

# Electric Dipole Moment Searches using Storage Rings

Frank Rathmann  
(on behalf of the JEDI collaboration)

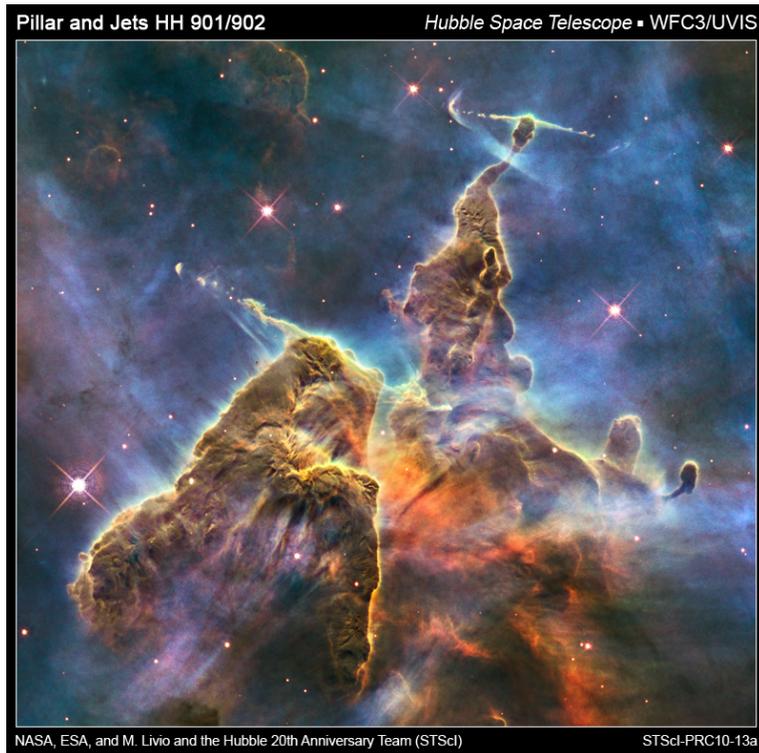
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# Baryon asymmetry in the Universe



**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]

# Precision frontier

EDMs possibly constitute missing cornerstone to explain surplus of matter over antimatter in the Universe:

- SCM gets it wrong by about 9 orders of magnitude.
- Non-vanishing EDMs would add fourth quantum number to fundamental particles

Large worldwide effort to search for EDMs of fundamental particles:

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

Why search for charged particle EDMs using a storage ring?

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

- Charged hadron EDM experiments provide potentially higher sensitivity than for neutrons:
  - longer lifetime,
  - more stored polarized protons/deuterons available than neutrons, and
  - one can apply larger electric fields in storage ring.
- Approach complimentary to neutron EDM searches.
- **EDM of single particle not sufficient to identify  $CP$  violating source [4]**

# Naive estimate of scale of nucleon EDM

From Khriplovich & Lamoreux [5]:

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

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

- 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 BSM physics ( $\theta_{\text{QCD}} = 0$ ) from nucleon EDMs:

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

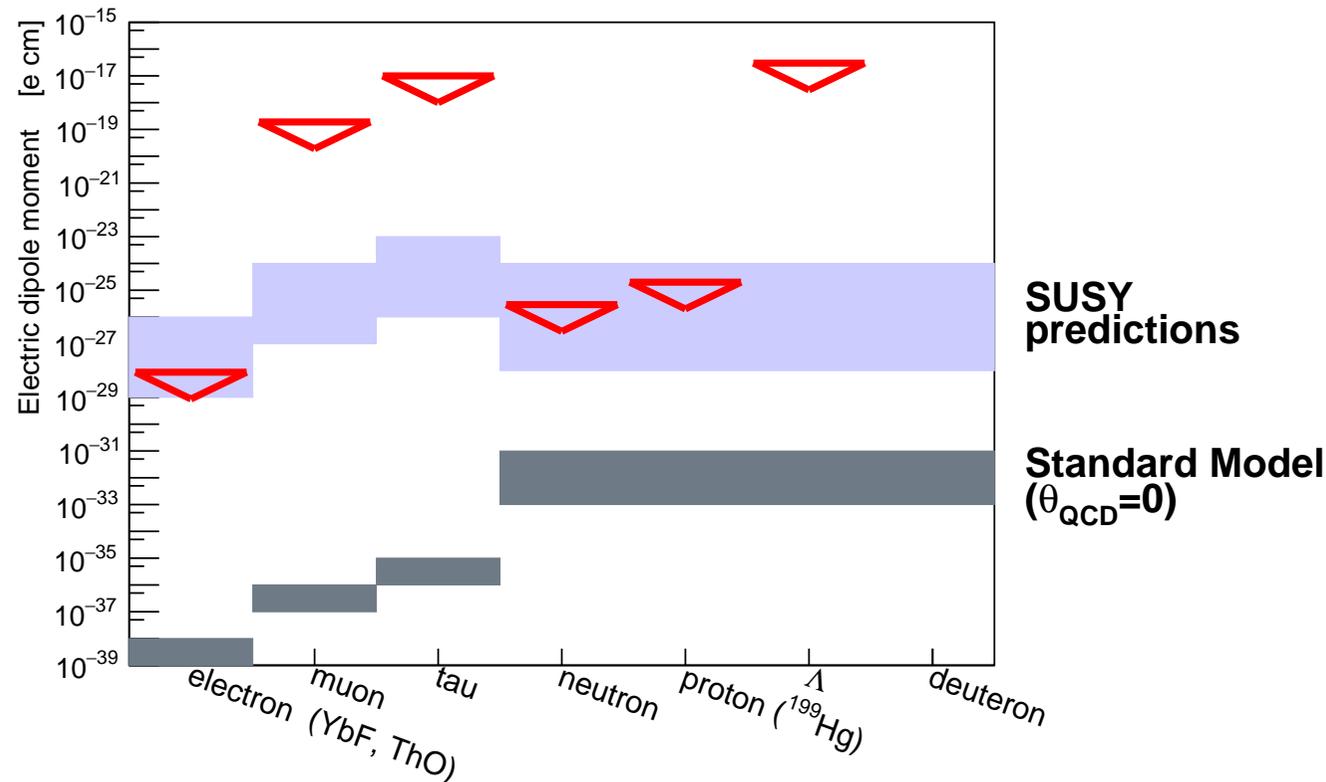
# Status of EDM searches I

## 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	$< 3 \times 10^{-17}$			1981 [9]
Neutron	$(-0.21 \pm 1.82) \times 10^{-26}$	$\approx 10^{-28}$	$10^{-28}$	2015 [10]
$^{199}_{80}\text{Hg}$	$< 7.4 \times 10^{-30}$	$10^{-30}$	$< 1.6 \times 10^{-26}$ [11]	2016 [12]
$^{129}_{54}\text{Xe}$	$< 6.0 \times 10^{-27}$	$\approx 10^{-30}$ to $10^{-33}$	$\approx 10^{-26}$ to $10^{-29}$	2001 [13]
Proton	$< 2 \times 10^{-25}$	$\approx 10^{-29}$	$10^{-29}$	2016 [12]
Deuteron	not available yet	$\approx 10^{-29}$	$\approx 3 \times 10^{-29}$ to $5 \times 10^{-31}$	

# Status of EDM searches II



Missing are *direct* EDM measurements:

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

# Experimental requirements for storage ring EDM searches

## High precision, primarily electric storage ring

- Crucial role of alignment, stability, field homogeneity, and shielding from perturbing magnetic fields.
- High beam intensity:  $N = 4 \times 10^{10}$  particles per fill.
- High polarization of stored polarized hadrons:  $P = 0.8$ .
- Large electric fields:  $E = 10$  MV/m.
- Long spin coherence time:  $\tau_{\text{SCT}} = 1000$  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:

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

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

# Particles with magnetic and electric dipole moment

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

- non-relativistic Hamiltonian:

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

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

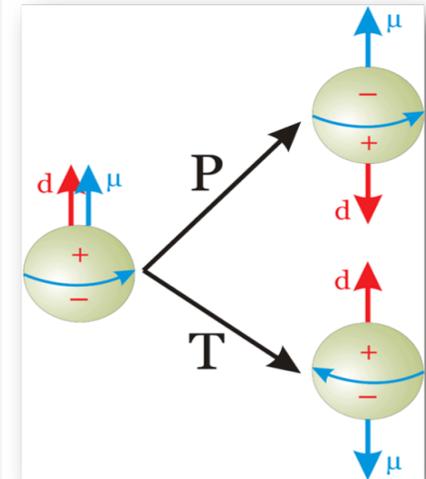
$$-\vec{\mu} \cdot \vec{B} \xrightarrow{P \text{ or } T} -\vec{\mu} \cdot \vec{B}, \quad (2)$$

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

$$\vec{s} \cdot \vec{E} \xrightarrow{P \text{ or } T} -\vec{s} \cdot \vec{E}, \quad (3)$$

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



In rest frame of particle,

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

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}. \quad (4)$$

# Frozen-spin

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

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

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

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

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

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

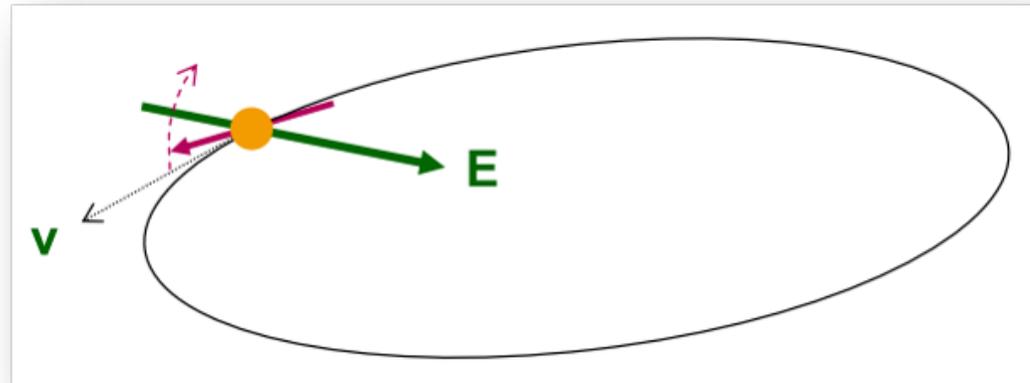
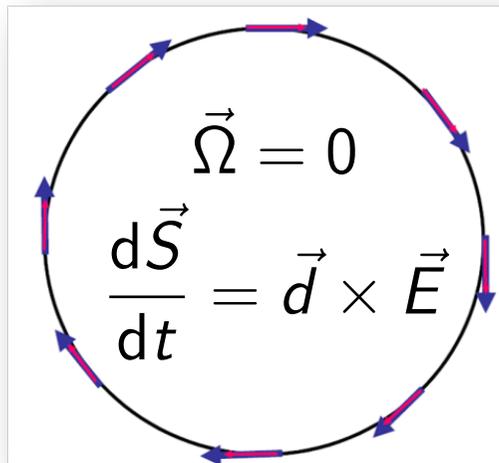
For protons, (6) leads to *magic momentum*:

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

# Protons at magic momentum in pure electric ring:

## Recipe to measure EDM of proton:

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



## New method to measure EDMs of charged particles:

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

# Search for charged particle EDMs with frozen spins

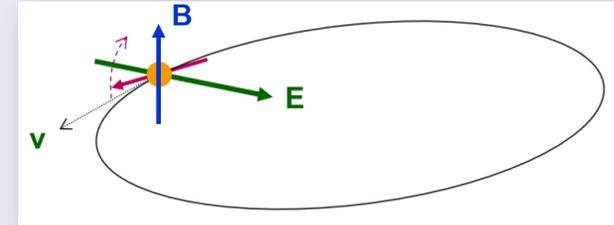
Magic storage rings

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

- Generalized solution for magic momentum

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

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

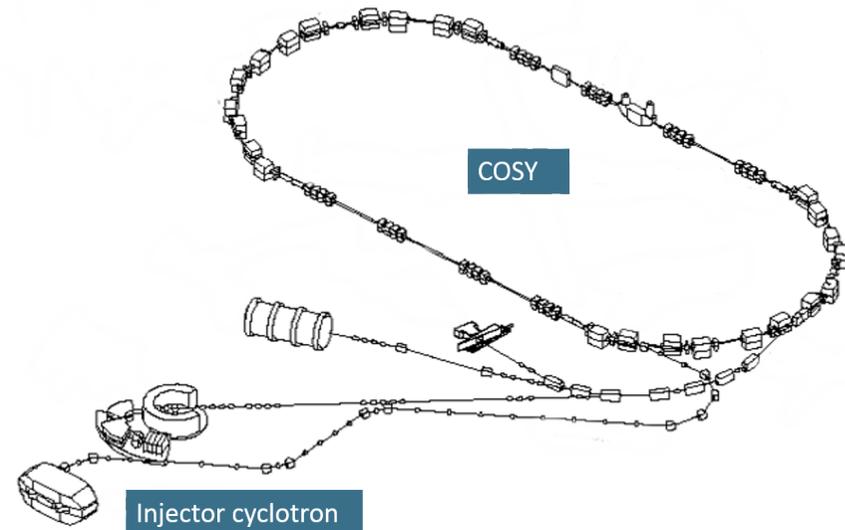
**EDMs of protons, deuterons, and helions in one and the same machine.**

# Progress toward storage ring EDM experiments

Complementing the spin physics tool box

## COoler SYnchrotron COSY

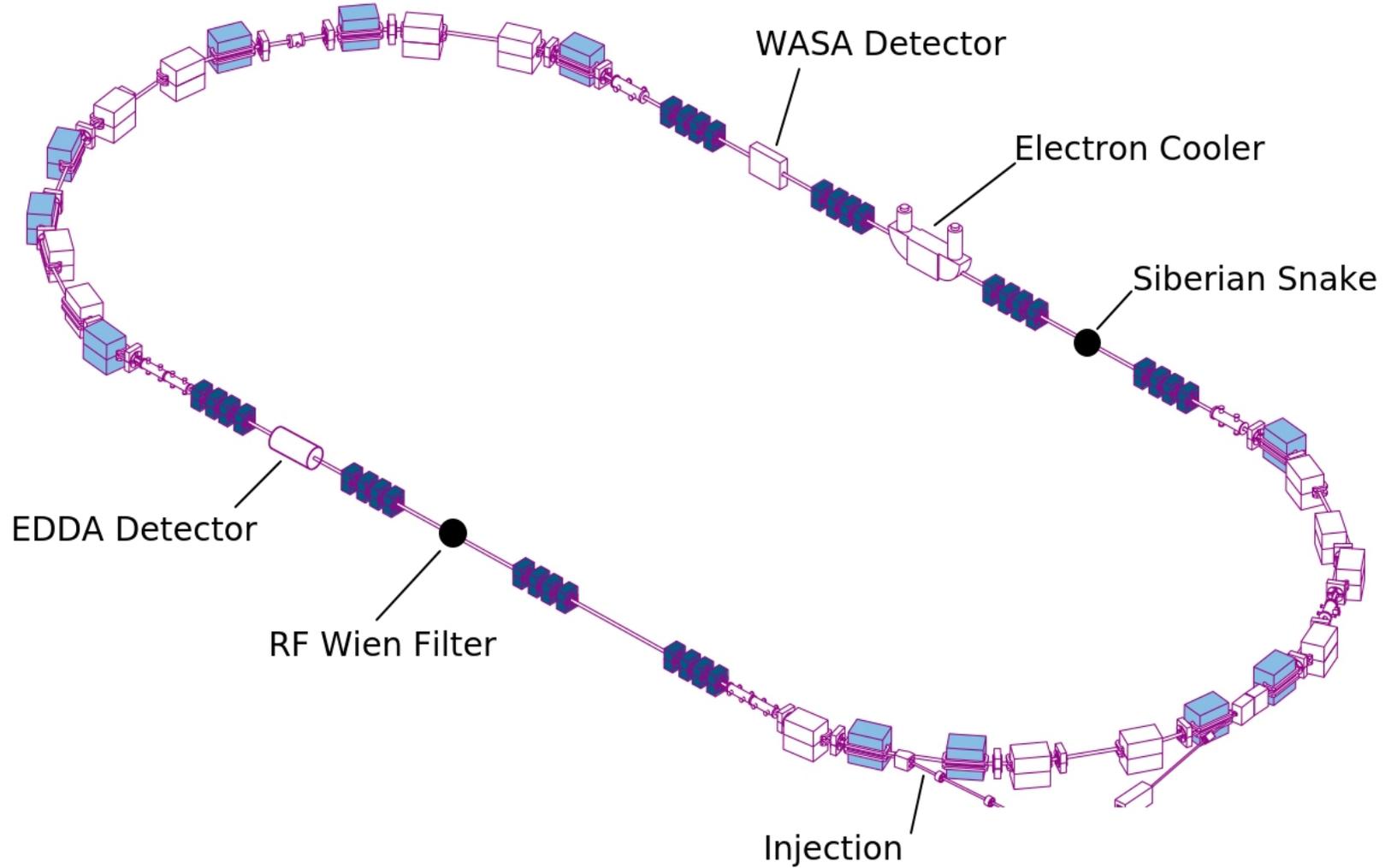
- Cooler and storage ring for (polarized) protons and deuterons.
- Momenta  $p = 0.3 - 3.7 \text{ GeV}/c$ .
- Phase-space cooled internal and extracted beams.



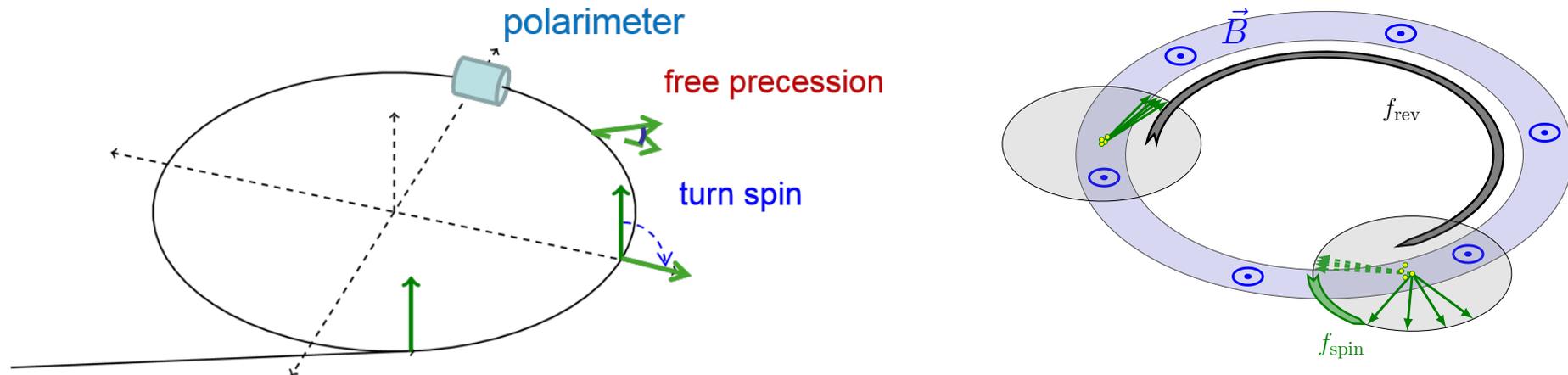
**COSY formerly used as spin-physics machine for hadron physics:**

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

# COSY Landscape



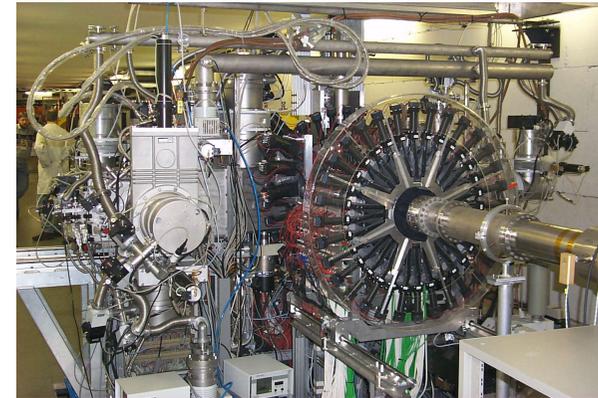
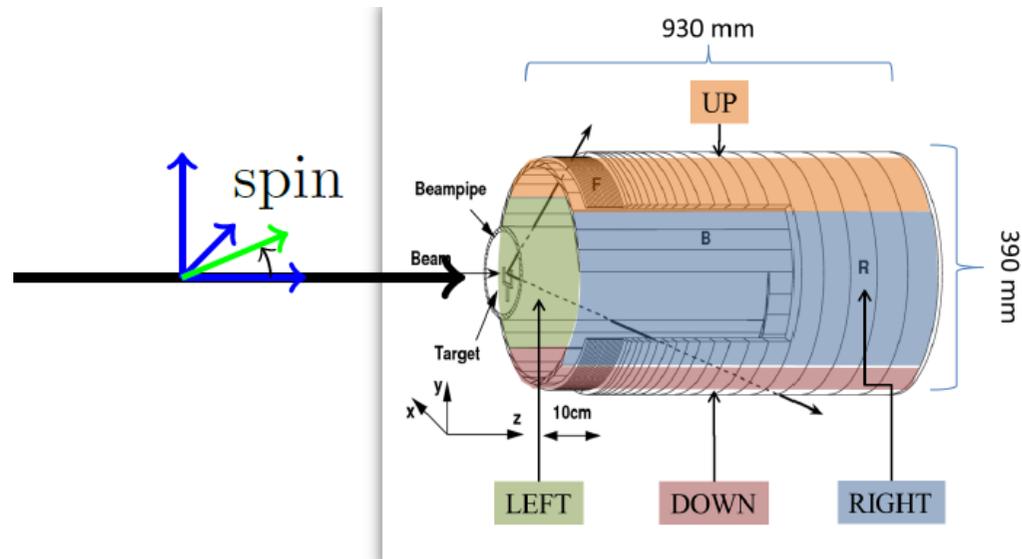
# Principle of spin-coherence time measurement



## 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 [14]



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:

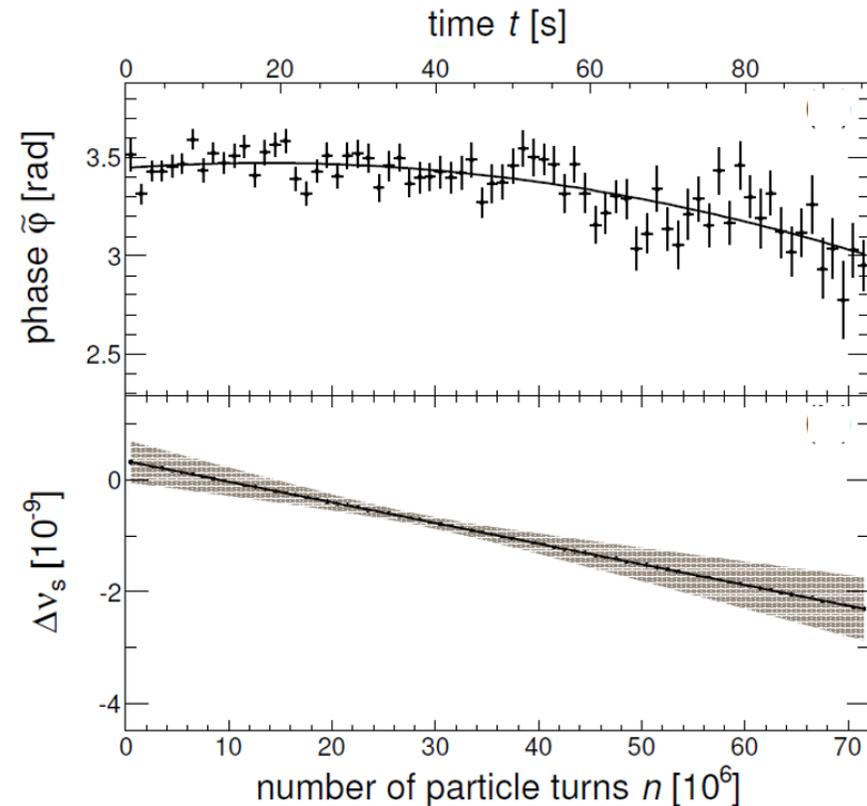
$$N_{U,D} \propto 1 \pm \frac{3}{2} p_z A_y \sin(\underbrace{\nu_s}_{f_s} f_{\text{rev}} t), \text{ where } f_{\text{rev}} = 750 \text{ kHz.} \quad (9)$$

# Precision determination of the spin tune [15, 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:

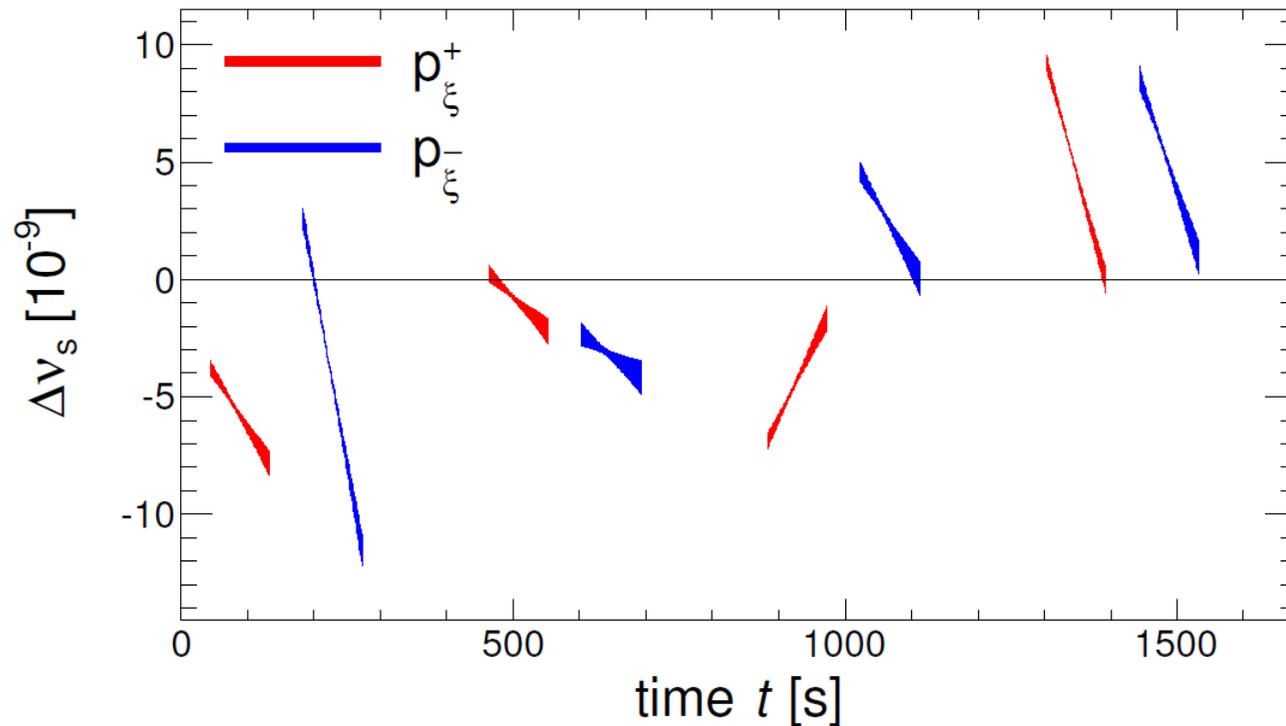
$$\begin{aligned}\nu_s(n) &= \nu_s^{\text{fix}} + \frac{1}{2\pi} \frac{d\tilde{\phi}}{dn} \quad (10) \\ &= \nu_s^{\text{fix}} + \Delta\nu_s(n)\end{aligned}$$



## 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

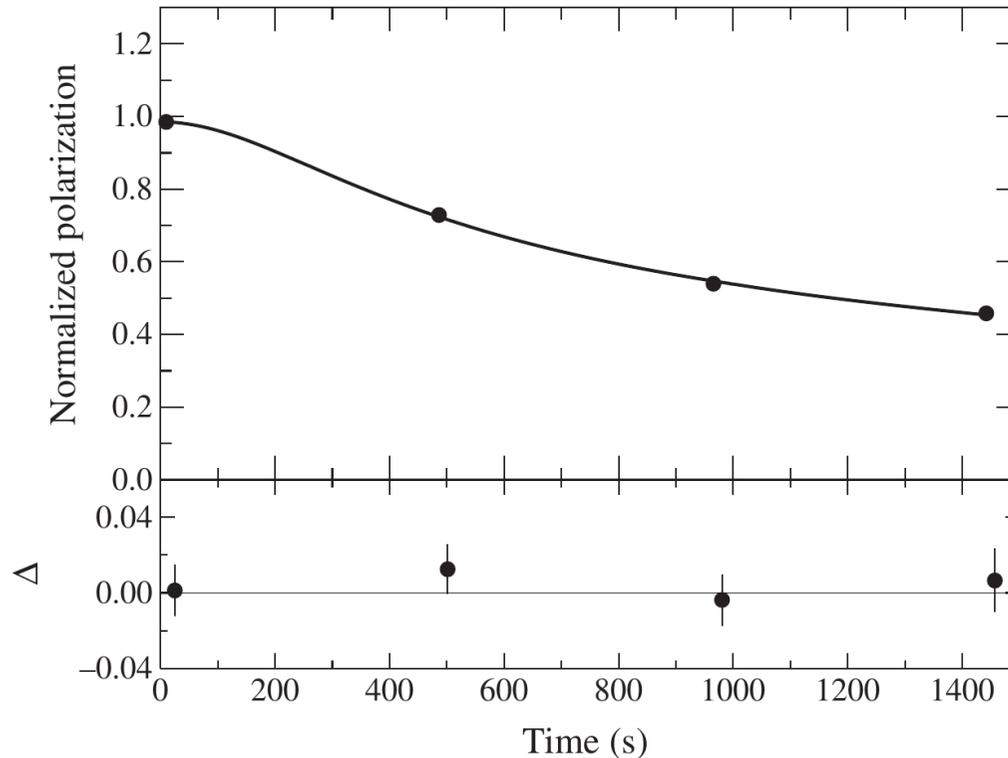


Walk of spin tune  $\nu_s$  [15].

## Applications of new technique:

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

# Optimizations of spin-coherence time: [17, PRL 2016]



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

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

- Previous record:  
 $\tau_{\text{SCT}}(\text{VEPP}) \approx 0.5 \text{ s}$  [16]  
 $(\approx 10^7 \text{ spin revolutions})$ .

## 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 (1), since  $\sigma_{\text{stat}} \propto \tau_{\text{SCT}}^{-1}$ .

# Phase locking spin precession in machine to device RF

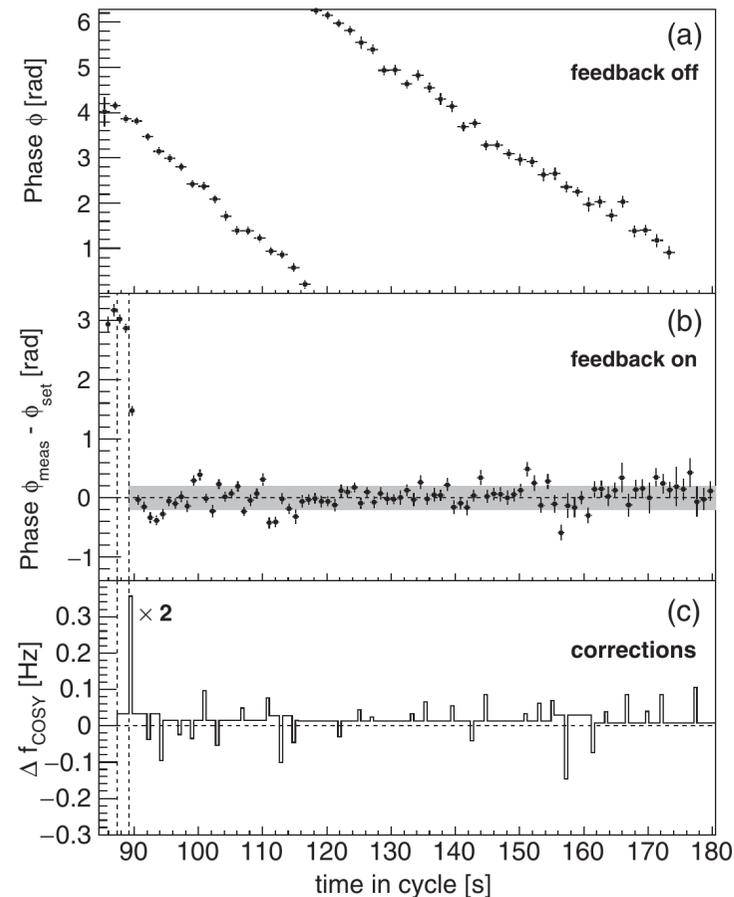
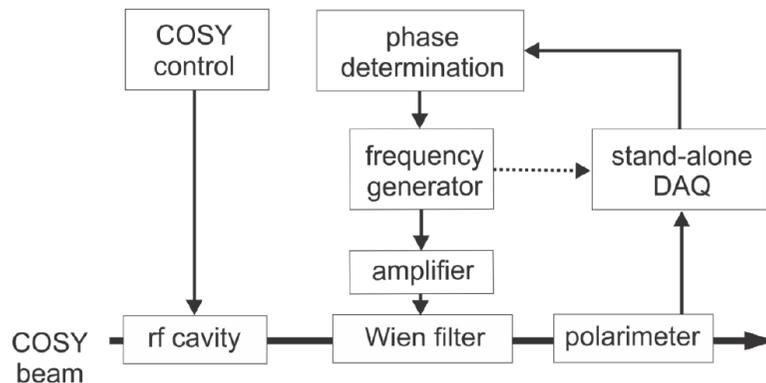
PhD work of Nils Hempelmann

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 [18, PRL 2017].

# Study of machine imperfections

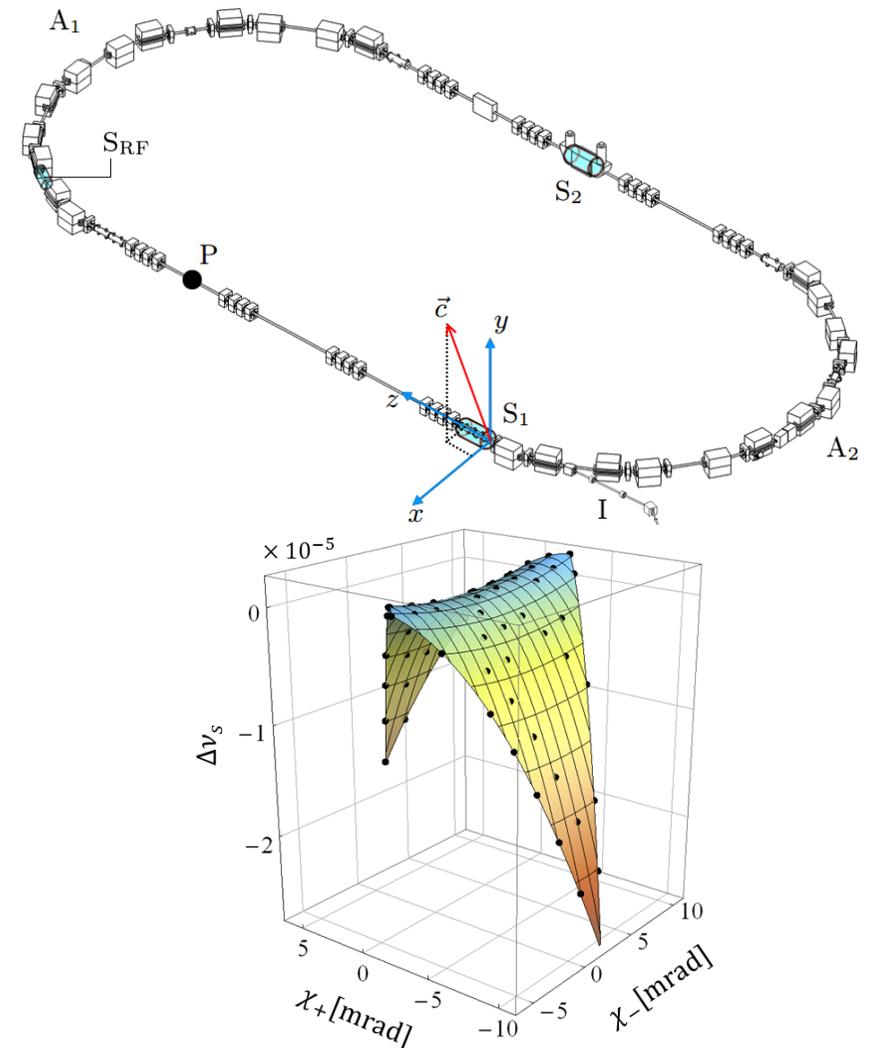
PhD work of Artem Saleev

JEDI developed new method to investigate magnetic machine imperfections based on highly accurate determination of spin-tune [19, 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.



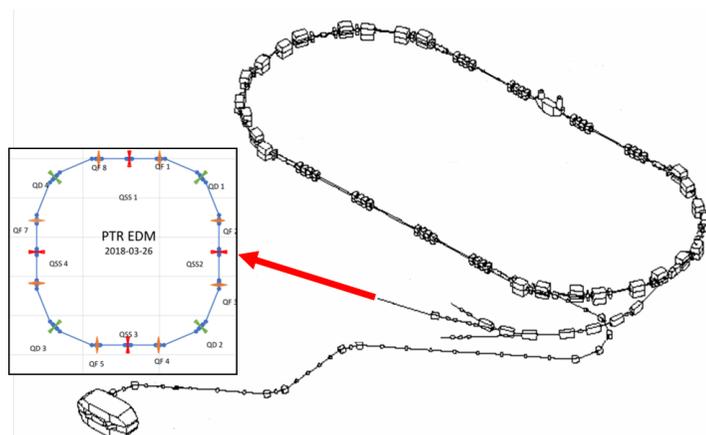
# Prototype EDM storage ring

## 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



- 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 planning and time frame:

1	⇒	2	⇒	3
<b>Precursor Experiment</b>		<b>Prototype Ring</b>		<b>All-electric Ring</b>
<b>dEDM proof-of-capability</b> (orbit and polarization control; first dEDM measurement)		<b>pEDM proof-of-principle</b> (key technologies, first direct pEDM meas.		<b>pEDM precision experiment</b> (sensitivity goal: $10^{-29}$ e cm)
<ul style="list-style-type: none"> <li>- Magnetic storage ring</li> <li>- Polarized deuterons</li> <li>- d-carbon polarimetry</li> <li>- RF Wien filter</li> </ul>		<ul style="list-style-type: none"> <li>- High-current all-electric ring</li> <li>- Simultaneous CW/CCW op.</li> <li>- Frozen spin control (with combined <math>E/B</math> ring)</li> <li>- Phase-space beam cooling</li> </ul>		<ul style="list-style-type: none"> <li>- Frozen-spin all-electric ring (at <math>p = 0.7</math> GeV/c)</li> <li>- Simultaneous CW/CCW op.</li> <li>- <math>B</math>-shielding, high <math>E</math> fields</li> <li>- Design: cryogenic, hybrid, ...</li> </ul>
<b>Ongoing at COSY Jülich</b>		<b>Ongoing within CPEDM</b>		<b>After construction and operation of prototype</b>
2014 → 2021		2017 → 2020 (CDR) → 2022 TDR Start construction > 2022		> 2027?

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

# 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).

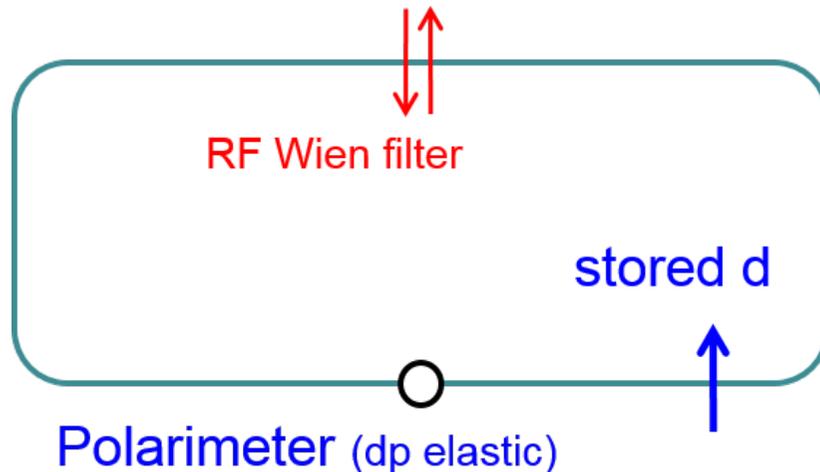
Goal of proof-of-principle experiment:

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.

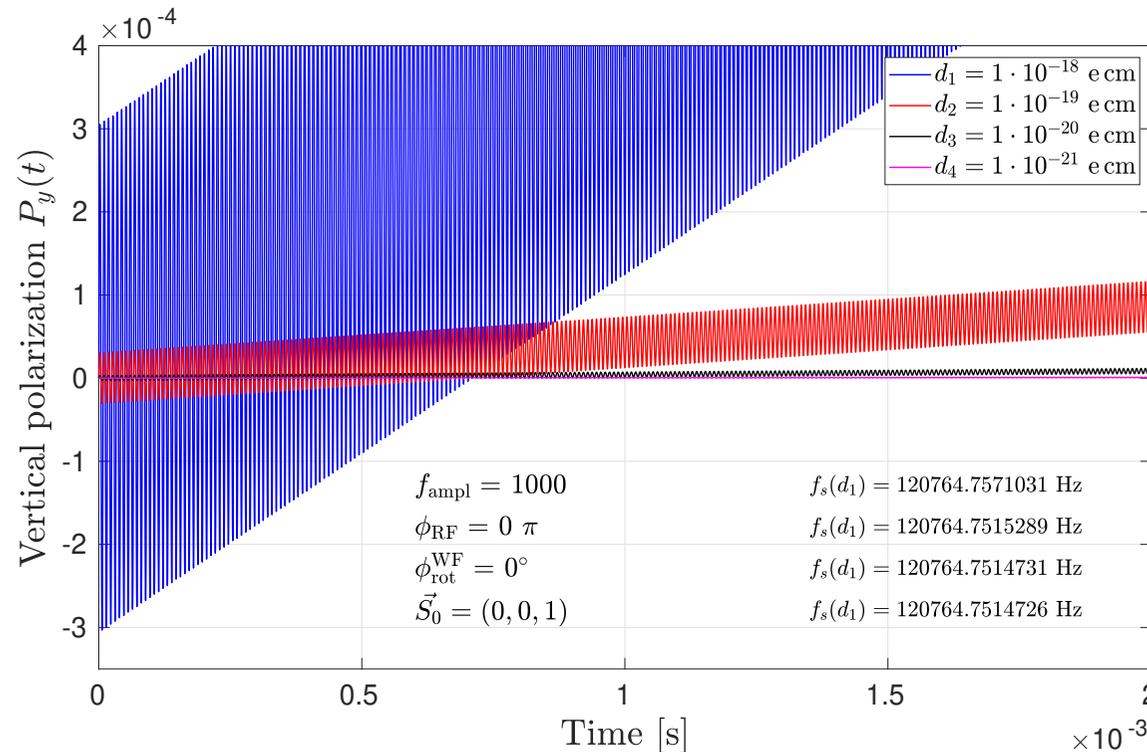
## Statistical sensitivity:

- 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.

# Model calculation of EDM buildup 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) [20, 2016].

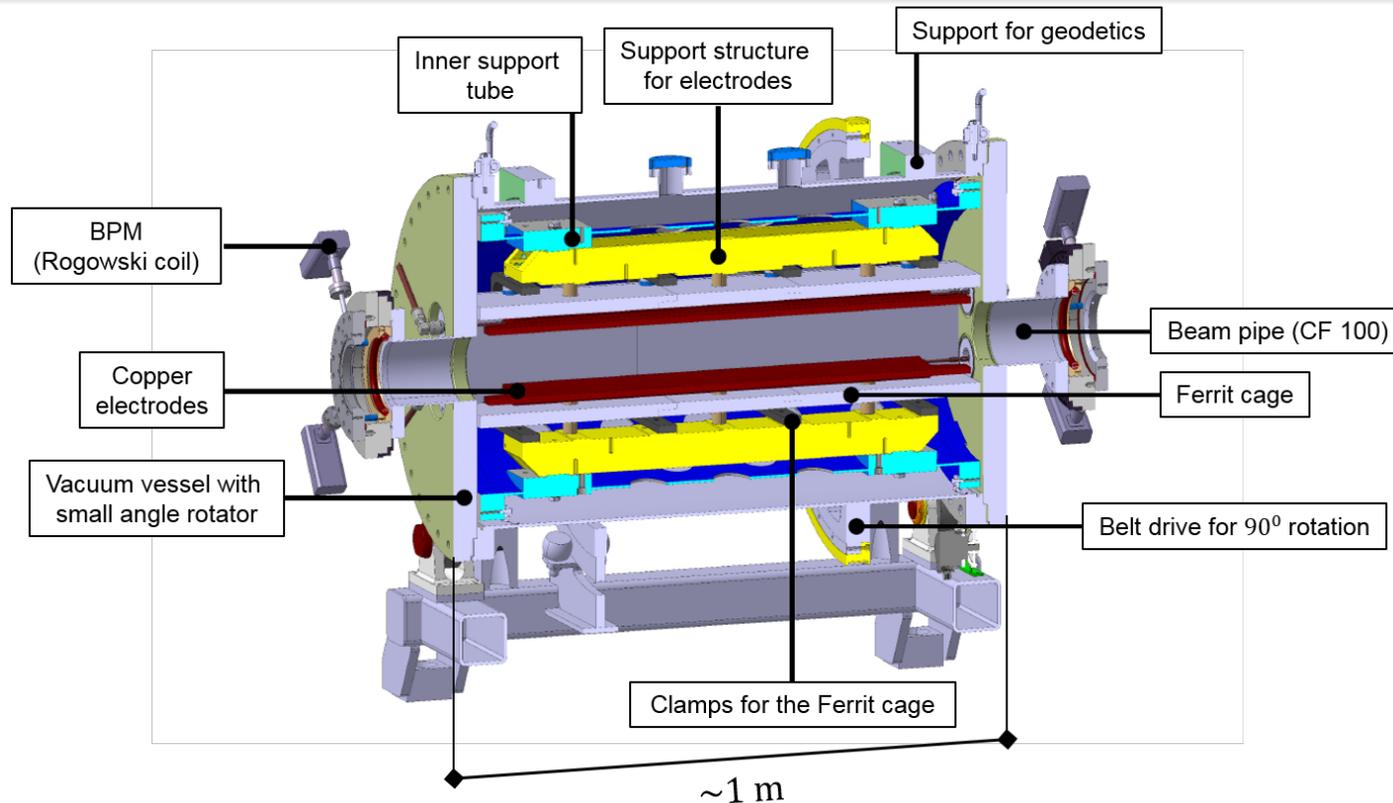


EDM accumulates in  $P_y(t) \propto d_{\text{EDM}}$  [19, 21, 22].

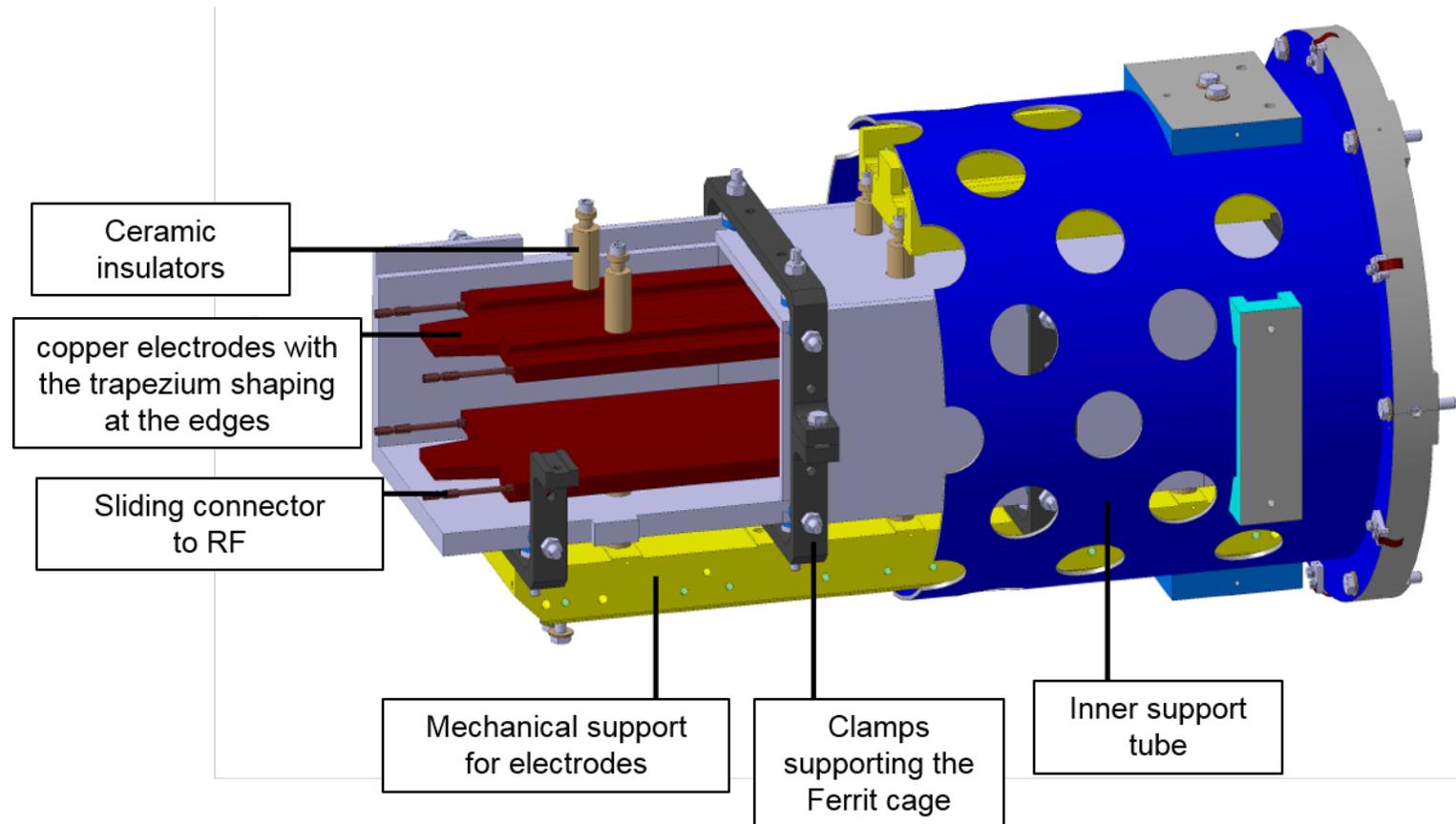
# Design of waveguide RF Wien filter

## Joint Jülich – RWTH Aachen development:

- Institute of High Frequency Technology, RWTH Aachen University:
  - Heberling, Hölscher, and PhD Student **Jamal Slim**, and ZEA-1 of Jülich.
- **Waveguide provides  $\vec{E} \times \vec{B}$  by design.**
- Minimal  $\vec{F}_L$  by careful electromagnetic design of all components [20].



# Internal structure



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

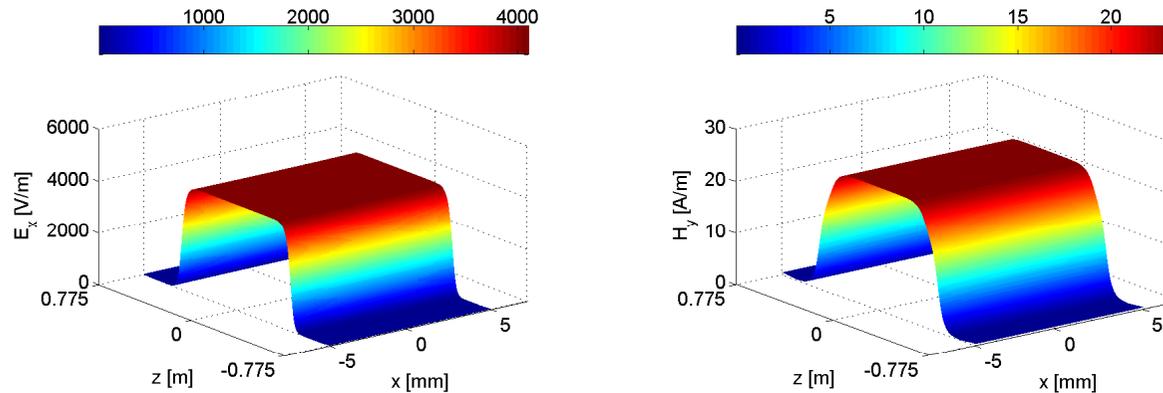
- Electromagnetic performance [20] and mechanical tolerances [23].
- Excellent cooperation with RWTH Aachen University and ZEA-Jülich.

# Electromagnetic field simulations (incl. ferrites) [24]

## Full-wave simulations

- using CST Microwave Studio<sup>a</sup>.

<sup>a</sup>Computer Simulation Technology AG, Darmstadt, Germany, <http://www.cst.com>



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

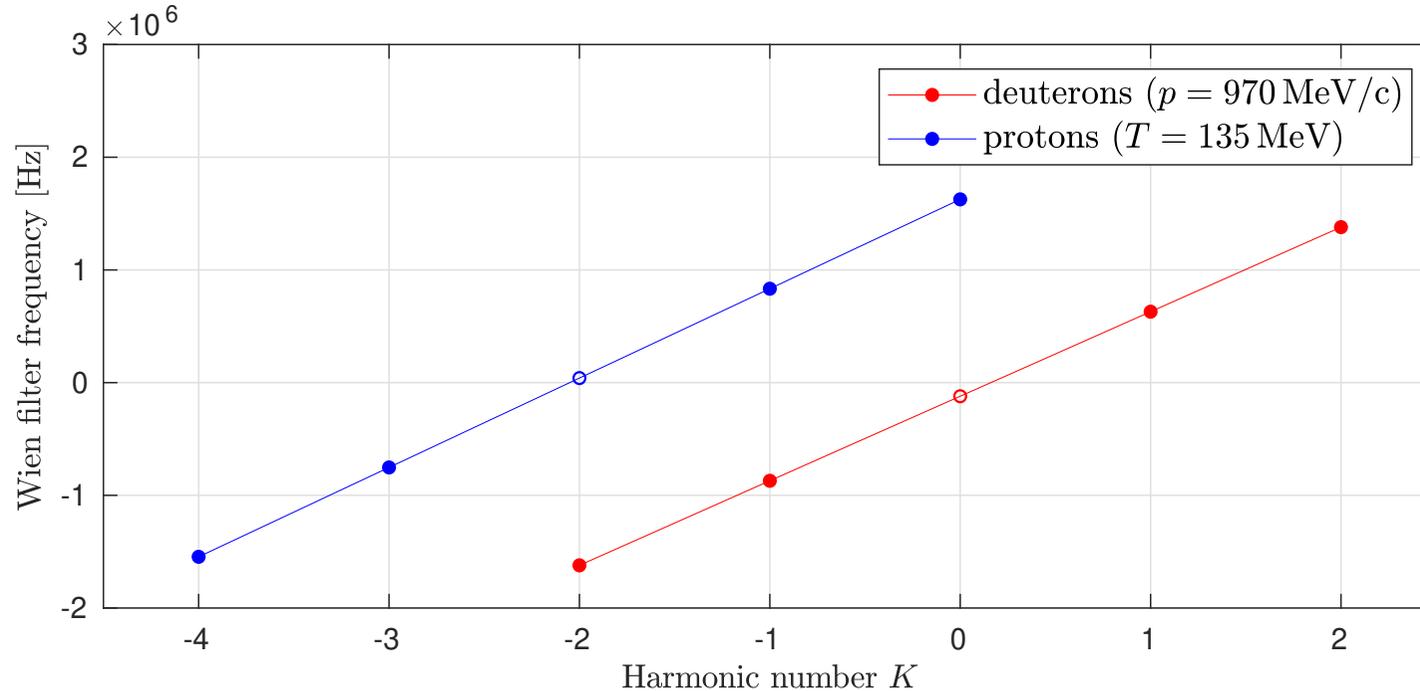
$$\int_{-\ell/2}^{\ell/2} \vec{B} dz = \begin{pmatrix} 2.73 \times 10^{-9} \\ 2.72 \times 10^{-2} \\ 6.96 \times 10^{-7} \end{pmatrix} \text{ T mm}, \quad \int_{-\ell/2}^{\ell/2} \vec{E} dz = \begin{pmatrix} 3324.577 \\ 0.018 \\ 0.006 \end{pmatrix} \text{ V} \quad (11)$$

# Frequencies of RF Wien filter

Resonance condition:

$$f_{\text{WF}} = f_{\text{rev}} (\gamma G \pm K) , k \in \mathbb{Z}. \quad (12)$$

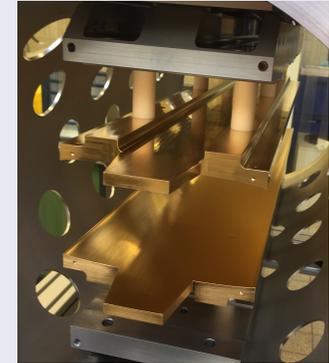
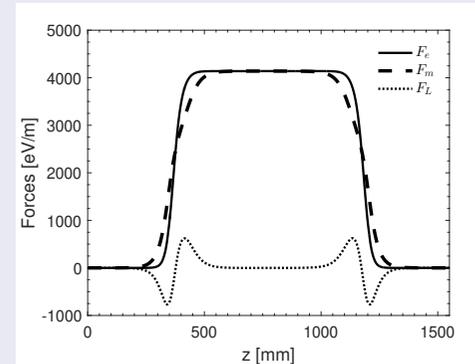
- RF Wien filter operates at frequencies between 0 to 2 MHz,
- Open symbols not reachable with present setup of driving circuit, *i.e.*,
  - deuterons at  $K = 0$  ( $-120.8$  kHz), and
  - protons at  $K = -2$  ( $39.4$  kHz).



# Lorentz force compensation [20]

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

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



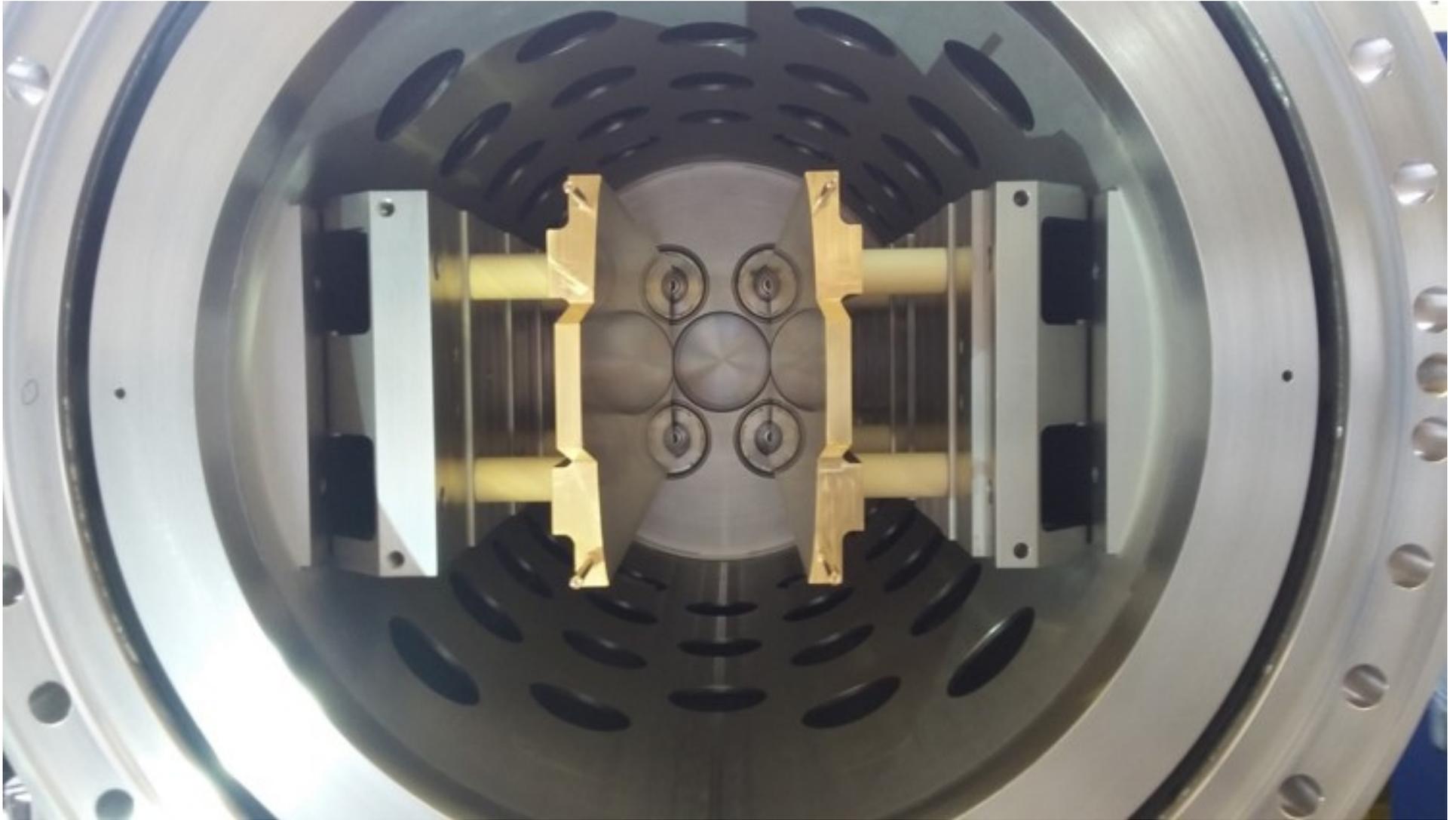
## Lorentz force

$$\vec{F}_L = q \left( \vec{E} + \vec{v} \times \vec{B} \right), \quad (13)$$

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

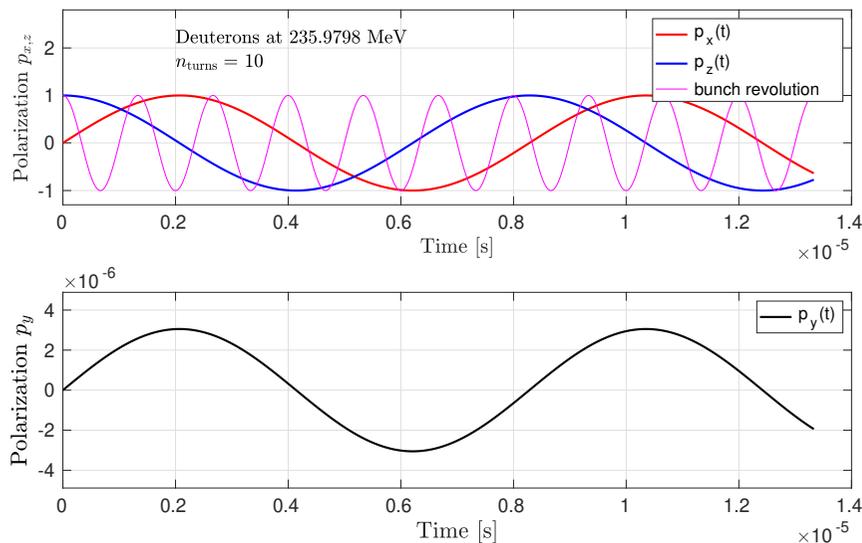
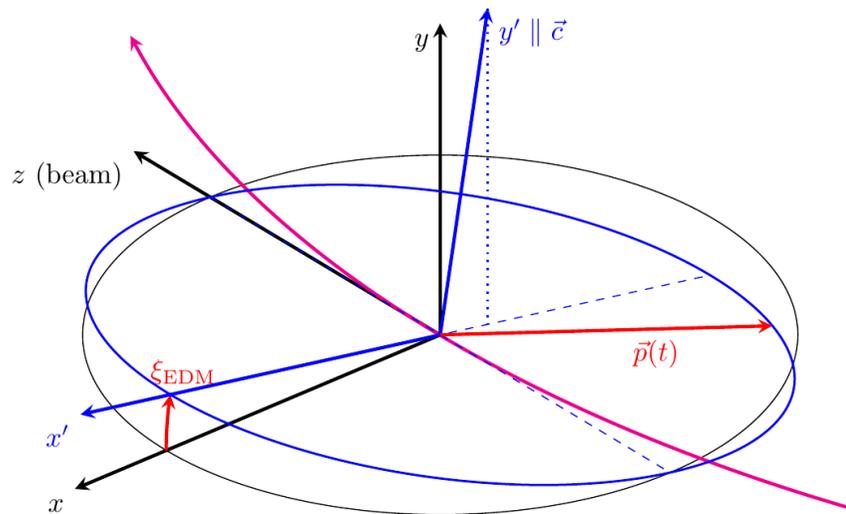
$$E_x = -c \cdot \beta \cdot \mu_0 \cdot H_y \quad \Rightarrow \quad Z_q = -\frac{E_x}{H_y} = c \cdot \beta \cdot \mu_0 \approx 173 \, \Omega. \quad (14)$$

# Installation at COSY II



View along the beam axis in the RF Wien filter.

# Effect of EDM on stable spin axis of the ring



## Beam particles move along z direction

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

# Strength of EDM resonance

## EDM induced vertical polarization oscillations,

- can generally be described by

$$p_y(t) = a \sin(\Omega^{p_y} t + \phi_{\text{RF}}). \quad (15)$$

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

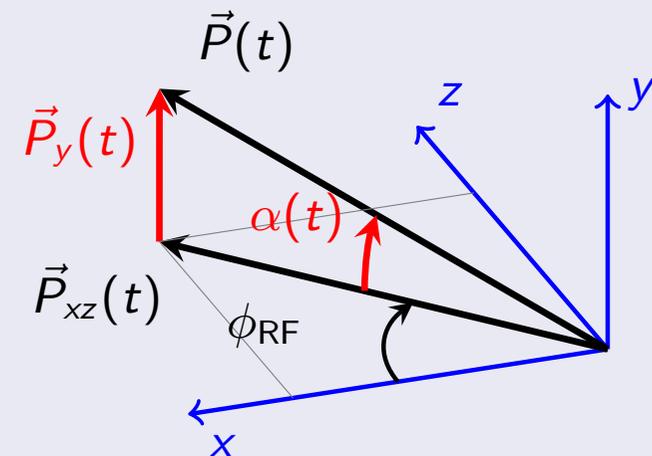
$$\varepsilon^{\text{EDM}} = \frac{\Omega^{p_y}}{\Omega^{\text{rev}}}, \quad (16)$$

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

- through variation of  $\phi_{\text{RF}}$

$$\varepsilon^{\text{EDM}} = \frac{\dot{p}_y(t)|_{t=0}}{a \cos \phi_{\text{RF}}} \cdot \frac{1}{\Omega^{\text{rev}}}. \quad (17)$$

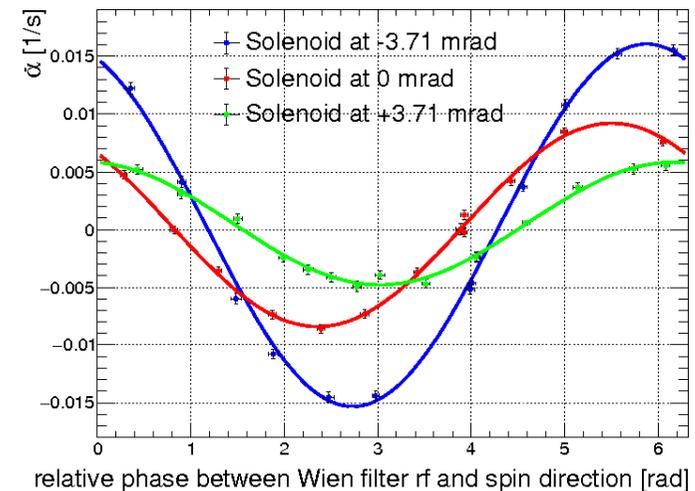
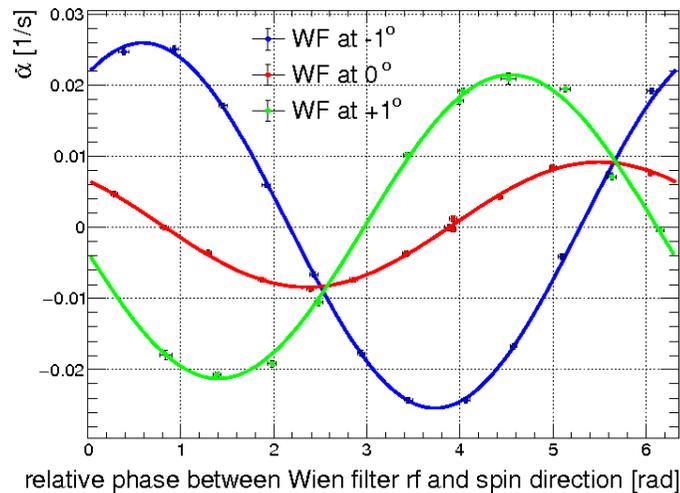
- If  $|\vec{P}| = 1 \Rightarrow \dot{p}_y(t) = \dot{\alpha}(t)$



# First measurement of EDM-like buildup signals

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

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



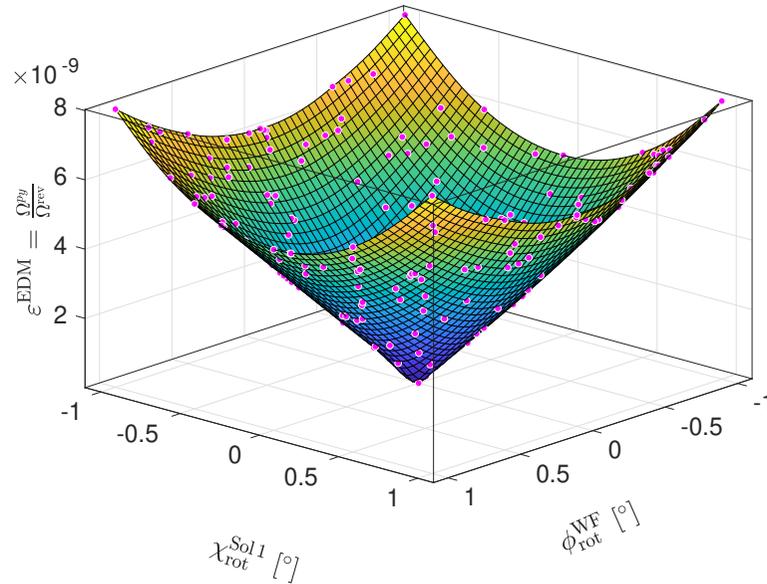
$\dot{\alpha}$  for  $\phi_{\text{rot}}^{\text{WF}} = -1^\circ, 0^\circ, +1^\circ$  and  $\chi_{\text{rot}}^{\text{Sol}1} = 0$ .

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

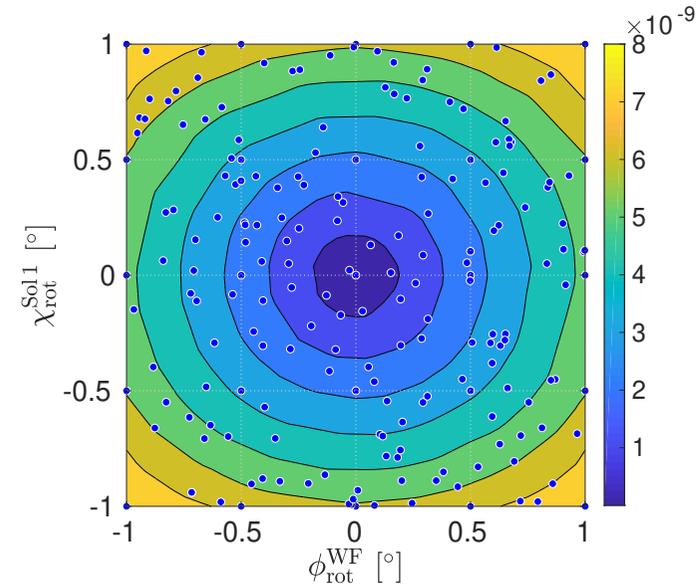
## Planned measurements:

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

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



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

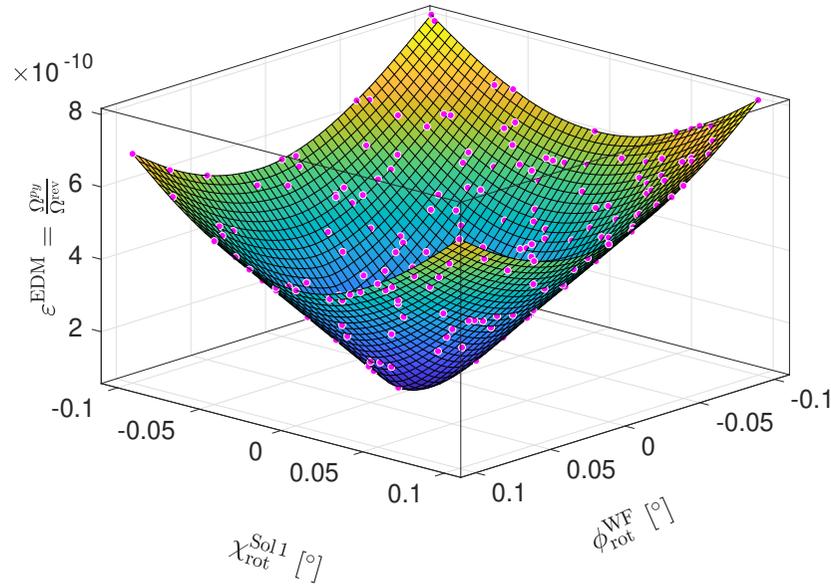


(b) Contour plot of (a).

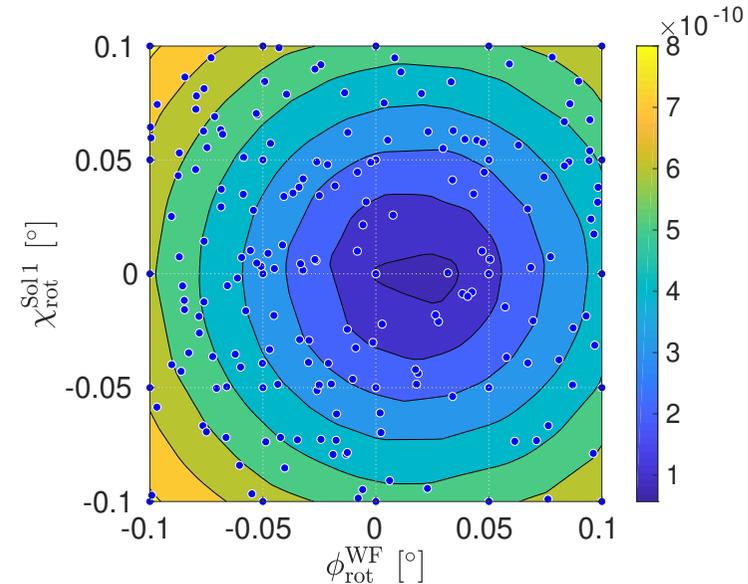
Resonance strengths  $\varepsilon^{\text{EDM}}$  from Eq. (16) ( $\approx 175$  random-points)

- $\phi_{\text{rot}}^{\text{WF}} = [-1^\circ, \dots, +1^\circ]$ ,
- $\chi_{\text{rot}}^{\text{Sol1}} = [-1^\circ, \dots, +1^\circ]$  (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



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

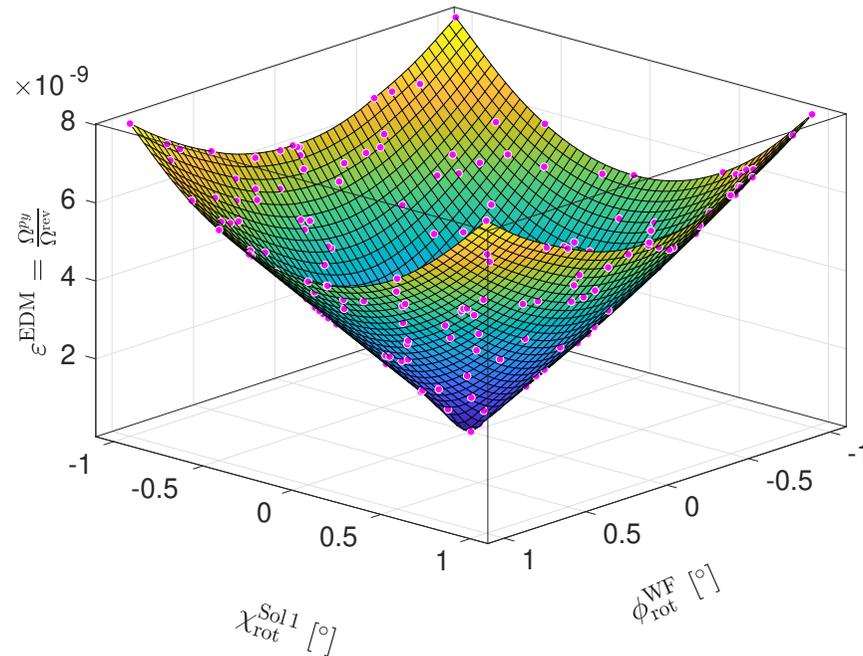


(d) Contour plot of (c).

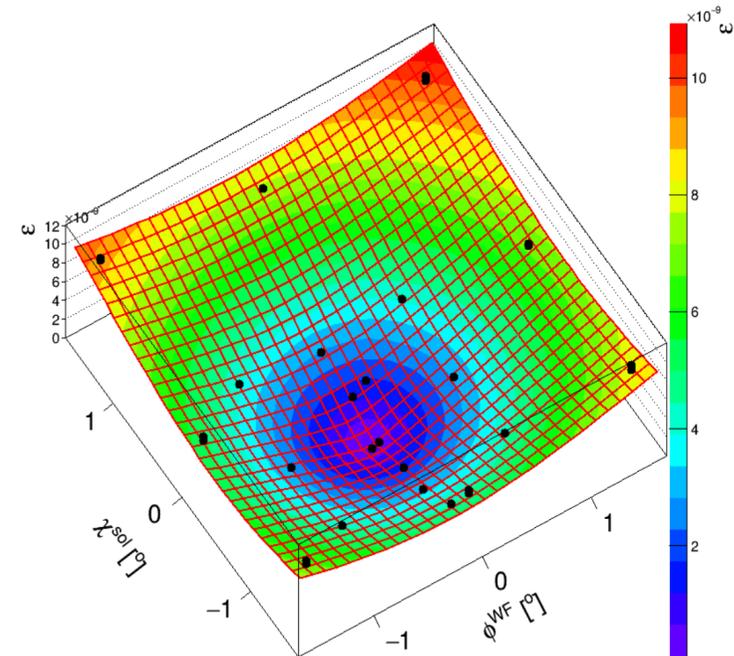
## Resonance strengths $\varepsilon^{\text{EDM}}$ from Eq. (16) ( $\approx 175$ random-points)

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

# First results from the measurement in Nov.-Dec. 2018



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



(f) First  $9 + 9 + 14$  data points on 3 maps ( $\approx 2$  weeks)

## Importance of spin tracking simulations

- Orientation of stable spin axis at location of RF Wien filter *including the EDM* is determined from minimum of map.
- Spin tracking calculations to provide orientation of stable spin axis *w/o* EDM.

# Summary

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

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

## Present investigations

- JEDI is making steady progress in spin dynamics of relevance to future searches for EDM.
- COSY remains a unique facility for such studies.
- First direct JEDI deuteron EDM measurement at COSY underway.
  - 6 wk run Nov.-Dec. '18, and planned 6 wk run in 2019.
  - Sensitivity  $10^{-18}$  to  $10^{-20}$  e cm.

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

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

# JEDI Collaboration



## JEDI = Jülich Electric Dipole Moment Investigations

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



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

# More technical challenges of storage ring EDM experiments

## Overview

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

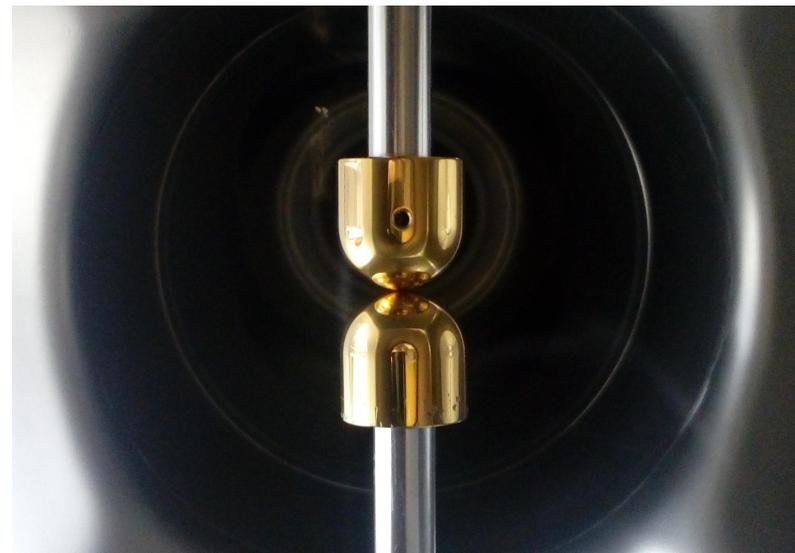
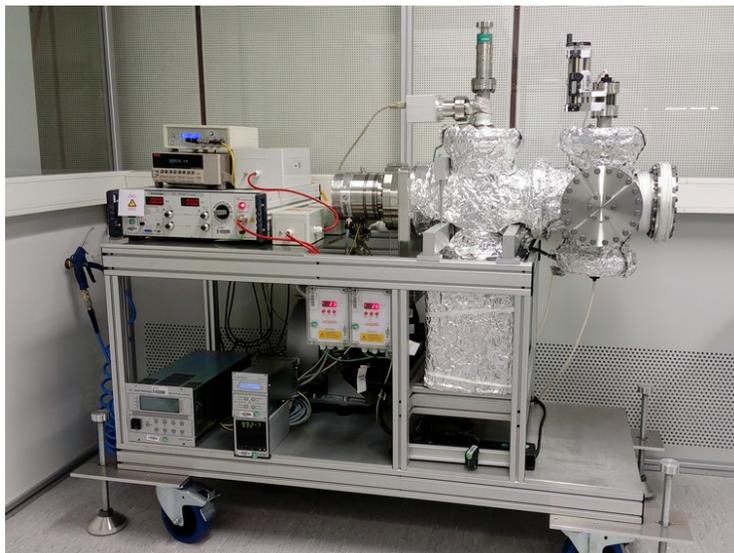
### Main issues:

- Large electric field gradients  $\sim 10$  to  $20$  MV/m.
- Spin coherence time  $\tau_{\text{SCT}} \sim 1000$  s [17, 2016].
- Continuous polarimetry with relative errors  $< 1$  ppm [25, 2012].
- Beam position monitoring with precision of  $10$  nm.
- High-precision spin tracking.
- Alignment of ring elements, ground motion, ring imperfections.
- Magnetic shielding.
- For deuteron EDM with frozen spin: precise reversal of magnetic fields for CW and CCW beams required.

# E/B Deflector development using small-scale lab setup [26]

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

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

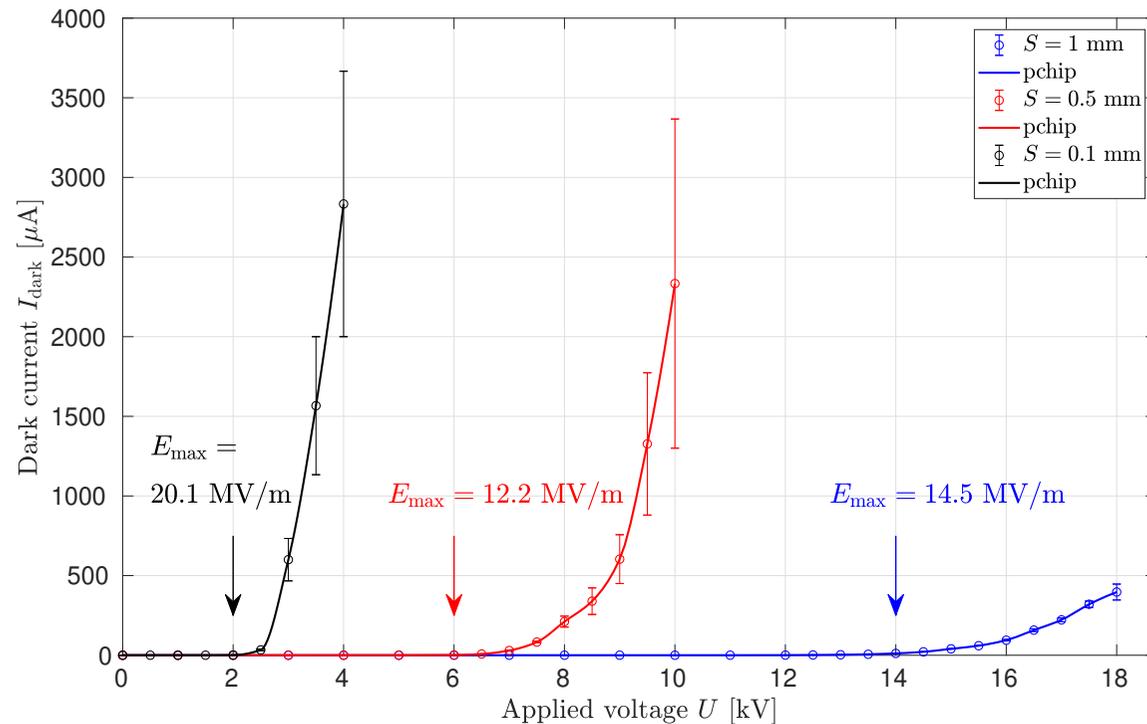


# Recent results

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

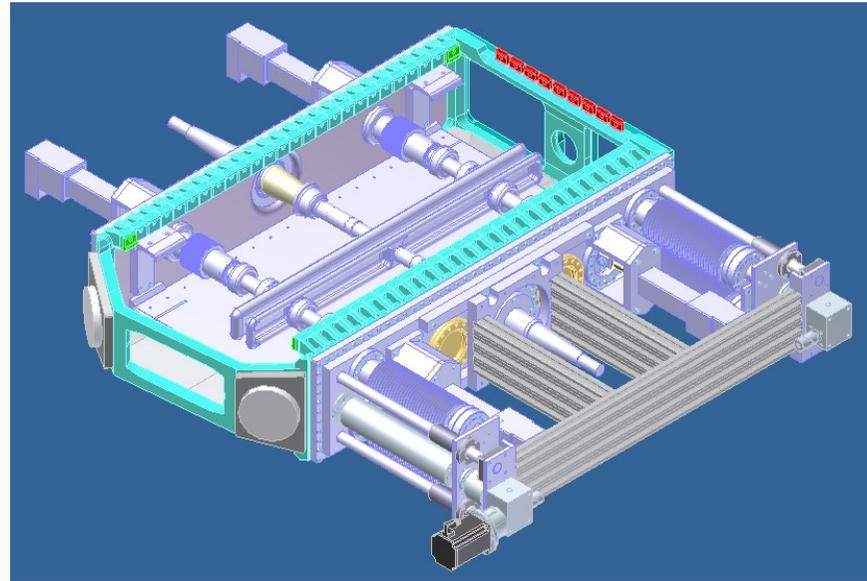
- distances  $S = 1, 0.5, \text{ and } 0.1 \text{ mm}$ , where

$$E_{\max} = \frac{U}{S} \cdot F, \text{ where } F = \frac{1}{4} \left[ 1 + \frac{S}{R} + \sqrt{\left(1 + \frac{S}{R}\right)^2 + 8} \right], \quad (18)$$



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:

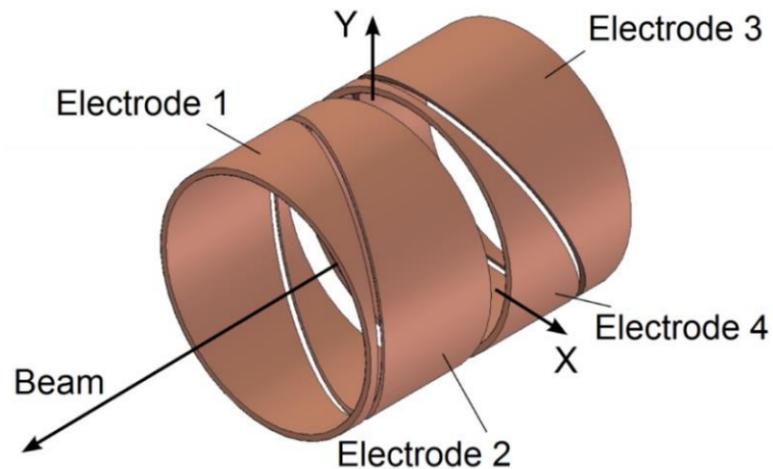
Equipment ready for assembling. First test results expected before Christmas.

# Beam position monitors for srEDM experiments

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

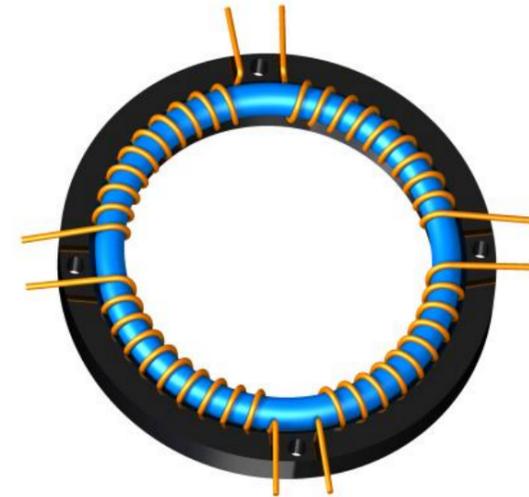
## Development of compact BPM based on segmented Rogowski coil

- Main advantage is short installation length of  $\approx 1$  cm (along beam direction)



### Conventional BPM

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

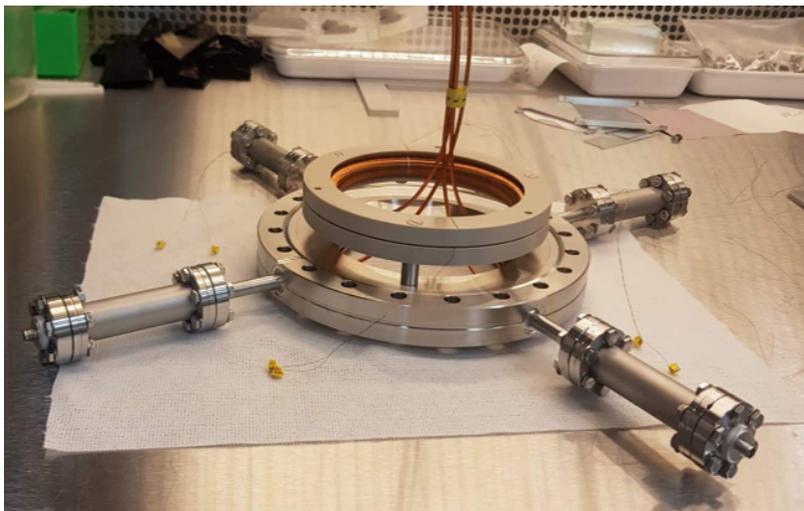
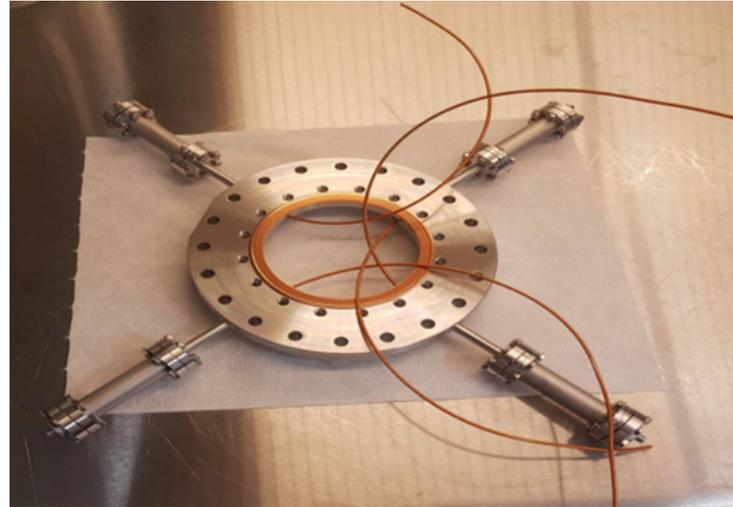


### Rogowski BPM (warm)

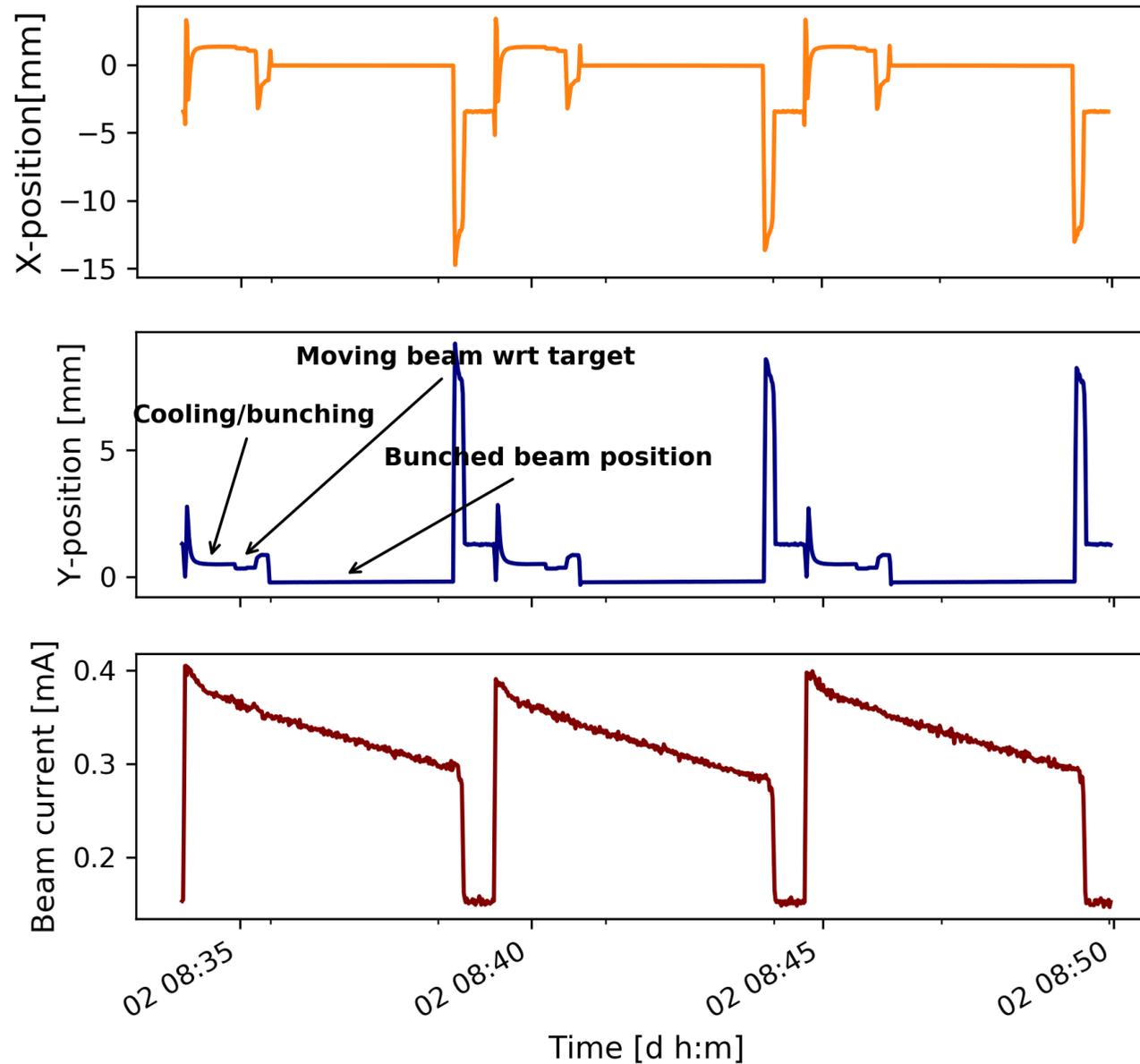
- Excellent RF-signal response
- length = 1 cm
- resolution  $\approx 1.25 \mu\text{m}$

- 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 ongoing run



# $dC$ polarimetry data base I

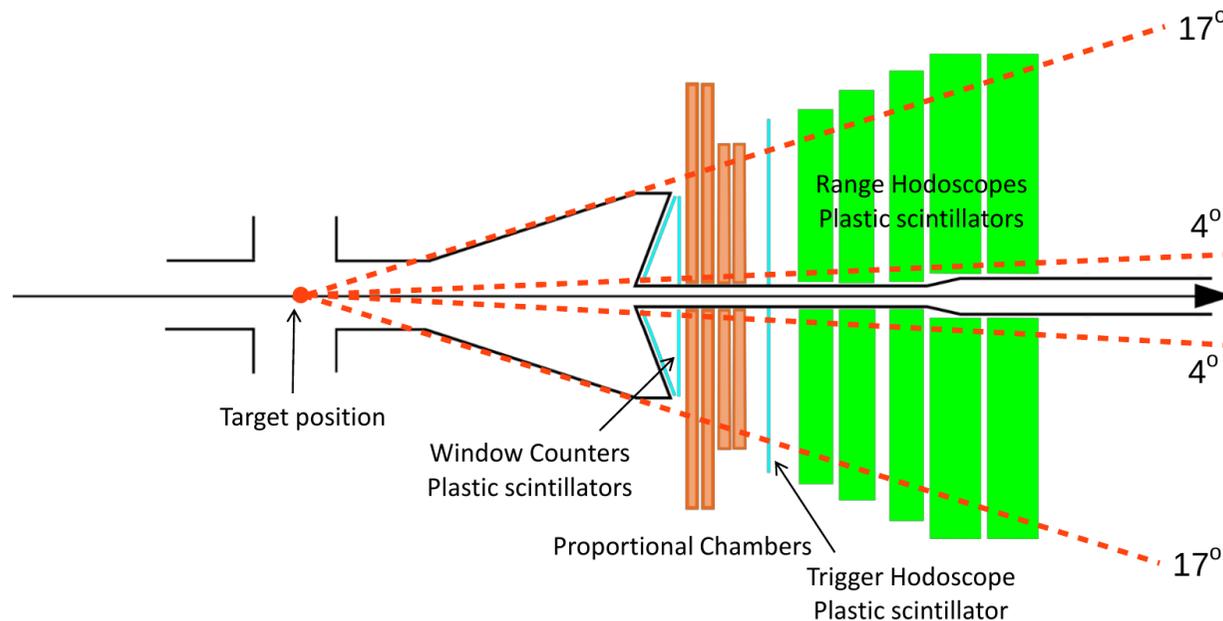
Data analysis mainly by Maria Zurek and PhD Fabian Müller

Motivation: Optimize polarimetry for ongoing JEDI experiments:

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

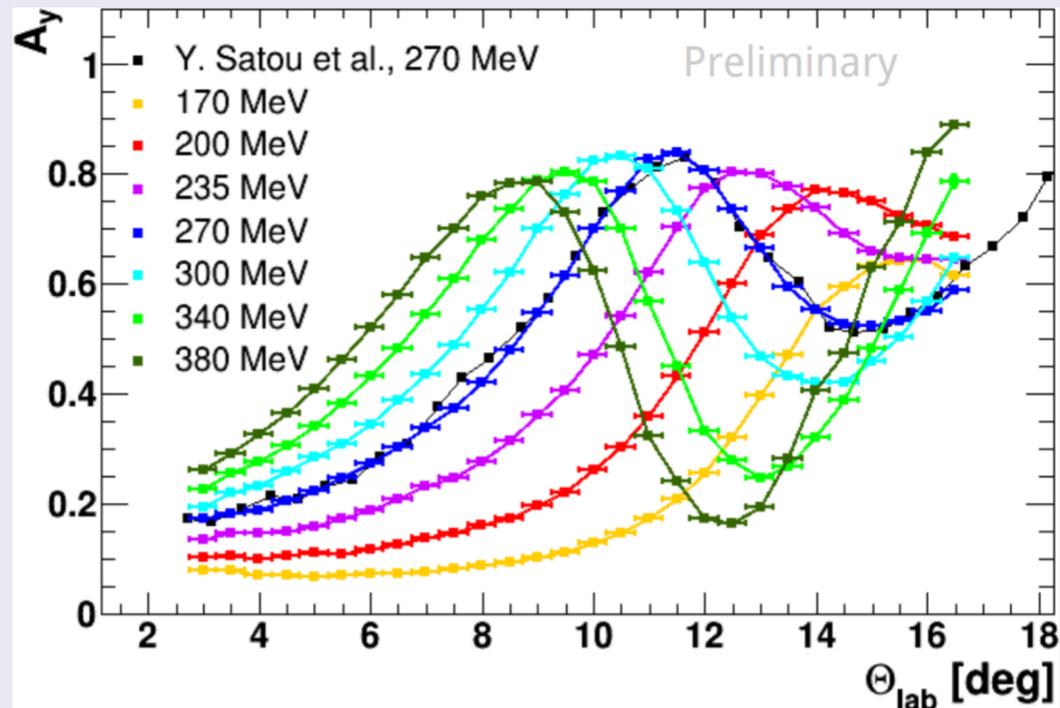
Detector system: former WASA forward detector, modified

- 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

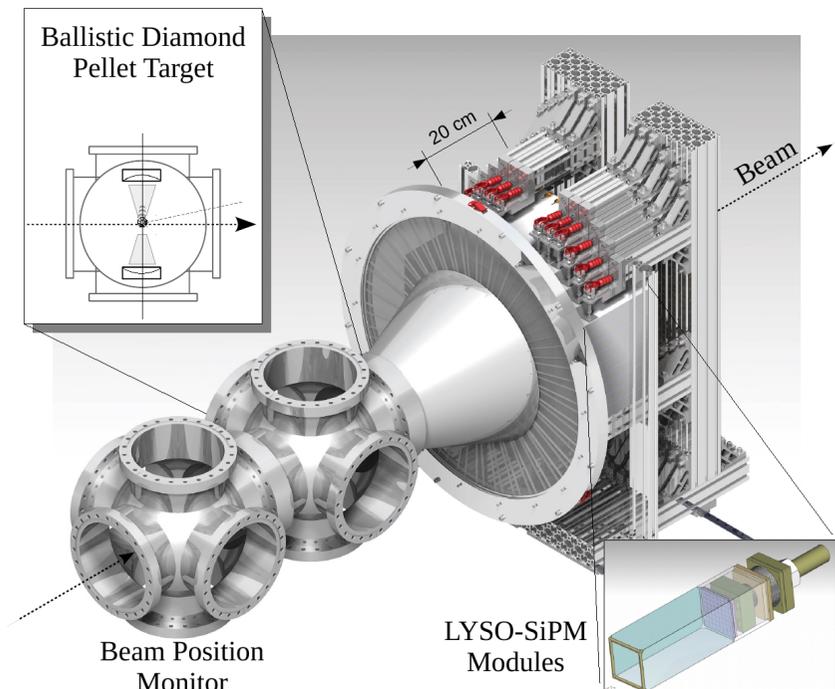
Development led by Irakli Keshelashvili

## Based on LYSO Scintillation Material

- Saint-Gobain Ceramics & Plastics:  $\text{Lu}_{1.8}\text{Y}_{.2}\text{SiO}_5:\text{Ce}$
- 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:

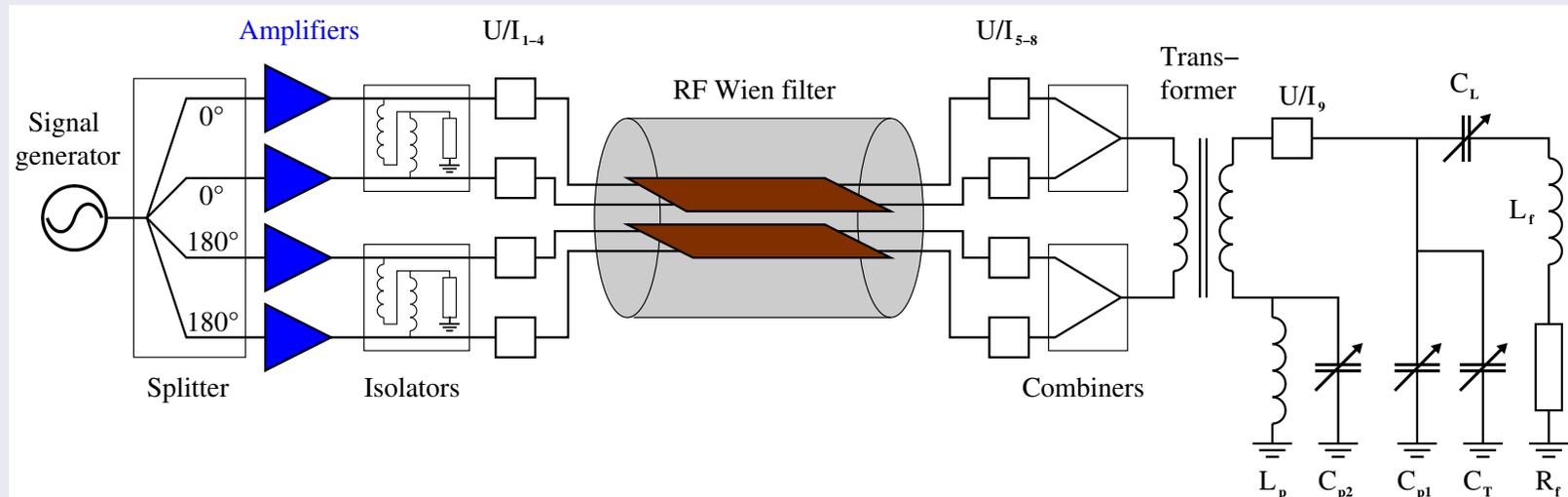
- System ready for installation at COSY in 2019.
- Not yet ready: Ballistic diamond pellet target for homogeneous beam sampling.



# Driving circuit

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

- Design layout using four separate 1 kW power amplifiers.



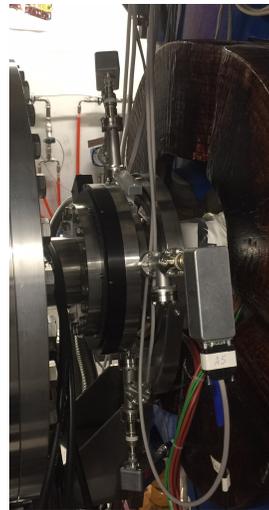
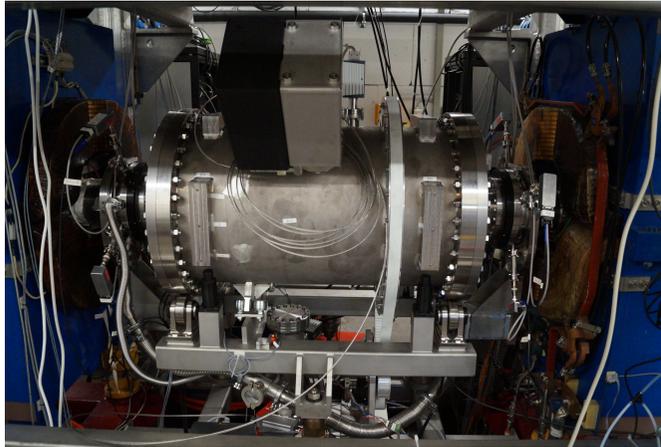
Circuit fully operational

- Tuneable elements<sup>a</sup> allow [20]:
  - 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.

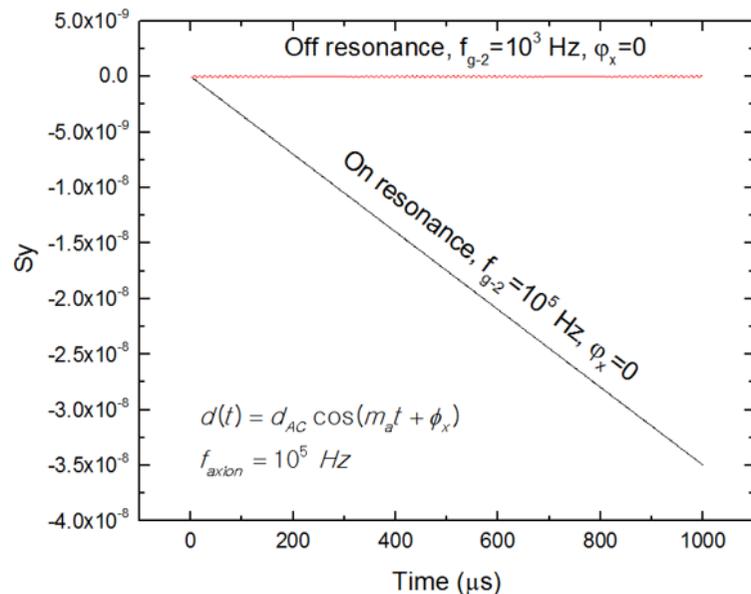
# (Oscillating) Axion-EDM search using storage ring

Motivation: Paper by Graham and Rajendran [27, 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

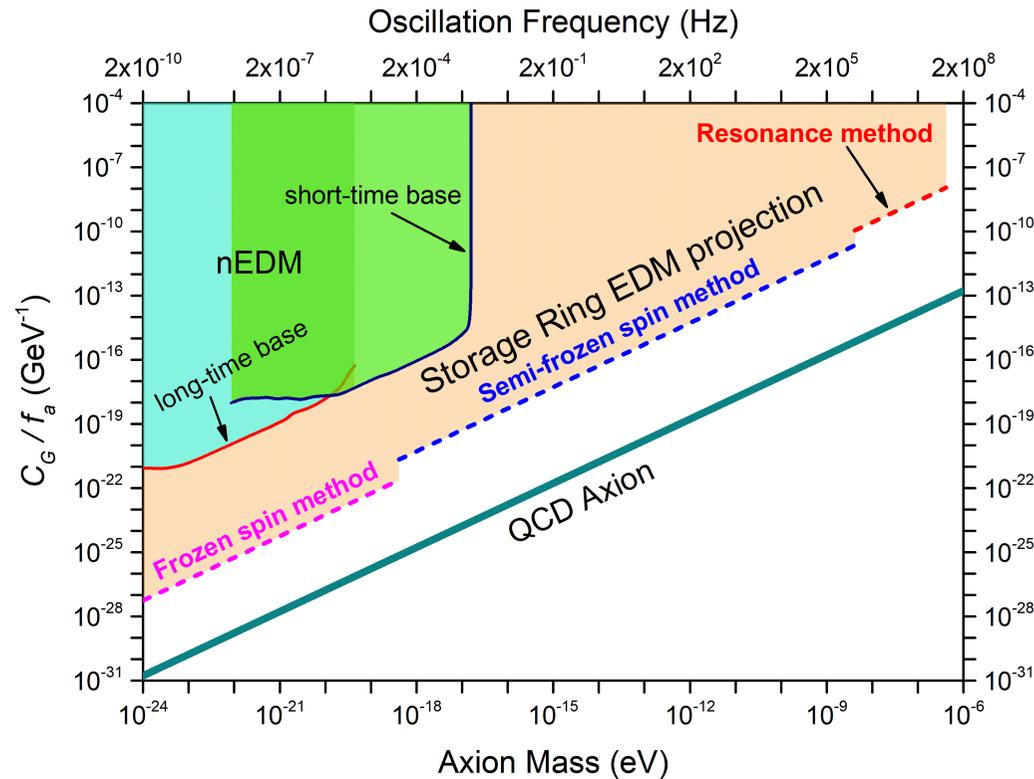


Figure from S.P. Chang et al. [28]

## Realization

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