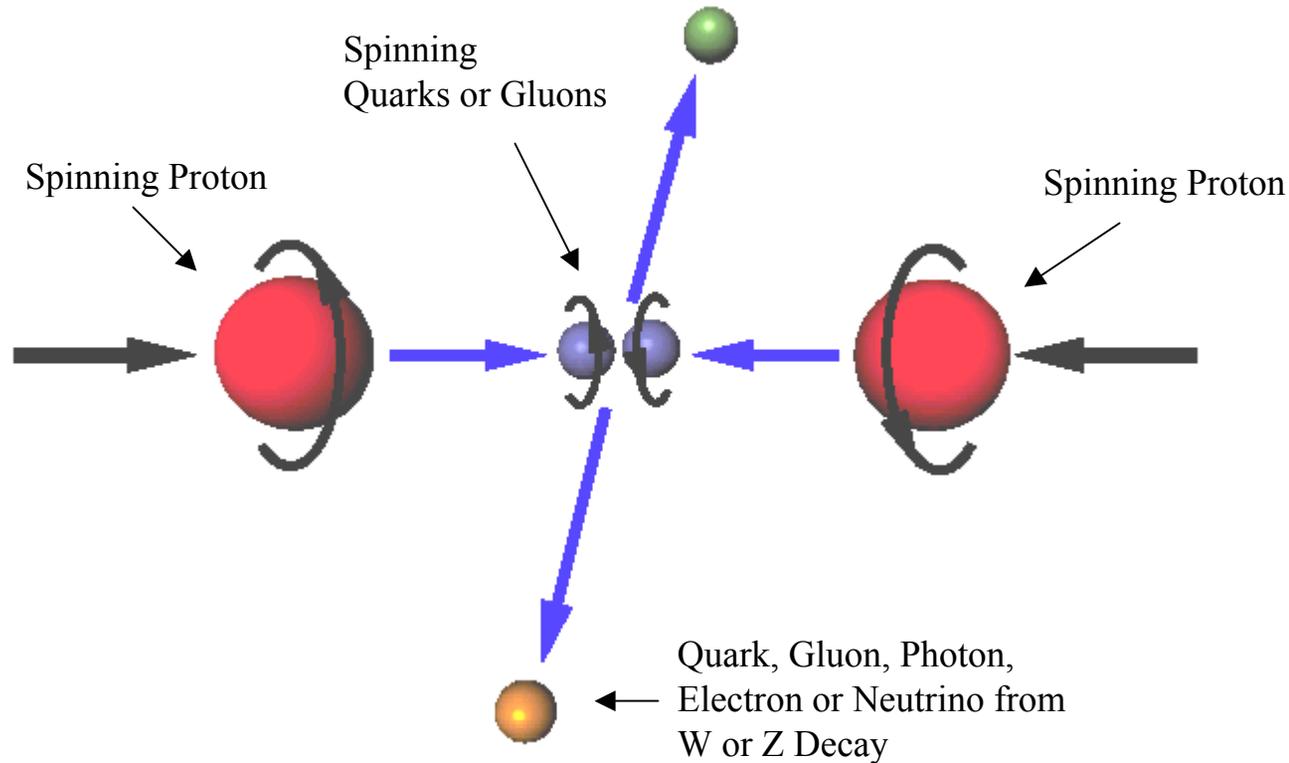
Spin dynamics and Siberian Snakes

Polarized proton acceleration in AGS and RHIC

High energy proton beam polarimetry

Strong partial Siberian snake for the AGS

RHIC Spin Physics



- Spin structure functions of gluon and anti-quarks
- Parity violation in parton-parton scattering

Spin Dynamics

Precession Equation in Laboratory Frame:

(Thomas [1927], Bargmann, Michel, Telegdi [1959])

$$d\mathbf{P}/dt = - (e/\gamma m) [G\gamma\mathbf{B}_\perp + (1+G)\mathbf{B}_0] \times \mathbf{P}$$

Lorentz Force equation:

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

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

Depolarizing Spin Resonances

Spin tune: Number of 360 degree spin rotations per turn

Depolarizing resonance condition:

Number of spin rotations per turn = Number of spin kicks per turn

Imperfection resonance (magnet errors and misalignments):

$$G\gamma = \nu_{sp} = n$$

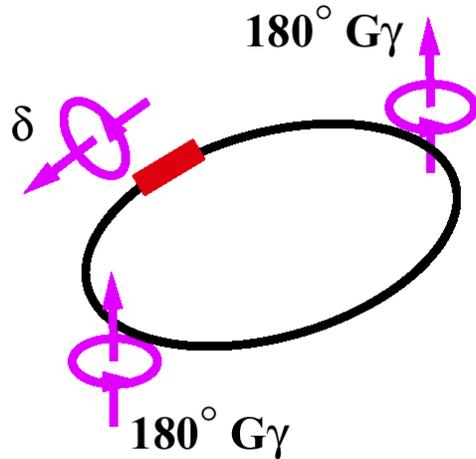
Intrinsic resonance (Vertical focusing fields):

$$G\gamma = \nu_{sp} = Pn \pm \nu_y$$

P: Superperiodicity [AGS: 12]

ν_y : Betatron tune [AGS: 8.75]

Siberian Snakes (Local Spin Rotators)

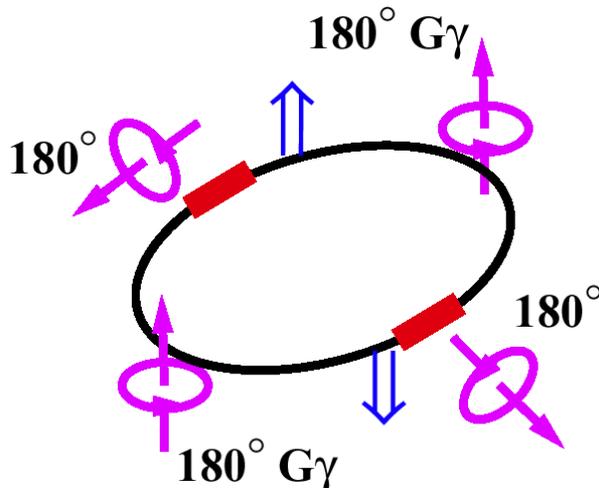


$$\cos(180^\circ \nu_{sp}) = \cos(\delta/2) \cdot \cos(180^\circ G\gamma)$$

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

No imperfection resonances

Partial Siberian snake (AGS)



$$\delta = 180^\circ \rightarrow \nu_{sp} = 1/2$$

No imperfection resonances and

No Intrinsic resonances

Full Siberian Snake

Two Siberian Snakes in RHIC

(Naïve) Limits for Siberian Snakes

Spin rotation of Siberian snake $>$ Spin rotation of driving fields

Imperfection resonances

$$\varepsilon \propto \mathbf{Energy}$$

Intrinsic resonances

$$\varepsilon \propto \sqrt{\mathbf{Energy}}$$

Partial Siberian snake (AGS, $\delta = 9^\circ$)

$$\varepsilon = \delta/360^\circ$$

One full snake

$$\varepsilon = 1/2$$

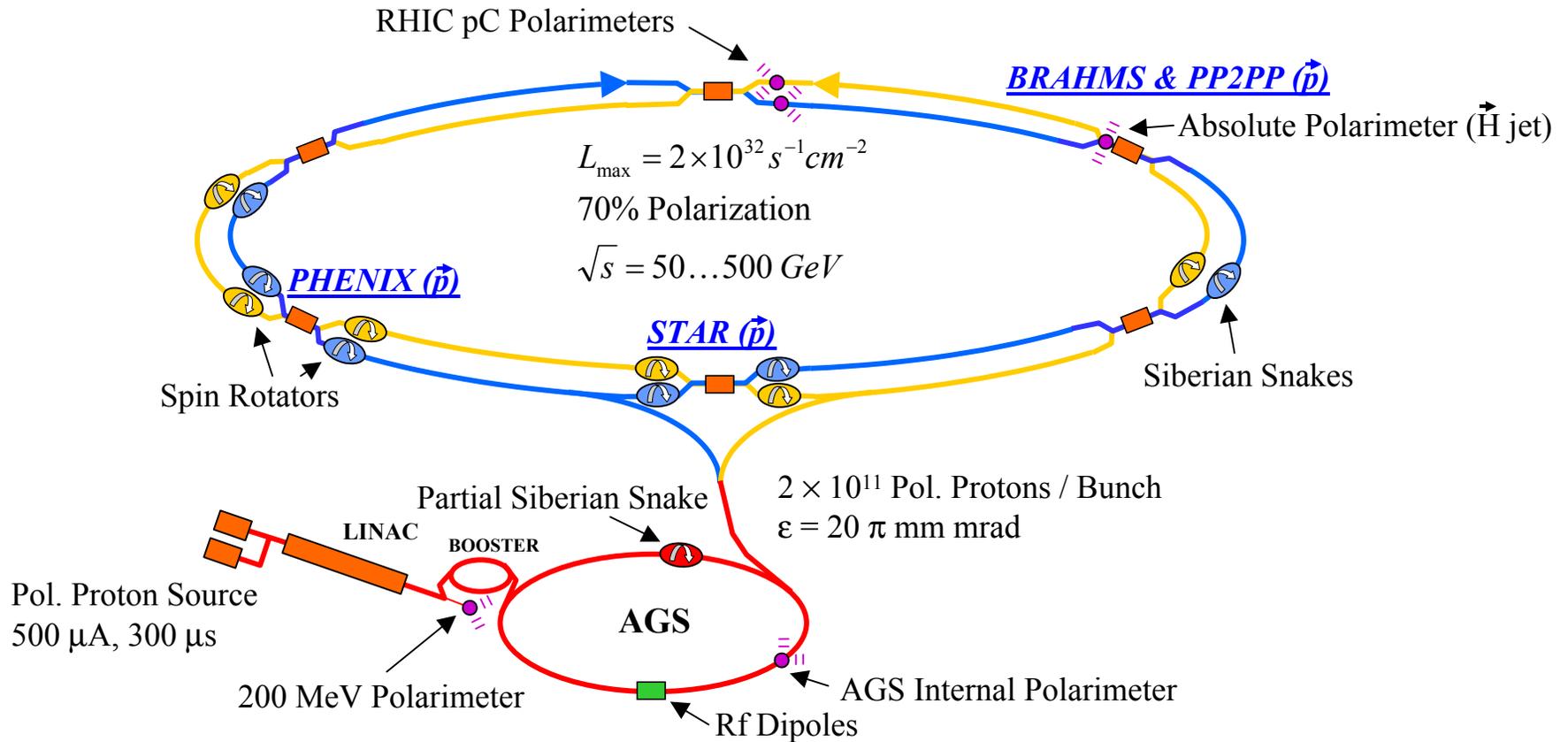
Two full snakes (RHIC)

$$\varepsilon = 1$$

N full snakes (HERA, LHC)

$$\varepsilon = N/2$$

Polarized proton collisions in RHIC



High intensity polarized H⁻ source



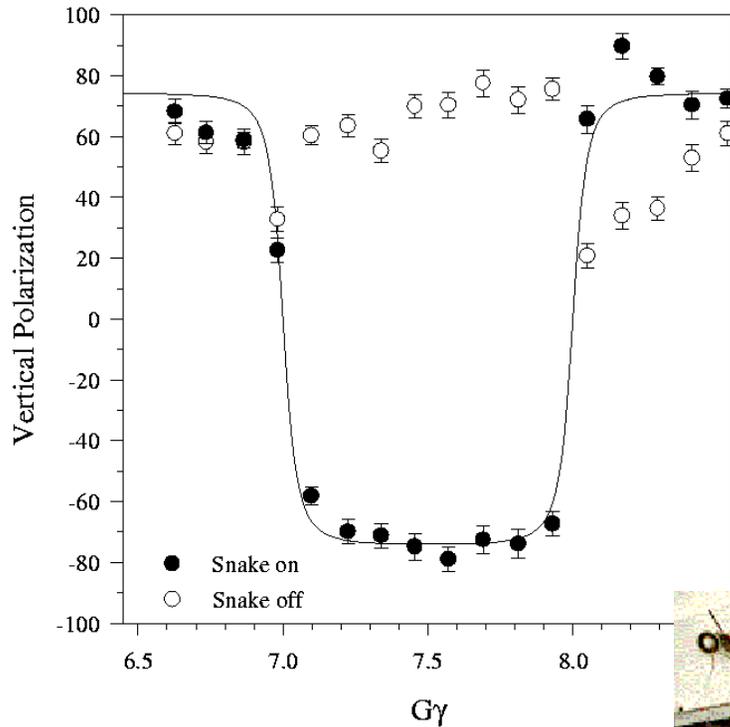
KEK OPPIS
upgraded at TRIUMF

70 - 80 % Polarization

15×10^{11} protons/pulse
at source

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

AGS Partial Siberian Snake Solenoid

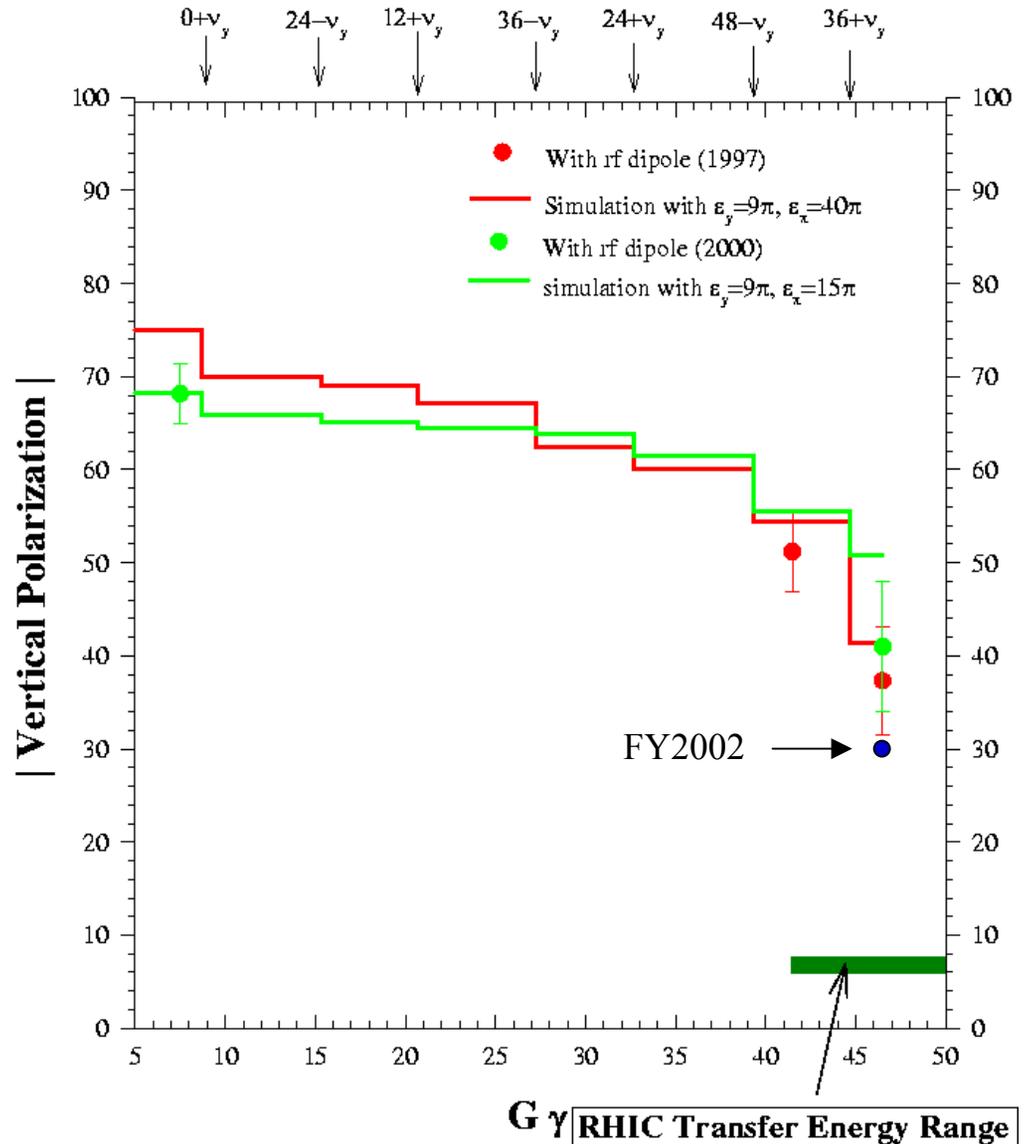


- 4.7 Tm solenoid
- 9 degree spin rotation
- Reverses spin every 523 MeV without loss of polarization

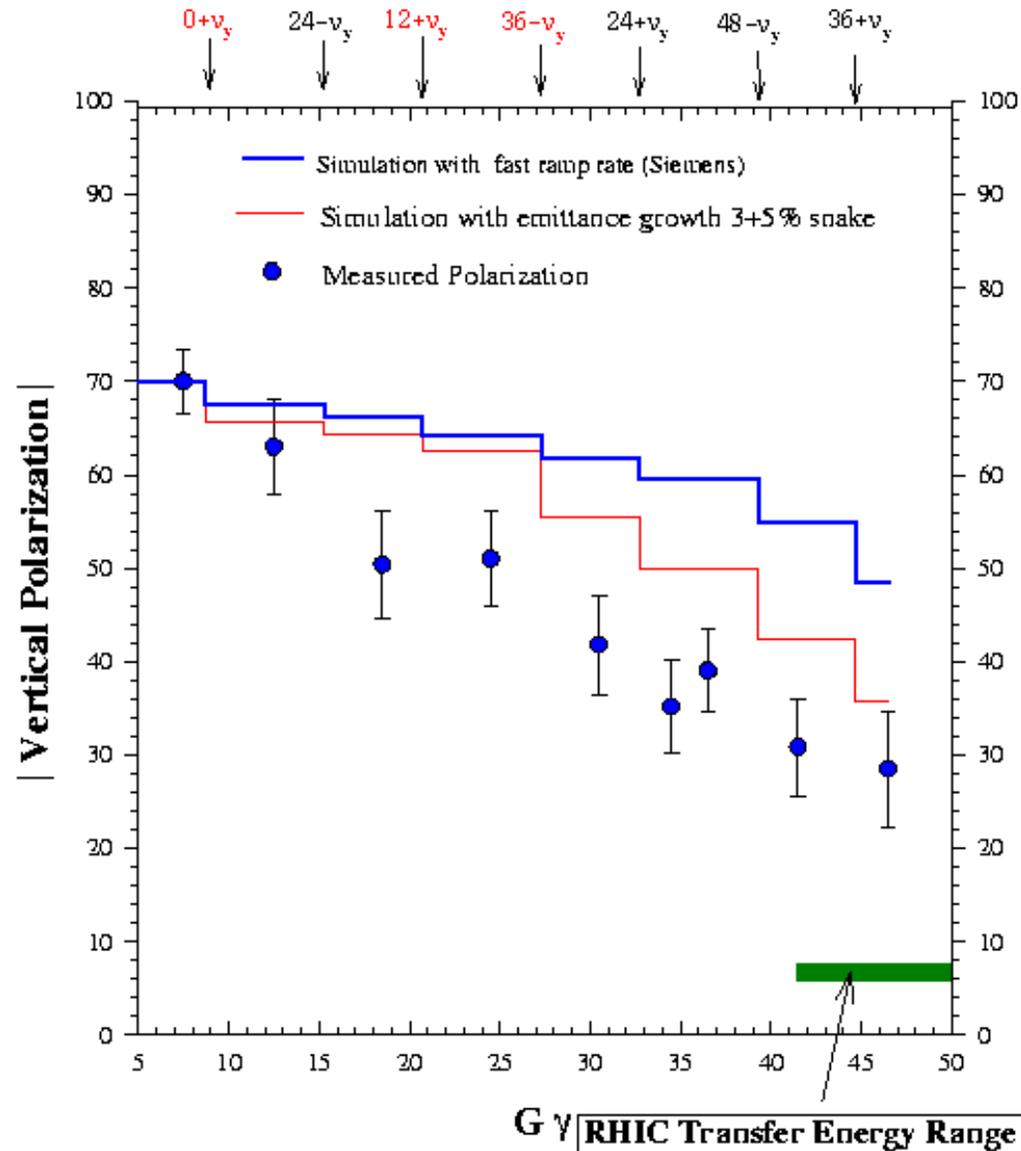


Proton polarization at the AGS

- Full spin flip at all imperfection resonances using partial Siberian snake
- Full spin flip at strong intrinsic resonances using rf dipole
- Remaining polarization loss from coupling and weak intrinsic resonances
- Larger polarization loss in FY2002 due to lower ramp-rate motor-generator and higher bunch intensity (?)



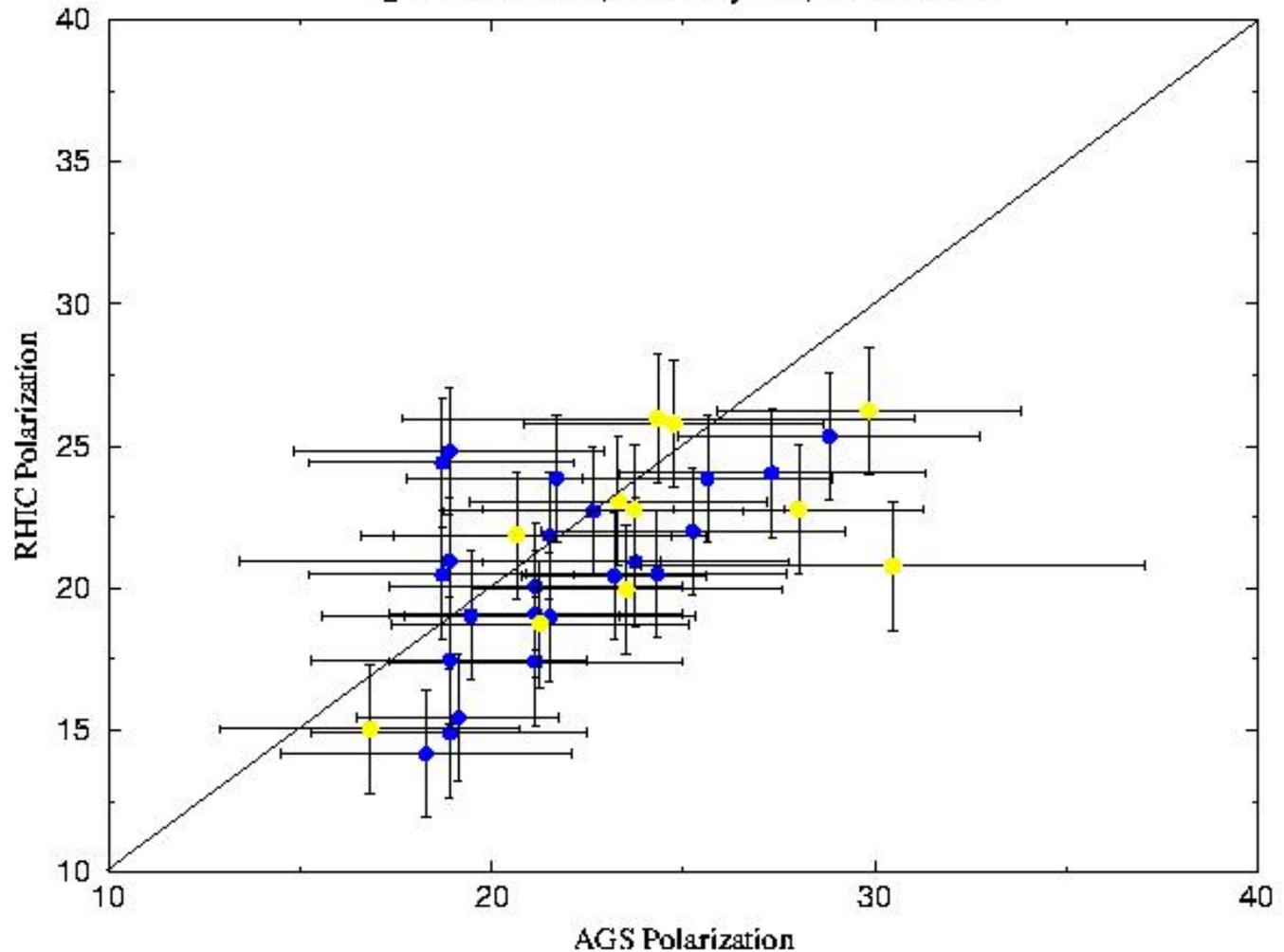
AGS polarization vs. energy (FY2002)



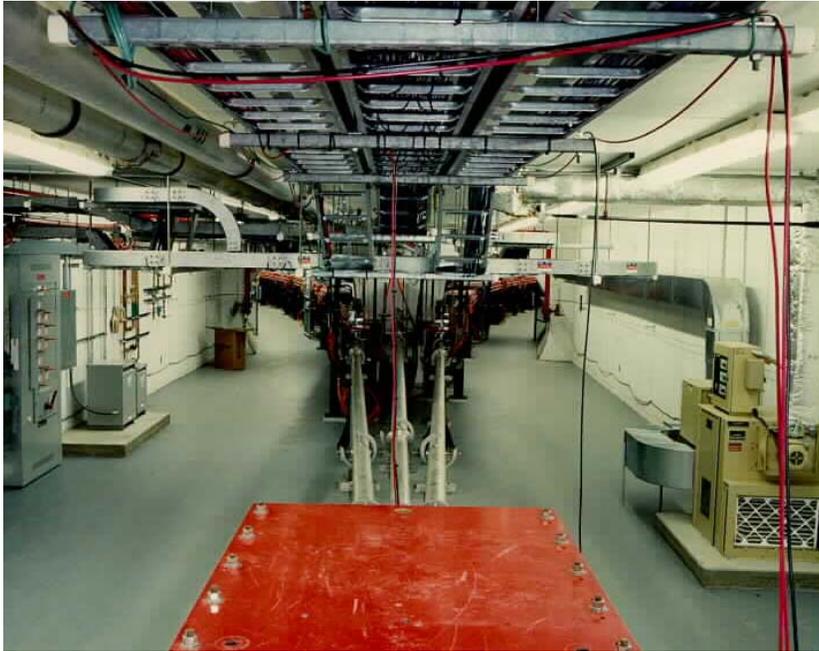
AGS-to-RHIC polarization transfer

Polarization of RHIC injection and AGS extraction

$A_N = 1.27\%$ for blue, 1.33% for yellow, 0.534% for AGS



RHIC Pictures (1)

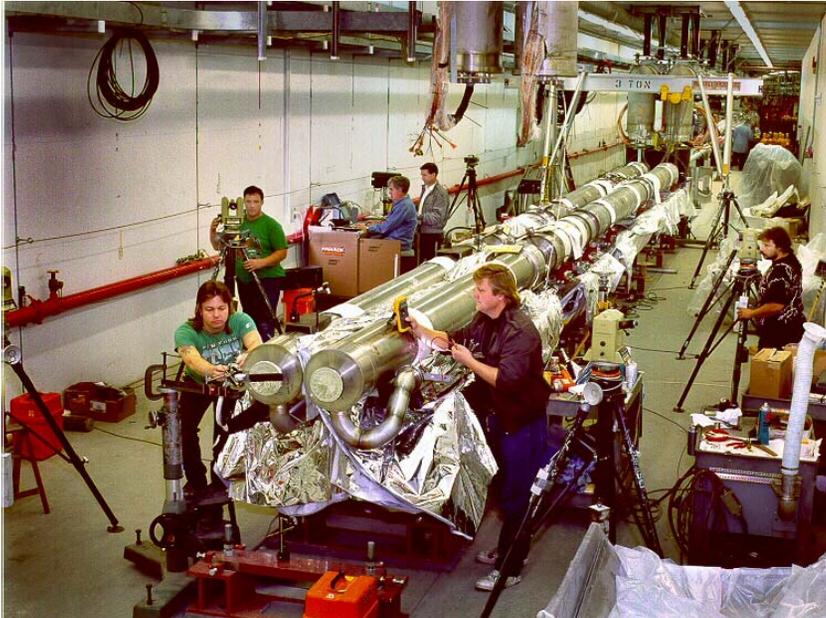


Injection arcs to
blue and yellow rings



Blue and yellow rings

RHIC Pictures (2)



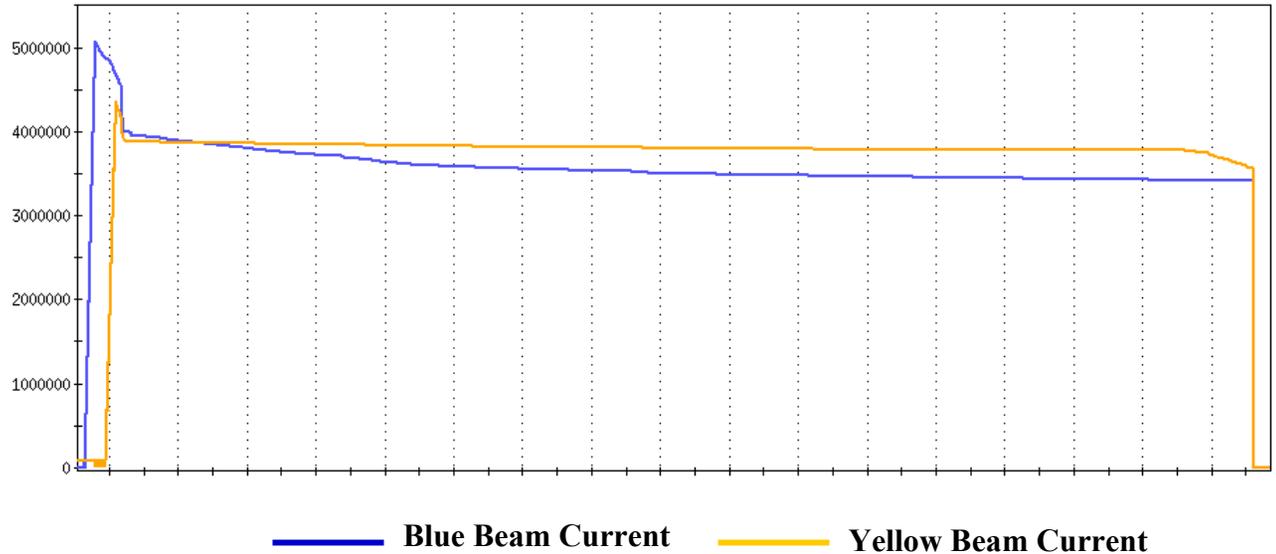
Installation of final focussing triplets

Rf storage cavities



“Typical Store” # 2304

Beam currents [$\times 10^6$ ions]

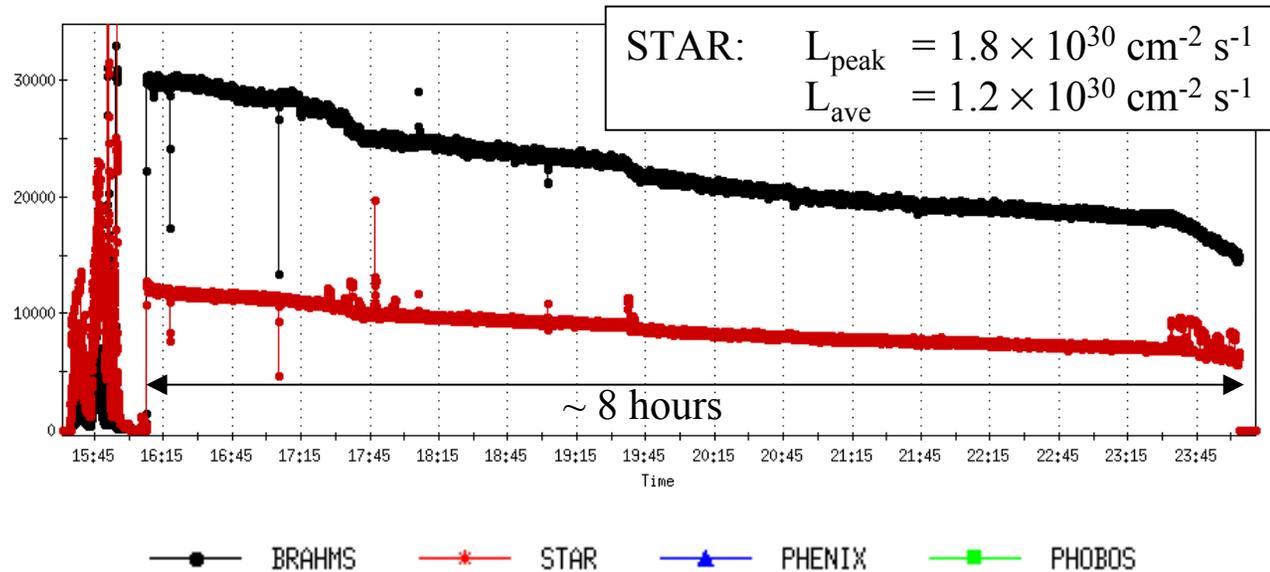


Collision rate [Hz]

Vernier scans:

STAR: $10^4 \rightarrow 0.6 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$

PHENIX: $10^4 \rightarrow 1.6 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$



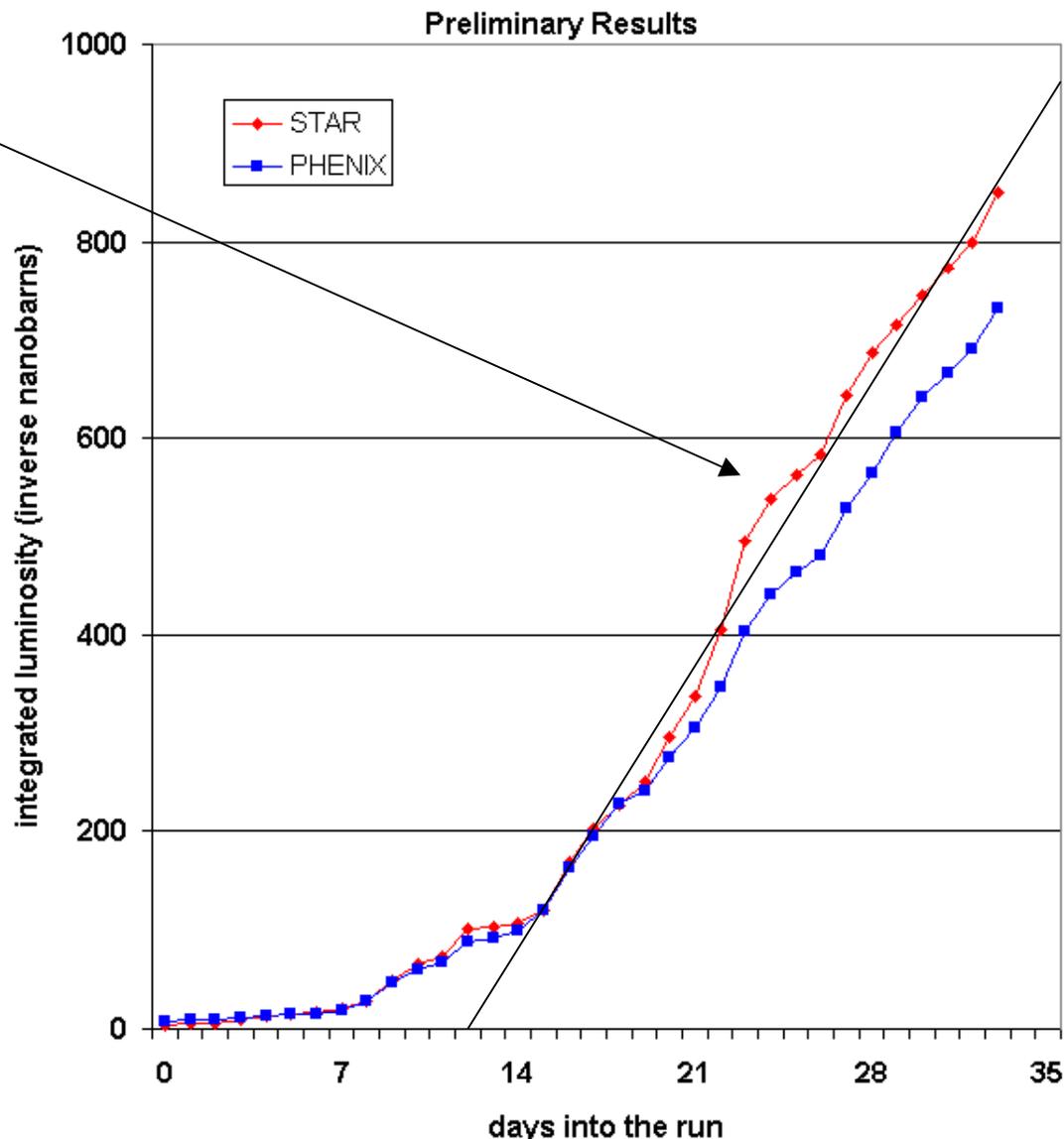
Integrated p - p luminosity

STAR during last 20 days:

$290 \text{ (nb)}^{-1}/\text{week}$

$L_{\text{ave}}(\text{week}) = 0.5 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$

$L_{\text{ave}}(\text{week})/L_{\text{ave}}(\text{store}) = 42 \%$



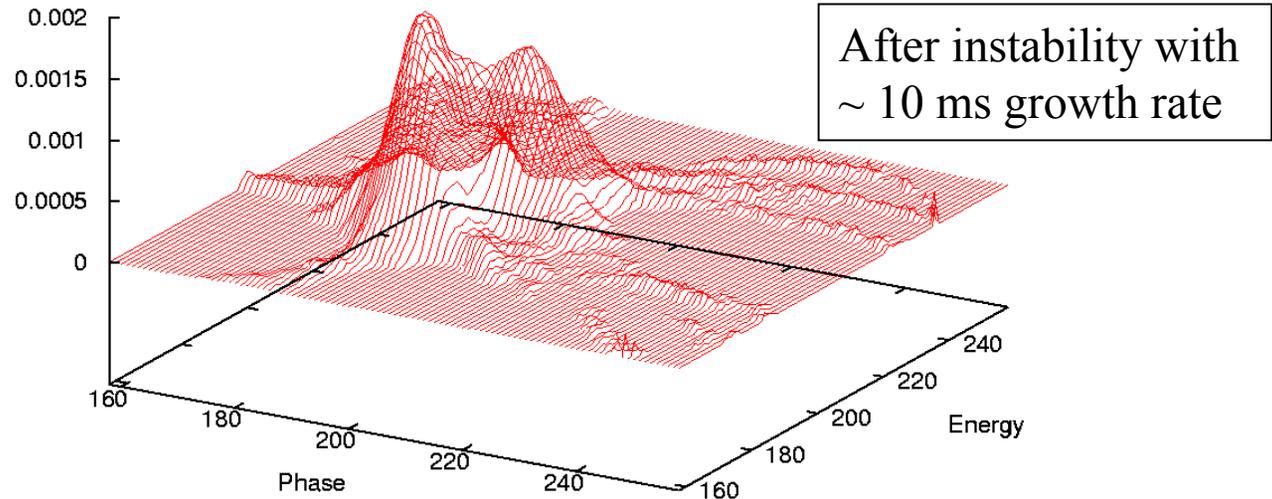
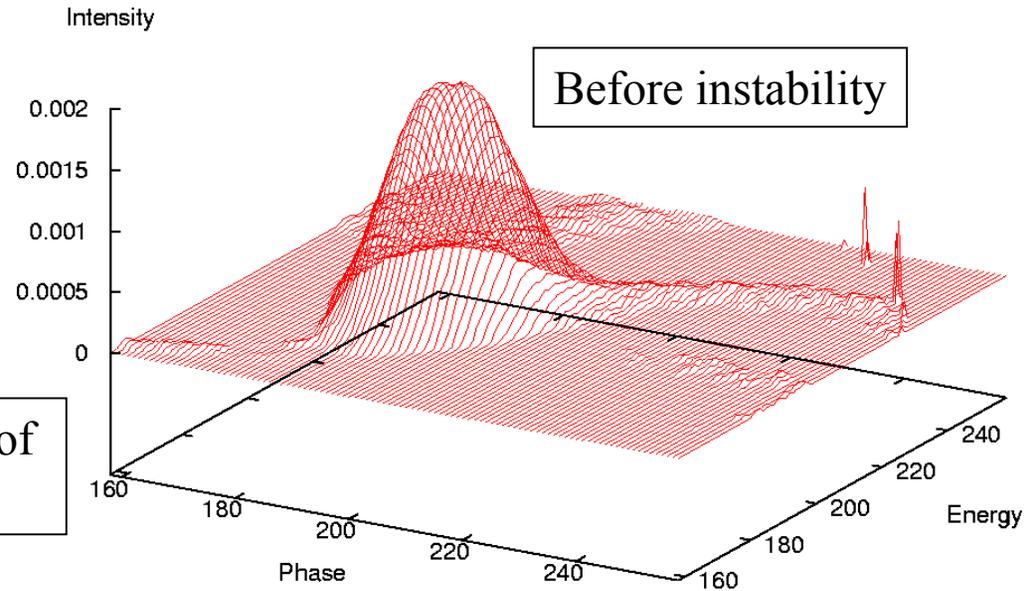
Transverse instabilities in RHIC

High sensitivity around transition

Effect of vacuum chamber impedance, electron cloud (?)

Cures: beam-beam tune spread, octupoles, transverse dampers, rf quad, ...

Tomographic reconstruction of 2D bunch density

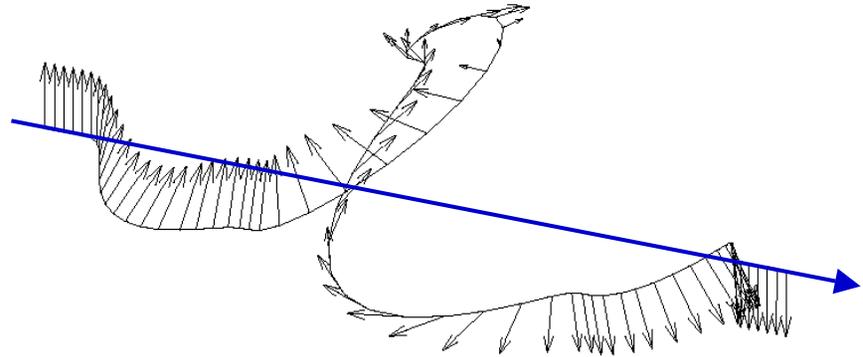
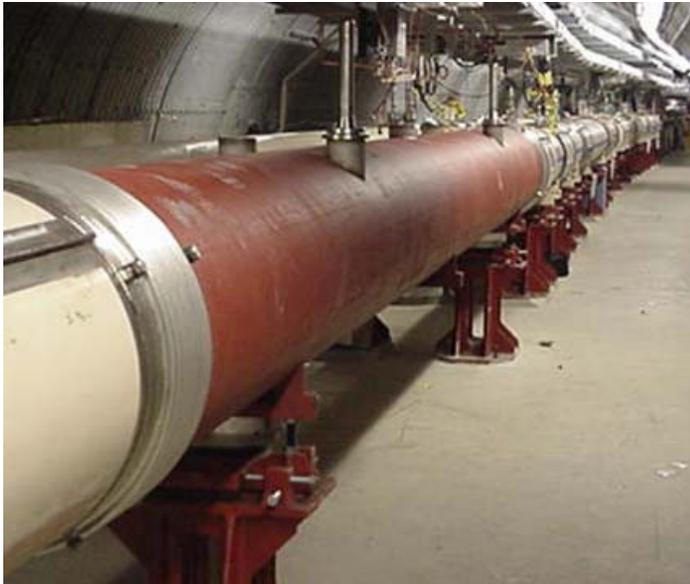


RHIC intensity limitations

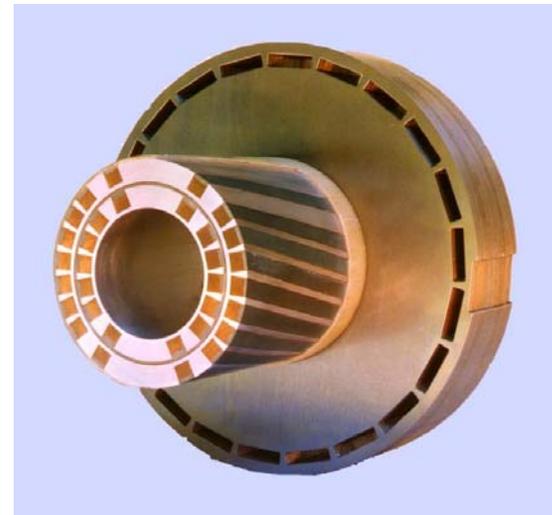
- Single- and multi-bunch instabilities
 - Effect of vacuum chamber impedance, electron cloud (?)
- Intensity limitation due to vacuum break-down
 - Limited to about 40×10^9 Au/ring
 - Electron cloud ? Ion or electron desorption ?
- Intra-Beam Scattering (IBS) (only Au)
 - Transverse and longitudinal emittance growth
 - Eventually will need electron cooling (see below)
- Beam-beam tune shift and spread
 - First strong-strong hadron collider (after ISR)

First Siberian Snake in RHIC Tunnel

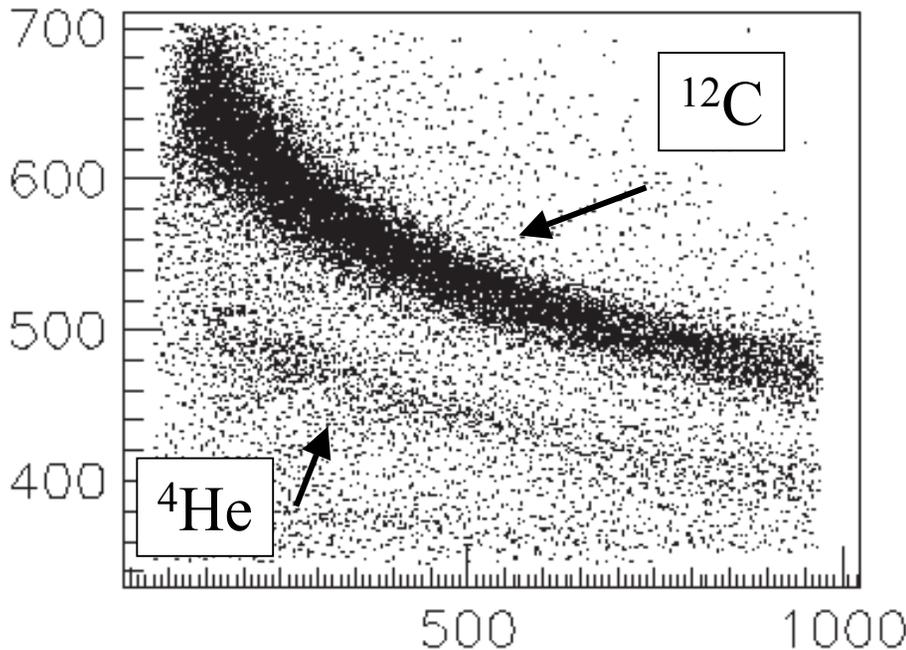
Siberian Snake: 4 superconducting helical dipoles, 4 Tesla,
2.4 m long with full 360° twist



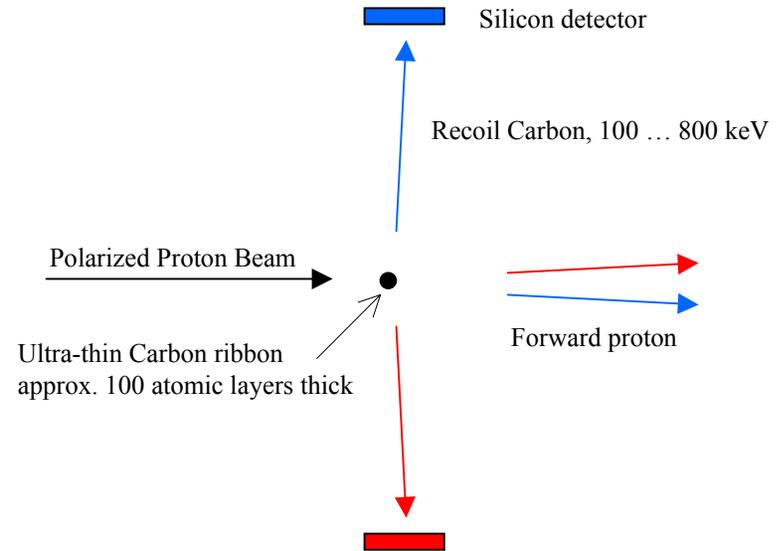
Funded by RIKEN, Japan
Designed and constructed at BNL



RHIC proton-carbon polarimeter



Energy vs. ToF spectrum



- $\sim 1.2\%$ energy independent analyzing power for small-angle elastic scattering in the Coulomb-Nuclear Interference (CNI) region
- Slow recoil Carbon detected in between bunch crossings
- Fiber target allows for polarization profile measurement

RHIC Polarization Set-up

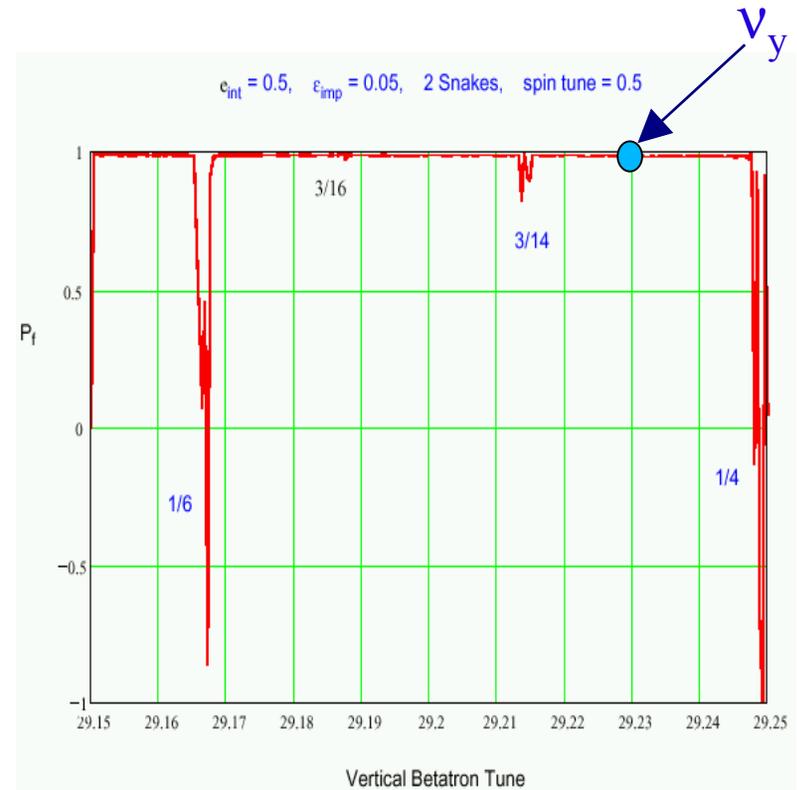
2 Siberian Snakes per ring hold the spin tune $\frac{1}{2}$ all the way up during the acceleration

The vertical tune was chosen at **0.23**, between 2 high-order spin resonances:

- $1/4=0.25$; depends on vertical orbit
- $3/14=0.2143$; exists even without orbit errors

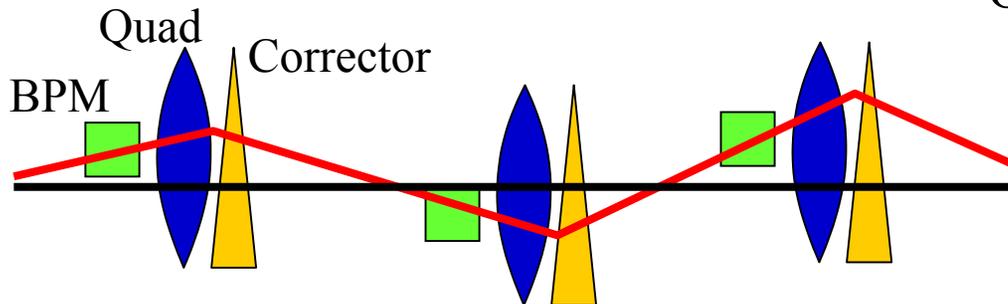
The special vertical orbit, "really" flat was used as the ideal orbit

- Made from measured misalignment data (3 years old).
- The goal number for vertical orbit correction was **0.5mm rms**
- No measured orbit data in defocusing quads

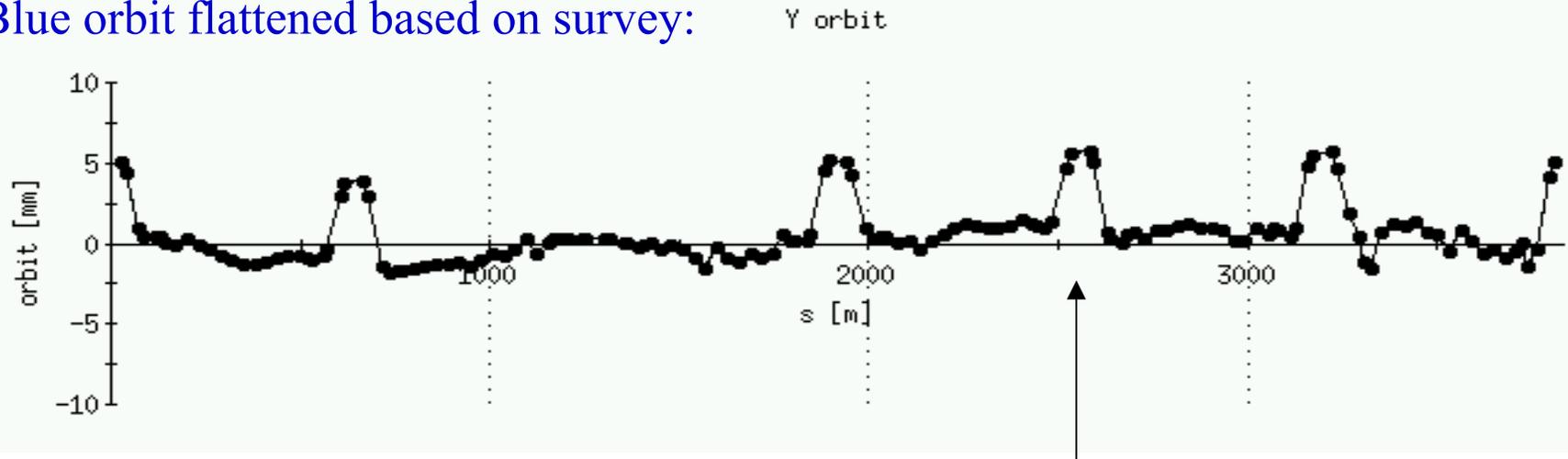


Ideal Orbit for Polarization

Correct orbit to minimize kicks: — Orbit going through center of BPM's
— Orbit without kicks



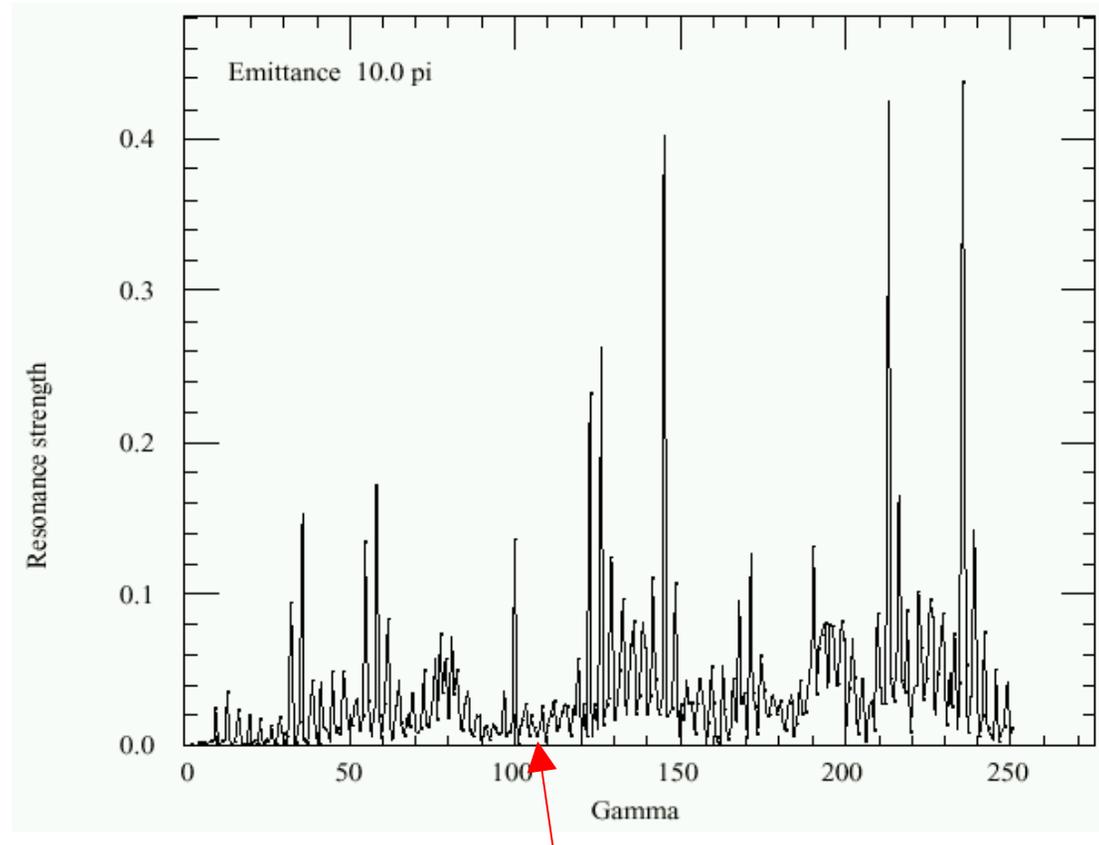
Blue orbit flattened based on survey:



Vertical bumps to avoid collisions

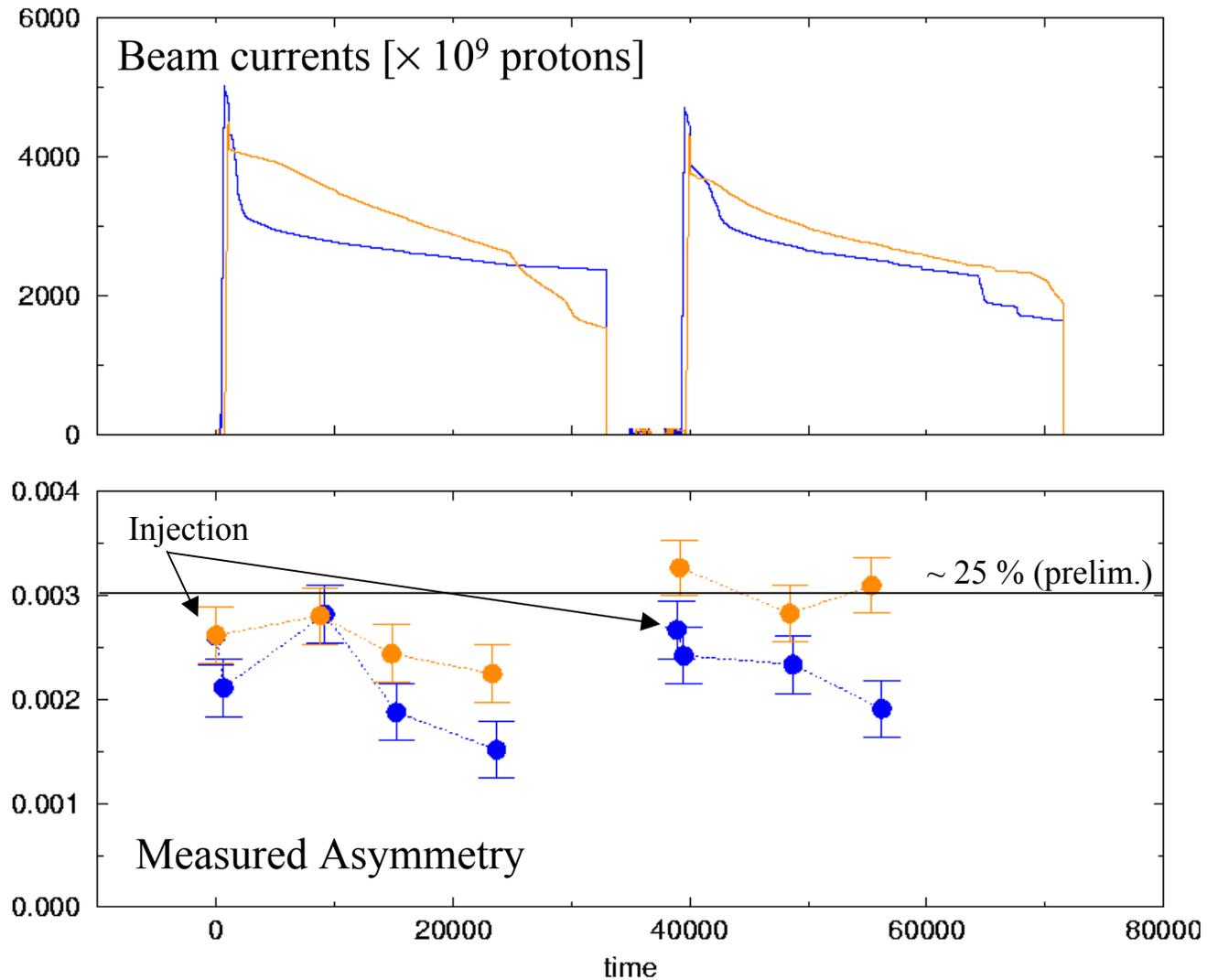
Polarization preservation

- Special attention to tunes and orbits at 4 strong intrinsic resonances
- Yellow polarization transmission was good the most of time
- Blue polarization transmission required more attention and periodical corrections (mostly tune corrections)
- Beam emittance was $\sim 25 \pi$ mm mrad

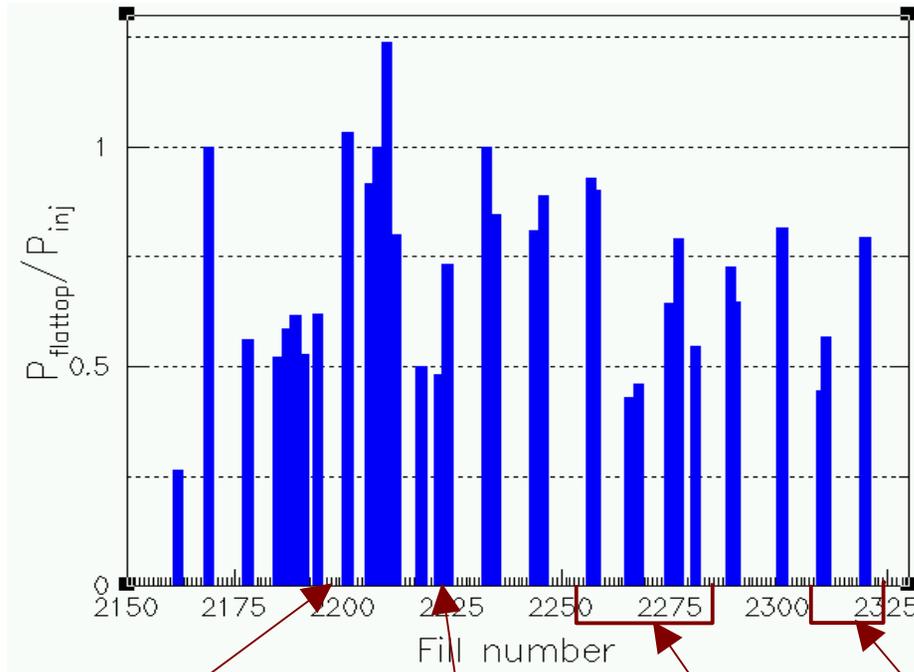


Flattop energy for this run

RHIC Beam Polarization



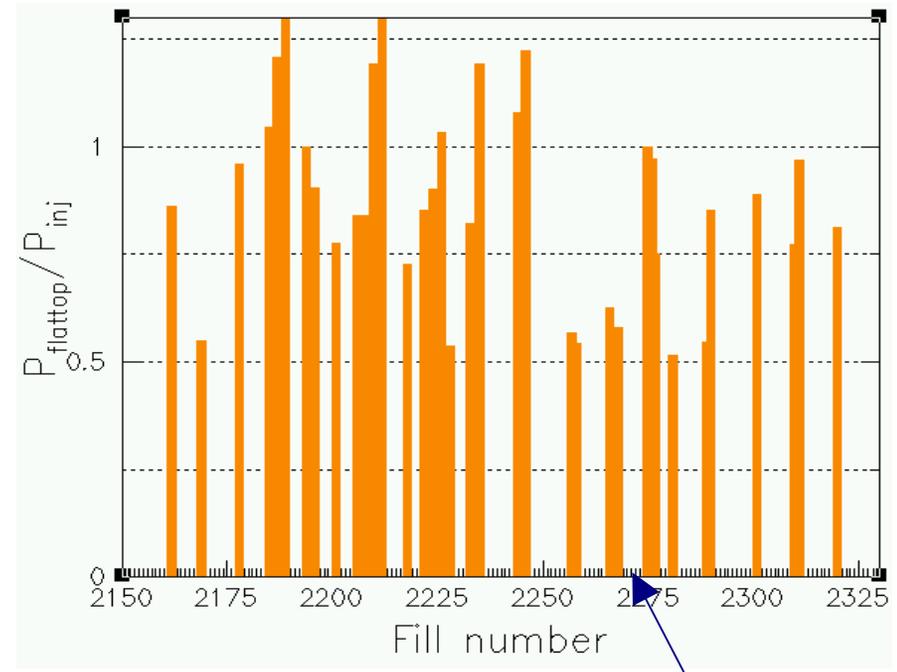
Polarization transmission on ramp



Orbit Correction

Tune Correction
 $v_y < 0.235$

$v_y < v_x$ at flattop



Tune correction

The empirical rules for ramp

Keep the vertical tune between 0.235 and $3/14$

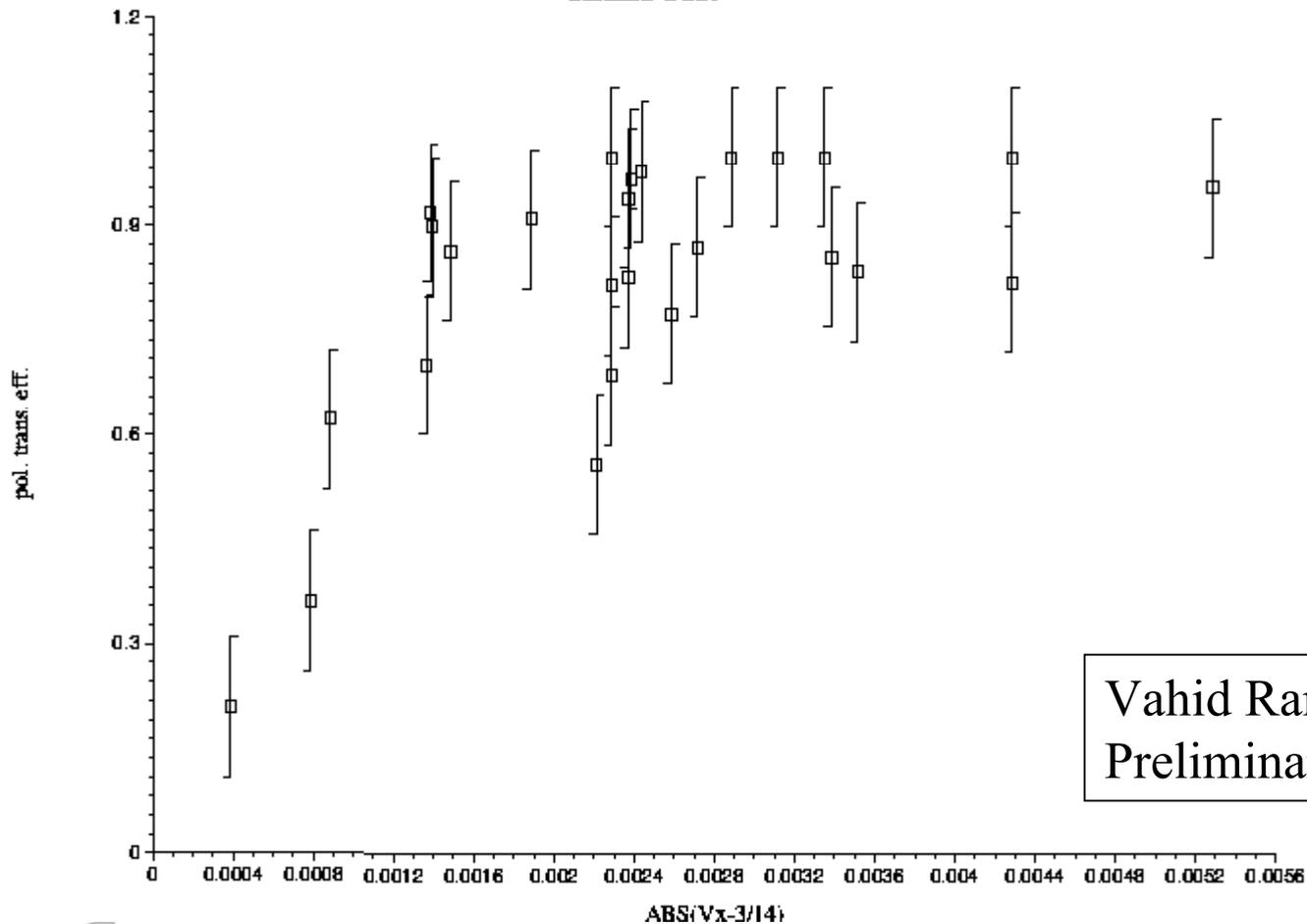
- Total polarization loss when ν_y exceeded 0.245 at the end of the ramp
- Polarization deterioration during the store when the vertical and horizontal tunes were switched in Yellow.

Horizontal tune and coupling are important too keep the orbit rms below 1 mm

- Blue depolarization was observed with the horizontal orbit rms higher than 1.5 mm and/or ν_x close to $3/14$

Depolarization from 3/14 coupling resonance

Yellow High Intensity runs Points collected from Dominant snake res.



Vahid Ranjbar
Preliminary

Results from first RHIC polarized proton run

- 55 bunches per ring with 0.8×10^{11} p[↑]/bunch
- Charge/bunch and total charge higher than with gold beams
- Lattice with constant β^* of 3 m during ramp
- Peak luminosity at beginning of store: 1.5×10^{30} cm⁻² s⁻¹
- Energy/beam: 100 GeV
- Beam polarization ~ 25 %
RHIC polarimeters work reliably
- Little if any depolarization in RHIC during acceleration and store
Siberian Snakes work
- ~ 60 % polarization loss in AGS; aggravated by lower ramp-rate from Westinghouse motor-generator
- **Strong Siberian snake in AGS (~ 30 % of full snake) could avoid all depolarization in the AGS**

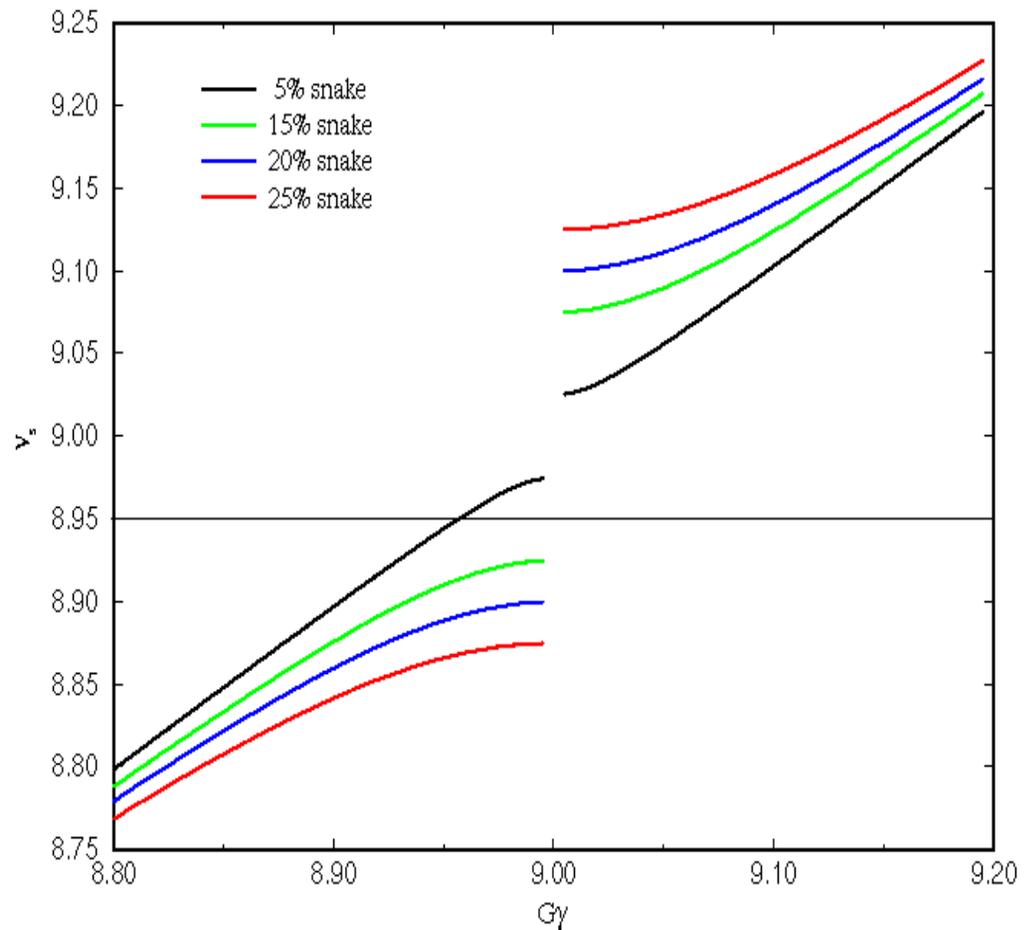
Strong Partial Siberian Snake for AGS

A strong partial Siberian snake generates large spin tune gap for $G\gamma=N$. With strong enough snake gap is large enough to cover both imperfection and intrinsic spin resonances.

Helical snake will not generate coupling spin resonances

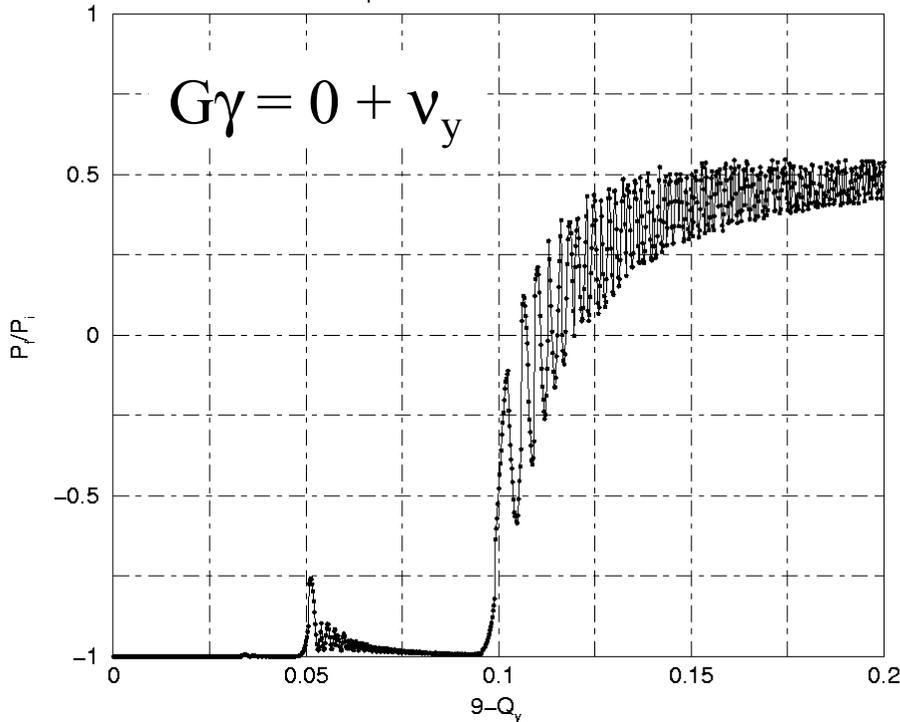
Note: With a strong snake, the stable spin detection will deviate from vertical direction (18 degree for 20% snake).

Spin Tune for a partial snake

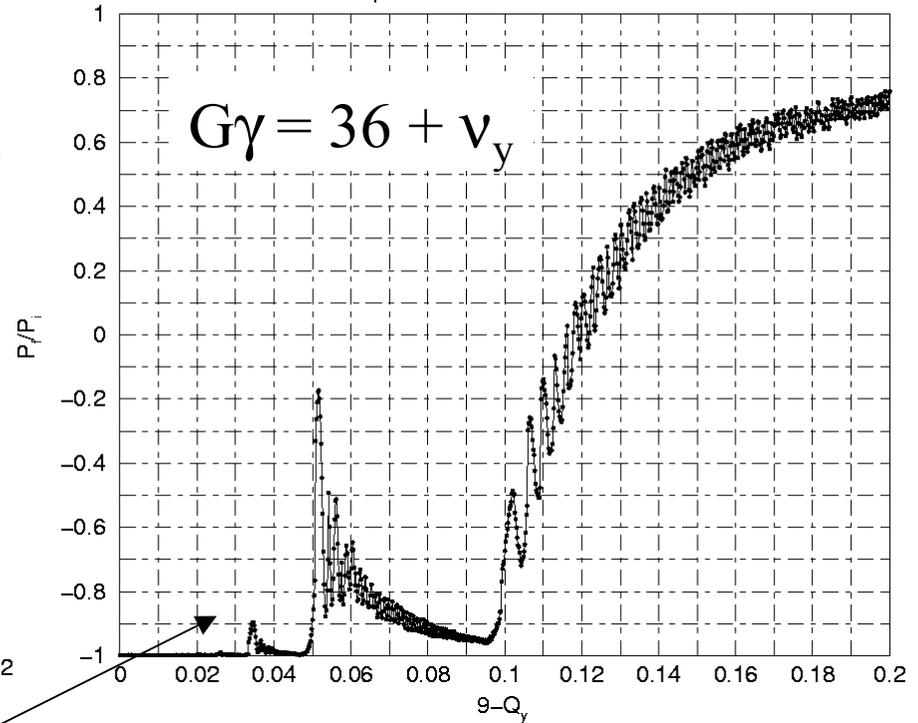


Modeling of AGS resonances with 20% Snake

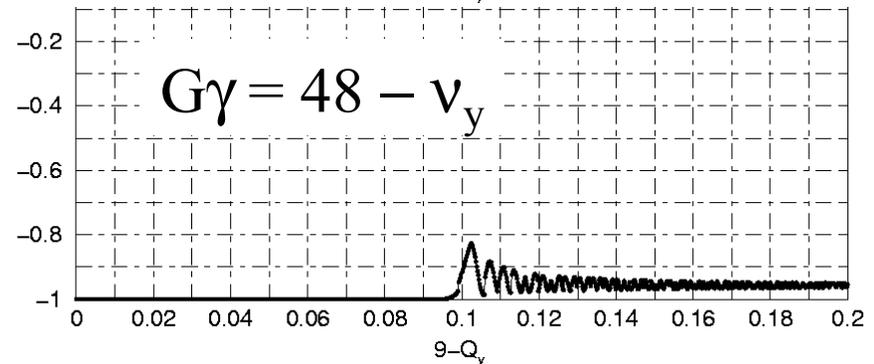
$G\gamma=0+v$, $\varepsilon=0.0067$
64 pts w. 10π mm-mrad emittance



$G\gamma=36+v$, $\varepsilon=0.011$
64 pts w. 10π mm-mrad emittance



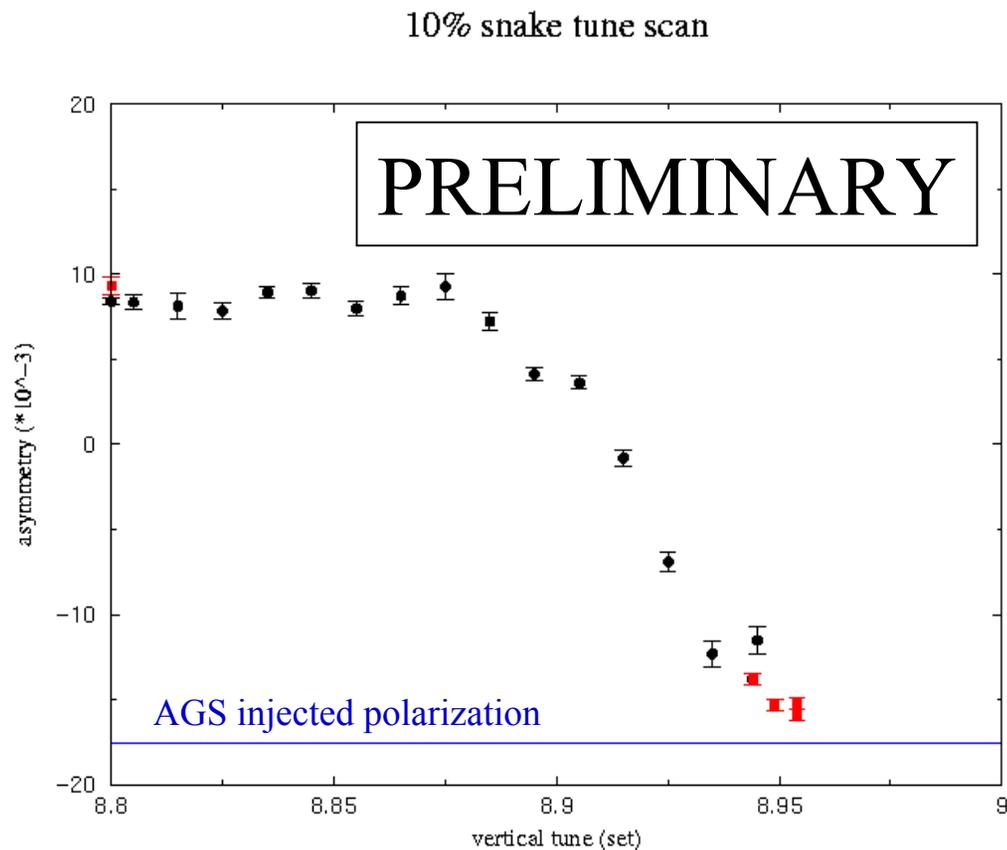
“Partial Snake Resonances”
if $v_{sp} = n v_y$



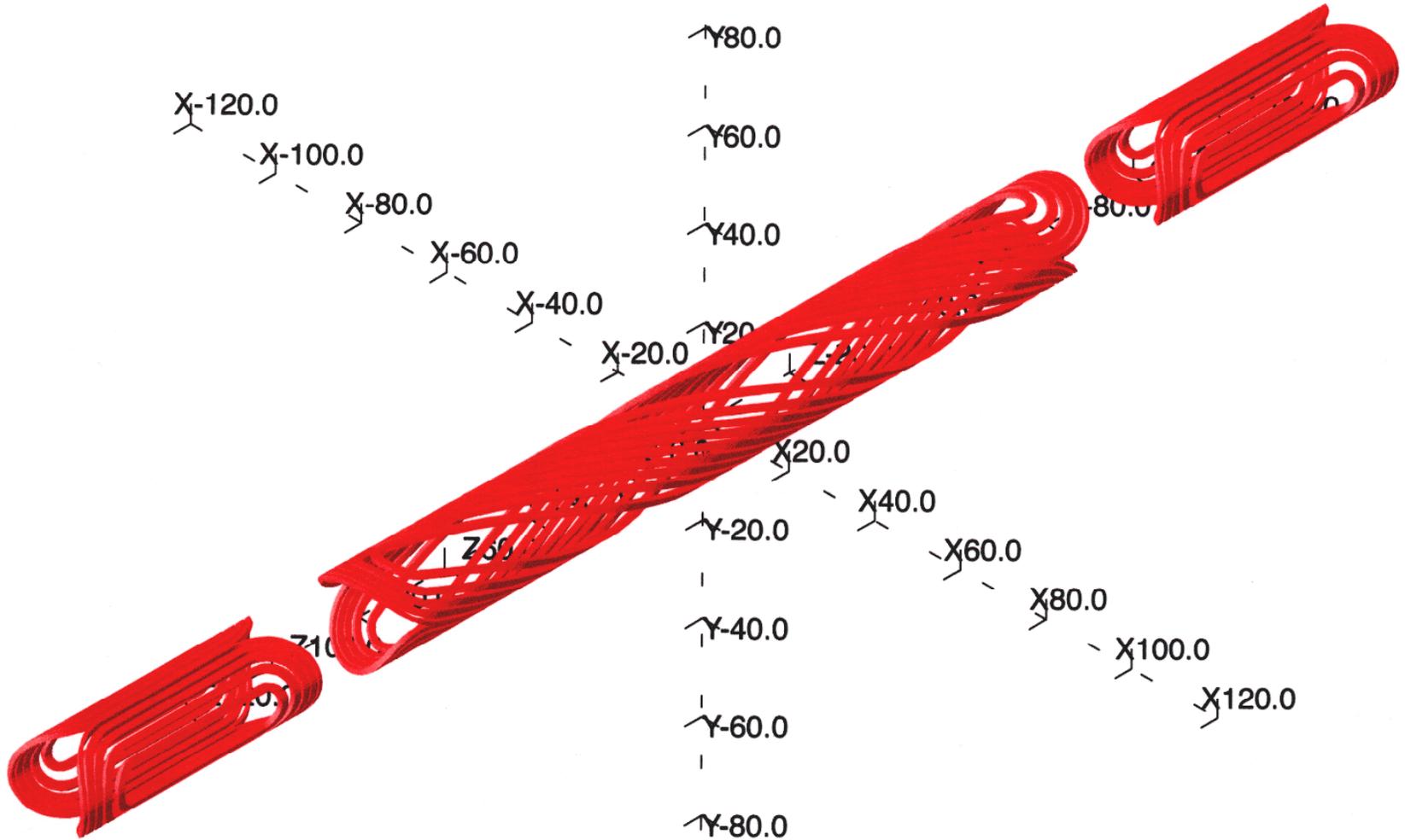
Test results with 10% snake at 0 + ν

The difference between the red measurements and blue line is due to the coupling resonance and tilted stable spin direction.

Excellent agreement with model.



AGS super conducting helical snake (coils)

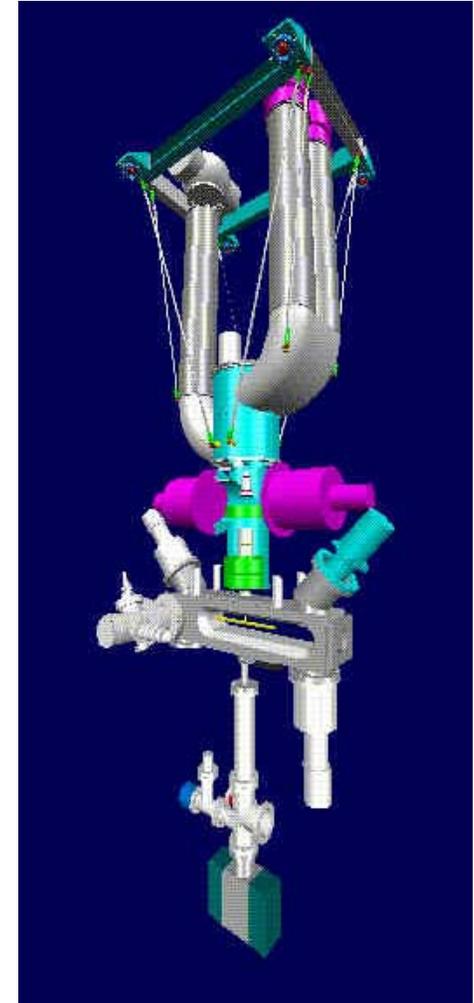


Polarized Hydrogen Jet Target

- pC polarimeter is used as fast relative polarization monitor and was calibrated in AGS at 22 GeV to about 15 %.
- Polarized hydrogen jet target allows for absolute beam polarization measurement:

$$P_{\text{Beam}} = P_{\text{Target}} \frac{N_{B\uparrow T\uparrow} - N_{B\downarrow T\downarrow} + N_{B\uparrow T\downarrow} - N_{B\downarrow T\uparrow}}{N_{B\uparrow T\uparrow} - N_{B\downarrow T\downarrow} - N_{B\uparrow T\downarrow} + N_{B\downarrow T\uparrow}}$$

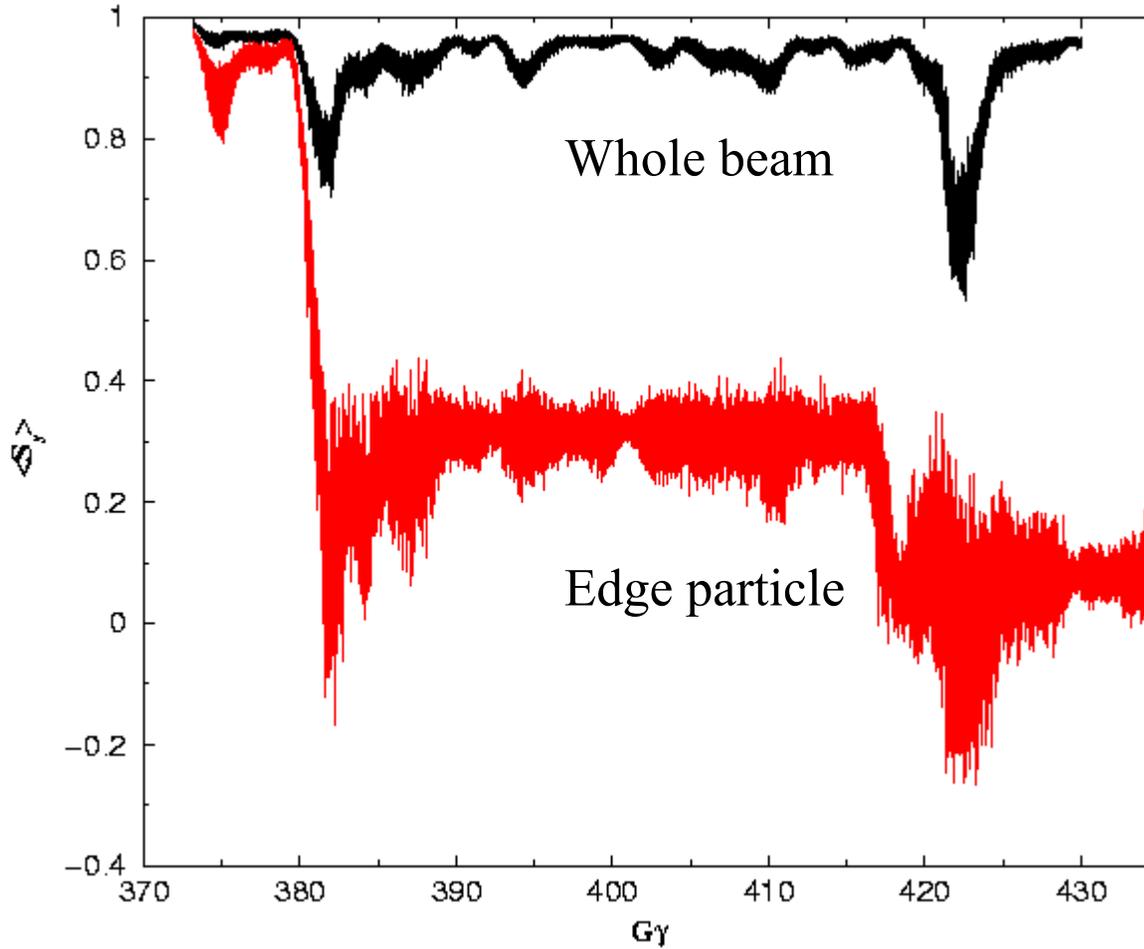
- Jet target thickness of $3 \times 10^{11} \text{ cm}^{-2}$ achievable (HERMES, PINTEX, NIKHEF)
- Jet polarization measurable to better than 3% using Stern-Gerlach method
- Collaboration started with Wisconsin, IUCF, and Amsterdam



Summary

- Very successful first RHIC spin commissioning and short data run
- 100 GeV on 100 GeV polarized proton collisions with $\sim 25\%$ polarization
- RHIC Polarimeters commissioned and work reliably from injection to 100 GeV
- Collisions of polarized protons at 500 GeV possible during FY2003

Spintracking trough strongest RHIC resonance



- Two Siberian snakes
- 1 mm rms misalignment (Survey: < 0.5 mm)
- 0.2 mm rms closed orbit
- $20 \pi \mu\text{m}$ emittance (95%)
($\sim 10 \pi \mu\text{m}$ in RUN2000)

Next Run

Higher energy-> stronger resonances

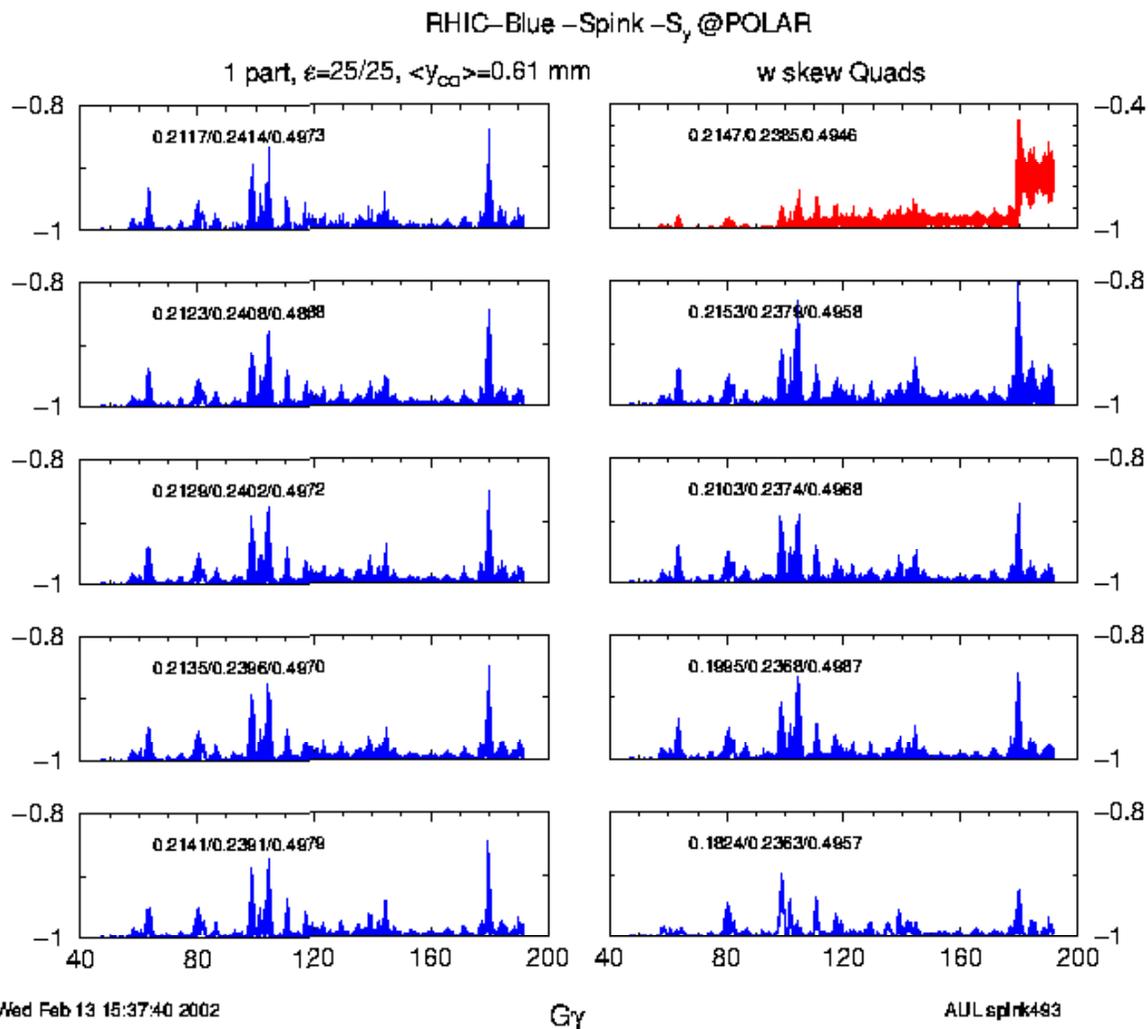
The goal orbit needs to be revisited

- Newly measured misalignment data
- Analysis of the corrector strengths
- Coupling and dynamic aperture from the ideal orbit going off center in quads and sextupoles.

Better beam control on the ramp would be necessary

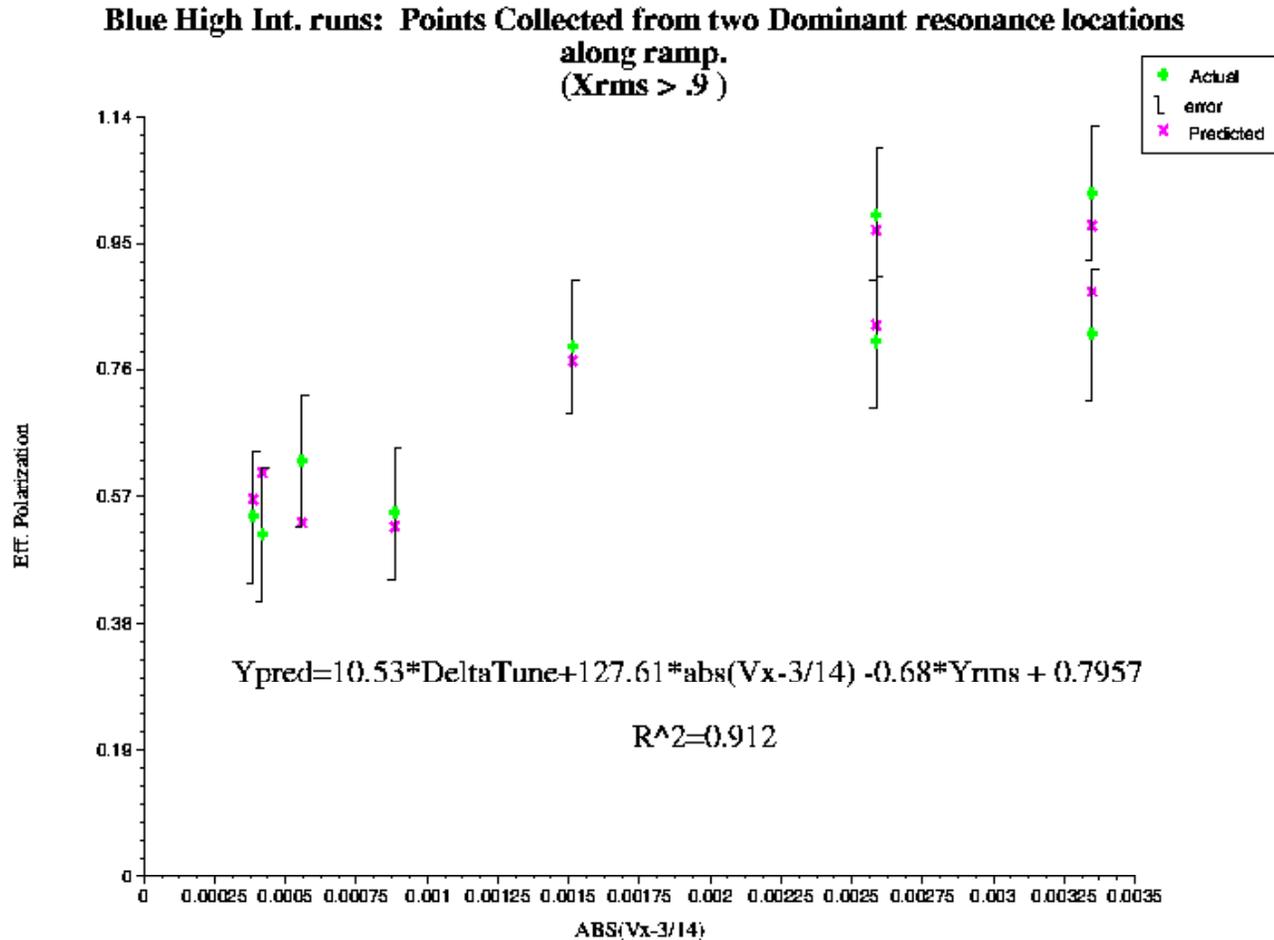
- Tune feedback
- Improved orbit correction (below 0.4mm rms)
- Coupling control on the ramps

SPINK modeling of 3/14 resonance in the presence of betatron coupling



Blue data for the 3/14 resonance

The resonance was not so pronounced as in Yellow



Spin matching at injection and extraction

Stable Spin Direction (SSD) in AGS is tilted away from vertical due to a strong snake. We have to match the injected and extracted beam stable spin direction to avoid polarization loss.

Injection:

1. one possibility is to raise the injection energy to get $G\gamma$ from 4.7 to 5 (2.27 GeV/c to 2.44 GeV/c) and run the Booster vertical tune at 5.1 (in the past it was set at 4.9). Then the SSD is in horizontal plane in both Booster and AGS. A proper choice of 5th harmonic corrector setting of the Booster can match the SSD in the Booster to the SSD in AGS.
2. Use the current solenoid snake in the BtA line as a spin rotator. But it needs a lot space.

Extraction:

There are many ways to manipulate SSD in RHIC (snakes, spin rotators). It is less a problem.

Design of the snake

The snake is going to be a super-conducting full helical dipole magnet.

The available space in the AGS is 2.6 meter long. Two bending dipole magnets on both sides of the helical snake.

2-layer design with 400A to reach 4T.

Beam pipe is 6" by 6" (15cm by 15cm).

1.36 meter long and operation field is 3.28T(30% at injection).

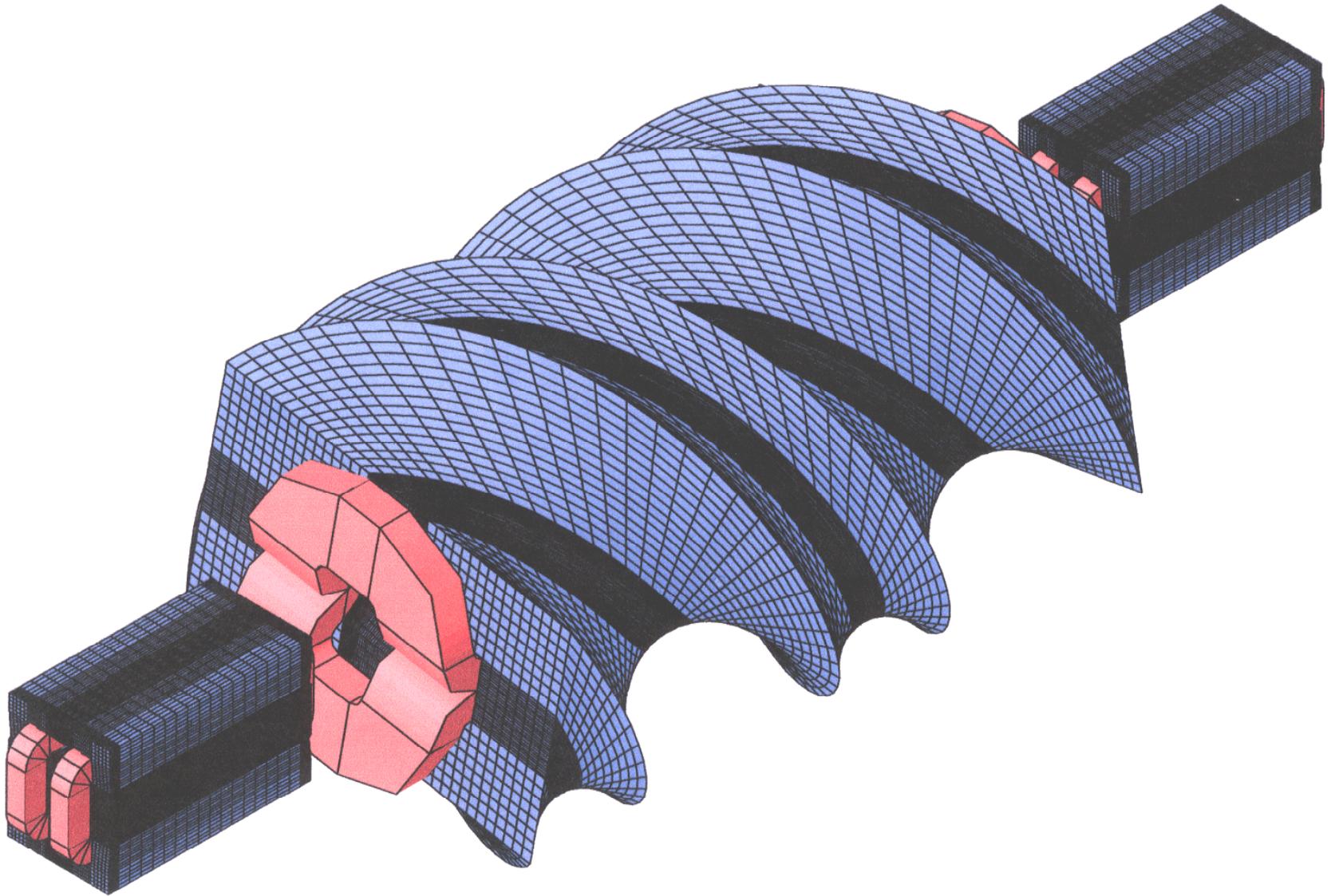
Cryogenic design: try to reach 1w heat load. But as long as the heat load is below 5w, then the cryo dewar can be filled once/day (without ring access).

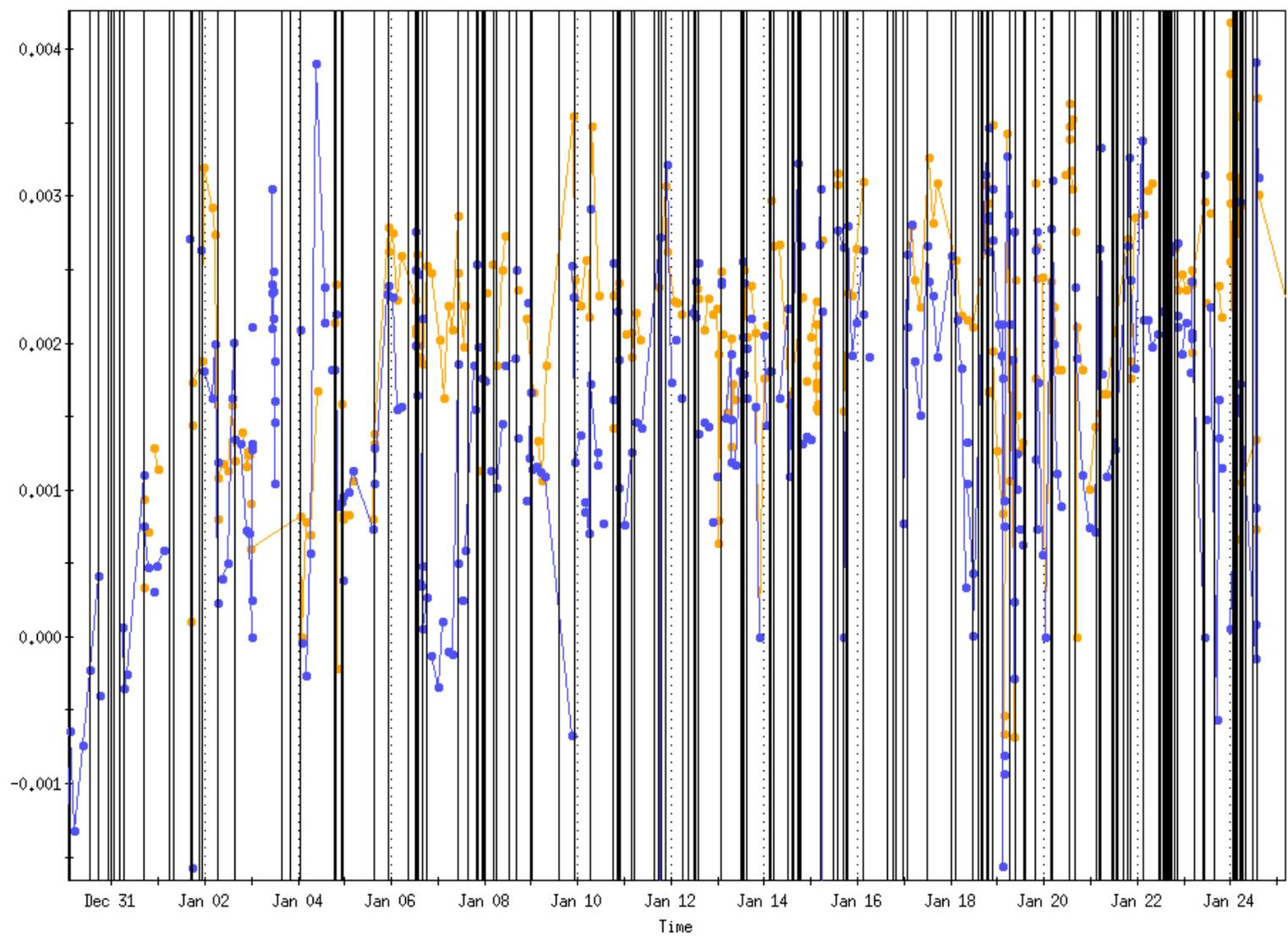
Coupling at injection is still significant due to sextupole field feed down. The design goal is to have no sextupole field along the beam trajectory by adding compensation coils.

AGS super conducting helical snake

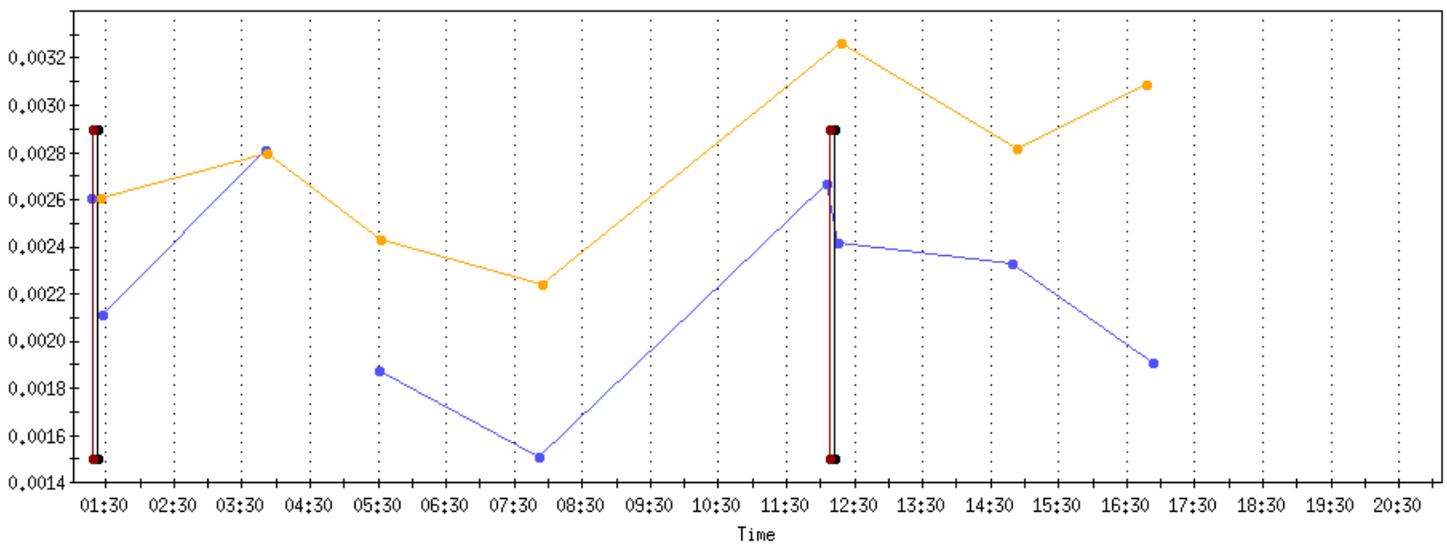
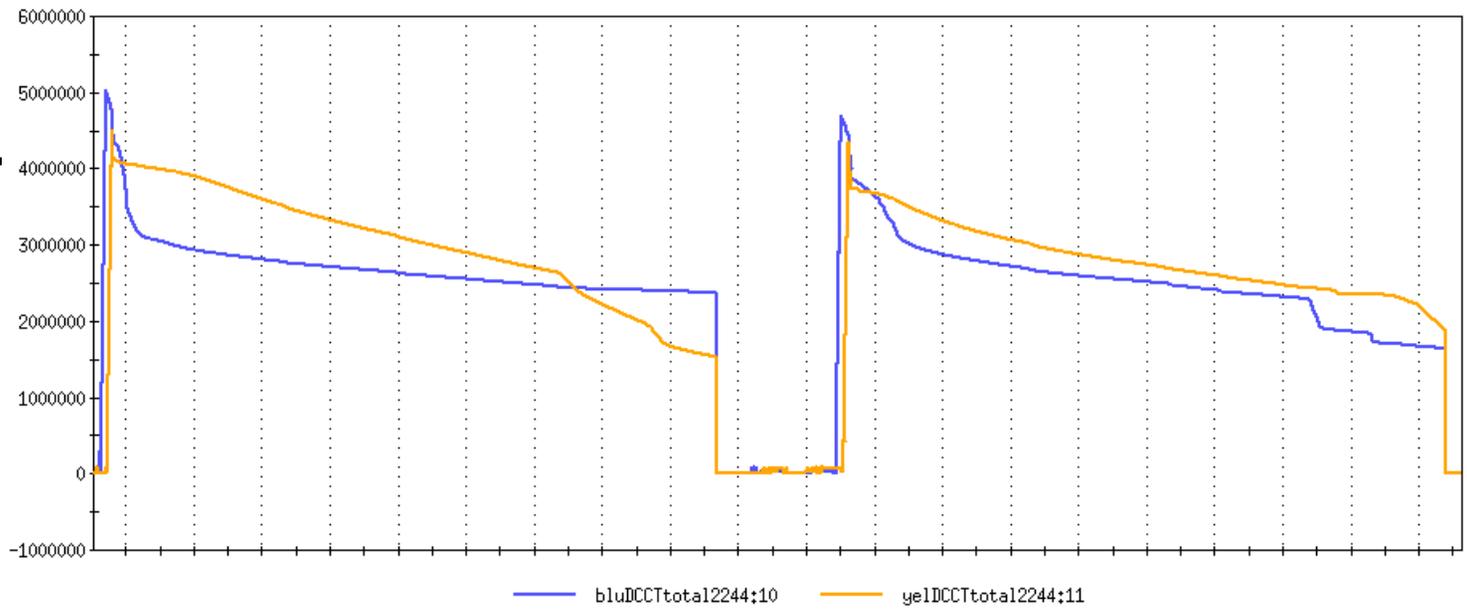


AGS normal conducting 5% helical snake





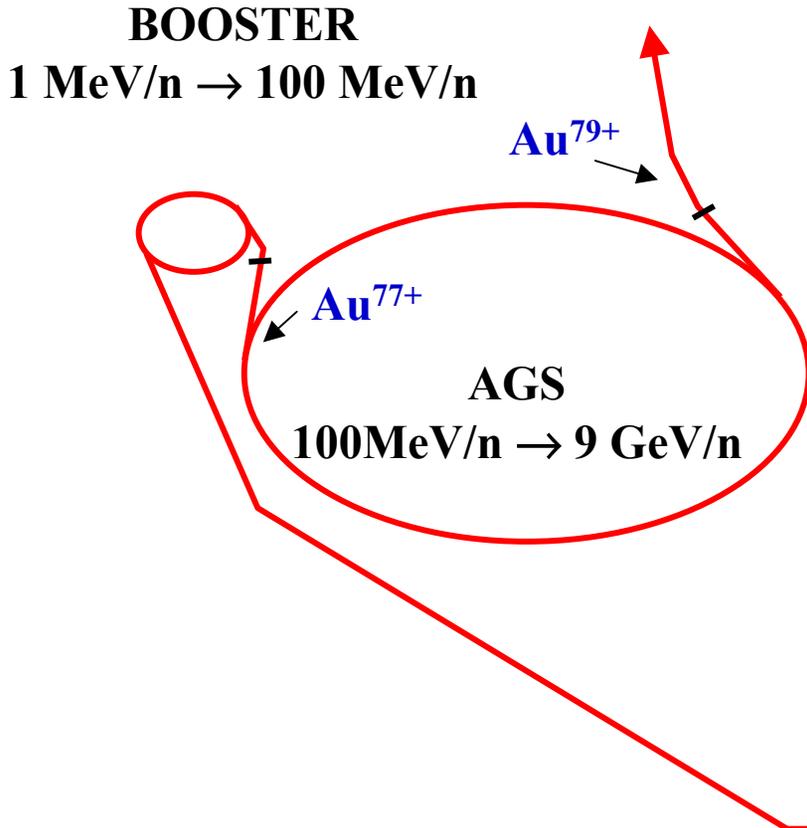
—●— polarimeter.yel:avgAsymXS:value2127:4
 —●— polarimeter.blu:avgAsymXS:value2114:5
 —●— ev-flattop



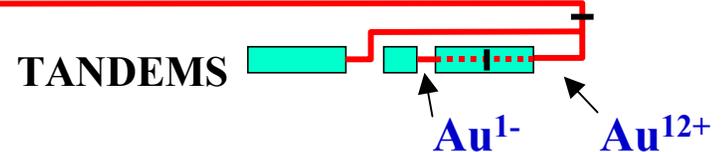
FY2001 - 02 RHIC Gold Parameters

- **55 - 56 bunches** per ring ✓ (110 bunches per ring tested, intensity limited)
- **7.5×10^8 Au/bunch @ storage energy** (intensity limited during acceleration)
- **1×10^9 Au/bunch achieved @ injection** ✓
- **Longitudinal emittance:** 0.5 eVs/nucleon/bunch (0.3-0.6 Design) ✓
- **Transverse emittance at storage:** $15 \pi \mu\text{m}$ (norm, 95%) ✓
- **Storage energy:** 100 GeV/ amu ($\gamma = 107.4$) ✓ 10 GeV / amu ($\gamma=10.5$) ✓
- **Lattice with β^* squeeze during acceleration ramp:**
 - $\beta^* = 3 \text{ m}$ and 10m @ all IP at injection ✓
 - $\beta^* = 1 \text{ m}$ @ 8 and 2 m @ 2, 6 and 10 o'clock at storage ✓
- **Peak Luminosity:** $5 \times 10^{26} \text{ cm}^{-2} \text{ s}^{-1}$ ($2.5 \times$ design average) ✓
- **Bunch length:** 5ns (200 Mhz operational, diamond length: $\sigma = 20 \text{ cm}$) ✓

Au Injector Performance (needs update)



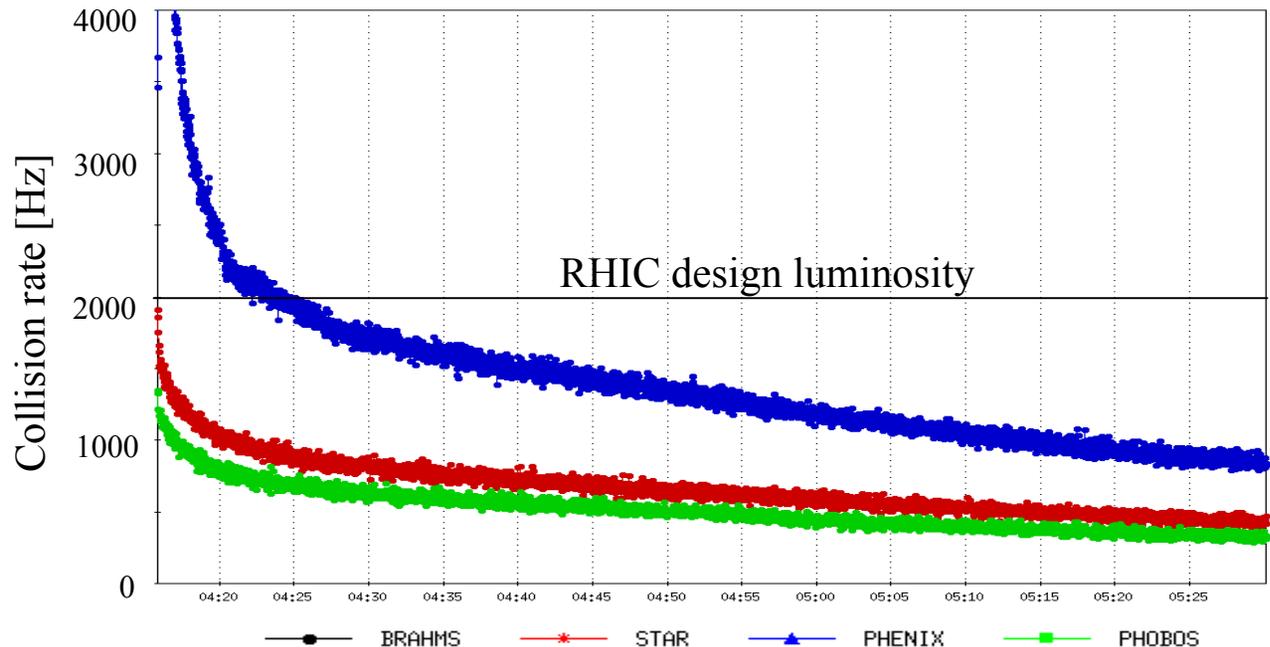
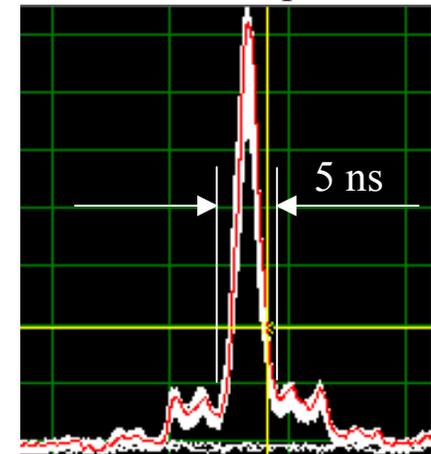
	<u>Intensity/RHIC bunch</u>	<u>Efficiency[%]</u>
Tandem	$5.4(3.8) \times 10^9$	
Booster Inj.	$2.9(2.2) \times 10^9$	54 (58)
Booster Extr.	$2.4(1.8) \times 10^9$	83 (81)
AGS Inj.	$1.2(0.9) \times 10^9$	50 (50)
AGS Extr.	$1.1(0.9) \times 10^9$	<u>92 (95)</u>
Total		20 (23)



RHIC performance

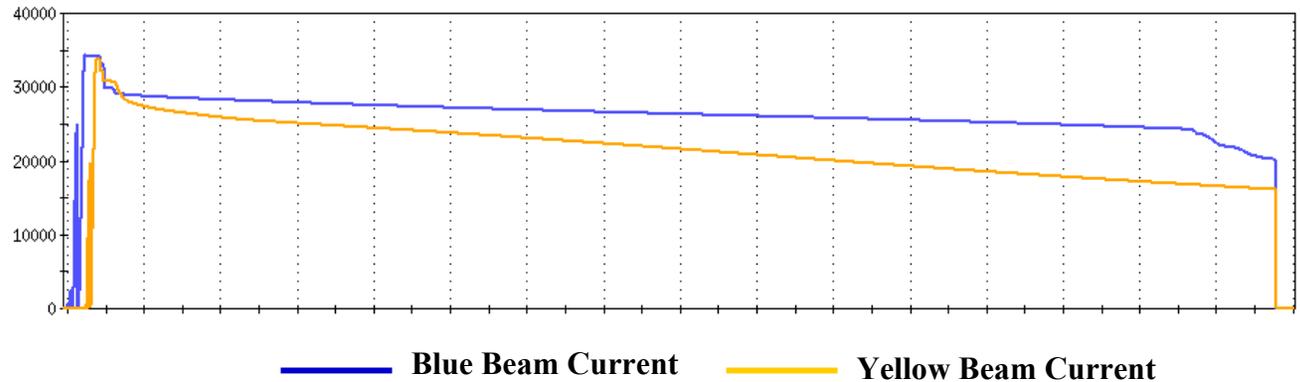
- Collisions at RHIC design beam energy (100 GeV/nucl)
- 200 MHz rf system operational
 - 5 ns bunch length and an interaction region with $\sigma \sim 25$ cm
- Luminosity exceeding RHIC design luminosity of $2 \times 10^{26} \text{ cm}^{-2} \text{ s}^{-1}$
- 40% availability is limiting total integrated luminosity

RHIC bunch profile

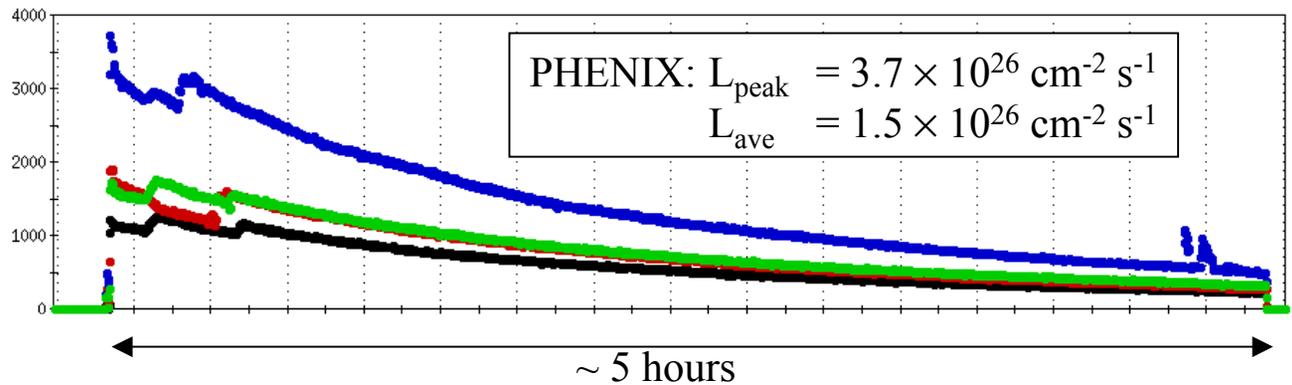


“Typical Store” # 1812

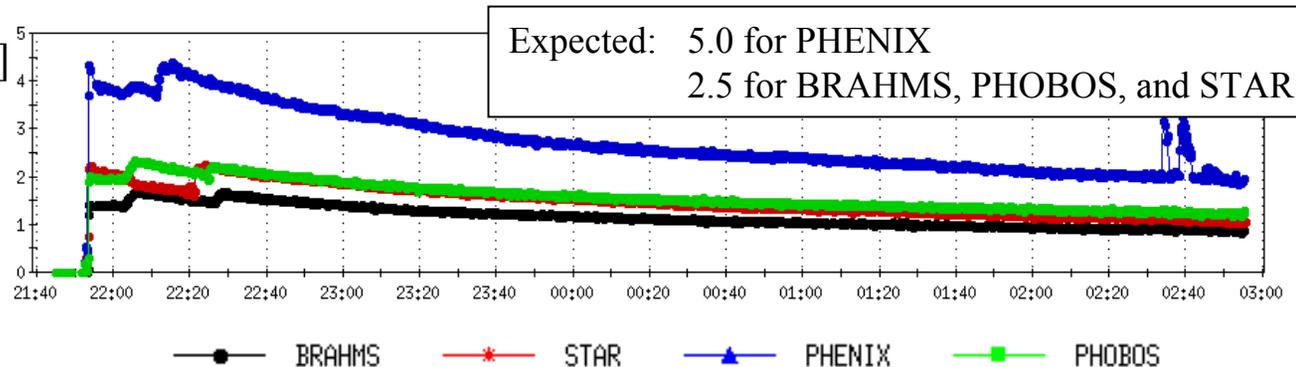
Beam currents [$\times 10^6$ ions]



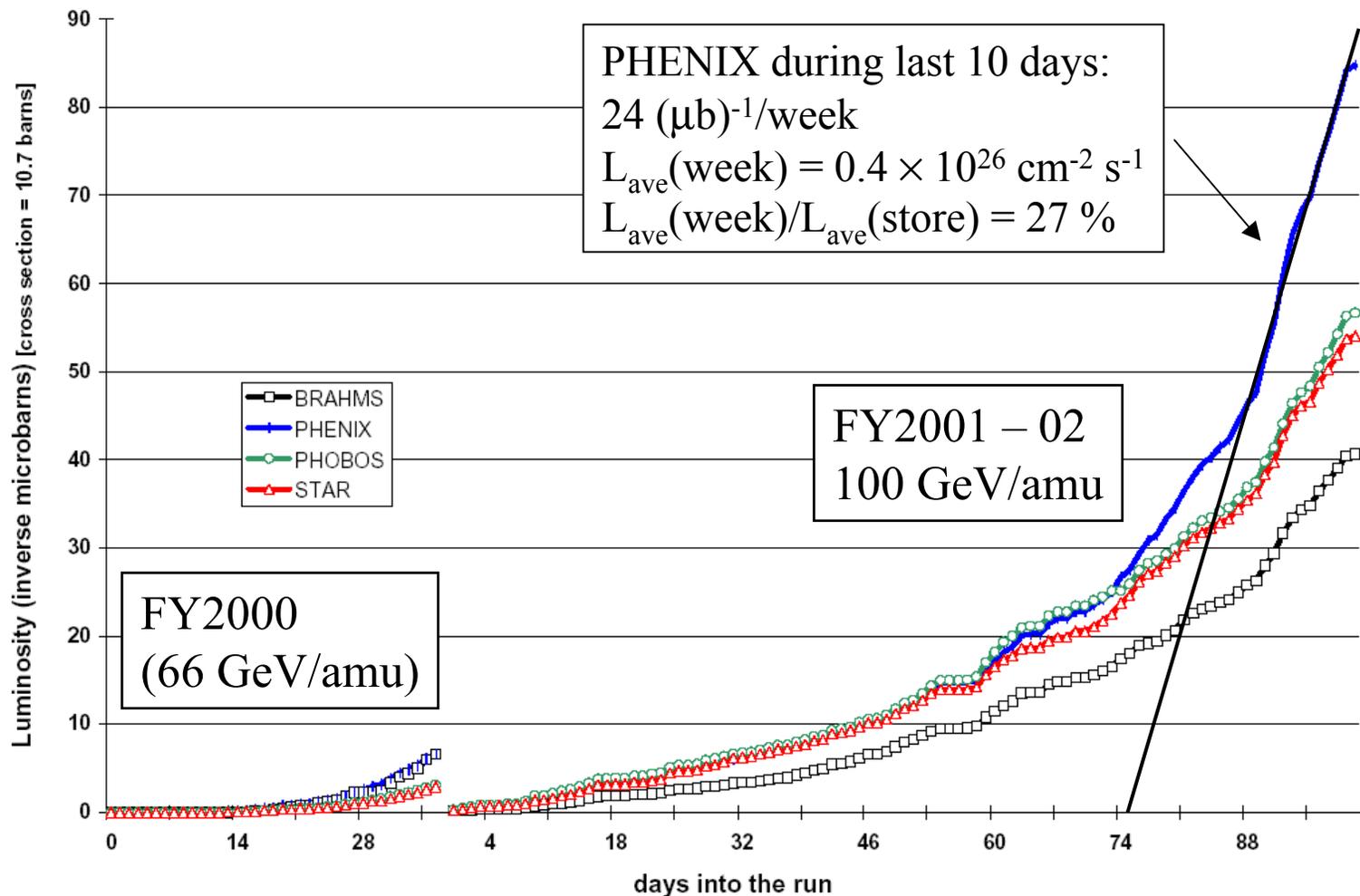
Collision rate [Hz]



Specific luminosity [$\text{Hz}/10^{18}$]

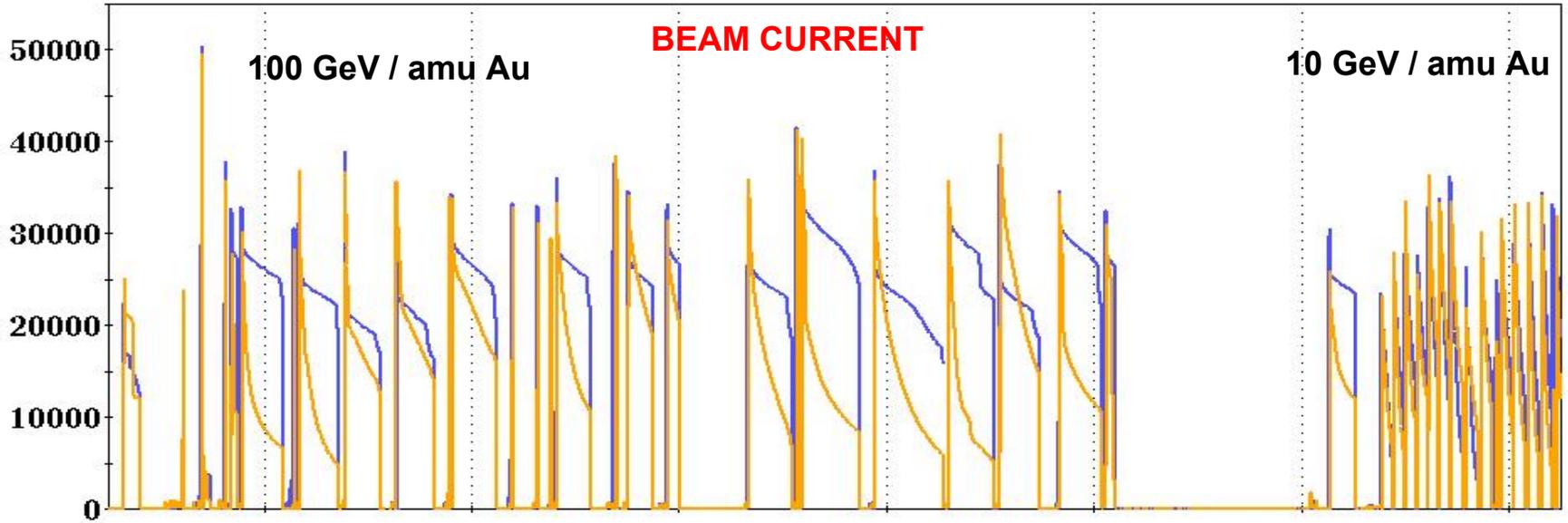


Integrated Au-Au luminosity



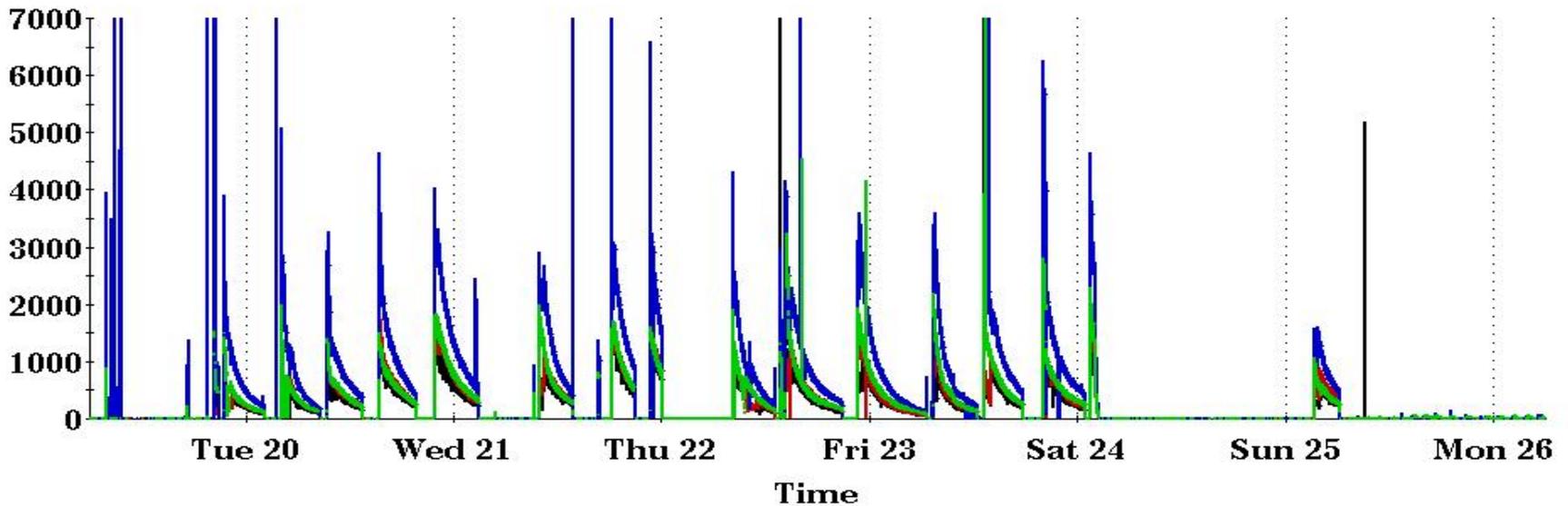
RHIC PERFORMANCE

$\times 10^6$ Au



$\times 10^{23}$ cm⁻² sec⁻¹

LUMINOSITY



RUN2003 Goals (~ 3-4 weeks into run)

- Prepare for four modes; all with:

Energy/beam: 100 GeV/nucleon, diamond length: $\sigma = 20$ cm, $L_{\text{ave}}(\text{week})/L_{\text{ave}}(\text{store}) = 40$ %

Mode	# bunches	Ions/bunch [$\times 10^9$]	β^* [m]	Emittance [$\pi\mu\text{m}$]	L_{peak} [$\text{cm}^{-2}\text{s}^{-1}$]	$L_{\text{ave}}(\text{store})$ [$\text{cm}^{-2}\text{s}^{-1}$]	$L_{\text{ave}}(\text{week})$ [week^{-1}]
Au-Au	56	1	1	15-40	14×10^{26}	3×10^{26}	$70 (\mu\text{b})^{-1}$
$(p\uparrow-p\downarrow)^*$	112	100	1	25	16×10^{30}	10×10^{30}	$2.8(\text{pb})^{-1}$
d-Au	56	100(d), 1(Au)	2	20	5×10^{28}	2×10^{28}	$5 (\text{nb})^{-1}$
Si-Si	56	7	1	20	5×10^{28}	2×10^{28}	$5 (\text{nb})^{-1}$

* Beam polarization ≥ 50 %; Acceleration test to 250 GeV

- New hardware installed and to be commissioned:
 - All eight spin rotators for PHENIX and STAR

RUN2003 Integrated Luminosity Estimate

Estimate for integrated luminosity for 29 week FY2003 run (starting October 1, 2002):

- 4 weeks cool down, 1 week warm-up, 2 weeks setup (for each mode),
3 weeks ramp up (for each mode): →
29 weeks of cryo ops.: 2 modes: 7 weeks at “final” luminosity / mode
 3 modes: 3 weeks at “final” luminosity / mode
 4 modes: 1 week at “final” luminosity / mode
- Minimum: performance at end of FY2001/02 run
- Maximum: luminosities from previous slide

Mode	L_{ave} (week) [week ⁻¹]	Int. Lumi. 2 modes	Int. Lumi. 3 modes	L_{ave} (week) [week ⁻¹]	Int. Lumi. 2 modes	Int. Lumi. 3 modes
Au-Au	24(μb) ⁻¹	168(μb) ⁻¹	72(μb) ⁻¹	70 (μb) ⁻¹	490(μb) ⁻¹	210(μb) ⁻¹
(p↑-p↑)*	0.3(pb) ⁻¹	2.1(pb) ⁻¹	0.9(pb) ⁻¹	2.8(pb) ⁻¹	19.6(pb) ⁻¹	8.4(pb) ⁻¹
d-Au	?	?	?	5 (nb) ⁻¹	35 (nb) ⁻¹	15 (nb) ⁻¹
Si-Si	?	?	?	5 (nb) ⁻¹	35 (nb) ⁻¹	15 (nb) ⁻¹