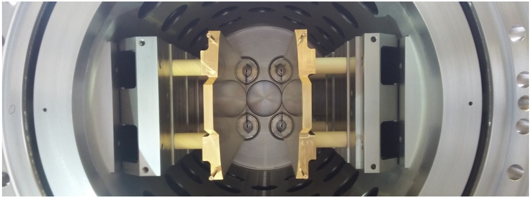


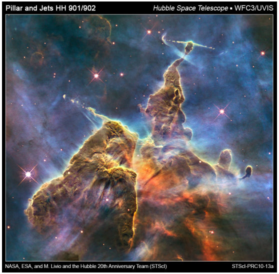
First direct hadron EDM measurement with deuterons using COSY
– A realistic strategy toward a dedicated EDM ring –

Frank Rathmann
(on behalf of the JEDI collaboration)

Willy Haeberli Memorial Symposium
June 19 – June 20, 2022
https://www.physics.wisc.edu/haeberli-symposium/

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]

- 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:

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

  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

$$\vec{s} \cdot \vec{E} \overbrace{\longrightarrow}^{P \text{ or } T} -\vec{s} \cdot \vec{E}, \tag{1}$$

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 4^{th} 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.
- $\sim$ 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.

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

- 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):

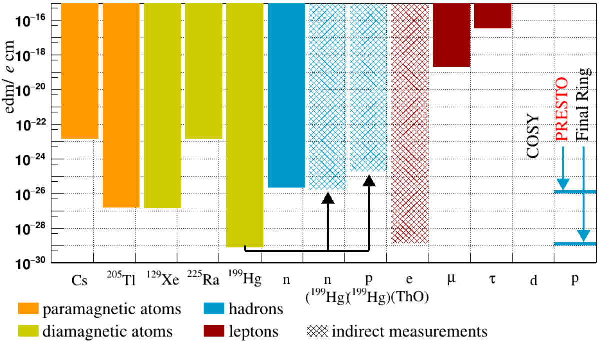
$$\boxed{|d_N| \sim 10^{-7} \times 10^{-24}\,\mathrm{e\,cm} \sim 10^{-31}\,\mathrm{e\,cm}}$$

Region to search for Beyond Standard Model (BSM) physics

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

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

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 $^{199}_{80}\mathrm{Hg}$.
- **No measurement at all of deuteron EDM.**

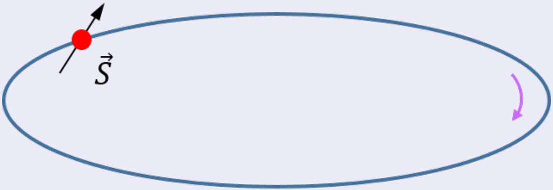
Spin precession of particles with MDM and EDM

In rest frame of particle,

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

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

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:

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

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

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

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

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

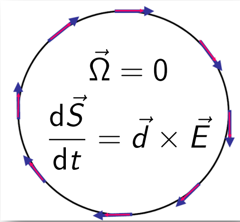
For protons, (4) leads to *magic momentum*:

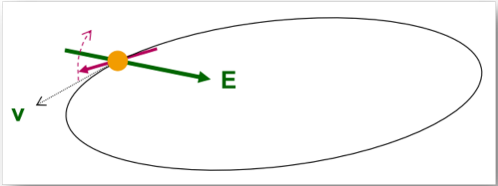
$$G - \frac{1}{\gamma^2-1} = 0 \Leftrightarrow G = \frac{m^2}{p^2} \quad \Rightarrow \quad \boxed{p = \frac{m}{\sqrt{G}} = 700.740\,\mathrm{MeV\,c^{-1}}} \quad (5)$$

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: $E = 10\,\mathrm{MV/m}$.
- 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:

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

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

Progress toward storage ring EDM experiments

Complementing the spin physics tool box

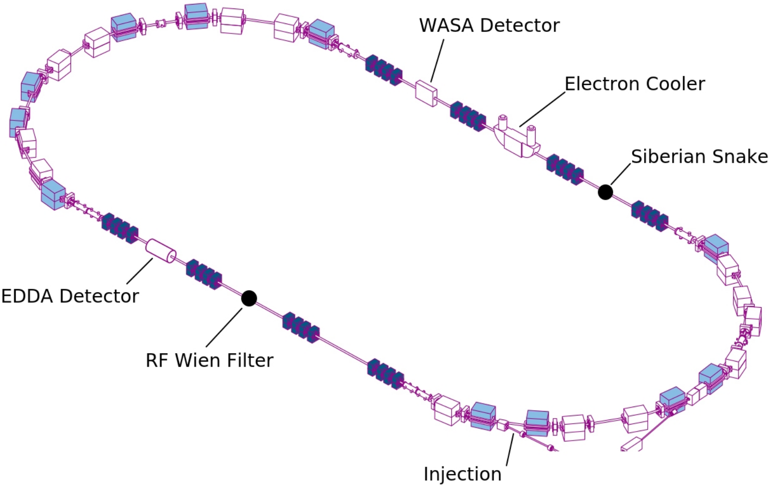
COoler SYnchrotron COSY

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

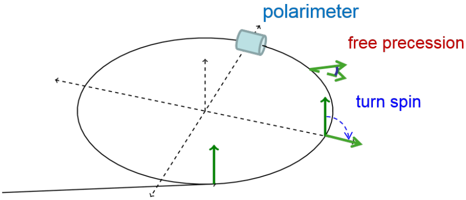
COSY formerly used as spin-physics machine for hadron physics:

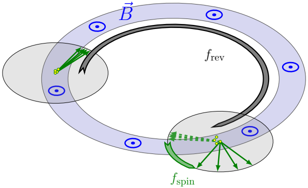
- Provides an ideal starting point for srEDM related R&D.
- Will be used for a first direct measurment of deuteron EDM.

COSY Landscape



Principle of spin-coherence time measurement

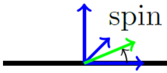


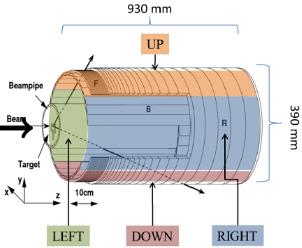


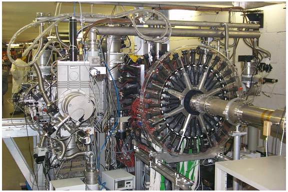
Measurement procedure:

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.

Detector system: EDDA [8]







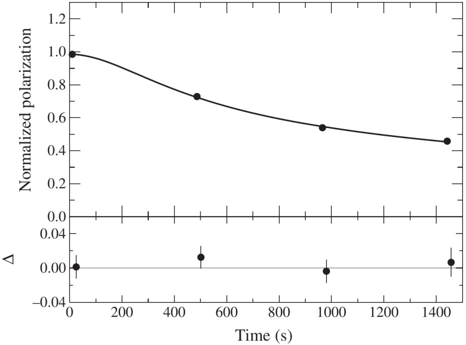
EDDA used to determine $\vec{p}\vec{p}$ elastic polarization observables:

- 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:

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

Optimizations of spin-coherence time [10]

Precise adjustments of three sextupole families in the ring



JEDI progress on τ_{SCT}:

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

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

Spring 2015: Way beyond anybody's expectation:

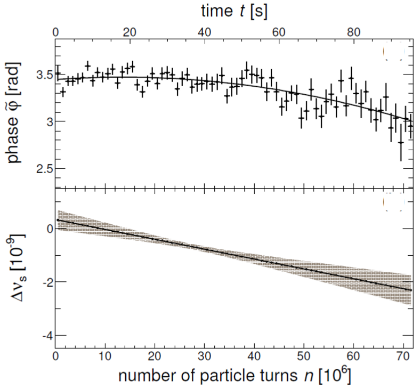
- With about 10^9 stored deuterons.
- Long spin coherence time was one of main obstacles of srEDM experiments.
- Large value of τ_{SCT} of crucial importance (6), since $\sigma_{\text{stat}} \propto \tau_{\text{SCT}}{}^{-1}$.

Precision determination of the spin tune [11]

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:

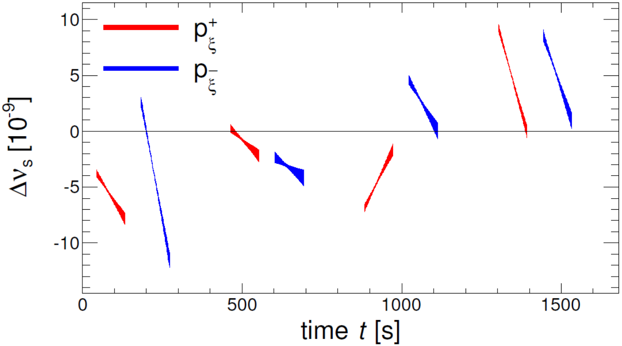
$$\nu_s(n) = \nu_s^{\text{fix}} + \frac{1}{2\pi}\frac{\mathrm{d}\tilde{\phi}}{\mathrm{d}n} = \nu_s^{\text{fix}} + \Delta\nu_s(n) \quad (8)$$



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 ($\rightarrow$ **phase-lock**).
- Studies of machine imperfections.

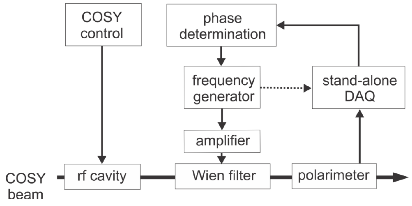
Phase locking spin precession in machine to device RF

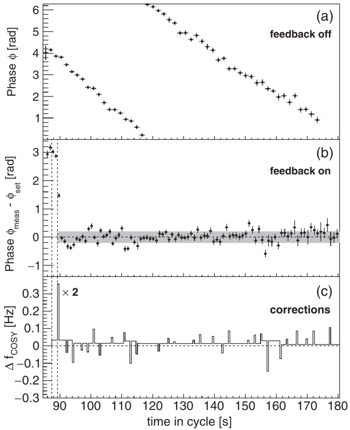
At COSY, one cannot freeze the spin precession

$\Rightarrow$ 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 WF)





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

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 ($< 10^{-28}\,\mathrm{e\,cm}$).
  - 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 ($\sim 1000\,\mathrm{s}$).

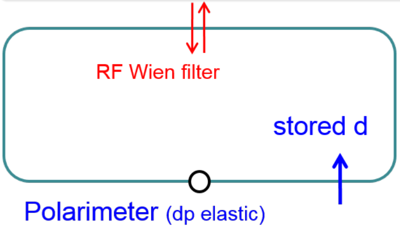
Goal of proof-of-principle experiment:

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, 14]).
  - EDM measurement mode: $\vec{B} = (0, B_y, 0)$ and $\vec{E} = (E_x, 0, 0)$.



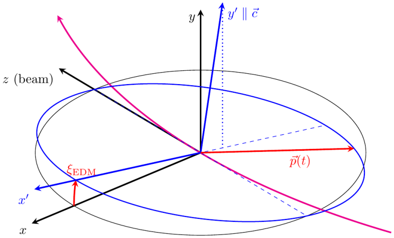
- Deuteron spins lie in machine plane.
- If $d \neq 0 \Rightarrow$ *accumulation* of vertical polarization P_y, during spin coherence time $\tau_{\mathrm{SCT}} \sim 1000\,\mathrm{s}$.

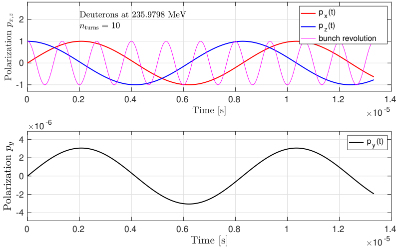
Statistical sensitivity:

- in the range 10^{-23} to $10^{-24}\,e\,\mathrm{cm}$ for $d(deuteron)$ 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 [15]

Without RF WF





Beam particles move along z direction

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

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

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

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

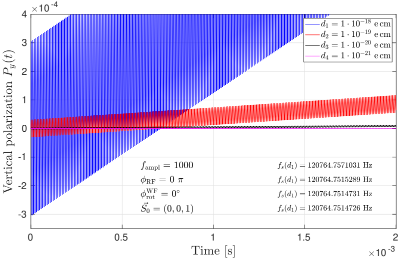
- $p_x(t)$, $p_z(t)$ and $p_y(t)$.
- Bunch revolution indicated as well.
- p_y oscillation amplitude corresponds to tilt angle $\xi_{\rm EDM}$.

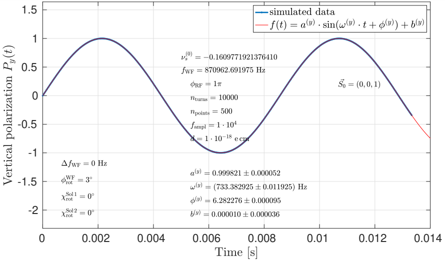
Model calculation of polarization buildup due to EDM [15]

With RF Wien filter

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

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





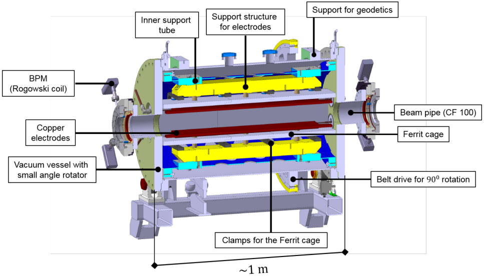
Features of EDM induced vertical polarization buildup

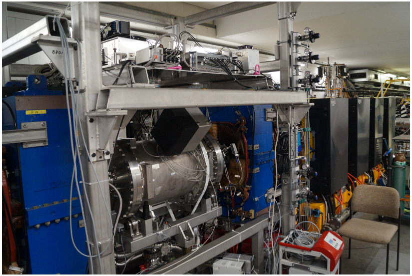
- EDM accumulates in $p_y(t) \propto d_{\mathrm{EDM}}$ [17–19].
- $\rightarrow$ Full oscillation of vertical polarization $p_y(t)$ with proper feedback via pilot bunch.

Design of waveguide RF Wien filter

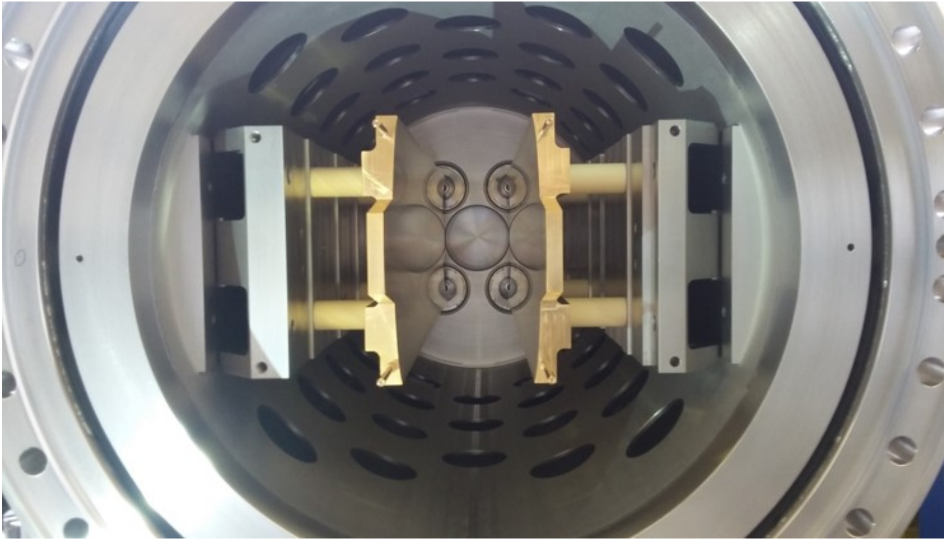
Joint Jülich – RWTH Aachen development:

- 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 [16].





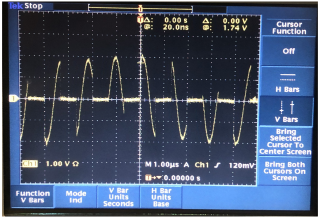
View along the beam axis in the RF Wien filter

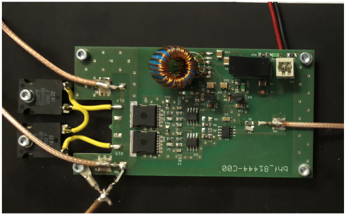


Fast switches[1] for RF power of Wien filter

GaN HEMT-based solution (Gallium Nitride Transistors):

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





- symmetric switch on/off times (≈ few ns).
- −30 dB power damping.

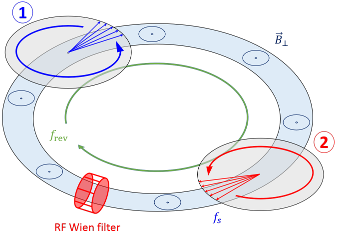
Installed switches:

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

[1] developed together with Fa. barthel HF-Technik GmbH, Aachen

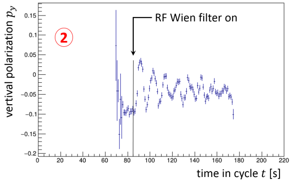
Bunch-selective spin manipulation (co-magnetometry) I

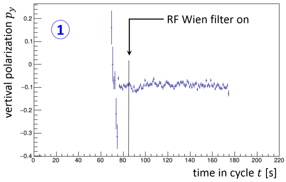
World-first (September 2020 JEDI, with d at 970 MeV/c)



- 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 [16] with *radial* field $\vec{B}_r$
  - on resonance[2] 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 $\rightarrow$ co-magnetometer)



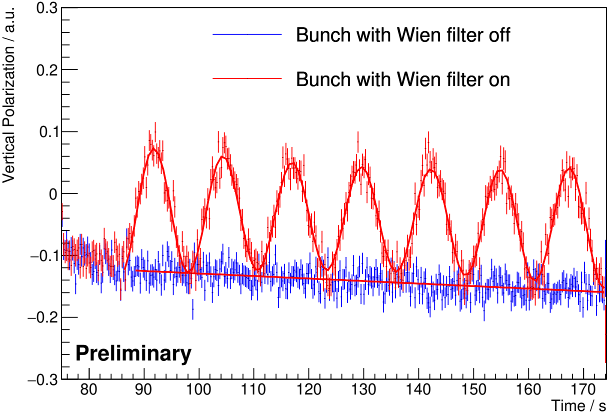


[1] $f_{\text{WF}} = K \cdot f_{\text{rev}} + f_s = (K + \nu_s) f_{\text{rev}}$, where $K \in \mathbb{Z}$ and ν_s is spin tune

Bunch-selective spin manipulation (co-magnetometry) II

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

Preliminary results: to be submitted soon by JEDI

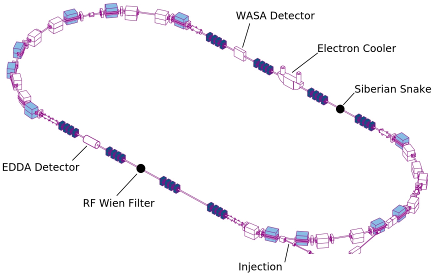


Analysis of pilot bunch run by Jamal Slim

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

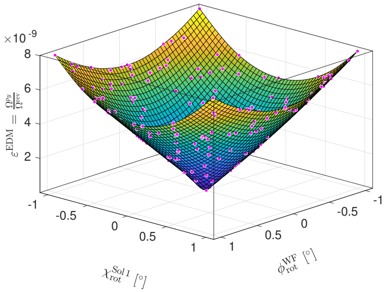


How is the EDM effect actually measured?

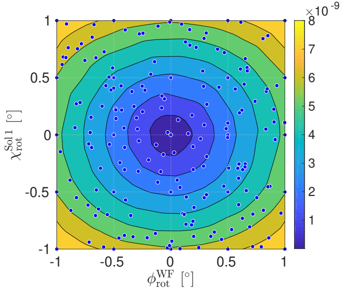
Two features are simultaneously applied in the ring:

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: $d = 10^{-20}\,\mathrm{e\,cm}$ in ideal COSY ring [15]



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



(b) Contour plot of (a).

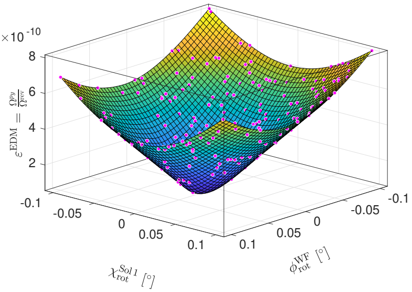
Function describing the surface

- Surface described by *elliptic paraboloid* [15]:

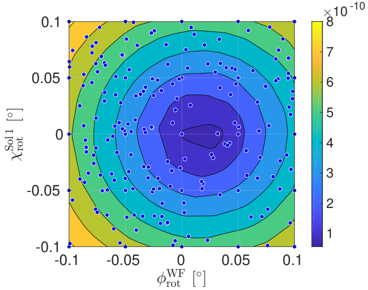
$$\left(\varepsilon^{\mathrm{EDM}}\right)^2 = \frac{\psi_{\mathrm{WF}}^2}{16\pi^2} \cdot \left[A\left(\phi^{\mathrm{WF}} - \phi_0^{\mathrm{WF}}\right)^2 + B\left(\frac{\chi^{\mathrm{Sol}}}{2\sin \pi\nu_s^{(2)}} + \chi_0^{\mathrm{Sol}}\right)^2 + C\right].$$

  - A and B account for possible deviations of $\varepsilon^{\mathrm{EDM}}$ along ϕ^{WF} and χ^{Sol}.

Expectation: $d = 10^{-18}\,\mathrm{e\,cm}$ in ideal COSY ring [15, PRAB '20]



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



(d) Contour plot of (c).

Function describing the surface

- Surface described by *elliptic paraboloid* [15, PRAB '20]:

$$\left(\varepsilon^{\mathrm{EDM}}\right)^2 = \frac{\psi^2_{\mathrm{WF}}}{16\pi^2} \cdot \left[A\left(\phi^{\mathrm{WF}} - \phi^{\mathrm{WF}}_0\right)^2 + B\left(\frac{\chi^{\mathrm{Sol}}}{2\sin\pi\nu_s^{(2)}} + \chi^{\mathrm{Sol}}_0\right)^2 + C\right].$$

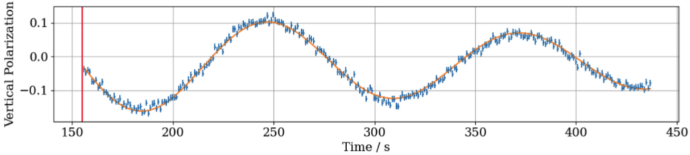
  - A and B account for possible deviations of $\varepsilon^{\mathrm{EDM}}$ along ϕ^{WF} and χ^{Sol}.

Preliminary results of precursor experiment I

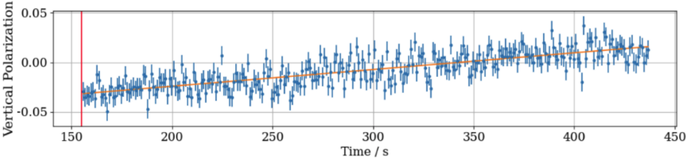
Wien filter mapping

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

- Signal bunch



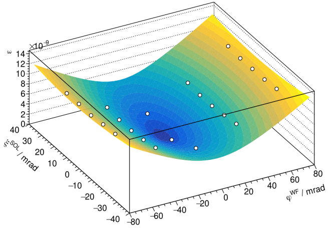
- Pilot bunch



- Decoherence clearly visible in signal bunch.
- No oscillations in pilot bunch.
- Determine oscillation frequencies $\Omega^{p_y} \rightarrow$ Wien filter map via $\varepsilon^{\mathrm{EDM}} = \frac{\Omega^{p_y}}{\Omega^{\mathrm{rev}}}$

Preliminary results of precursor experiment II

Example map of resonance strength ε^{EDM}



Determination of minimum via fit with surface function:

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

Extraction of deuteron EDM:

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

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]

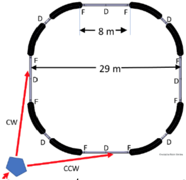
Stage 1

- precursor experiment

- magnetic storage ring
- Now

Stage 2

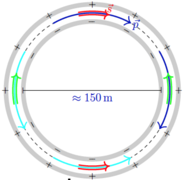
- prototype ring



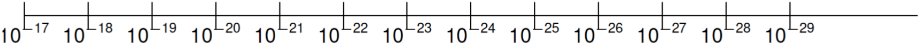
- electric/magnetic bends
- simultaneous ⟲ and ⟳ beams
- 5 years

Stage 3

- dedicated storage ring



- at magic p momentum
- 10 years



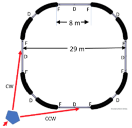
Next step: Stage 2: Prototype EDM storage ring (PTR)

Build demonstrator for charged-particle EDM

- Project prepared by new **CPEDM** collaboration (CERN + JEDI + srEDM).
- Physics Beyond Collider process (CERN) & ESPP 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 bends
- 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 and perform 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, ^{3}He)
    - EDMs $\rightarrow$ probes of CP-violating interactions
    - Matter-antimatter asymmetry
  - Search for oscillating EDMs ($\rightarrow$ see talk by Ed Stephenson)
    - Axion gluon coupling
    - Dark matter search
  - Potential sensitivity to gravitational effects [20].
- Results & achievements at COSY summarized in CYR [6].

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.
  - Operation planned to cease end of 2024.
- First direct JEDI deuteron EDM measurement at COSY:
  - Two runs (6 wk '18 and 6 wk '21):
    - Many upgrades and improvements of COSY and RF Wien filter.
    - Data analysis and systematics studies in progress.
  - Anticipated deuteron EDM 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: **CYR** [6] → EU Design Study for PTR:
    - **Realistic strategy** toward a dedicated EDM ring
    - Partners: INFN, GSI, CERN, MPG, RWTH, Liverpool, Krakow, Georgia
    - 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

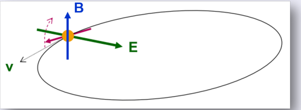
Magic storage rings

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

- Generalized solution for magic momentum

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

where E_x is radial, and B_y vertical field.



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

particle	G	$p\,[\mathrm{MeV\,c^{-1}}]$	$T\,[\mathrm{MeV}]$	$E_x\,[\mathrm{MV\,m^{-1}}]$	$B_y\,[\mathrm{T}]$
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

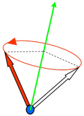
protons, deuterons, and helions in one and the same machine.

Spin coherence time

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

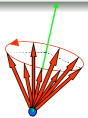
Spins aligned:

Ensemble *coherent*



Spin vectors out of phase:

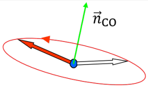
Ensemble *decoherent*



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

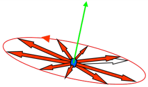
With frozen spins: $\vec{S} \perp \vec{n}_{\text{co}}$:

Spins aligned



With time:

Spins out of phase in horizontal plane



$\Rightarrow$ **Longitudinal polarization vanishes**

In machines with frozen spins:

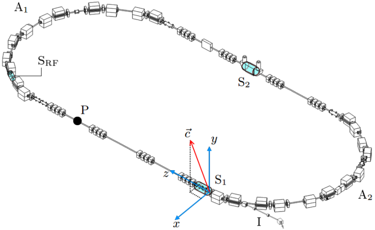
Buildup time t to observe polarization $P_y(t)$ limited by τ_{SCT}.

Study of machine imperfections

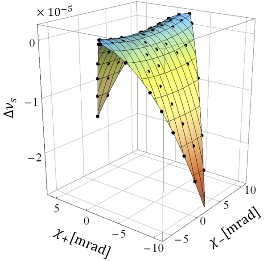
JEDI developed new method to investigate magnetic machine imperfections based on highly accurate determination of spin-tune [17, PRAB '17].

Spin tune mapping

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



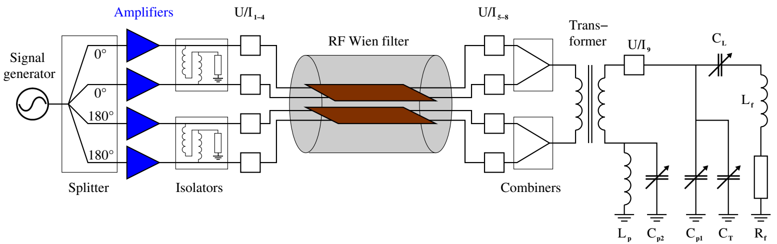
- Position of saddle point determines tilt of stable spin axis by magnetic imperfections.
- Control of background from MDM at level $\Delta c = 2.8 \times 10^{-6}$ rad.
- Systematics-limited sensitivity for deuteron EDM at COSY $\sigma_d \approx 10^{-20}$ e cm.



Driving circuit [21]

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

- Design layout using four separate 1 kW power amplifiers.



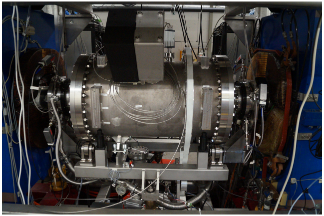
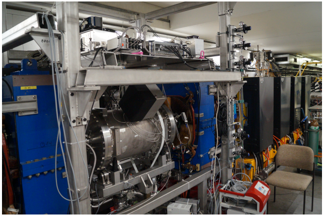
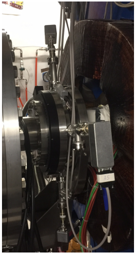
Circuit fully operational

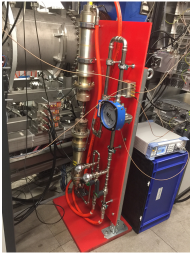
- Tuneable elements[a] allow [16]:
  - minimization of Lorentz-force, and
  - velocity matching to β of the beam.
- Power upgrade to 4×2 kW: $\int B_z \mathrm{d}z = 0.218\,\mathrm{T\,mm}$ possible.

[a] built 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 Ω resistor.

Two runs for deuteron precursor EDM measurement

1. **Nov-Dec 2018:** feedback during 1$^{\text{st}}$ quarter of oscillation period p_y
2. **Feb-Mar 2021:** feedback via pilot bunch $\rightarrow$ observation of many oscillations.

Improvements between runs:

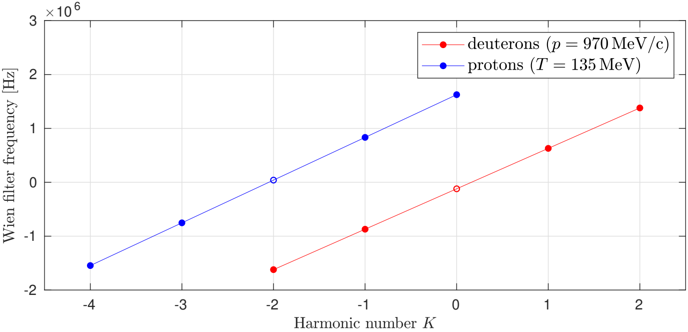
- COSY:
    1. Better understanding of injection process into COSY [22]
    2. Alignment campaigns of COSY magnet system
    3. Beam-based alignment [23]
    4. Improvements of COSY signals and distribution
    5. New tools for fast tune and chromaticity measurements; EPICS archiving
    6. New JEDI Polarimeter [24, 25]
- RF WF
    1. 8-channel Zurich Instruments signal generator to feed signals homogeneously
    2. Improved matching of RF Wien filter
        - ⋆ beam oscillations $\approx 1\,\mu$m at BPM opposite WF [13, PRAB '21]).
    3. Optimization of Rogowski BPM system [26]
    4. Upgrade of slow-control system
    5. Implementation of fast RF switches

Frequencies of RF Wien filter [15]

Spin resonance condition:

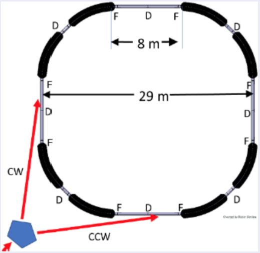
$$f_{\mathrm{WF}} = f_{\mathrm{rev}}\left(\gamma G \pm K\right), k \in \mathbb{Z}.$$

- 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]

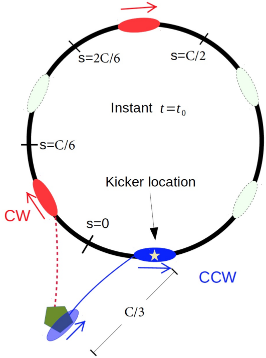


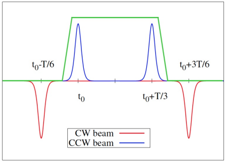
	E only	E & B frozen spin		unit
Bending radius	8.86	8.86		m
Kinetic energy	**30**	**30**	**45**	**MeV**
$\beta = v/c$	0.247	0.247	0.299	
γ (kinetic)	1.032	1.032	1.048	
Momentum	239	239	294	MeV/c
Electric field E	**6.67**	**4.56**	**7.00**	**MV/m**
Magnetic field B		**0.0285**	**0.0327**	**T**
rms $\epsilon_x = \epsilon_y$	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]





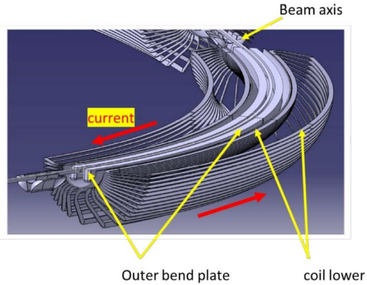
Test at COSY: spin manipulation after injection appears feasible:

- 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].

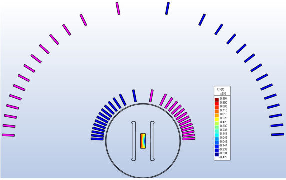


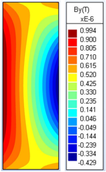
		units
Electric		
electric field	7.00	MV/m
gap between plates	**60**	**mm**
plate height (straight part)	**151.5**	**mm**
plate length	**6.959**	**m**
total bending length	55.673	m
total straight length	44.800	m
bend angle per unit	**45**	deg

- **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.





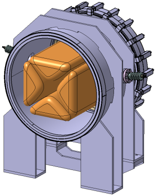
Magnetic		
magnetic field	0.0327	T
current density	5.000	A/mm^2
windings/element	60	

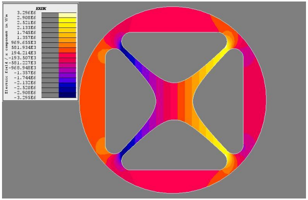
- Magnet system included in prototype development with RWTH-Aachen (IAEW High Voltage)

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

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 [27] 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

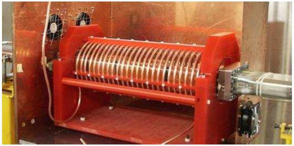
- Control proton beam emittance during measurements: 30 MeV to 45 MeV.
- Cooling should compensate emittance growth of 5×10^{-3} mm mrad/s.
  - Used successfully at COSY to compensate emittance growth of beam during interaction with internal gas targets.
  - Interplay between stochastic cooling and evolution 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.**

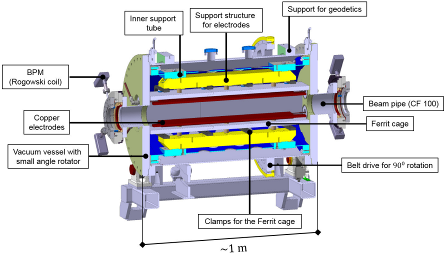
RF Cavity

- 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 $\approx 200\,\text{ms}$.
  - optimize design for PTR.



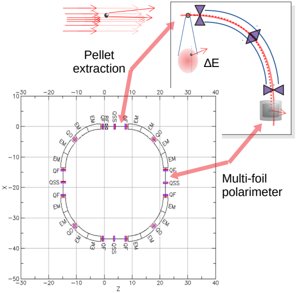


- **RF Wien filter** [16] applies **transverse magnetic fields** to spin, while excerting minimal Lorentz force on beam:
  - COSY: spin manipulation of individual bunches by fast RF switches feasible.
  - optimize design for PTR, need two of them for CW-CCW operations.

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

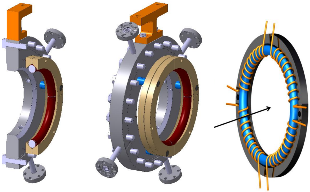
- dC (pC) scattering using white noise extraction works for relative polarization errors $\Delta p/p = 10^{-6}$ [28].
- Polarimeter system for dedicated ring described in [24, 25, 29].

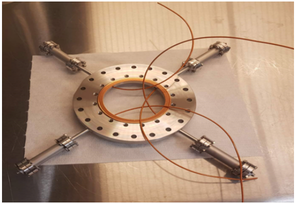
- Polarization profile determination at low energies:
  - Carbon multifoil polarimeter [30] based on Silicon detectors with pellet extraction
    - ★ (PhD J. Gooding, University of Liverpool).
  - Ballistic Si pellet target for homogeneous beam sampling [31, App. K].
  - Eloss of 100 keV in 50 μm pellet $\rightarrow$ track displaced by 2.5 cm behind 90° bend.



Development of prototype BPM based on segmented toroidal coil [26]

- Rogowski coil





- advantages over conventional split-cylinder BPMs
    - short insertion length $\rightarrow$ 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

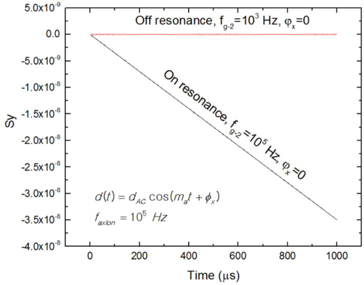
(Oscillating) Axion-EDM search using storage ring

Motivation: Paper by Graham and Rajendran [32, 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

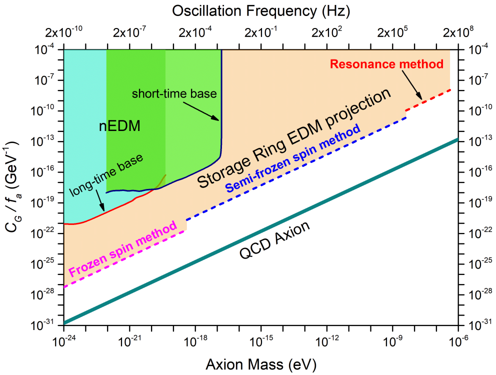


Figure from S.P. Chang et al. [33]

Realization

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