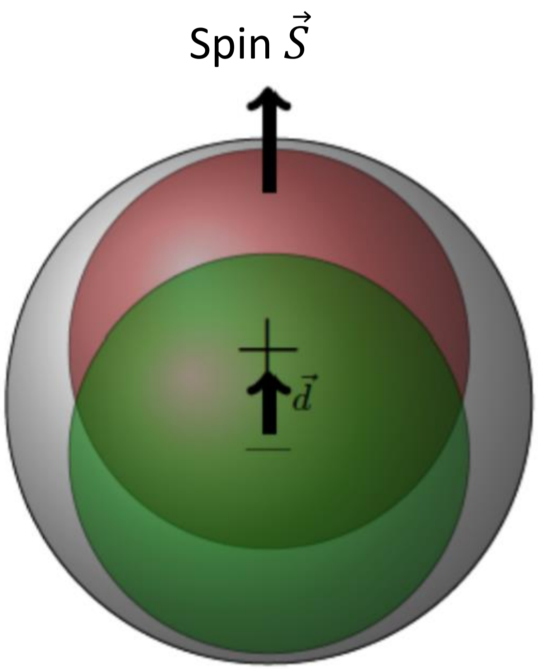
EDM: recent progress of JEDI Collaboration @ COSY

July 09, 2018 | Artem Saleev on behalf of JEDI collaboration
International Workshop on Spin Physics at NICA | Praha

Outlook

- EDM: why? Fundamental symmetries and baryogenesis
- EDM: how? Future dedicated EDM storage rings
- EDM at COSY: unique facility for EDM-related spin dynamics, proof-of-principle studies by JEDI
- JEDI: past. Record spin coherence time, record precision spin tune, first in situ determination of stable spin axis and first look at magnetic imperfections, first spin phase lock at storage rings
- JEDI: present. Wien Filter experimentation, polarimetry development, Rogowski coils, beam based alignment, polarimetry database
- JEDI: future. Precursor experiment in pipeline, still non-magic all-electric prototype, crossed ExB magic prototype ring ----> Technical Design Report

Electric dipole moment and fundamental symmetries



- Permanent separation of + and - charge

- EDM $\vec{d}$ and MDM $\vec{\mu}$ of particle are aligned along spin $\vec{S}$

- Possible only if P and T-symmetries are broken

Electric dipole moment and baryogenesis

- Sakharov (1967): CP violation is imperative for baryogenesis in the Big Bang Cosmology

	observed	*SM prediction*
$\frac{n_B - n_{\bar{B}}}{n_\gamma}$	$(6.1 \pm 0.3) \times 10^{-10}$	10^{-18}
neutron EDM limit $(e \cdot cm)$	3×10^{-26}	10^{-31}

- EDM as a high-precision window at physics Beyond Standard Model
- nEDM: plans to increase sensitivity by 1 order in magnitude
- pEDM: statistical accuracy of 10^{-29} is aimed at dedicated all-electric storage ring
- COSY as a test bench for ultimate precision spin dynamics
- dEDM and pEDM in precursor experiment at COSY: dEDM $\sim 10^{-20}$ is within reach?
- Prototype pure electric ring is under consideration (at CERN? at COSY?...)

Why charged particles besides neutrons?

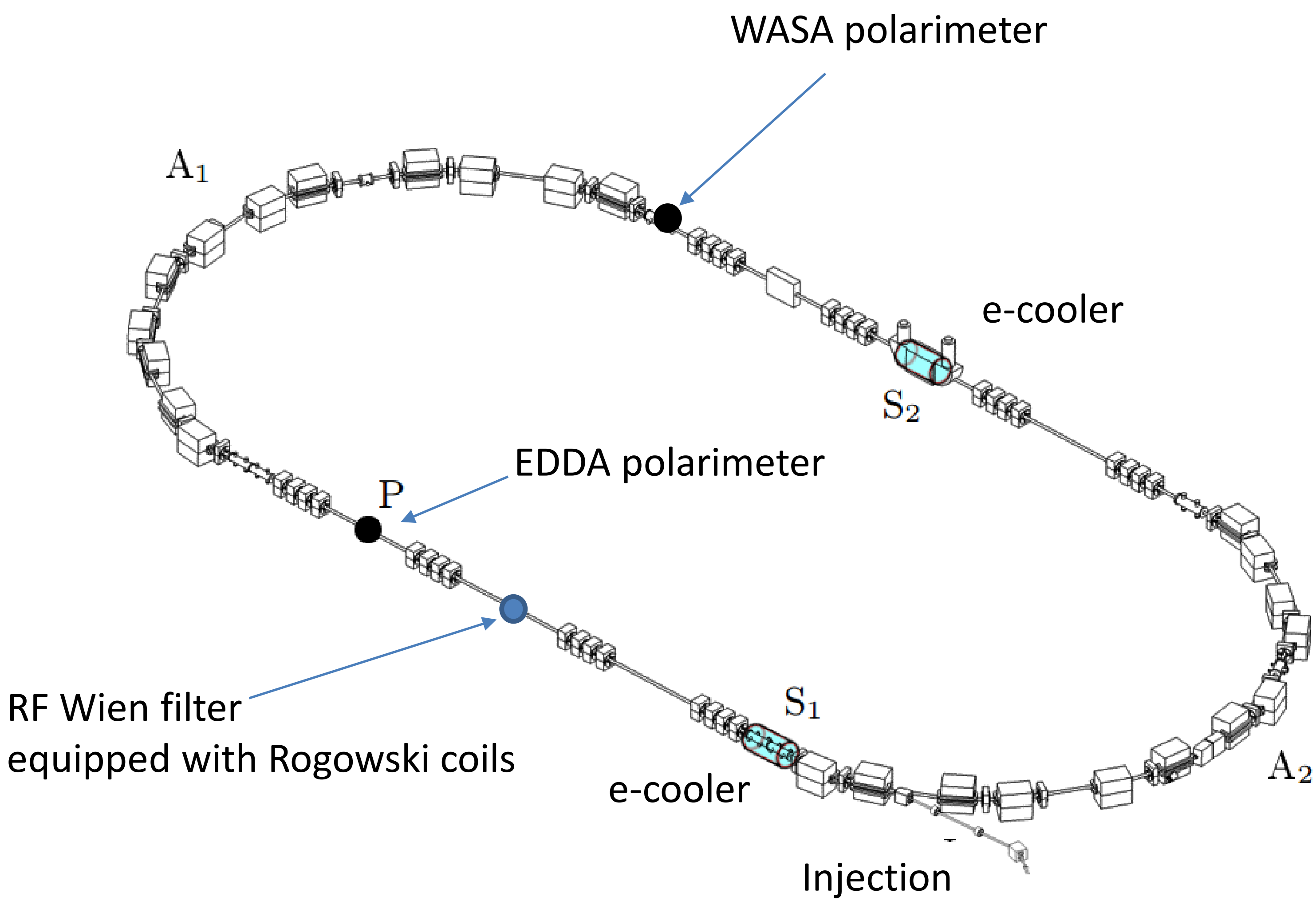
- Isotopic properties of CP violation Beyond the Standard Model are entirely unknown: $d_p \gg d_n$ is not excluded

- Even with CP violation from isoscalar QCD θ-term the theory predicts $d_p \neq d_n$

- Deuteron: besides d_p and d_n the deuteron d_d may receive new contributions from T- and CP –violating np-interaction

- The same is true for helium-3 and other nuclei

COSY Landscape



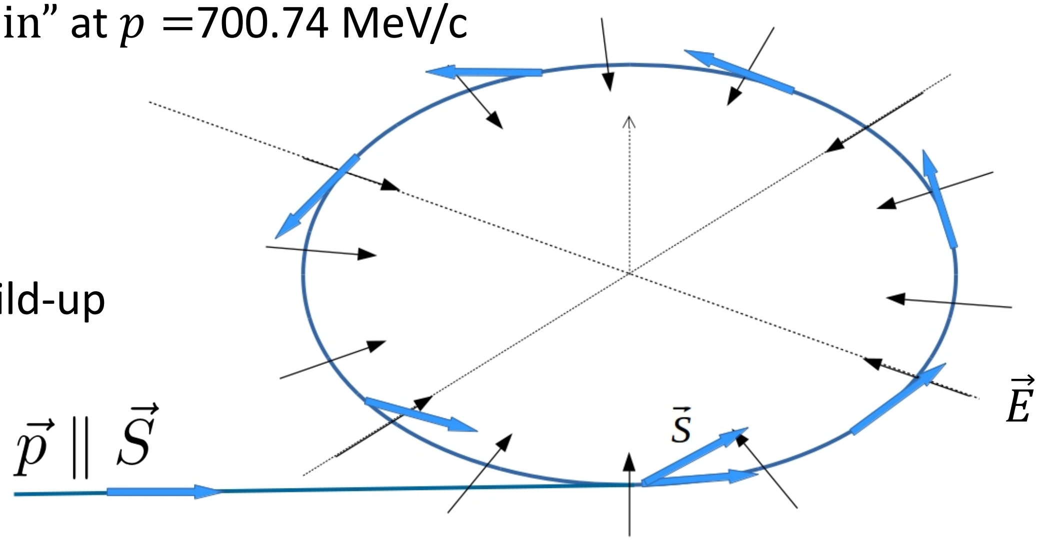
A principle of EDM measurement: spin rotation by EDM-interaction with E-fields

- In circular accelerators and storage rings spin dynamics is described by T-BMT eq.:
- $$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S}(t) = -\frac{q}{m}\Big(\underbrace{G\vec{B} + \Big(\frac{1}{\gamma^2-1} - G\Big)\vec{\beta} \times \vec{E}}_{\text{MDM}} + \underbrace{\frac{1}{2}\eta(\vec{E} + \vec{\beta} \times \vec{B})}_{\text{EDM}}\Big) \times \vec{S}(t)$$

EDM $\quad d = \frac{\eta \hbar q}{2mc}$

All-electric ring is ideal for protons

- MDM-term → 0 - "frozen spin" at p =700.74 MeV/c
- Longitudinal initial spin
- EDM signal: vertical spin build-up per turn → $\pi\beta\gamma\eta$



Ideal experimental setup

- Ideal storage ring (alignment, stability, field homogeneity, no systematics)
- high intensity beams ($N = 4 \times 10^{10}$ per fill)
- polarized hadron beams ($P = 0.8$)
- large electric fields ($E = 10$ MV/m)
- long spin coherence time ($\tau = 1000$ s)
- polarimetry (analyzing power A = 0.6, f = 0.005)

$$\sigma_{\text{stat}} \approx \frac{1}{\sqrt{Nf\tau PAE}} \quad \Rightarrow \sigma_{\text{stat}}(1\text{year}) = 10^{-29}\ e\cdot\text{cm}$$

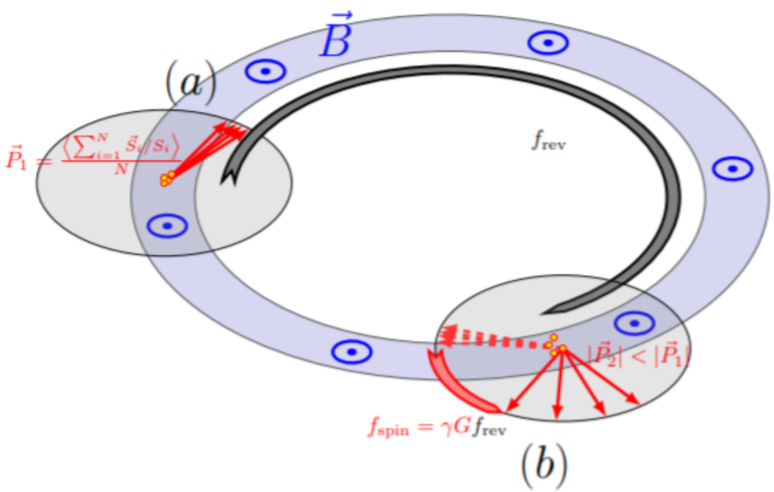
challenge: get σ_{sys} to the same level

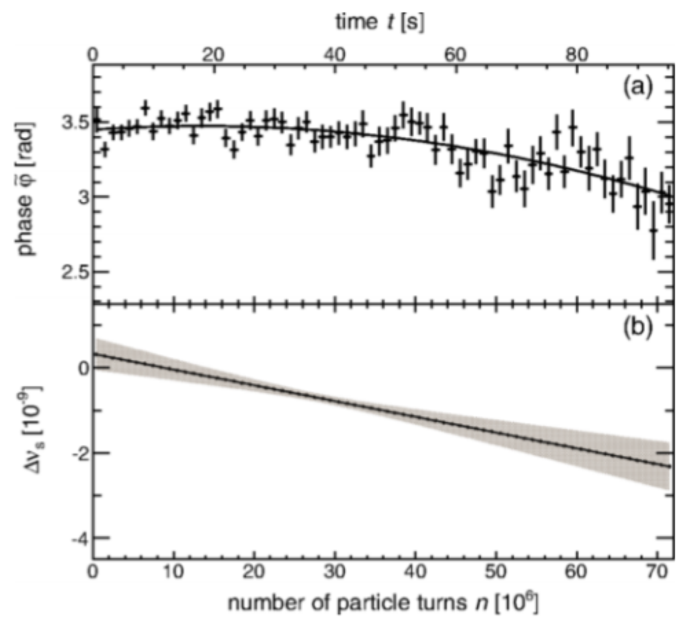
JEDI: EDM searches at COSY
Precursor experiment in the pipeline

- COSY is all-magnetic storage ring, unique for studying spin dynamics but still needs upgrades for EDM searches
- Statistical accuracy for $d_d = 10^{-24} e \cdot cm$ is reachable at COSY
- Systematic effects: horizontal imperfection magnetic fields are evil because MDM >> EDM and MDM rotations give false EDM signal
- JEDI studies: MDM background can be suppressed to 10^{-6} level. Further suppression of systematics is possible
- EDM $\leq 10^{-6}$MDM $\cong 10^{-20}\ e \cdot cm$

JEDI at COSY: record spin tune precision

- A principle: continuous polarimetry of spin precession





$\sigma(\nu_s = \gamma G) \approx 10^{-10}$ in 100 s

Note: $\gamma G = \dfrac{f^{MDM}_{spin}}{f_{rev}}$, $\quad \dfrac{f^{EDM}_{spin}}{f_{rev}} \approx 10^{-10}$ for EDM $d = 10^{-24}\, e\,\mathrm{cm}$

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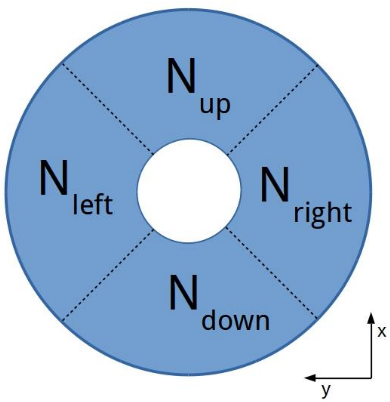
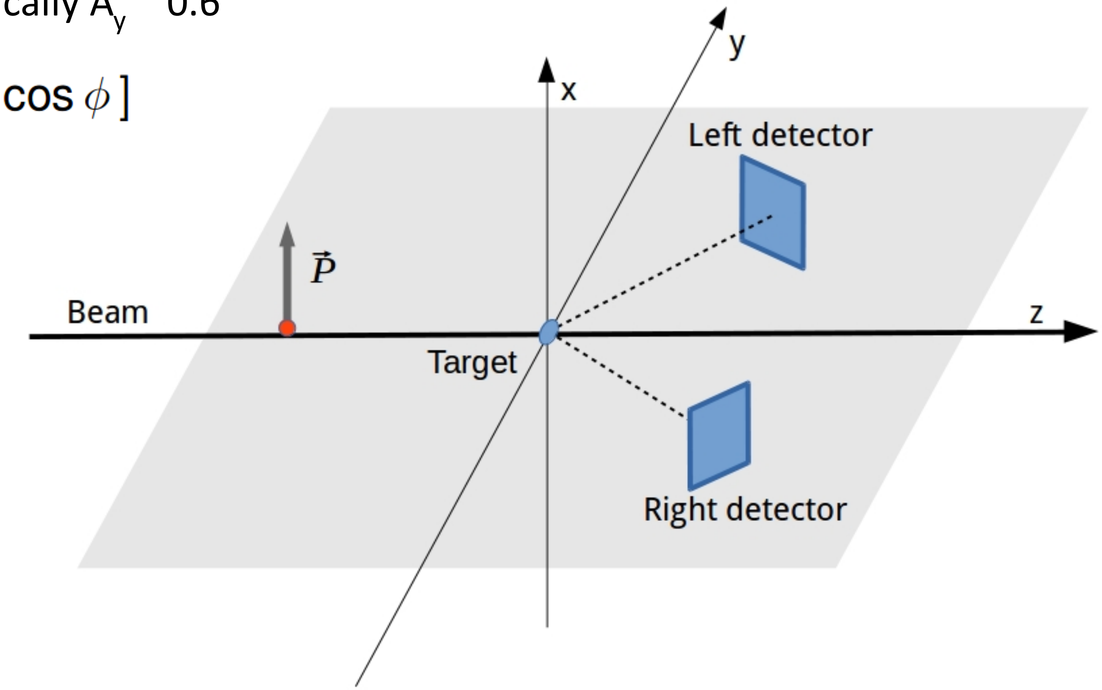
How to measure beam polarization?

- Scattering from Carbon target, typically $A_y \sim 0.6$

$$\sigma^{pol}(\theta,\phi) = \sigma_0(\theta)[1 + \tfrac{3}{2} P A_y(\theta) \cos\phi]$$



2π detector - “beam” view



Right/Left asymmetry ∝ vertical polarization P_y → EDM signal appears here

Up/Down asymmetry ∝ horizontal polarization P_x → Maintaining “frozen spin” condition

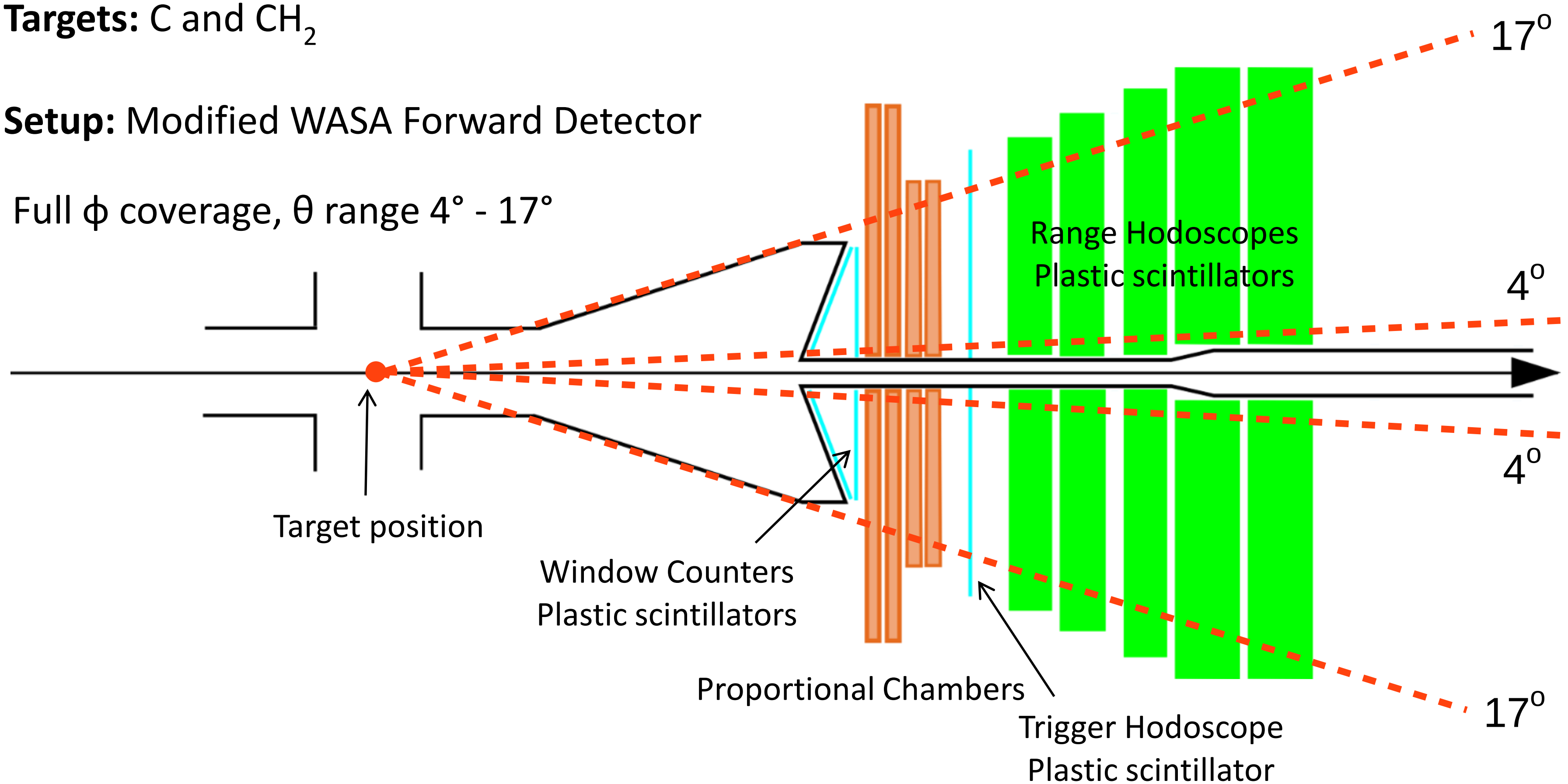
JEDI: polarimetry at COSY

- Early studies based on EDDA polarimeter
- Present studies: WASA is a polarimeter

Targets: C and CH_2

Setup: Modified WASA Forward Detector

Full ϕ coverage, θ range 4° - 17°



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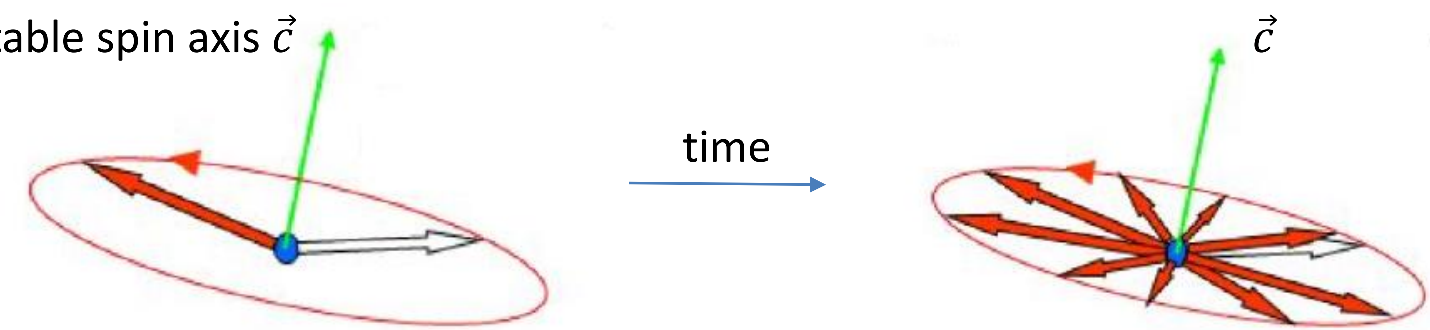
Spin coherence time

- Long spin coherence is crucial for high sensitivity to EDM signal



Inititally all spins aligned

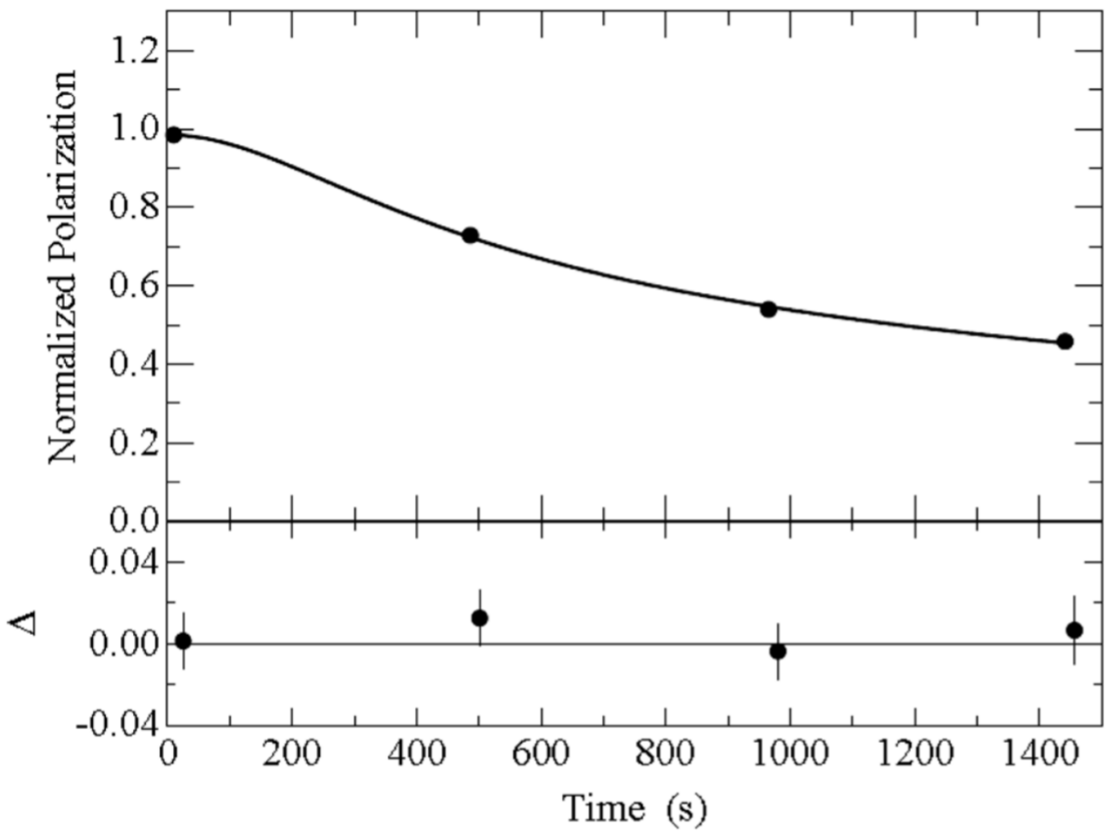
Spins decohered - polarization vanishes

Prerequisites for long SCT:

- use bunched beam
- decrease beam emittance via electron-cooling
- fine-tune sextupole families settings to suppress chromaticity

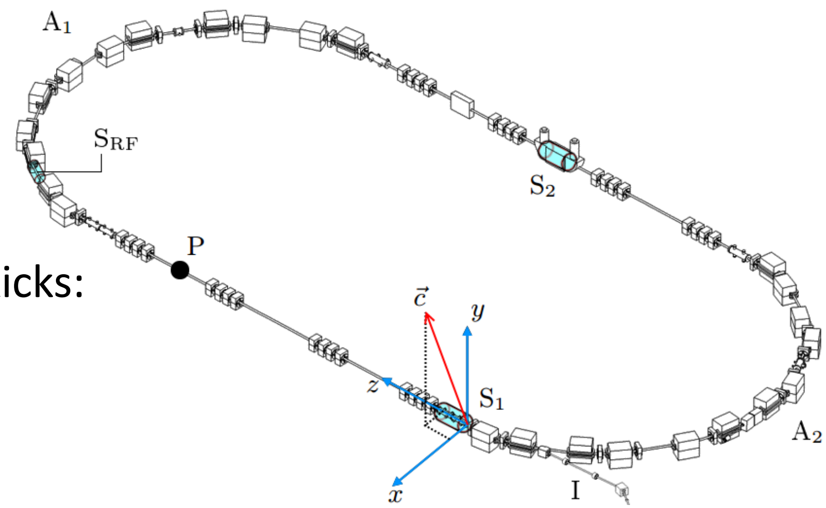
JEDI: record spin coherence time

- JEDI routinely runs at COSY with SCT of more than 1000 seconds

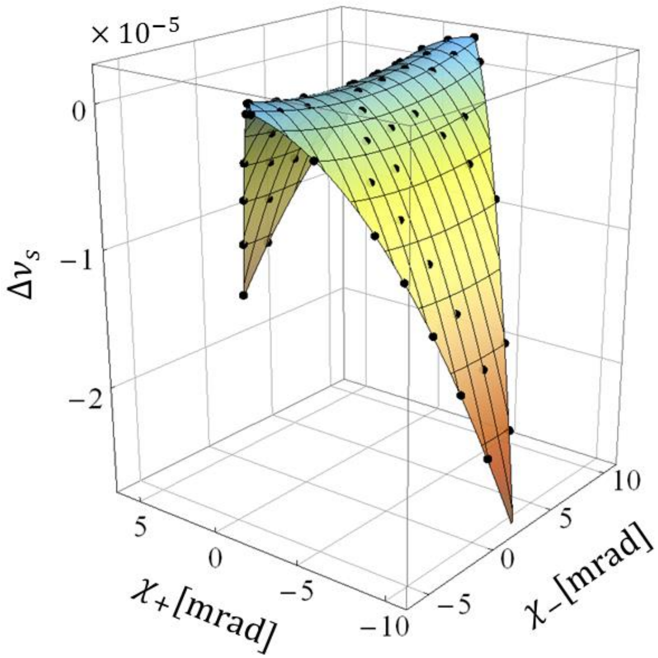


JEDI: spin tune mapping evaluation of imperfection magnetic fields at COSY

- Two cooler solenoids as spin rotators to generate artificial imperfection fields



- Measure spin tune shift vs solenoid spin kicks:



- Position of the saddle point determines a tilt of stable spin axis by magnetic imperfections

- Control of MDM background at level $\Delta c = 2.8 \times 10^{-6}$ rad

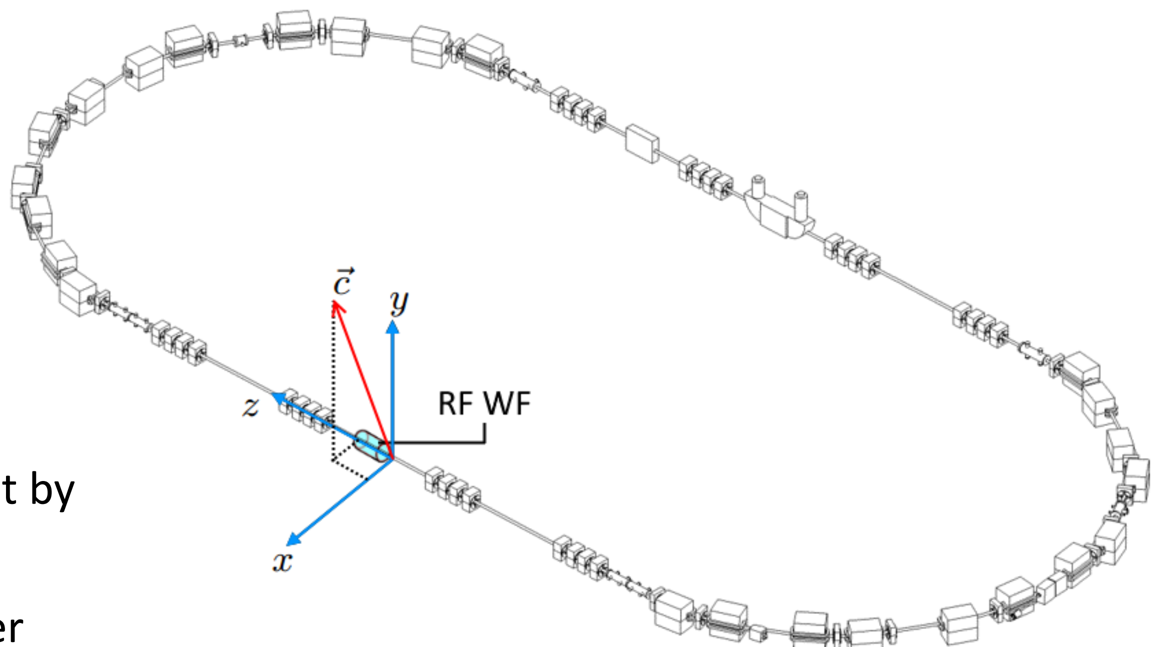
- Systematics-limited sensitivity $\sigma_{d_d} \approx 10^{-20} e \cdot cm$

JEDI: RF Wien-Filter-based first direct measurement of EDM at COSY

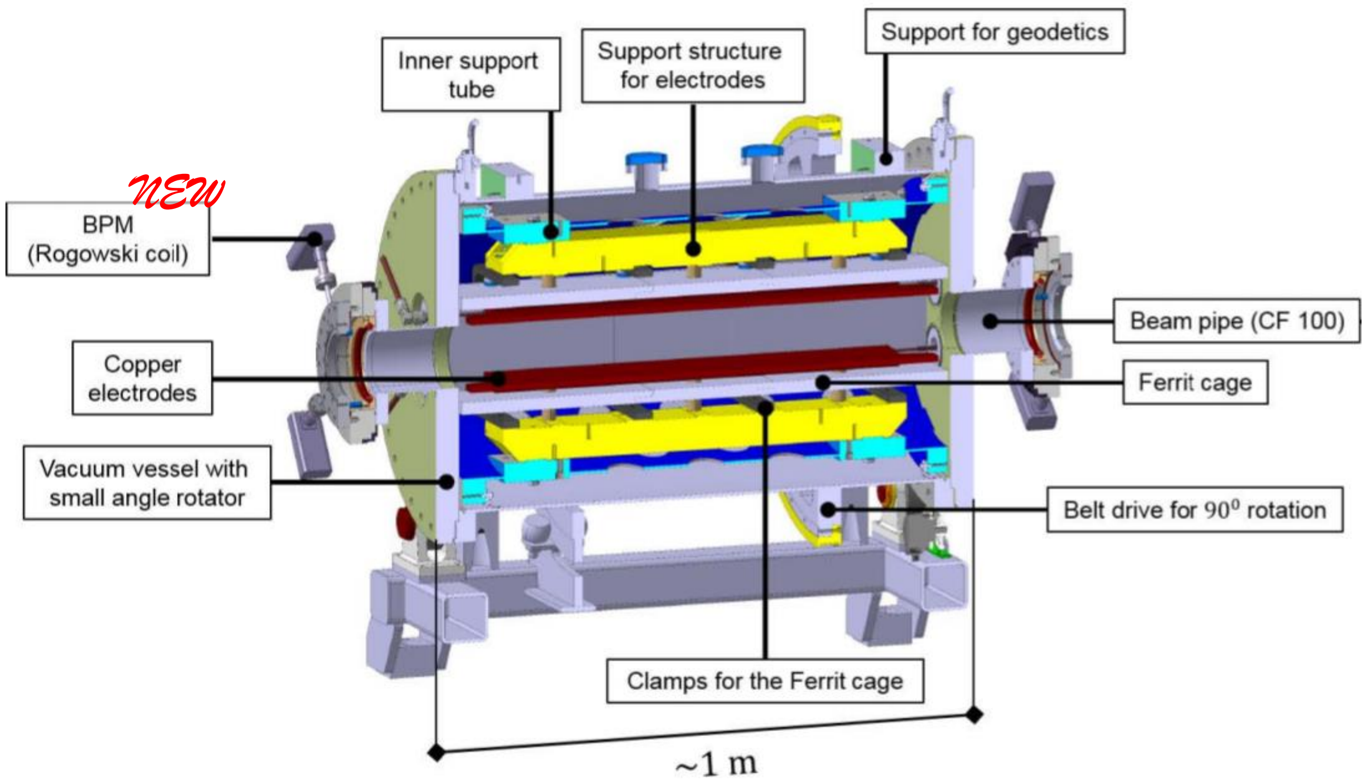
- In pure magnetic storage ring, T-BMT eq.:
- $\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S}(t) = -\frac{q}{m}\left(G\vec{B} + \frac{1}{2}\eta(\vec{E} + \vec{\beta} \times \vec{B})\right) \times \vec{S}(t)$
- EDM effect in the stable spin axis: $\vec{c} = \vec{e}_x \sin\xi_{\mathrm{EDM}} + \vec{e}_y \cos\xi_{\mathrm{EDM}}$

$$\tan\xi_{\mathrm{EDM}} = \frac{\eta\beta}{2G}$$

- EDM signal is a tilt of stable spin axis in- or outwards the ring
- Measure EDM-induced tilt by spin resonance with radiofrequency Wien filter



JEDI: Waveguide RF Wien filter with crossed RF E&B fields



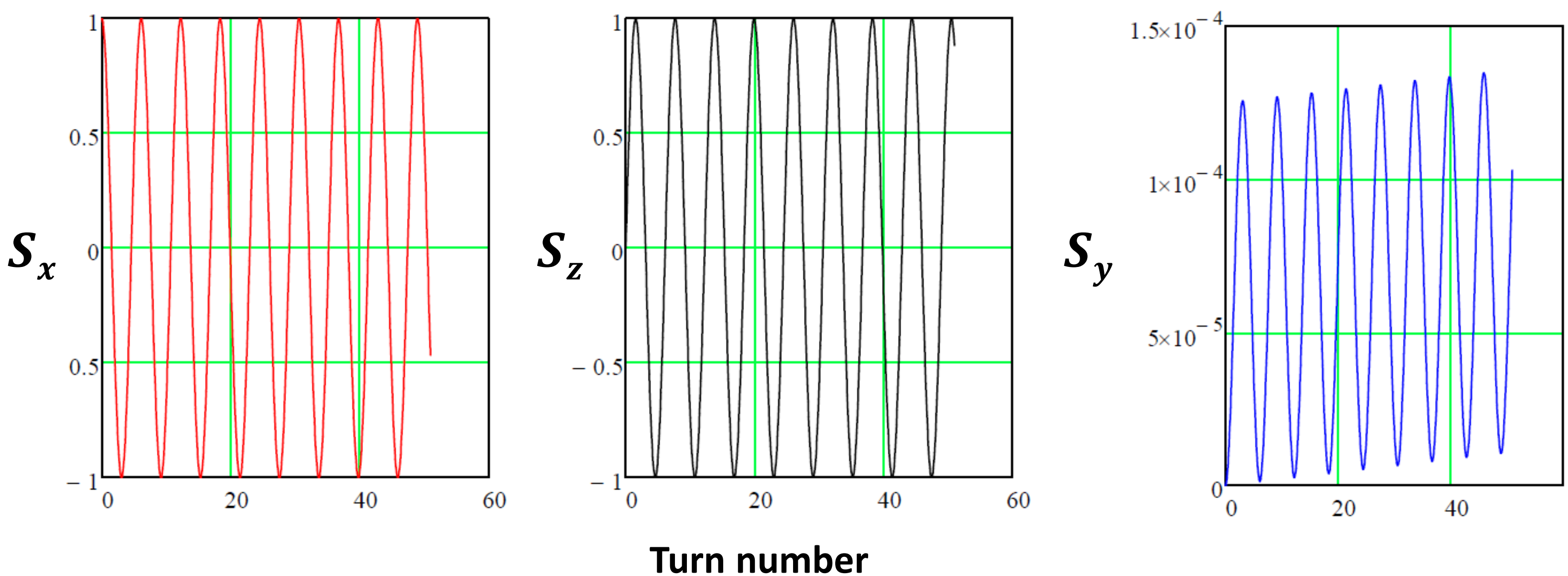
- RF spin rotation by radial E and vertical B fields without orbit distortions
- Developed at FZJ in collaboration with RWTH-Aachen
- Installed in the PAX low-β section at COSY

Spin dynamics with RF WF

- RF WF works on spin tune frequency $\nu_{\mathrm{RF}} = \nu_s + K$, cyclotron harmonics $K = -2, -1, 1, 2$
- Relative phase Δ_{RF} between the rf field and spin rotation phase as extra knob

$$\theta_{\mathrm{RF}}(n) = \theta_{\mathrm{s}}(n) + \Delta_{\mathrm{RF}}$$

- A simulated pattern of EDM-induced resonance deuteron vertical spin build-up at $\Delta_{\mathrm{RF}} = 0$, and initial spin $S_{\mathrm{x}} = 1$ at $d_{\mathrm{d}} = 10^{-19} e \cdot cm$:



Spin rotation with RF Wien filter

- With RF WF, spin resonance strength is

$$\epsilon = \frac{1}{2}\chi_{\mathrm{WF}} \left|\vec{c} \times \vec{w}\right|$$

- Infinite time: angle between vertical and horizontal polarization is:

$$S_{\mathrm{y}}(t) = S_{\mathrm{H}}(0) \sin \Delta_{\mathrm{RF}} \sin(\alpha(t))$$

$$\alpha(t) = 2\pi\epsilon f_R t = \operatorname{atan}\left(\frac{S_{\mathrm{y}}(t)}{S_{\mathrm{H}}(t)}\right)$$

- Slope of the vertical polarization build-up

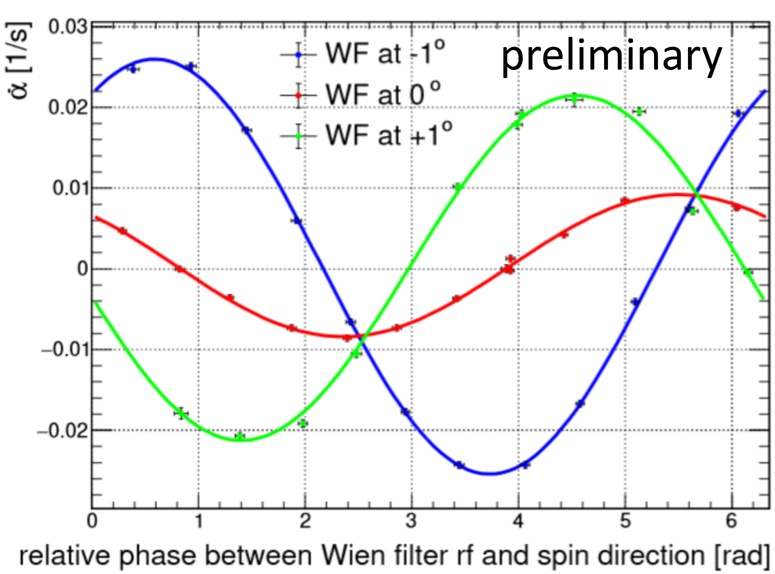
$$\left.\frac{dS_y}{dt}\right|_{t=0} = 2\pi\epsilon f_R S_{\mathrm{H}}(0) \sin \Delta_{\mathrm{RF}}$$

- Continuous phase lock is called for to keep the resonance condition

JEDI: first studies of spin dynamics with RF Wien filter at COSY. Build-up slope vs relative phase Δ_{WF}

- The slope of vertical polarization build up, $\dot{\alpha}$, was measured against different setting of relative phase Δ_{WF} for three orientations of Wien filter

- Testing $\epsilon = \frac{1}{2}\chi_{\mathrm{WF}} \left|\vec{c} \times \vec{w}\right|$ varying orientations of the Wien filter and stable spin axis



- Rotate Wien filter by small angle ξ_z around Z-axis

$$\vec{w} \approx \vec{e}_y + \xi_z \vec{e}_x$$

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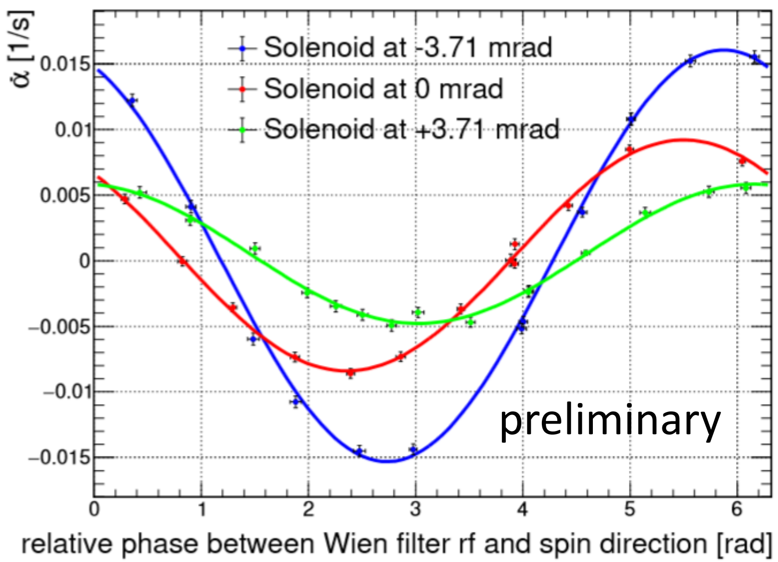
JEDI: Build-up slope vs relative phase Δ_{WF}

- Change the stable spin axis $\vec{c}$ of the ring by a static solenoid: first cooler solenoids were used, afterwards JEDI switched to superconducting Siberian Snake

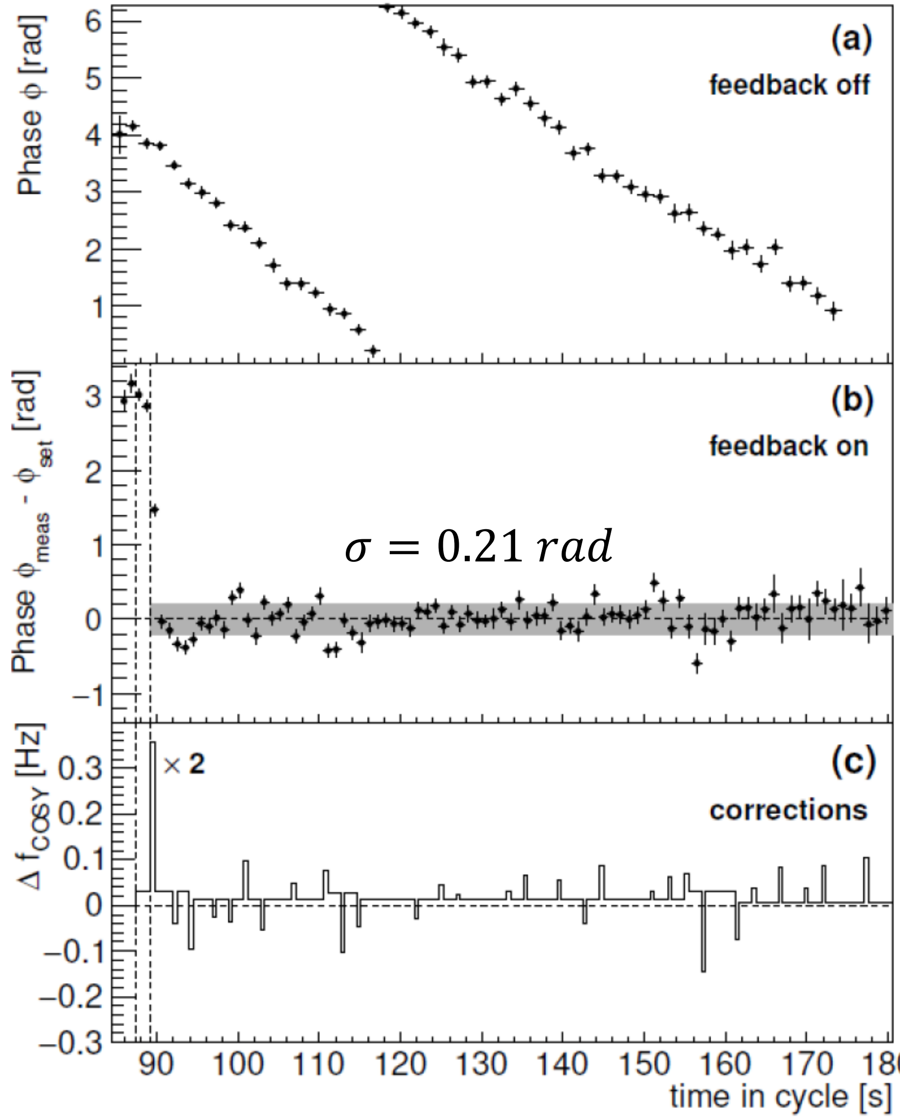


- 120-keV cooler solenoid at straight section opposite to RF WF rotated $\vec{c}$ at location of Wien filter by $\cong \pm 3.71$ rad

- Eventually mapping the resonance strength with good statistics would allow for determination of initial stable spin axis

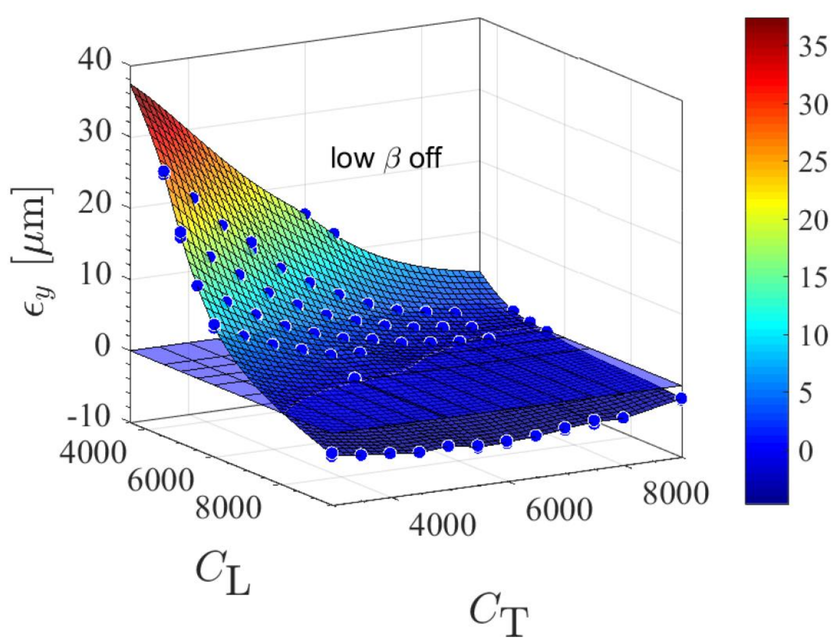
JEDI: Phase lock to maintain resonance condition

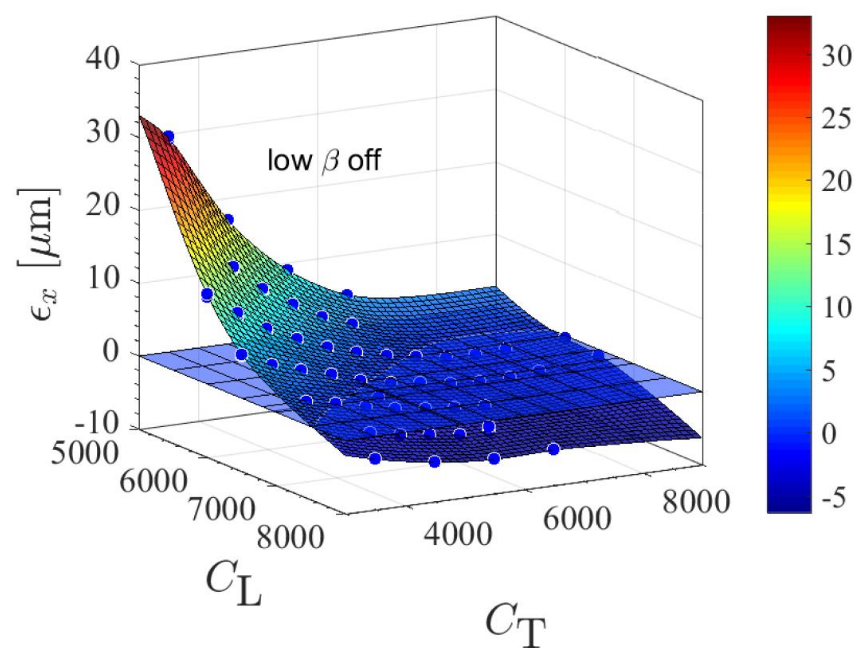
- Active feedback system was developed
- To compensate a drift of spin tune, RF Wien filter frequency is adjusted every 2 seconds to maintain Δ_{WF}
- Early tests conducted rather varying spin tune at fixed RF by changing RF cavity frequency (revolution freq. changes)
- Spin phase was maintained constant within 0.21 rad



JEDI: testing zero Lorentz force properties of RF WF installed at COSY

- Control the ratio and relative phase of E- and B-field in the Wien filter by two capacitors CL and CT in RF circuit
- Non-zero Lorentz force in RF WF induces coherent betatron oscillation of the beam - measure the vertical and horizontal kicks:



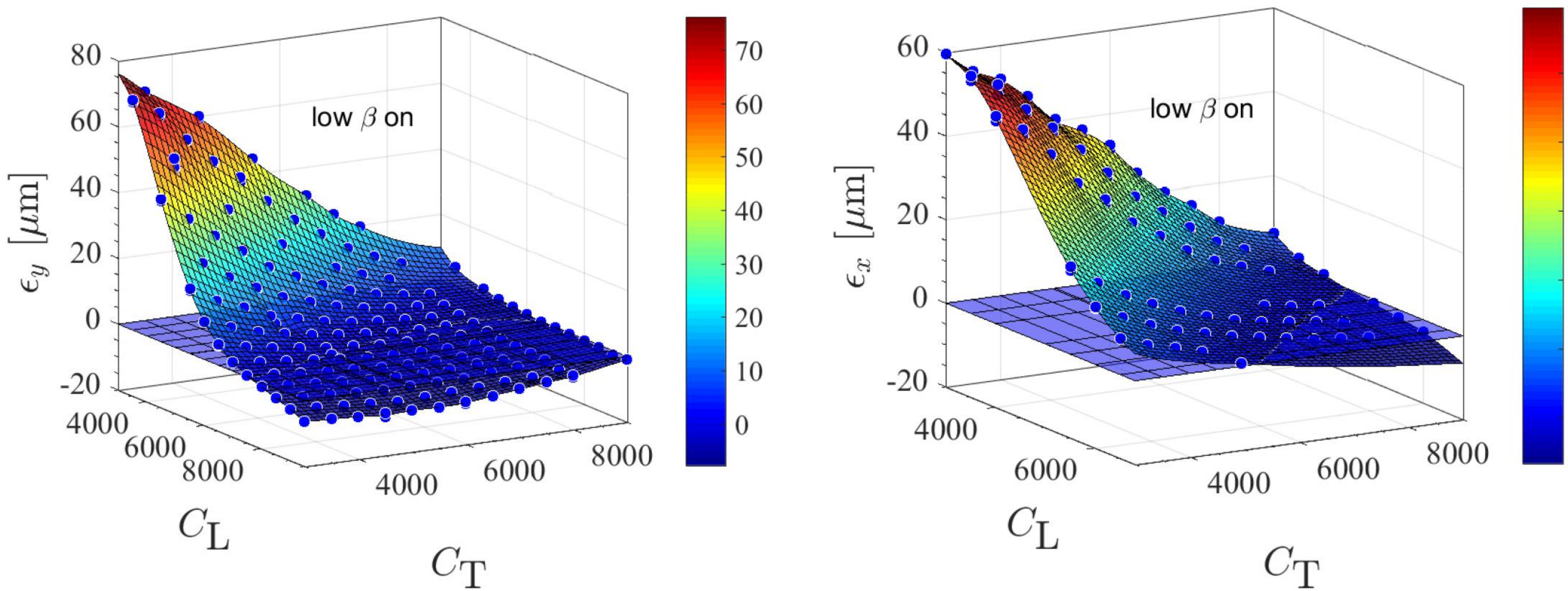


- Effects are different for different RF harmonics

JEDI: Lorentz force properties of RF WF

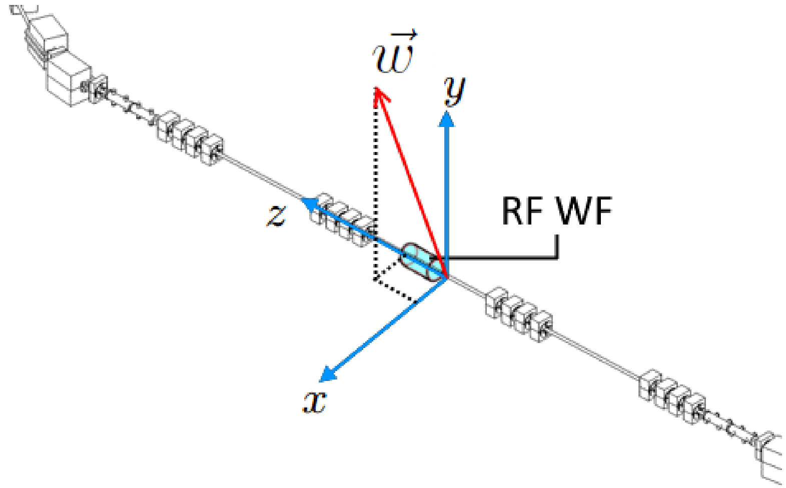
- low-β → off-axial trajectories → non-zero Lorentz forces are stronger

- Orbit effects are amplified at low-β :



JEDI: controlling alignment of RF WF

- Accuracy of Wien filter orientation was determined during recent COSY magnet survey & alignment campaign



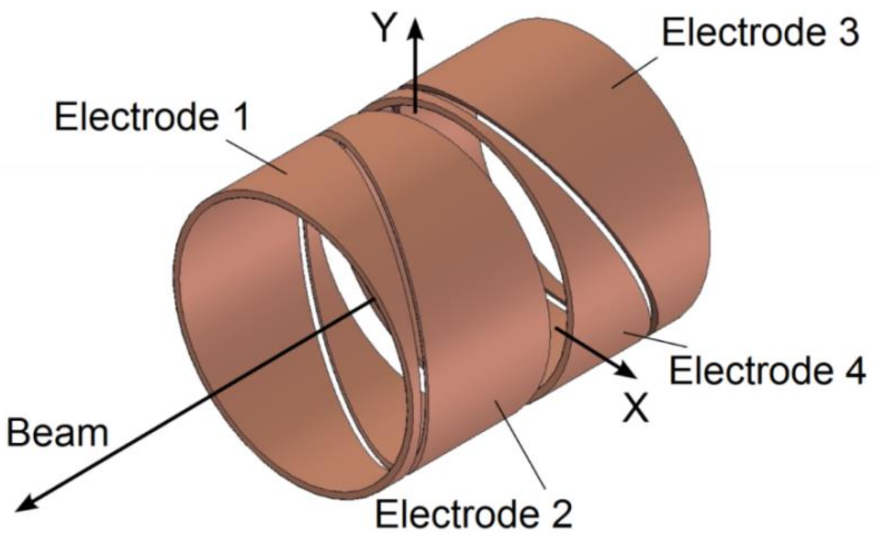
- New electronic levels implemented to set WF rotation angle with accuracy of at least 170 µrad:

- EDM mode: $\theta(\vec{B} \parallel \vec{e}_y) = (+0.74 \pm 0.17)$ mrad at T = 21.006 °C
- MDM mode: $\theta(\vec{B} \parallel \vec{e}_x) = (+0.57 \pm 0.17)$ mrad at T = 20.865 °C

- $\vec{e}_\mathrm{y}$ denotes true normal to ring plane, and $\vec{e}_\mathrm{x}$ is outward-pointing radial vector in ring plane

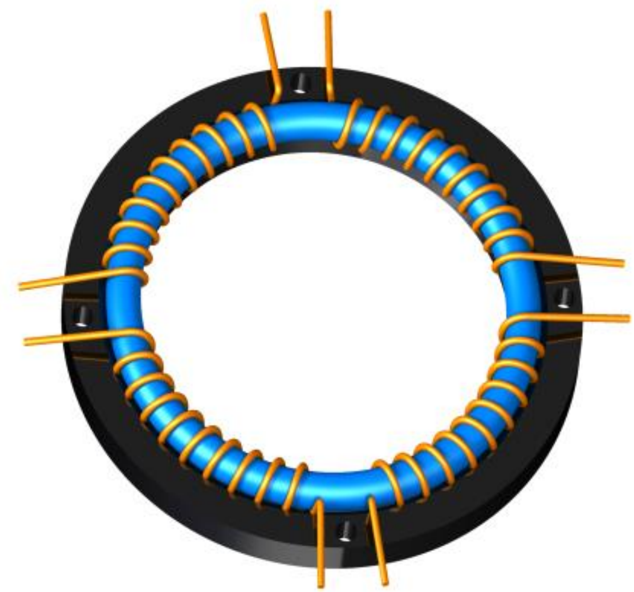
JEDI: Rogowski coil beam position monitors

Conventional BPM



- Easy to manufacture
- Length ~ 20 cm
- Relative resolution ~ 10 µm
- Absolute accuracy ~ 1 mm

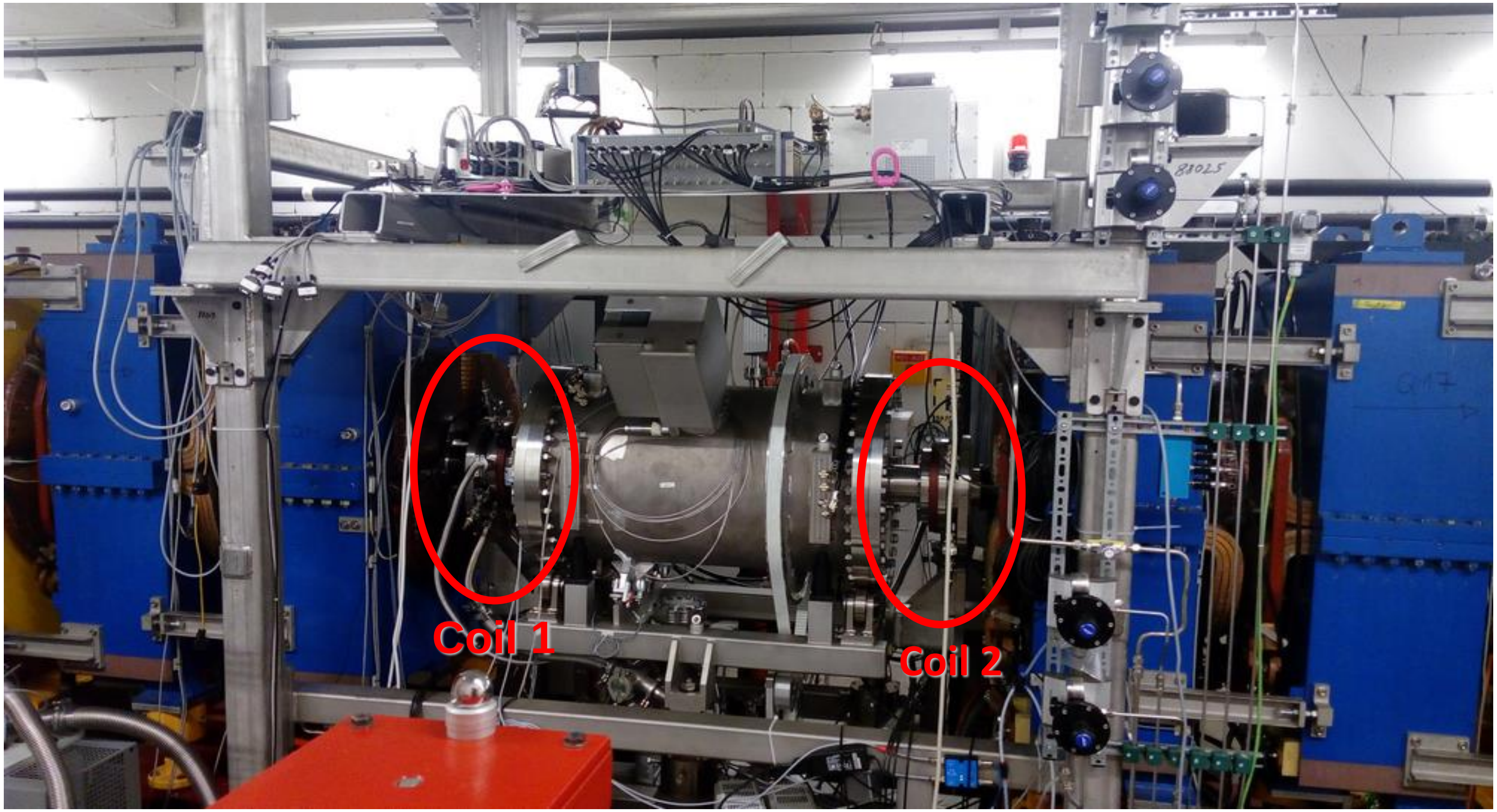
Rogowski coil BPM



- Excellent rf-signal response
- Length ~ 1 cm
- Relative resolution ~ 1.25 µm
- Absolute accuracy ~ 150 µm

Rogowski coil BPM’s: ultimate choice for future EDM experiments

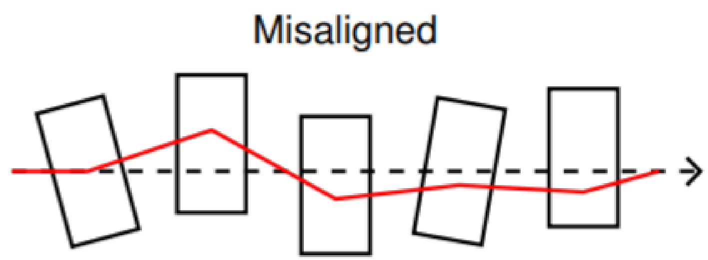
- Two Rogowski coils installed at entrance and exit of RF Wien filter



JEDI: beam-based alignment

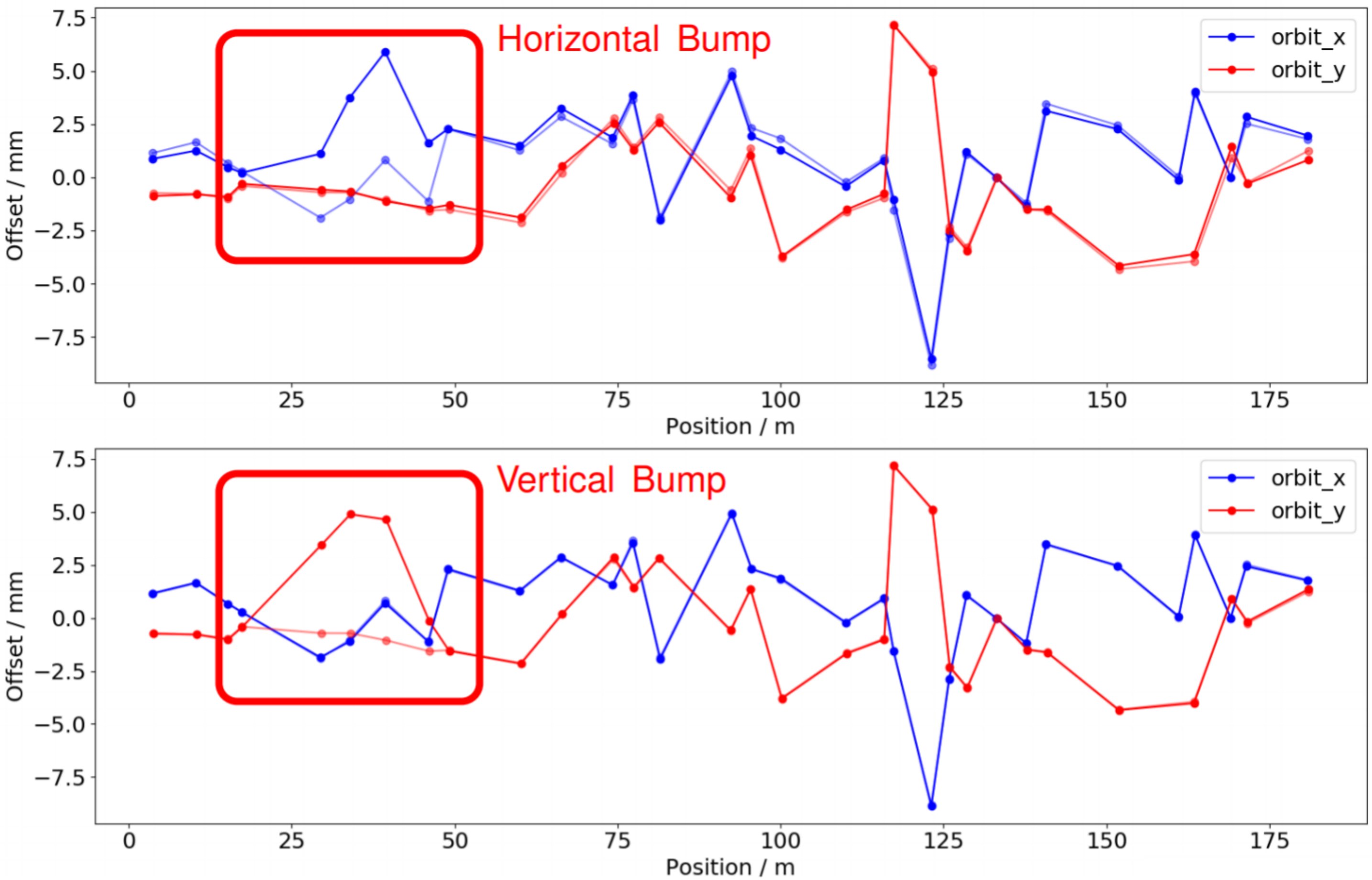
- Beam-based alignment of magnetic center of quadrupoles - needed to overcome systematic errors appearing from misalignments of quads

- Use beam to optimize the beam position
- Vary quadrupole strength
- Observe orbit change
- Try to minimize the orbit change



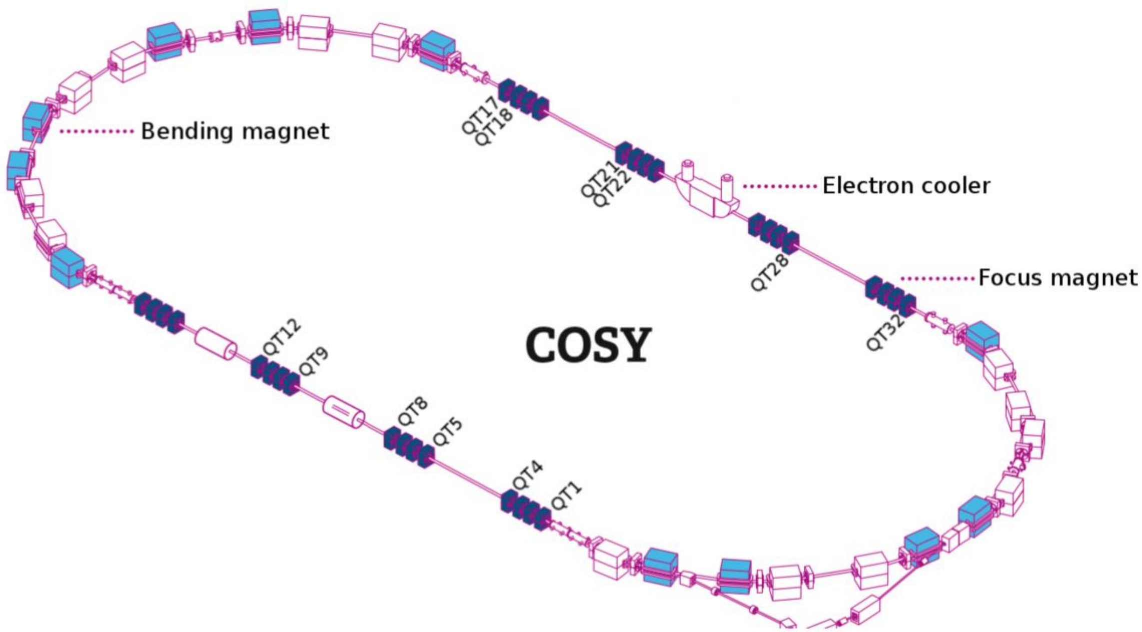
Beam-based alignment at COSY

- Steerers around the quadrupole QT12 (located at 30 m) are varied to adjust the beam position inside the quadrupole



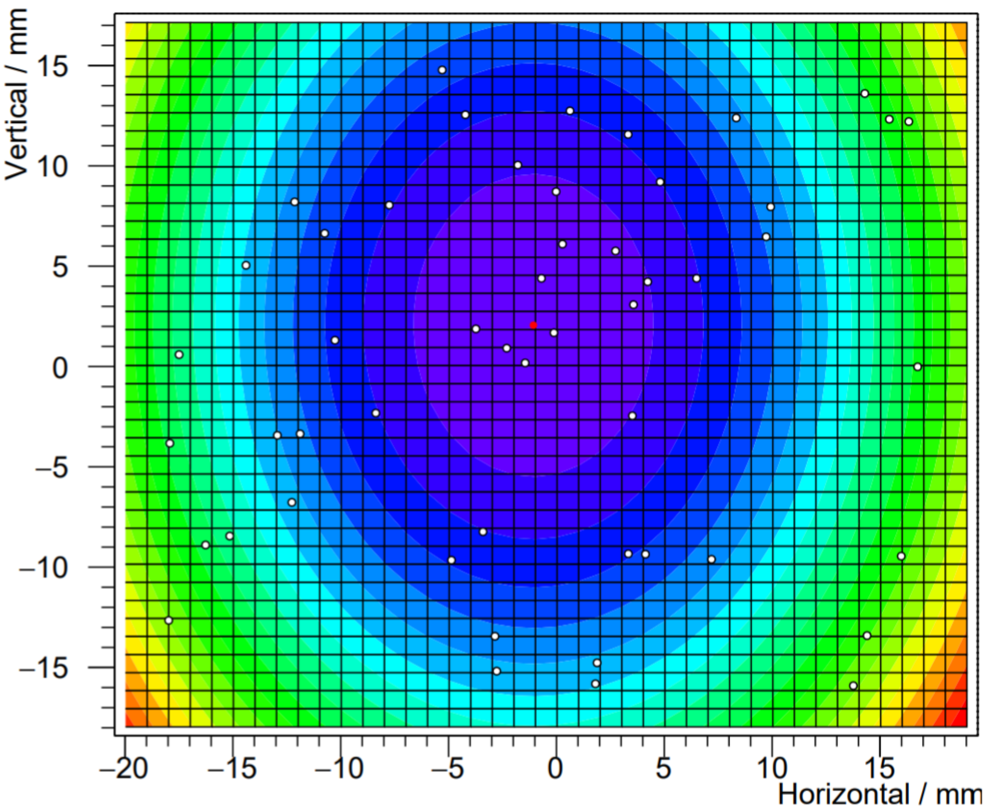
Beam-based alignment at COSY cont'd

- Quadrupole magnets have additional coils which are powered separately. They allow to vary quadrupole strength k
- The further the beam is off the center of quadrupole, the stronger is the orbit change w.r.t. to Δk
- A merit function: beam deviation over the ring vs quadrupole strength Δk



Beam-based alignment at COSY: JEDI preliminary results

- Optimal beam position was found for quadrupole QT12 at COSY:



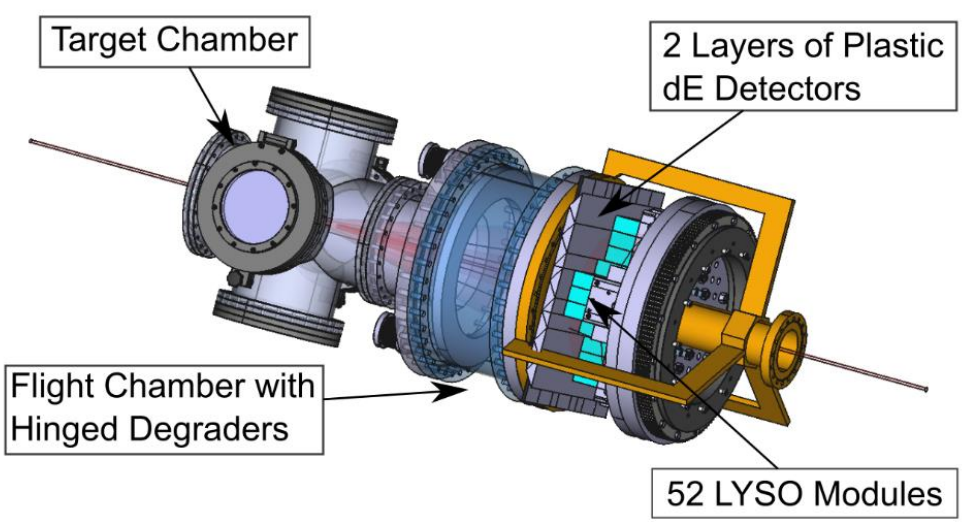
X = −1.14 ± 0.02 mm
Y = 2.08 ± 0.03 mm

Outlook:
All quadrupole magnets to be controlled

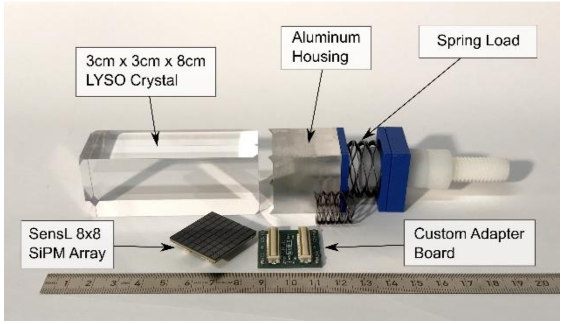
JEDI: from EDDA to WASA to dedicated LYSO polarimetry

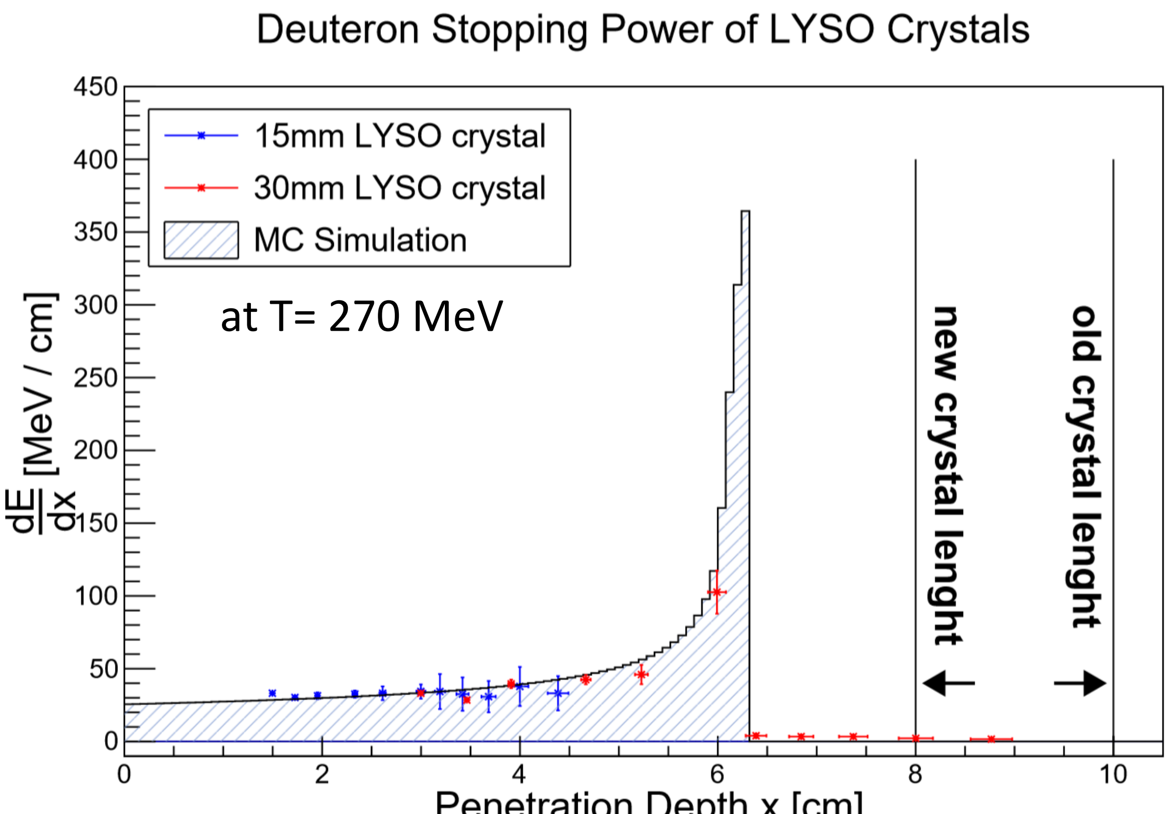
- Early studies were based on EDDA polarimeter
- Present studies: WASA is a polarimeter

- Current polarimetry development: polarimeter based on LYSO crystals
  - Advantages: high energy resolution, high yield, compactness
  - Successfully tested in the extracted beam at COSY

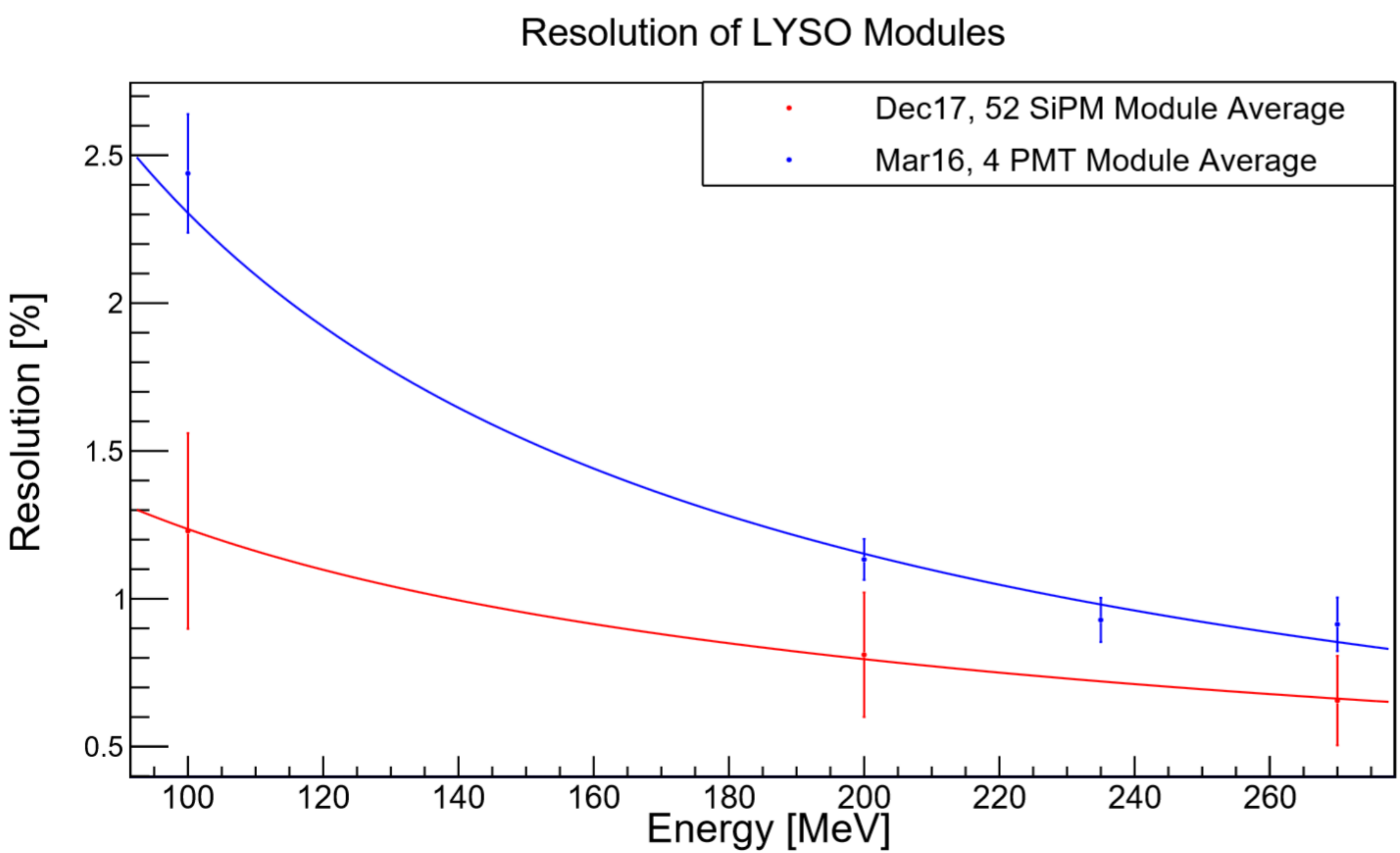


JEDI polarimeter based on LYSO calorimetry





JEDI LYSO polarimeter



JEDI: deuteron database experiment at modified WASA Forward Detector

- Motivation: optimize polarimetry for ongoing JEDI activities
- Goal: vector and tensor analyzing power
- $d\sigma/d\Omega$ for dC elastic scattering
- Main background from deuteron breakup
- **Beamtime in November 2016 (2 weeks):**
- Deuteron energies: 170, 200, 235, 270, 300, 340, 380 MeV
- Nominal beam polarization: $(P_y, P_{yy}) = (0,0), (-\frac{2}{3},0), (\frac{2}{3},0), (\frac{1}{2}, -\frac{1}{2}), (-1, 1)$
- Targets: C and CH_2

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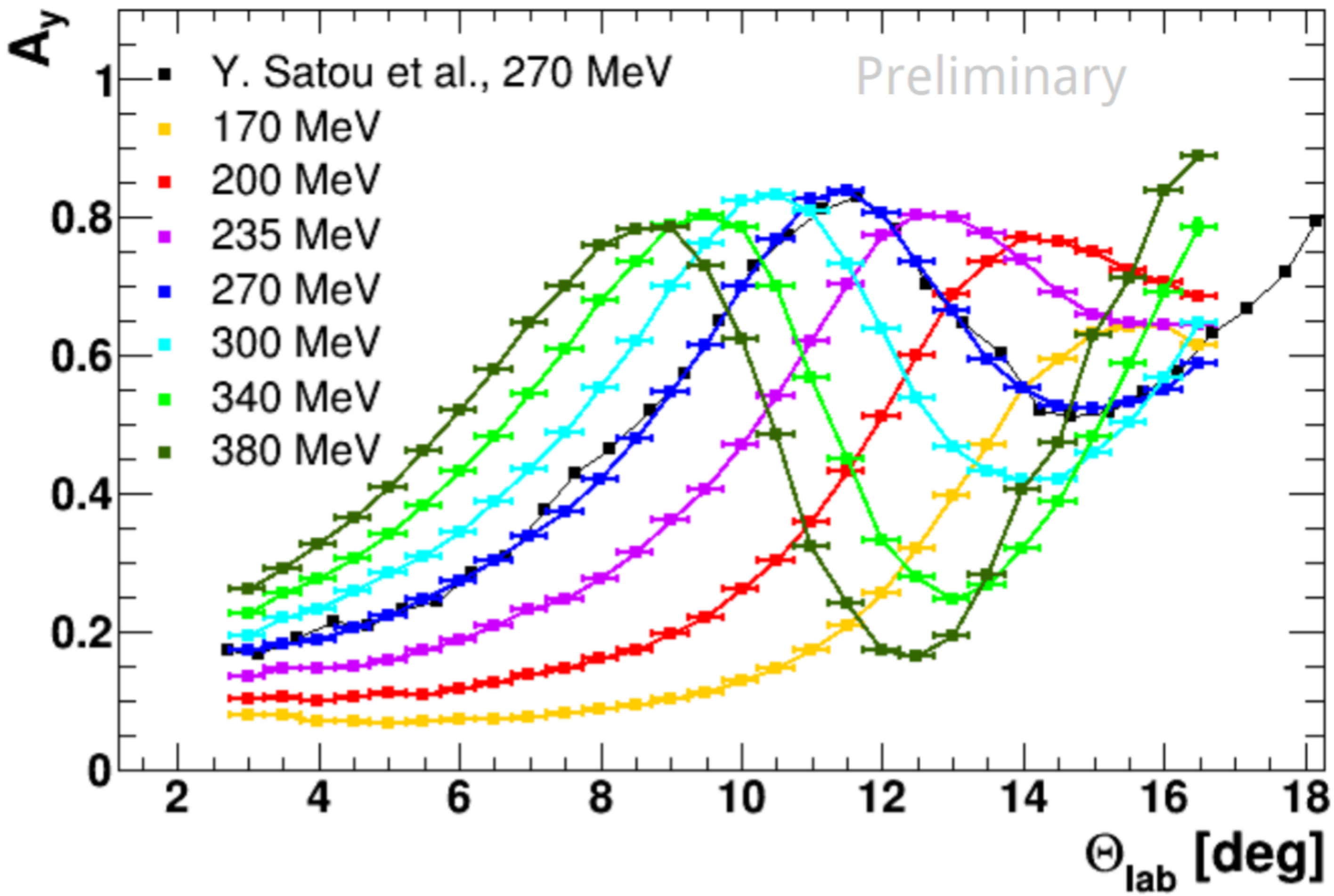
JEDI: database experiment at WASA

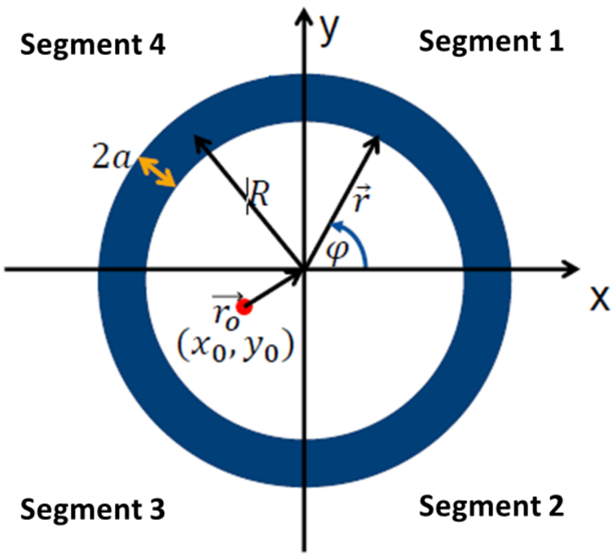
- Vector Analyzing power for elastic dC scattering



Summary and outlook

- JEDI is making steady progress in spin dynamics of relevance to future searches for EDM
- COSY remains a unique facility for such studies
- Precursor JEDI search for the deuteron EDM at COSY under preparation
- Strong interest of high energy community in storage ring searches for EDM of protons and light nuclei as part of physics program of the post-LHC era
- Proposals for prototype all-electric 30 MeV EDM storage ring are under consideration (CERN? COSY?)
- Crossed ExB field prototype EDM storage ring might be an option before going to TDR for ultimate EDM machine

Position determination



$$\frac{\Delta U_{\text{hor}}}{\Sigma U_i} = \frac{(U_1 + U_2) - (U_3 + U_4)}{U_1 + U_2 + U_3 + U_4} \qquad \frac{\Delta U_{\text{ver}}}{\Sigma U_i} = \frac{(U_1 + U_4) - (U_2 + U_3)}{U_1 + U_2 + U_3 + U_4}$$

$$\frac{\Delta U}{\Sigma U_i} = c_1 x_0 - c_3 \left(x_0^3 - 3y_0^2 x_0\right) + c_5 \left(x_0^5 - 10 y_0^2 x_0^3 + 5 y_0^4 x_0\right)$$

$$c_1 = \frac{2}{\pi\sqrt{R^2 - a^2}} = 10.9 \cdot 10^{-3} \frac{1}{\text{mm}}$$

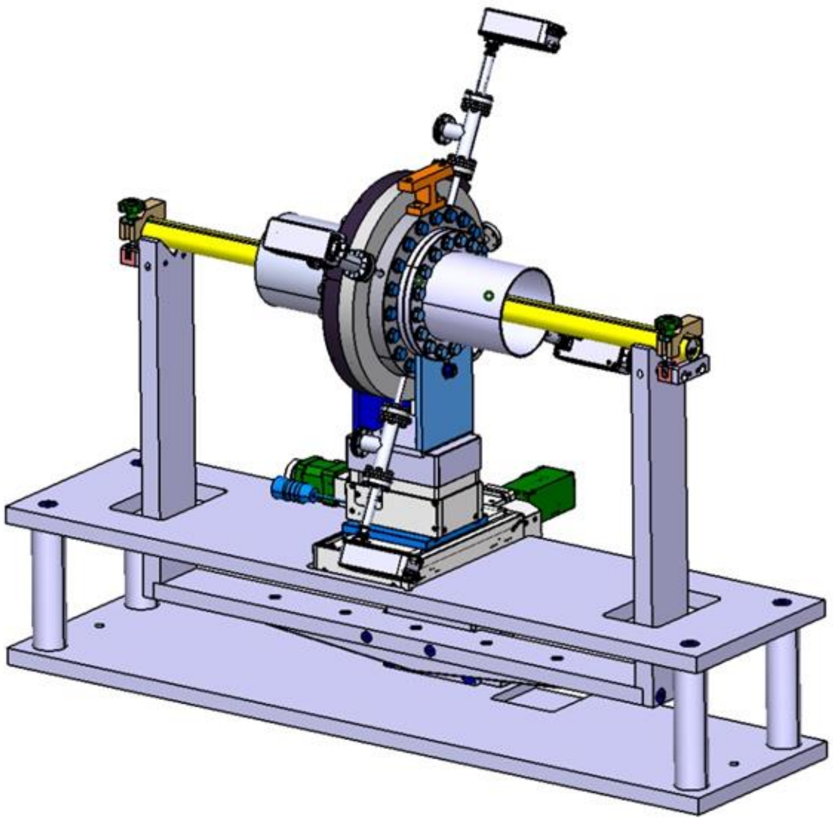
$$c_3 = \frac{a^2 R}{3\pi (R^2 - a^2)^{5/2}(R - \sqrt{R^2 - a^2})} = 1.0818 \cdot 10^{-6} \frac{1}{\text{mm}^3}$$

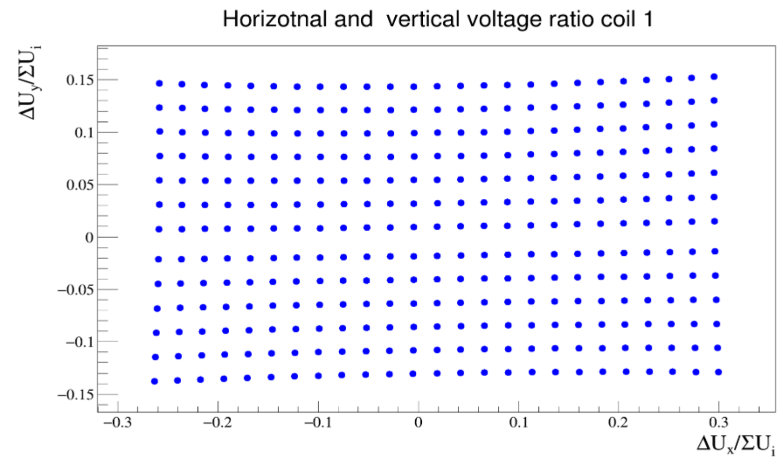
$$c_5 = \frac{a^2 R (4R^2 + 3a^2)}{20\pi (R^2 - a^2)^{9/2}(R - \sqrt{R^2 - a^2})} = 0.1951 \cdot 10^{-9} \frac{1}{\text{mm}^5}$$

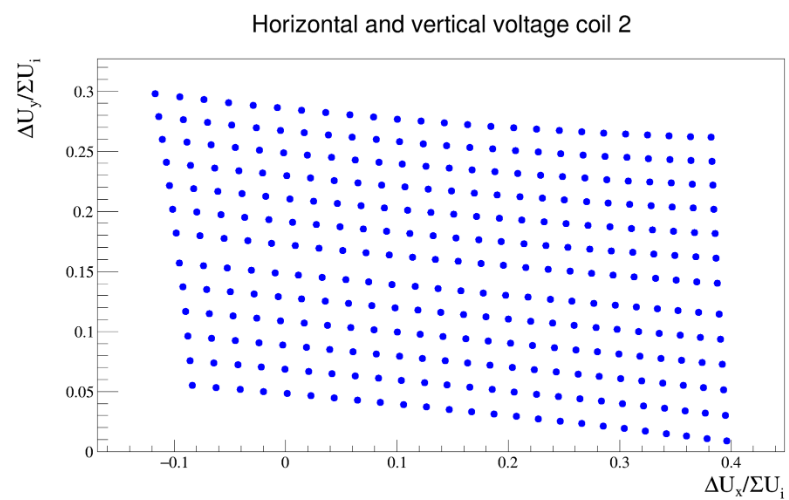
Coil parameters

- R = 58.625 mm
- a = 6.375 mm
- n = 434
- s = 0.15 mm

Calibration







Beam-based alignment

$$f = \frac{1}{N_{\mathrm{BPM}}} \sum_{i=1}^{N_{\mathrm{BPM}}} (x_i(+\Delta k) - x_i(-\Delta k))^2$$

$$f \propto (\Delta x)^2 \propto (x(\bar{s}))^2$$

- Merit function is calculated for different initial beam positions in quadrupole
- By finding the minima of merit function, optimal beam position can be found