Determination of the Invariant Spin Axis in a COSY model using Bmad

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Motivation - Matter/Antimatter Asymmetry

- Big Bang:
  Equal amount of matter & antimatter

$$N_B = N_{\bar{B}}$$

$\Downarrow$

- Early universe:
  Asymmetric annihilation process $B + \bar{B} \rightarrow \gamma\gamma + \ldots$

$\Downarrow$

- Today:
  Asymmetry between matter and antimatter.

Sakharov Criteria:

1. Baryon number violation
2. No thermal equilibrium
3. C and CP-Violation

Asymmetry	from SCM	measured
$(N_B - N_{\bar{B}})/N_\gamma$	10^{-18}	10^{-10}

$\Rightarrow$ According to A. Sakharov: More CP Violation is needed

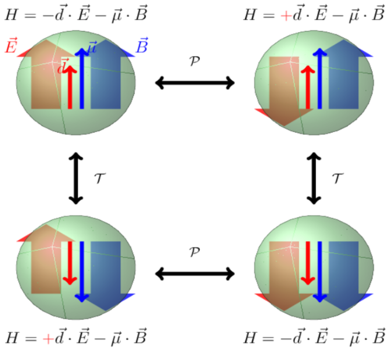
EDM - Electric Dipole Moment

- EDM and MDM are fundamental properties of elementary particles:

$$\vec{d} = d \cdot \vec{S} = \eta_{EDM} \frac{e}{2mc} \vec{S}$$

$$\vec{\mu} = \mu \cdot \vec{S} = g_{MDM} \frac{e}{2mc} \vec{S}$$

- EDM violates **P** and **CP** symmetry assuming **CPT Theorem** holds!
  $\Rightarrow$ no finite EDM measured so far
  $\Rightarrow$ candidate for more CP violation than established in SM



- EDM measurement of various particles necessary to test different mechanism.

Thomas-BMT - Spin Dynamics

- Evolution of spin motion in a storage ring is described by **Thomas-BMT Equation**.
- One is able to seperate spin precession due to MDM and due to EDM.
- In a pure magnetic storage ring the magnetic field $\vec{B}$ field is applied vertically:
  - MDM causes in storage ring plane precession.
  - EDM causes a **fast vertical** precession (out of storage ring plane) with **small** amplitude.

$$\frac{d\vec{S}}{dt} = (\vec{\Omega}_{MDM} + \vec{\Omega}_{EDM}) \times \vec{S} = \frac{q}{m}\left(G\vec{B} + \frac{\eta}{2}\vec{\beta} \times \vec{B}\right) \times \vec{S}$$

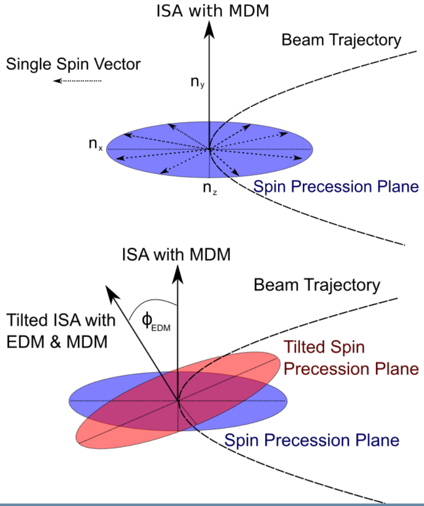
- In plane spin precession takes place around the **ISA (Invariant Spin Axis)** $\vec{n}_{ISA}$.

ISA - Invariant Spin Axis

- Spin vectors are aligned with ISA
  $\Rightarrow$ No spin precession!
- Spin vectors are not aligned with ISA:
  - MDM: Precession in ring plane
  - EDM: **Permanent ISA tilt** in radial direction and precession **out of** ring plane

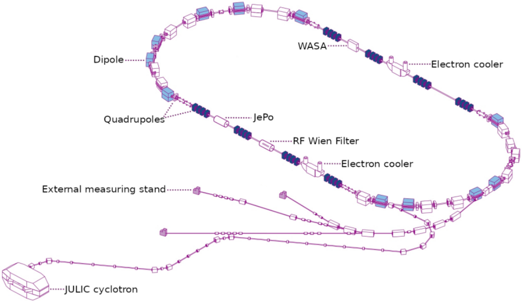
$$\phi_{EDM} = \arctan\left(\frac{\eta_{EDM}\beta}{2G}\right)$$

$$\vec{n}_{ISA} \approx \begin{pmatrix} \phi_{EDM} + \phi_{Ring} \\ 1 \\ \xi_{Ring} \end{pmatrix}$$



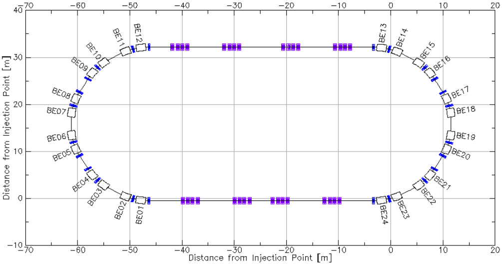
COSY - COoler SYnchrotron

- Circumference $184\,\mathrm{m}$
- **Polarized**/Unpolarized **Deuterons** and Protons
- $p = 0.30 - 3.70\,\mathrm{GeV/c}$
- **Internal** and external experiments
- Stored particles/cycle $N \approx 10^9$
- 2 Electron Coolers
- $p_{Deuteron} = 0.970\,\mathrm{GeV/c}$
  - Electron Cooler is operating at that energy



Simulation - Bmad Model of COSY

- 24 **Dipoles** including
  Fringe Field and Field Errors
  - Large impact on hor. Orbit
- 56 idealized **Quadrupoles**
- Approx. 30 hor./ver. **BPMs**
- Approx. 20 hor./ver. **Steerers**
  - Minimize systematic Orbit observed by BPM
  - Correct systematic orbit from misaligned magnets.

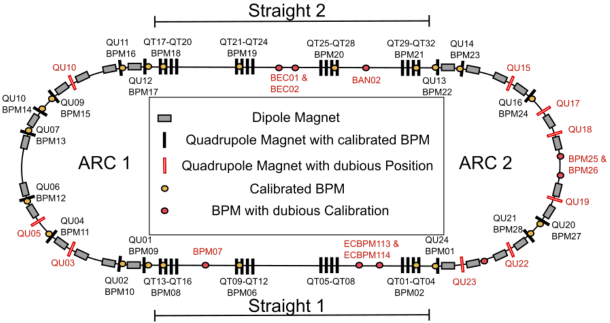


- **Challenge:** Simulate the systematic orbit, seen by BPM!
  - Position of BPM center and quadrupole center to design orbit of COSY is unknown!

Magnet Alignment Campaigns

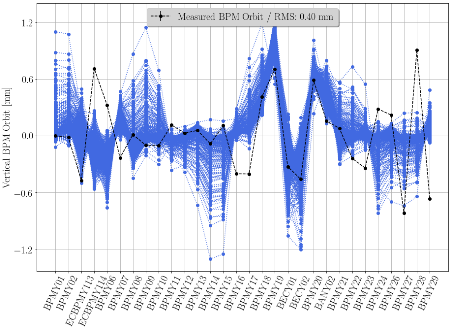
- Two different measurement campaigns have been performed:
  - **BBA**: Identify **relative position** quadrupole to BPM center (BBA Group: BPM + Quads)!
  - **LB**: Laser based measurement of **magnet frame** orientation (individual Quad)!

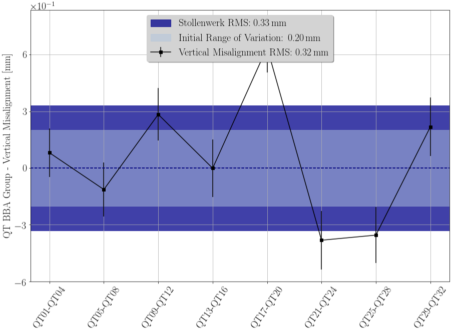
- Precision of BBA (Group): $\pm 40\ \mu$m
- Precision of LB (individual Quad): $\pm 200\ \mu$m
- **Overall Problem**:
  - Simulation demands absolute alignment
  - Rel. Alignment $\neq$ Abs. Alignment



Optimization of BPM Orbit

- Vary misalignments of Quads, BPMs and BBA Groups within given precision.
- **Optimizer**: Bring BPM orbit to zero by adjusting misalignments of the BBA Groups!

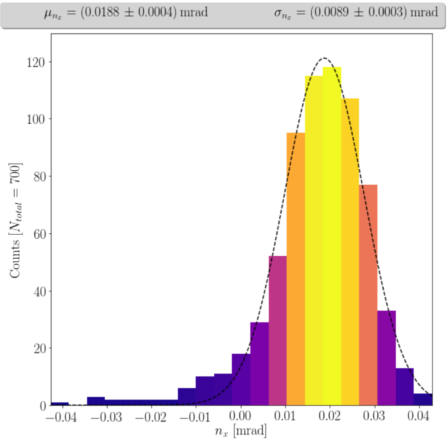




- Apart from a few BPM values, **simulation and measurement** match well!

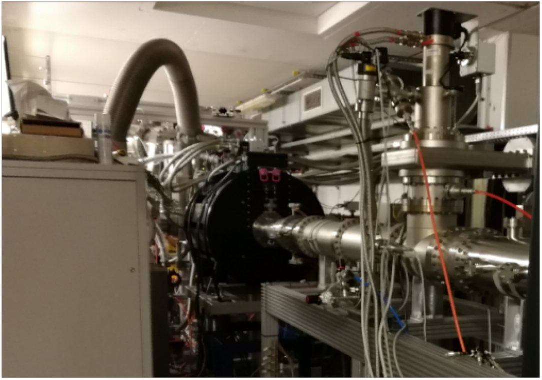
Results - Simulation vs. Experiment

- Bmad Simulation predicts the rad. and lon. ISA to be **well below** 0.1 mrad.
- The experiment measures ISA in **mrad range** (2-5 mrad).
- Such large ISA tilts require an absolut vertical orbit of ± 20 mm.
- Bmad Simulation confirms that experiment **does not** measure the ISA!



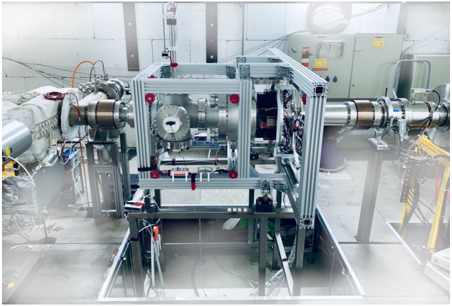
- Research is ongoing, what causes the problem in the experimental procedure.

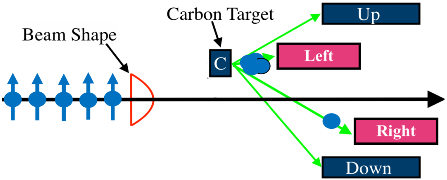
Appendix - Solenoid



- Provides longitudinal magnetic field:
  - Used to rotate polarization in horizontal plane (RF Solenoid).
  - Also provides compensation field (Snake Solenoid / 2 MeV Solenoid).

Appendix - JEPO - JEdi POlarimeter

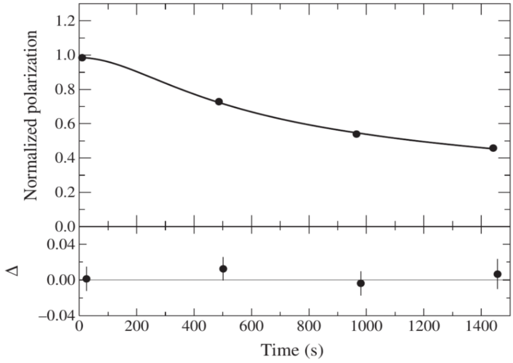




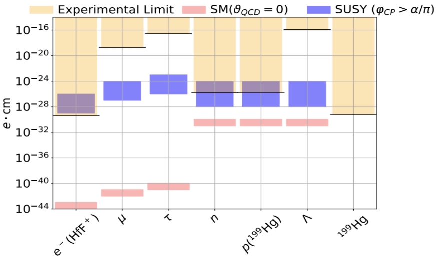
- JEPO for Determination of Beam Polarization:
  - Left-Right Assymetry indicates vertical Polarization
  - Up-Down Assymetry indicates horizontal Polarization

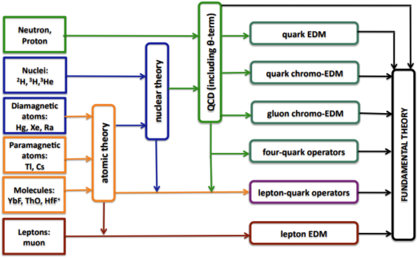
Appendix - SCT - Spin Coherence Time

- τ_{SCT} defines time until initial polarization falls below 1/e.
- Precise adjustments of three sextupole families in the ring.
- In COSY τ_{SCT} of over 1000 seconds with about 10^9 stored deuterons achieved.
- Large value of τ_{SCT} of crucial importance, since $\sigma_{stat} \propto \tau_{SCT}^{-1}$.
- Build-up time to observe polarization $P_y(t)$ limited by τ_{SCT}.



EDM - Ongoing Research



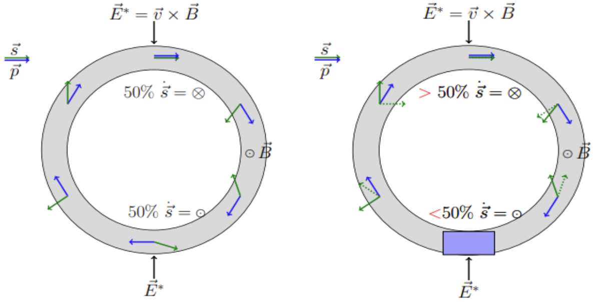


J. de Vries

- No finite EDM found yet. No direct measurement on charged hadrons.
- EDM measurement of various particles necessary to test different mechanism.

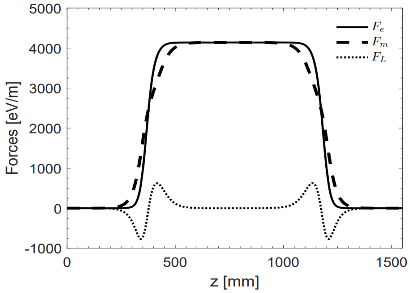
ISA - Measurement Principle

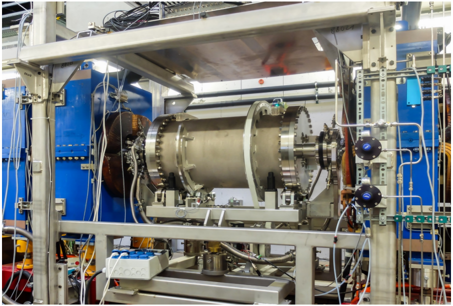
- Observable quantity is polarization: $\vec{P} = 1/n \sum \vec{S}$.
- **Problem**: No net EDM effect observable
  50% of revolution time polarization is $||$ to momentum
  50% of revolution time polarization is anti-$||$ to momentum.



- **Solution**:
  Utilize resonant device:
  $\rightarrow$ No impact on orbit
  $\rightarrow$ Impact on spin precession
- Net EDM effect can be observed!

Spin Manipulator - RF (Radiofrequency) Wien Filter

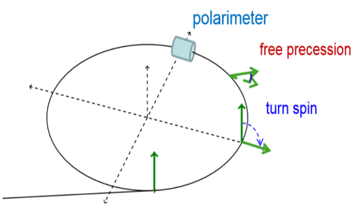




- RF device with E-Field and B-Field, tuned to spin precession frequency ω.
  - Rad. E-field: $E_x \propto \cos(\omega t + \phi_{rel})$
  - Ver. M-field: $B_y \propto \cos(\omega t + \phi_{rel})$
- Lorentz Force in the center vanishes. Beam Orbit is not perturbated.

ISA - Measurement Set-Up

- Inject vertically polarized deuteron beam.
- **RF Solenoid**:
  Rotate polarization into accelerator plane.
- **Radiofrequency Wien-Filter (WF)**:
  Resonant device tuned to spin precession.
  Macroscopic build-up of vertical polarization.
- **Polarimeter**:
  Measure build-up of vertical polarization.

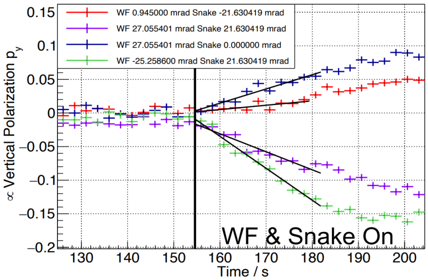


- Challenges:
  - Ring imperfections cause systematic effects
  - Compensation via static solenoid ξ_{Sol}

$$\vec{n}_{ISA} \approx \begin{pmatrix} \phi_{EDM} + \phi_{Ring} \\ 1 \\ \xi_{Sol} + \xi_{Ring} \end{pmatrix}$$

Vertical Build Up with WF and Solenoid

- Vertical build up $\frac{d}{dt}p_y(t)$ depends on:
  - WF fields $\vec{n}_{WF}$ relative to ISA $\vec{n}_{ISA}$
  - Static solenoid strength
- Compensation of radial systematics by **rotating WF** by angle ϕ_{WF}
- Compensation of long. systematics by **adjusting solenoid** field ξ_{Sol}



$$\frac{d}{dt}p_y(t) \propto \left|\vec{n}_{WF} \times \vec{n}_{ISA}\right|^2 = \left| \begin{pmatrix} \phi_{WF} \\ 1 \\ 0 \end{pmatrix} \times \begin{pmatrix} \phi_{EDM} + \phi_{Ring} \\ 1 \\ \xi_{Sol} + \xi_{Ring} \end{pmatrix} \right|^2$$

$$= \left((\phi_{EDM} + \phi_{Ring}) - \phi_{WF}\right)^2 + \left(\xi_{Sol} + \xi_{Ring}\right)^2$$

Learnings from BBA

- BBA: Identification of the **relative position** of quadrupole center to BPM center!
- Only possible if quadrupole is in vicinity of BPM:
  - **Straights:** Quadrupole tripplets can be seen as one unit (4x Quads, 1x BPM).
  - **Arcs:** Equal distribution over arc only allows one to one match up (1x Quad, 1x BPM).
- Precision of alignment: $\pm 40\,\mu$m
- **Problems**:
  - No partner in vicinity of some BPMs/Quads
  - Rel. Alignment $\neq$ Abs. Alignment