

# Electric Dipole Moment Searches using Storage Rings

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# 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	$(6.11^{+0.3}_{-0.2}) \times 10^{-10}$ $(5.53 - 6.76) \times 10^{-10}$	Best Fit Cosmological Model [1] 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 4<sup>th</sup> 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  $\mu_N$ .

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

- 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  $\theta_{\text{QCD}}$  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  $\theta_{\text{QCD}} = 0$ :

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

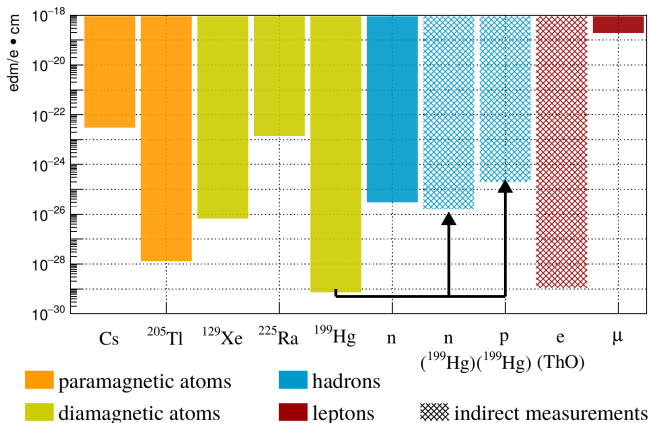
# Status of EDM searches I

## EDM limits in units of [e cm]:

- Long-term goals for neutron,  $^{199}_{80}\text{Hg}$ ,  $^{129}_{54}\text{Xe}$ , 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	$< 3 \times 10^{-17}$	$\approx 10^{-28}$	$10^{-28}$	1981 [9]
Neutron	$(-0.21 \pm 1.82) \times 10^{-26}$			2015 [10]
$^{199}_{80}\text{Hg}$	$< 7.4 \times 10^{-30}$			2016 [12]
$^{129}_{54}\text{Xe}$	$< 6.0 \times 10^{-27}$			2001 [13]
Proton	$< 2 \times 10^{-25}$			2016 [12]
Deuteron	not available yet	$\approx 10^{-29}$	$\approx 3 \times 10^{-29}$ to $5 \times 10^{-31}$	

# Status of EDM searches II [14, Fig. 2.1]



Missing are *direct* EDM measurements:

- No direct measurements of electron: limit obtained from (ThO molecule).
- No direct measurements of proton: limit obtained from <sup>199</sup><sub>80</sub>Hg.
- **No measurement at all of deuteron EDM.**

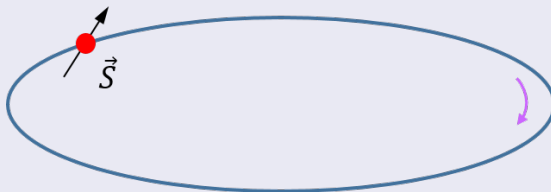
# Spin precession of particles with MDM and EDM

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 [15].

# Frozen-spin

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

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

$\Rightarrow \vec{\Omega} = 0$  **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*:

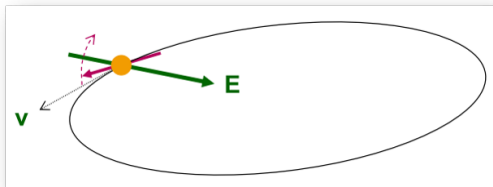
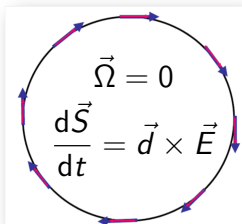
$$G - \frac{1}{\gamma^2 - 1} = 0 \Leftrightarrow G = \frac{m^2}{p^2} \quad \Rightarrow \quad \boxed{p = \frac{m}{\sqrt{G}} = 700.740 \text{ MeV c}^{-1}} \quad (5)$$



# 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  $P_y(t) \propto d$ .

# Search for charged particle EDMs with frozen spins

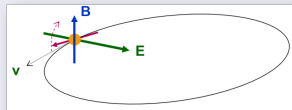
Magic storage rings

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

- Generalized solution for magic momentum

$$\frac{E_x}{B_y} = \frac{Gc\beta\gamma^2}{1 - G\beta^2\gamma^2}, \quad (6)$$

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 <sup>-1</sup> ]	$T$ [MeV]	$E_x$ [MV m <sup>-1</sup> ]	$B_y$ [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.**

# 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:

$$\sigma_{\text{stat}} = \frac{1}{\sqrt{N f \tau_{\text{SCT}} P A_y E}} \Rightarrow \boxed{\sigma_{\text{stat}}(1 \text{ yr}) = 10^{-29} \text{ e cm}}. \quad (7)$$

- **Experimentalist's goal is to provide  $\sigma_{\text{syst}}$  to the same level.**

# Progress toward storage ring EDM experiments

Complementing the spin physics tool box

## COoler SYnchrotron COSY

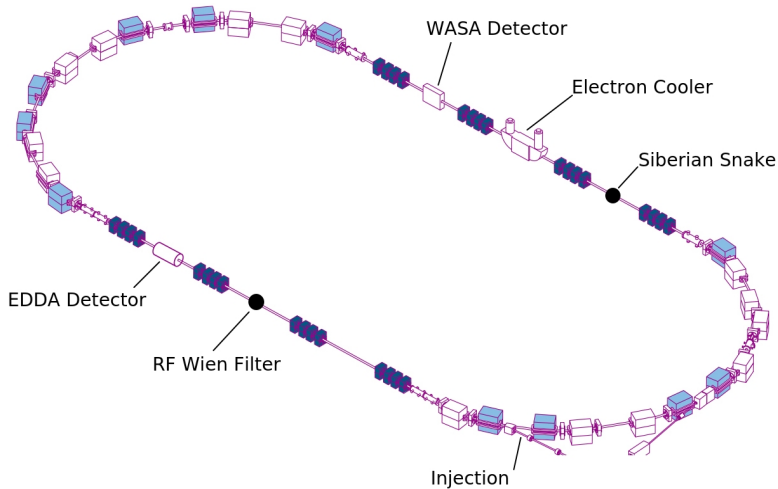
- Cooler and storage ring for (polarized) protons and deuterons.
- Momenta  $p = 0.3 - 3.7 \text{ GeV}/c$ .
- Phase-space cooled internal and extracted beams.



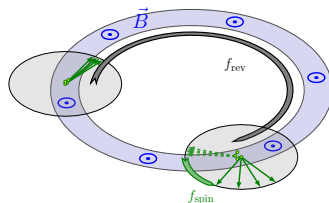
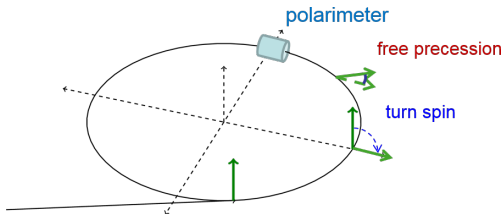
## COSY formerly used as spin-physics machine for hadron physics:

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

# COSY Landscape



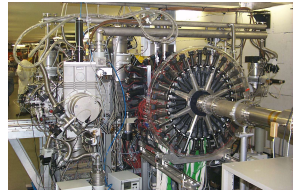
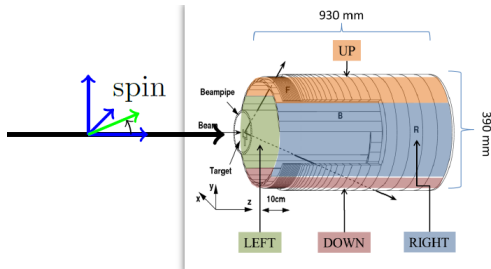
# Principle of spin-coherence time measurement



## 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 [16]



EDDA previously 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:

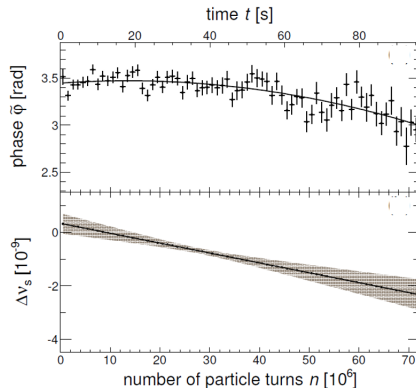
$$N_{U,D} \propto 1 \pm \frac{3}{2} p_z A_y \sin(\underbrace{\nu_s \cdot f_{\text{rev}}}_{f_s = -120.7 \text{ kHz}} \cdot t), \text{ where } f_{\text{rev}} = 750.0 \text{ kHz}. \quad (8)$$

# Precision determination of the spin tune [17, PRL 2015]

## Time-stamping events accurately,

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

$$\begin{aligned}\nu_s(n) &= \nu_s^{\text{fix}} + \frac{1}{2\pi} \frac{d\tilde{\phi}}{dn} \quad (9) \\ &= \nu_s^{\text{fix}} + \Delta\nu_s(n)\end{aligned}$$

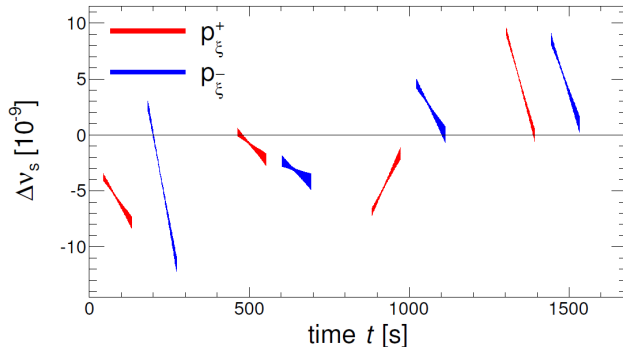


## Experimental technique allows for:

- Spin tune  $\nu_s$  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

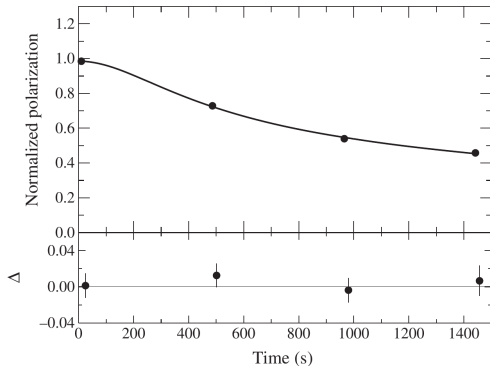


Walk of spin tune  $\nu_s$  [17].

## 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.

# Optimizations of spin-coherence time: [19, PRL 2016]



JEDI progress on  $\tau_{\text{SCT}}$ :

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

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

**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  $\tau_{\text{SCT}}$  of crucial importance (7), since  $\sigma_{\text{stat}} \propto \tau_{\text{SCT}}^{-1}$ .

# Phase locking spin precession in machine to device RF

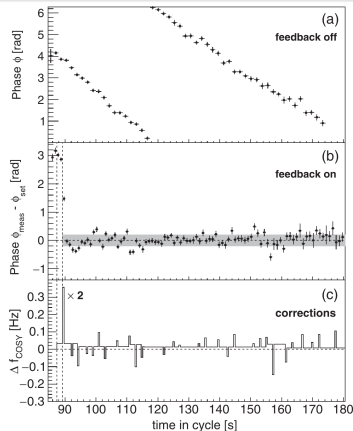
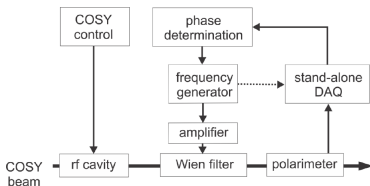
PhD work of Nils Hempelmann

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 Wien filter)



**Major achievement** : Error of phase-lock  $\sigma_{\phi} = 0.21$  rad [20, PRL 2017].

# Study of machine imperfections

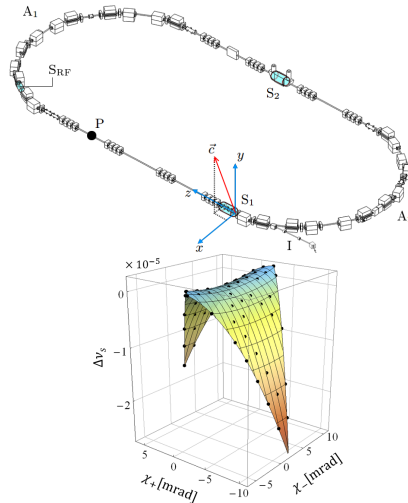
PhD work of Artem Saleev

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



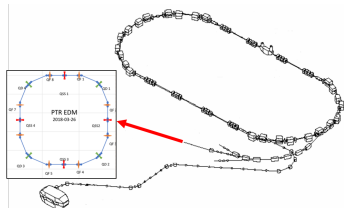
# Prototype EDM storage ring

## 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



Electric Dipole Moment Searches using Storage Rings

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

# Charged Particle Electric Dipole Moment Collaboration<sup>1</sup>

Stages of project and time frame toward dedicated EDM ring: [14, arXiv 2019]

## Stage 1

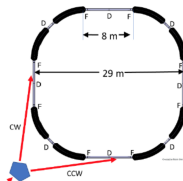
- precursor experiment



- magnetic storage ring
- Now

## Stage 2

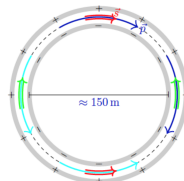
- prototype ring



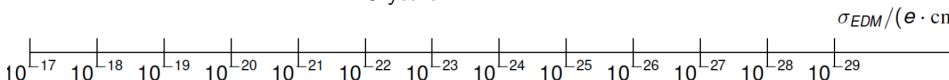
- electric/magnetic bends
- simultaneous  $\circlearrowleft$  and  $\circlearrowright$  beams
- 5 years

## Stage 3

- dedicated storage ring



- at magic  $p$  momentum
- 10 years



<sup>1</sup><http://pbc.web.cern.ch/edm/edm-default.htm>

# 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:

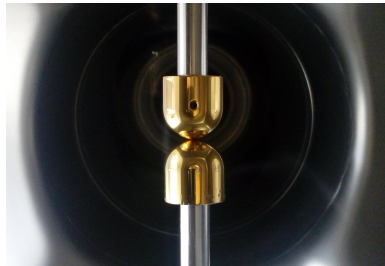
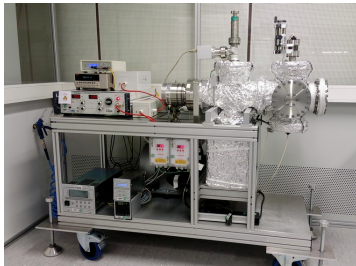
### Main issues:

- Spin coherence time  $\tau_{\text{SCT}} \sim 1000 \text{ s}$  [19, 2016].
- Continuous polarimetry with relative errors  $< 1 \text{ ppm}$  [22, 2012].
- Beam position monitoring with precision of 10 nm.
- Alignment of ring elements, ground motion, ring imperfections.
- Magnetic shielding.
- Large electric field gradients  $\sim 10$  to 20 MV/m.
- High-precision spin tracking.
- d EDM with frozen spin  $\rightarrow$  precise  $B$  field reversal for CW and CCW beams.

# E/B Deflector development using small-scale lab setup [23]

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.



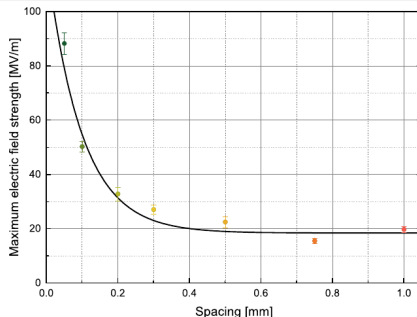
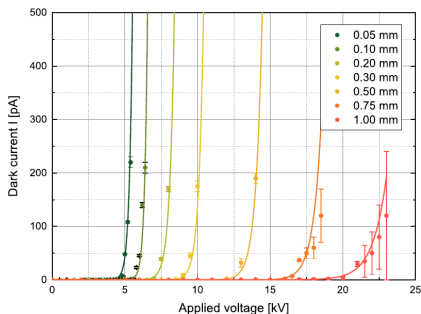


# Recent results, published in [24, RSI 2019]

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

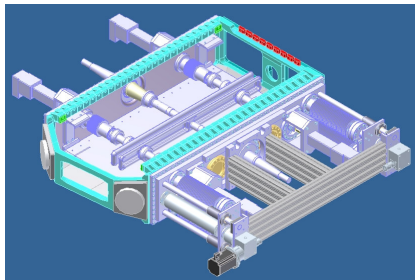
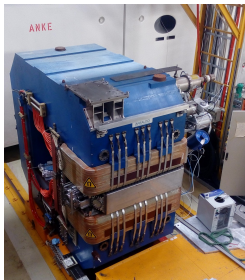
- distances  $S = 1, 0.75, \dots, 0.05$  mm, where

$$E_{\max} = \frac{U}{S} \cdot F, \text{ where } F = \frac{1}{4} \left[ 1 + \frac{S}{R} + \sqrt{\left( 1 + \frac{S}{R} \right)^2 + 8} \right], \quad (10)$$



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

# E/B deflector development using real-scale lab setup



## Equipment:

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

## Parameters:

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

## Next steps:

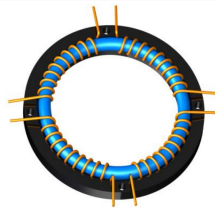
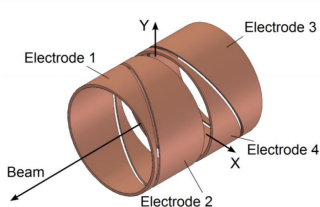
Equipment ready for assembling. First test results expected in the near future.

# 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  $\approx 1$  cm (along beam direction)



### Conventional BPM

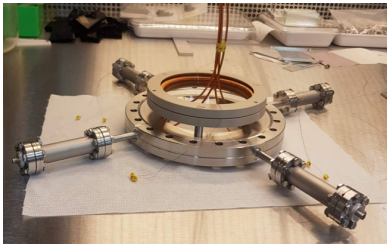
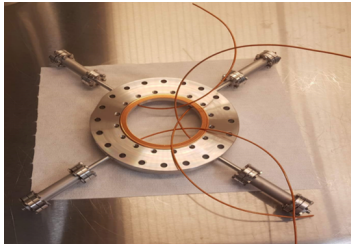
- Easy to manufacture
- length = 20 cm
- resolution  $\approx 10 \mu\text{m}$

### Rogowski BPM (warm)

- Excellent RF-signal response
- length = 1 cm
- resolution  $\approx 1.25 \mu\text{m}$

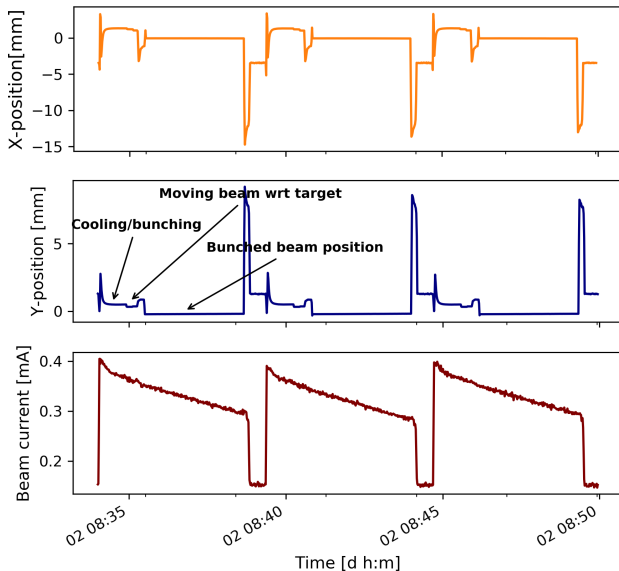
- Two Rogowski coil BPMs installed at entrance and exit of RF Wien filter

# Assembly stages of one Rogowski-coil BPM



# Measured beam positions at entrance of RF Wien filter

from a run in 2019



# $dC$ polarimetry data base I

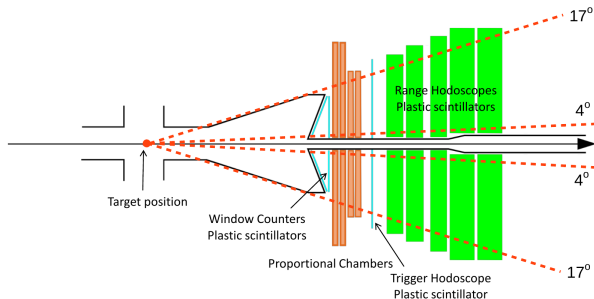
Data analysis mainly by Maria Zurek and PhD Fabian Müller

## Motivation: Optimize polarimetry for ongoing JEDI experiments:

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

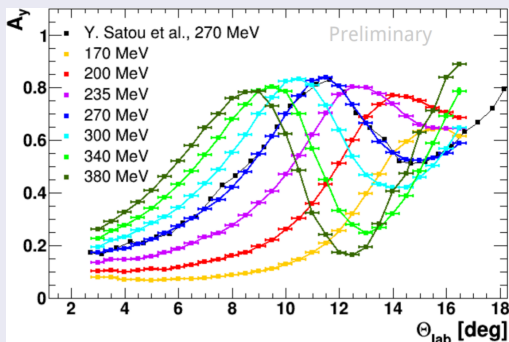
## Detector system: former WASA forward detector, modified

- Targets: C and CH<sub>2</sub>
- 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

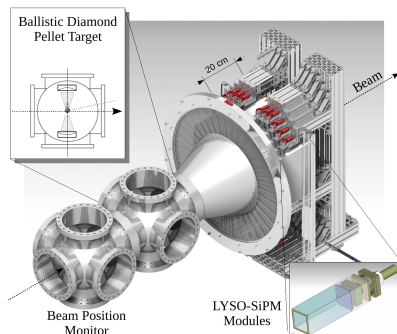
Development led by Irakli Keshelashvili

## Based on LYSO Scintillation Material

- Saint-Gobain Ceramics & Plastics:  $\text{Lu}_{1.8}\text{Y}_{0.2}\text{SiO}_5:\text{Ce}$
- Compared to NaI, LYSO provides
  - high density (7.1 vs 3.67 g/cm<sup>3</sup>),
  - very fast decay time (45 vs 250 ns).

## After several runs with external beam:

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





# Beam-based alignment for EDM measurement at COSY

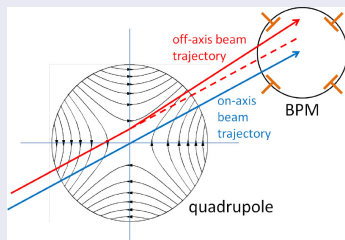
PhD work of Tim Wagner

## Surveys and alignment campaigns of accelerator ensure magnets aligned properly

- Surveys makes use of markers mounted on magnets as reference points.
- When COSY was built, nobody thought of precision experiments
  - no markers on Beam position monitors (BPMs), exact positions are unknown.
- EDM measurements require as good an orbit as possible
  - small RMS deviation to ideal orbit
- Goal: develop and implement method to determine exact positions of BPMs:
  - **Beam-based alignment**

## Machine orbit is defined by potential minimum in quadrupole magnets

- Beam is deflected when it passes through a misaligned quad.
- Beam-based alignment minimizes steering effect of quadrupoles



# Beam-based alignment II

PhD work of Tim Wagner

## Orbit change when quadrupole strength is varied

$$\Delta x(s) = \frac{\Delta k \cdot x(s_0) l}{B \rho} \cdot \frac{1}{1 - k \frac{l \beta(s_0)}{2 B \rho \tan \pi \nu}} \cdot \frac{\sqrt{\beta(s) \beta(s_0)}}{2 \sin \pi \nu} \cos [\phi(s) - \phi(s_0) - \pi \nu] \quad (11)$$

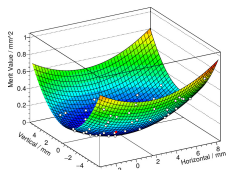
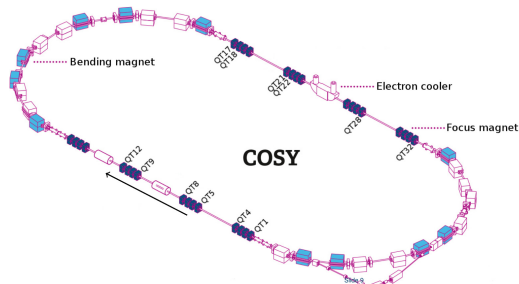
- $s, s_0$  positions along orbit,  $\beta$  betatron functions,  $\nu$  working point,  $\phi$  betatron phase advance,  $B$  magnetic field,  $l$  magnet current,  $\rho$  bending radius.
- Not all parameters in (11) known well  $\rightarrow$  not possible to determine  $x(s_0)$ .
- Instead, use merit function

$$f = \frac{1}{N_{\text{BPM}}} \sum_{i=1}^{N_{\text{BPM}}} [x_i(+\Delta k) - x_i(-\Delta k)]^2 \propto x(s_0)^2 \quad (12)$$

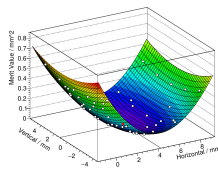
from which optimum ( $f \rightarrow 0$ ) is found by minimization.

# Beam-based alignment III

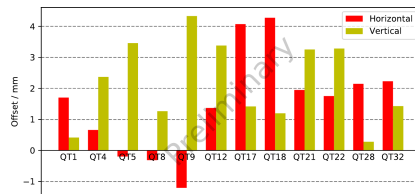
PhD work of Tim Wagner



QT1,  $\chi^2_{d.o.f.} = 0.96$



QT18,  $\chi^2_{d.o.f.} = 1.77$



# Beam-based alignment IV

Preliminary results for a subset of quadrupoles

## Obtained offsets of the beam-position monitors:

BPM	$s$ [m]	hor. corr. [mm]	vert. corr. [mm]
BPM02	10.4	$1.705 \pm 0.008$	$0.416 \pm 0.005$
BPM06	29.5	$1.371 \pm 0.007$	$3.382 \pm 0.011$
BPM18	100.2	$4.177 \pm 0.007$	$1.308 \pm 0.005$
BPM19	110.1	$1.868 \pm 0.005$	$3.273 \pm 0.010$
BPM20	123.3	$2.149 \pm 0.007$	$0.281 \pm 0.007$
BPM21	133.2	$2.232 \pm 0.008$	$1.430 \pm 0.006$

## Remarkable precision of better than $10\text{ }\mu\text{m}$ reached

- orbit improvement:  $RMS_y = 1.21\text{ mm} \rightarrow 1.01\text{ mm}$  with only 20% of BPMs.
- Extended data set (run in Sept. '19) now covers all quadrupoles and BPMs.

# 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 ( $< 10^{-28}$  e cm).
  - In this environment, magnetic fields mean evil (since  $\mu$  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 ( $\sim 1000$  s).

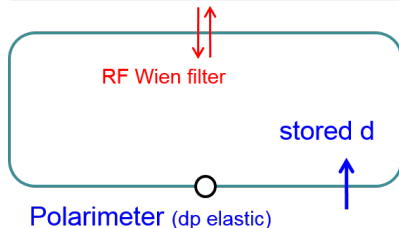
Goal of proof-of-principle experiment:

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  $\tau_{\text{SCT}} \sim 1000$  s.

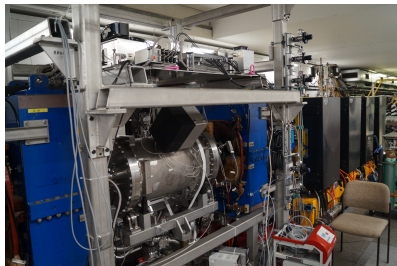
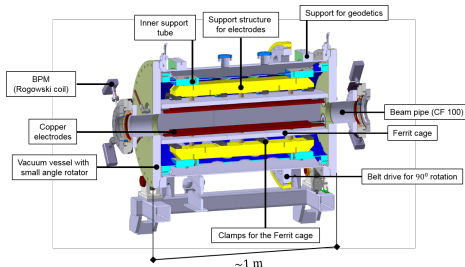
## Statistical sensitivity:

- 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.

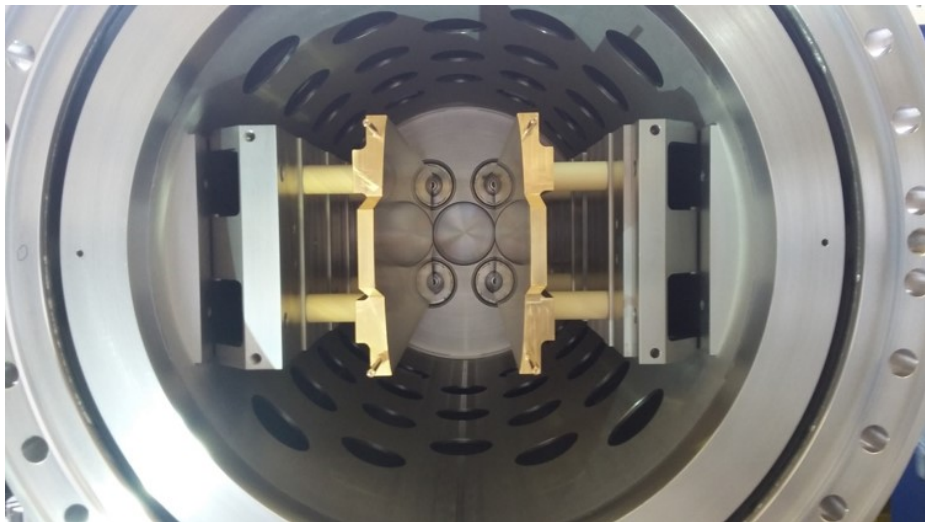
# Design of waveguide RF Wien filter

## 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 [25, 2016].



# Installation at COSY



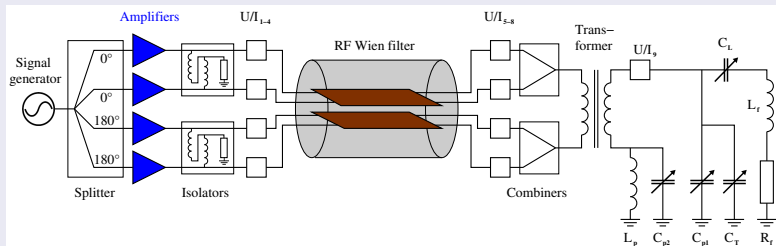
View along the beam axis in the RF Wien filter.



# Driving circuit

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

- Design layout using four separate 1 kW power amplifiers.



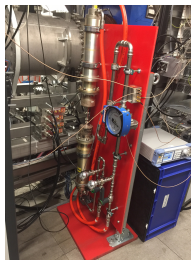
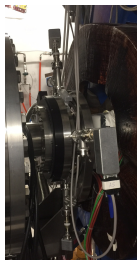
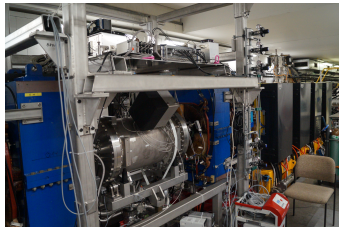
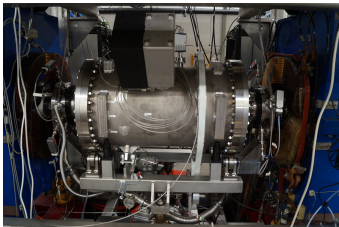
## Circuit fully operational

- Tunable elements<sup>a</sup> allow [25]:
  - minimization of Lorentz-force, and
  - velocity matching to  $\beta$  of the beam.
- Power upgrade to  $4 \times 2$  kW:  $\int B_z dz = 0.218$  T mm possible.

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

# RF Wien filter

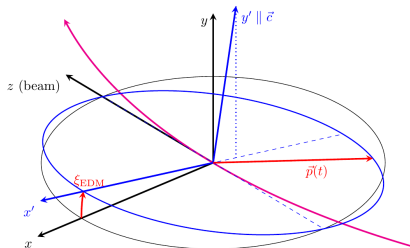
## Installation at COSY



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

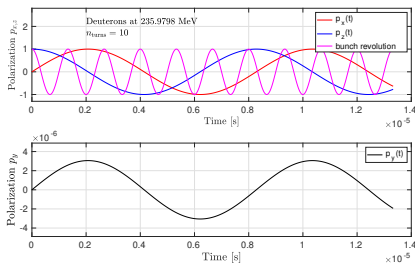
# Effect of EDM on stable spin axis of the ring

## 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 [ $\vec{p}_0 = (0, 0, 1)$ ]

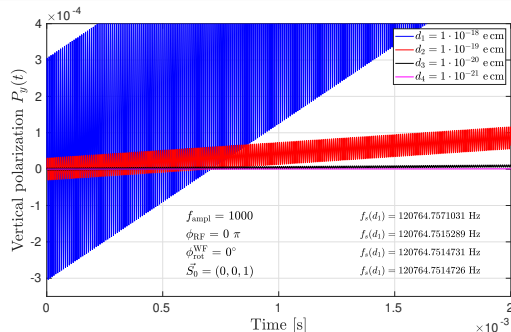
- $p_x(t)$ ,  $p_z(t)$  and  $p_y(t)$ .
- Bunch revolution indicated as well.
- $p_y$  oscillation amplitude corresponds to tilt angle  $\xi_{\text{EDM}}$ .

# Model calculation of EDM buildup [28, arXiv 2019]

With RF Wien filter

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

- $G = -0.143$ ,  $\gamma = 1.126$ ,  $f_s = f_{\text{rev}}(\gamma G + K_{(=0)}) \approx 120.765 \text{ kHz}$
- Electric RF field integral assumed  $1000 \times \int E_{\text{WF}} \cdot d\ell \approx 2200 \text{ kV}$  (w/o ferrites) [25, 2016].



EDM accumulates in  $P_y(t) \propto d_{\text{EDM}} [21, 26, 27]$ .

# Strength of EDM resonance

## EDM induced polarization oscillation,

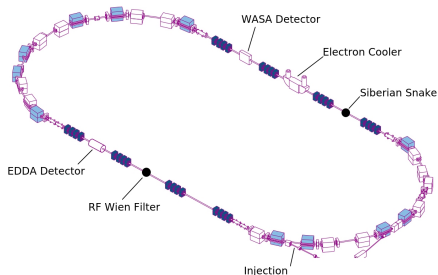
- can generally be described by

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

$y$  perpendicular to ring plane.

- EDM resonance strength** defined as ratio of angular frequency  $\Omega^{p_y}$  to orbital angular frequency  $\Omega^{\text{rev}}$ ,

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



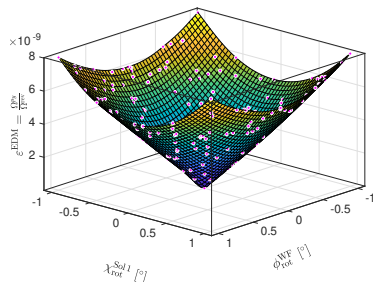
## How is the EDM effect actually measured?

Two features are simultaneously applied in the ring:

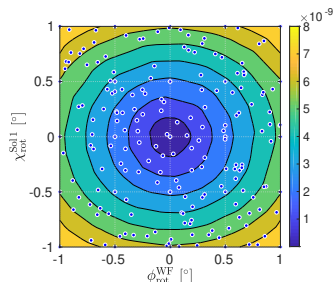
1. the RF Wien filter is rotated by a small angle. This generates a tiny radial magnetic RF field, which affects the spin evolution.
2. In addition, a longitudinal magnetic field in the ring opposite to the Wien filter, about which the spins rotate as well.

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

[28, arXiv 2019]



(a)  $\epsilon_{\text{EDM}}$  for  $d = 10^{-20}$  e cm.



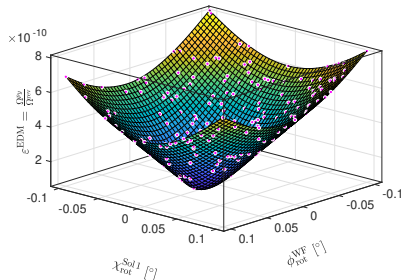
(b) Contour plot of (a).

Resonance strengths  $\epsilon_{\text{EDM}}$  from Eq. (13) ( $\approx 175$  random-points)

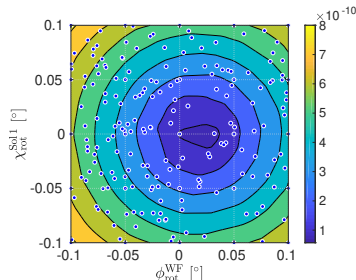
- $\phi_{\text{rot}}^{\text{WF}} = [-1^\circ, \dots, +1^\circ]$ ,
- $\chi_{\text{rot}}^{\text{Sol 1}} = [-1^\circ, \dots, +1^\circ]$  (100 keV cooler), and
- Each point from calculation with  $n_{\text{turns}} = 50\,000$  and  $n_{\text{points}} = 200$ .

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

[28, arXiv 2019]



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



(d) Contour plot of (c).

Resonance strengths  $\varepsilon^{\text{EDM}}$  from Eq. (13) ( $\approx 175$  random-points)

- $\phi_{\text{rot}}^{\text{WF}} = [-0.1^\circ, \dots, +0.1^\circ]$ ,
- $\chi_{\text{rot}}^{\text{Sol1}} = [-0.1^\circ, \dots, +0.1^\circ]$  (100 keV cooler), and
- Each point from calculation with  $n_{\text{turns}} = 200\,000$  and  $n_{\text{points}} = 100$ .

# Preliminary results of Wien filter mapping I

Nov.-Dec. 2018 run

## Function describing the surface

- As shown in [28, arXiv 2019], the resulting surface can be described by an *elliptic paraboloid*:

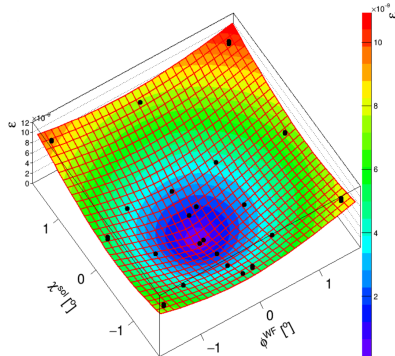
$$\left(\varepsilon^{\text{EDM}}\right)^2 = \frac{\psi_{\text{WF}}^2}{16\pi^2} \cdot \left[ A \left( \phi^{\text{WF}} - \phi_0^{\text{WF}} \right)^2 + B \left( \frac{\chi^{\text{Sol1}}}{2 \sin \pi \nu_s^{(2)}} + \chi_0^{\text{Sol1}} \right)^2 + C \right]. \quad (13)$$

- Eq. (13) contains two parameters (not required)  $A$  and  $B$  to account for possible deviations of the magnitude of  $\varepsilon^{\text{EDM}}$  along  $\phi^{\text{WF}}$  and  $\chi^{\text{Sol1}}$ .



# Preliminary results of Wien filter mapping II

Nov.-Dec. 2018 run



## First data

- 9 + 9 + 14 data points on 3 maps
- took  $\approx 2$  weeks pure measuring time
- Preliminary results of fit using Eq. (13):

$$\begin{aligned}
 \phi_0^{WF} &= -3.9 \pm 0.05 \text{ mrad} \\
 \chi_0^{Sol 1} &= -6.8 \pm 0.04 \text{ mrad} \\
 A &= 0.559 \pm 0.005 \\
 B &= 0.583 \pm 0.005 \\
 C &= (-1.2 \pm 0.1) \cdot 10^{-10}
 \end{aligned} \tag{14}$$

## Where are we today?

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

# Summary I

## 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 EDM measurement using RF Wien filter

- 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.
  - 6 wk run Nov. -Dec. '18, and foreseen 6 wk run in '20.
  - Planned upgrades:
    - consolidation of beam-based alignment,
    - implementation of multi-channel frequency generator,
    - test of pilot bunch technique,
    - measurement of spin tune change as function of orbit bumps.
  - Sensitivity  $10^{-18}$  to  $10^{-20}$  e cm.

# Summary II

## Strong interest of high energy community in storage ring EDM searches

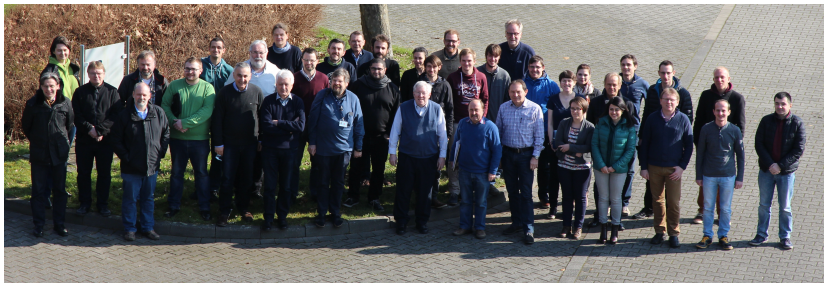
- protons and light nuclei as part of physics program of the post-LHC era:
  - Physics Beyond Collider process (CERN), and
  - European Strategy for Particle Physics Update.
  - As part of this process, proposal for prototype EDM storage ring prepared by CPEDM ([14] → CERN Yellow Report)
    - possible host sites: CERN or COSY.

# JEDI Collaboration



## JEDI = Jülich Electric Dipole Moment Investigations

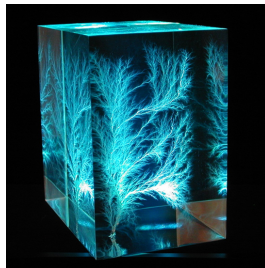
- ~ 140 members (Aachen, Daejeon, Dubna, Ferrara, Indiana, Ithaka, Jülich, Krakow, Michigan, Minsk, Novosibirsk, St Petersburg, Stockholm, Tbilisi, ...)
- <http://collaborations.fz-juelich.de/ikp/jedi>



# Georg Christoph Lichtenberg (1742 – 1799)

German scientist, satirist, and Anglophile:

- First to hold professorship dedicated to experimental physics in Germany.
- Remembered for his discovery of strange tree-like electrical discharge patterns, now called *Lichtenberg figures*.



From his Sudelbücher [29]:

- *Man muß etwas Neues machen, um etwas Neues zu sehen.*
- *You have to make (create) something new, if you want to see something new.*

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[<http://science.sciencemag.org/content/343/6168/269.full.pdf>].
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# Spare Slides

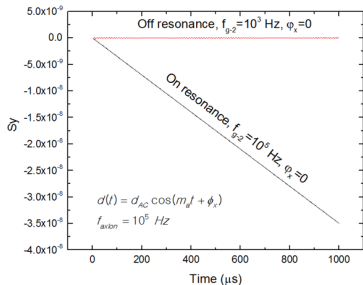
# (Oscillating) Axion-EDM search using storage ring

Motivation: Paper by Graham and Rajendran [30, 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

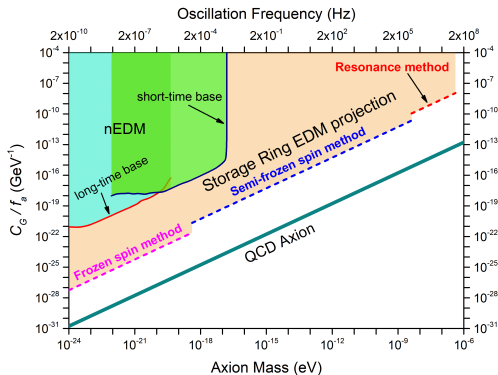


Figure from S.P. Chang et al. [31]

## Realization

- No new/additional equipment required!
- Can be done in magnetic storage ring (*i.e.*, COSY).
- First test experiment carried out in I/2019.