# First Spin Simulations for a Final EDM Storage Ring

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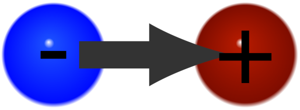
# Electric Dipole Moment




- Classical

$$\vec{d} = \sum q_i \vec{r}_i$$

- Subatomic particle

$$\vec{d} = d\vec{s}$$

**$\mathcal{T}$ and $\mathcal{P}$ violation of EDM**

- $H = -\mu\vec{s}\vec{B} - d\vec{s}\vec{E}$
- $\mathcal{T}: H = -\mu\vec{s}\vec{B} + d\vec{s}\vec{E}$
- $\mathcal{P}: H = -\mu\vec{s}\vec{B} + d\vec{s}\vec{E}$

- Assuming $\mathcal{CPT}$ is conserved $\mathcal{CP}$ must be violated
- A permanent EDM could explain the matter antimatter asymmetry and would be a sign for physics beyond the SM

# Measurement of EDM

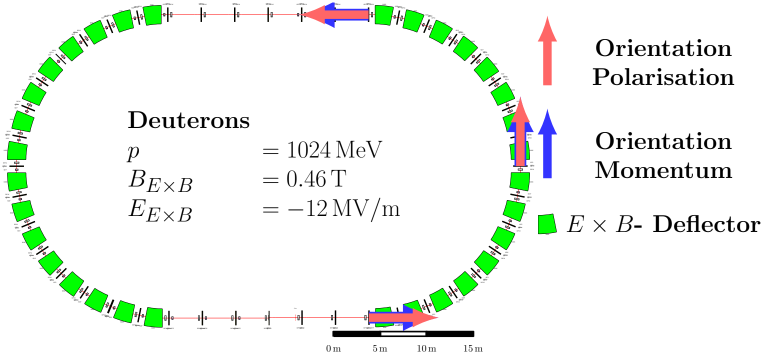
## T-BMT Equation

$$\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s} = -\frac{q}{m}\left\{ \underbrace{G\vec{B} + \left(\frac{1}{\gamma^2 - 1} - G\right)\vec{\beta} \times \vec{E}}_{MDM} + \underbrace{\frac{dm}{qs}\left(\vec{E} + \vec{\beta} \times \vec{B}\right)}_{EDM} \right\} \times \vec{s}$$

$(dx.doi.org/10.1103/PhysRevLett.2.435)$
$(arXiv{:}1308.1580v3)$

# Frozen Spin

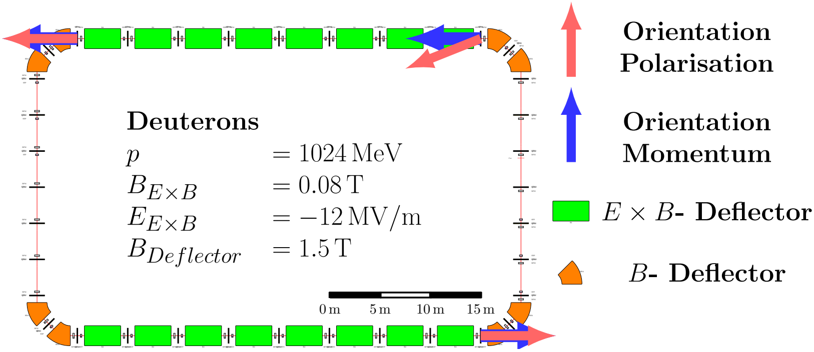
- $\frac{d\vec{s}_{MDM}}{dt} = -\frac{q}{m}\left\{G\vec{B} + \left(\frac{1}{\gamma^2-1} - G\right)\vec{\beta}\times\vec{E}\right\}\times\vec{s} = 0$




*Senichev, Y., et al. (IPAC15)*

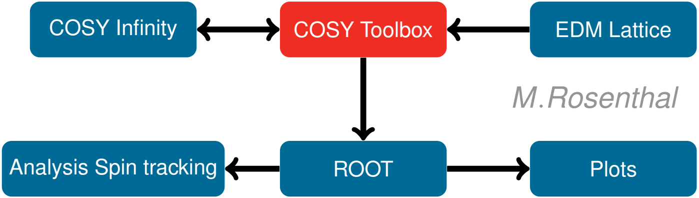
# Quasi Frozen Spin

- $\left\langle \frac{d\vec{s}_{MDM}}{dt} \right\rangle = -\left\langle \frac{q}{m} \left\{ G\vec{B} + \left( \frac{1}{\gamma^2 - 1} - G \right) \vec{\beta} \times \vec{E} \right\} \times \vec{s} \right\rangle = 0$
- Main benefit is the simplification of bending elements

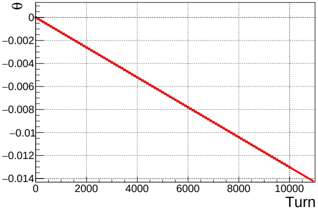


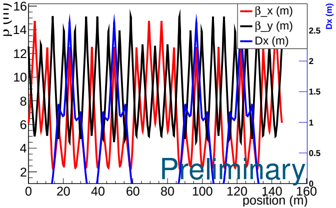

*Senichev, Y., et al. (IPAC15)*

# Spin Tracking Software

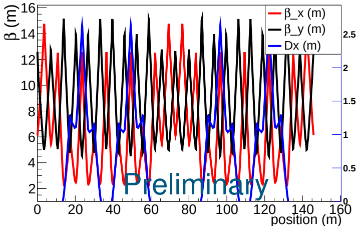



*M.Rosenthal*

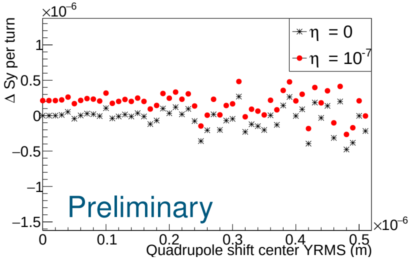


# Quadrupole Misalignments Frozen Spin




- Quadrupole strengths $\frac{\partial B_x}{\partial y} \approx 10\,\mathrm{T/m}$
- Beam width $10^{-6}$ m
- $\frac{\Delta p}{p} = 10^{-6}$
- $\eta = 10^{-7} \hat{\approx}$ $d = 5 \cdot 10^{-22}$ e cm




- First simulations
- At the moment only one random shift per quadrupole
- 1,000 particles
- 10,000 turns

# Gradient Fields

- Beside the artificial vertical spin build up by spin decoherence other effects exist
- Due to gradient fields additional spin rotations turn up
- How large are these effects?

## Spin motion due to gradient fields

$$\left(\frac{d\vec{s}}{dt}\right)_{\nabla}=\frac{1}{\gamma+1}\frac{1}{m}\vec{s}\times\left(\vec{\beta}\times\nabla\right)\left[\mu\vec{s}\cdot\vec{R}_1(\vec{B},\vec{E},\vec{v})+\underbrace{\frac{2dm}{es}\vec{s}\cdot\vec{R}_2(\vec{B},\vec{E},\vec{v})}_{\approx 0}\right]$$

*Metodiev, E., et al.* (*arXiv* : 1507.04440)

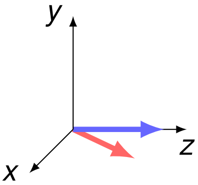
Member of the Helmholtz-Association

# Gradient Fields Frozen Spin

- In a Frozen Spin ring is the spin parallel aligned along the direction of momentum. Due to the Frozen Spin conditions
- $\vec{\beta}\perp\vec{s}$, $\vec{\beta}\perp\vec{B}$, $\vec{\beta}\perp\vec{E}$, $\vec{B}\perp\vec{s}$, $\vec{E}\perp\vec{s}$
- $$\Rightarrow\left(\frac{d\vec{s}}{dt}\right)_{\nabla}=\frac{1}{\gamma+1}\frac{1}{m}\vec{s}\times\left(\vec{\beta}\times\nabla\right)\left[\mu\underbrace{\vec{s}\cdot\vec{R}\left(\vec{B},\vec{E},\vec{v}\right)}_{=0}\right]=0$$
- No effect on the spin motion for an ideal Frozen Spin ring for the reference particle

*Metodiev, E., et al.(arXiv : 1507.04440)*

# Gradient Fields in Quasi Frozen Spin



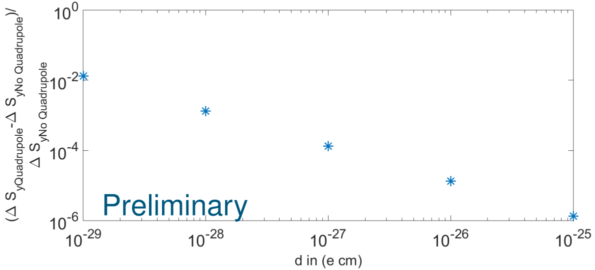

- In a Quasi Frozen Spin ring the spin is not always parallel aligned the momentum
- Gradient fields appear in quadrupoles

$$\left(\frac{d\vec{s}}{dt}\right)_{\nabla} = \frac{\partial B_x}{\partial y} \cdot \frac{\mu\beta}{\gamma+1} \frac{1}{m} \vec{s} \times \begin{pmatrix} s_x \\ 0 \\ -s_y \end{pmatrix}$$

- A perfect Quasi Frozen ring evokes an artificial build up of vertical polarisation by quadrupoles

# Effect of Gradient Fields in Quasi Frozen Spin

- After a half turn the spin is rotated by an angle $\gamma G\pi$ with respect to the momentum
- Compare the vertical spin build up for a ring the reference beam with and without gradient field effect. Particle motion due to gradient fields is neglected



# Outlook

- Examine further misalignments for Frozen Spin
- Include misalignment simulations for Quasi Frozen Spin
- Analyse of the effect of fringe fields
- Expand the analysis for gradient field effects, e.g. include the motion relative to the beam

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