RHIC Spin Flipper

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Outline

- Introduction
  - Spin dynamics
  - How to flip spin

- RHIC spin Flipper

- Summary
Thomas-BMT Equation

\[ \frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = -\frac{e}{\gamma m} [(1 + G\gamma)\vec{B}_\perp + (1 + G)\vec{B}_\parallel] \times \vec{S} \]

Spin vector in particle’s rest frame

- \( G \) is the anomalous \( g \)-factor, for proton, \( G = 1.7928474 \)
- \( \gamma \): Lorenz factor

Magnetic field along the direction of the particle’s velocity

Magnetic field perpendicular to the particle’s velocity
Spin Motion in a Circular Accelerator

- In a perfect accelerator, spin vector precesses around its guiding field along the vertical direction.

- Spin tune $Q_s$: number of precessions in one orbital revolution. In general,

$$Q_s = G \gamma$$
Spin Resonance

- horizontal field kicks the spin vector away from its vertical direction, and can lead to polarization loss.

\[ Q_s = \text{tune of the kick on the spin} \]
Spin Resonance Crossing

- **Frossart-Stora formula**

\[
P_f = P_i \left( 2e^{-\frac{\pi |\varepsilon|^2}{\alpha}} - 1 \right)
\]

\(\varepsilon\) is the strength of the resonance.

\(\alpha\) is the speed of resonance crossing

- **When an resonance is crossed slowly, i.e.**

\[
\frac{\pi |\varepsilon|^2}{\alpha} \gg 1 \quad P_f = -P_i
\]
How to excite an isolated resonance

- A rotating field
How to excite an isolated resonance

- A rotating field

\[
\frac{d\vec{S}}{d\theta} = \vec{S} \times \left[ G\gamma \hat{y} + \phi_{\text{rot}} \left( x\cos Q_{sf}\theta + \hat{z}\sin Q_{sf}\theta \right) \right]
\]

\[
\frac{d\vec{\psi}}{d\theta} = -\frac{i}{2} \left[ G\gamma \sigma_3 + \phi_{\text{rot}} \sigma_1 e^{i\sigma_3 Q_{sp}\theta} \right] \vec{\psi}(\theta)
\]

\[
\vec{\psi} = \begin{pmatrix} u \\ d \end{pmatrix}; \quad S_i = \langle \sigma_i | \vec{\psi} | \sigma_i \rangle;
\]

\[
\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_1 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_1 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}
\]

\[
M_{\text{rot}} = e^{-\frac{i}{2} \phi_{\text{rot}} \left( \cos Q_{sf}\theta \sigma_1 + \sin Q_{sf}\theta \sigma_2 \right)}
\]

2x2 spin transfer map of rotating field
Traditional spin flipping technique: single ac dipole

- Adiabatically crossing an artificial spin resonance induced by an ac dipole.
- This technique has been demonstrated in the Brookhaven AGS, IUCF Cooler Ring as well as the Cozy 3 GeV storage ring

\[
\frac{d\tilde{S}}{d\theta} = \tilde{S} \times \left[ G \gamma \hat{y} + (1 + G \gamma) \frac{\Delta BL}{B \rho} (\hat{x} \cos Q_{sf} \theta) \right]
\]

\[
\frac{d\tilde{\psi}}{d\theta} = -\frac{i}{2} \left[ G \gamma \sigma_3 + (1 + G \gamma) \frac{\Delta BL}{B \rho} \sigma_1 (e^{i\sigma_3 Q_{sp} \theta} + e^{-i\sigma_3 Q_{sp} \theta}) \frac{1}{2} \right] \tilde{\psi}(\theta)
\]
Pros and Cons of single ac dipole excitation

- It is simple

- This technique excites not only an resonance at $Q_{sf}$ but Also an resonance at $-Q_{sf}$. Hence, the condition of adiabatic resonance crossing is broken when the beam spin precession tune is at or close to $\frac{1}{2}$, and one can not achieve full spin flipping.
Spin tracking with single ac dipole

Spin tune 0.5, ac dipole tune sweeps from 0.49 to 0.51

Spin tune 0.47, ac dipole tune sweeps from 0.46 to 0.48
Spin flipper for RHIC

- It is critical for the single ac dipole technique to have spin precession tune stay away from 1/2 requires to detune the snake settings. This requirement makes the single ac dipole technique very difficult to be an operational tool to realize routine spin flipping at high energy colliders like RHIC.

- Has to provide full spin flip in the presence of the nominal snake configuration, i.e. the beam spin precession tune is at or close to 1/2
Implementation of spin flipper using rotating field

- To produce a spin transfer map similar to the map of rotating field

\[ M_{\text{rot}} = e^{-\frac{i}{2} \phi_{\text{rot}} (\cos Q_{sf} \theta \sigma_1 + \sin Q_{sf} \theta \sigma_2)} \]

- Schematic layout

\[ \Delta B L \cos (Q_{sf} \theta + \chi_1) \quad \Delta B L \sin (Q_{sf} \theta + \chi_2) \]

where for each ac dipole,

\[ \phi_{\text{osc}} = (1 + G \gamma) \frac{\Delta B L}{B \rho} \]
Spin flipper using rotating field

Let $\psi_0 = 90^\circ$, we then get:

$$M_{\text{spinflipper}} = e^{\frac{i}{2} \psi_0 \sigma_3} e^{\frac{i}{2} \phi_{osc} \sin Q_{sf} \theta \sigma_1} - e^{\frac{i}{2} \psi_0 \sigma_3} e^{\frac{i}{2} \phi_{osc} \cos Q_{sf} \theta \sigma_1}$$

For small $\phi_{osc}$, the equation then becomes:

$$\approx e^{\frac{i}{2} \phi_{osc} \sin Q_{sf} \theta (\cos \psi_0 \sigma_1 - \sin \psi_0 \sigma_2) - \phi_{osc} \cos Q_{sf} \theta \sigma_1}$$

$$M_{\text{spinflipper}} = e^{\frac{-i}{2} \phi_{osc} (\sin Q_{sf} \theta \sigma_2 + \cos Q_{sf} \theta \sigma_1)}$$

For any $\psi_0$, $\chi_1 - \chi_2 = 180^\circ + \psi_0$
Simulation results

- Single particle with spin tune = 0.5
- Spin flipper:
  - Amplitude: 20 Gauss-m
  - Tune: 0.49 -> 0.51
  - Sweep in half million turns
RHIC spin flipper
\[ \chi_1 - \chi_2 = 180^\circ + \psi_0 \]
Specs

✧ Ac dipole:
  • field amplitude: up to 100 Gauss-m
  • frequency: 39kHz +- 400 Hz

✧ DC Spin rotator:
  • magnet: DC dipole with vertical field
  • integrated field strength: 0.9 Tesla-m
  • dipole deflection:
    • 100 GeV: 2.7 mrad
    • 250 GeV: 1.1 mrad
AC dipole: Meng, Oddo, Pai

- Current: \( I_0 = 118.58 \) A
- Central field: \( B_0 = 99.085 \) Gauss
- Integrated dipole field = 100.58 Gauss-meter
- Ratio of integrated 6-pole to dipole < 1E-4 (@R=2 cm)
- Ferrite: (cmd5005) thickness (1.0 inch), length (0.92 m)
DC dipole: Meng, Pearson, Phil, Yousef, …

Magnet core length: 72”
   = 182.88 cm
Gap: 6” = 15.24 cm

Io = 687.21 A
N = 30 (per pole)
Bo = 3392 Gauss
\[ \int B_y \, dz = 6.796e5 \, \text{G-cm} \]
   = 0.68 T-m
\[ L_{\text{eff}} = 2.004 \, \text{m} \]

Wuzheng’s harm.analy.
Main field quality:
6.8E-4 (quad)
-8.7E-7 (sext)
(@R=2.5 cm)

W. Meng

2 inch septum
shielding plate
tapered to 0.5 inch at ends
Other application of RHIC spin flipper
Spin tune meter

- Instead of sweeping the spin flipper tune across the beam spin precession tune, one can also keep the spin flipper tune fixed nearby the beam spin tune. In this case, the stable spin direction is given by

\[
P_x = \frac{\varepsilon_{sf}}{\sqrt{|Q_{sf} - Q_{spin}|^2 + |\varepsilon_{sf}|^2}} \cos(Q_{sf} \theta)
\]

\[
P_y = \frac{Q_{sf} - Q_{spin}}{\sqrt{|Q_{sf} - Q_{spin}|^2 + |\varepsilon_{sf}|^2}}
\]

\[
P_z = \frac{\varepsilon_{sf}}{\sqrt{|Q_{sf} - Q_{spin}|^2 + |\varepsilon_{sf}|^2}} \sin(Q_{sf} \theta)
\]

- The beam spin tune can be calculated by measuring the turn by turn horizontal and vertical asymmetry
Using rotating field

Using a single ac dipole
Spin vector in the rotating frame

Using rotating field

Using a single ac dipole
Summary

For high energy accelerator like RHIC, rotating field spin flipper allows one to achieve spin flip with spin tune staying at $\frac{1}{2}$

This device also allows us to measure spin tune at RHIC store energy.

Conceptual design is done. Most of the parts are done and ready for installation. We expect to have the system commissioned during the coming polarized proton run.

Currently, we are working on detailed spin simulations with spin rotators included.
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