Studies of systematic limitations in the EDM searches at storage rings

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Introduction

- Why there is a baryon asymmetry in the Universe? CP violation is mandatory
- Nonvanishing EDM if CP & P violation. SM predicts $d_p \sim 10^{-31}$ $\mathrm{e} * \mathrm{cm}$. EDM as a handle on CP violation mechanism.
- Experiments on searches of neutron EDM already rule out MSSM and two-Higgs models.
- Go after the EDM of charged particles at storage rings.

- The proton and deuteron EDM storage ring: BNL. Needs huge investment.
- EDM at existing storage ring: COSY.
- Complement magnetic ring with RF electric spin rotators to induce the EDM spin precession.

EDM in the RF-free storage ring

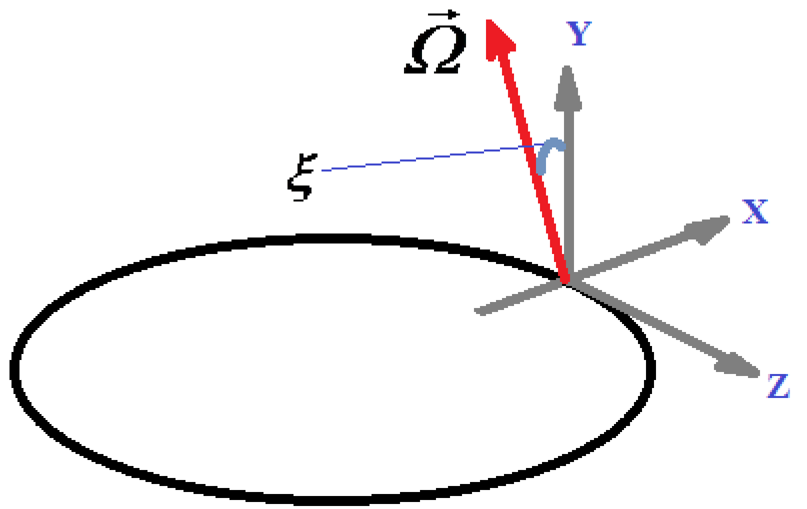
- Pure magnetic ring with vertical B-field:

$$\frac{d\vec{S}(t)}{dt} = \vec{\Omega} \times \vec{S}(t), \qquad \vec{\Omega} = -\frac{e}{m}\left(G\vec{B} + \eta(\vec{\beta} \times \vec{B})\right)$$

- $\eta = d\frac{m}{e}$
- $\vec{\beta} \times \vec{B}$ acts as an *imperfection field*

$$\vec{\Omega} = -Q_s \Omega_R (\vec{e}_Y \cos\xi + \vec{e}_X \sin\xi)$$

- ξ is correlated to the EDM:
- $\tan\xi = -\frac{\eta\beta}{G}$
- EDM tilts the stable spin axis



- The spin tune $Q_s = \frac{G\gamma}{\cos\xi}$

RF EDM rotator in the Wien filter mode

- Wien filter → zero Lorentz force → no coherent betatron oscillations
- Wien filter is EDM-transparent, but rotates spin by MDM
- Spin kick around vertical axis, on k-th turn,

$$\psi(k) = \psi \cos(2\pi Q_s k + \varphi)$$

induces frequency modulation of the spin tune.

- Coupling to the static motional electric field in the ring
- Resulting EDM resonance strength is $\epsilon = \frac{\psi\xi}{2}$
- EDM effect is masked by MDM interaction with imperfection magnetic fields

Existing probes for studies of systematic limitations at COSY

1. Mapping of imperfection fields by static solenoids at idle spin precession
   – Planned for September 2014

2. Measurements of oscillating horizontal spin at RF spin resonance: oscillation phase shift due to imperfections.

3. Mapping of imperfection fields by RF solenoid at RF spin resonance

– 2 and 3 are available after RF Wien filter commissioning

1. Mapping and correcting for the imperfections

- Any imperfection field perturbs spin tune Q_s

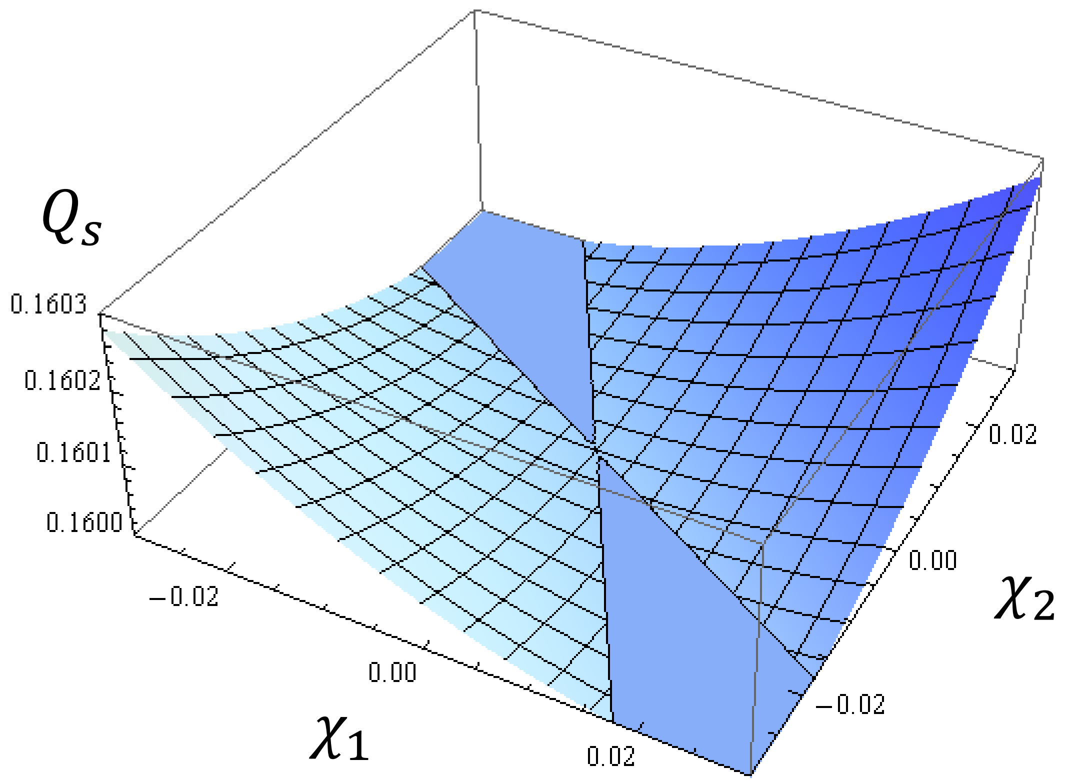
- Adding to a ring 2 artificial imperfections (static solenoids)
- Explore imperfection response in spin tune by varying solenoids strength

- Static solenoids with kicks $\chi_{1,2}$ at $\theta = 0$ and $\theta = \pi$ and the imperfection kick α_z at θ^*, spin tune is given by

$$\cos \pi Q_s = \cos[\pi G\gamma] \cos\frac{\chi_1}{2} \cos\frac{\chi_2}{2} \cos\frac{\alpha_z}{2} - \cos[(\pi - \theta^*)G\gamma] \sin\frac{\chi_1}{2} \cos\frac{\chi_2}{2} \sin\frac{\alpha_z}{2} - \cos[G\gamma\theta^*] \cos\frac{\chi_1}{2} \sin\frac{\chi_2}{2} \sin\frac{\alpha_z}{2} - \sin\frac{\chi_1}{2} \sin\frac{\chi_2}{2} \cos\frac{\alpha_z}{2}$$

Mapping and correcting for the imperfections

- In case of no imperfections in the ring, $\alpha_z = 0$
  - spin tune map is precisely symmetric,
  - saddle point is located at $\chi_{1,2} = 0$ with $Q_s = G\gamma$



Sea level
$Q_s = G\gamma = 0.16$

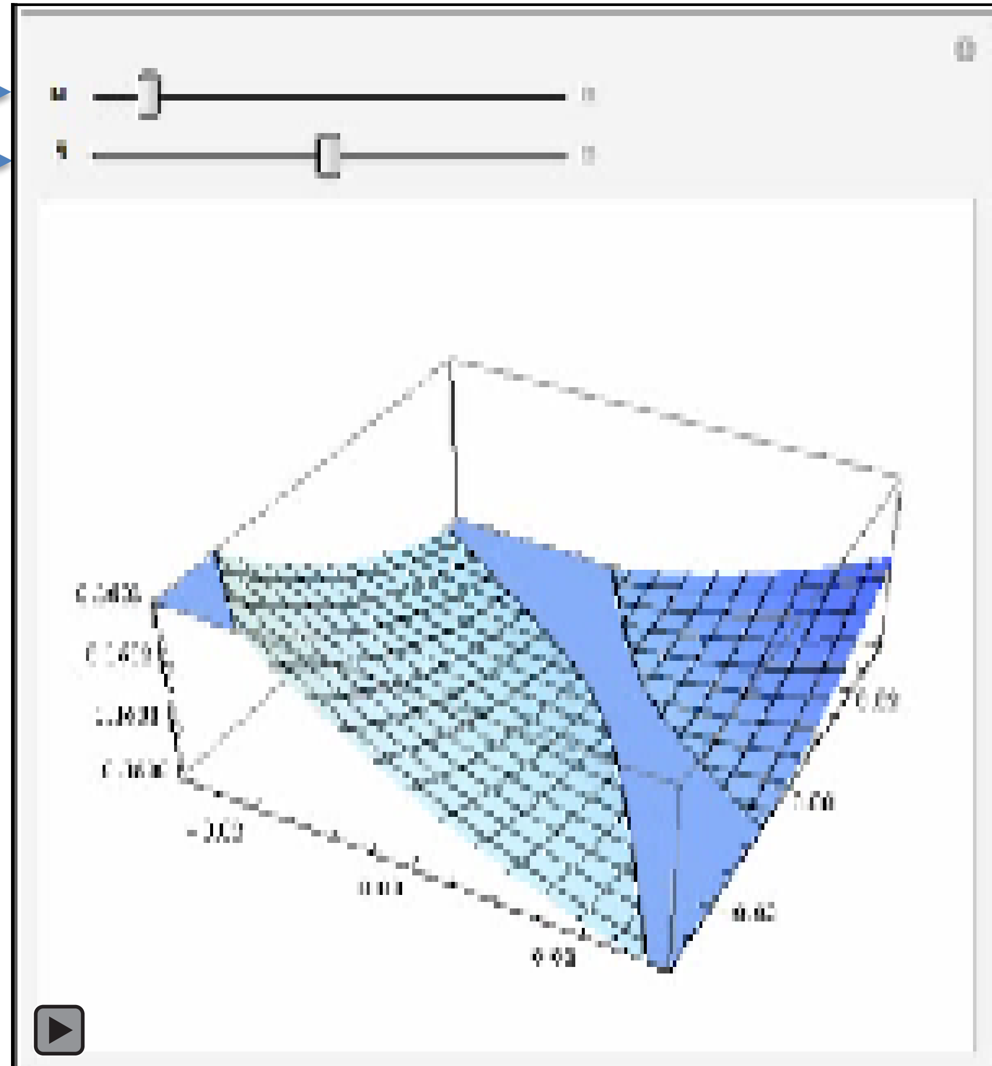
- In presence of imperfections in the ring, saddle point is moved away from center and $Q_s \neq G\gamma$
- Spin tune map at different values of α_z and θ^*:

$\alpha_z = [-0.015\,..\,0.015]$

$\theta^* = [0\,..\,\pi]$

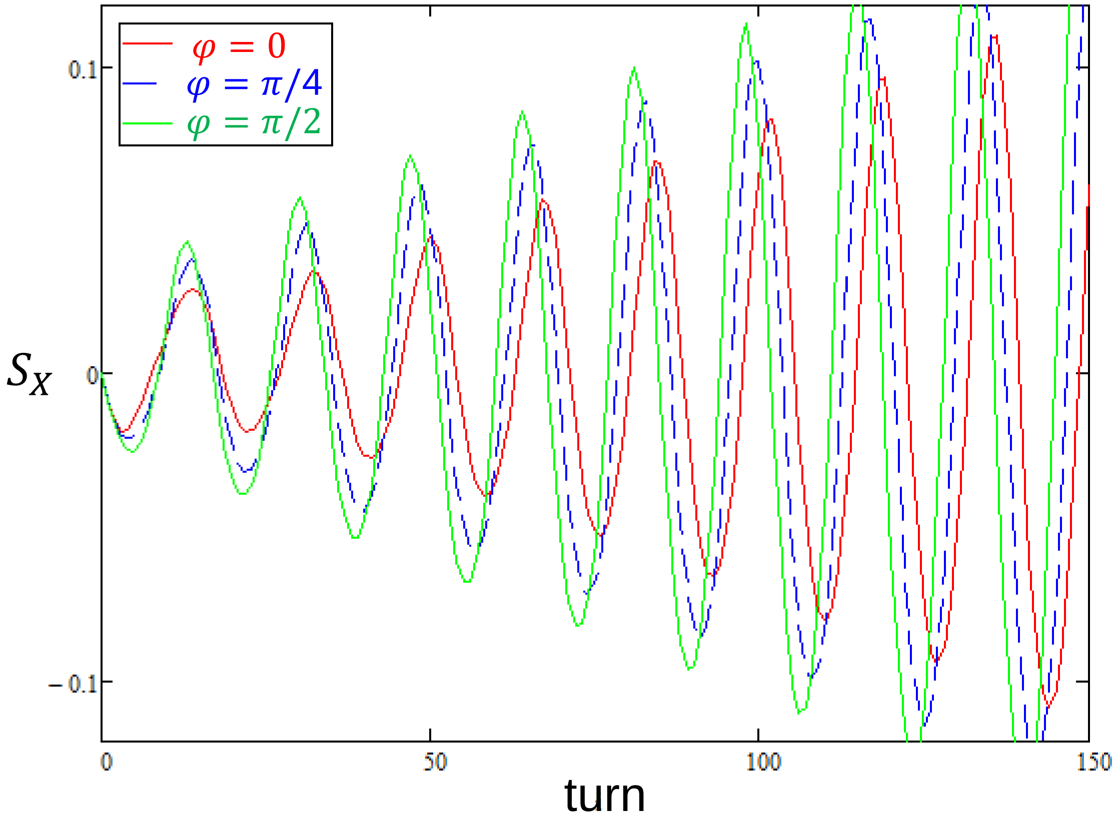
Sea level

$Q_s = G\gamma = 0.16$



2. RF spin resonance: oscillation phase shift

- Spin resonance with the RF Wien filter: AM of horizontal spin



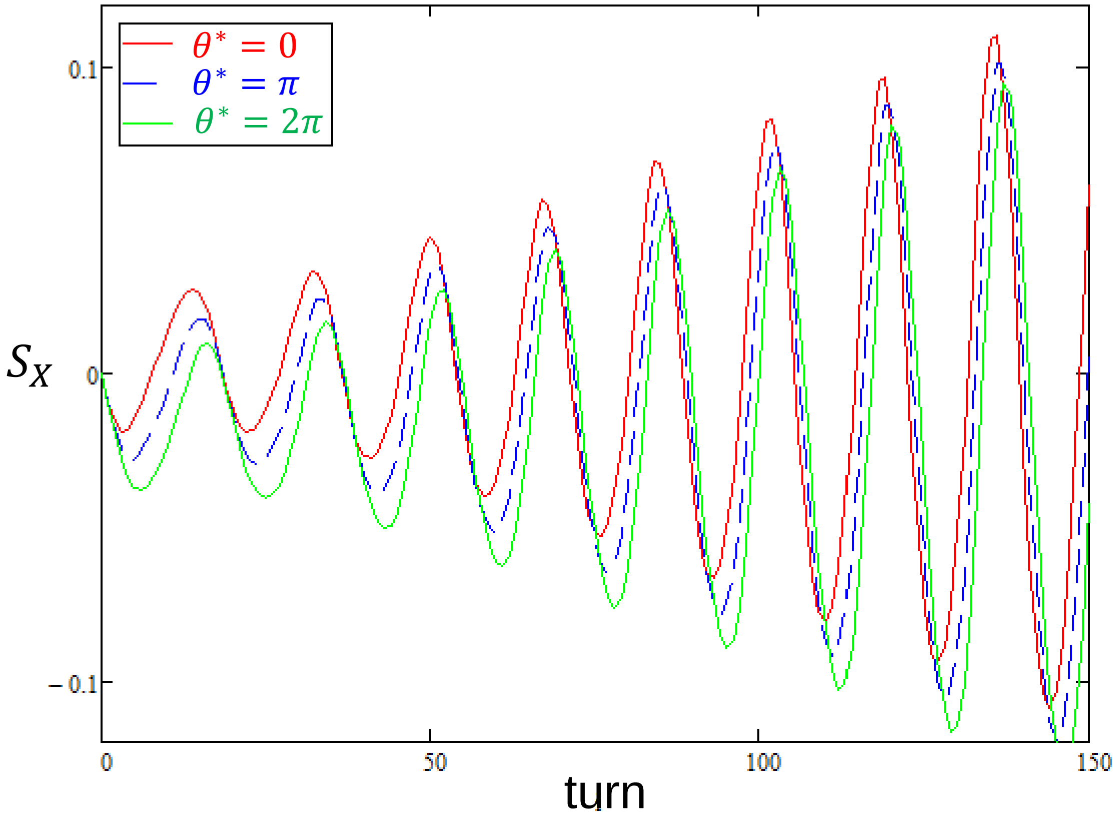
RF Wien filter drives imperfection resonance

Initial $S_Y = 1$

- Phase of RF Wien filter φ determines shift of oscillation pattern
- Phase shift is measurable by time-stamp polarimetry

Disentangling EDM and MDM spin precession

- Spin resonance with the RF Wien filter with different imperfection phase



RF Wien filter drives imperfection resonance

Initial $S_Y = 1$

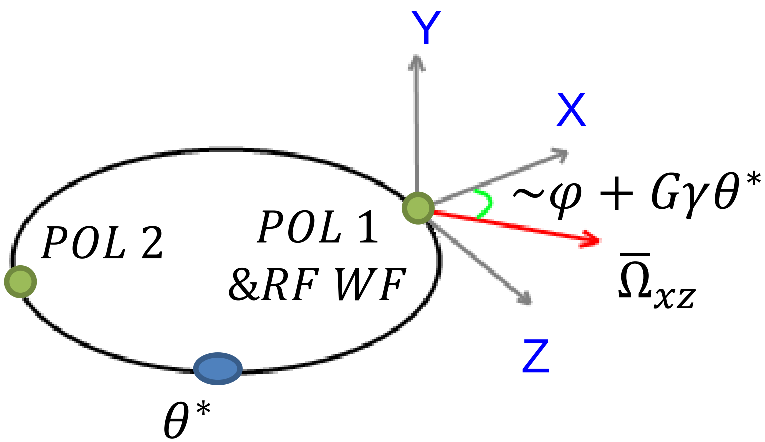
$\varphi = 0$

- Imperfection shifts oscillation pattern
- Phase shift depends on $G\gamma\theta^*$

Disentangling EDM and MDM spin precession

- Imperfection (i.e., longitudinal tilt of the dipole magnet) strength

$$\alpha_z = (1+G)\frac{\int B_z dl}{B\rho}$$



- To first order, vector of RSA in polarimeter no.1 is given by:

$$\Omega_x = \frac{\psi\alpha_z}{4\sin(\pi G\gamma)}\cos(\varphi + G\gamma\theta^*)$$

$$\Omega_z = \frac{\psi\alpha_z}{4\sin(\pi G\gamma)}\sin(\varphi + G\gamma\theta^*)$$

- The resonance strength is

$$\epsilon \approx \frac{\psi\alpha_z}{4\sin(\pi G\gamma)} \gg \frac{\psi\xi}{2}$$

Disentangling EDM and MDM spin precession

1. Use many polarimeters.
2. Change phase φ of RF WF field in different runs
3. Use several bunches, which come to RF field in phase delay $\varphi = \phi G\gamma$, where $\phi = 0..\pi$

3. Mapping of imperfection fields by RF solenoid at RF spin resonance

- Add RF solenoid to drive the resonance with RF WF simultaneously: direction of RSA and resonance strength is determined by phases of both RF fields and by $G\gamma\theta^*$

$$\Omega_x = \frac{\chi}{2}\cos\varphi_{sol} + \frac{\psi\alpha_z}{4\sin(\pi G\gamma)}\cos(\varphi + G\gamma\theta^*)$$

$$\Omega_z = \frac{\chi}{2}\sin\varphi_{sol} + \frac{\psi\alpha_z}{4\sin(\pi G\gamma)}\sin(\varphi + G\gamma\theta^*)$$

- RF solenoid phase φ_{sol} and amplitude of spin kick χ
- RF Wien filter phase φ

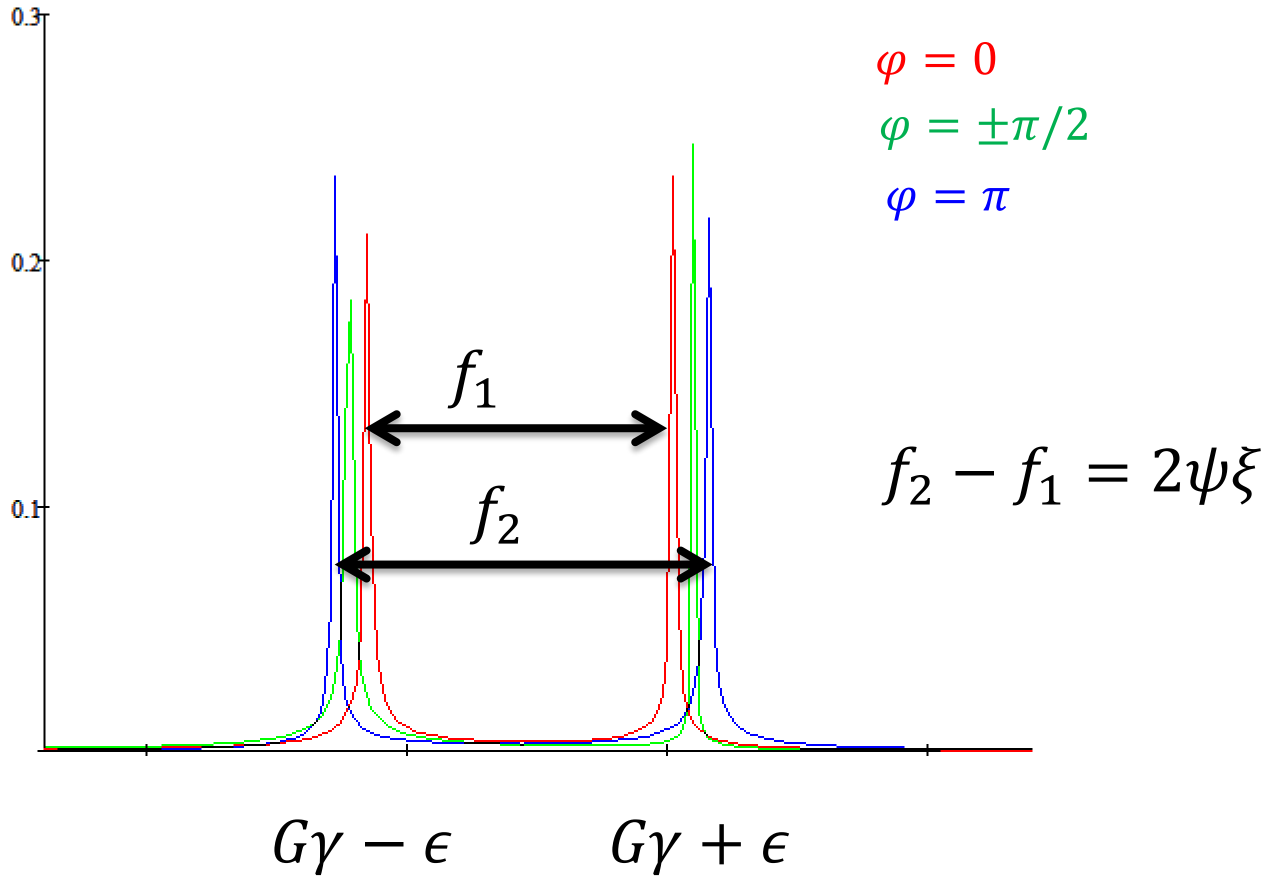
Frequency spectra of precessing horizontal spin component at RF spin resonance

- On RF spin resonance, spin tune spectrum exhibits two sidebands

$$Q_s = G\gamma \pm \epsilon$$

- Resonance strength ϵ can be measured directly from the oscillation of the vertical spin S_Y

- Resonance with RF solenoid and RF Wien filter in *ideal ring*, Fourier spectra of S_X at different φ:

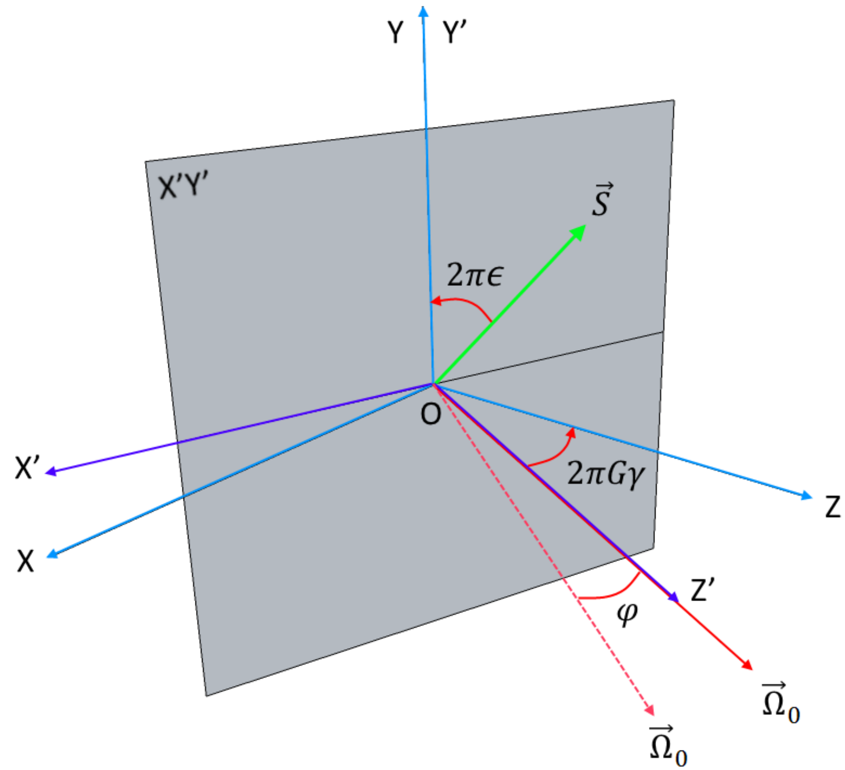


Summary

- Fine tuning the static solenoid fields and mapping Q_s gives a hint on the imperfection kicks
- RF Solenoid locked on RF Wien filter (or RF-E flipper) frequency with the tunable phase delay φ, provides mechanism for separation of EDM on top of MDM spin precession.
- The goal is to stabilize imperfections and suppress decoherence effects, to achieve sensitivity to deuteron and proton EDM to order $d \sim 10^{-24}\ \mathrm{e} * \mathrm{cm}$ at COSY.

Thank you

Running spin axis at RF spin resonance



- $\vec{S}$ lies in resonance precessing frame X'Y'
- $\vec{S}$ precesses around running spin axis $\overrightarrow{\Omega}_0$ by $2\pi\epsilon$,
- X'Y' rotates by $2\pi G\gamma$ each particle revolution.
- Initial direction of RSA is defined by RF phase φ