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 processes $B + \bar{B} \rightarrow \gamma\gamma + \dots$

$\Downarrow$

- Today:
  Asymmetry between matter and antimatter.

Sakharov Criteria:

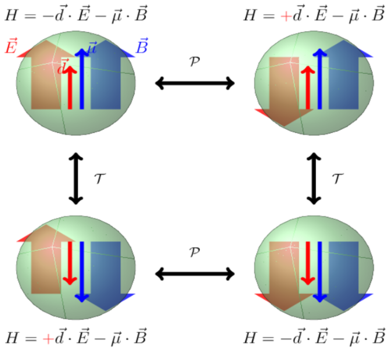
1. Baryon number violation
2. No thermal equilibrium
3. C and CP-Violation

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

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

EDM - Electric Dipole Moment

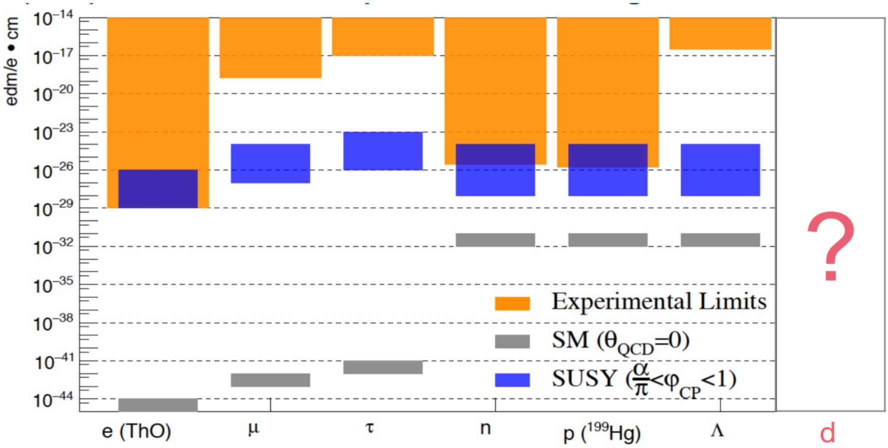
- Fundamental property of a elementary particle:
  $\vec{d} = d \cdot \vec{S} = \frac{\eta}{2}\frac{e}{m}\vec{S}$
- Similar to the MDM (Magnetic Dipole Moment):
  $\vec{\mu} = \mu \cdot \vec{S} = \frac{g}{2}\frac{e}{m}\vec{S}$



$$\hat{\mathcal{H}} = -d\cdot\vec{S}\cdot\vec{E} - \mu\cdot\vec{S}\cdot\vec{B}$$
$$\mathcal{P}(\hat{\mathcal{H}}) = +d\cdot\vec{S}\cdot\vec{E} - \mu\cdot\vec{S}\cdot\vec{B}$$
$$\mathcal{T}(\hat{\mathcal{H}}) = +d\cdot\vec{S}\cdot\vec{E} - \mu\cdot\vec{S}\cdot\vec{B}$$

- EDM violates both P and CP symmetry assuming CPT Theorem holds
- EDM is a probe for CP violation beyond the SM

EDM Limits



edm/e • cm
10^{-14}
10^{-17}
10^{-20}
10^{-23}
10^{-26}
10^{-29}
10^{-32}
10^{-35}
10^{-38}
10^{-41}
10^{-44}
Experimental Limits
SM (θ_{QCD}=0)
SUSY ($\frac{\alpha}{\pi}<\varphi_{CP}<1$)
?
e (ThO)
μ
τ
n
p (^{199}Hg)
Λ
d

Spin Dynamics in a Storage Rings

- The EDM of charged particles can be measured by studying the spin motion of particles in a storage ring.
- Evolution of spin motion in a storage ring is described by the **Thomas-BMT Equation** defined by MDM and EDM contributions.
- As in a pure magnetic storage rings the magnetic field $\vec{B}$ field is applied vertically
  - MDM causes in plane precession.
  - EDM causes out of plane precession.

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

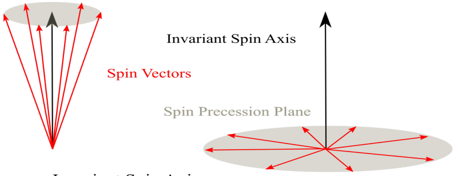
- In plane spin precession takes place around the **ISA (Invariant Spin Axis)** $\vec{n}_{ISA}$.

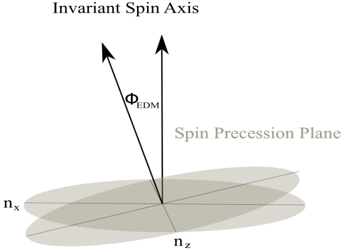
Invariant Spin Axis

- No spin precession when spin vectors are aligned with ISA.
- Due to MDM, spin precesses in horizontal plane when not aligned with ISA.
- Due to EDM, the ISA is tilted in the radial direction n_x:

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

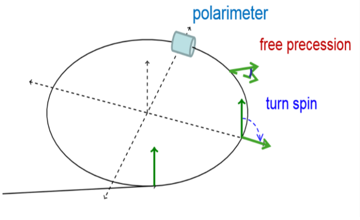
$$\vec{n}_{ISA} = \begin{pmatrix} \sin\phi_{EDM} \\ \cos\phi_{EDM} \\ 0 \end{pmatrix} \approx \begin{pmatrix} \phi_{EDM} \\ 1 \\ 0 \end{pmatrix}$$





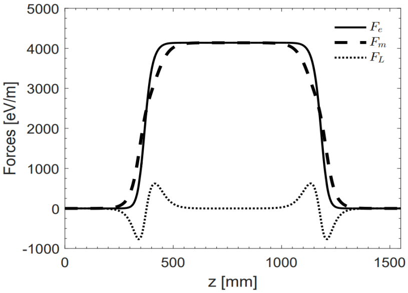
Measurement Principle of ISA

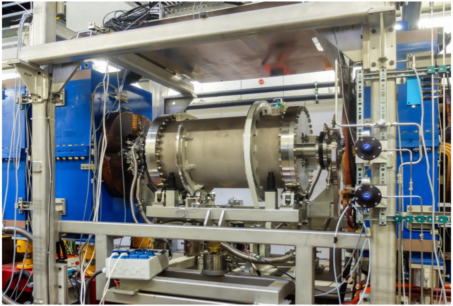
- Inject vertically polarized deuteron beam.
- **Solenoid**: Rotate polarization into accelerator plane. Also used to compensate long. fields.
- Polarization vector precesses in accelerator plane around ISA.
- **Wien-Filter**: RF Device for torque on EDM. Originally in-plane polarization goes out-of-plane.
- **Polarimeter**: Measure build-up of vertical polarization.
- Challenges:
  - Sufficient Spin Coherence Time
  - Ring imperfections cause systematic effects



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

Radiofrequency (RF) Wien Filter



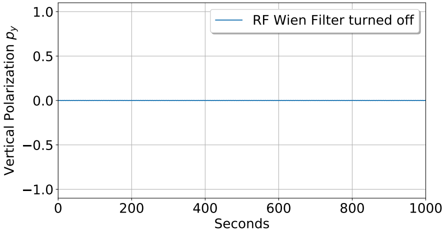


- RF device with E-Field and B-Field, tuned to spin precession frequency ω.
  - Rad. E-field: $E_x \propto \cos\left(\omega t + \phi_{rel}\right)$
  - Ver. M-field: $B_y \propto \cos\left(\omega t + \phi_{rel}\right)$
- Lorentz Force in the center vanishes. Beam Orbit is not perturbated.

Resonant Wien Filter Method

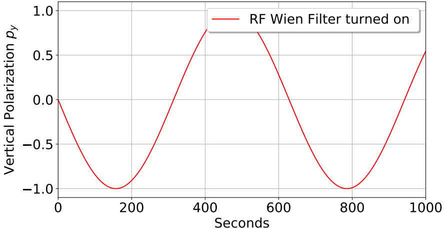
- **RF Wien Filter not included:**
  In plane spin precession due to MDM, small, fast oscillating vertical polarization due to EDM.

⇒ No net build up of vertical polarization measurable.



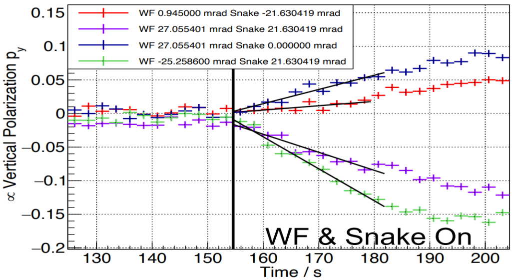
- **RF Wien Filter included:**
  As its tuned to spin precession frequency and used to accumulate the EDM signal.

⇒ Enhanced oscillation, therefore net build up of vertical polarization measurable.



Vertical Polarization Build Up

- Build up $\epsilon \propto \frac{d}{dt} p_y(t)$ depends on orientation of ISA $\vec{n}_{ISA}$ to Wien Filter Fields $\vec{n}_{WF}$ and compensation of long. fields via Solenoid.
- To compensate EDM signal and radial systematics the Wien filter is **rotated** by an angle ϕ_{WF} around beam.

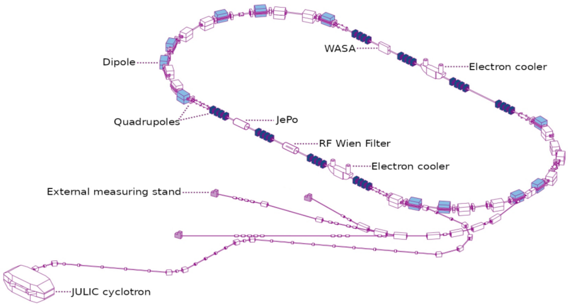


$$\epsilon^2(\phi_{WF}, \xi_{Sol}) \propto |\vec{n}_{WF} \times \vec{n}_{ISA}|^2 = \left| \begin{pmatrix} \phi_{WF} \\ 1 \\ 0 \end{pmatrix} \times \begin{pmatrix} \phi_{EDM} + \phi_{Ring} \\ 1 \\ \xi_{Sol} + \xi_{Ring} \end{pmatrix} \right|^2$$

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

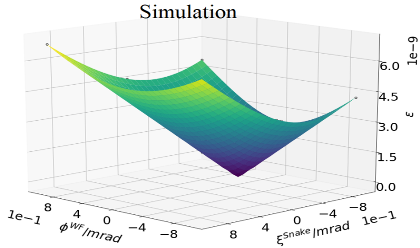
COSY - COoler SYnchrotron

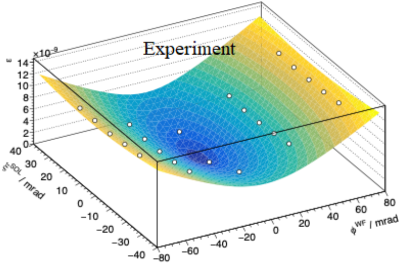
- Circumference 184 m
- Accelerates and Stores **Polarized**/Unpolarized **Deuterons** and Protons
- $p = 0.3 - 3.7$ GeV/c
- **Internal** and external experiments
- Hadron Physics/**Precision** Experiments
- 2 **Electron** Coolers
- 1 **Stochastic** Coolers



Precursor Runs

- Direct Measurement of deuteron EDM performed in the two so called precursor runs by the JEDI-Collaboration.
- Exp. Res.: $\phi_{WF} \approx -1.76(1)$ mrad , $\xi_{Sol} \approx +5.53(4)$ mrad
  Sim. Res.: $\phi_{WF} \approx -0.1119(3)$ mrad, $\xi_{Sol} \approx -0.3697(3)$ mrad



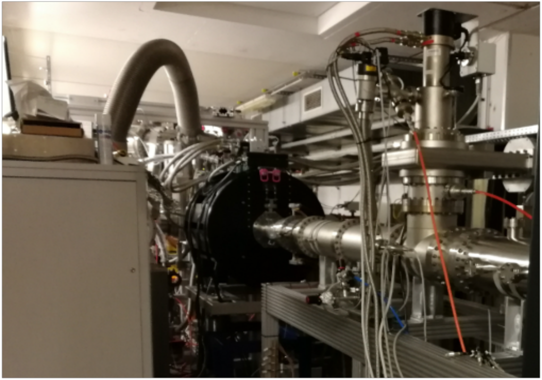


- Differences are yet to be explained. One problem is that the fit is only correct if Beam $\| \vec{B}_{sol}$, also the simulation model needs improvements e.g. the orbit.

Summary and Outlook

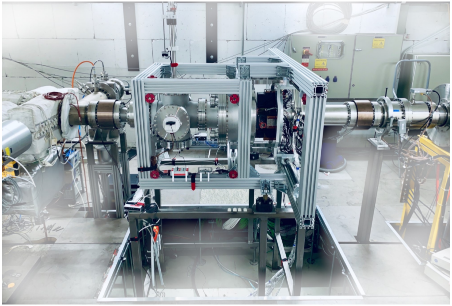
- EDMs of charged particles can be directly measured in storage rings. An **RF Wien Filter** device can be used for such a purpose to causes a net build-up of vertical polarization.
- The **Invariant Spin Axis** is the observable for the EDM magitude. It is impacted by the EDM as well as **ring imperfections**.
- The results of the precurser runs can yet not be explained within the simulation. Further improvements on the **simulation model** as well in determining **correction factors** for non ideal trajectories through the devices are needed.
- A **new beam time** is planned for this purpose within the next months.

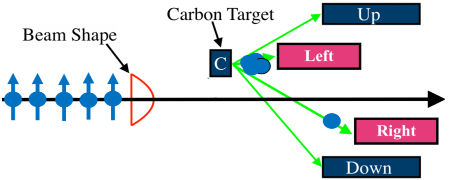
Appendix - Siberian Snake - Solenoid



- Provides longitudinal magnetic field:
  - Used to rotate polairzation in horizontal plane.
  - Also provides field to search for the ISA.

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} defined as the 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 $\sigma_{stat} \propto \tau_{SCT}^{-1}$.
- Buildup time t to observe polarization $P_y(t)$ limited by τ_{SCT}.