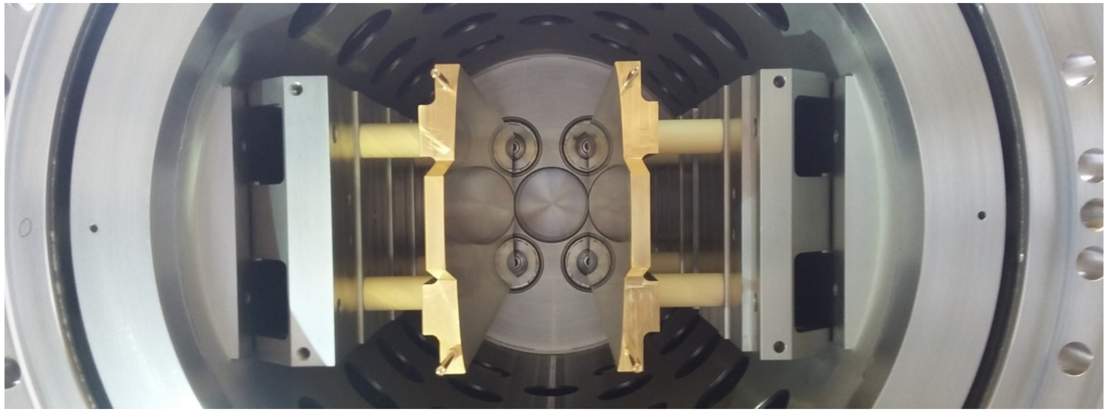


Electric Dipole Moment Searches using Storage Rings

Frank Rathmann
(on behalf of the JEDI collaboration)

Paul-Scherrer Institut, 06.12.2018

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.
- Non-vanishing EDMs would add fourth quantum number to fundamental particles

Large worldwide effort to search for EDMs of fundamental particles:

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

Why search for charged particle EDMs using a storage ring?

Up to now, no direct measurement of charged hadron EDMs are available:

- Charged hadron EDM experiments provide 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 single particle not sufficient to identify *CP* violating source [4]**

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:

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

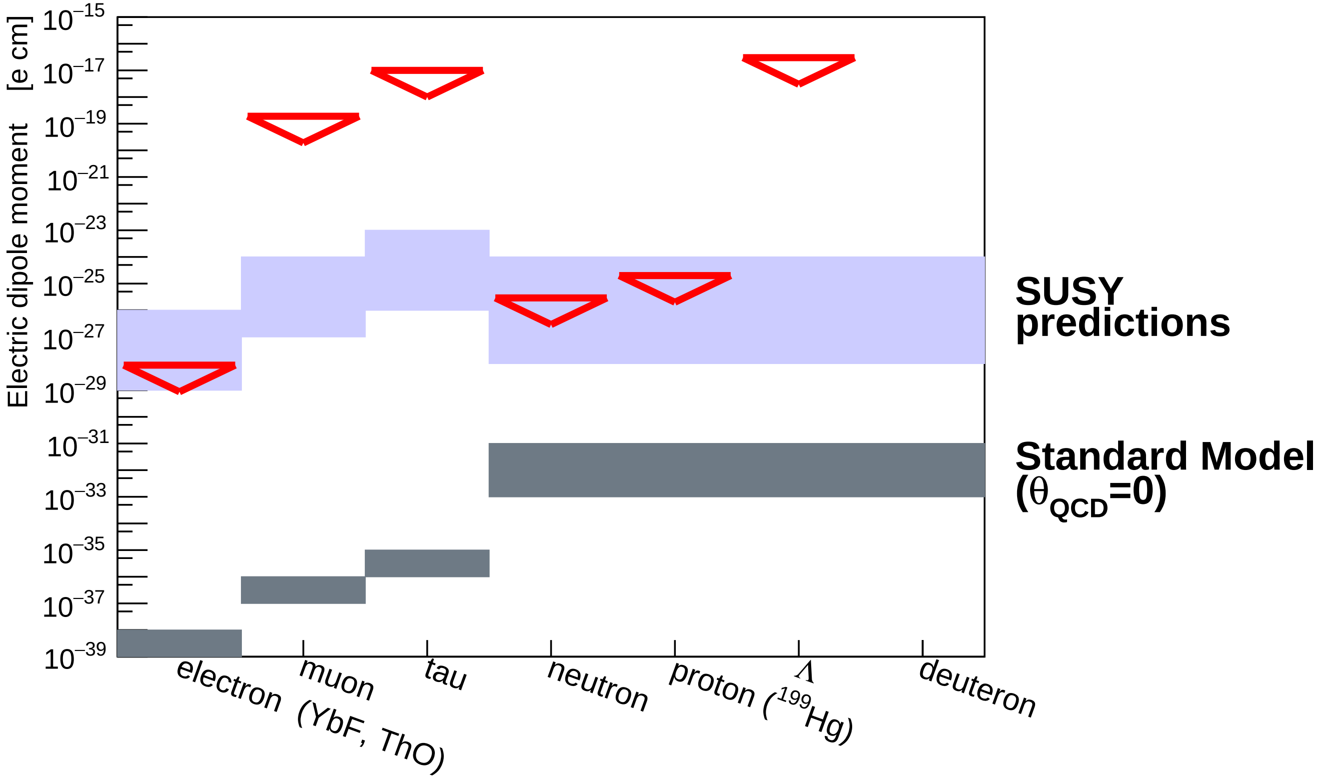
Status of EDM searches I

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	$< 8.7 \times 10^{-29}$	$\approx 10^{-29}$		2014 [6]
Muon	$< 1.8 \times 10^{-19}$			2009 [7]
Tau	$< 1 \times 10^{-17}$			2003 [8]
Lambda	$< 3 \times 10^{-17}$			1981 [9]
Neutron	$(-0.21 \pm 1.82) \times 10^{-26}$	$\approx 10^{-28}$	10^{-28}	2015 [10]
$^{199}_{80}\mathrm{Hg}$	$< 7.4 \times 10^{-30}$	10^{-30}	$< 1.6 \times 10^{-26}$ [11]	2016 [12]
$^{129}_{54}\mathrm{Xe}$	$< 6.0 \times 10^{-27}$	$\approx 10^{-30}$ to 10^{-33}	$\approx 10^{-26}$ to 10^{-29}	2001 [13]
Proton	$< 2 \times 10^{-25}$	$\approx 10^{-29}$	10^{-29}	2016 [12]
Deuteron	not available yet	$\approx 10^{-29}$	$\approx 3 \times 10^{-29}$ to 5×10^{-31}	

Status of EDM searches II



Missing are *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:

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

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

Particles with magnetic and electric dipole moment

For particles with EDM $\vec{d}$ and MDM $\vec{\mu}$ ($\propto \vec{s}$),

- non-relativistic Hamiltonian:

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

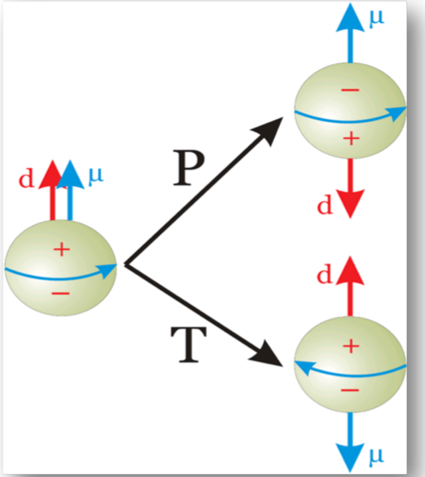
  - **Energy of magnetic dipole** invariant under P and T:

$$-\vec{\mu} \cdot \vec{B} \overbrace{\longrightarrow}^{P \text{ or } T} -\vec{\mu} \cdot \vec{B}, \tag{2}$$

    No other direction than spin $\Rightarrow$ $\vec{d}$ parallel to $\vec{\mu}$ ($\vec{s}$).
  - **Energy of electric dipole** $H = -\vec{d} \cdot E$, includes term

$$\vec{s} \cdot \vec{E} \overbrace{\longrightarrow}^{P \text{ or } T} -\vec{s} \cdot \vec{E}, \tag{3}$$

- **Thus, EDMs violate both P and T symmetry.**



In rest frame of particle,

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

$$\frac{\mathrm{d}\vec{S}}{\mathrm{d}t} = \vec{\Omega} \times \vec{S} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}. \tag{4}$$

Frozen-spin

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

$$\begin{aligned}\vec{\Omega} &= \vec{\Omega}_{\mathrm{MDM}} - \vec{\Omega}_{\mathrm{cyc}} \\ &= -\frac{q}{\gamma m}\left[G\gamma\vec{B}_{\perp} + (1+G)\vec{B}_{\parallel} - \left(G\gamma - \frac{\gamma}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right].\end{aligned} \tag{5}$$

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

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

$$\vec{\Omega} = 0, \text{ if } \left(G\gamma - \frac{\gamma}{\gamma^2-1}\right) = 0. \tag{6}$$

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

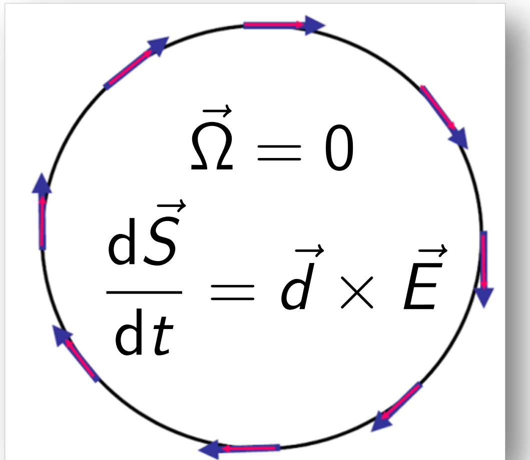
For protons, (6) leads to *magic momentum*:

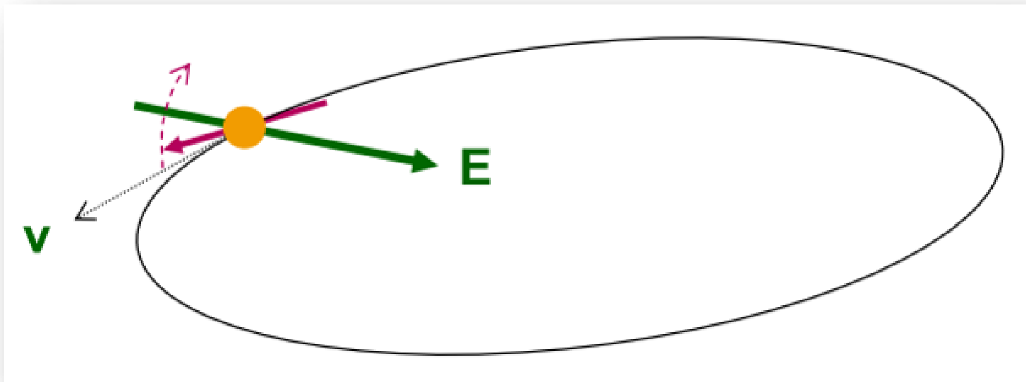
$$G - \frac{1}{\gamma^2-1} = 0 \Leftrightarrow G = \frac{m^2}{p^2} \quad \Rightarrow \quad \boxed{p = \frac{m}{\sqrt{G}} = 700.740\,\mathrm{MeV\,c^{-1}}} \tag{7}$$

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 of particle.
- Polarization buildup $P_y(t) \propto d$.

Search for charged particle EDMs with frozen spins

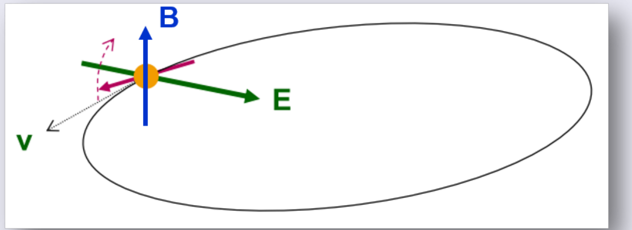
Magic storage rings

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

- Generalized solution for magic momentum

$$E_r = \frac{G B_y c \beta \gamma^2}{1 - G\beta^2\gamma^2}, \quad (8)$$

where E_r is radial, and B_y vertical field.



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

particle	G	$p\,[\text{MeV}\,\text{c}^{-1}]$	$T\,[\text{MeV}]$	$E\,[\text{MV}\,\text{m}^{-1}]$	$B\,[\text{T}]$
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

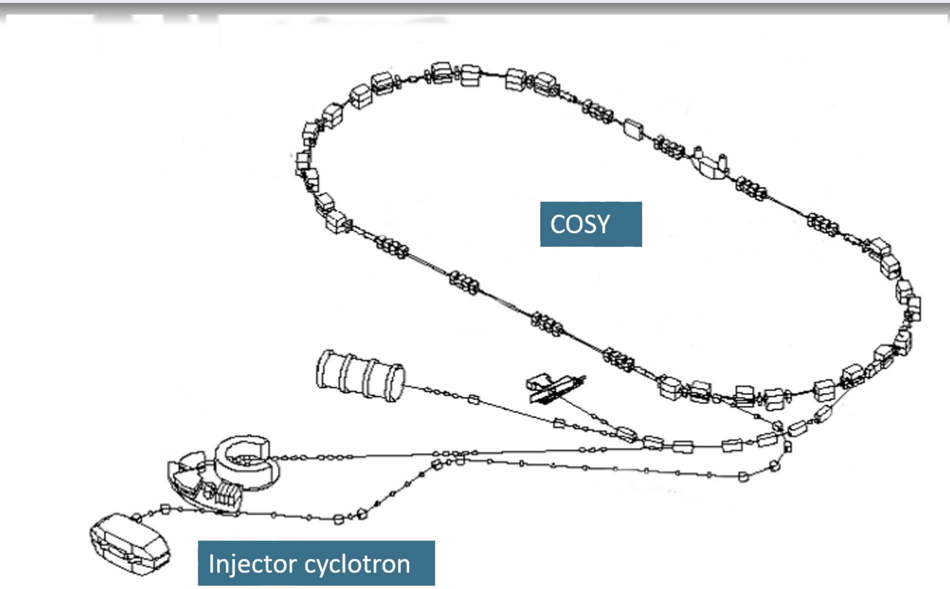
EDMs of protons, deuterons, and helions in one and the same machine.

Progress toward storage ring EDM experiments

Complementing the spin physics tool box

COoler SYnchrotron COSY

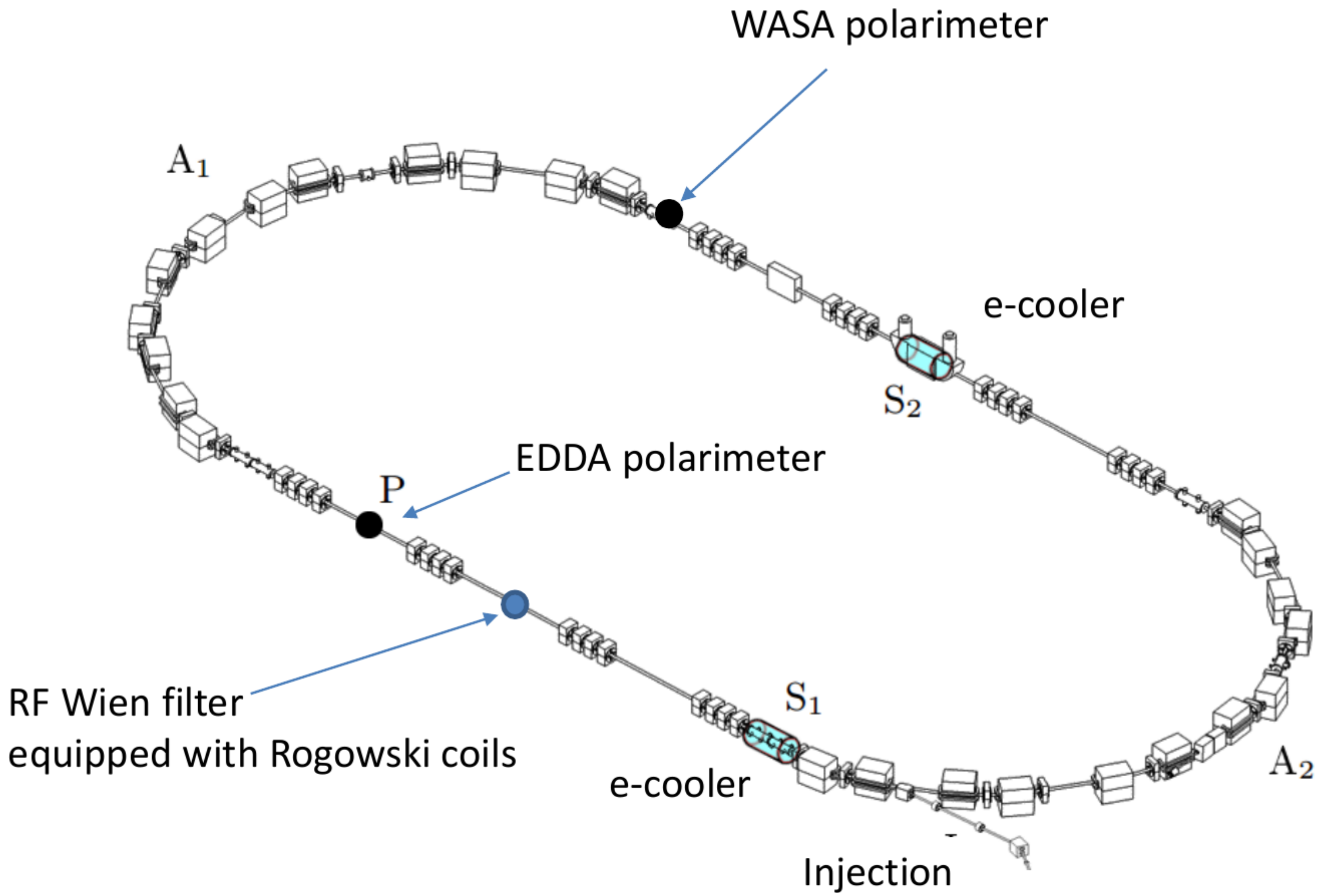
- Cooler and storage ring for (polarized) protons and deuterons.
- Momenta $p = 0.3 - 3.7\,\text{GeV}/c$.
- Phase-space cooled internal and extracted beams.



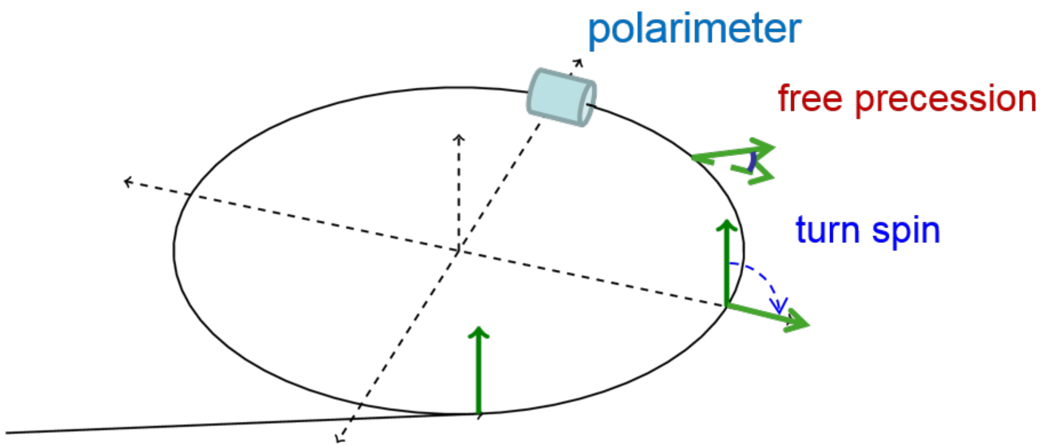
COSY formerly used as spin-physics machine for hadron physics:

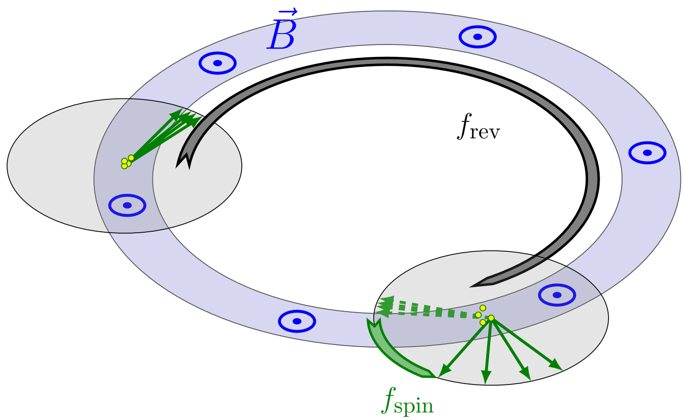
- Provides an ideal starting point for srEDM related R&D.
- Will be used for a first direct measurment of deuteron EDM.

COSY Landscape



Principle of spin-coherence time measurement

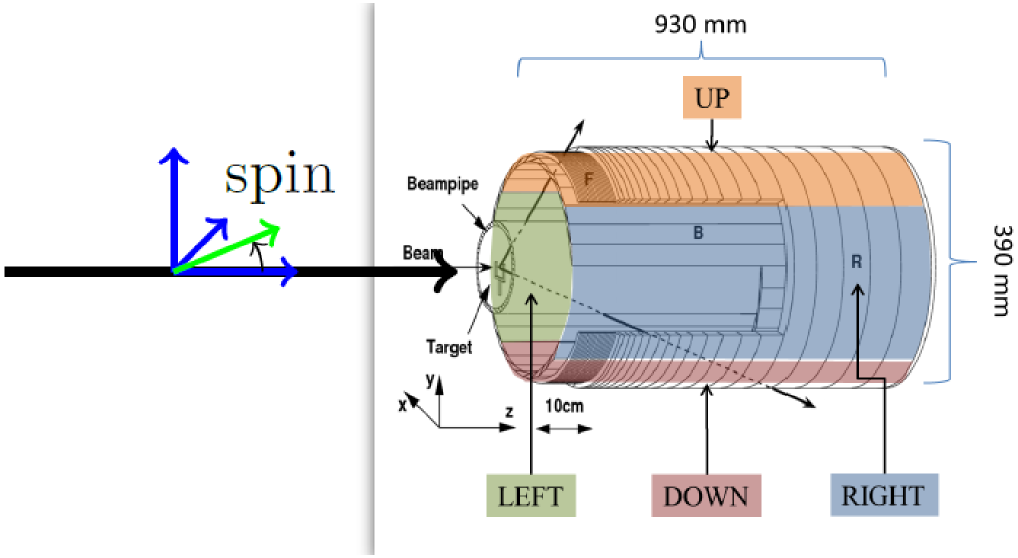


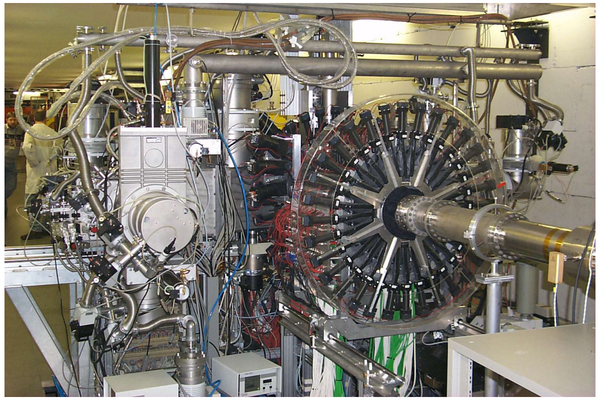


Measurement procedure:

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 [14]





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:

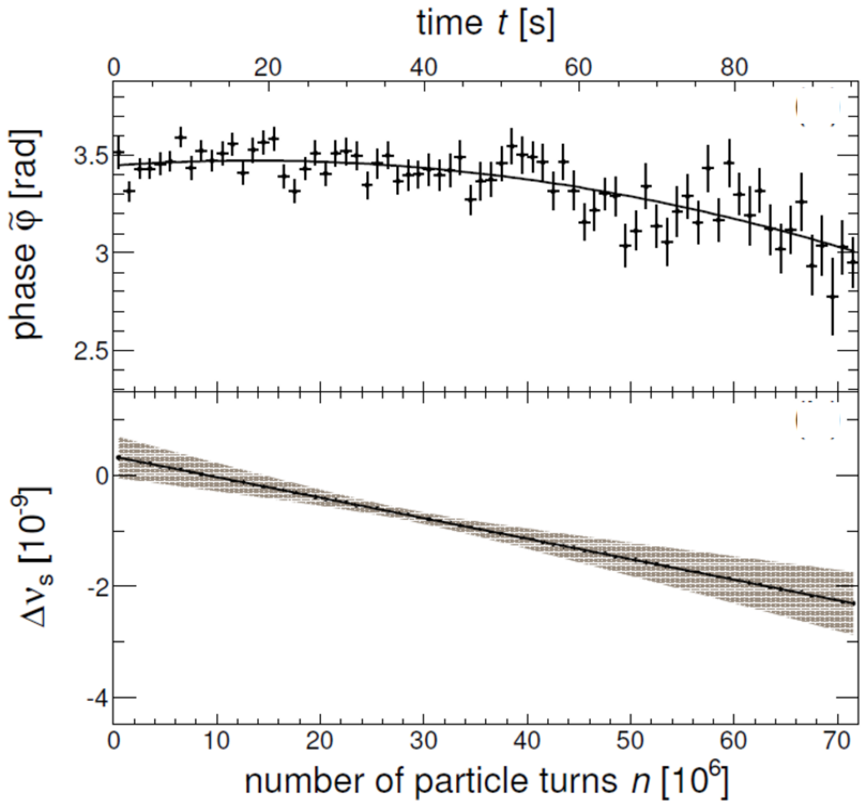
$$N_{\mathrm{U,D}} \propto 1 \pm \frac{3}{2} p_z A_y \sin(\nu_s f_{\mathrm{rev}}\, t), \text{ where } f_{\mathrm{rev}} = 781\,\mathrm{kHz}. \tag{9}$$

Precision determination of the spin tune [15, 2015]

Time-stamping events accurately,

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

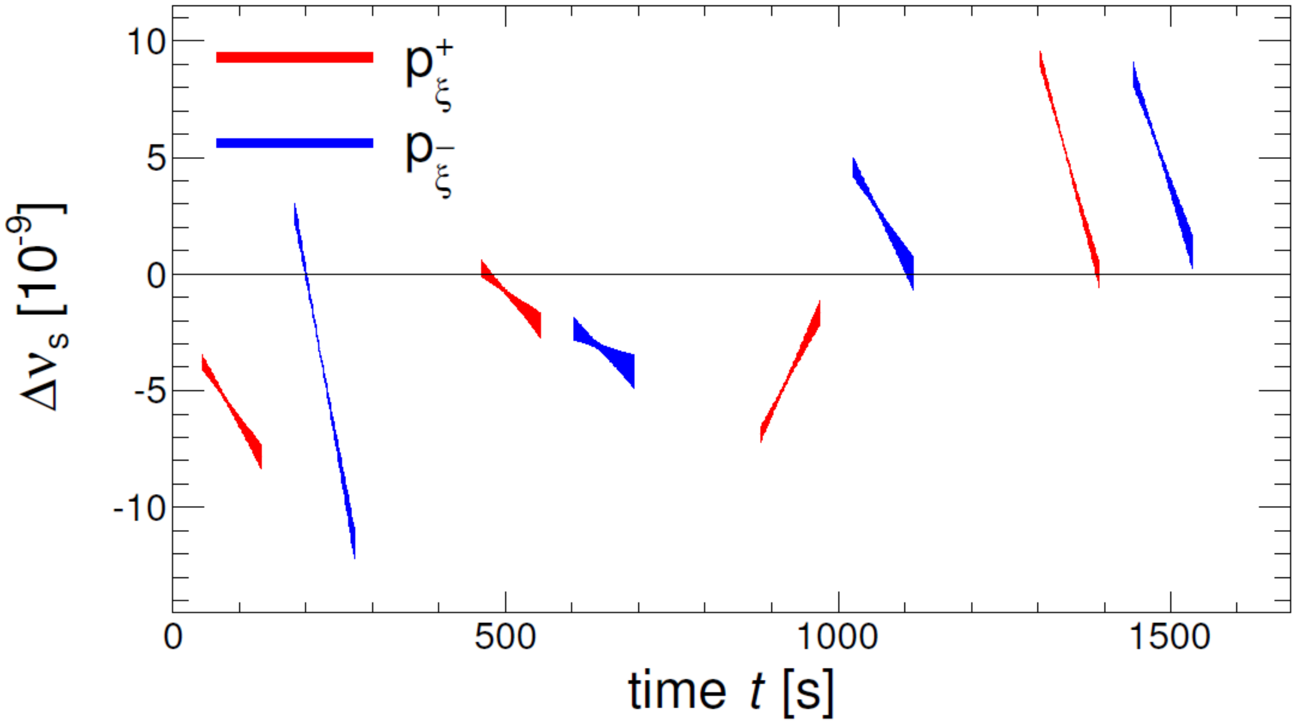
$$\begin{aligned} \nu_s(n) &= \nu_s^{\text{fix}} + \frac{1}{2\pi}\frac{\mathrm{d}\tilde{\phi}}{\mathrm{d}n} \\ &= \nu_s^{\text{fix}} + \Delta\nu_s(n) \end{aligned} \tag{10}$$



Experimental technique allows for:

- Spin tune ν_s determined to $\approx 10^{-8}$ in 2 s time interval.
- In a 100 s cycle at $t \approx 38$ s, interpolated spin tune amounts to $|\nu_s| = (16097540628.3 \pm 9.7) \times 10^{-11}$, *i.e.*, $\Delta\nu_s/\nu_s \approx 10^{-10}$.
- $\Rightarrow$ **new precision tool to study systematic effects in a storage ring.**

Spin tune as a precision tool for accelerator physics

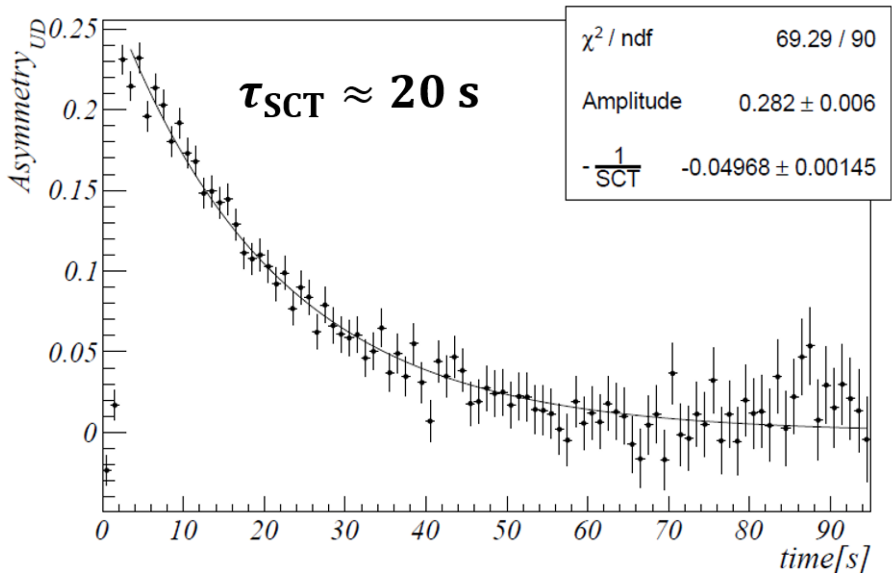


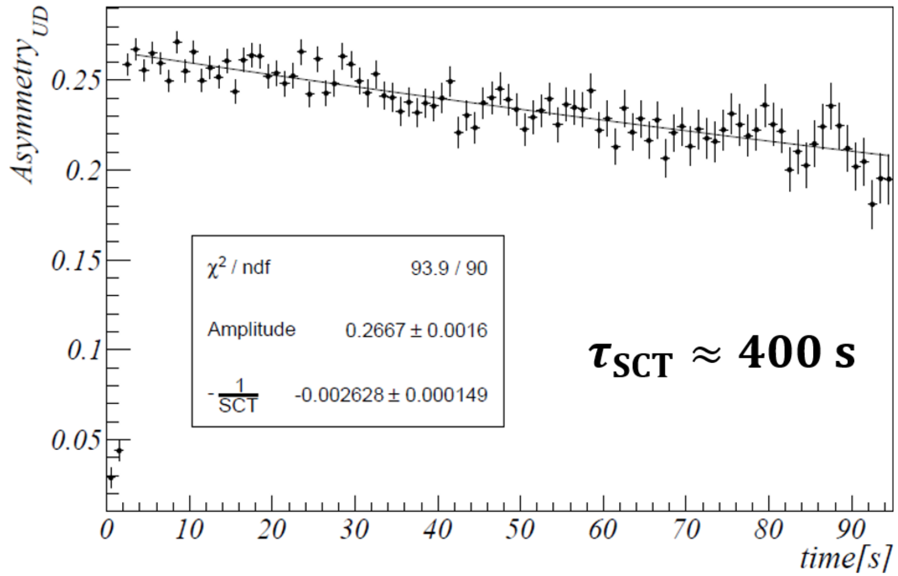
Walk of spin tune ν_s [15].

Applications of new technique:

- Study long term stability of an accelerator.
- Feedback system to stabilize phase of spin precession relative to phase of RF devices (so-called **phase-lock**).
- Studies of machine imperfections.

Optimization of spin-coherence time: [16, 2014]



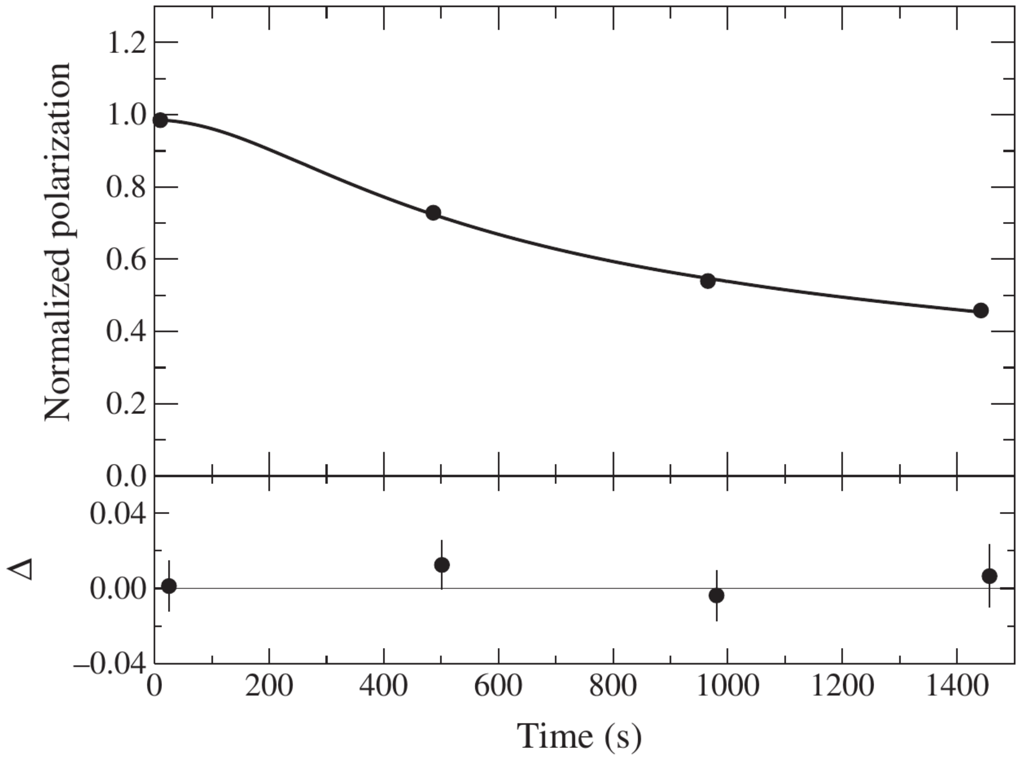


2012: Observed experimental decay of asymmetry

$$\epsilon_{\mathrm{UD}}(t) = \frac{N_D(t) - N_U(t)}{N_D(t) + N_U(t)}. \qquad (11)$$

2013: Using sextupole magnets, higher order effects are corrected, and spin coherence substantially increased.

More optimizations of spin-coherence time: [18, 2016]



Recent progress on τ_{SCT}:

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

- Previously: $\tau_{\mathrm{SCT}}(\mathrm{VEPP}) \approx 0.5\,\mathrm{s}$ [17] ($\approx 10^7$ spin revolutions).

Spring 2015: Way beyond anybody's expectation:

- With about 10^9 stored deuterons.
- Long spin coherence time was one of main obstacles of srEDM experiments.
- Large value of τ_{SCT} of crucial importance (1), since $\sigma_{\mathrm{stat}} \propto \frac{1}{\tau_{\mathrm{SCT}}}$.

Phase locking spin precession in machine to device RF

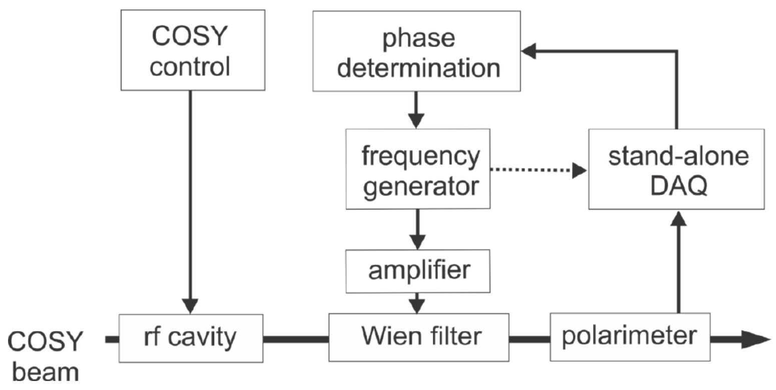
PhD work of Nils Hempelmann

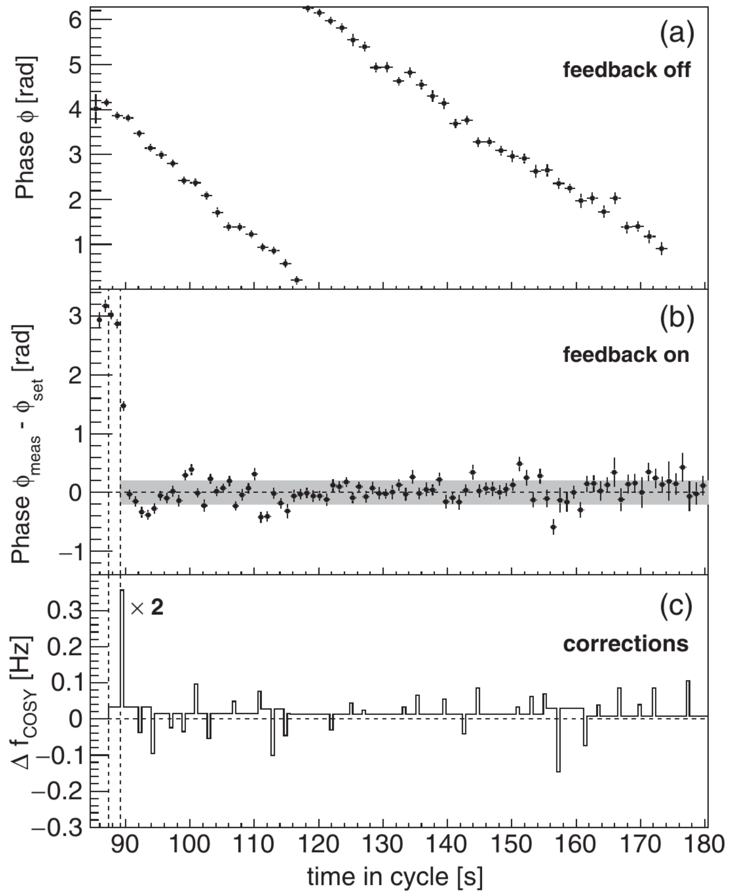
At COSY, one cannot freeze the spin precession

$\Rightarrow$ To achieve precision for EDM, phase-locking is next best thing to do.

Feedback system maintains

1. resonance frequency, and
2. phase between spin precession and device RF (solenoid or Wien filter)





Major achievement : Error of phase-lock $\sigma_\phi = 0.21\,\text{rad}$ [19, 2017].

More technical challenges of storage ring EDM experiments

Overview

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

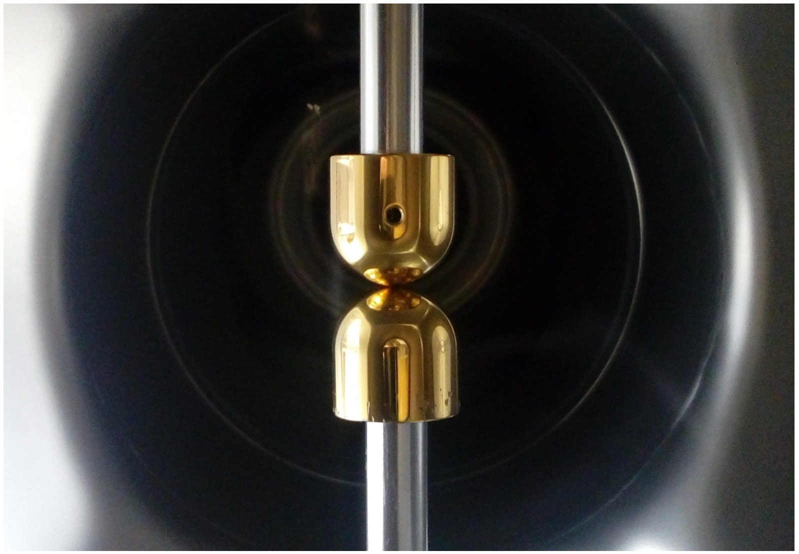
Main issues:

- Large electric field gradients $\sim$ 10 to 20 MV/m.
- Spin coherence time $\tau_{\mathrm{SCT}} \sim 1000\,\mathrm{s}$ [18, 2016].
- Continuous polarimetry with relative errors $< 1\,\mathrm{ppm}$ [20, 2012].
- Beam position monitoring with precision of 10 nm.
- High-precision spin tracking.
- Alignment of ring elements, ground motion, ring imperfections.
- Magnetic shielding.
- For deuteron EDM with frozen spin: precise reversal of magnetic fields for CW and CCW beams required.

E/B Deflector development using small-scale lab setup

Work by Kirill Grigoriev (IKP, RWTH Aachen and FZJ)

- Polished stainless steel
  - 240 MV/m reached at distance of 0.05 mm with half-sphere facing flat surface.
  - 17 MV/m with 1 kV at 1 mm with two small half-spheres.
- Polished aluminum
  - 30 MV/m measured at distance of 0.1 mm using two small half-spheres.
- TiN coating
  - Smaller breakdown voltage.
  - Zero dark current.

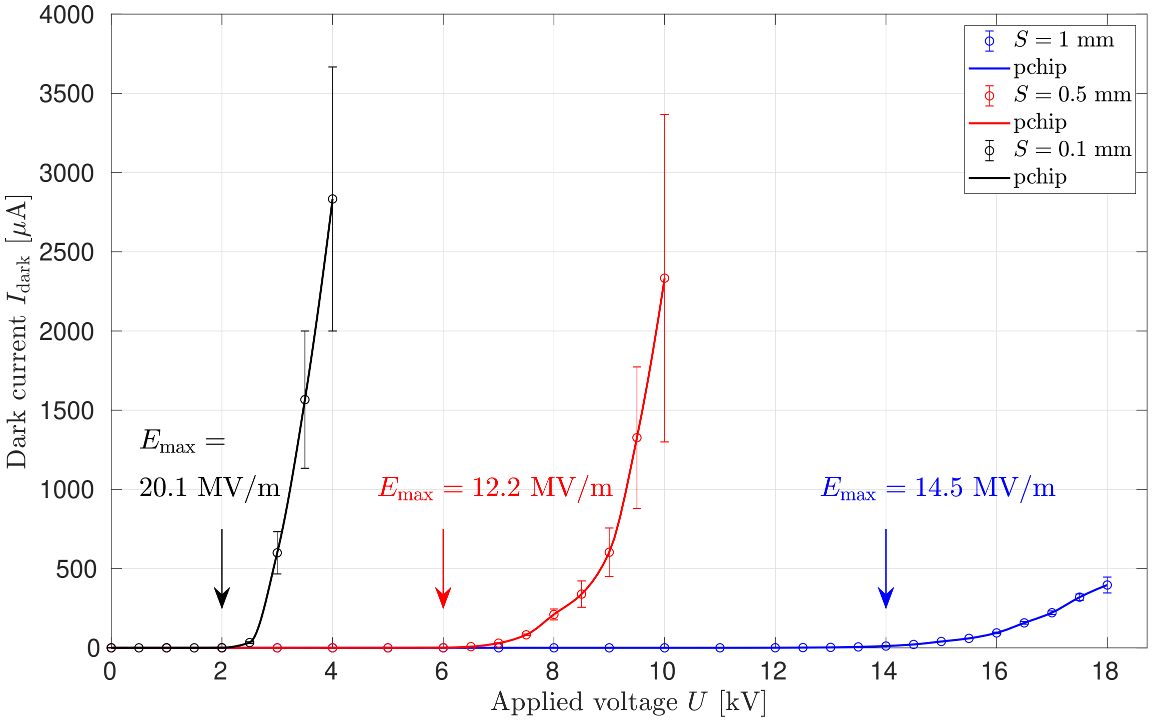


Recent results

Dark current of stainless-steel half-sphere electrodes (10 mm radius)

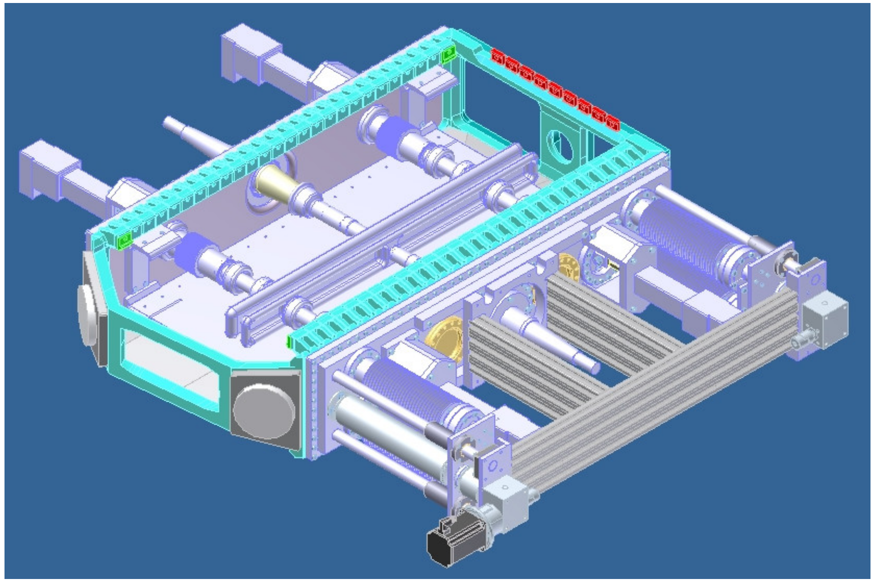
- distances $S = 1$, 0.5, and 0.1 mm, where

$$E_{\text{max}} = \frac{U}{S} \cdot F\,, \text{ where } F = \frac{1}{4}\left[1 + \frac{S}{R} + \sqrt{\left(1 + \frac{S}{R}\right)^2 + 8}\,\right], \tag{12}$$



Results promising, but tests with real size deflector elements are necessary.

E/B deflector development using real-scale lab setup



Equipment:

- Dipole magnet $B_{\max} = 1.6\,\mathrm{T}$
- Mass $= 64\,\mathrm{t}$
- Gap height $= 200\,\mathrm{mm}$
- Protection foil between chamber wall and deflector

Parameters:

- Electrode length $= 1020\,\mathrm{mm}$
- Electrode height $= 90\,\mathrm{mm}$
- Electrode spacing $= 20$ to $80\,\mathrm{mm}$
- Max. electric field $= \pm 200\,\mathrm{MV}$
- Material: Aluminum coated by TiN

Next steps:

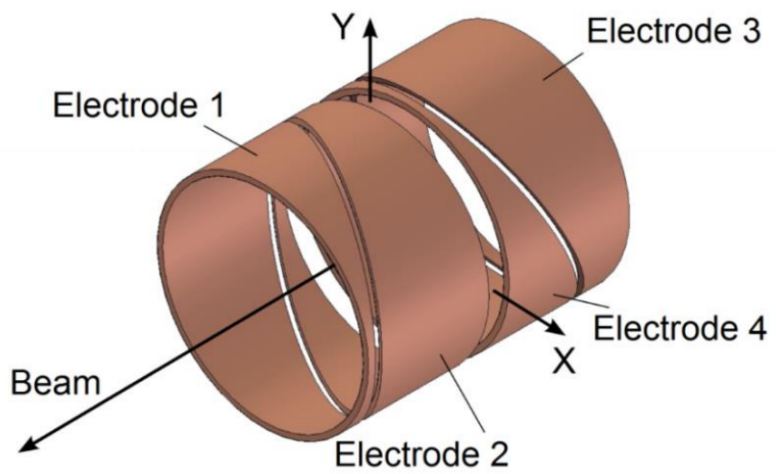
Equipment ready for assembling. First test results expected before Christmas.

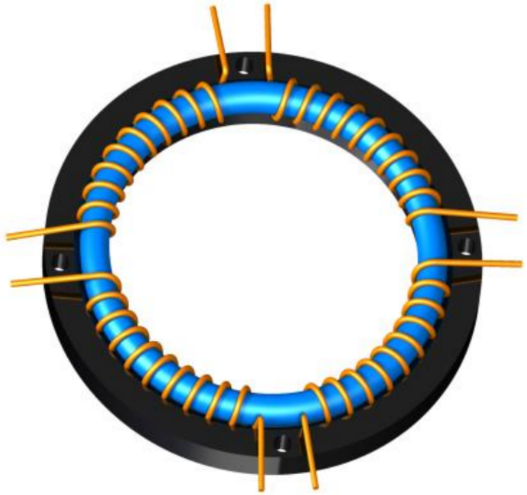
Beam position monitors for srEDM experiments

PhD work of Falastine Abusaif, improving earlier work by F. Trinkel

Development of compact BPM based on segmented Rogowski coil

- Main advantage is short installation length of ≈ 1 cm (along beam direction)





Conventional BPM

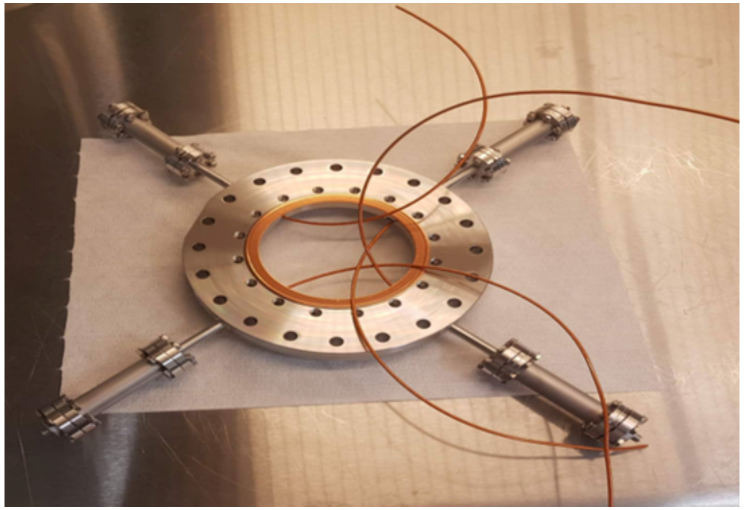
- Easy to manufacture
- length = 20 cm
- resolution ≈ 10 μm

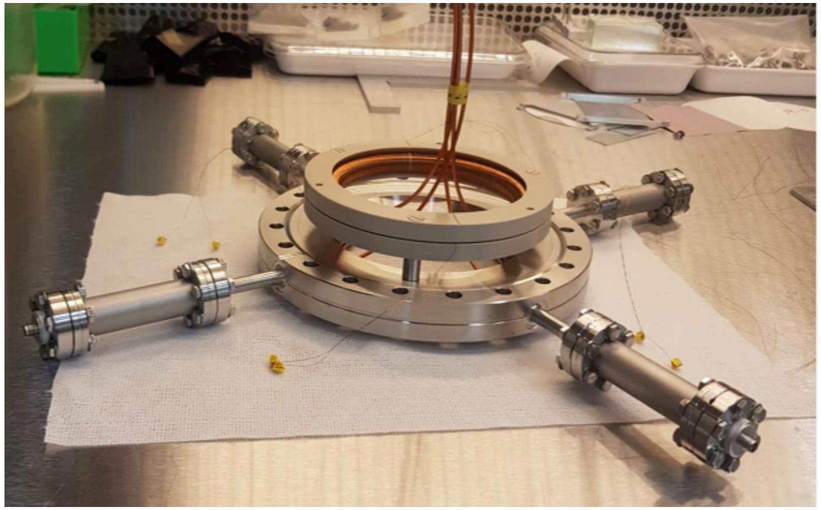
Rogowski BPM (warm)

- Excellent RF-signal response
- length = 1 cm
- resolution ≈ 1.25 μm

- Two Rogowski coil BPMs installed at entrance and exit of RF Wien filter

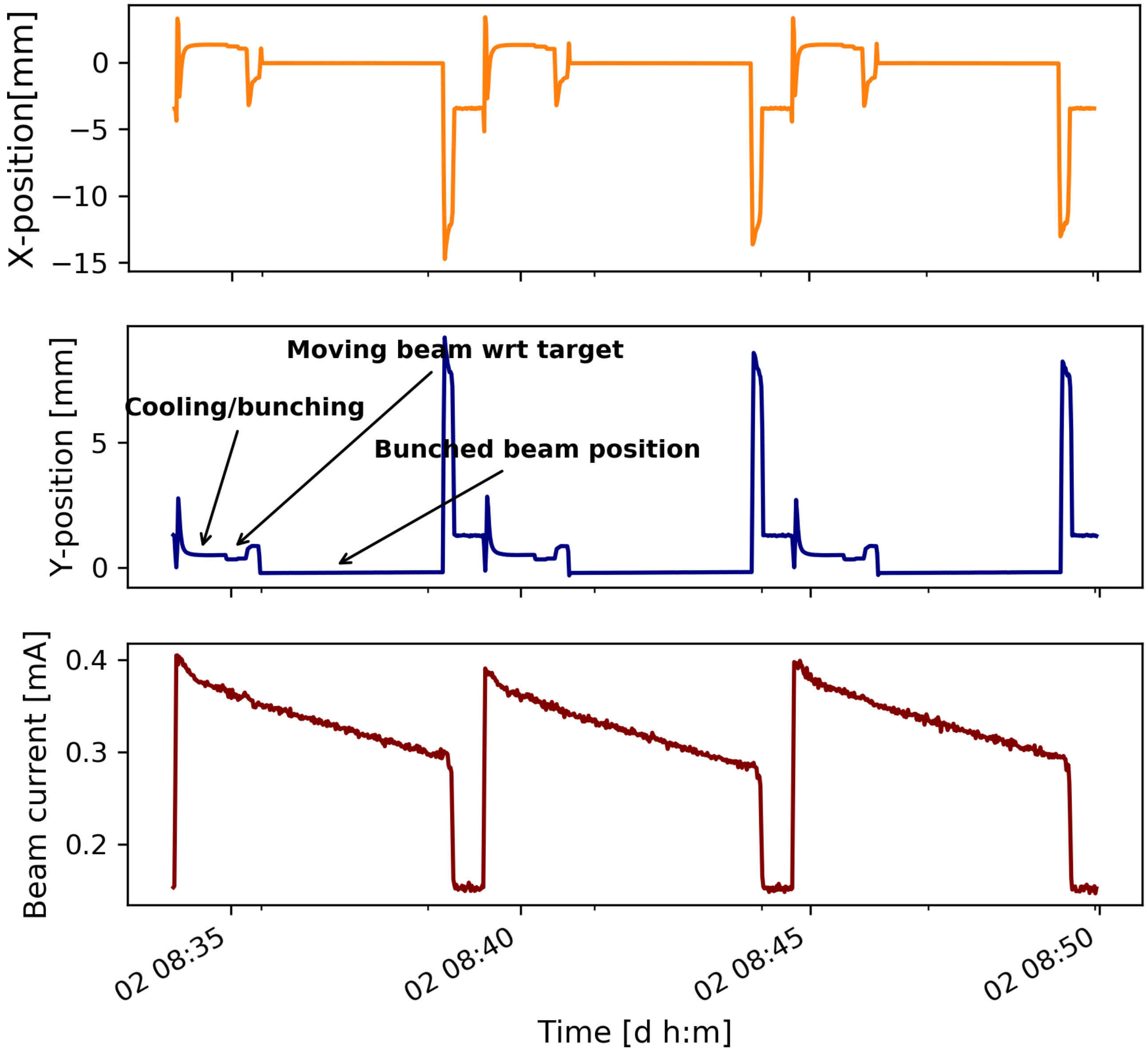
Assembly stages of one Rogowski-coil BPM





Measured beam positions at entrance of RF Wien filter

from ongoing run



dC polarimetry data base I

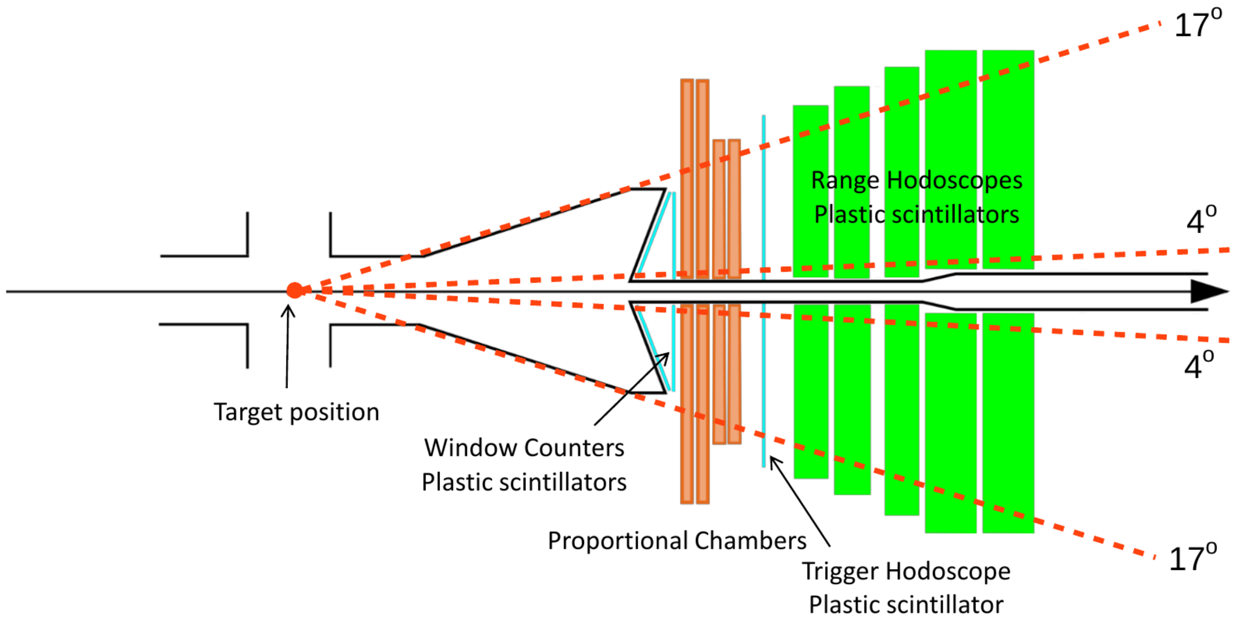
Data analysis mainly by Maria Zurek and PhD Fabian Müller

Motivation: Optimize polarimetry for ongoing JEDI experiments:

- Determine vector and tensor analyzing powers A_y, A_{yy}, and differential cross sections $\mathrm{d}\sigma/\mathrm{d}\Omega$ of *dC* elastic scattering at
  - deuteron kinetic energies $T = 170 - 380\,\mathrm{MeV}$.

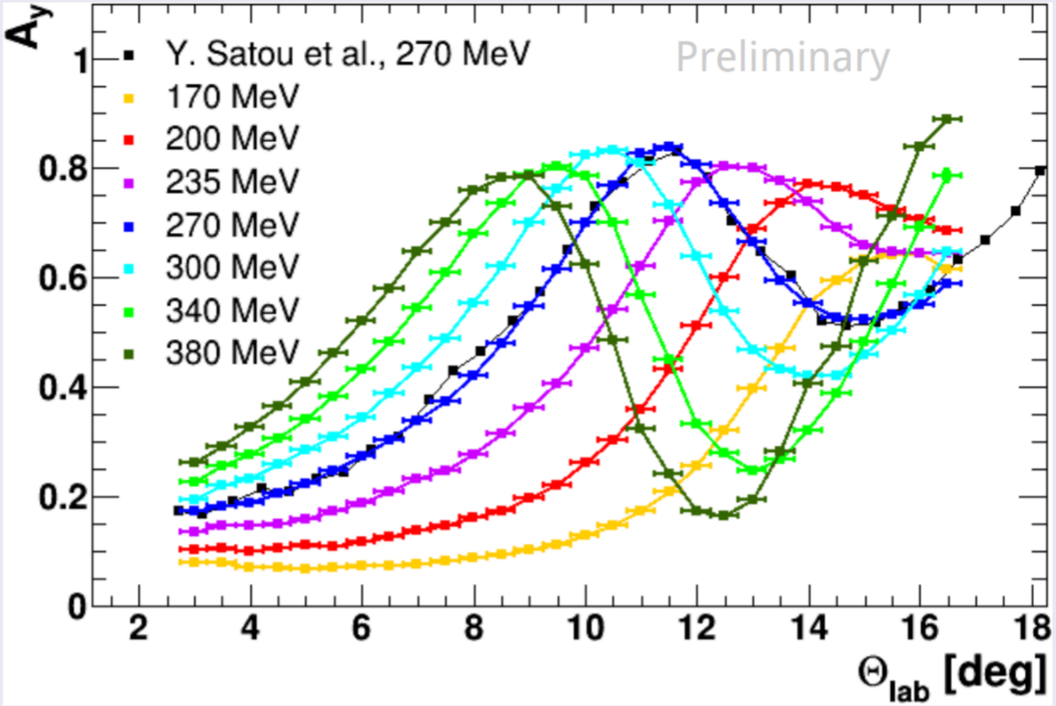
Detector system: former WASA forward detector, modified

- Targets: C and CH2
- Full azimuthal coverage, scattering angle range $\theta = 4^\circ - 17^\circ$.



dC polarimetry data base II

Preliminary results of elastic dC analyzing powers



- Analysis of differential *dC* cross sections in progress.
- Similar data base measurements carried out to provide *pC* data base.

High-precision beam polarimeter with internal C target

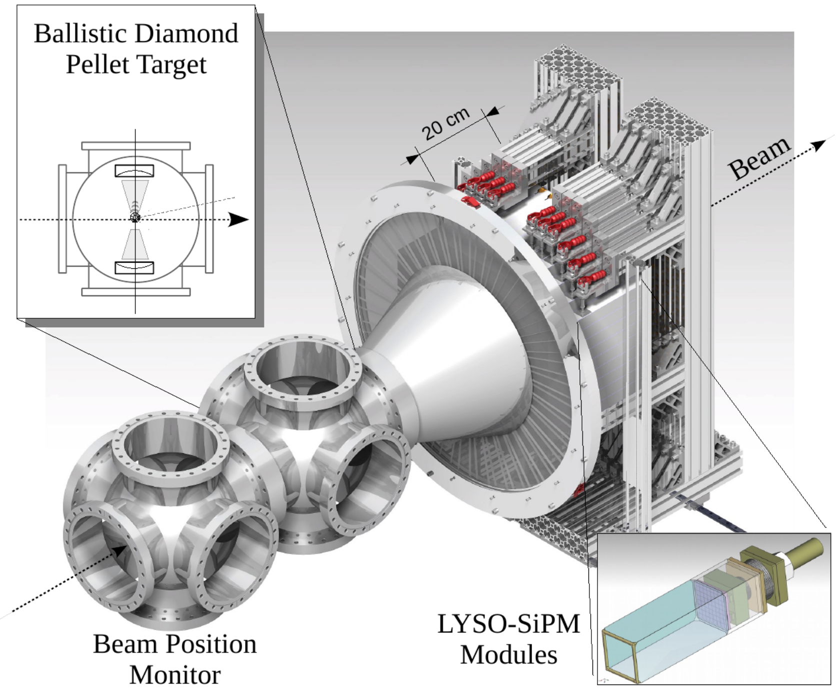
Development led by Irakli Keshelashvili

Based on LYSO Scintillation Material

- Saint-Gobain Ceramics & Plastics: $Lu_{1.8}Y_{.2}SiO_5$:Ce
- Compared to NaI, LYSO provides
  - high density (7.1 vs 3.67 g/cm^3),
  - very fast decay time (45 vs 250 ns).

After several runs with external beam:

- System ready for installation at COSY in 2019.
- Not yet ready: Ballistic diamond pellet target for homogeneous beam sampling.



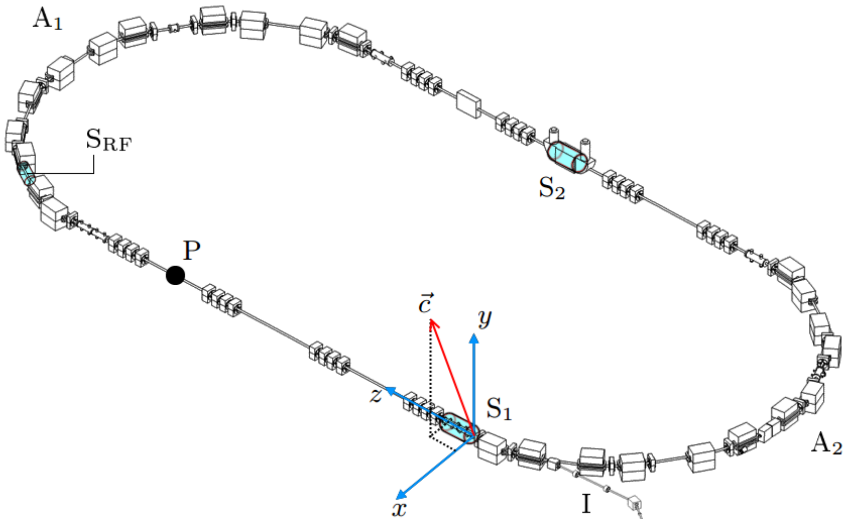
Study of machine imperfections

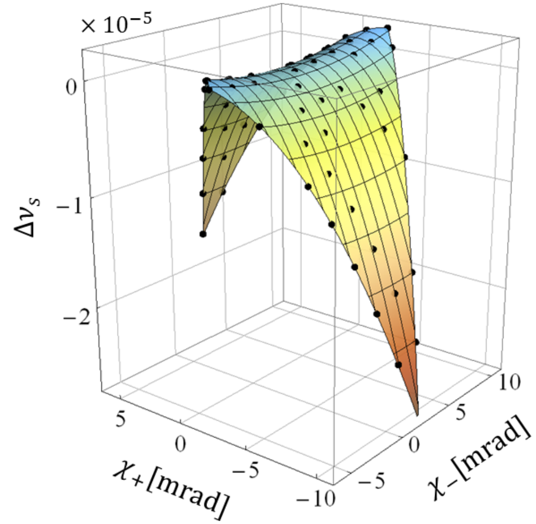
PhD work of Artem Saleev

JEDI developed new method to investigate magnetic machine imperfections based on highly accurate determination of spin-tune [21, 2017].

Spin tune mapping

- Two cooler solenoids act as spin rotators $\Rightarrow$ generate artificial imperfection fields.
- Measure spin tune shift vs spin kicks.





- Position of saddle point determines tilt of stable spin axis by magnetic imperfections.
- Control of background from MDM at level $\Delta c = 2.8 \times 10^{-6}$ rad.
- Systematics-limited sensitivity for deuteron EDM at COSY $\sigma_d \approx 10^{-20}\,$e cm.

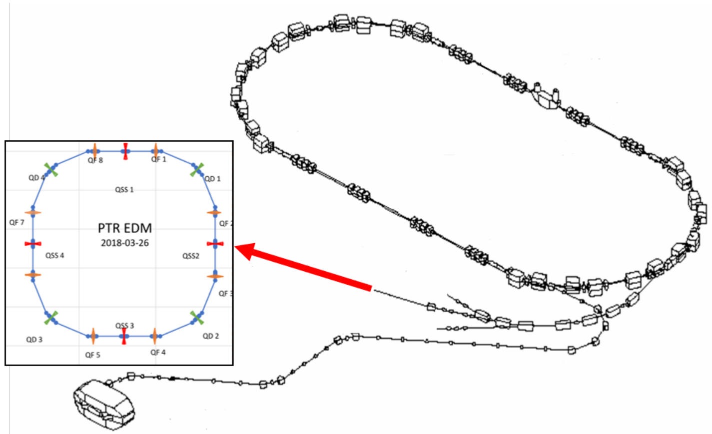
Prototype EDM storage ring

Next step:

- Build **demonstrator for charged-particle EDM**.
- Project prepared by a new **CPEDM** collaboration (CERN + JEDI + srEDM).
    - Physics Beyond Collider process (CERN), and the
    - European Strategy for Particle Physics Update.
- Possible host sites: COSY or CERN

Scope of prototype ring of 100 m circumference:

- p at 30 MeV all-electric CW-CCW beams operation.
- p at 45 MeV frozen spin including additional vertical magnetic fields



- Storage time
- CW/CCW operation
- Spin coherence time
- Polarimetry
- magnetic moment effects
- Stochastic cooling
- pEDM measurement

CPEDM time frame

1 Precursor Experiment →	2 Prototype Ring →	3 All-electric Ring
dEDM proof-of-capability (orbit and polarization control; first dEDM measurement)	**pEDM proof-of-principle** (key technologies, first direct pEDM measurement)	**pEDM precision experiment** (sensitivity goal: 10^{-29} e cm)
- Magnetic storage ring - Polarized deuterons - d-Carbon polarimetry - Additional E-field by RF Wien-filter	- High-current all-electric ring - Simultaneous CW/CCW op. - Frozen spin control (with combined E/B-field ring) - Phase-space beam cooling	- Frozen spin all-electric (at p = 0.7 GeV/c) - Simultaneous CW/CCW op. - B-shielding, high E-fields - Design: cryogenic, hybrid, …
Ongoing at COSY (Jülich) 2014 → 2021	Ongoing within CPEDM 2017 → 2020 (CDR) → 2022 (TRD) Start construction > 2022	After construction and operation of prototype > 2027?

Proof of principle experiment using COSY

Precursor experiment

Highest EDM sensitivity shall be 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 provides required sensitivity ($< 10^{-28}\,\mathrm{e\,cm}$).
  - In this environment, magnetic fields mean evil (since μ is large).

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

- In magnetic machine, particle spins (deuterons, protons) precess about stable spin axis ($\simeq$ direction of magnetic fields in dipole magnets).
- 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 function of time in cycle ($\sim 1000\,\mathrm{s}$).

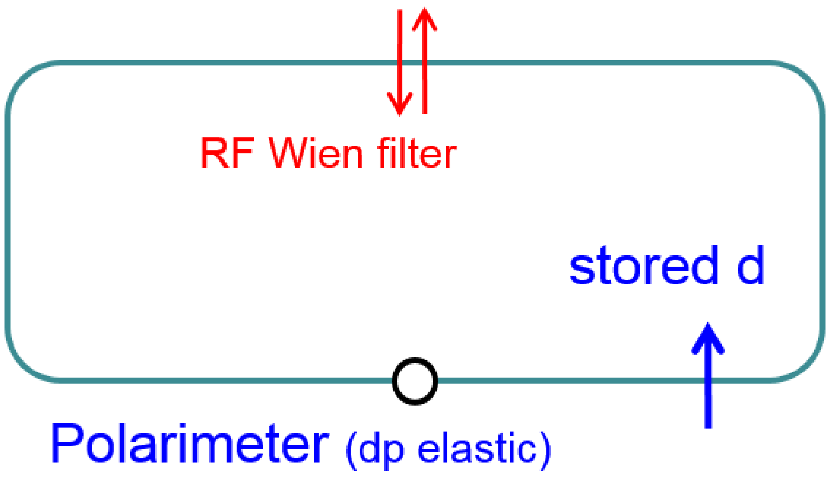
Goal of proof-of-principle experiment:

Show that conventional storage ring useable for 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 $\tau_{\mathrm{SCT}} \sim 1000\,\mathrm{s}$.

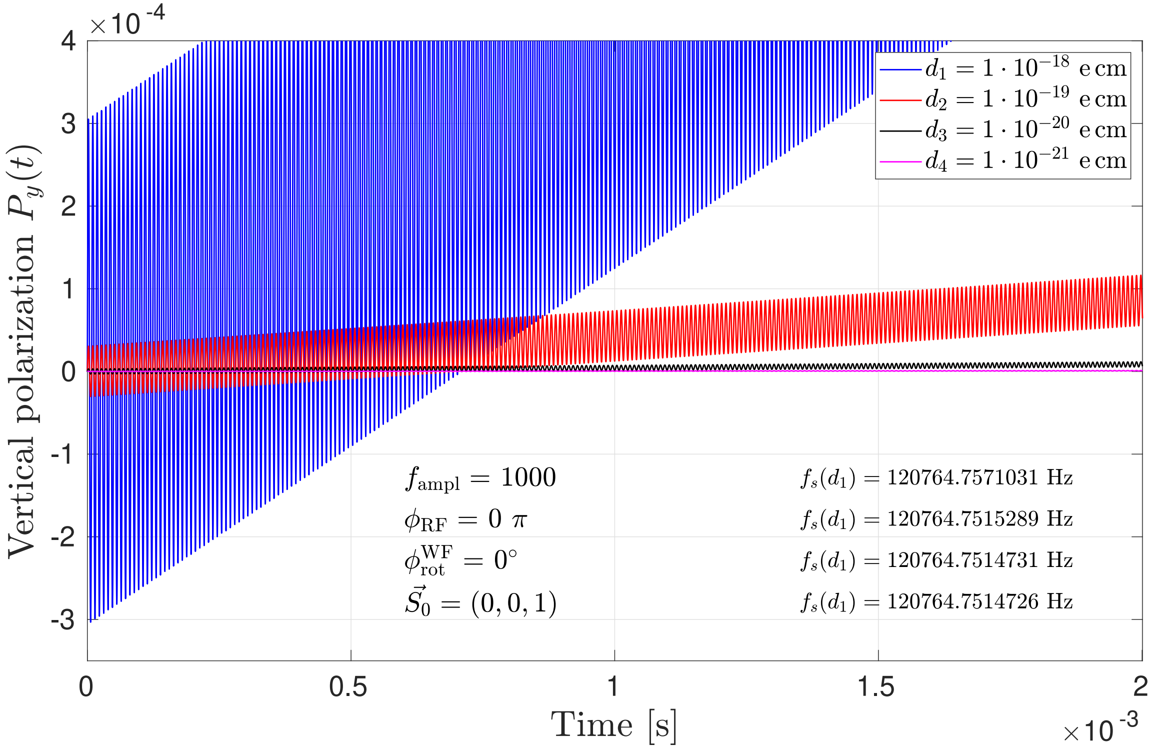
Statistical sensitivity:

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

Model calculation of EDM buildup with RF Wien filter

Ideal COSY ring with deuterons at $p_d = 970\,\mathrm{MeV/c}$:

- $G = -0.143$, $\gamma = 1.126$, $f_s = f_{\mathrm{rev}}(\gamma G + K_{(=0)}) \approx 120.765\,\mathrm{kHz}$
- Electric RF field integral assumed $1000 \times \int E_{\mathrm{WF}} \cdot \mathrm{d}\ell \approx 2200\,\mathrm{kV}$ (w/o ferrites) [22, 2016].

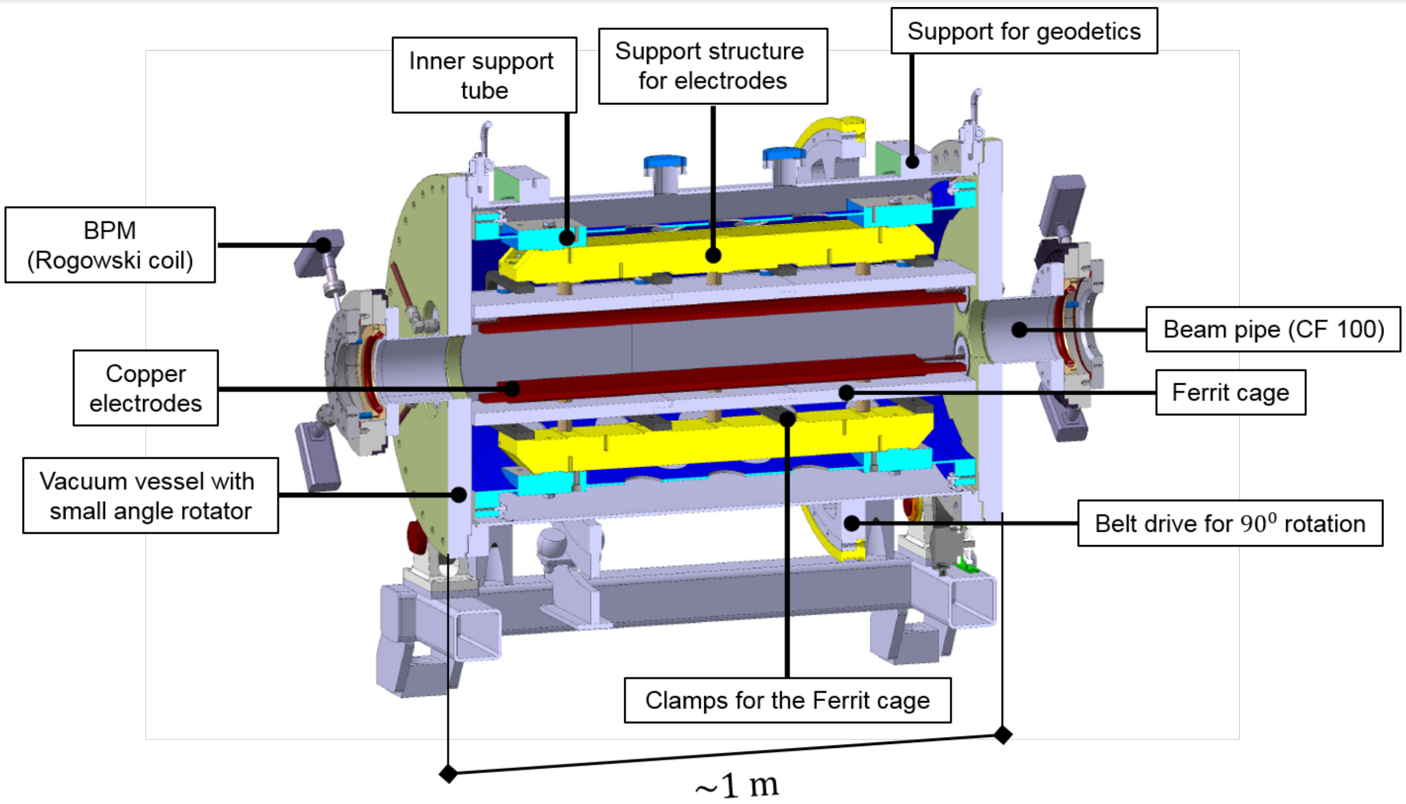


EDM accumulates in $P_y(t) \propto d_{\mathrm{EDM}}$ [21, 23, 24].

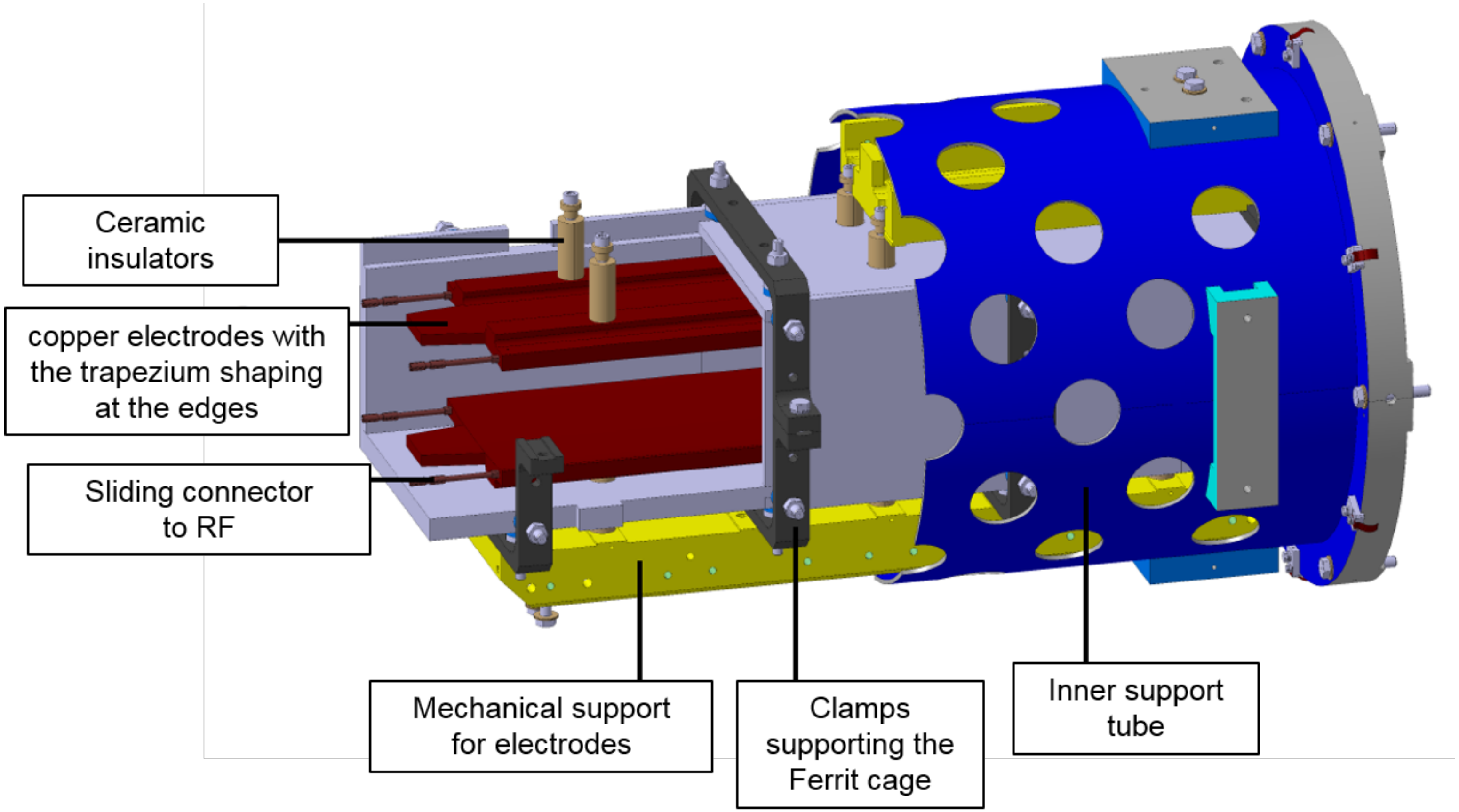
Design of waveguide RF Wien filter

Joint Jülich – RWTH Aachen development:

- 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 [22].



Internal structure



Aim was to build the best possible device, with respect to

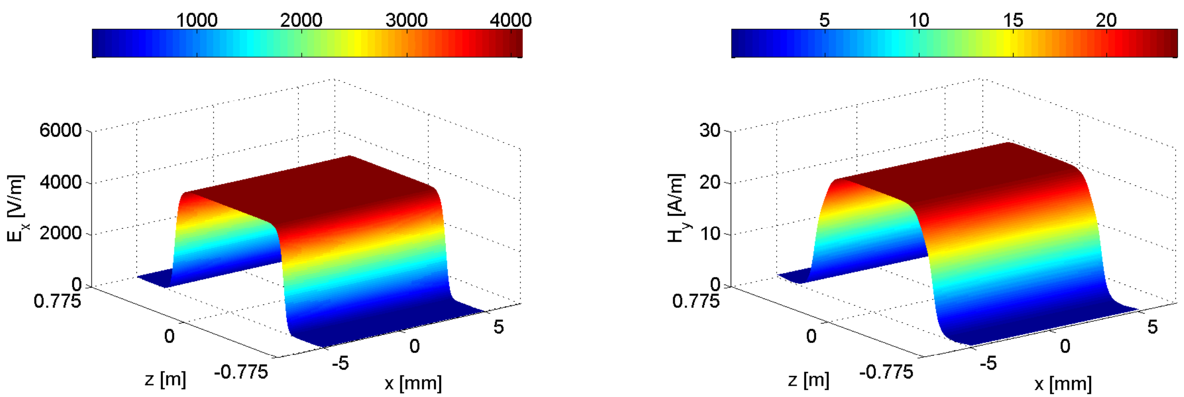
- Electromagnetic performance [22] and mechanical tolerances [25].
- Excellent cooperation with RWTH Aachen University and ZEA-Jülich.

Electromagnetic field simulations (incl. ferrites) [?]

Full-wave simulations

- using CST Microwave Studio[a].

[a] Computer Simulation Technology AG, Darmstadt, Germany, `http://www.cst.com`



At an input power of 1 kW, magnetic and electric field integrals are ($\ell = 1.550\,\text{m}$):

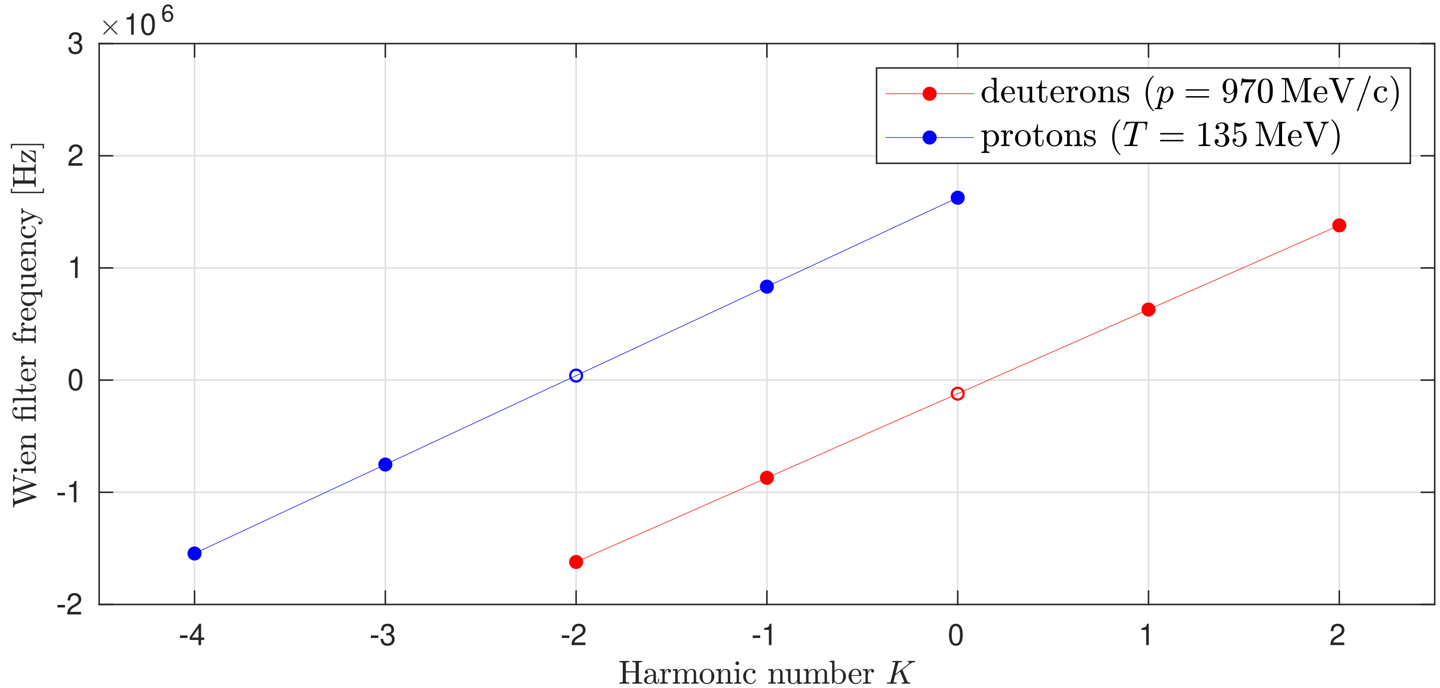
$$\int_{-\ell/2}^{\ell/2} \vec{B} dz = \begin{pmatrix} 2.73 \times 10^{-9} \\ \mathbf{2.72 \times 10^{-2}} \\ 6.96 \times 10^{-7} \end{pmatrix} \text{T mm}\,, \quad \int_{-\ell/2}^{\ell/2} \vec{E} dz = \begin{pmatrix} \mathbf{3324.577} \\ 0.018 \\ 0.006 \end{pmatrix} \text{V} \tag{13}$$

Frequencies of RF Wien filter

Resonance condition:

$$f_{\mathrm{WF}} = f_{\mathrm{rev}} \left(\gamma G \pm K\right), k \in \mathbb{Z}. \tag{14}$$

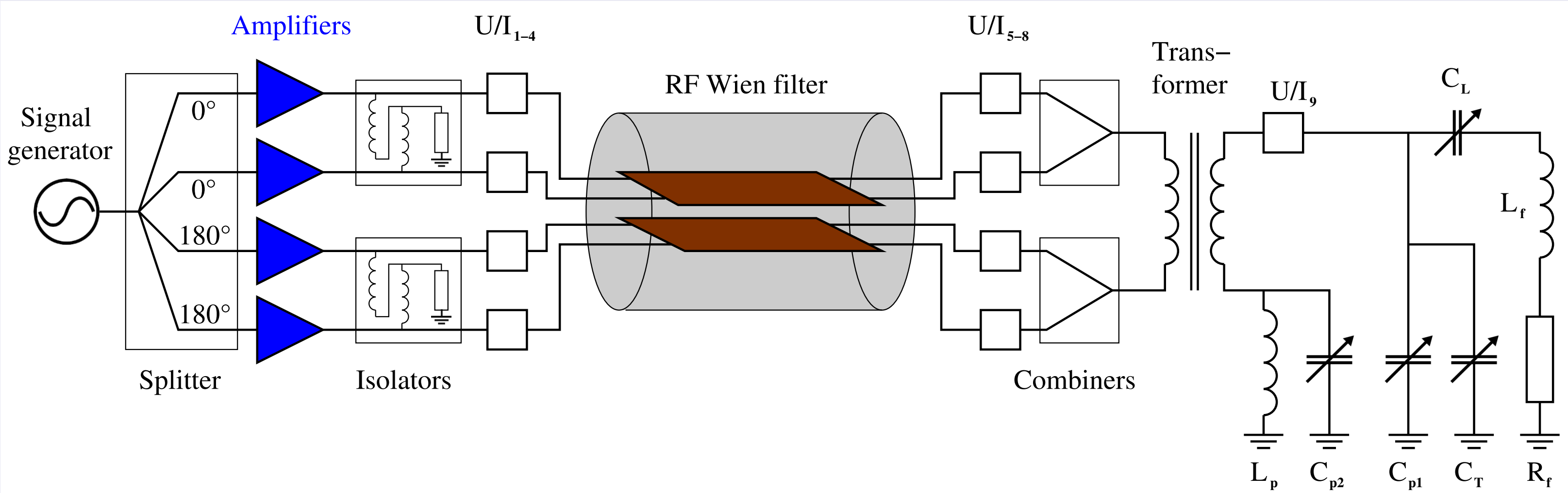
- RF Wien filter operates at frequencies between 0 to 2 MHz,
- Open symbols not reachable with present setup of driving circuit, *i.e.*,
  - deuterons at $K = 0$ (-120.8 kHz), and
  - protons at $K = -2$ (39.4 kHz).



Driving circuit

Realization with load resistor and tunable elements (L's and C's):

- Design layout using four separate 1 kW power amplifiers.



Circuit fully operational

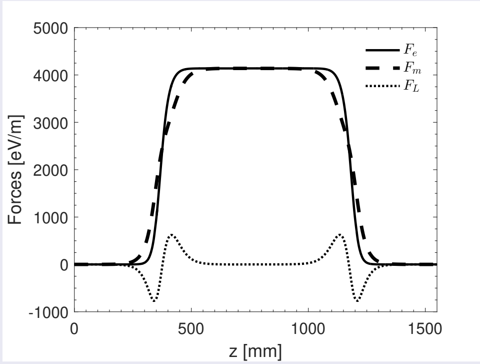
- Tuneable elements[a] allow [22]:
  - minimization of Lorentz-force, and
  - velocity matching to β of the beam.
- Power upgrade to $4 \times 2\,\mathrm{kW}$: $\int B_z \mathrm{d}z = 0.218\,\mathrm{T\,mm}$ possible.

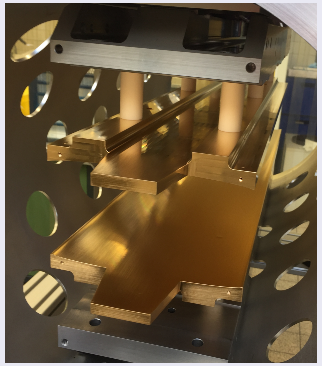
[a] built by Fa. Barthel, `http://www.barthel-hf.de`.

Lorentz force compensation [22]

Integral Lorentz force is of order of $-3\,\mathrm{eV/m}$:

- Electric force F_e, magnetic force F_m, and Lorentz force F_L inside RF Wien filter.
- Trapezoid-shaped electrodes determine crossing of electric and magnetic forces.





Lorentz force

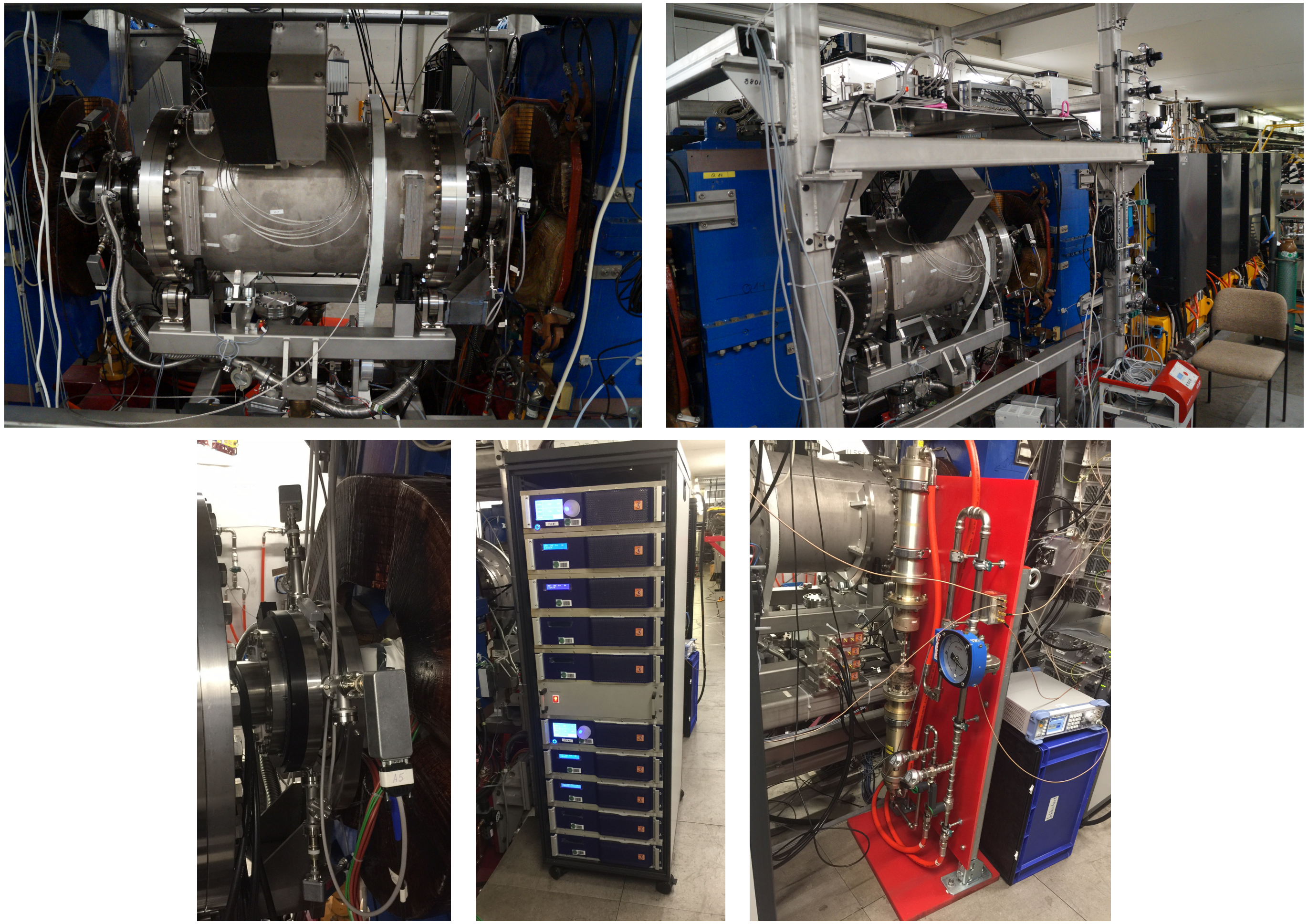
$$\vec{F}_\mathrm{L} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)\,, \qquad (15)$$

- particle charge q, velocity vector $\vec{v} = c(0, 0, \beta)$, fields $\vec{E} = (E_x, E_y, E_z)$ and $\vec{B} = \mu_0(H_x, H_y, H_z)$, μ_0 vacuum permeability.
- For vanishing Lorentz force $\vec{F}_\mathrm{L} = 0$, field quotient Z_q given by

$$E_x = -c \cdot \beta \cdot \mu_0 \cdot H_y \quad \Rightarrow \quad \boxed{Z_q = -\frac{E_x}{H_y} = c \cdot \beta \cdot \mu_0 \approx 173\ \Omega}\,. \qquad (16)$$

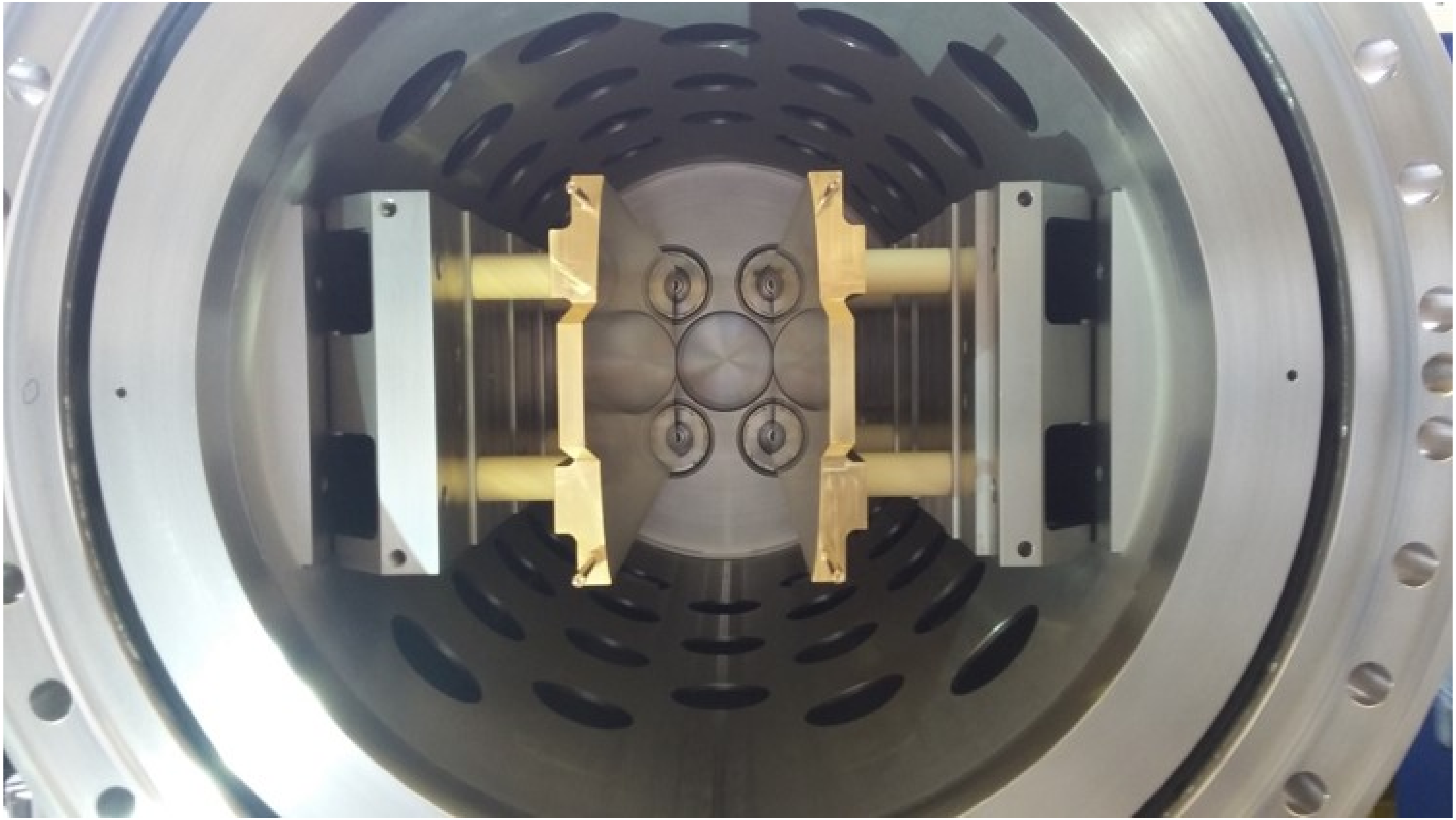
RF Wien filter

Installation at COSY



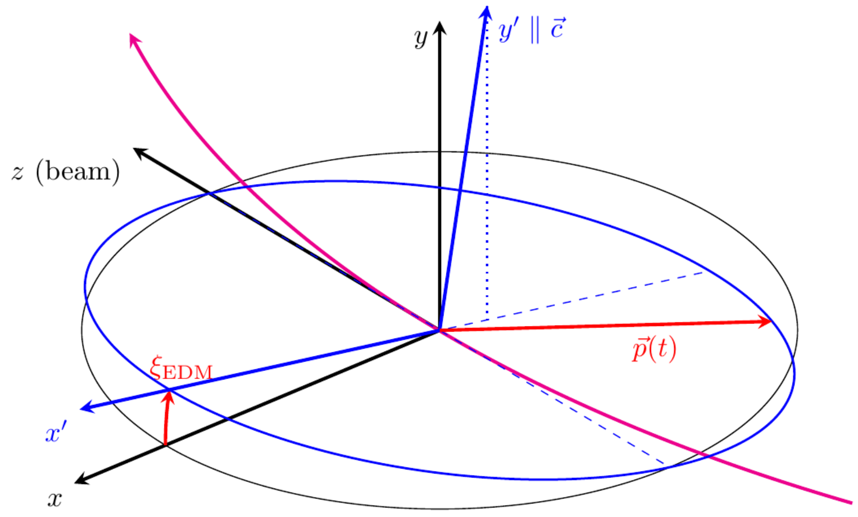
- RF Wien filter between PAX magnets. Upstream Rogowski coil; racks with power amplifiers, each unit delivers up to 500 W; water-cooled 25 Ω resistor.

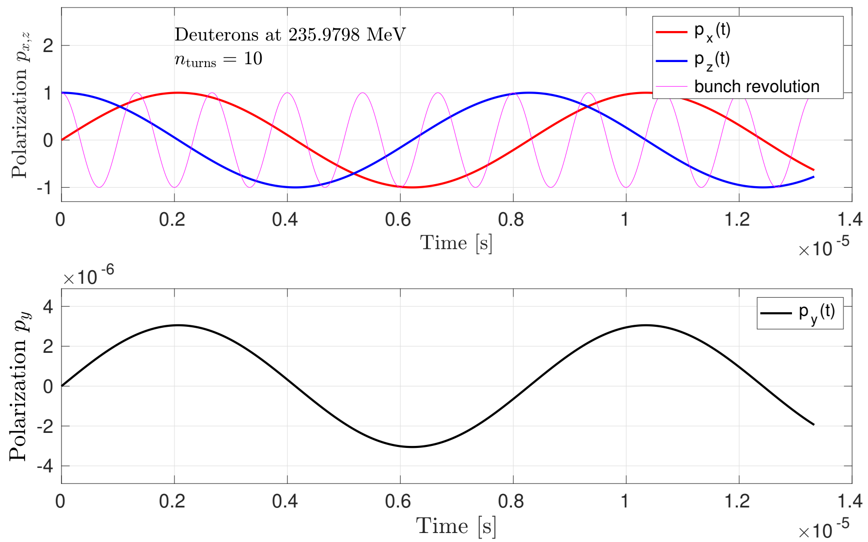
Installation at COSY II



View along the beam axis in the RF Wien filter.

Effect of EDM on stable spin axis of the ring





Beam particles move along z direction

- Presence of an EDM $\Rightarrow \xi_{\mathrm{EDM}} > 0$.

$\Rightarrow$ Spins precess around the $\vec{c}$ axis.

$\Rightarrow$ Oscillating vertical polarization component $p_y(t)$ is generated.

Evolution for 10 turns ($\vec{p}_0 = (0, 0, 1)$)

- $p_x(t)$, $p_z(t)$ and $p_y(t)$.
- Bunch revolution indicated as well.
- Magnitude of p_y oscillation amplitude corresponds to tilt angle ξ_{EDM}.

Strength of EDM resonance

EDM induced vertical polarization oscillations,

- can generally be described by

$$p_y(t) = a \sin(\Omega^{p_y}\, t + \phi_{\mathrm{RF}})\,. \tag{17}$$

- Define **EDM resonance strength** $\varepsilon^{\mathrm{EDM}}$ as ratio of angular frequency Ω^{p_y} relative to orbital angular frequency Ω^{rev},

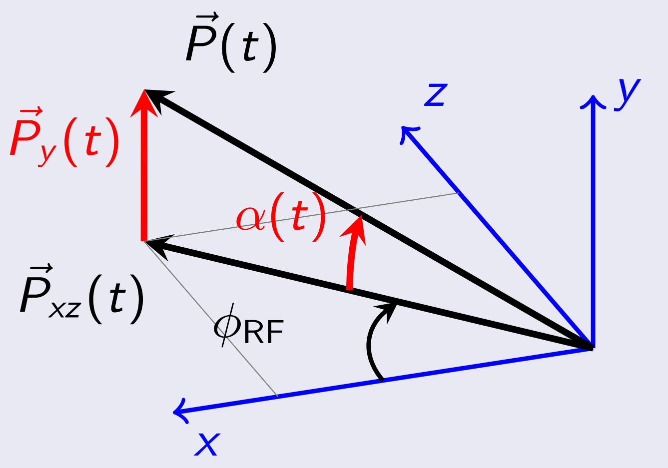
$$\varepsilon^{\mathrm{EDM}} = \frac{\Omega^{p_y}}{\Omega^{\mathrm{rev}}}\,, \tag{18}$$

Alternatively, $\varepsilon^{\mathrm{EDM}}$ is determined from the measured initial slopes $\dot{p}_y(t)|_{t=0}$

- through variation of ϕ_{RF}

$$\varepsilon^{\mathrm{EDM}} = \frac{\dot{p}_y(t)|_{t=0}}{a\,\cos\phi_{\mathrm{RF}}} \cdot \frac{1}{\Omega^{\mathrm{rev}}}\,. \tag{19}$$

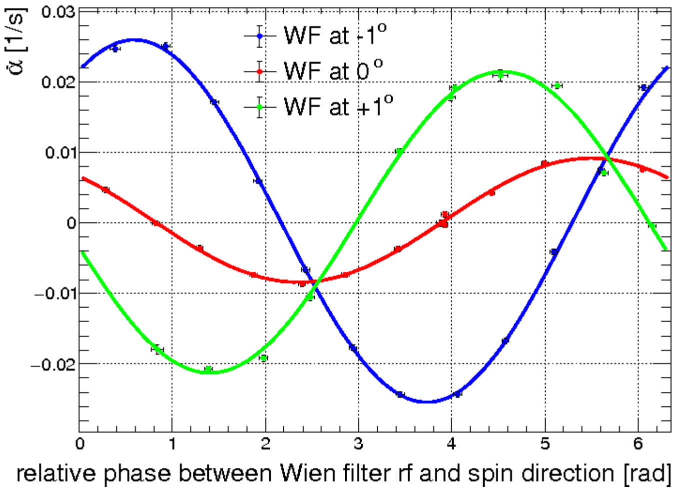
- If $|\vec{P}| = 1 \quad \Rightarrow \quad \dot{p}_y(t) = \dot{\alpha}(t)$



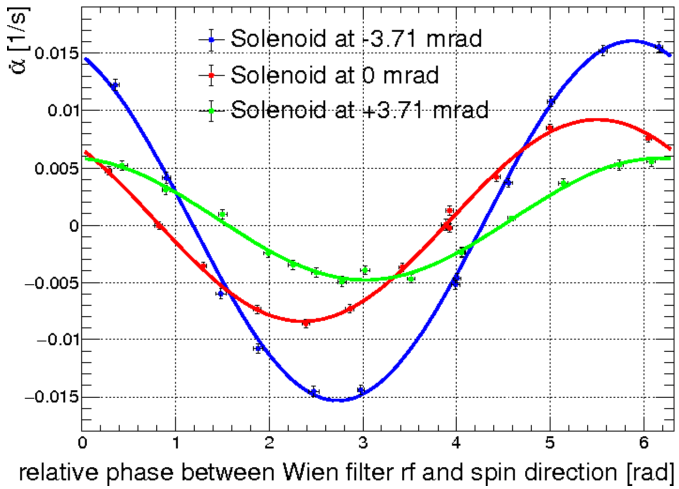
First measurement of EDM-like buildup signals

Rate of out-of-plane rotation angle $\dot{\alpha}(t)|_{t=0}$ as function of Wien filter RF phase ϕ_{RF}

- B field of RF Wien filter normal to the ring plane.
- Wien filter operated at $f_{\text{WF}} = 871\,\text{kHz}$.
- Variations of $\phi^{\text{WF}}_{\text{rot}}$ and $\chi^{\text{Sol 1}}_{\text{rot}}$ affect the pattern of observed initial slopes $\dot{\alpha}$.



$\dot{\alpha}$ for $\phi^{\text{WF}}_{\text{rot}} = -1^\circ, 0^\circ, +1^\circ$ and $\chi^{\text{Sol 1}}_{\text{rot}} = 0$.

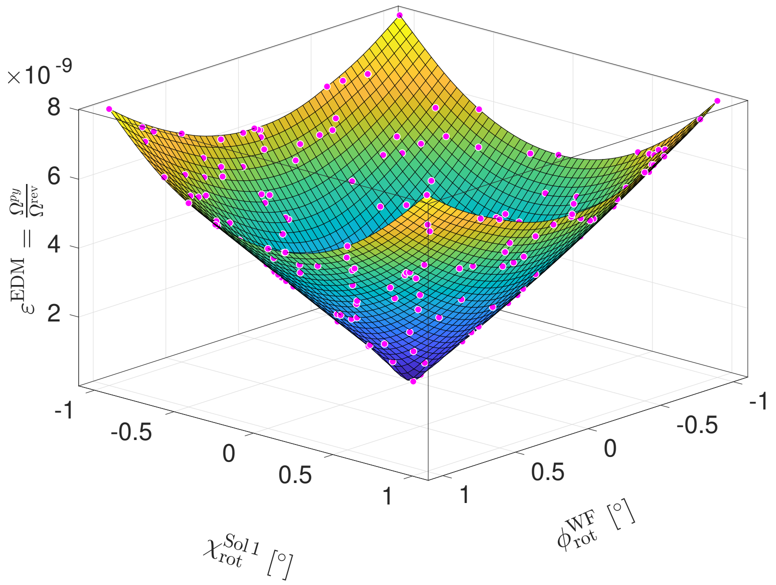


$\dot{\alpha}$ for $\chi^{\text{Sol 1}}_{\text{rot}} = -1, 0, +1^\circ$ and $\phi^{\text{WF}}_{\text{rot}} = 0$.

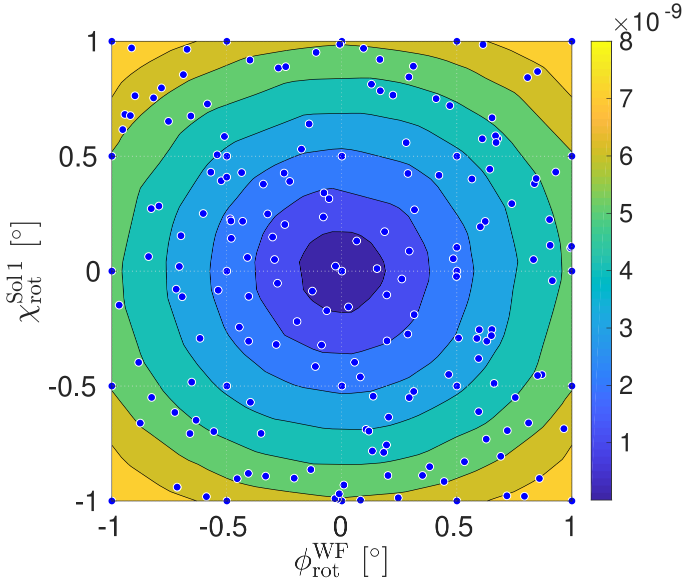
Planned measurements:

- 1st EDM measurement run Nov-Dec/2018 (6 wk, ongoing).
- 2nd run planned for Fall/Winter 2019 (6 wk).

Expectation for $d = 10^{-20}\,\mathrm{e\,cm}$ in ideal COSY ring



(a) $\varepsilon^{\mathrm{EDM}}$ for $d = 10^{-20}\,\mathrm{e\,cm}$.

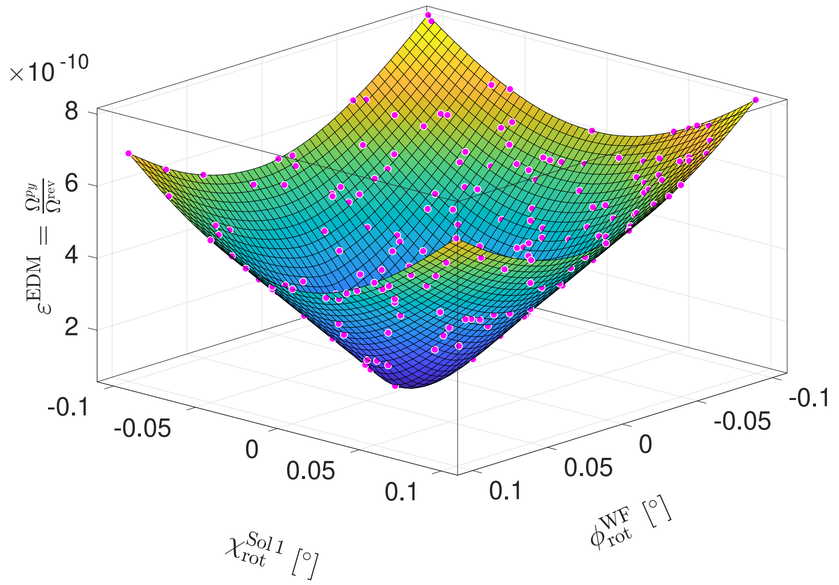


(b) Contour plot of (a).

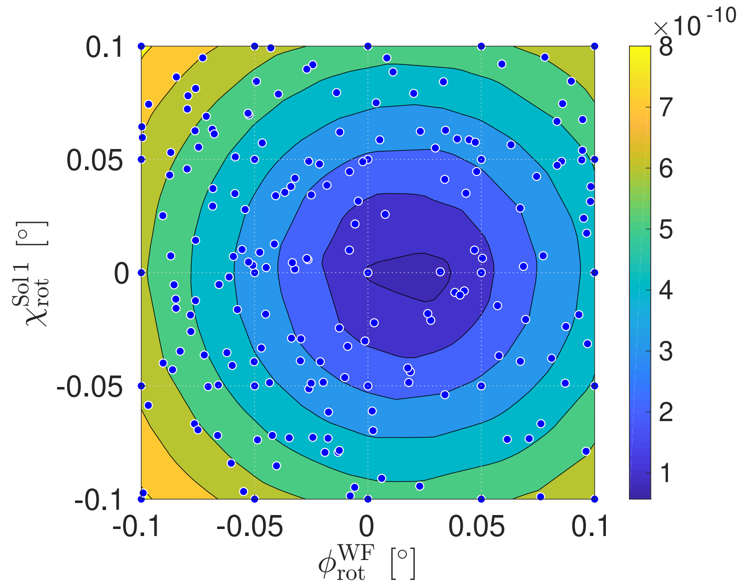
Resonance strengths $\varepsilon^{\mathrm{EDM}}$ from Eq. (18) ($\approx$ 175 random-points)

- $\phi^{\mathrm{WF}}_{\mathrm{rot}} = [-1\,^\circ, \dots, +1\,^\circ]$,
- $\chi^{\mathrm{Sol\,1}}_{\mathrm{rot}} = [-1\,^\circ, \dots, +1\,^\circ]$ (100 keV cooler), and
- $\chi^{\mathrm{Sol\,2}}_{\mathrm{rot}} = 0$ (2 MeV cooler).
- Each point from calculation with $n_{\mathrm{turns}} = 50\,000$ and $n_{\mathrm{points}} = 200$.

Expectation for $d = 10^{-18}\,\mathrm{e\,cm}$ in ideal COSY ring



(c) $\varepsilon^{\mathrm{EDM}}$ for $d = 10^{-18}\,\mathrm{e\,cm}$.

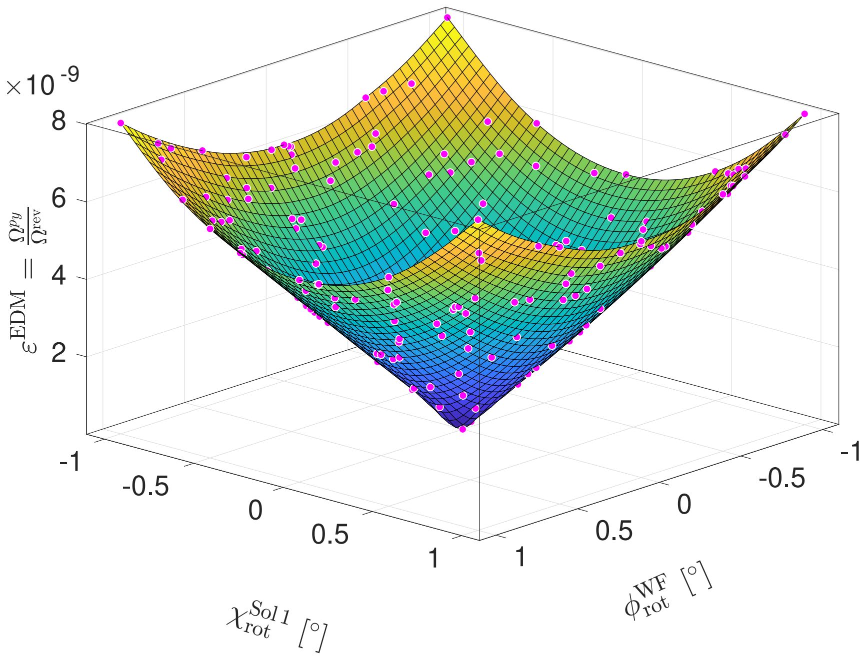


(d) Contour plot of (c).

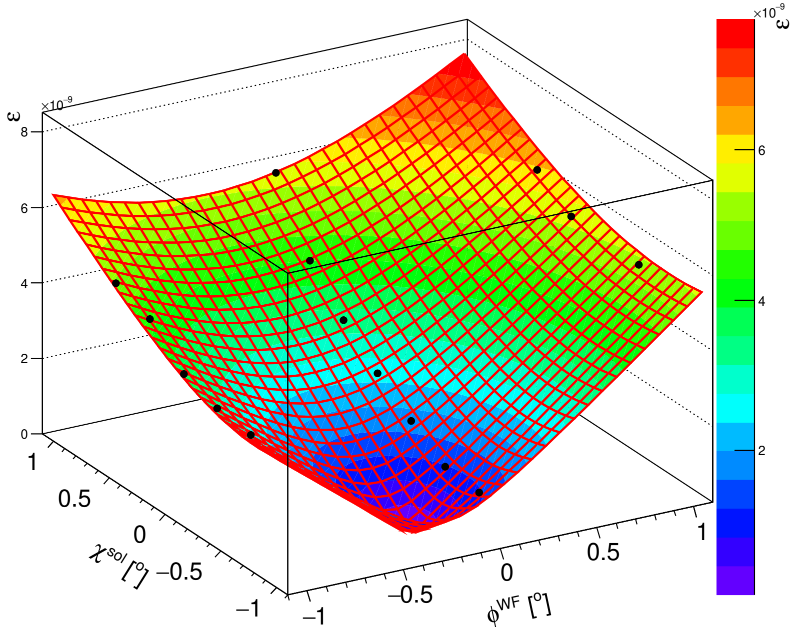
Resonance strengths $\varepsilon^{\mathrm{EDM}}$ from Eq. (18) (≈ 175 random-points)

- $\phi_{\mathrm{rot}}^{\mathrm{WF}} = [-0.1\,°, \ldots, +0.1\,°]$,
- $\chi_{\mathrm{rot}}^{\mathrm{Sol\,1}} = [-0.1\,°, \ldots, +0.1\,°]$ (100 keV cooler), and
- $\chi_{\mathrm{rot}}^{\mathrm{Sol\,2}} = 0$ (2 MeV cooler).
- Each point from calculation with $n_{\mathrm{turns}} = 200\,000$ and $n_{\mathrm{points}} = 100$.

First results from the test run in May-June '18



(e) Simulated ε^{EDM} for $d = 10^{-20}$ e cm.



(f) First 16 points on the map.

Importance of spin tracking simulations

- Orientation of stable spin axis at location of RF Wien filter *including the EDM* is determined from minimum of map.
- Spin tracking calculations shall provide orientation of stable spin axis *without* EDM.

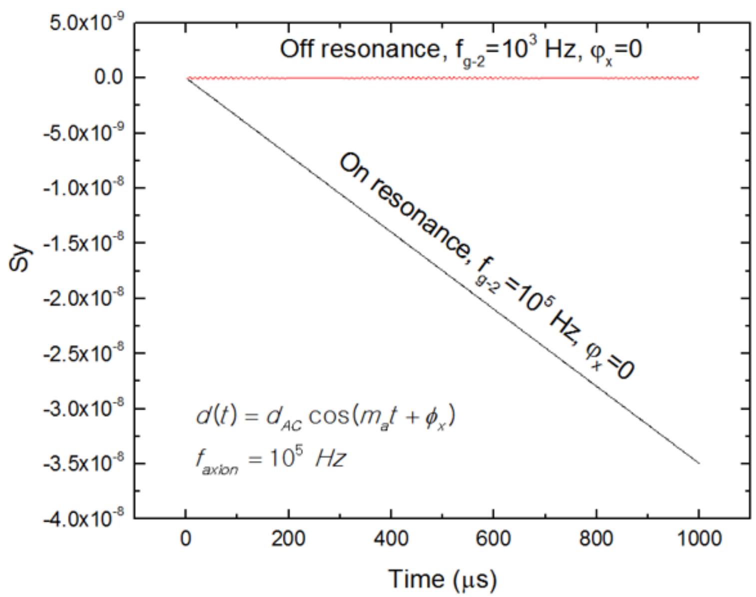
(Oscillating) Axion-EDM search using storage ring

Motivation: Paper by Graham and Rajendran [26, 2011]

- Oscillating axion field is coupled with gluons and induces an oscillating EDM in hadronic particles.

Measurement principle:

- When oscillating EDM resonates with particle $g-2$ precession frequency in the storage ring, the EDM precession can be accumulated.
- Due to strong effective electric field (from $\vec{v} \times \vec{B}$), sensitivity improved significantly.



Courtesy of Seongtae Park (IBS, Daejeon, ROK)

Limits for axion-gluon coupled to oscillating EDM

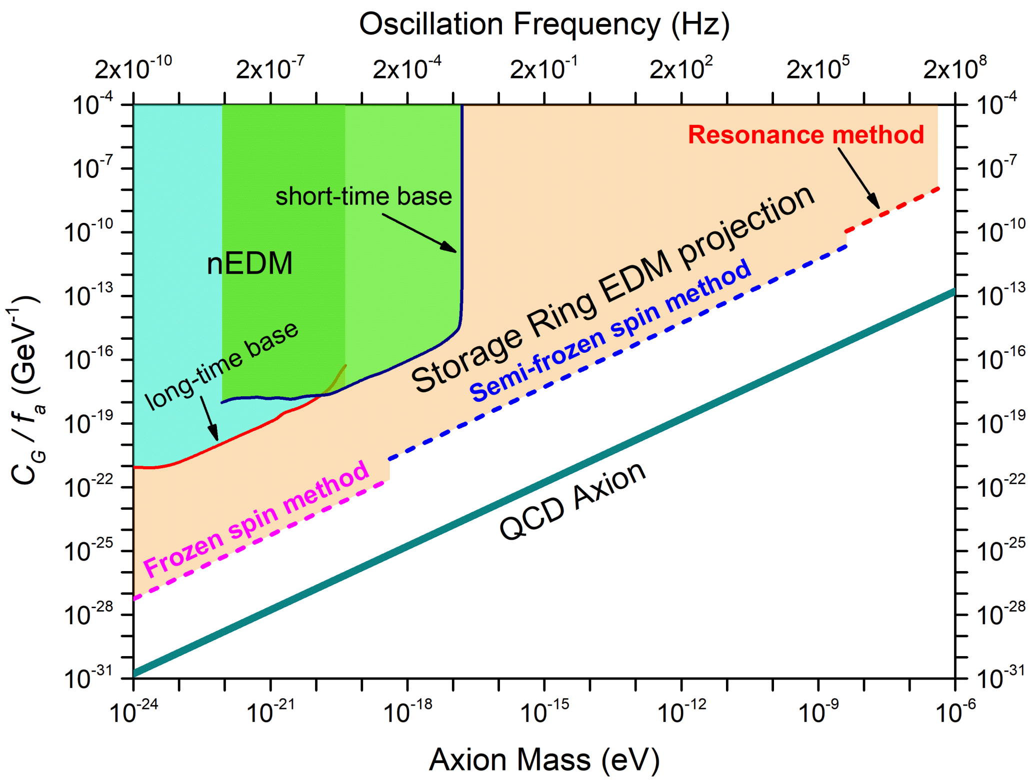


Figure from S.P. Chang et al. [27]

Realization

- No new/additional equipment required!
- Can be done in magnetic storage ring (*i.e.*, COSY).
- Proposal for test beam time accepted by CBAC.
- Experiment scheduled for I/2019.

Summary

Search for charged hadron particle EDMs (proton, deuteron, light ions):

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

Present investigations

- JEDI is making steady progress in spin dynamics of relevance to future searches for EDM.
- COSY remains a unique facility for such studies.
- First direct JEDI deuteron EDM measurement at COSY underway.
  - Ongoing 6 wk run Nov.-Dec. '18.
  - Sensitivity $10^{-19} - 10^{-20}$ e cm.

Strong interest of high energy community in storage ring EDM searches

- protons and light nuclei as part of physics program of the post-LHC era.
  - Physics Beyond Collider process (CERN), and
  - European Strategy for Particle Physics Update.
  - As part of this process, proposal for prototype EDM storage ring being prepared by CPEDM (possible hosts: CERN or COSY).

JEDI Collaboration

JEDI = Jülich Electric Dipole Moment Investigations

- $\sim$ 140 members (Aachen, Daejeon, Dubna, Ferrara, Indiana, Ithaka, Jülich, Krakow, Michigan, Minsk, Novosibirsk, St Petersburg, Stockholm, Tbilisi, . . .
- `http://collaborations.fz-juelich.de/ikp/jedi`

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