RHIC Spin Flipper

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Outline

- Introduction
  - Spin dynamics
  - How to flip spin
- RHIC spin Flipper
- Summary

Thomas-BMT Equation

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

Spin vector in particle's rest frame

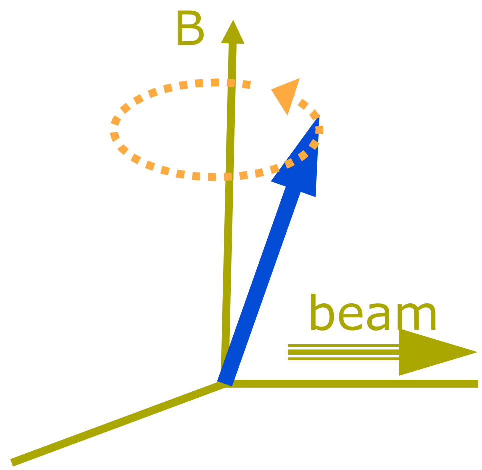
Magnetic field along the direction of the particle's velocity

- G is the anomoulous g- factor, for proton,
  G=1.7928474
- γ: Lorenz factor

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**



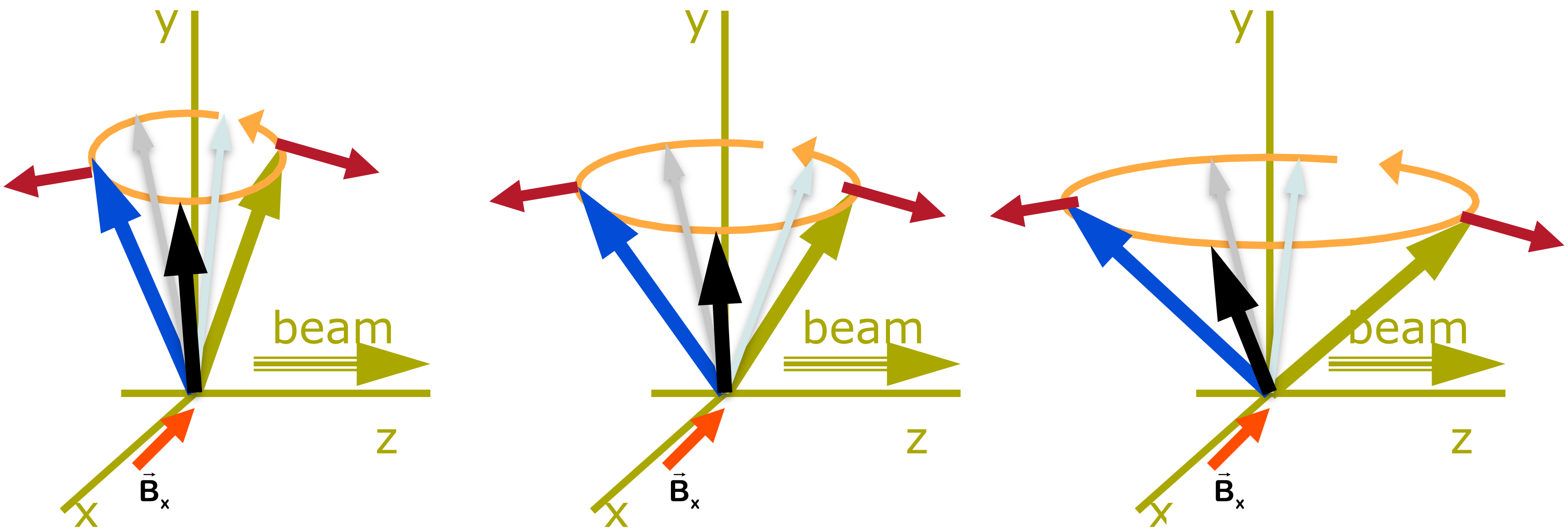
- **Spin tune Q_s: number of precessions in one orbital revolution. In general,**

$$\mathbf{Q_s} = \mathbf{G}\gamma$$

Spin Resonance

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

$$Q_s = \text{tune of the kick on the spin}$$



Initial

1st encounter

2nd encounter

Spin Resonance Crossing

- **Frossart-Stora formula**

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

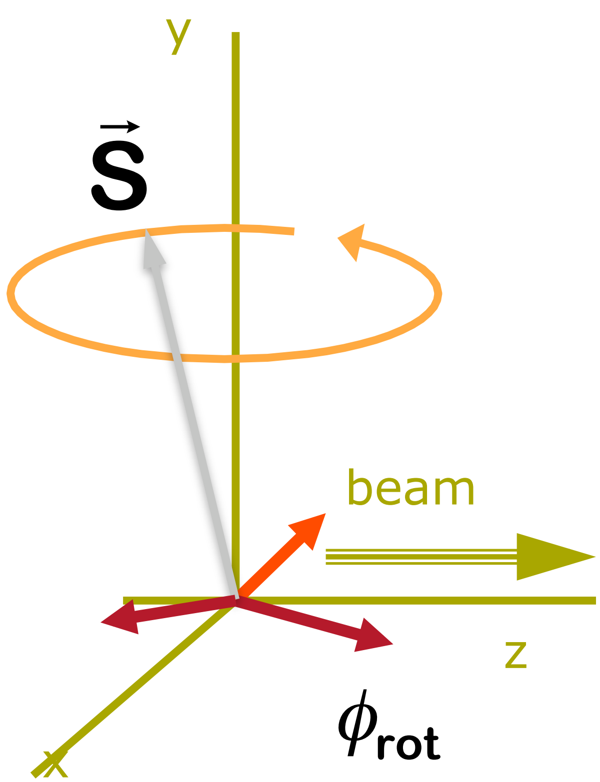
ε is the strength of the resonance.
α is the speed of resonance crossing

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

$$\frac{\pi|\varepsilon|^2}{\alpha} >> 1 \qquad P_f = -P_i$$

How to excite an isolated resonance

- **A rotating field**



How to excite an isolated resonance

- **A rotating field**

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

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

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

$$\sigma_1=\begin{pmatrix}0&1\\1&0\end{pmatrix},\ \sigma_1=\begin{pmatrix}0&-i\\i&0\end{pmatrix},\ \sigma_1=\begin{pmatrix}1&0\\0&-1\end{pmatrix}$$

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

2x2 spin transfer map of rotating field

Traditional spin flipping technique: single ac dipole

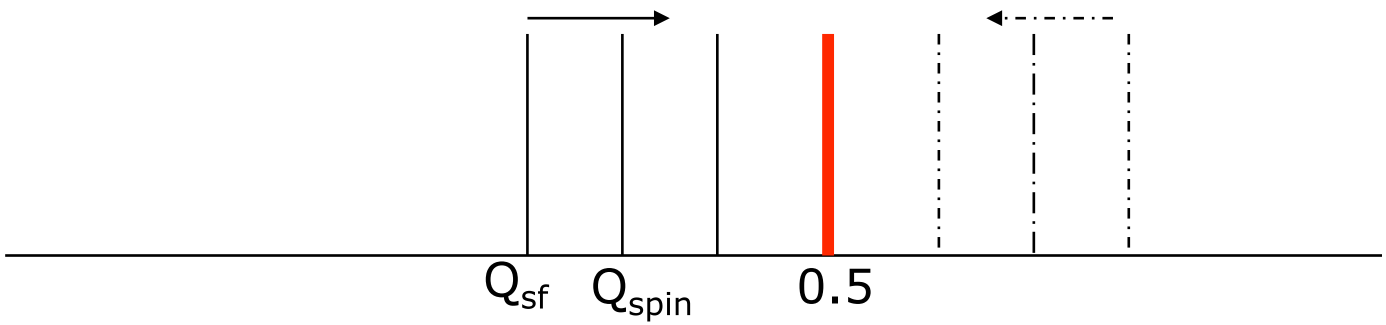
- Adiabatically crossing an artificial spin resonance induced by an ac dipole.
- This technique has been demonstrated in the Brookhaven AGS, IUCF Cooler Ring as well as the Cozy 3 GeV storage ring

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

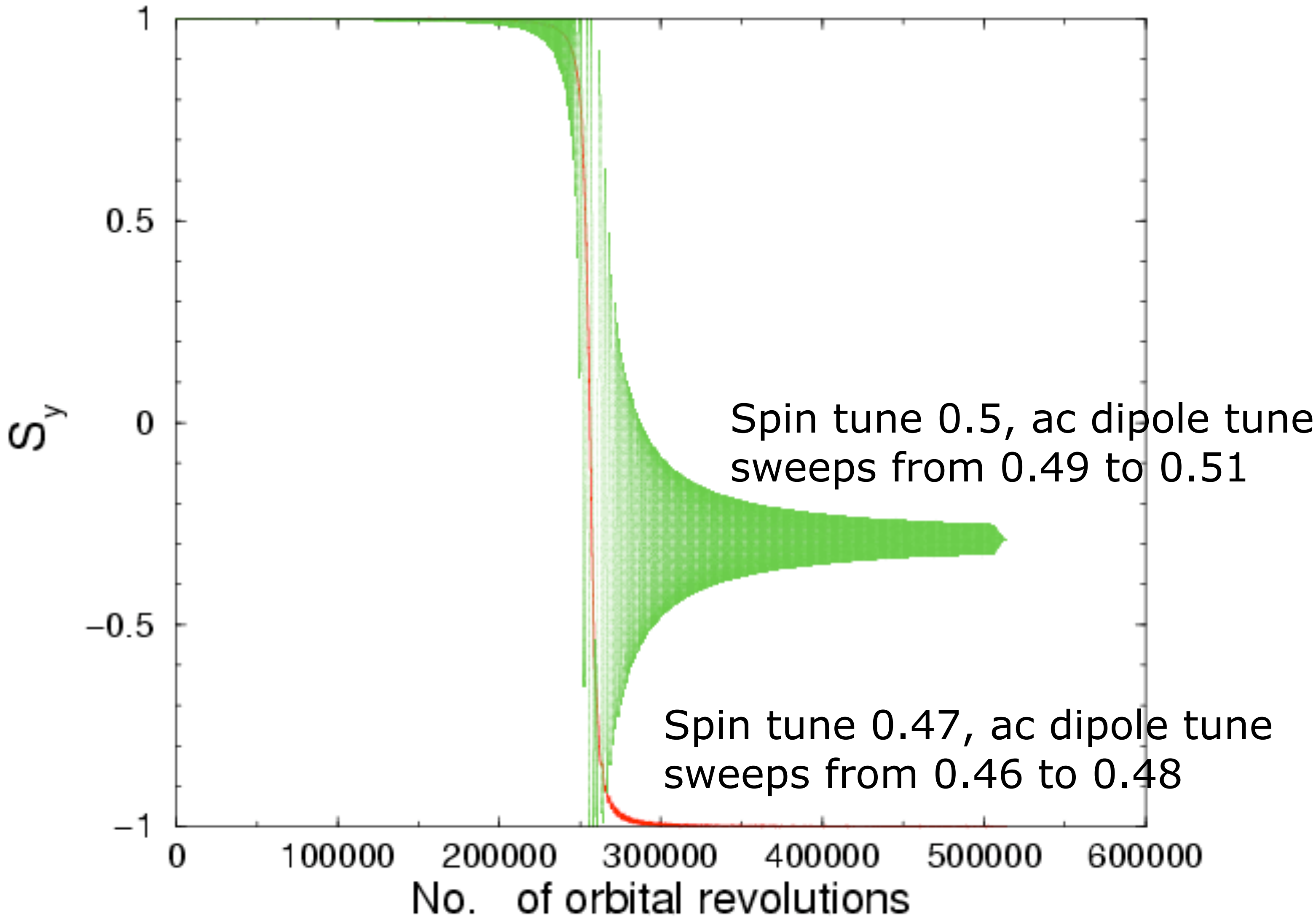
$$\frac{d\vec{\psi}}{d\theta} = -\frac{i}{2}\left[\mathrm{G}\gamma\sigma_3 + (1 + \mathrm{G}\gamma)\frac{\Delta \mathrm{BL}}{\mathrm{B}\rho}\sigma_1(\mathrm{e}^{\mathrm{i}\sigma_3 \mathrm{Q}_{\mathrm{sp}}\theta} + \mathrm{e}^{-\mathrm{i}\sigma_3 \mathrm{Q}_{\mathrm{sp}}\theta})\frac{1}{2} \right]\vec{\psi}(\theta)$$

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 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.

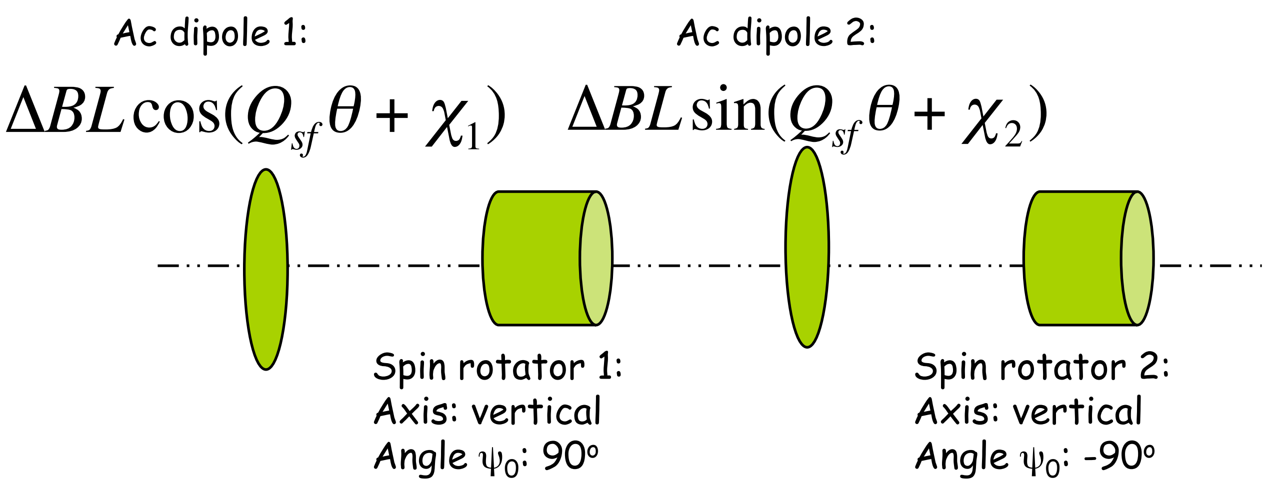
- Has to provide full spin flip in the presence of the nominal snake configuration, i.e. the beam spin precession tune is at or close to ½

Implementation of spin flipper using rotating field

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

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

- Schematic layout



where for each ac dipole,

$$\phi_{osc} = (1 + G\gamma)\frac{\Delta BL}{B\rho}$$

Spin flipper using rotating field

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

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

$$= e^{\frac{i}{2}\psi_0\sigma_3} e^{-\frac{i}{2}\psi_0\sigma_3} e^{\frac{i}{2}\phi_{osc}\sin Q_{sf}\theta(\cos\psi_0\sigma_1 - \sin\psi_0\sigma_2)} e^{-\frac{i}{2}\phi_{osc}\cos Q_{sf}\theta\sigma_1}$$

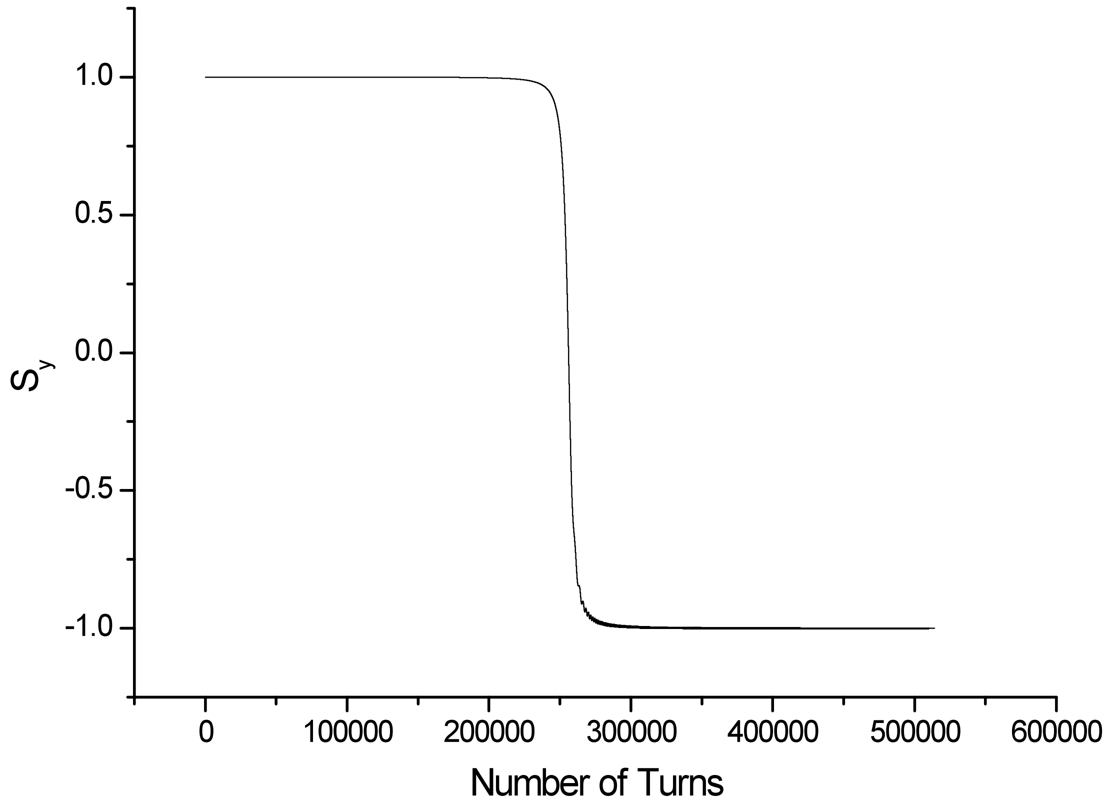
For small ϕ_{osc}, the equation then becomes:

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

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

For any ψ_0, $\chi_1 - \chi_2 = 180^o + \psi_0$

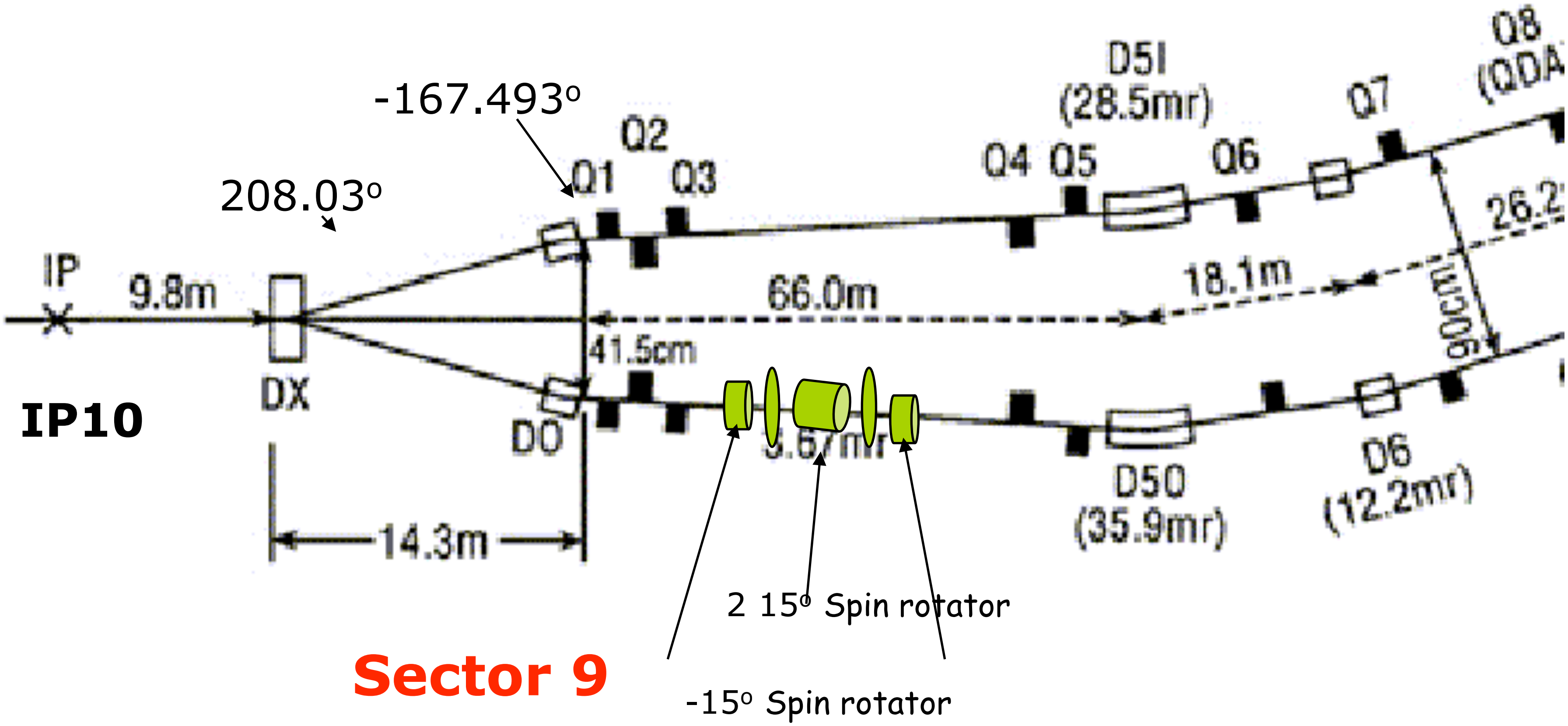
Simulation results



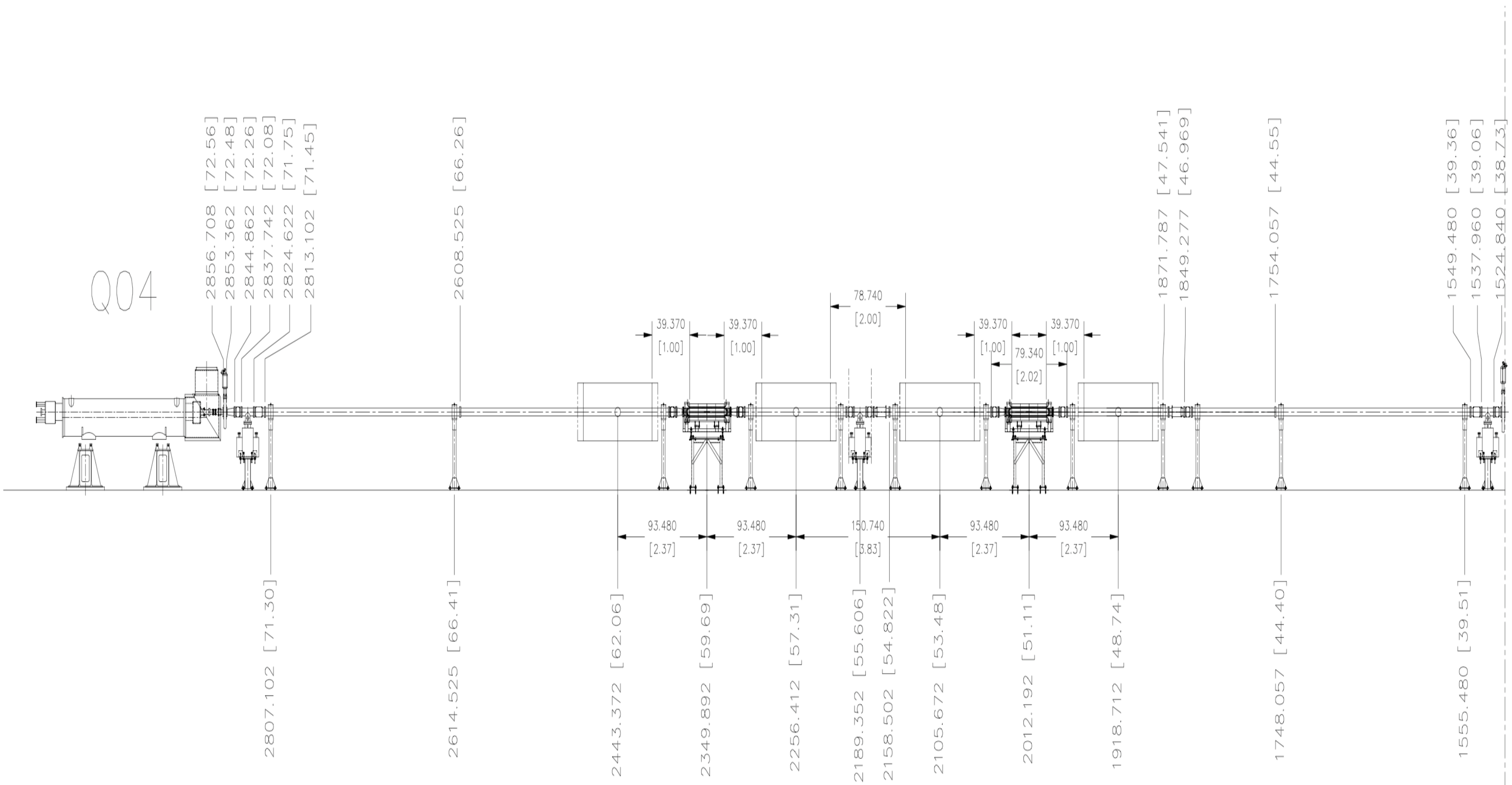
- Single particle with spin tune = 0.5
- Spin flipper:
  - Amplitude: 20 Gauss-m
  - Tune: 0.49 -> 0.51
  - Sweep in half million turns

RHIC spin flipper

Location



$$\chi_1 - \chi_2 = 180^{o} + \psi_0$$



BLUE INNER SECTOR 9 WITH SPIN FLIPPER

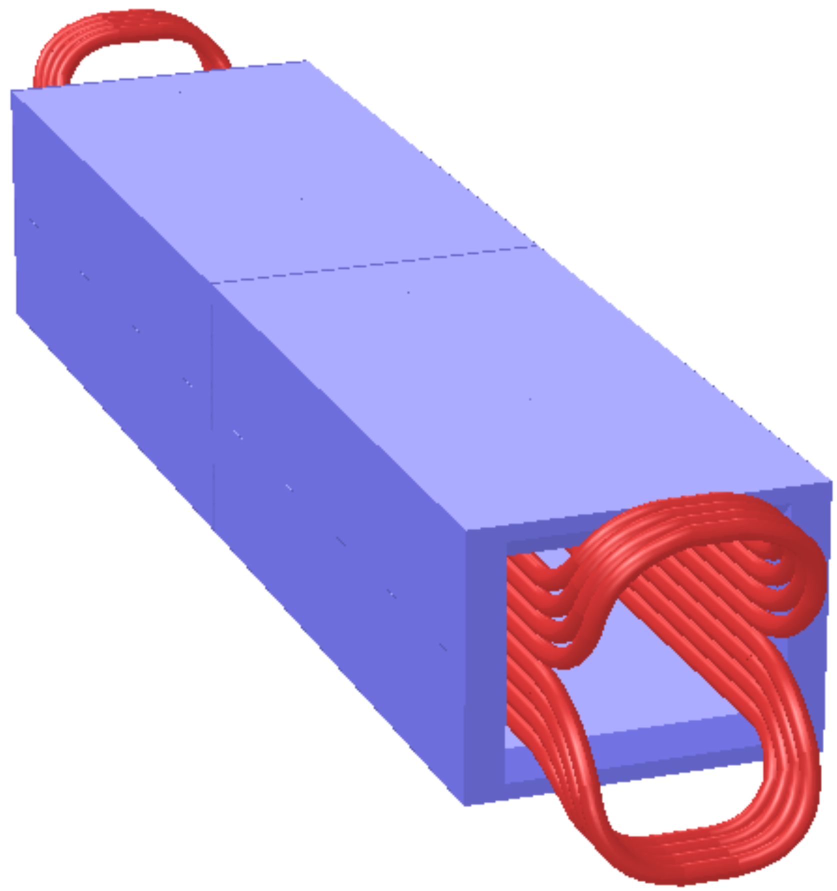
VIEW LOOKING OUT FROM RING CENTER

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: 1.1mrad

AC dipole: Meng, Oddo, Pai

- Current: Io = 118.58 A
- Central field: Bo = 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



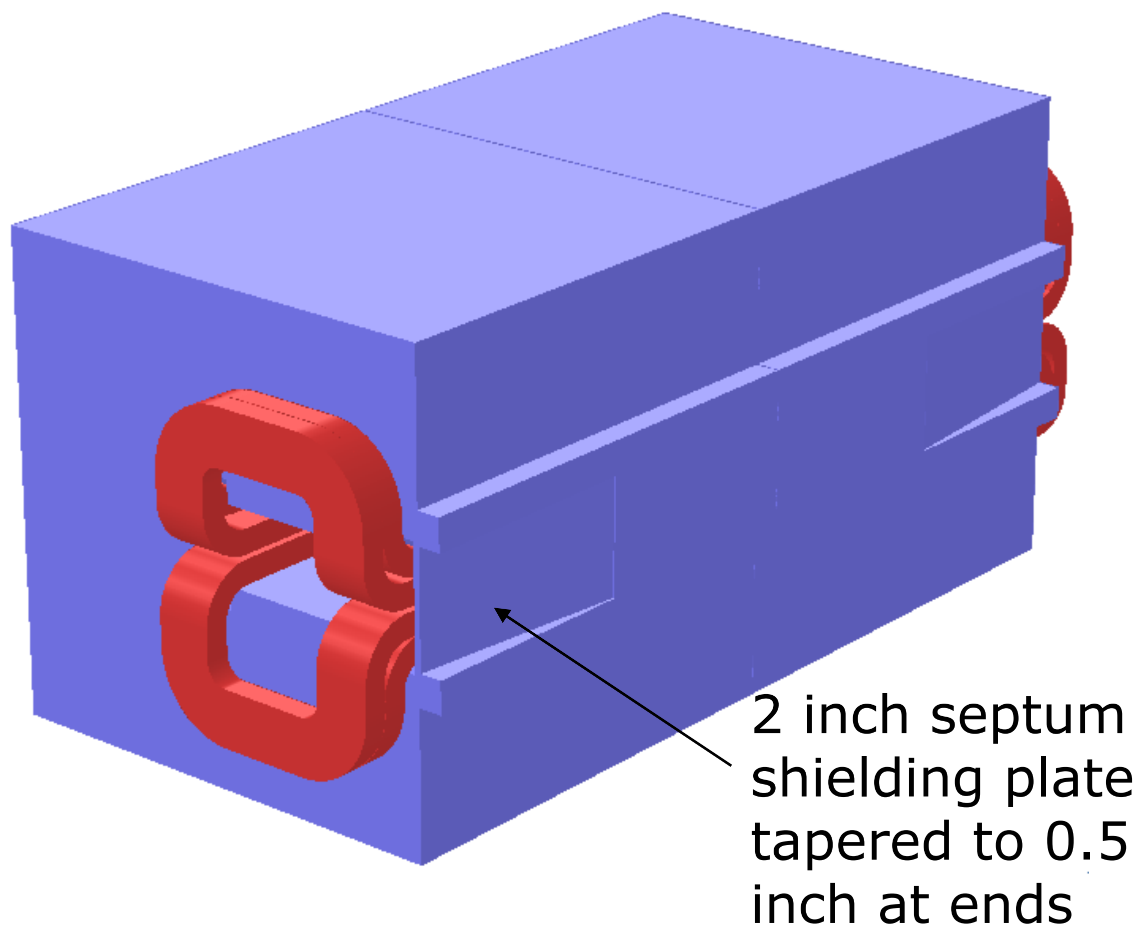
DC dipole: Meng, Pearson, Phil, Yousef, …

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 G-cm
 = 0.68 T-m
L_{eff} = 2.004 m

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

W. Meng



Other application of RHIC spin flipper

Spin tune meter

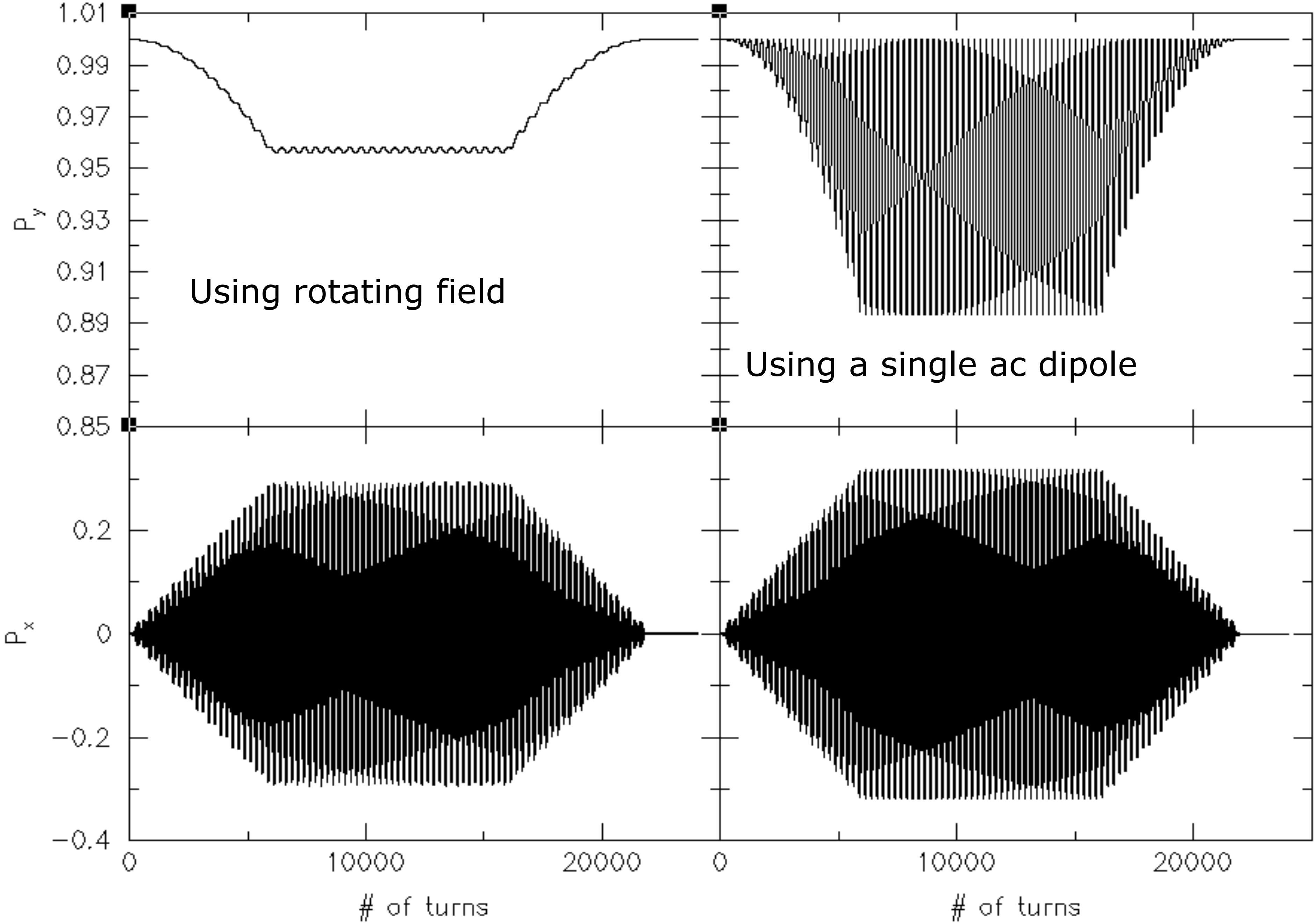
- Instead of sweeping the spin flipper tune across the beam spin precession tune, one can also keep the spin flipper tune fixed nearby the beam spin tune. In this case, the stable spin direction is given by

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

$$P_y = \frac{Q_{sf} - Q_{spin}}{\sqrt{\left|Q_{sf} - Q_{spin}\right|^2 + \left|\varepsilon_{sf}\right|^2}}$$

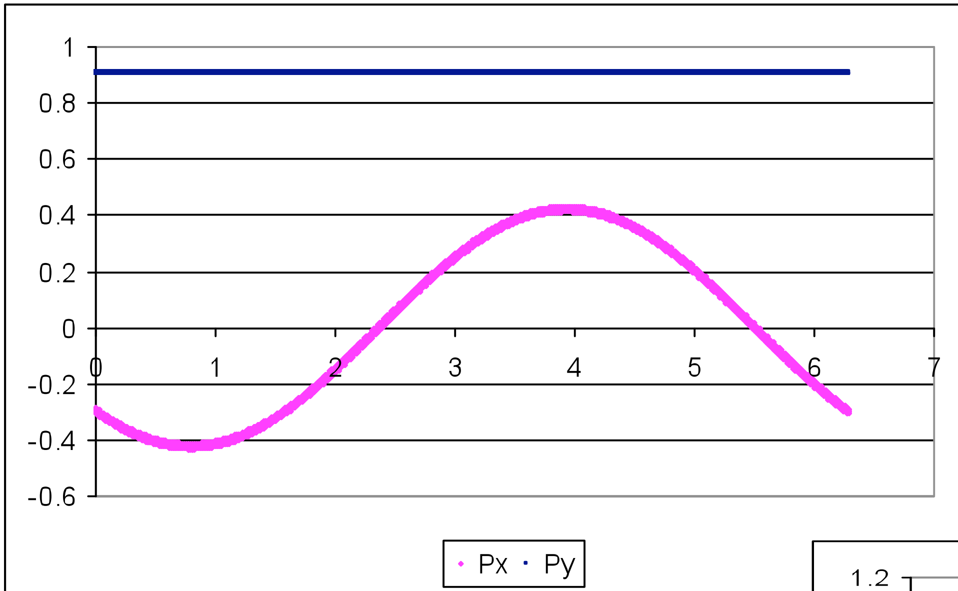
$$P_z = \frac{\varepsilon_{sf}}{\sqrt{\left|Q_{sf} - Q_{spin}\right|^2 + \left|\varepsilon_{sf}\right|^2}} \sin(Q_{sf}\theta)$$

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



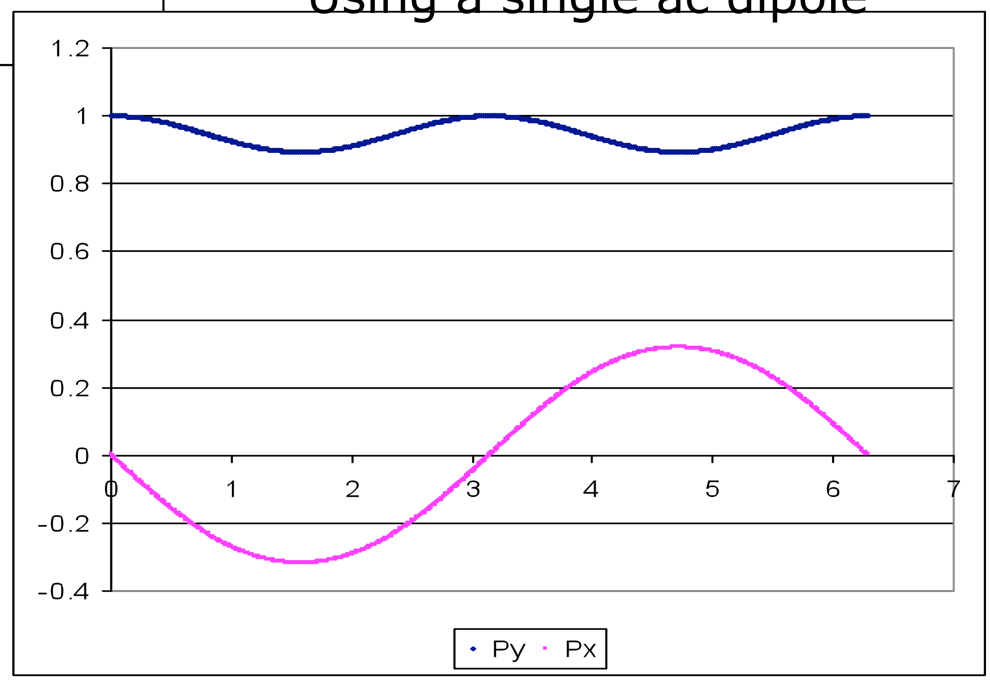
1.01
0.99
0.97
0.95
0.93
0.91
0.89
0.87
0.85
P_y
Using rotating field
Using a single ac dipole
0.2
0
−0.2
−0.4
P_x
0
10000
20000
# of turns
0
10000
20000
# of turns

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 ½

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.

Acknowledgement

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