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

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Motivation

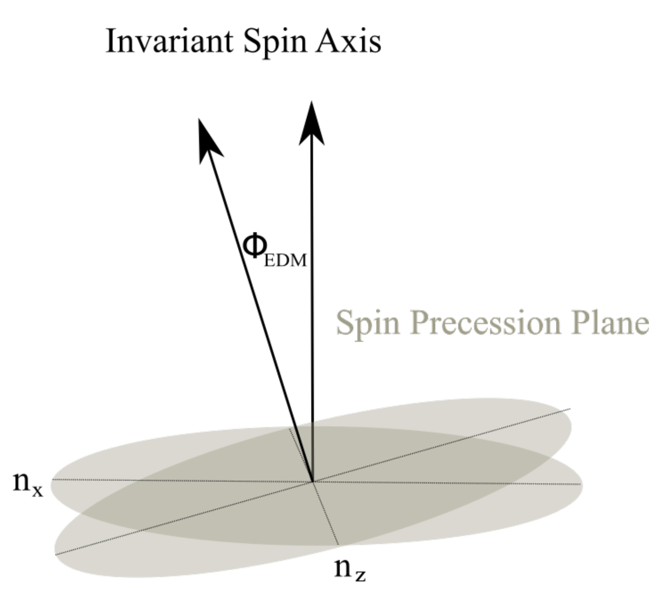
The Electric Dipole Moment (EDM) is a fundamental property of a particle, similar to the Magnetic Dipole Moment (MDM). As a source of $\mathcal{P}$ and $\mathcal{T}$ violation ($\overset{\mathcal{CPT}}{=}$ $\mathcal{CP}$ violation) it is closely connected to **matter/antimatter asymmetry** [1].

As it has an impact on the spin rotation, the EDM of charged particles can be measured in a storage ring by determining the radial **tilt of the ISA** $\vec{n}_{\mathrm{ISA}}$ (Invariant Spin Axis).

Additionally, **systematic effects** $\phi_{\mathrm{Ring}}, \xi_{\mathrm{Ring}}$ caused by magnet misalignments etc. have to be disentangled from a potential EDM signal. Solenoidal fields ξ_{Sol} can directly 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

A determination of the tilt of the ISA was performed at the storage ring **COSY** (Cooler Synchrotron) in Jülich by the JEDI (Jülich Electric Dipole moment Investigations) collaboration for the first measurement of the **deuteron EDM**.

To measure the tilt of radial and longitudinal ISA simultaneously, the so-called RF (Radio-Frequency) **Wien filter**, an RF device with radial electric E_x^{WF} and vertical magnetic field B_y^{WF} was implemented into COSY.

While the orbit in the center of this device is not perturbed, as the fields are set up so that the Lorentz force is zero, the particles receive a phase dependend spin kick each turn. The Wien filter is changing its fields on one of the harmonics k of the spin precession frequency ν_s.

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

Using this device, the 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 $\epsilon \propto \frac{d}{dt}P_y(t)$ depends on the orientation of ISA $\vec{n}_{\mathrm{ISA}}$ to the Wien filter fields $\vec{n}_{\mathrm{WF}}$ and the longitudinal fields by solenoids. By rotating the Wien filter is by an angle ϕ_{WF} around the beam it can be matched to the radial tilt of the ISA.

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

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.

Another method to determine the longitudinal ISA can be used complementary. By observing the spin tune changes $\Delta\nu_s$ in dependency of the solenoidal strength B_{Sol} the **projection of the longitudinal ISA** c_{Sol} at position of the solenoid as well as the solenoid calibration factor k_{Sol}, giving the relation between solenoidal field B_{Sol} and spin kick $\xi_{\mathrm{Sol}} = k_{\mathrm{Sol}} \cdot B_{\mathrm{Sol}}$ can be measured [4].

$$\Delta\nu_s = -\frac{1}{\pi}\left(\cot(\pi\nu_s)\left(\cos\frac{k_{\mathrm{Sol}}B_{\mathrm{Sol}}}{2} - 1\right)\right) - c_{\mathrm{Sol}} \sin\frac{k_{\mathrm{Sol}}B_{\mathrm{Sol}}}{2}.$$

References

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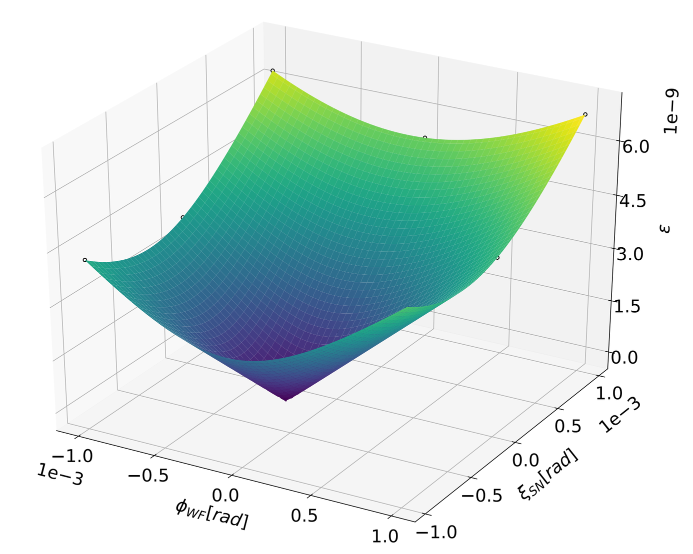
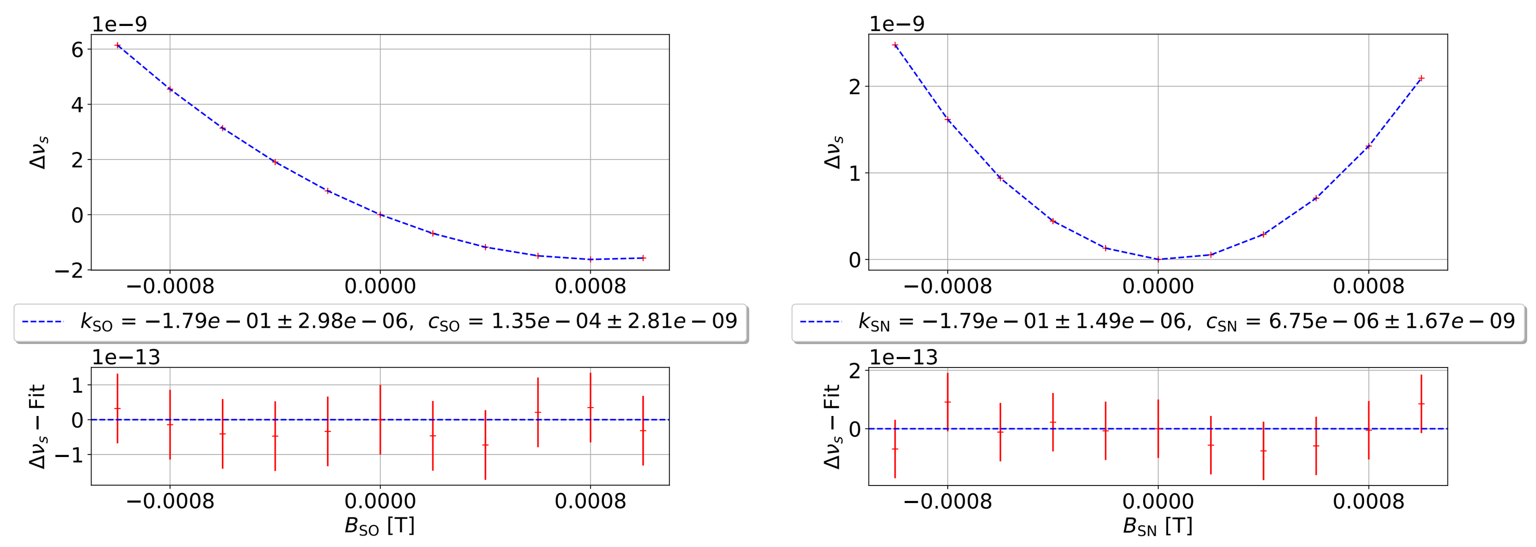
EDM Resonance Map and Solenoid Calibration

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**.

As a simulation is needed to disentangle a potential EDM signal from systematics a Bmad simulation using all known magnet strengths, misalignments and other systematic effects was written. By implementing the Wien filter an EDM resonance map was calculated [5].



During the precursor runs also the projection of the longitudinal ISA was measured experimentally by performing **solenoid calibrations**. Two different solenoid have been used. One was the **Snake-Solenoid** (lower right graph), which also contributed to the EDM resonance map, the other one was the so-called the **2MeV-Solenoid** (lower left graph).



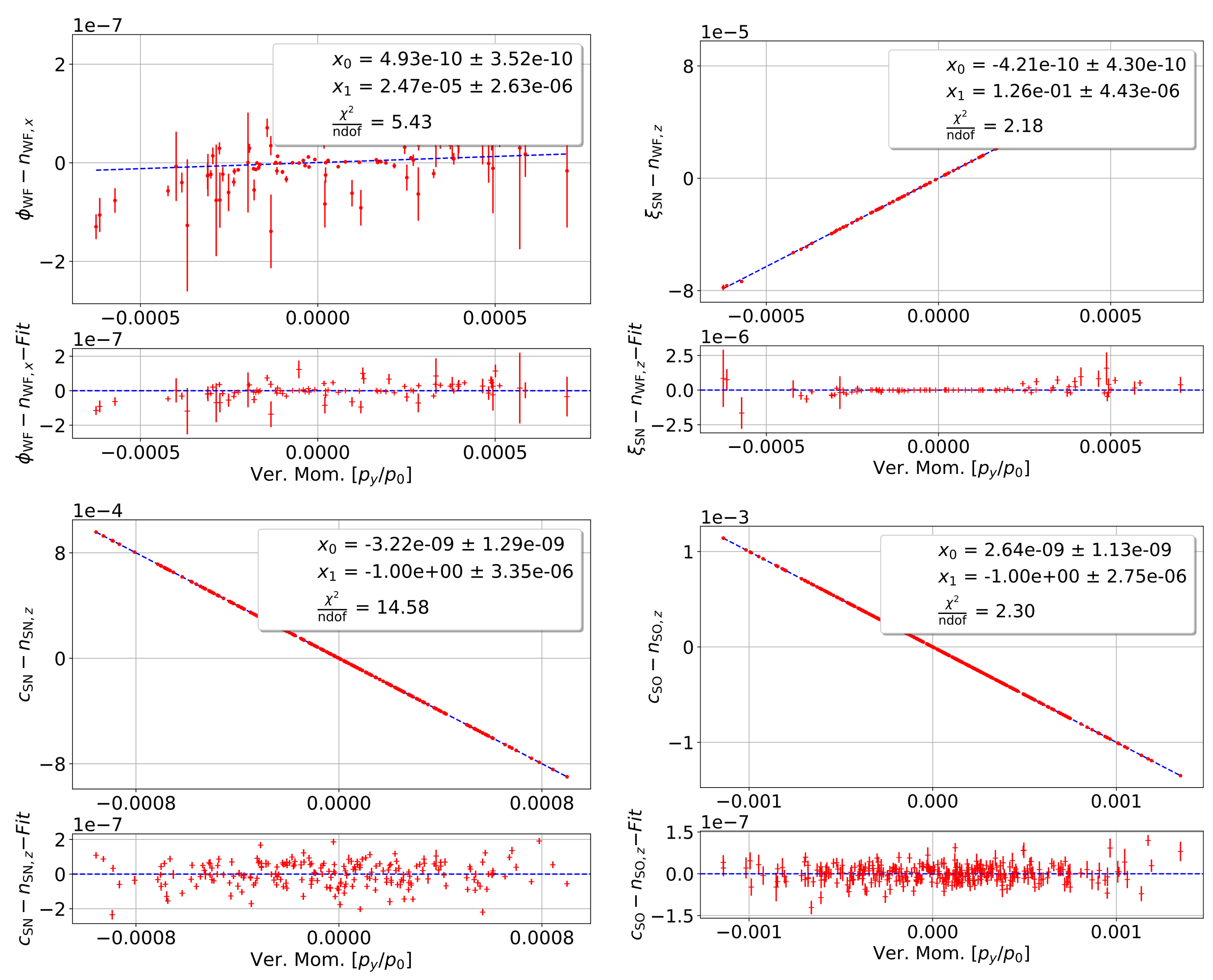
Method	ϕ_{WF}	ξ_{SN}	c_{SN}	c_{SO}
Precursor Experiments	-2.91(8) mrad	-5.22(7) mrad	-0.0612(9) mrad	-0.0585(5) mrad
Bmad Simulation	-0.1119(3) mrad	-0.3697(3) mrad	-0.006747(2) mrad	-0.135302(3) mrad

Unfortunately, simulation and experimental results differ by **one order of magnitude**. Reasons could be the **inaccuracy of the COSY model** to describe orbit and tune precisely, or the need for **correction factors** when the beam passes the devices with an angle.

Correction Factors

For an ideal lattice, the parameter ϕ_{WF}, ξ_{SN}, c_{SN} and c_{SO} are in perfect agreement with the tilt of the ISA $n_{\mathrm{WF},x}$, $n_{\mathrm{WF},z}$, $n_{\mathrm{SN},z}$ and $n_{\mathrm{SO},z}$ at their position. In case the lattice is **distorted**, a correction has to be applied.

This was investigated by giving an ideal lattice a random **vertical perturbation** via vertical steerers. The parameters were then compared with the real tilt of the ISA at their position for different sets of vertical perturbations.



As expected, this correction depends on the **vertical angle** when passing through the devices. This is quite logical, as it reflects a transformation to the particles reference frame.

From a simulation point of view, it is now under investigation, whether further corrections are needed, if the horizontal orbit gets distortet additionally.