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

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Motivation

Electric Dipole Moment (EDM) is a fundamental property of a particle, similar to the Magnetic Dipole Moment (MDM).

Source of $\mathcal{P}$ and $\mathcal{T}$ violation ($\stackrel{\mathcal{CPT}}{=}$ $\mathcal{CP}$ violation) and therefore closely connected to **matter/antimatter asymmetry** [1].

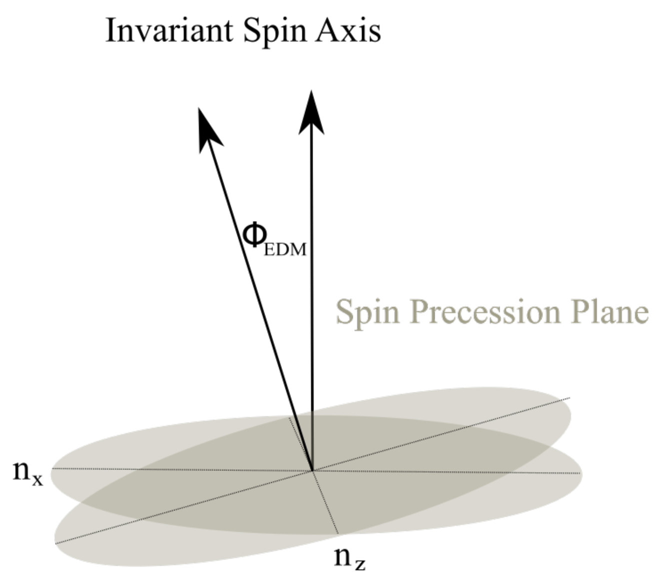
Impacts the spin rotation in a storage ring so EDM of charged particles can be measured by determining the radial **tilt of the ISA** $\vec{n}_{\mathrm{ISA}}$ (Invariant Spin Axis).

Systematic effects $\phi_{\mathrm{Ring}}, \xi_{\mathrm{Ring}}$ induced by magnet misalignments etc. cause similar effects.

Additinally solenoidal fields ξ_{Sol} can be used to influence the longitudinal tilt of the ISA.

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

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



Methodology

Determination of ISA for **deuterons** was performed at the storage ring **COSY** (Cooler Synchrotron) in Jülich by the JEDI (Jülich Electric Dipole moment Investigations) collaboration.

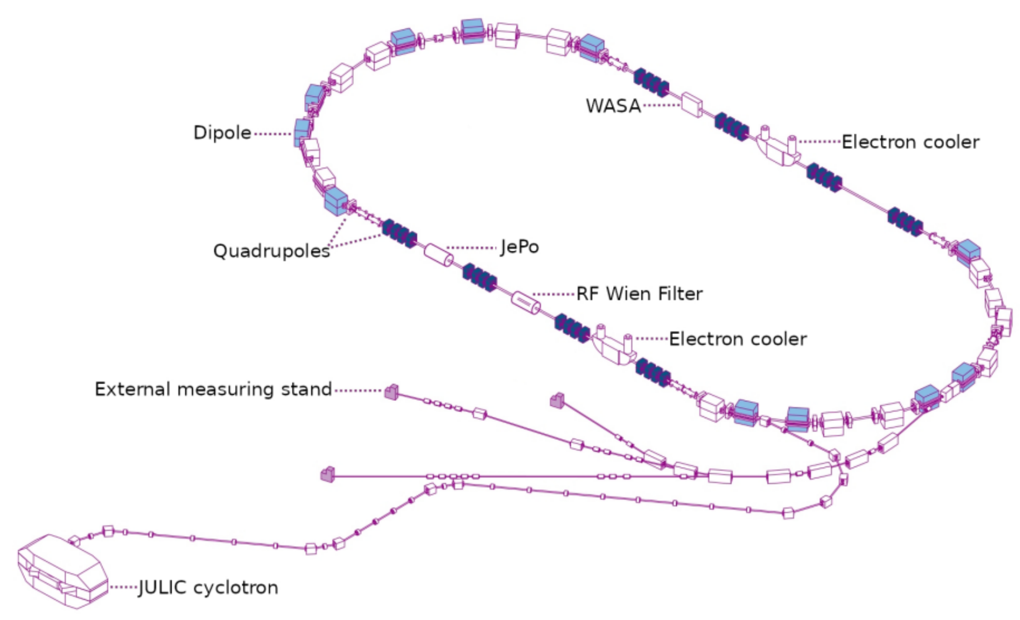
Circumference 184 m.

Accelerates and Stores **Polarized**/Unpolarized **Deuterons** and Protons.

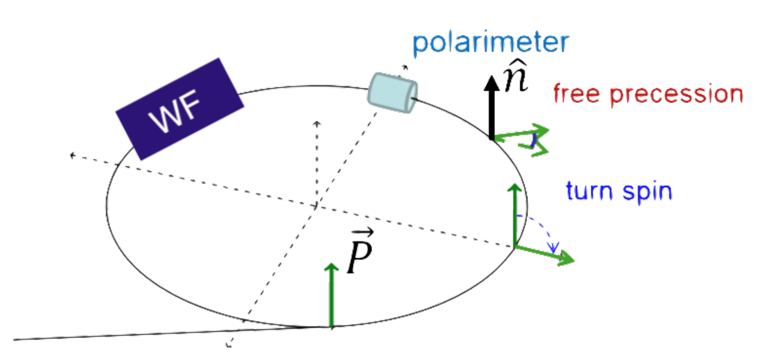
$p = 0.3 - 3.7$ GeV/c

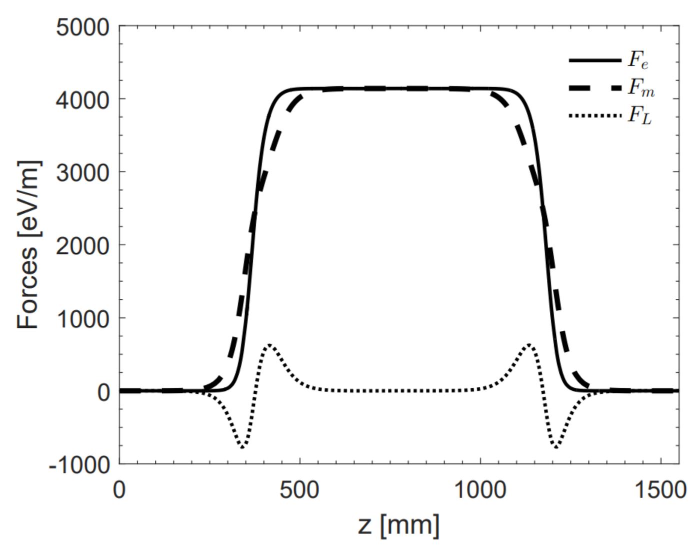
Internal and External Experiments

Electron and Stochastic Cooling available



Operation Principle: injection of vertically polarized deuteron beam ⇒ solenoid to rotate polarization into accelerator plane ⇒ free polarization precession in accelerator plane around ISA ⇒ polarization is constantly measured by a polarimeter.





Measurement of ISA by operating the so-called RF (Radio-Frequency) **Wien Filter**.

The Wien Filter is an RF device with radial electric E_x^{WF} and vertical magnetic field B_y^{WF}.

Fields of RF Wien Filter are set up so Lorentz force is zero in its center and the orbit is not perturbated. Therefore its an ideal spin manipulator.

The Wien filter is changing its fields on one of the harmonics k of the spin precession frequency ν_s.

$$E_x^{\mathrm{WF}} = E_0 \cos(2\pi f_{\mathrm{COSY}} |k + \nu_s| + \phi_{rel})$$
$$B_y^{\mathrm{WF}} = B_0 \cos(2\pi f_{\mathrm{COSY}} |k + \nu_s| + \phi_{rel}).$$

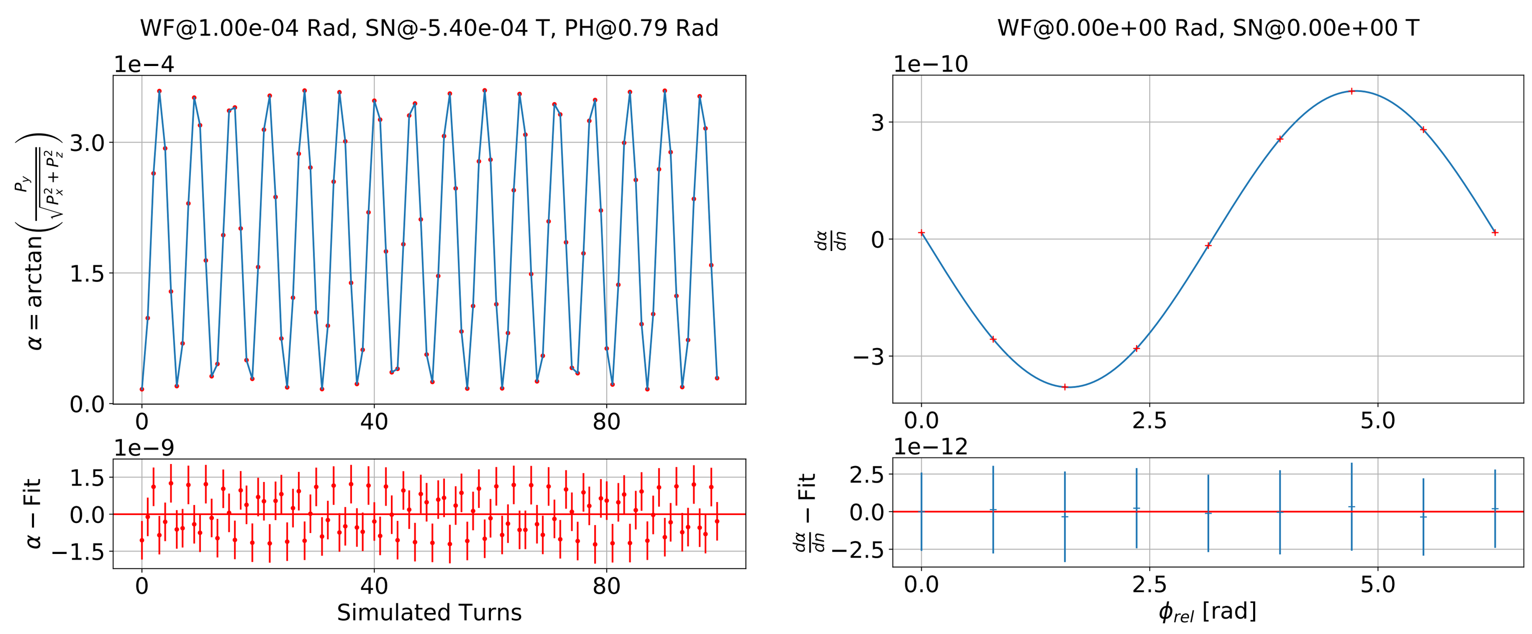
This way a possible EDM signal can **accumulate over time**, resulting in a **build-up of vertical polarization** P_y if the Wien filter runs on resonance [2,3].

The build-up $\epsilon \propto \frac{d}{dn}P_y(n)$ depends on the orientation of ISA $\vec{n}_{\mathrm{ISA}}$ to the Wien filter fields $\vec{n}_{\mathrm{WF}}$ and the compensation of longitudinal fields by solenoids. No build-up occurs in case of $\vec{n}_{\mathrm{WF}} \parallel \vec{n}_{\mathrm{ISA}}$.

EDM Resonance Map

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

The dependence of the build-up ϵ on ϕ_{WF} and ξ_{Sol} is summarized by the **EDM resonance map**. Its minimum indicates the tilt of the ISA at the position of the Wien filter.

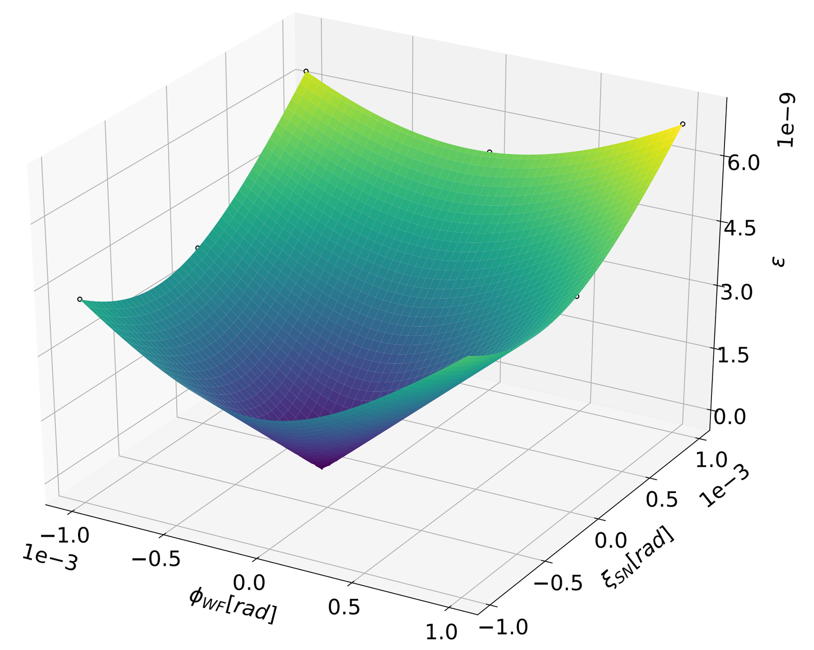


The measurement of the tilt of the ISA to determine the deuteron EDM was performed in 2018 and 2020 in the so-called **precursor runs** (Poster Achim Andres).

Simulations are needed to disentangle a potential EDM signal from systematics.

Therefore a Bmad simulation using all known magnet strengths, misalignments and other systematic effects was written [4].

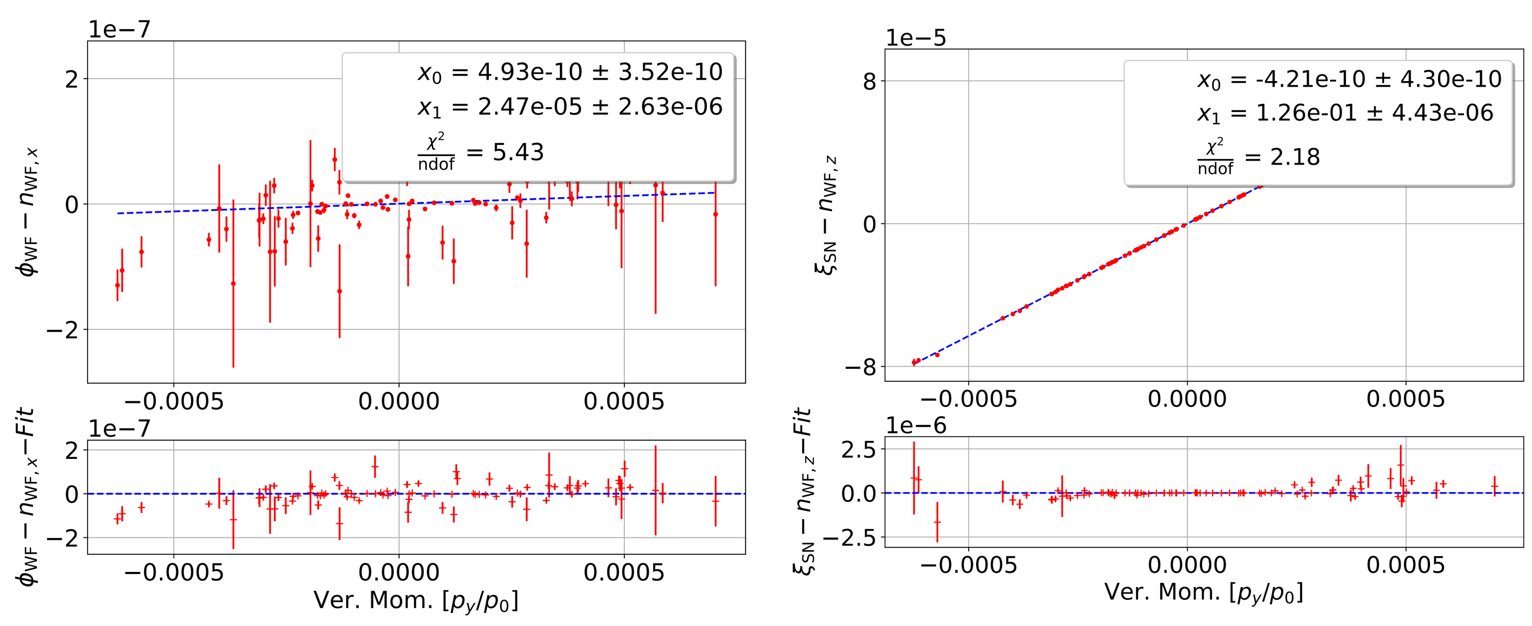
Disagreement between simulation and measurement is currently under investigation.



Method	ϕ_{WF}	ξ_{SN}
Precursor Experiments	-2.91(8) mrad	-5.22(7) mrad
Bmad Simulation	-0.1119(3) mrad	-0.3697(3) mrad

Correction Factors

As the EDM resonance map was derived for an unperturbated orbit, corrections have to be considered to ϕ_{WF}, ξ_{SN} in case the lattice is **distorted** to be in agreement with the tilt of the ISA $n_{\mathrm{WF},x}$, $n_{\mathrm{WF},z}$.



The vertical perturbation of the lattice leads to correction factor $A = \gamma - 1$ which has to be applied to the long. map minimum ξ_{SN}. Research about further corrections in progress.

$$\phi_{WF} = n_z(s_{WF}) \ \wedge \ \xi_{SN} = n_z(s_{WF}) - A \cdot p_y(s_{WF}/P_0)$$

References

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[2] F. Rathmann, A. Saleev, and N. N. Nikolaev, "The search for electric dipole moments of light ions in storage rings", *Journal of Physics: Conference Series, Vol. 45*, 2014, pp. 229–233

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[4] D. C. Sagan, "Bmad: A relativistic charged particle simulation library", *Nuclear Instruments and Methods in Physics Research A, Vol. 558*, 2006, pp. 356-359