

First direct hadron EDM measurement with deuterons using COSY

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(on behalf of the JEDI collaboration)

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Contents

Introduction

- Baryon asymmetry in the Universe
- Electric dipole moments
- Frozen-spin method and magic machines

Progress toward storage ring EDM experiments

- Spin coherence time, spin tune, and phase lock

First direct deuteron EDM measurement using COSY

- RF Wien filter method
- Technical realization of RF Wien filter
- Fast RF switches and pilot bunch
- Measurements of EDM-induced polarization buildup

Outlook

- From JEDI to CPEDM: a prototype EDM storage ring

Summary

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]

► SCM gets it wrong by about 9 orders of magnitude.

Electric dipole moments (EDMs)

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 :

$$-\vec{\mu} \cdot \vec{B} \xrightarrow{P \text{ or } T} -\vec{\mu} \cdot \vec{B}$$

No other direction than spin $\Rightarrow \vec{d}$ parallel to $\vec{\mu} (\vec{s})$.

- ▶ **Energy of electric dipole** $H = -\vec{d} \cdot \vec{E}$, includes term

$$\vec{s} \cdot \vec{E} \xrightarrow{P \text{ or } T} -\vec{s} \cdot \vec{E}, \quad (1)$$

Thus, EDMs violate both P and T symmetry

- ▶ EDMs possibly constitute the missing cornerstone to explain surplus of matter over antimatter in the Universe.
 - ▶ Non-vanishing EDMs would add 4th quantum number to fundamental particles (besides m , q , and s).

Motivation

Large worldwide effort to search for EDMs of fundamental particles:

- ▶ hadrons, leptons, solids, atoms and molecules.
- ▶ ~ 500 researchers (estimate by Harris, Kirch).

Why search for charged particle EDMs using a storage ring?

1. Up to now, no direct measurement of charged hadron EDM available:
2. 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.
3. Approach complimentary to neutron EDM searches.

Theorists keep repeating that

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 .

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

- ▶ 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:

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

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

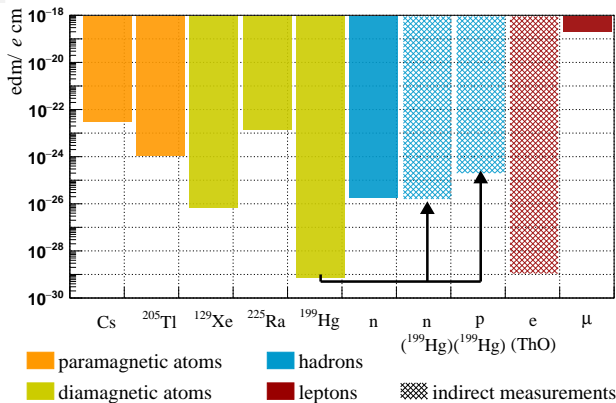
$$|d_N| \sim 10^{-7} \times 10^{-24} \text{ e cm} \sim 10^{-31} \text{ e cm}$$

Region to search for Beyond Standard Model (BSM) physics

- ▶ from nucleon EDMs with $\theta_{\text{QCD}} = 0$:

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

Status of EDM searches [6, CYR '21]



Missing are *direct* EDM measurements:

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

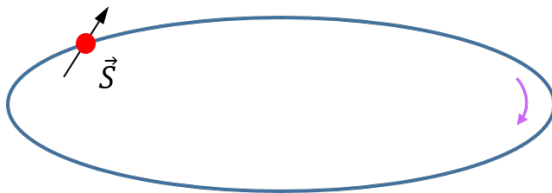
Spin precession of particles with MDM and EDM

In rest frame of particle,

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

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}. \quad (2)$$

Put the protons in a ring



- Spin-precession in presence of MDMs and EDMs is described by Thomas-BMT equation [7].

Frozen-spin

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

$$\begin{aligned}\vec{\Omega} &= \vec{\Omega}_{\text{MDM}} - \vec{\Omega}_{\text{cyc}} \\ &= -\frac{q}{\gamma m} \left[G\gamma \vec{B}_{\perp} + (1+G)\vec{B}_{\parallel} - \left(G\gamma - \frac{\gamma}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} \right].\end{aligned}\quad (3)$$

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

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

$$\vec{\Omega} = 0, \text{ if } \left(G\gamma - \frac{\gamma}{\gamma^2 - 1} \right) = 0. \quad (4)$$

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

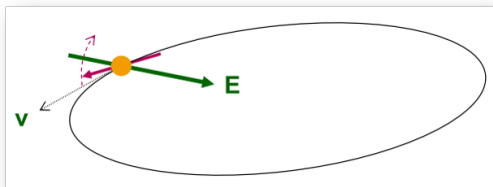
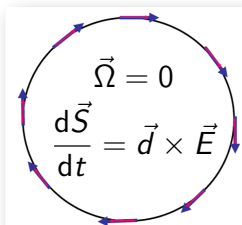
For protons, (4) leads to *magic momentum*:

$$G - \frac{1}{\gamma^2 - 1} = 0 \Leftrightarrow G = \frac{m^2}{p^2} \quad \Rightarrow \quad \boxed{p = \frac{m}{\sqrt{G}} = 700.740 \text{ MeV c}^{-1}} \quad (5)$$

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 $P_y(t) \propto d$.

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: $E = 10 \text{ MV/m}$.
- ▶ Long spin coherence time: $\tau_{\text{SCT}} = 1000 \text{ s}$.
- ▶ 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:

$$\sigma_{\text{stat}} = \frac{1}{\sqrt{N f \tau_{\text{SCT}} P A_y E}} \Rightarrow \boxed{\sigma_{\text{stat}}(1 \text{ yr}) = 10^{-29} \text{ e cm}} . \quad (6)$$

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

Progress toward storage ring EDM experiments

Complementing the spin physics tool box

COoler SYnchrotron COSY

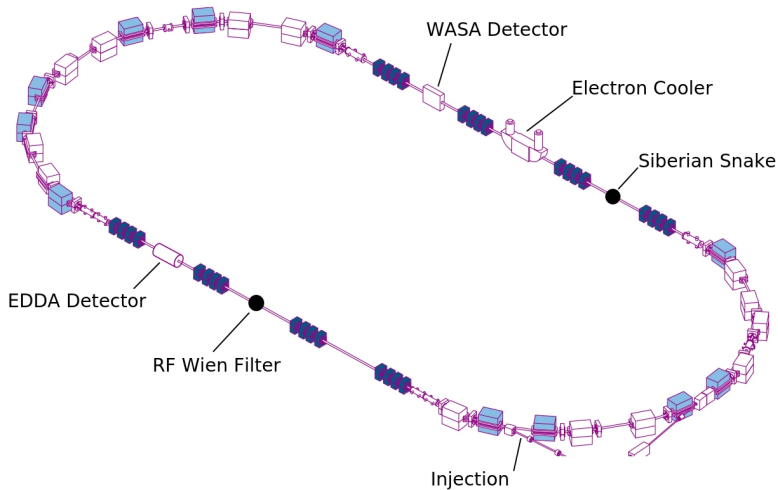
- ▶ Cooler and storage ring for (polarized) protons and deuterons.
- ▶ Momenta $p = 0.3 - 3.7 \text{ GeV}/c$.
- ▶ Phase-space cooled internal and extracted beams.



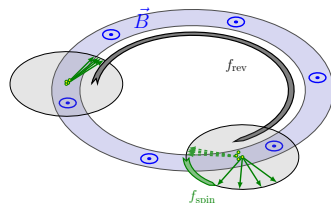
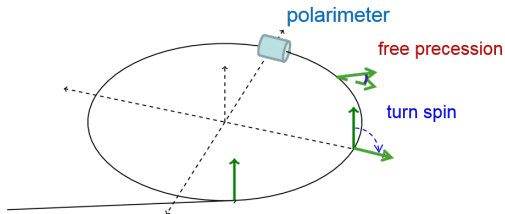
COSY formerly used as spin-physics machine for hadron physics:

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

COSY Landscape



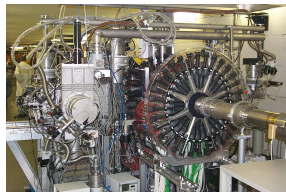
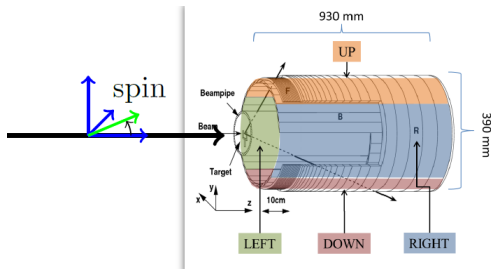
Principle of spin-coherence time measurement



Measurement procedure:

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

Detector system: EDDA [8]



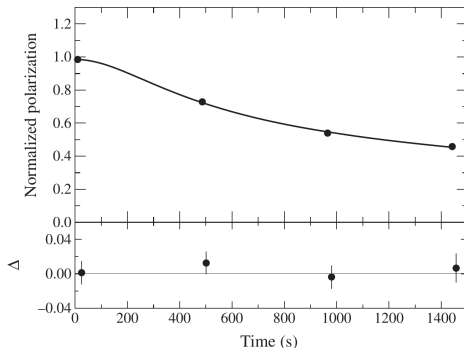
EDDA used to determine $\vec{p}\vec{p}$ elastic polarization observables:

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

$$N_{U,D} \propto 1 \pm \frac{3}{2} p_x A_y \sin(\underbrace{\nu_s \cdot f_{\text{rev}}}_{f_s = -120.7 \text{ kHz}} \cdot t), \text{ where } f_{\text{rev}} = 750.0 \text{ kHz}. \quad (7)$$

Optimizations of spin-coherence time: [10, PRL '16]

Precise adjustments of three sextupole families in the ring



JEDI progress on τ_{SCT} :

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

- Previous record:
 $\tau_{\text{SCT}}(\text{VEPP}) \approx 0.5 \text{ s}$ [9]
 $(\approx 10^7 \text{ spin revolutions})$.

Spring 2015: Way beyond anybody's expectation:

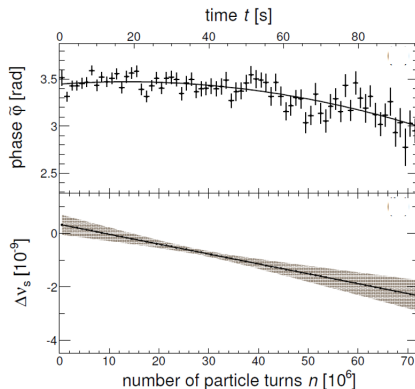
- With about 10^9 stored deuterons.
- Long spin coherence time was one of main obstacles of srEDM experiments.
- Large value of τ_{SCT} of crucial importance (6), since $\sigma_{\text{stat}} \propto \tau_{\text{SCT}}^{-1}$.

Precision determination of the spin tune [11, PRL '15]

Precise time-stamping of events,

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

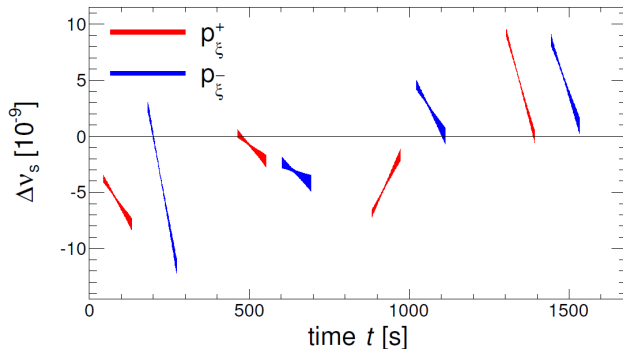
$$\begin{aligned}\nu_s(n) &= \nu_s^{\text{fix}} + \frac{1}{2\pi} \frac{d\tilde{\phi}}{dn} \\ &= \nu_s^{\text{fix}} + \Delta\nu_s(n)\end{aligned}\quad (8)$$



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 [11].

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 (→ **phase-lock**).
- ▶ Studies of machine imperfections.

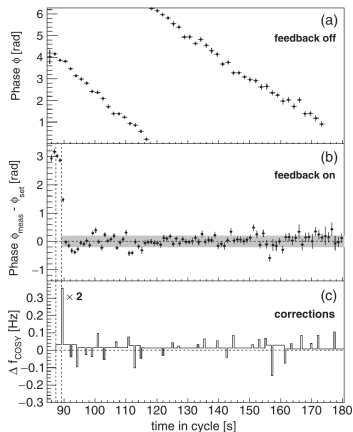
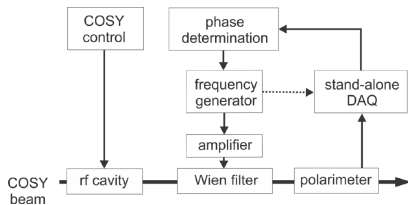
Phase locking spin precession in machine to device RF

At COSY, one cannot freeze the spin precession

⇒ 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 WF)



Major achievement : Error of phase-lock $\sigma_\phi = 0.21$ rad [12, PRL '17].

First direct hadron EDM measurement with deuterons using COSY

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First direct deuteron EDM measurement 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 ($< 10^{-28}$ e cm).
 - ▶ In this environment, magnetic fields mean evil (since μ is large).

Idea of proof-of-principle experiment with 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 (~ 1000 s).

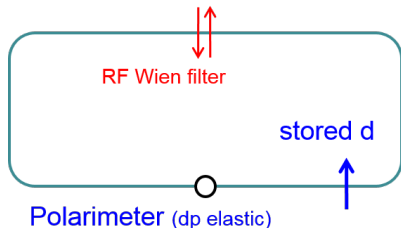
Goal of proof-of-principle experiment:

Show that conventional storage ring useable for first direct EDM measurement

RF Wien filter method

More aspects about the technique:

- ▶ RF Wien filter ($\vec{E} \times \vec{B}$) avoids coherent betatron oscillations in the beam:
 - ▶ Lorentz force $\vec{F}_L = q(\vec{E} + \vec{v} \times \vec{B}) = 0$ (JEDI paper on collective oscillations near quantum limit [13, PRAB '21]).
 - ▶ EDM measurement mode: $\vec{B} = (0, B_y, 0)$ and $\vec{E} = (E_x, 0, 0)$.



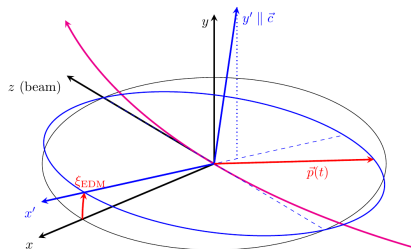
- ▶ Deuteron spins lie in machine plane.
- ▶ If $d \neq 0 \Rightarrow$ *accumulation* of vertical polarization P_y , during spin coherence time $\tau_{\text{SCT}} \sim 1000$ s.

Statistical sensitivity:

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

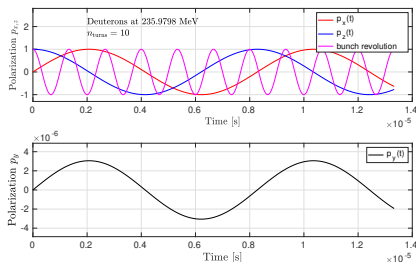
Effect of EDM on stable spin axis of the ring

Without RF WF



Beam particles move along z direction

- Presence of an EDM $\Rightarrow \xi_{\text{EDM}} > 0$.
- \Rightarrow Spins precess around the \vec{c} axis.
- \Rightarrow Oscillating vertical polarization component $p_y(t)$ is generated.



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

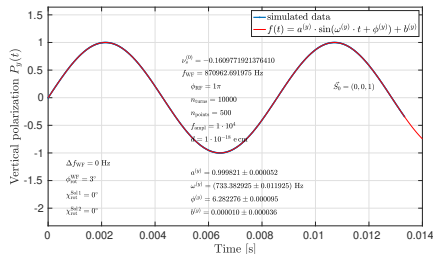
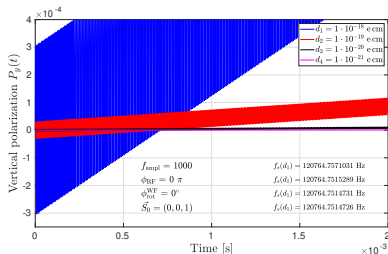
- $p_x(t)$, $p_z(t)$ and $p_y(t)$.
- Bunch revolution indicated as well.
- p_y oscillation amplitude corresponds to tilt angle ξ_{EDM} .

Model calculation of EDM buildup [18, PRAB '20]

With RF Wien filter

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

- ▶ $G = -0.143$, $\gamma = 1.126$, $f_s = f_{\text{rev}}(\gamma G + K_{(=0)}) \approx 120.765 \text{ kHz}$
- ▶ Enhanced RF field integral $f_{\text{ampl}} \times \int E_{\text{WF}} \cdot d\ell \approx 2200 \text{ kV}$ (w/o ferrites) [14, '16].



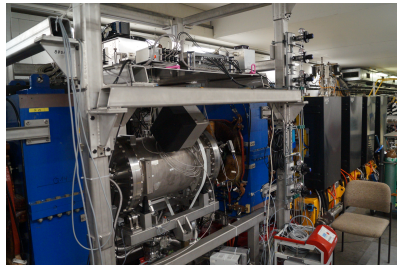
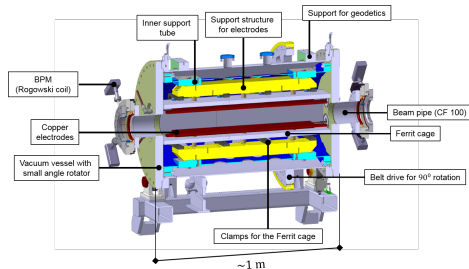
Features of EDM induced vertical polarization buildup

- ▶ EDM accumulates in $p_y(t) \propto d_{\text{EDM}}$ [15–17].
- ▶ → Full oscillation of vertical polarization $p_y(t)$ with proper feedback via pilot bunch.

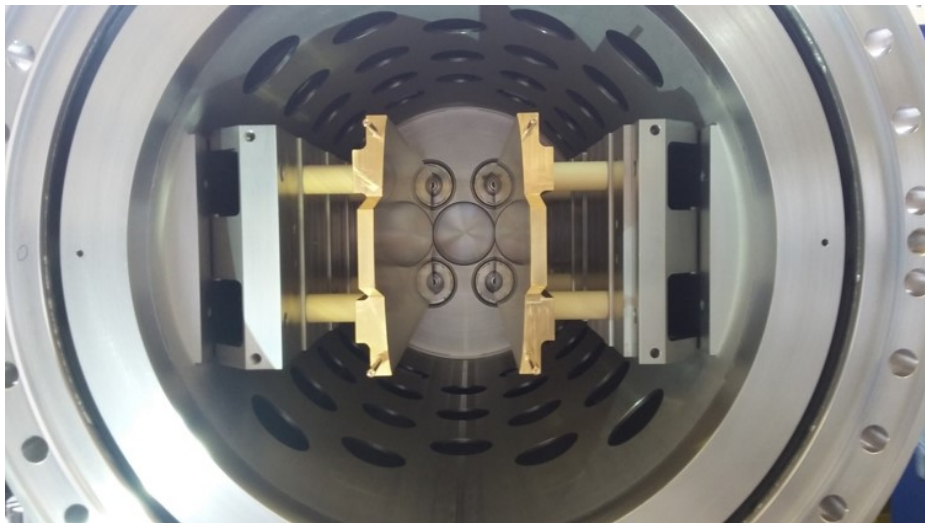
Design of waveguide RF Wien filter

Joint Jülich – RWTH Aachen development:

- ▶ Institute of High Frequency Technology, RWTH Aachen University:
- ▶ **Waveguide provides $\vec{E} \times \vec{B}$ by design.**
- ▶ Minimal \vec{F}_L by careful electromagnetic design of all components [14, '16].



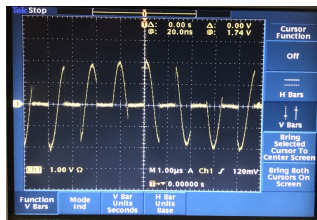
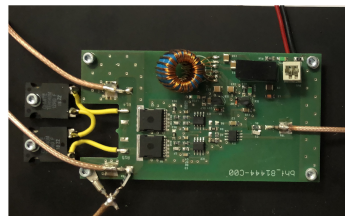
View along the beam axis in the RF Wien filter



Fast switches for RF power of Wien filter

GaN HEMT-based solution (Gallium Nitride Transistors):

- ▶ Short switch on/off times (\approx few ns).
- ▶ High power capabilities (\approx few kV).
- ▶ On board power damping.



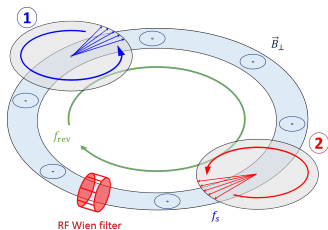
- ▶ symmetric switch on/off times (\approx few ns).
- ▶ -30 dB power damping.

Installed switches:

- ▶ capable to handle up to 200 W each
- ▶ permits system to run near a total power of 0.8 kW in pulsed mode

Bunch-selective spin manipulation, EDM co-magnetometry

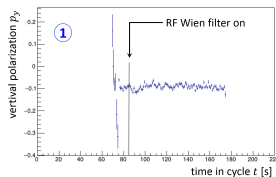
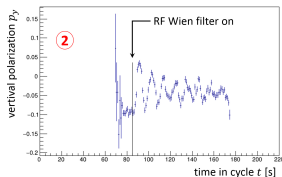
World-first (September 2020 JEDI, with d at 970 MeV/c)



- ▶ bunches ① and ② orbit at $f_{\text{rev}} \approx 750$ kHz:
 - ▶ coherent ensembles in ring plane
 - ▶ precessing at $f_s \approx 120$ kHz
- ▶ waveguide RF WF [14] with *radial* field \vec{B}_r
 - ▶ on resonance¹ at $f_{\text{WF}} = 871.430\,646$ kHz

▶ Apply bunch-selective gating of RF Wien filter in ①:

▶ ② oscillating $p_y(t)$, ① not affected (pilot bunch → co-magnetometer)



¹ $f_{\text{WF}} = K \cdot f_{\text{rev}} + f_s = (K + \nu_s)f_{\text{rev}}$, where $K \in \mathbb{Z}$ and ν_s is spin tune

Strength of EDM resonance

EDM induced polarization oscillation,

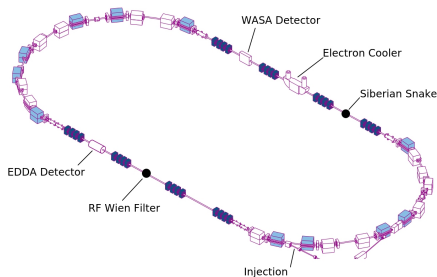
- can generally be described by

$$p_y(t) = a \sin(\Omega^{p_y} t + \phi_{\text{RF}}),$$

y perpendicular to ring plane.

- EDM resonance strength** defined as ratio of angular frequency Ω^{p_y} to orbital angular frequency Ω^{rev} ,

$$\epsilon^{\text{EDM}} = \frac{\Omega^{p_y}}{\Omega^{\text{rev}}},$$

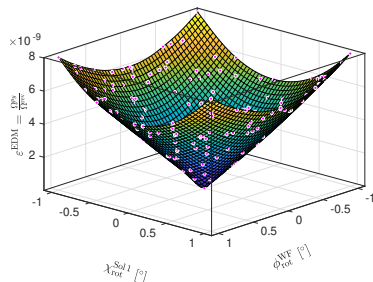


How is the EDM effect actually measured?

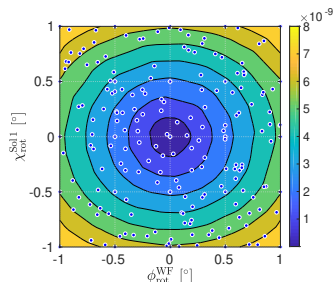
Two features are simultaneously applied in the ring:

1. the RF Wien filter is rotated by a small angle. This generates a tiny radial magnetic RF field, which affects the spin evolution.
2. In addition, a longitudinal magnetic field in the ring opposite to the Wien filter, about which the spins rotate as well.

Expectation: $d = 10^{-20}$ e cm in ideal COSY ring [18, PRAB '20]



(a) ε^{EDM} for $d = 10^{-20}$ e cm.



(b) Contour plot of (a).

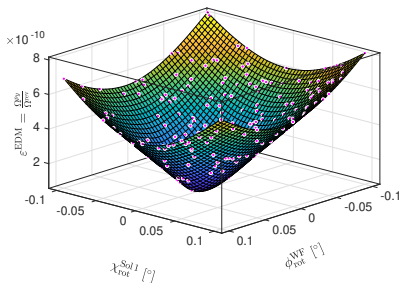
Function describing surface

- Surface described by *elliptic paraboloid* [18, PRAB '20]:

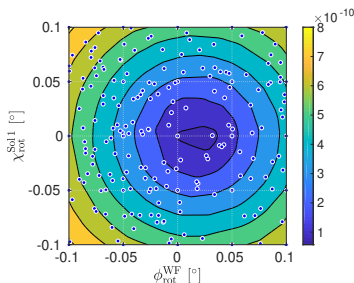
$$\left(\varepsilon^{\text{EDM}}\right)^2 = \frac{\psi_{\text{WF}}^2}{16\pi^2} \cdot \left[A \left(\phi^{\text{WF}} - \phi_0^{\text{WF}} \right)^2 + B \left(\frac{\chi^{\text{Sol}}}{2 \sin \pi \nu_s^{(2)}} + \chi_0^{\text{Sol}} \right)^2 + C \right].$$

- A and B account for possible deviations of ε^{EDM} along ϕ^{WF} and χ^{Sol} .

Expectation: $d = 10^{-18}$ e cm in ideal COSY ring [18, PRAB '20]



(c) ε^{EDM} for $d = 10^{-18}$ e cm.



(d) Contour plot of (c).

Function describing surface

- Surface described by *elliptic paraboloid* [18, PRAB '20]:

$$\left(\varepsilon^{\text{EDM}}\right)^2 = \frac{\psi_{\text{WF}}^2}{16\pi^2} \cdot \left[A \left(\phi^{\text{WF}} - \phi_0^{\text{WF}} \right)^2 + B \left(\frac{\chi^{\text{Sol}}}{2 \sin \pi \nu_s^{(2)}} + \chi_0^{\text{Sol}} \right)^2 + C \right].$$

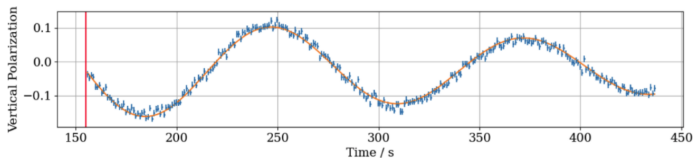
- A and B account for possible deviations of ε^{EDM} along ϕ^{WF} and χ^{Sol} .

Preliminary results of precursor experiment I

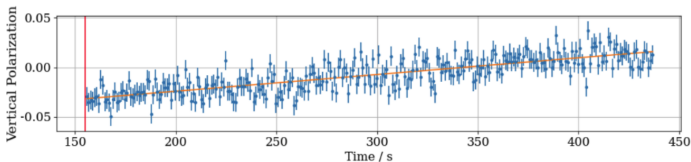
Wien filter mapping

Observation of $p_y(t)$ with two stored bunches: **Signal and pilot bunch**

► Signal bunch



► Pilot bunch



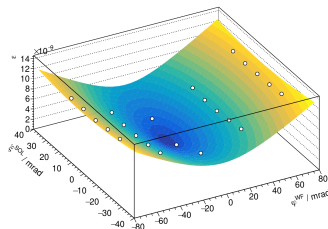
► Decoherence clearly visible in signal bunch.

► No oscillations in pilot bunch.

► Determine oscillation frequencies $\Omega^{Py} \rightarrow$ Wien filter map via $\varepsilon^{\text{EDM}} = \frac{\Omega^{Py}}{\Omega^{\text{rev}}}$

Preliminary results of precursor experiment II

Example map of resonance strength ε^{EDM}



Determination of minimum via fit with surface function:

► $\phi_0^{\text{WF}}/\text{mrad} = -2.05 \pm 0.02$ and $\xi_0^{\text{Sol}}/\text{mrad} = 4.32 \pm 0.06$

Extraction of deuteron EDM:

1. Minimum determines spin rotation axis (3-vector) at RF WF *including* EDM.
2. Spin tracking in COSY lattice → orientation of stable spin axis *w/o* EDM.
3. EDM is obtained from the difference of 1. and 2.

Two runs for deuteron precursor EDM measurement

1. **Nov-Dec 2018:** feedback during 1st quarter of oscillation period p_y
2. **Feb-Mar 2021:** feedback via pilot bunch → observation of many oscillations.

Improvements between runs:

► COSY:

1. Better understanding of injection process into COSY [19]
2. Alignment campaigns of COSY magnet system
3. Beam-based alignment [20]
4. Improvements of COSY signals and distribution
5. New tools for fast tune and chromaticity measurements; EPICS archiving
6. New JEDI Polarimeter [21, 22]

► RF WF

1. 8-channel Zurich Instruments signal generator to feed signals homogeneously
2. Improved matching of RF Wien filter
 - beam oscillations $\approx 1 \mu\text{m}$ at BPM opposite WF [13, PRAB '21]).
3. Optimization of Rogowski BPM system [23]
4. Upgrade of slow-control system
5. Implementation of fast RF switches

Strategy toward dedicated EDM ring

CPEDM Collaboration: <http://pbc.web.cern.ch/edm/edm-default.htm>

Stages of project and time frame toward dedicated EDM ring: [6, CYR '21]

Stage 1

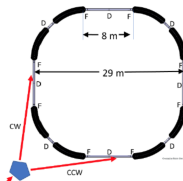
- ▶ precursor experiment



- ▶ magnetic storage ring
- ▶ Now

Stage 2

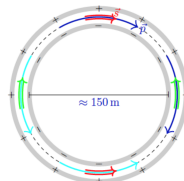
- ▶ prototype ring



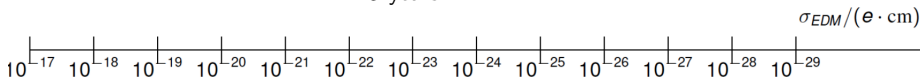
- ▶ electric/magnetic bends
- ▶ simultaneous \odot and \ominus beams
- ▶ 5 years

Stage 3

- ▶ dedicated storage ring



- ▶ at magic p momentum
- ▶ 10 years



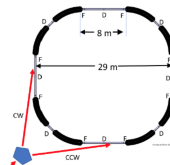
Next step: Stage 2: Prototype EDM storage ring (PTR)

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.

100 m circumference

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



Challenges – open issues

- ▶ All electric & E/B combined deflection
- ▶ Storage time
- ▶ CW-CCW operation with orbit difference to pm
- ▶ Spin-coherence time
- ▶ Polarimetry
- ▶ Magnetic moment effects
- ▶ Stochastic cooling

Primary purpose of PTR

- ▶ study open issues.
- ▶ first direct proton EDM measurement.

Summary I

Search for charged hadron particle EDMs (p , d , light ions):

- ▶ New window to disentangle sources of CP violation, and to possibly explain matter-antimatter asymmetry of the Universe.
 - ▶ Search for static charged particle EDMs (p , d , ^3He)
 - ▶ EDMs \rightarrow probes of CP-violating interactions
 - ▶ Matter-antimatter asymmetry
 - ▶ Search for oscillating EDMs
 - ▶ Axion gluon coupling
 - ▶ Dark matter search
 - ▶ Potential sensitivity to gravitational effects [24].
- ▶ Results and achievements at COSY are summarized in [6, App. A].

Summary II

Present EDM measurement using RF Wien filter

- ▶ JEDI with steady progress in spin dynamics relevant to future EDM searches.
- ▶ COSY remains a unique facility for such studies.
- ▶ First direct JEDI deuteron EDM measurement at COSY:
 - ▶ Two runs: 6 wk run Nov-Dec '18, and 6 wk run Feb-Mar '21.
 - ▶ Many upgrades and improvements of COSY and RF Wien filter.
 - ▶ Data analysis and systematics studies in progress.
 - ▶ Anticipated sensitivity 10^{-18} to 10^{-20} e cm.

Strong interest of high energy community in srEDM 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, EU Design Study for PTR:
 - ▶ Continuation of CPEDM work described in [CERN Yellow Report \[6, '21\]](#).
 - ▶ HORIZON-INFRA-2022-DEV-01-01: Research infrastructure concept
 - ▶ Partners: CERN, RWTH, INFN, MPI-HD, Liverpool, Krakow
 - ▶ CERN mandate to contribute to this effort.
 - ▶ possible host sites: CERN or COSY.

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Spare Slides

Search for charged particle EDMs with frozen spins

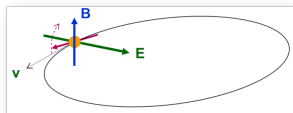
Magic storage rings

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

- Generalized solution for magic momentum

$$\frac{E_x}{B_y} = \frac{Gc\beta\gamma^2}{1 - G\beta^2\gamma^2}, \quad (9)$$

where E_x is radial, and B_y vertical field.



- Some configurations for circular machine with fixed radius $r = 25$ m:

particle	G	p [MeV c ⁻¹]	T [MeV]	E_x [MV m ⁻¹]	B_y [T]
proton	1.793	700.740	232.792	16.772	0.000
deuteron	-0.143	1000.000	249.928	-4.032	0.162
helion	-4.184	1200.000	245.633	14.654	-0.044

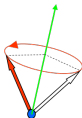
Offers possibility to determine EDMs of
protons, deuterons, and helions in one and the same machine.

Spin coherence time

Most polarization experiments don't care about coherence of spins along \vec{n}_{co}

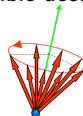
Spins aligned:

Ensemble *coherent*



Spin vectors out of phase:

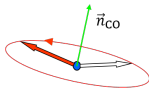
Ensemble *decoherent*



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

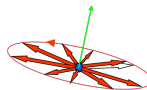
With frozen spins: $\vec{S} \perp \vec{n}_{co}$:

Spins aligned



With time:

Spins out of phase in horizontal plane



\Rightarrow Longitudinal polarization vanishes

In machines with frozen spins:

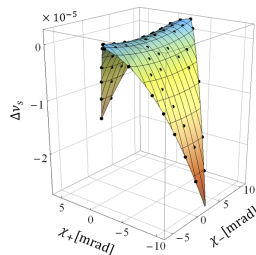
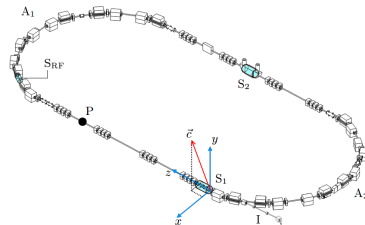
Buildup time t to observe polarization $P_y(t)$ limited by τ_{SCT} .

Study of machine imperfections

JEDI developed new method to investigate magnetic machine imperfections based on highly accurate determination of spin-tune [15, PRAB '17].

Spin tune mapping

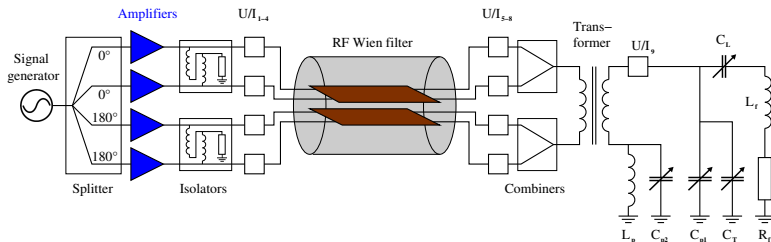
- ▶ Two cooler solenoids act as spin rotators \Rightarrow generate artificial imperfection fields.
- ▶ Measure spin tune shift vs spin kicks.
- ▶ Position of saddle point determines tilt of stable spin axis by magnetic imperfections.
- ▶ Control of background from MDM at level $\Delta c = 2.8 \times 10^{-6}$ rad.
- ▶ Systematics-limited sensitivity for deuteron EDM at COSY $\sigma_d \approx 10^{-20}$ e cm.



Driving circuit [25]

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

- Design layout using four separate 1 kW power amplifiers.



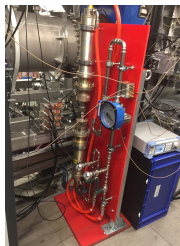
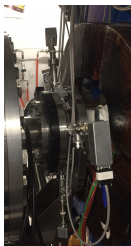
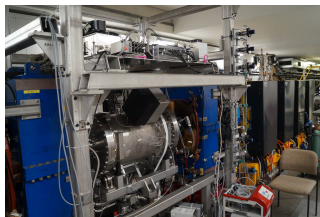
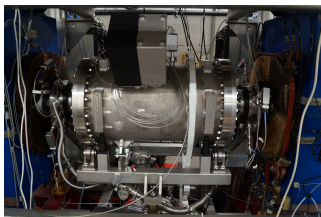
Circuit fully operational

- Tuneable elements² allow [14]:
 - minimization of Lorentz-force, and
 - velocity matching to β of the beam.
- Power upgrade to 4×2 kW: $\int B_z dz = 0.218$ T mm possible.

²built by Fa. Barthel, <http://www.barthel-hf.de>.

RF Wien filter

Installation at COSY



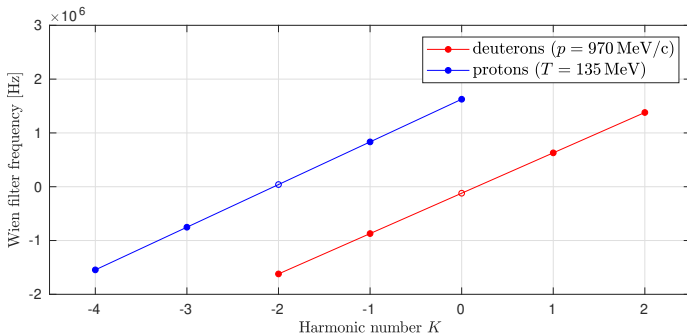
- ▶ RF Wien filter between PAX magnets. Upstream Rogowski coil; racks with power amplifiers, each unit delivers up to 500 W; water-cooled $25\ \Omega$ resistor.

Frequencies of RF Wien filter [18]

Spin resonance condition:

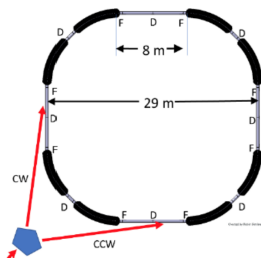
$$f_{\text{WF}} = f_{\text{rev}} (\gamma G \pm K), \quad k \in \mathbb{Z}.$$

- ▶ 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).



PTR lattice design (protons)

Basic beam parameters and layout [6, chap. 7]

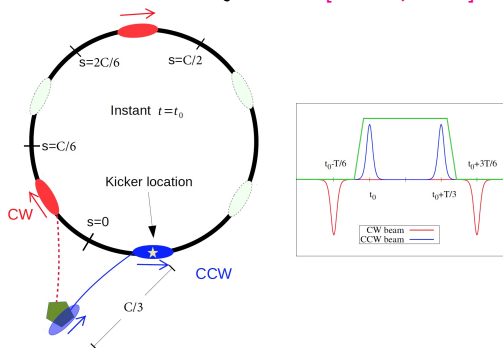


	<i>E</i> only	<i>E</i> & <i>B</i> frozen spin		unit
Bending radius	8.86	8.86		m
Kinetic energy	30	30	45	MeV
$\beta = v/c$	0.247	0.247	0.299	MeV/c
γ (kinetic)	1.032	1.032	1.048	
Momentum	239	239	294	
Electric field <i>E</i>	6.67	4.56	7.00	MV/m
Magnetic field <i>B</i>		0.0285	0.0327	T
rms $\epsilon_x = \epsilon_y$	1	1		π mm mrad
Transv. acc. $a_x = a_y$	> 10	> 10		π mm mrad

- ▶ *p* at 30 MeV all-electric CW-CCW beams operation
- ▶ *p* at 30 to 45 MeV frozen spin, with additional vertical *B* field

Beam transfer and injection system

S. Martin, R. Talman, C. Carli, M. Haj Tahar: [6, chap. 7.8]



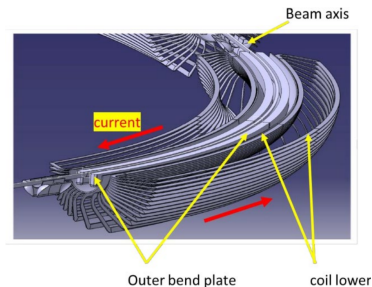
Test at COSY: spin manipulation after injection appears feasible:

- ▶ could simplify injection scheme, no need for fast switches
- ▶ orient spin directions in bunches after injection of DC beam

Electrostatic deflector

with additional magnetic bend

- Concept for electrostatic deflector element available [6, chap. 7.6].

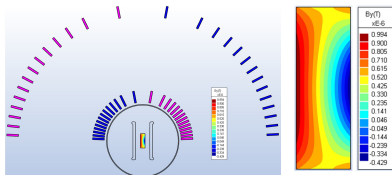


		units
Electric		
electric field	7.00	MV/m
gap between plates	60	mm
plate height (straight part)	151.5	mm
plate length	6.959	m
total bending length	55.673	m
total straight length	44.800	m
bend angle per unit	45	deg

- **Next step:** build prototype with RWTH-Aachen (IAEW High Voltage)
- Studies of straight E/B deflector element to improve voltage holding capability ongoing at Jülich.

Magnetic bends

- ▶ Concept for magnetic add-on to deflector available [6, chap. 7.6].
- ▶ Magnetic system ($\cos \theta$) placed outside the vacuum tube.



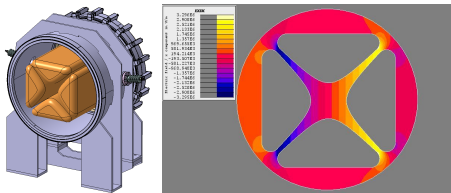
Magnetic		
magnetic field	0.0327	T
current density	5.000	A/mm ²
windings/element	60	

- ▶ Magnet system included in prototype development with RWTH-Aachen (IAEW High Voltage)

Multipole elements

Quadrupoles

- ▶ Design of electrostatic elements by J. Borburgh (CERN) [6, chap. 9])
- ▶ Electrostatic quadrupoles
 - ▶ aperture diameter 80 mm, applied ± 20 kV.
 - ▶ Simulated design with vacuum chamber of 400 mm diameter.



- ▶ PTR quadrupoles max. pole tip potential 30 kV (margin for conditioning)
- ▶ 3D design available:
 - ▶ sextupole, octupole and higher harmonics reasonable
 - ▶ 800 mm longitudinal length and radial diameter of 620 mm.

Needs strong support

Vacuum system

- ▶ Ring vacuum given by minimum required beam lifetime of about 1000 s.
 - ▶ N_2 partial pressures below 10^{-12} mbar
 - ▶ H_2 partial pressures below 5×10^{-11} mbar.
- ▶ Stochastic cooling rate better than 5×10^{-3} mm mrad/s.
- ▶ non-vibrational system that avoids generation of magnetic fields
 - ▶ Cryogenic or NEG pumping systems may be used:
 1. NEG material becomes saturated after several pump-downs.
 2. Aging NEG material leaves dust particles in vacuum vessel.
 3. PTR will have significant number of pump-downs during program.
 4. High-voltage system requires excellent vacuum.
 5. System based on NEG cartouches [26] under discussion.
- ▶ Mechanical alignment of elements inside vacuum pipe of 400 mm diameter
 - ▶ active compensation of oscillations/ground motion
- ▶ Shielding (passive versus active)

Stochastic cooling

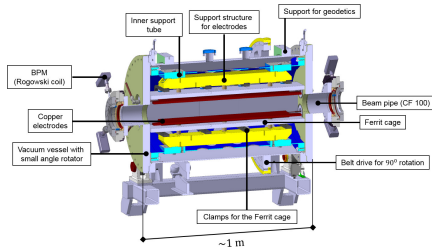
- ▶ Control proton beam emittance during measurements: 30 MeV to 45 MeV.
- ▶ Cooling should compensate emittance growth of 5×10^{-3} mm mrad/s.
 - ▶ Used successfully at COSY to compensate emittance growth of beam during interaction with internal gas targets.
 - ▶ Interplay between stochastic cooling and evolution of horizontally polarized ensemble of particles unknown.
 - ▶ **Studies of emittance growth and spin coherence time not possible at any other ring prior to PTR.**
- ▶ **Aim: provide basic design of stochastic cooling system for PTR.**

RF Cavity

- ▶ Azimuthal magnetic fields of RF cavities lead to spin rotations of the magnetic moment.
- ▶ Even in case of a perfectly aligned cavity, individual particles experience horizontal magnetic fields and spin rotations into vertical and horizontal directions.
- ▶ Effect on EDM measurement strongly suppressed:
 - ▶ cancellation of effect for different particles crossing cavity gap each turn with different betatron phases and transverse positions.
- ▶ Design of RF cavity required that minimizes unwanted spin rotations.

Spin manipulation tools

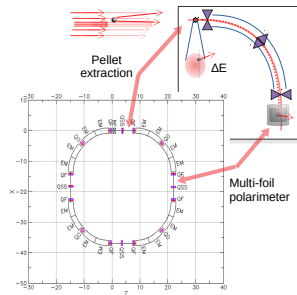
- ▶ Vertical polarisation of stored beam rotated into horizontal plane by **longitudinal field of RF solenoid**.
 - ▶ Typical ramp-up times from vertical to horizontal polarisation are ≈ 200 ms.
 - ▶ optimize design for PTR.



- ▶ **RF Wien filter** [14] applies **transverse magnetic fields** to spin, while exerting minimal Lorentz force on beam:
 - ▶ COSY: spin manipulation of individual bunches by fast RF switches feasible.
 - ▶ optimize design for PTR, need two of them for CW-CCW operations.

High-precision beam polarimeter (... with pellet extraction)

- ▶ dC (pC) scattering using white noise extraction works for relative polarization errors $\Delta p/p = 10^{-6}$ [27].
- ▶ Polarimeter system for dedicated ring described in [21, 22, 28].
- ▶ Polarization profile determination at low energies:
 - ▶ Carbon multifoil polarimeter [29] based on Silicon detectors with pellet extraction
 - ▶ (PhD J. Gooding, University of Liverpool).
 - ▶ Ballistic Si pellet target for homogeneous beam sampling [30, App. K].
 - ▶ Eloss of 100 keV in 50 μm pellet \rightarrow track displaced by 2.5 cm behind 90° bend.

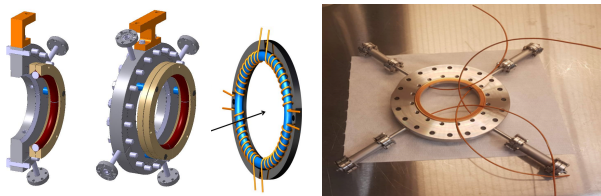


Beam diagnostics

Beam Position Monitors

Development of prototype BPM based on segmented toroidal coil [23]

- ▶ Rogowski coil



- ▶ advantages over conventional split-cylinder BPMs
 - ▶ short insertion length → many BPMs can be installed
 - ▶ inexpensive
 - ▶ high sensitivity to position of bunched beams
- ▶ Other diagnostics needed:
 - ▶ Beam profile monitor, non-destructive for emittance measurement
 - ▶ BCT, also to adjust CW/CCW beam currents

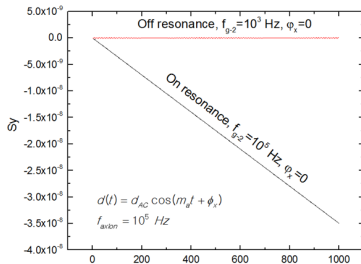
(Oscillating) Axion-EDM search using storage ring

Motivation: Paper by Graham and Rajendran [31, 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

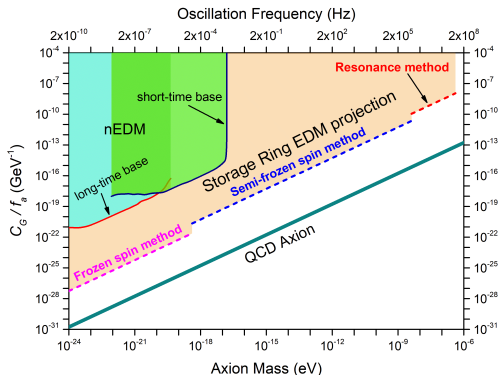


Figure from S.P. Chang et al. [32]

Realization

- ▶ No new/additional equipment required!
- ▶ First test experiment carried out in I/2019 in magnetic storage ring COSY.
- ▶ Data analysis well in progress.