Spin Physics and Deuteron EDMs in Storage Rings

Frank Rathmann
(on behalf of JEDI collaboration)

Forschungszentrum Jülich

f.rathmann@fz-juelich.de

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Contents

Baryon asymmetry in the Universe

Carina Nebula: Largest-seen star-birth regions in the galaxy

Observation and expectation from Standard Cosmological Model (SCM):

	$\eta = (n_b - n_{\bar{b}})/n_\gamma$	
Observation	$(6.11^{+0.3}_{-0.2}) \times 10^{-10}$	Best Fit Cosmological Model [1]
	$(5.53 - 6.76) \times 10^{-10}$	WMAP [2]
Expectation from SCM	$\sim 10^{-18}$	Bernreuther (2002) [3]

Precision frontier

EDMs possibly constitute missing cornerstone

to explain surplus of matter over antimatter in the Universe:

- SCM gets it wrong by about 8 orders of magnitude.

Large worldwide effort to search for EDMs of fundamental particles using:

- $\sim$ 500 researchers (estimate by Harris, Kirch).
- neutrons, solids, atoms and molecules.

Why search for charged particle EDMs using a storage ring?

So far, no direct measurement of charged hadron EDMs:

- potentially higher sensitivity than for neutrons:
  - longer lifetime,
  - more stored polarized protons/deuterons available than neutrons, and
  - one can apply larger electric fields in storage ring.
- Approach complimentary to neutron EDM searches.
- **EDM of a single particle not sufficient to identify *CP* violating source [4] (see talk by Jordy de Vries).**

Naive estimate of scale of nucleon EDM

From Khriplovich & Lamoreux [5]:

- CP and P conserving magnetic moment $\approx$ nuclear magneton μ_N.

$$\mu_N = \frac{e}{2m_p} \sim 10^{-14}\,\mathrm{e\,cm}.$$

- A non-zero EDM requires:
  - P violation: price to pay is $\approx 10^{-7}$, and
  - CP violation (from K decays): price to pay is $\sim 10^{-3}$.
- In summary:

$$\boxed{|d_N| \sim 10^{-7} \times 10^{-3} \times \mu_N \sim 10^{-24}\,\mathrm{e\,cm}}$$

- In Standard model (without θ_{QCD} term):

$$\boxed{|d_N| \sim 10^{-7} \times 10^{-24}\,\mathrm{e\,cm} \sim 10^{-31}\,\mathrm{e\,cm}}$$

Region to search for BSM physics ($\theta_{\mathrm{QCD}} = 0$) from nucleon EDMs:

$$10^{-24}\,\mathrm{e\,cm} > |d_N| > 10^{-31}\,\mathrm{e\,cm}.$$

Status of EDM searches

Current EDM limits in units of [e cm]:

- Long-term goals for neutron, $^{199}_{80}\mathrm{Hg}$, $^{129}_{54}\mathrm{Xe}$, proton, and deuteron.
- Neutron equivalent values indicate value for neutron EDM d_n to provide same physics reach as indicated system:

Particle	**Current limit**	**Goal**	**d_n equivalent**	**date [ref]**
Electron	$< 1.85 \times 10^{-27}$	$\approx 10^{-29}$		2012 [6]
Neutron	$(-0.21 \pm 1.82) \times 10^{-26}$	$\approx 10^{-28}$	10^{-28}	2015 [7]
$^{199}_{80}\mathrm{Hg}$	$< 7.4 \times 10^{-30}$	10^{-30}	$< 1.6 \times 10^{-26}$ [8]	2016 [9]
$^{129}_{54}\mathrm{Xe}$	$< 6.0 \times 10^{-27}$	$\approx 10^{-30}$ to 10^{-33}	$\approx 10^{-26}$ to 10^{-29}	2001 [10]
Proton	$< 7.9 \times 10^{-25}$	$\approx 10^{-29}$	10^{-29}	2009 [11]
Deuteron	not available yet	$\approx 10^{-29}$	$\approx 3 \times 10^{-29}$ to 5×10^{-31}	

Missing direct EDM measurements:

- No direct measurements of electron: limit obtained from (ThO molecule).
- No direct measurements of proton: limit obtained from $^{199}_{80}\mathrm{Hg}$.
- No measurement at all of deuteron EDM.

Experimental requirements for storage ring EDM searches

High precision, primarily electric storage ring

- Crucial role of alignment, stability, field homogeneity, and shielding from perturbing magnetic fields.
- High beam intensity: $N = 4 \times 10^{10}$ particles per fill.
- High polarization of stored polarized hadrons: $P = 0.8$.
- Large electric fields: $E = 10\,\mathrm{MV/m}$.
- Long spin coherence time: $\tau_{\mathrm{SCT}} = 1000\,\mathrm{s}$.
- Efficient polarimetry with
  - large analyzing power: $A_y \simeq 0.6$,
  - and high efficiency detection $f \simeq 0.005$.

In terms of numbers given above:

- This implies:

$$\sigma_{\mathrm{stat}} = \frac{1}{\sqrt{N f}\, \tau_{\mathrm{SCT}}\, P\, A_y\, E} \quad \Rightarrow \quad \sigma_{\mathrm{stat}}(1\,\mathrm{yr}) = 10^{-29}\,\mathrm{e\,cm}. \tag{1}$$

- **Experimentalist's goal (nightmare) is to provide σ_{syst} to the same level.**

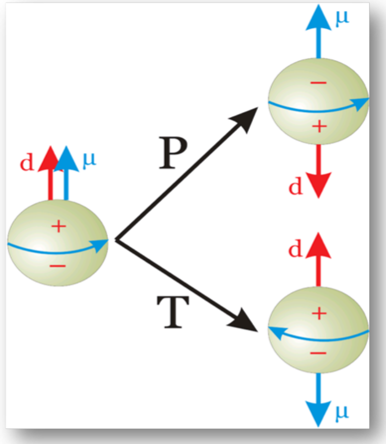
Particles with magnetic and electric dipole moment

For particles with EDM $\vec{d}$ and MDM $\vec{\mu}$,

- non-relativistic Hamiltonian given by:

$$H = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}.$$

  - P transformation: only $\vec{E}$ changes sign.
  - T transformation: $\vec{\mu}$ and $\vec{B}$ reverse.
- **Thus, EDMs violate both P and T symmetry.**



In rest frame of particle,

- equation of motion for spin vector $\vec{S}$ given by

$$\frac{\mathrm{d}\vec{S}}{\mathrm{d}t} = \vec{\Omega} \times \vec{S} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}. \tag{2}$$

Thomas-BMT equation with EDM and MDM

When particles orbit in an accelerator,

- Spin equation expressed in curvilinear laboratory reference frame.
- Solution called Thomas-BMT equation [12, 13] (historically ignoring EDM).
- Generalized form of Thomas-BMT equation, including EDMs [14]:

$$\boxed{\frac{\mathrm{d}\vec{S}}{\mathrm{d}t} = \vec{\Omega}_{\mathrm{MDM}} \times \vec{S} + \vec{\Omega}_{\mathrm{EDM}} \times \vec{S}}, \qquad \text{where}$$

$$\begin{aligned} \vec{\Omega}_{\mathrm{MDM}} &= -\frac{q}{m}\left[\left(G + \frac{1}{\gamma}\right)\vec{B} - \frac{G\gamma}{\gamma+1}\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta} - \left(G + \frac{1}{\gamma+1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right], \\ \vec{\Omega}_{\mathrm{EDM}} &= -\frac{q}{mc}\,\frac{\eta_{\mathrm{EDM}}}{2}\left[\vec{E} - \frac{\gamma}{\gamma+1}\left(\vec{\beta}\cdot\vec{E}\right)\vec{\beta} + c\vec{\beta}\times\vec{B}\right]. \end{aligned} \tag{3}$$

- $\vec{S}$ given in particle rest frame, $\vec{E}$ and $\vec{B}$ in laboratory system.
- MDM and EDM defined via dimensionless quantities g and η_{EDM}:

$$\boxed{\vec{\mu} = g\frac{q}{2m}\vec{S}}, \quad \text{and} \quad \boxed{\vec{d} = \eta_{\mathrm{EDM}}\frac{q}{2m\,c}\vec{S}}, \quad \text{with } G = \frac{g-2}{2}. \tag{4}$$

MDM precession (from [15])

Another way to look at $\vec{\Omega}_{\mathrm{MDM}}$:

- Decomposing precession frequencies: $\vec{\Omega}_{B_{//}}$, $\vec{\Omega}_{B_{\perp}}$, and $\vec{\Omega}_{E_{\perp}}$ leads to

$$
\begin{aligned}
\vec{\Omega}_{\mathrm{MDM}} &= \vec{\Omega}_{B_{//}} + \vec{\Omega}_{B_{\perp}} + \vec{\Omega}_{E_{\perp}} \\
&= -\frac{q}{\gamma m}\left[(1+G\gamma)\vec{B}_{\perp} + (1+G)\vec{B}_{//} - \left(G\gamma + \frac{\gamma}{\gamma+1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]
\end{aligned}
\tag{5}
$$

- Including an *electric* field, cyclotron frequency becomes

$$
\vec{\Omega}_{cyc} = -\frac{q}{\gamma m}\left(\vec{B}_{\perp} - \frac{\vec{\beta}\times\vec{E}}{\beta^2 c}\right), \text{ and} \tag{6}
$$

- particle momentum vector $\vec{p}$ rotates with

$$
\frac{\mathrm{d}\vec{p}}{\mathrm{d}t} = \vec{\Omega}_{\mathrm{cyc}} \times \vec{p}. \tag{7}
$$

Frozen-spin

Spin precession frequency of particle *relative* to direction of flight:

$$\begin{aligned}\vec{\Omega} &= \vec{\Omega}_{\text{MDM}} - \vec{\Omega}_{\text{cyc}} \\ &= -\frac{q}{\gamma m}\left[G\gamma\vec{B}_{\perp} + (1+G)\vec{B}_{//} - \left(G\gamma - \frac{\gamma}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right].\end{aligned} \tag{8}$$

$\Rightarrow$ $\vec{\Omega} = 0$ **called frozen spin, because momentum and spin stay aligned.**

- In the absence of magnetic fields ($B_{\perp} = \vec{B}_{//} = 0$),

$$\vec{\Omega} = 0, \text{ if } \left(G\gamma - \frac{\gamma}{\gamma^2-1}\right) = 0. \tag{9}$$

  - Possible only for particles with $G > 0$, such as proton ($G = 1.793$) or electron ($G = 0.001$).

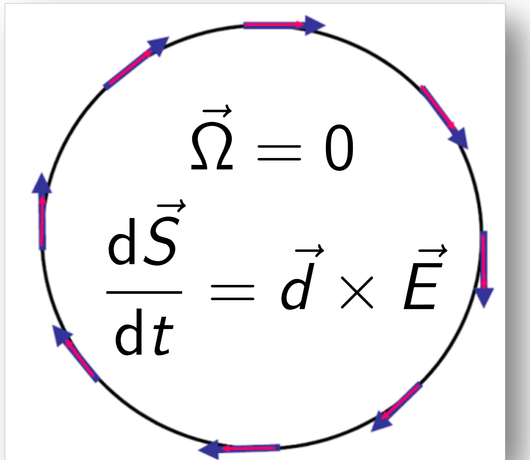
For protons, (9) leads to *magic momentum*:

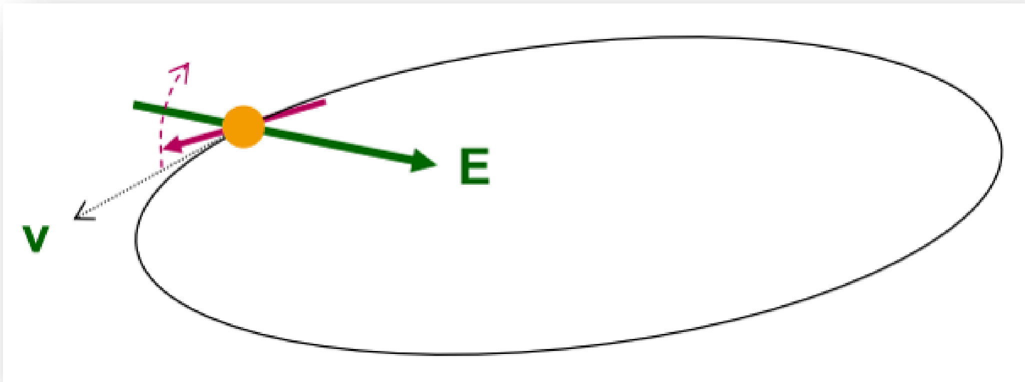
$$G - \frac{1}{\gamma^2-1} = 0 \Leftrightarrow G = \frac{m^2}{p^2} \quad \Rightarrow \quad \boxed{p = \frac{m}{\sqrt{G}} = 700.740\,\text{MeV}\,\text{c}^{-1}} \tag{10}$$

Protons at magic momentum in pure electric ring:

Recipe to measure EDM of proton:

1. Place polarized particles in a storage ring.
2. Align spin along direction of flight at magic momentum.
   $\Rightarrow$ *freeze* horizontal spin precession.
3. Search for time development of vertical polarization.





New Method to measure EDMs of charged particles:

- Magic rings with spin frozen along momentum.
- Polarization buildup $P_y(t) \propto d$.

Search for charged particle EDMs with frozen spins

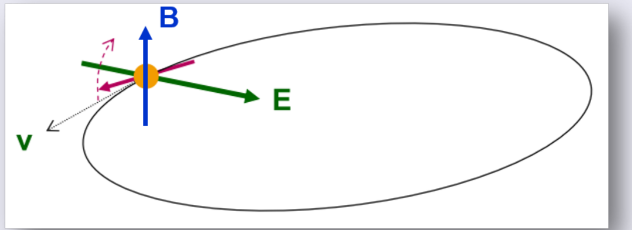
Magic storage rings

For any sign of G, in *combined* electric and magnetic machine:

- Generalized solution for magic momentum

$$E_r = \frac{G B_y c \beta \gamma^2}{1 - G \beta^2 \gamma^2}, \qquad (11)$$

where E_r is radial, and B_y vertical field.



- Some configurations for circular machine with fixed radius $r = 25\,\mathrm{m}$:

particle	G	$p\,[\mathrm{MeV\,c^{-1}}]$	$T\,[\mathrm{MeV}]$	$E\,[\mathrm{MV\,m^{-1}}]$	$B\,[\mathrm{T}]$
proton	1.793	701	232.8	16.789	0.000
deuteron	−0.143	1000	249.9	−3.983	0.160
helion	−4.184	1285	280.0	17.158	−0.051

Offers possibility to determine

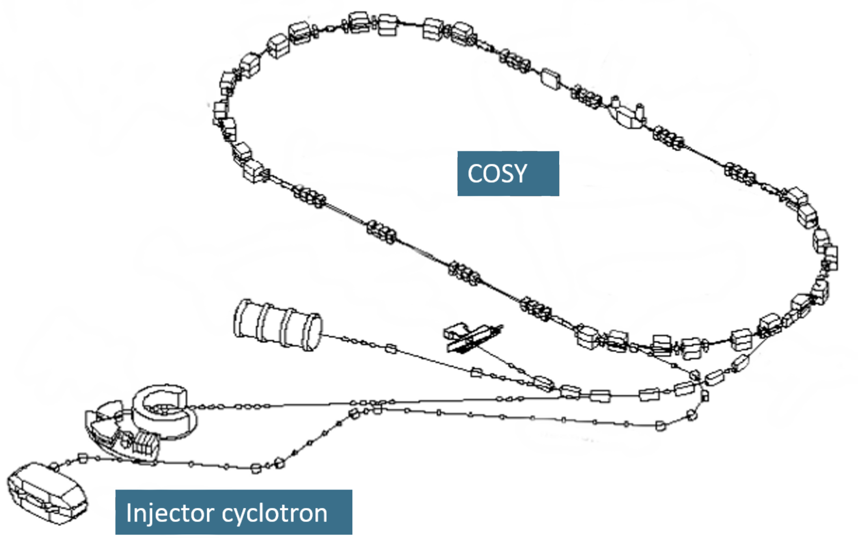
EDMs of protons, deuterons, and helions in one and the same machine.

Progress toward storage ring EDM experiments

Complementing the spin physics tool box

COoler SYnchrotron COSY

- Cooler and storage ring for (polarized) protons and deuterons.
- Momenta $p = 0.3 - 3.7\,\mathrm{GeV}/c$.
- Phase-space cooled internal and extracted beams.



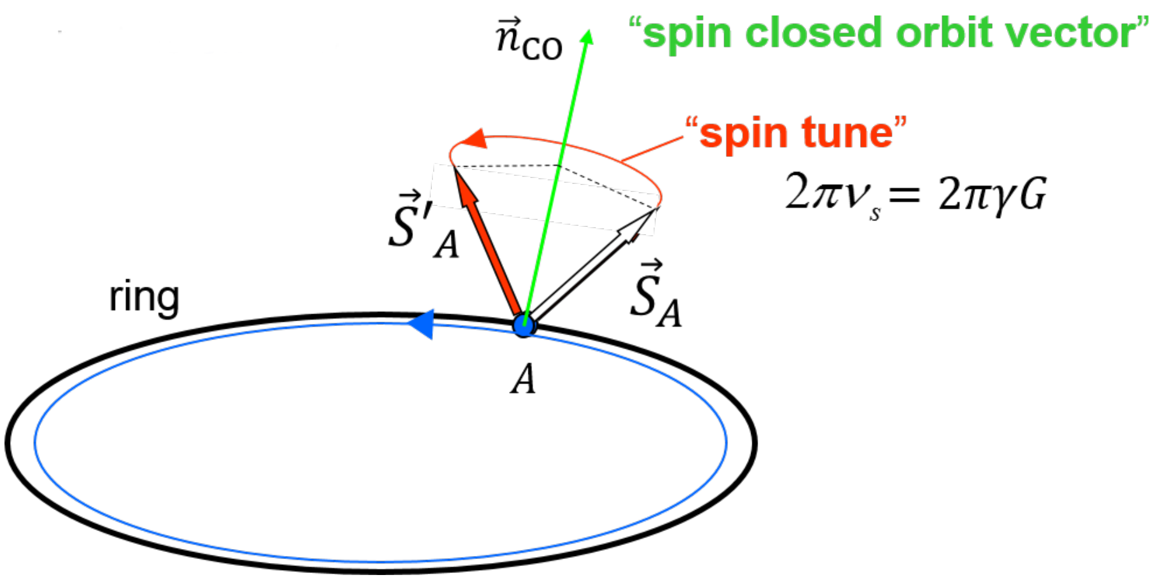
COSY formerly used as spin-physics machine for hadron physics:

- Provides now an ideal starting point for srEDM related R & D.
- Will be used for a first direct measurment of deuteron EDM.

Spin closed orbit and spin tune

One particle with magnetic moment makes one turn in machine ($A - A$):

- Stable direction of polarization in ring, if $\vec{S} \,//\, \vec{n}_{co}$.
- Vector $\vec{n}_{co}$ around which spins precess called spin-closed orbit:
  - stable direction $\vec{n}_{co} = \vec{n}_{co}(s)$ (in general a function of position in the ring).



Number of spin precessions per turn is called spin tune ν_s.

Spin coherence time

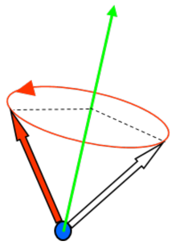
Most polarization experiments don‘t care about coherence of spins along $\vec{n}_{\mathrm{co}}$

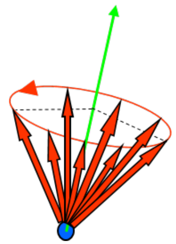
Spins aligned:

Ensemble *coherent*

With time, spin vectors out of phase:

Ensemble *decoherent*





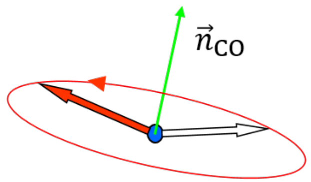
$\Rightarrow$ **Polarization along $\vec{n}_{\mathrm{co}}$ not affected**

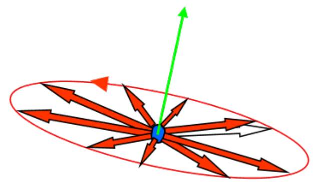
With frozen spins: $\vec{S} \perp \vec{n}_{\mathrm{co}}$:

Spins aligned

With time:

Spins out of phase in horizontal plane



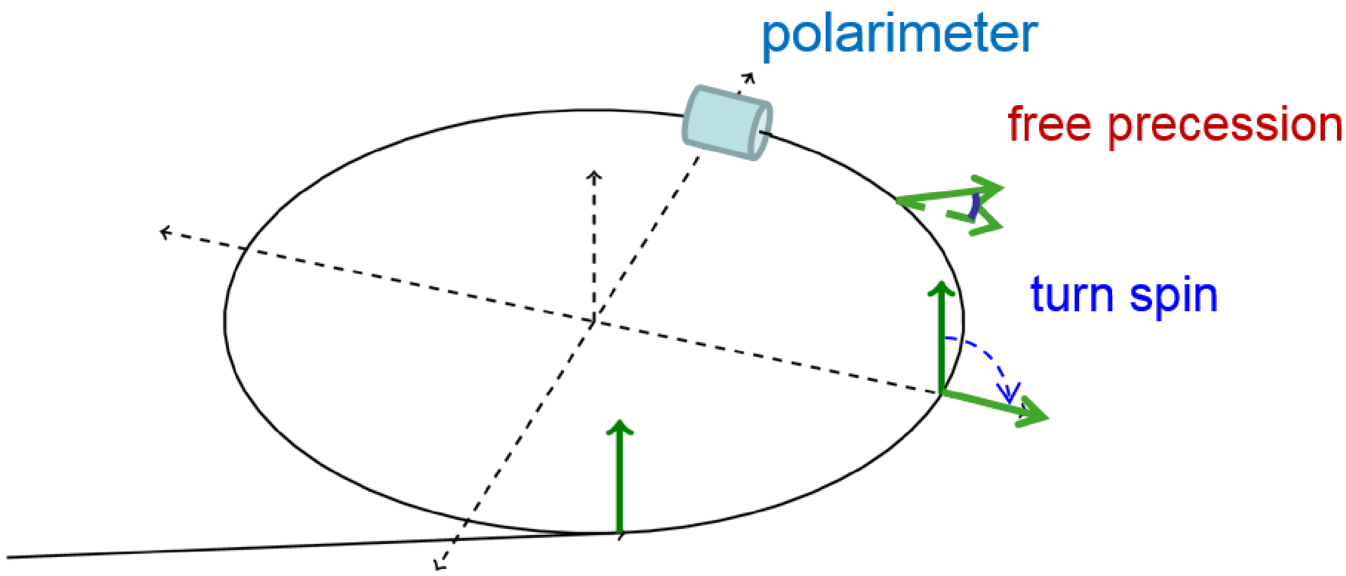


$\Rightarrow$ **Longitudinal polarization vanishes**

In machines with frozen spins:

Buildup time t to observe polarization $P_y(t)$ limited by τ_{SCT}.

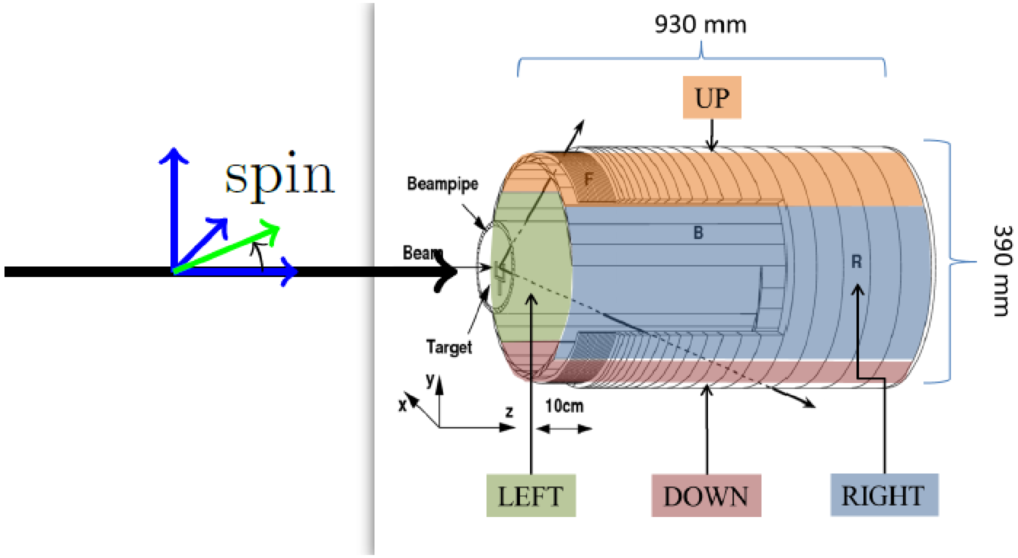
Spin coherence time measurement

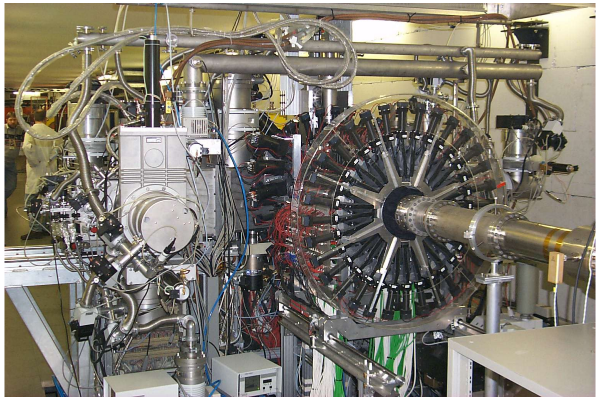


Measurement procedure:

1. Vertically polarized deuterons stored at $p \simeq 1\,\mathrm{GeV\,c^{-1}}$.
2. Polarization flipped into horizontal plane with RF solenoid ($\approx 200\,\mathrm{ms}$).
3. Beam extracted on Carbon target with ramped bump or by heating.
4. Horizontal (in-plane) polarization determined from $U - D$ asymmetry in polarimeter.

Detector system: EDDA [16]



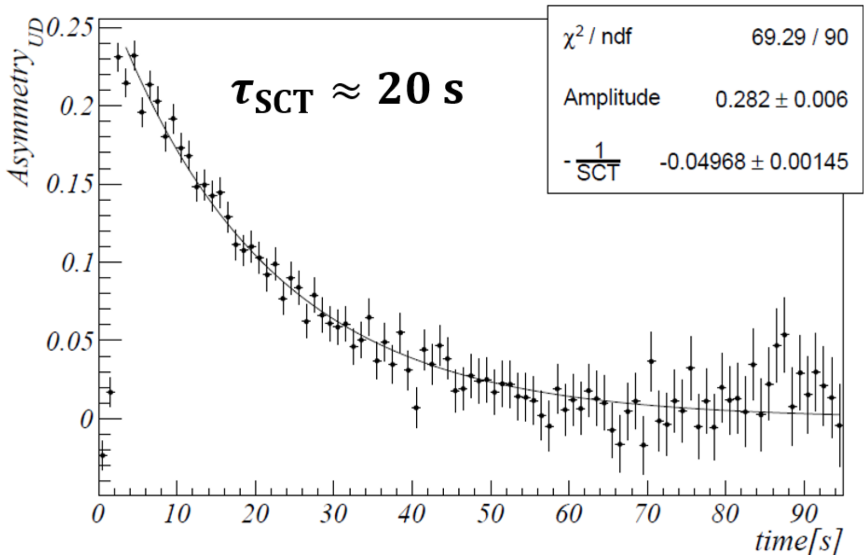


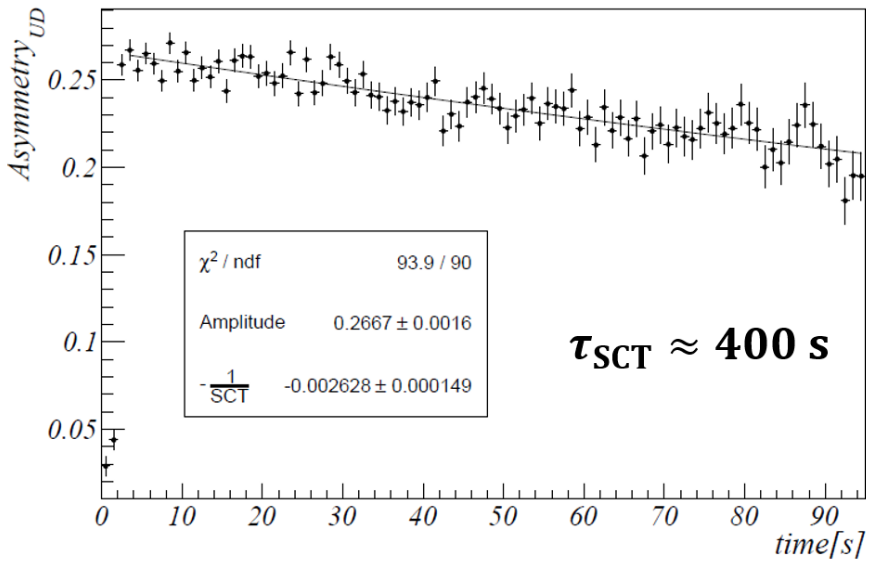
EDDA previously used to determine $\vec{p}\vec{p}$ elastic polarization observables:

- Deuterons at $p = 1\,\mathrm{GeV\,c^{-1}}$, $\gamma = 1.13$, and $\nu_s = \gamma G \simeq -0.161$
- Spin-dependent differential cross section on unpolarized target:

$$N_{\mathrm{U,D}} \propto 1 \pm \frac{3}{2} p_z A_y \sin(\nu_s f_{\mathrm{rev}}\, t), \text{ where } f_{\mathrm{rev}} = 781\,\mathrm{kHz}. \tag{12}$$

Spin coherence time



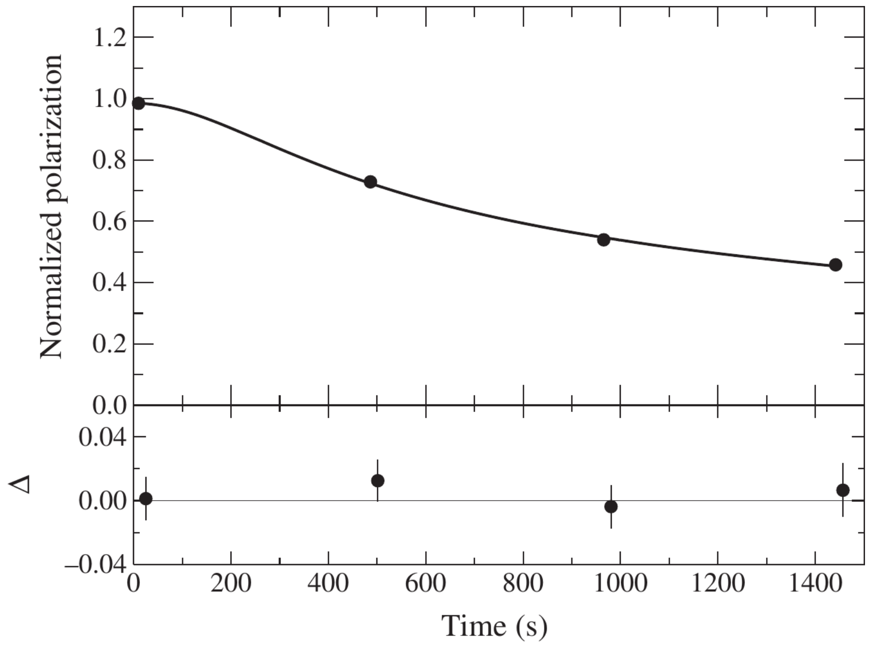


2012: Observed experimental decay of asymmetry

$$\epsilon_{\mathrm{UD}}(t) = \frac{N_D(t) - N_U(t)}{N_D(t) + N_U(t)}. \qquad (13)$$

2013: Using sextupole magnets in the machine, higher order effects can be corrected, and spin coherence is substantially increased.

Optimization of spin coherence time [19]



Recent progress on τ_{SCT} [17]:

$$\tau_{\text{SCT}} = (\mathbf{782} \pm \mathbf{117})\,\text{s}$$

- Previously: $\tau_{\text{SCT}}(\text{VEPP}) \approx 0.5\,\text{s}$ [18] ($\approx 10^7$ spin revolutions).

Spring 2015: Way beyond anybody's expectation:

- With about 10^9 stored deuterons.
- Making spin coherence time long was considered one of main obstacles.
- Large value of τ_{SCT} of crucial importance (1):

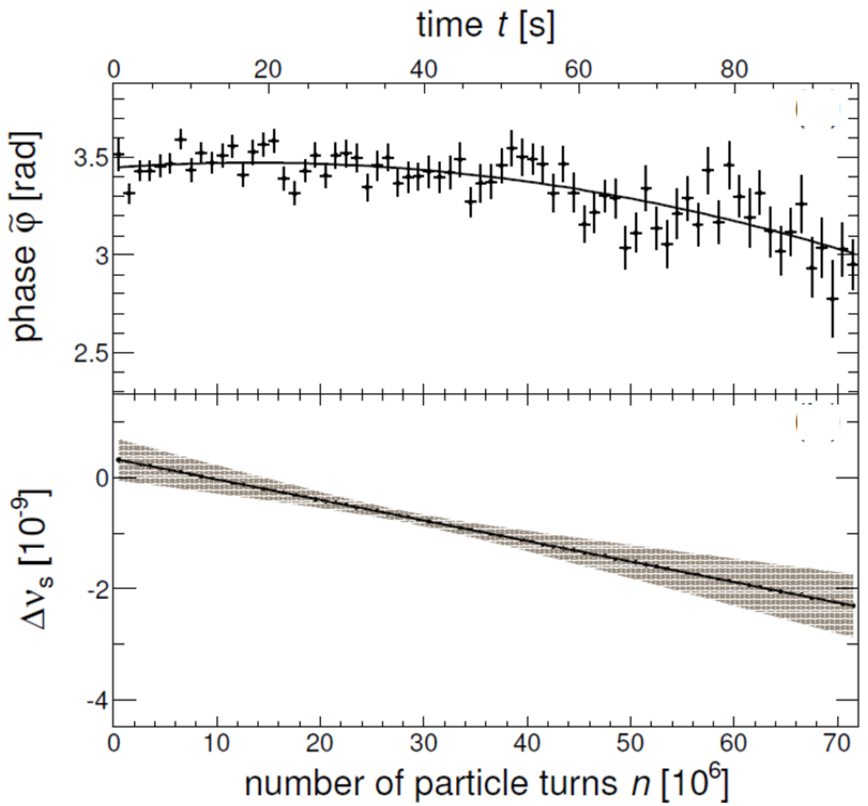
$$\sigma_{\text{stat}} \propto \frac{1}{\tau_{\text{SCT}}}$$

Precision determination of the spin tune

Time-stamping events accurately,

- allows us to monitor phase of measured asymmetry with (assumed) fixed spin tune ν_s in a 100 s cycle:

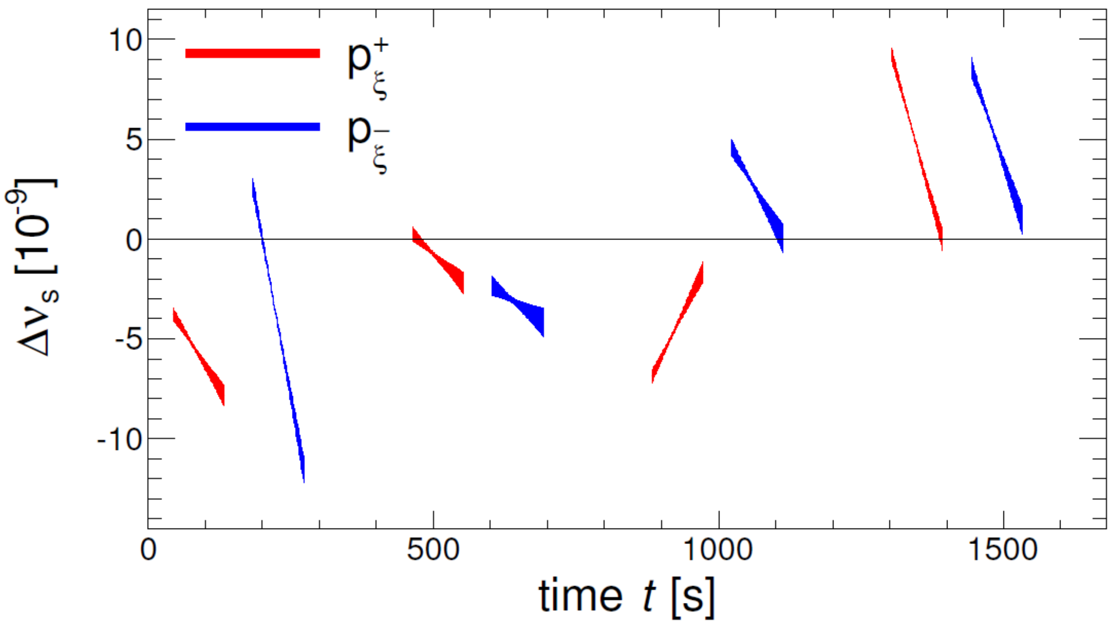
$$\begin{aligned}\nu_s(n) &= \nu_s^{\text{fix}} + \frac{1}{2\pi}\frac{\mathrm{d}\tilde{\phi}}{\mathrm{d}n} \qquad (14)\\ &= \nu_s^{\text{fix}} + \Delta\nu_s(n)\end{aligned}$$



Experimental technique described in PRL (2015) [20]:

- Spin tune ν_s determined to $\approx 10^{-8}$ in 2 s time interval, and
- in a 100 s cycle at $t \approx 30$ s to 10^{-10}.
- $\Rightarrow$ **new precision tool to study systematic effects in a storage ring.**

Spin tune as a precision tool for accelerator physics [20]



Walk of spin tune ν_s during subsequent cycles.

Applications of the new technique:

- Study long term stability of an accelerator.
- Feedback system to stabilize phase of spin precession relative to phase of RF devices (phase-lock) has been demonstrated as well.
- **Study of machine imperfections (see next talk by N.N. Nikolaev).**

Technical challenges of storage ring EDM experiments

Charged particle EDM searches require development of new class of high-precision machines with mainly electric fields for bending and focussing:

Main issues:

- Large electric field gradients of $\sim 17\,\mathrm{MV\,m^{-1}}$ at $\sim 2\,\mathrm{cm}$ plate distance.
- Spin coherence time $\tau_{\mathrm{SCT}} \leq 1000\,\mathrm{s}$ [17].
- Continuous polarimetry with relative errors $< 1\,\mathrm{ppm}$ [21].
- Beam position monitoring with precision of $10\,\mathrm{nm}$.
- High-precision spin tracking.

Other issues:

- Alignment of ring elements, ground motion.
- Magnetic shielding (**see talk by P. Fierlinger**).
- For deuteron EDM with frozen spin: also precise reversal of magnetic fields for CW and CCW beams required.

Proof of principle experiment using COSY
(“Precursor experiment”)

Highest sensitivity achieved with a new type of machine:

- An **electrostatic circular storage** ring, where
  - centripetal force produced primarily by electric fields.
  - E field couples to EDM and provide required sensitivity ($< 10^{-28}\,\mathrm{e\,cm}$).
  - In this environment, magnetic fields mean evil (since μ is large).

Idea for proof-of-principle experiment with novel RF Wien filter ($\vec{E} \times \vec{B}$):

- In magnetic machine, particle spins (deuterons, protons) precess about vertical (B field) direction.
- Use RF device operating on some harmonic of the spin-precession frequency:

  $\Rightarrow$ *Phase lock* between spin precession and device RF.

  $\Rightarrow$ Allows one to accumulate EDM effect as fct of time (cycle time $\sim 1000\,\mathrm{s}$).

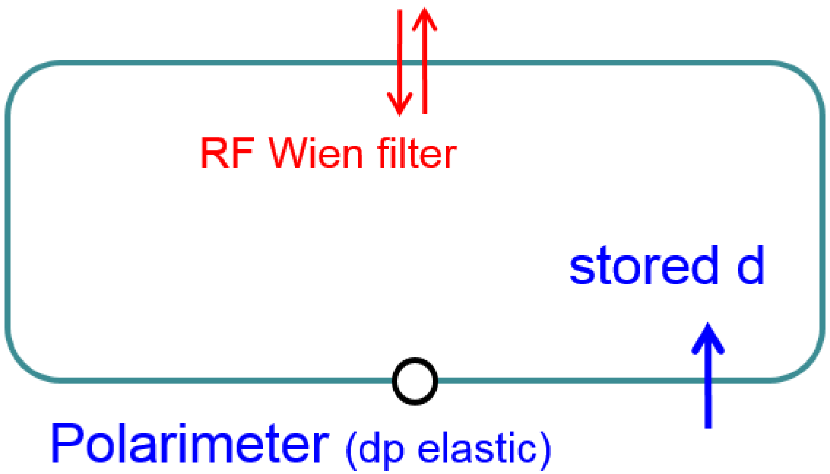
Goal of proof-of-principle experiment:

Show that storage ring (COSY) can be used for a first direct EDM measurement.

RF Wien filter

A couple more aspects about the technique:

- RF Wien filter ($\vec{E} \times \vec{B}$) avoids coherent betatron oscillations in the beam:
  - Lorentz force $\vec{F}_L = q(\vec{E} + \vec{v} \times \vec{B}) = 0$.
  - EDM measurement mode: $\vec{B} = (0, B_y, 0)$ and $\vec{E} = (E_x, 0, 0)$.



- Deuteron spins lie in machine plane.
- If $d \neq 0 \Rightarrow$ *accumulation* of vertical polarization P_y, during spin coherence time $\tau_{SCT} \sim 1000\,\text{s}$.

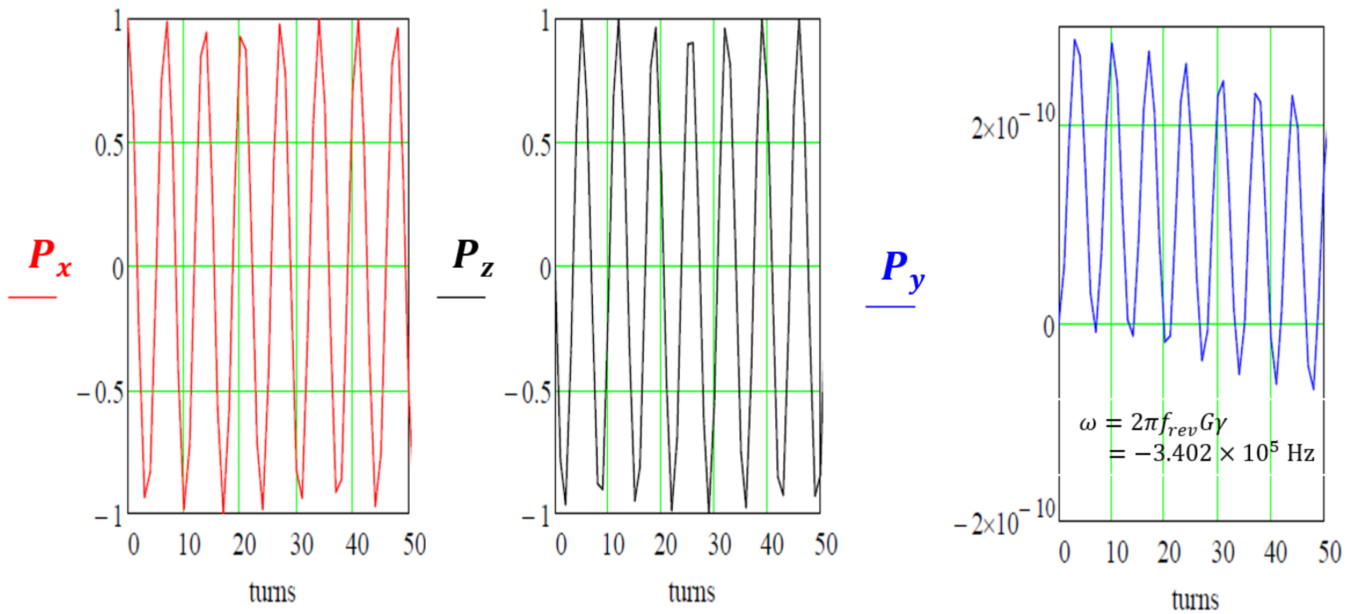
Statistical sensitivity:

- in the range 10^{-23} to $10^{-24}\,\text{e cm}$ for $d(deuteron)$ possible.
- Systematic effects: Alignment of magnetic elements, magnet imperfections, imperfections of RF-Wien filter etc.

Buildup of $P_y(t)$ using RF Wien filter for deuterons

A simple model calculation with parameters:

- Beam energy: $T_d = 50\,\mathrm{MeV}$,
- Length of device: $L_{\mathrm{RF}} = 1\,\mathrm{m}$.
- Assumed deuteron EDM: $d = 10^{-24}\,\mathrm{e\,cm}$.
- Electric RF field: $30\,\mathrm{kV\,cm^{-1}}$.

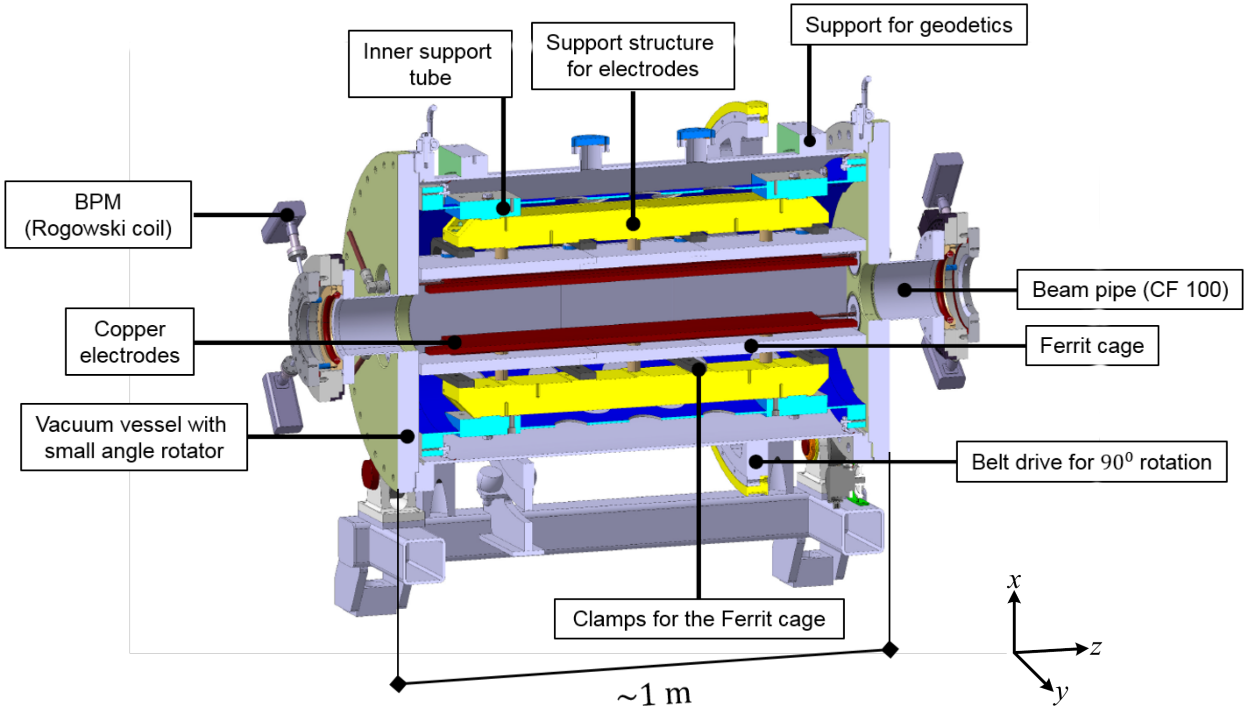


EDM effect accumulates in $P_y \propto d$ [22, 23].

Design of RF Wien filter

Device developed at Jülich in cooperation with RWTH Aachen:

- Institute of High Frequency Technology, RWTH Aachen University:
  - Heberling, Hölscher, and PhD Student **Jamal Slim**, and ZEA-1 of Jülich.
- **Waveguide provides $\vec{E} \times \vec{B}$ by design.**
- Minimal $\vec{F}_L$ by careful electromagnetic design of all components [24].



Summary

Search for charged particle EDMs:

- New window to disentangle sources of *CP* violation, and to possibly explain matter-antimatter asymmetry of the Universe.

Spin-physics tool-box:

- Large $\tau_{\mathrm{SCT}} \approx 1000\,\mathrm{s}$ observed in *magnetic* machine [17].
  - In dedicated EDM machine, τ_{SCT} even longer.
- Spin tune emerges as a novel precision tool for accelerator physics [20].
- Development of high-precision spin tracking tools, incl. RF structures.
- Development of high-field electrostatic deflectors (also $E_r \times B_y$), and high-precision beam position monitors.

Near future:

1. **04/2017:** Start first direct measurements of deuteron EDM.
   - Sensitivity $10^{-19} - 10^{-20}\,\mathrm{e\,cm}$.
   - RF Wien filter is presently assembled.
2. **2019:** Conceptual design for dedicated EDM ring (sensitivity $\simeq 10^{-29}\,\mathrm{e\,cm}$).

JEDI Collaboration

JEDI = Jülich Electric Dipole Moment Investigations

- $\sim$ 100 members (Aachen, Daejeon, Dubna, Ferrara, Indiana, Ithaka, Jülich, Krakow, Michigan, Minsk, Novosibirsk, St Petersburg, Stockholm, Tbilisi, ...
- $\sim$ 10 PhD students
- `http://collaborations.fz-juelich.de/ikp/jedi`

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