Improvements in the RHIC Polarized Proton Operation

Haixin Huang

March 28, 2011
PAC11
Spin Dynamics

- Spin precession in a planar circular accelerator [in the lab frame]
  \[ \frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = -\frac{e}{\gamma m} [G\gamma \vec{B}_\perp + (1 + G)\vec{B}_\parallel] \times \vec{S} \]

- Orbital motion
  \[ \frac{d\vec{P}}{dt} = \vec{\Omega}_{rev} \times \vec{P} = -\frac{e}{\gamma m} [\vec{B}_\perp] \times \vec{P} \]

- Spin tune
  \[ \nu_s = \frac{\Omega}{f_{rev}} = G\gamma \]

G is anomalous magnetic moment, G=1.793 for protons

In the frame which moves with the particle
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
**Depolarizing 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 Resonances**

- arising from sampling of error fields, fields due to closed orbit errors, etc.
- \( G_\gamma = n \) (integer)

**Intrinsic Resonances**

- arise from sampling of focusing fields due to finite beam emittance.
- \( G_\gamma = kP \pm \nu_y \)
  - \( P \): Superperiodicity [RHIC: 3]
  - \( \nu_y \): Vertical betatron tune [RHIC: \( \sim 29.675 \)]

**Horizontal Intrinsic Resonances**

1. horizontal non-vertical stable spin direction due to strong partial snake interaction with horizontal motion.
2. betatron motion coupled to the vertical betatron motion by coupling elements: solenoid, helical magnet.

- \( \nu_s = k \pm \nu_x \)

**Snake Resonances**

- \( \nu_{sp} = k \pm n\nu_y \)
  - \( n \): integer [snake resonance order]
  - \( \nu_y \): Vertical betatron tune [RHIC: \( \sim 29.675 \)]
Vertical Intrinsic Resonance Spectrum in RHIC

Intrinsic resonance strengths, protons in RHIC

Emittance 10.0 pi

Resonance strength

Gamma

0.0 0.1 0.2 0.3 0.4

0 50 100 150 200 250

Haixin Huang
RHIC – First Polarized Hadron Collider

Absolute Polarimeter (H↑ jet)

pC Polarimeters

Spin flipper

Siberian Snakes

Spin Rotators (longitudinal polarization)

PHENIX

STAR

Spin Rotators (long. pol.)

Siberian Snakes

Pol. H⁻ Source

200 MeV Polarimeter

10-25% Helical Partial Siberian Snake

5.9% Helical Partial Siberian Snake

Int. Polarimeter

pC Polarimeter

10-25% Helical Partial Siberian Snake
pC Scattering – the RHIC Polarimeters

Ultra thin Carbon ribbon Target
(3.5 $\mu$g/cm$^2$, 5 $\mu$m wide)

Si strip detectors
(ToF, $E_C$)

Two polarimeters in each ring, which can provide polarization and beam profiles information quickly.
Polarized Protons in the AGS

- Two strong partial Siberian snakes
- Vertical betatron tune at 8.98
- Pulsed quadrupoles to jump across the many weak horizontal spin resonances driven by the partial snakes.

Spin reverses at every spin resonance with partial snakes.

\[ n + \nu_x \]
\[ n + \nu_y \]
\[ n - \nu_x \]
\[ \nu_{sp} \]
\[ n - \nu_y \]

5  16  23  GeV
RHIC Polarization Transmission to 250GeV

• The relative gain of polarization by moving $Q_y$ from .68 to .675 is 1.12. The close orbit error reduction gives additional gain.
Betatron Tune on the Ramp
Spin Tune Shift due to the Horizontal Orbit Angle in Snakes

The spin tune shift due to horizontal orbit angles in Snakes and rotators:

\[ \delta Q_{sp} = \frac{1 + G \gamma}{2\pi} \left( 2\alpha_{sn} + \alpha_{rt\_ip6} + \alpha_{rt\_ip8} \right) \]

\[ \alpha_{sn} = x'_{co\_sn9} - x'_{co\_sn3} \]

\[ \alpha_{rt\_ip} = x'_{co\_rt\_left} - x'_{co\_rt\_right} \]

At 250 GeV:

<table>
<thead>
<tr>
<th>Orbit angle error, mrad</th>
<th>( \delta Q_{sp}, 10^{-3} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snakes</td>
<td>0.1</td>
</tr>
<tr>
<td>Rotator (in one IR)</td>
<td>0.1</td>
</tr>
</tbody>
</table>

On the acceleration ramp (the rotators are off) only \( \alpha_{sn} \) contributes.

• The variation of snake angles on the (last half of) ramp was maintained within established tolerances during the Run-9:
  7/10 resonance shift \(< \pm 0.001\) \(\Rightarrow\) \(\delta Q_{sp} < \pm 0.005\) \(\Rightarrow\) \(\alpha_{sn} < \pm 30\ \mu\text{rad}\)
Snake Angle Difference: run11 vs. run9

Sun Apr 5 03:45:59 2009 - Mon Feb 14 10:19:33 2011

Window Markers Analysis

Adding ramp event markers...

Snake angle (micro rad)
The simulations established the tolerance on vertical closed orbit rms at 0.3 mm, or $|\varepsilon_{\text{imp}}| < 0.07$.
Spin Tune Shift Caused by Imperfection Resonances

\[ |\Delta Q_s| \leq \frac{1}{\pi} \arcsin \left[ \sin^2 \left( \frac{\pi \epsilon_{\text{imp}}}{2} \right) \right] \quad \text{where } \epsilon_{\text{imp}} \text{ is the resonance strength} \]

The problem with reversed BPM offsets was found during Run10. Reversed offsets led to closed vertical orbit rms ~1 mm and the maximum imperfection resonance strength exceeding 0.1.

Corresponding spin tune shift along the acceleration ramp:

Above 100 GeV the spin tune shifts are considerable (>0.02 in Blue ring). Corresponding 7/10 resonance shift up to 0.004-0.005.
The realignment of the whole ring is done before run 11.
Orbit Statistics on the Ramp

![Graph showing orbit statistics over time.](image-url)
Motivation for 9 MHz

- Short bunches during the ramp result in lower luminosity because of:
  - Transverse emittance growth
  - Instability
- The objective is to have long bunches on the ramp and short bunches during store
- 9 MHz makes long bunches without the emittance blowup
- At store (250 GeV)
  - Emittance preservation
  - Adiabatic damping
  - Rebucketing into 197 MHz

At Store

- 0.66 eVs
- 250 GeV
- 300 kV, 28 MHz
Bunch Shape after 9MHz and 28MHz Ramps

Horizontal axis is in ns
Ramp efficiency in Run9 and Run11

Run11, mostly with 9MHz

Run9, with 28MHz
Benefit of 10Hz Feedback on Luminosity

Purpose: Stabilize beams against “natural” orbit oscillations at ~ 10 Hz. It also reduced backgrounds for experiment detectors.
## RHIC Polarized Proton Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy at injection</td>
<td>24.3</td>
<td>GeV/u</td>
</tr>
<tr>
<td>Energy at Store</td>
<td>250</td>
<td>GeV/c</td>
</tr>
<tr>
<td>Interaction points</td>
<td>6 8 10 12 2 4</td>
<td>clock</td>
</tr>
<tr>
<td>$\beta^*$ at injection</td>
<td>7.5 7.5 7.5 7.5 7.5 7.5</td>
<td>m</td>
</tr>
<tr>
<td>$\beta^*$ at store</td>
<td>.65 .65 7.5 7.5 3 7.5</td>
<td>m</td>
</tr>
<tr>
<td>Working points</td>
<td>ramp: (28.685, 28.675)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Store: (28.69, 29.68)</td>
<td></td>
</tr>
<tr>
<td>Snakes current</td>
<td>DC</td>
<td></td>
</tr>
<tr>
<td>Spin rotator current</td>
<td>Ramp up after energy ramp</td>
<td></td>
</tr>
<tr>
<td>Polarization at store</td>
<td>&gt;45%</td>
<td></td>
</tr>
<tr>
<td>Peak bunch intensity</td>
<td>$1.4 \times 10^{11}$</td>
<td></td>
</tr>
<tr>
<td>Peak luminosity</td>
<td>$10^{32}$</td>
<td>cm$^{-2}$s$^{-1}$</td>
</tr>
</tbody>
</table>
Polarization and Luminosity in a Store

![Graph showing polarization and luminosity over time](image)

- **ZDC coincidence rate [kHz]**
- **Polarization (%)**

- **Time since beginning of ramp (secc)**

Legend:
- **STAR ZDC**
- **PHENIX ZDC**
- **Blue Polarization**
- **Yellow Polarization**
Summary

• The higher polarization during this run comes from several improvements:
  • Much better orbit this run: vertical realignment; excellent orbit control on the ramp; BPM offset sign reversal.
  • Vertical tune moved further away from snake resonance 7/10. This is only possible with precise control of betatron tune.
  • High polarization out of AGS due to tune jump system.
  • Higher luminosity is achieved with better ramp efficiency after introducing 9MHz cavity.

• Remaining Tasks:
  • Understand any polarization loss scheme;
  • Careful setup jump quads in the AGS to get full benefit;
  • Control emittance through the whole accelerator chain;
  • Introduce electron lenses to compensate beam-beam effect.