III. Physikalisches Institut B

RWTH AACHEN UNIVERSITY

Status of a Design Study for a Proton EDM Ring

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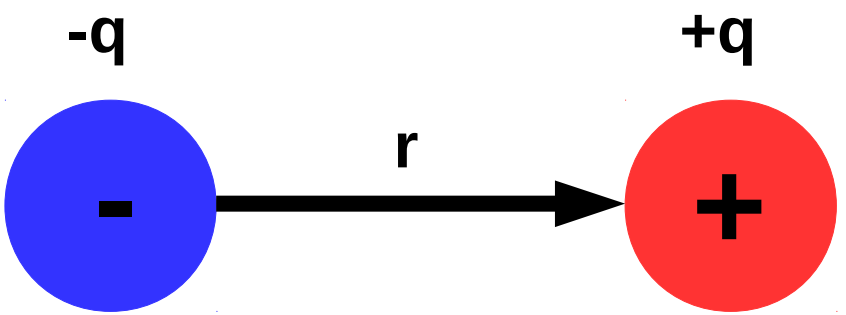
collaboration

European Research Council

Established by the European Commission

Electric Dipole Moments (EDMs)



$$\vec{d} = q\vec{r}$$

- **Permanent** electric dipole moments of elementary particles **along spin direction** violate parity (P) and time reversal (T) symmetry
- Via CPT theorem: EDMs are source of CP violation

Spin in Electromagnetic Field

In rest frame: $\frac{d\vec{S}}{d\tau} = \vec{\mu} \times \vec{B}^* + \vec{d} \times \vec{E}^*$

Transform fields into rest frame. use equation of motion
→ get T-BMT Equation, $G = \frac{g-2}{2}$, $\eta \approx 10^{-15}$ for $|\vec{d}| = 10^{-29}\, e \cdot \mathrm{cm}$

$$\frac{d\vec{S}}{dt} = \vec{S} \times (\vec{\Omega}_{MDM} + \vec{\Omega}_{EDM})$$

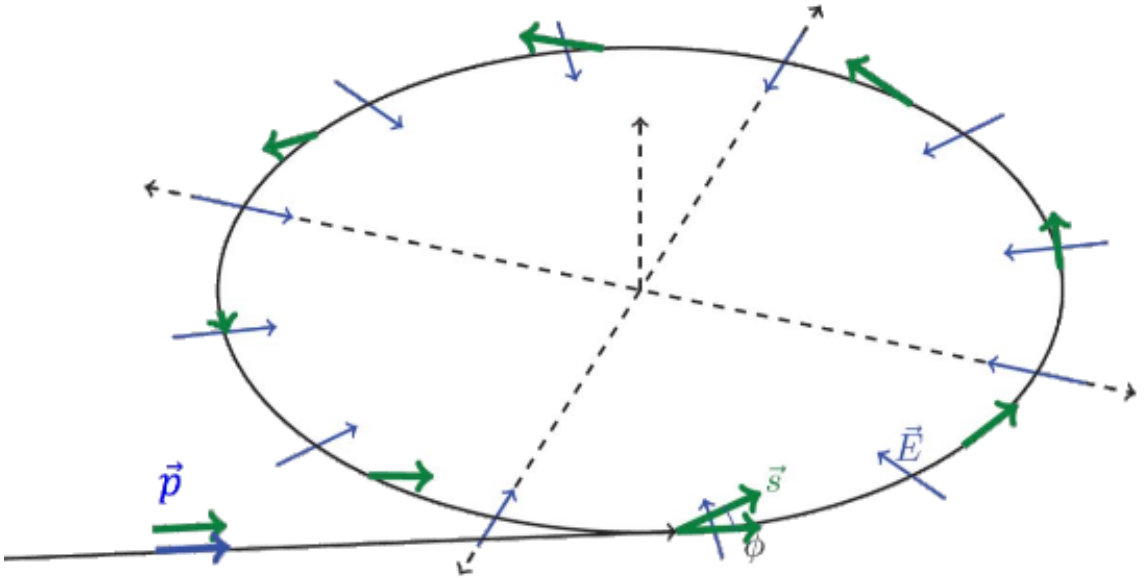
$$\vec{\Omega}_{MDM} = \frac{q}{m}\left(G\vec{B} - \frac{\gamma G}{\gamma+1}\vec{\beta}(\vec{\beta}\cdot\vec{B}) - \left(G - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right)$$

$$\vec{\Omega}_{EDM} = \frac{\eta q}{2mc}\left(\vec{E} - \frac{\gamma}{\gamma+1}\vec{\beta}(\vec{\beta}\cdot\vec{E}) + c\vec{\beta}\times\vec{B}\right)$$

$|\Omega_{EDM}| \ll |\Omega_{MDM}| \Rightarrow$ want $\Omega_{MDM} = 0$

- Possible for $\vec{B} = 0$, $p = \frac{mc}{\sqrt{G}} \approx 0.7\,\mathrm{GeV/c}$ (for protons)
- Have $\Omega_{EDM} \propto E$ → **want strong electric field!**

Measurement Principle (Frozen Spin)



- Inject longitudinal polarized beam
- Run in frozen spin mode
- Observe build-up of vertical polarization

$$(|\vec{E}| = 10\,\mathrm{MV/m},\ \eta = 10^{-15})$$

Expected build-up rate for protons (all electric ring):

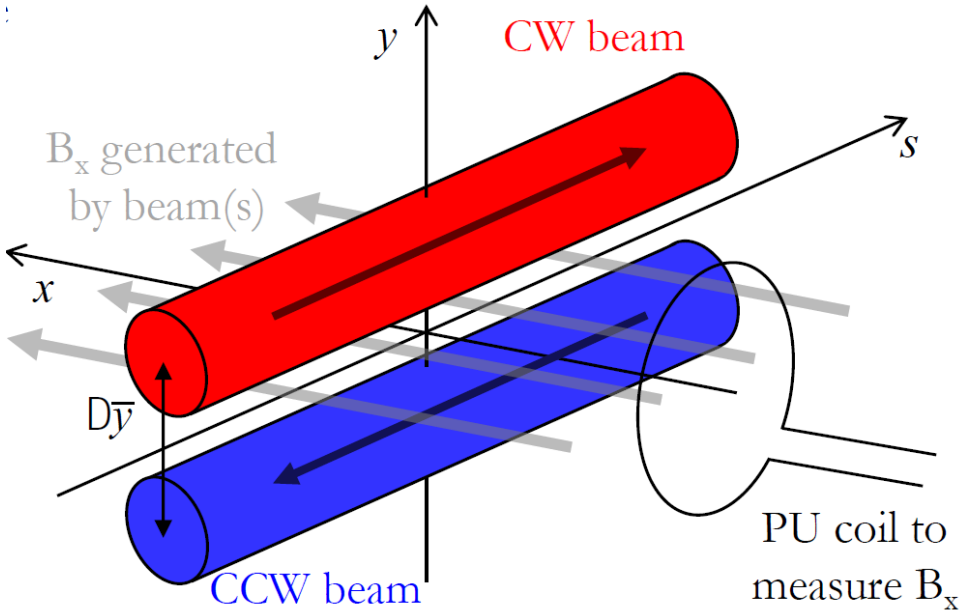
$|\vec{\Omega}_{EDM}| \approx 1.6 \cdot 10^{-9}\,\mathrm{rad/s}$

→ **requires long (polarization) lifetime, at least 1000s**

Bending radius (beam): $R \approx 42\,\mathrm{m}$

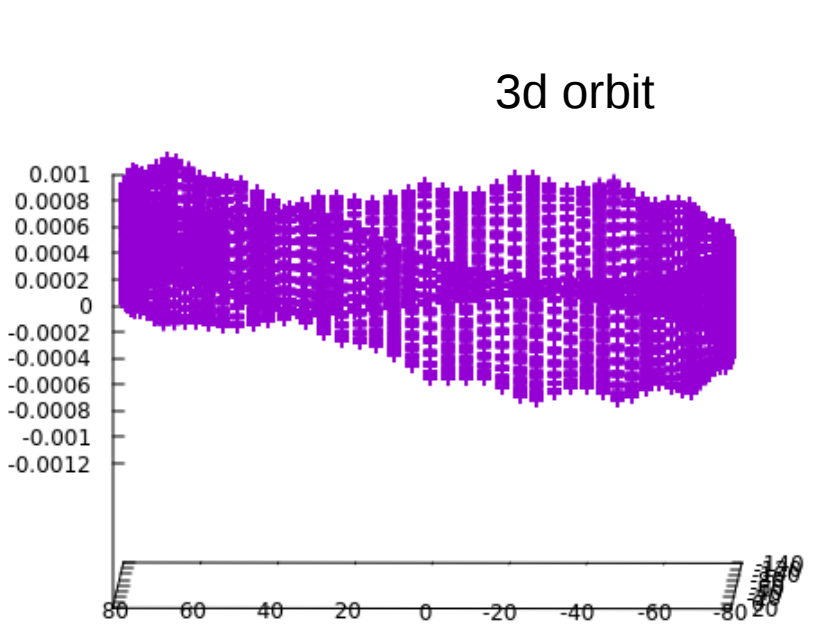
Systematic Error: Radial B-field

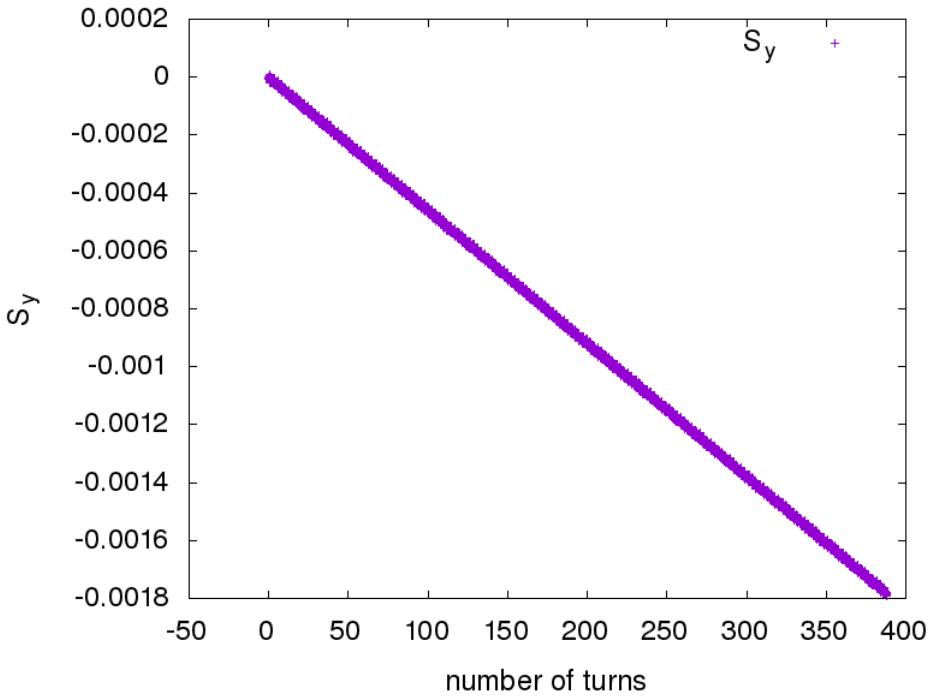
- Main systematic error: radial magnetic field (few aT)
- Strategy: Shield as good as possible, use CW/CCW beams
- Radial B-field separates beams vertically
- Separation can be measured with squids
- Requires: **equal beams, low vertical tune, symmetric lattice**
- Radial B-field from off-center passage through rf-cavity can be distinguished from EDM effect with CW/CCW beams



Systematic Error: Quadrupole Offsets

- Other source of vertical spin build-up: Vertical quadrupole offset
- Distorts orbit in 3d → average vertical velocity nonzero in deflectors
- Only seen with radial spin component → **use also transversely polarized bunches,** effect cancels with CW/CCW operation

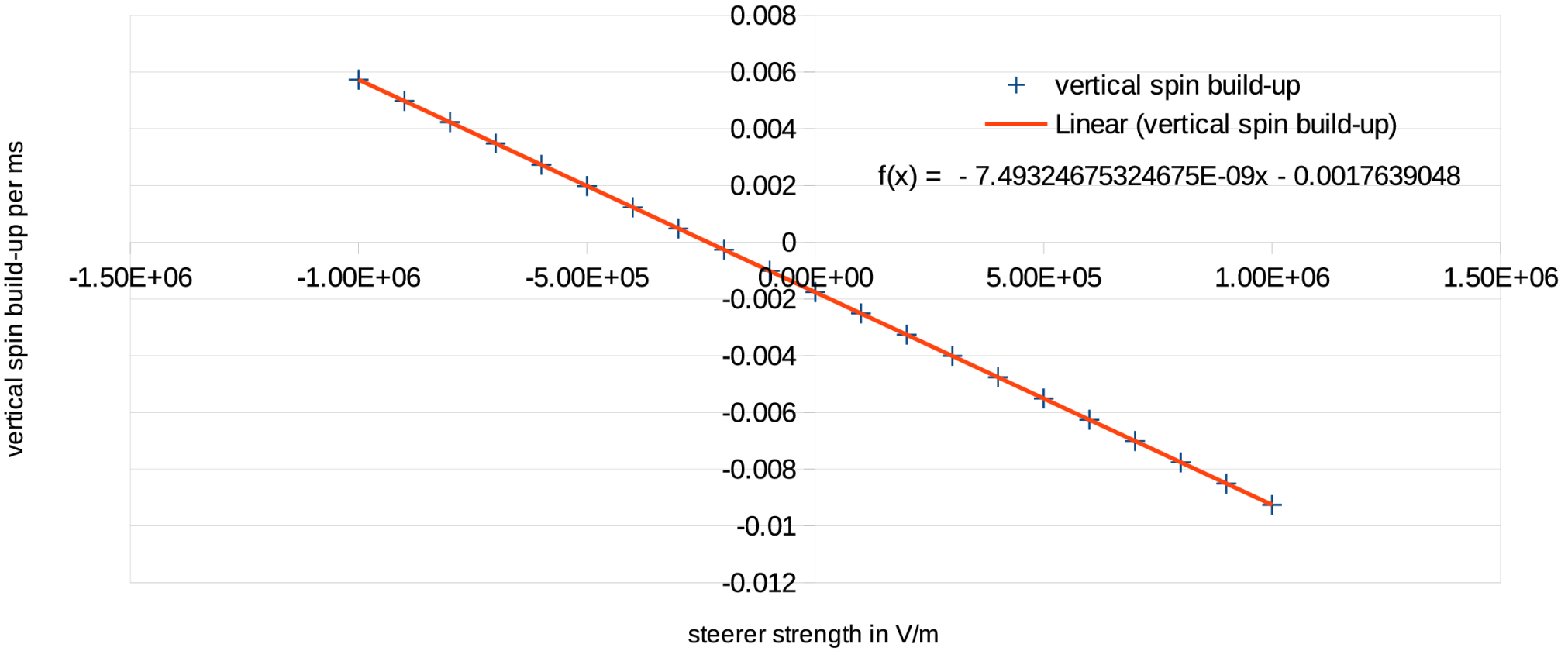




All quads randomly offset by 0.1 mm, simulated for 1 ms, start on design orbit

Correct for Quadrupole Offsets: Use Steerer

Solution: Add vertical steerer to lattice (length 0.5m)



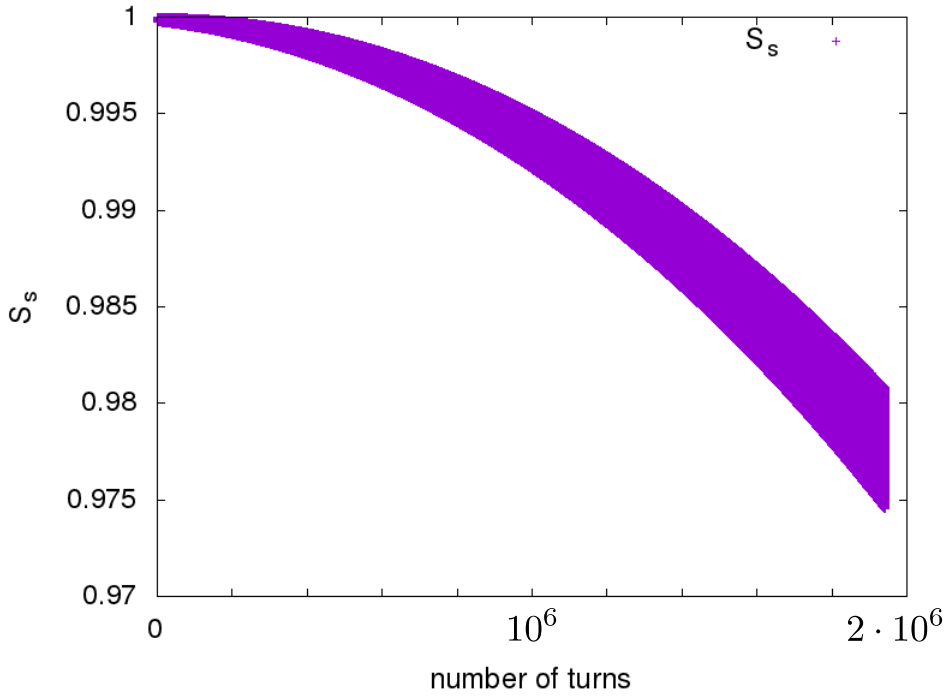
Spin Coherence Time

Perfect ring:

- Design particle has frozen spin
- Particle at magic momentum started from position off axis will oscillate
- If it oscillates around design orbit the orbit becomes longer → need higher energy to keep revolution frequency → off magic momentum → spin rotates
- Other option: oscillate about a different equilibrium orbit (negative average x-position) → off magic momentum inside field regions → spin rotates
- Betatron oscillations limit spin coherence time (SCT)

Spin Coherence Time

Simulate particle at magic momentum with initial x- and y-offset in straight section of 10mm for T = 5s:



Estimate precession rate:

$$\cos(\omega_y T) \approx 0.978$$

$$\Rightarrow \omega_y = \frac{\arccos(0.978)}{5\,\mathrm{s}} = 0.042\,1/\mathrm{s}$$

How long does it take for a 90° rotation?

$$\cos(\omega_y t) = 0$$

$$\Rightarrow t = \frac{\arccos(0)}{\omega_y} = 37.4\,\mathrm{s}$$

→ Very rough estimate for SCT: 10s-100s (depends on phase space distributions)

→ **need to make it longer by factor 10**

Summary

- Very interesting but challenging experiment for CERN/Physics Beyond Colliders Program
- Dominated by systematics
- Need high accuracy and proper beam instrumentation
- Need high quality simulations
- Have lots of experience in Jülich with deuteron EDM experiment (compare with talks of V. Schmidt, T. Wagner, K. Grigoriev)
- Looks prudent to build prototype (check lifetime, test components, etc.)

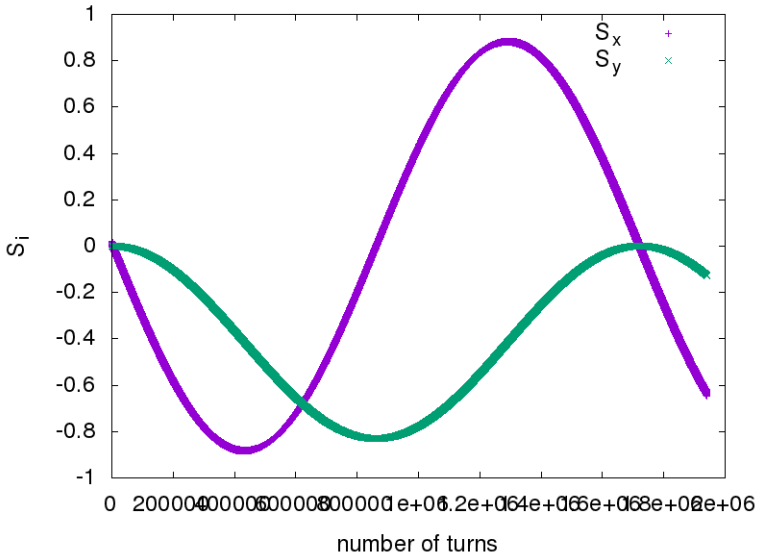
Influence of Imperfections

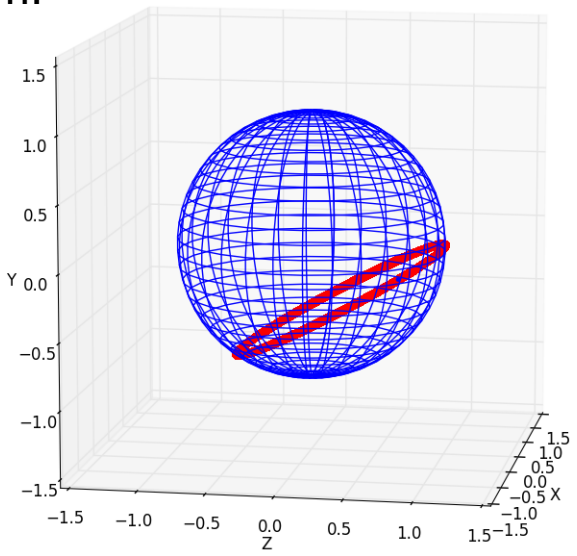
Simulate exactly the same situation as before but with some changes to the ring:

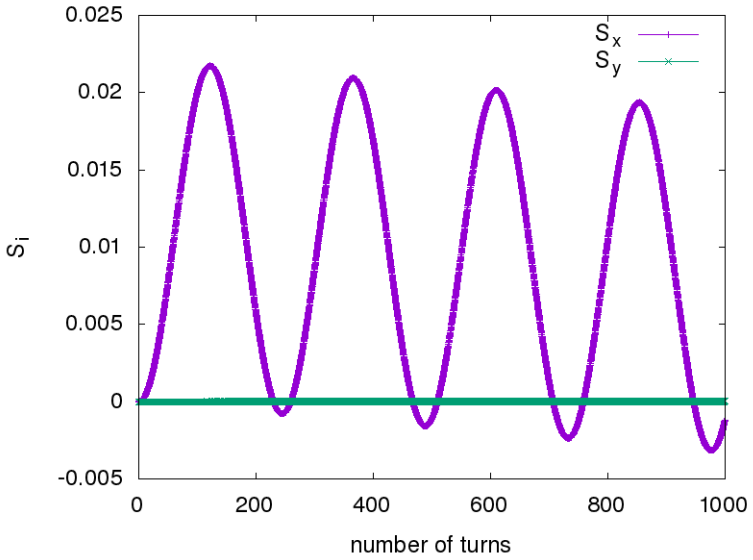
- Randomly misplace all quadrupoles, horizontally and vertically with one sigma offset = 10µm
- Randomly rotate all quads and bends with one sigma rotation of 10µrad
- Randomly change field strength of all elements with one sigma relative field change of 1e-5

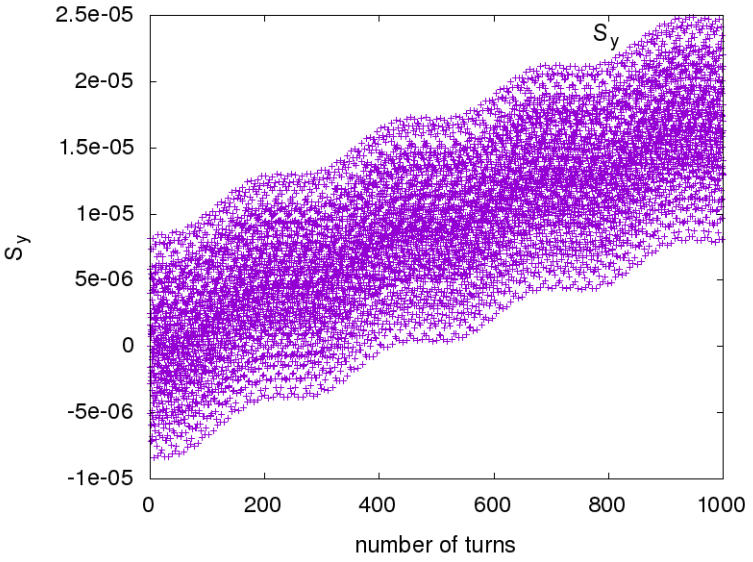
Influence of Imperfections

Particle started on the design orbit with magic momentum:









Influence of Imperfections

Particle started on the design orbit with magic momentum:

- Get extremely large vertical precession rate (compared to expected nrad/s EDM signal)!
  → **need feedback system**
- May not look that bad in shorter (1ms) simulations!
  → **requires (numerically) stable long term tracking**
- Cavity needs to be adjusted to freeze horizontal spin → happens only after 1-2 seconds of data taking
  → **need very high temporal stability of accelerator!**
- **CW/CCW beams will cancel error to large degree**