Spin Dynamics for EDM at Storage Rings

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XXIV Baldin Seminar, 17-22 September 2018

Outlook: selected issues from JEDI driven activity at COSY (a task for future SPD at NICA?)

- EDM: why? Fundamental symmetries and baryogenesis
- EDM: how? Spin rotation by electric fields
- JEDI@COSY: selected record setting results
- Systematic background from MDM in imperfection magnetic rings is an evil
- JEDI@COSY: spintune mapping as a tool to quantify imperfection fields
- Impact of synchrotron oscillations on spin coherence time: nonexponential decay of polarization and spin echo
- Gravity induced spin rotation as a false EDM signal: de Siitter (1916!) spin-orbit interaction and imperfection fields from focusing to compensate for the free fall

http://collaborations.fz-juelich.de/ikp/jedi/documents/colpapers.shtml

Why: EDM and baryogenesis

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

	observed	*SM prediction*
$\frac{n_B - n_{\overline{B}}}{n_\gamma}$	$(6.1 \pm 0.3) \times 10^{-10}$	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 1-2 orders in magnitude
- pEDM: statistical accuracy of 10^{-29} is aimed at dedicated all-electric storage rings
- dEDM and pEDM in precursor experiment at COSY: dEDM $\sim 10^{-20}$ is within reach?
- Sequel to JEDI: **CPEDM & prototype pure electric ring** (at CERN? at COSY?...) --- big international effort, CDR under preparation for the fall 2018

- **SM can not be a final truth: talk by Vadim Alexakhin at this meeting**

EDM vs. MDM (learnt from Lev Okun in 60's)

- MDM: allowed by all symmetries, a scale is set by a nuclear magneton μ_N
- Buy CPT: EDM is P and CP/T forbidden
- Price for the PV: 10^{-7} , for CPV extra 10^{-3} from K-decays
- Natural scale $d_N = \mu_N \times 10^{-7} \times 10^{-3} \sim 10^{-24} e \cdot cm$
- The SM: CPV linked to the flavor change. Pay 10^{-7} more to neutralize the flavor change

$$d_{N,SM} \sim \mu_N \times 10^{-7} \times 10^{-3} \times 10^{-7} \sim 10^{-31} e \cdot cm$$

Why charged particles besides neutrons?

- Neutrons are record holders: next generation expts in the pipeline wherever ultracold neutrons are available (PNPI, Grenoble, Oak Ridge, PSI, Triumf,…)

- 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 $d_p \neq d_n$
- (e.g. Bonn-Juelich Collab.)

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

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

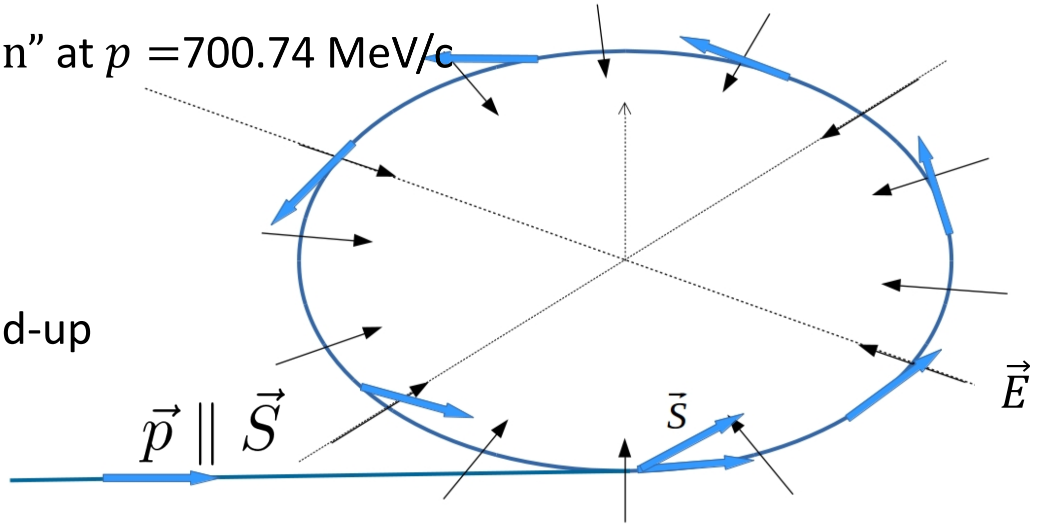
A principle of EDM measurement: spin rotation by EDM-interaction with E-fields

- FT-BMT eqn :
- $$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S}(t) = -\frac{q}{m}\Big(\underbrace{G\vec{B} + \Big(\frac{1}{\gamma^2-1} - G\Big)\vec{\beta} \times \vec{E}}_{\boxed{\text{MDM}}} + \underbrace{\frac{1}{2}\eta(\vec{E} + \vec{\beta} \times \vec{B})}_{\boxed{\text{EDM}}}\Big) \times \vec{S}(t)$$

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

All-electric ring is ideal for protons (Yu Orlov et al, srEDM at BNL)

- MDM-term → 0 - “frozen spin” at p =700.74 MeV/c
- Longitudinal initial spin
- EDM signal: vertical spin build-up per turn → πη



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

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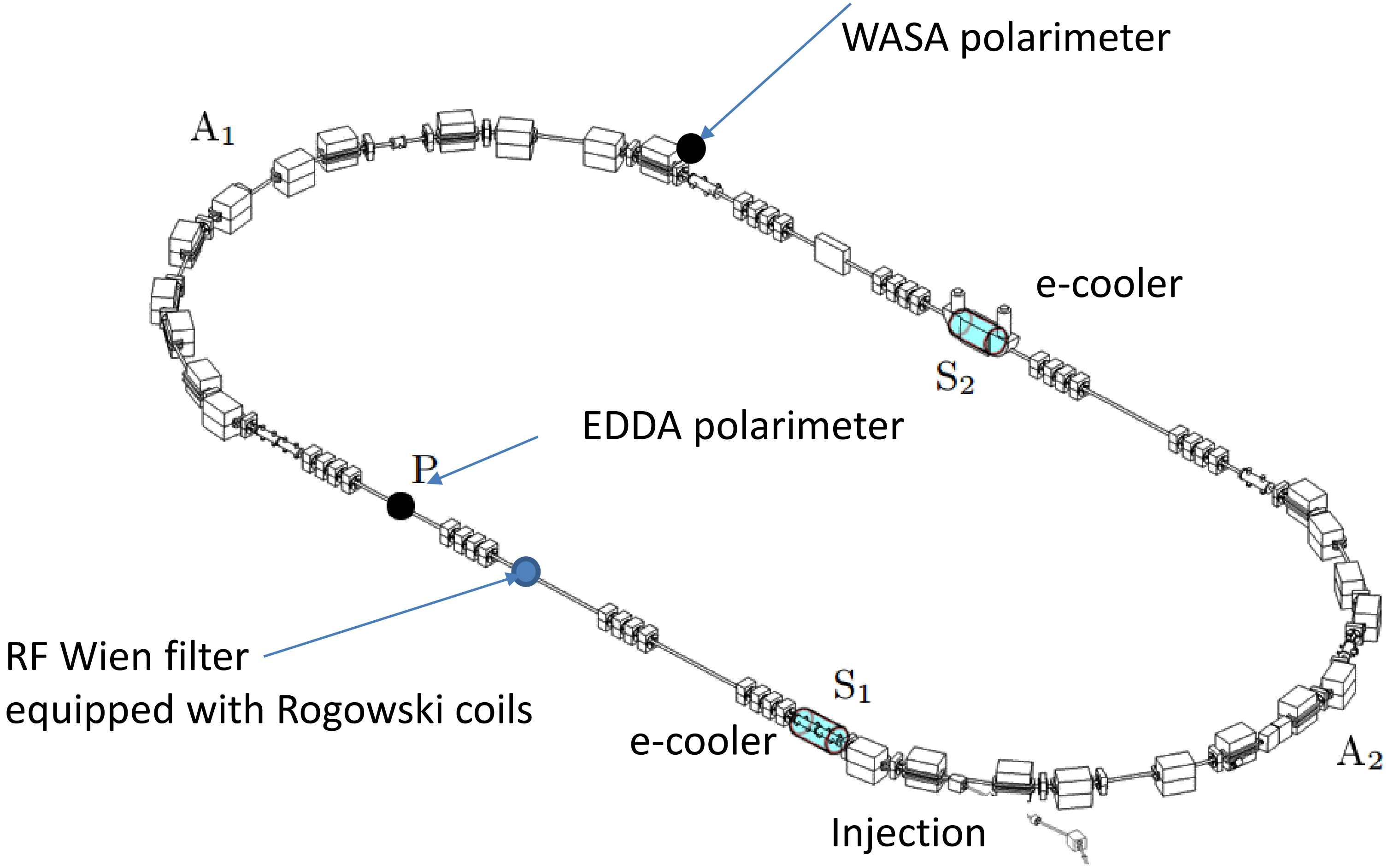
JEDI: EDM searches at COSY

Precursor experiment in the pipeline

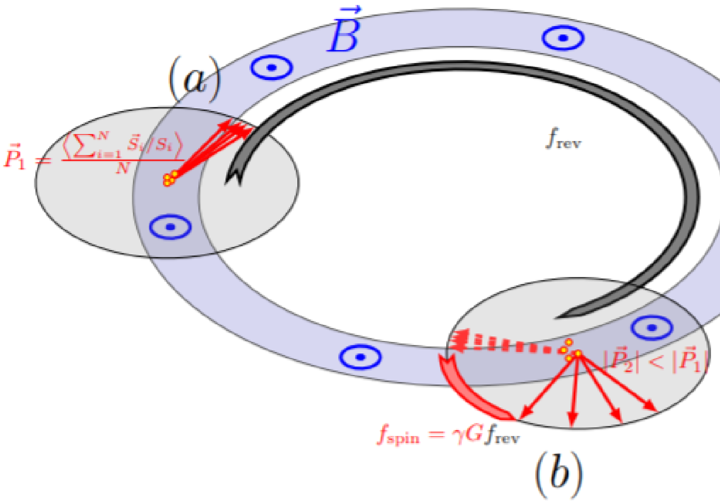
- COSY is all-magnetic storage ring, unique for studying spin dynamics but still needs upgrades for EDM searches
- Statistical accuracy for $d_d = 10^{-24} e \cdot cm$ is reachable at COSY
- Systematic effects: horizontal imperfection magnetic fields are evil because MDM >> EDM and MDM rotations give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

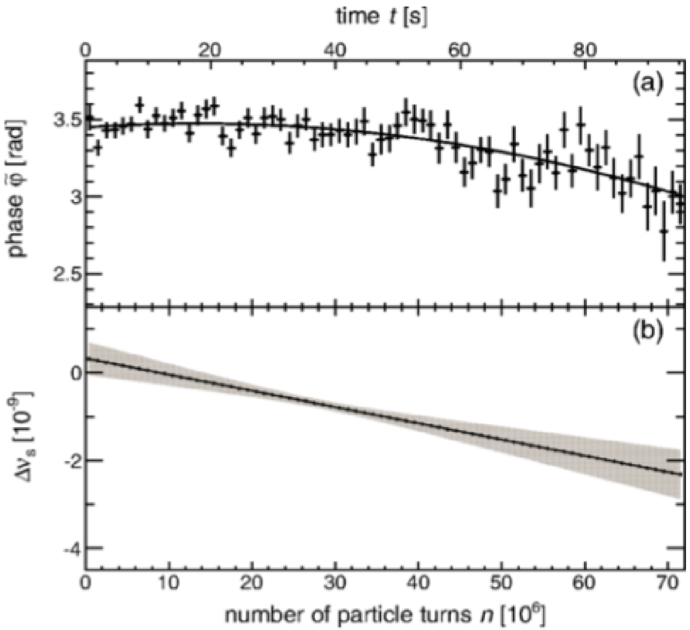
Till NICA we rely on COSY as a Testing Ground



JEDI at COSY: record spin tune precision

Continuous polarimetry of in-plane spin precession with time stamp





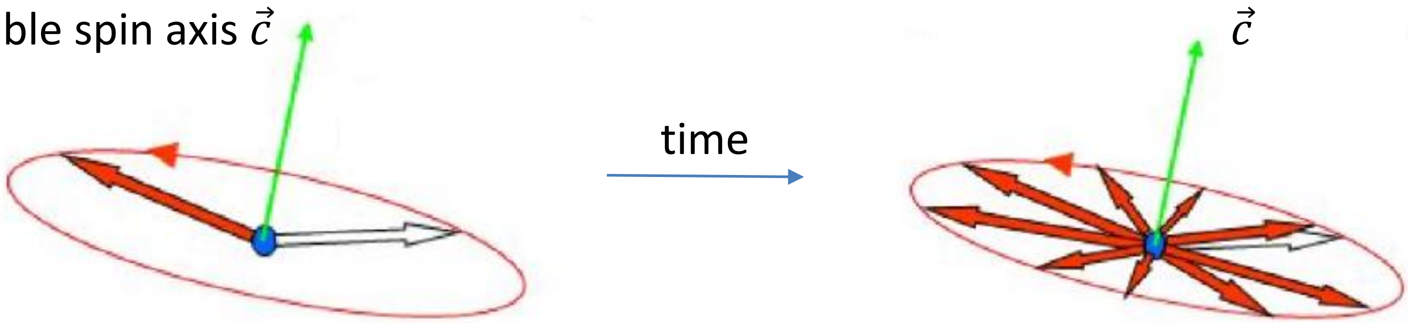
$$\sigma(\nu_s = \gamma G) \approx 10^{-10} \text{ in } 100\,\text{s}$$

$$\text{Note: } \gamma G = \frac{f_{spin}^{MDM}}{f_{rev}}, \qquad \frac{f_{spin}^{EDM}}{f_{rev}} \approx 10^{-10} \text{ for EDM } d = 10^{-24}\, e\,\text{cm}$$

JEDI: PRL 115, 094801 (2015); PRL, 119, 014801 (2017); PRST AB **21**, 042002 (2018)

Spin coherence time

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



Inititally all spins aligned

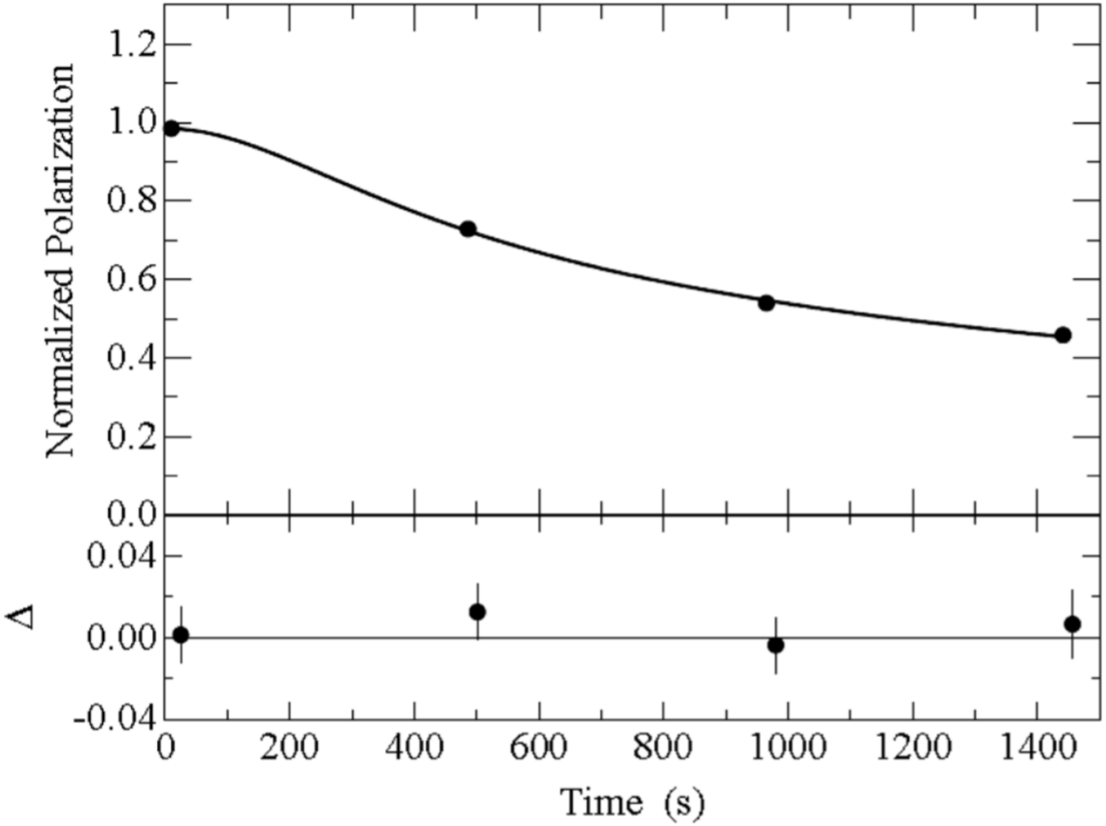
Spins decohered - polarization vanishes

Prerequisites for long SCT:

- use bunched beam
- decrease beam emittance via electron-cooling
- **Betatron oscillations**: fine-tune sextupole families to suppress chromaticity (old idea by Ivan Koop and Yuri Shatunov (1988))

JEDI: record spin coherence time

- From 2017 on JEDI routinely runs at COSY with SCT of more than 1000 s
- JEDI: PRL 117, 054801 (2016) PR AB 21, 024201 (2018);



EDM effect

- RF Wien-Filter entails a vanishing EDM term in the FT-BMT

- Still EDM enters via tilt of the stable spin axis $\vec{c}$

$$\vec{c} = \vec{e}_x \sin \xi_{\mathrm{EDM}} + \vec{e}_y \cos \xi_{\mathrm{EDM}}$$

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

- RF WF with upright B-field and spin kick χ_{WF} still rotates spin with resonance tune (Morse et al. PRSTAB 16 (2013)114001, NNN (2013) unpublished)

$$\epsilon_{\mathrm{EDM}} = \frac{1}{4\pi} \chi_{\mathrm{WF}} \sin \xi_{\mathrm{EDM}}$$

- EDM from either stable spin axis or resonance tune?

EDM effect

- A pitfall: false EDM signal from MDM rotation in imperfection magnetic fields

$$\sin\xi_{\mathrm{EDM}}]\vec{e}_x \ \rightarrow c_{\mathrm{y}}\vec{e}_y + [c_{\mathrm{x}}(\mathrm{MDM}) + \sin\xi_{\mathrm{EDM}}]\vec{e}_x + c_{\mathrm{z}}(\mathrm{MDM})\vec{e}_z$$

$$\epsilon_0 = \frac{1}{4\pi}\chi_{\mathrm{WF}}|\vec{c}\times\vec{w}|$$

$\vec{w}$ is a WF magnetic field axis

- Spin tune depends on the imperfection fields

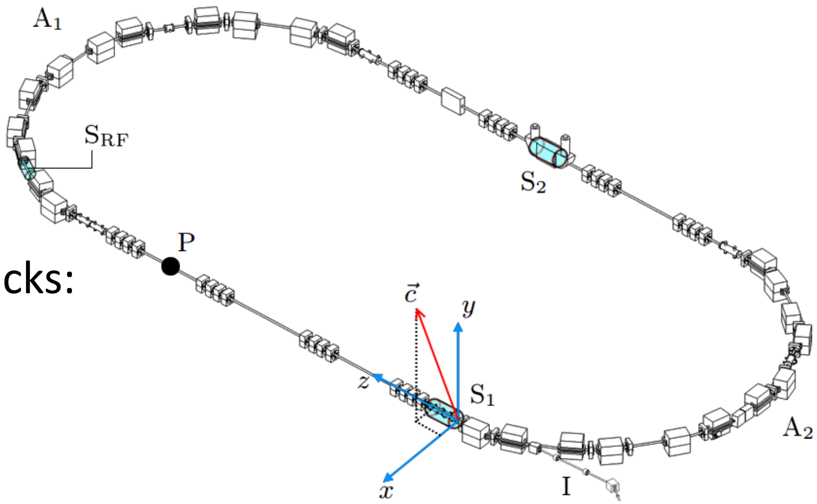
- Spin tune mapping: convert a record precision of spin tune to a tool to determine imperfections $c_{\mathrm{x},z}$.

- Probe imperfection complementing a ring with artificial in-plane magnetic fields

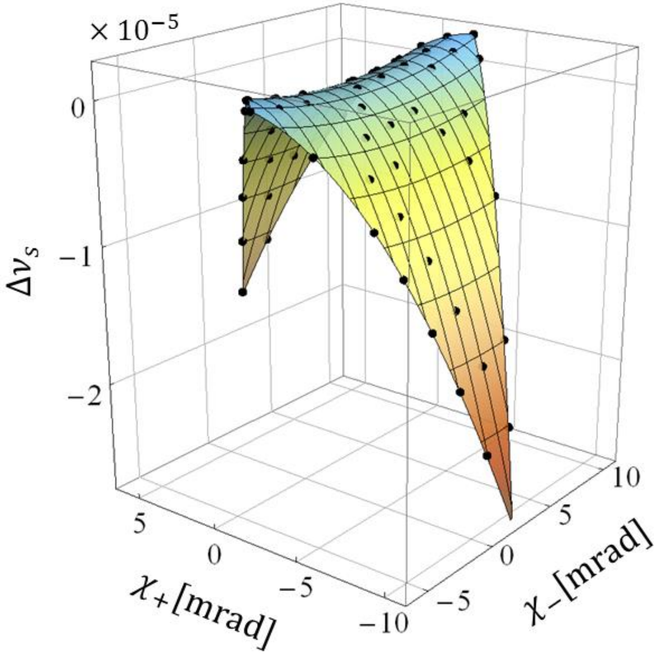
- Realized experimentally: JEDI: Phys.Rev. AB 20, 072801 (2017)

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

RF WF in the EDM mode (vertical magnetic field axis)

- Spin transfer matrix with running RF WF

$$T(n) = \exp[-i\pi\nu_s n(\vec{\sigma}\cdot\vec{c})]\cdot\exp[-i\pi\epsilon_0 n(\vec{\sigma}\cdot\vec{u})]$$

- Axis of driven spin rotation (**envelope evolution**)

$$\vec{u} = \cos\Delta_{WF}\,\vec{m} + \sin\Delta_{WF}\,\vec{k}$$

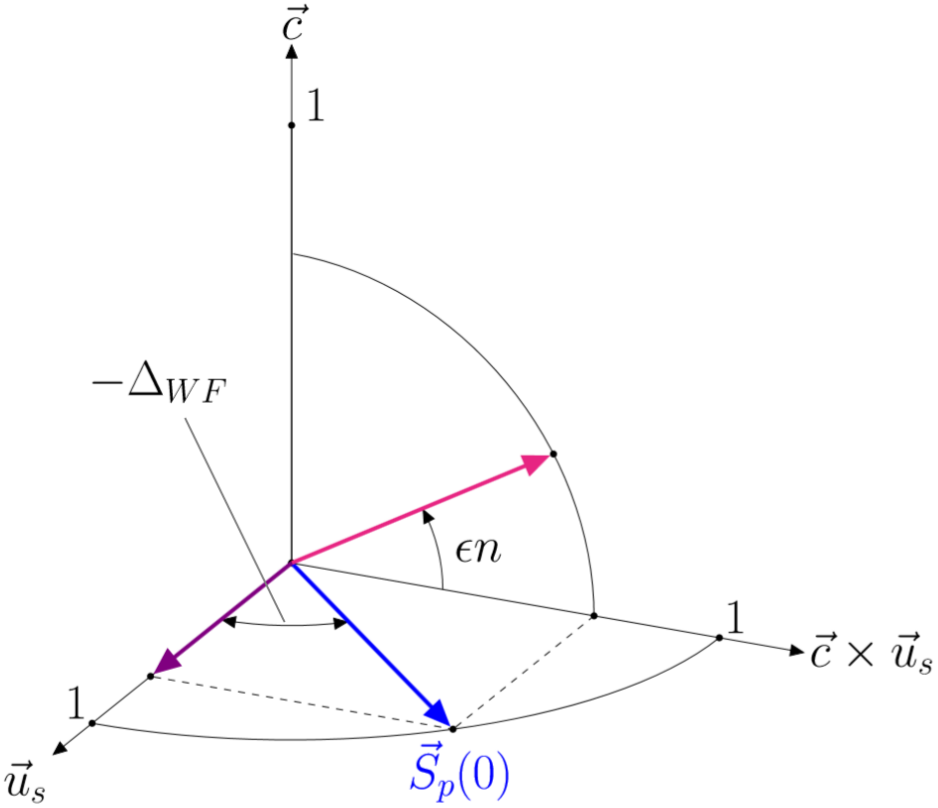
- Δ_{WF} - a phase shift between the spin precession and RF phases

$$\vec{k} = \frac{[\vec{c}\times\vec{w}]}{|\vec{c}\times\vec{w}|}, \qquad m = \vec{k}\times\vec{c}$$

- Idle precession of driven rotation axis

$$\vec{u}_s(n) = \vec{u}\cos 2\pi\nu_s n + [\vec{c}\times\vec{u}]\sin 2\pi\nu_s n$$

Rotating frame



- Rotating frame: one component of the initial in-plane polarization participates the RF WF driven spin resonance
- The second component keeps idle precession
- The initial vertical polarization does not generate the idle precessing component

Synchrotron oscillations

- Synchrotron oscillations: Nikolaev, Saleev, Rathmann, JETP Lett. 106(4), 213-216 (2017
- Spin phase is modulated with two random parameters: amplitude and phase

$$\Delta\theta_s(n) = \psi_s \xi[\cos(2\pi\nu_z n + \lambda) - \cos\lambda]$$

$$\psi_s = \frac{G\gamma\beta^2\sqrt{2}}{\nu_z}\left\langle\left(\frac{\Delta p}{p}\right)^2\right\rangle^{1/2}$$

- Related modulation of the RF phase (η_{SF} is a slip factor)

$$\Delta\theta_{WF}(n) - \Delta\theta_S(n) = C_{WF}\Delta\theta_S(n)$$

$$C_{WF} = \frac{\nu_{WF} + K}{\nu_s} \cdot \frac{\eta_{SF}}{\beta^2} - 1$$

- Set of decoherence-free magic energies at $C_{WF} = 0$ (Lehrach et al (2012))

Synchrotron oscillations

- Jittering of the driven spin rotation (envelope evoluition) axis vs. phase λ

$$\vec{u}(\lambda) = \vec{u}\cos(y\cos\lambda) - [\vec{c}\times\vec{u}]\sin(y\cos\lambda)$$

$$y = C_{WF}\psi_S\xi = y_0\xi$$

- Driven rotation of each individual spin rotation in its own λ -dependent plane.

- Driven resonance tune does not depend on the synchrotron phase λ

$$\epsilon(\xi) = \epsilon J_0(y)$$

- All individual driven rotation planes share the same stable spin axis $\vec{c}$

Synchrotron oscillations and spin echo

- Averaging over synchrotron phase for initial vertical $\vec{S}(0) = \vec{c}$

$$\vec{S}(\vec{c};n) = \cos(2J_0(y)\pi\epsilon_0 n)\,\vec{c} - \boldsymbol{J_0(y)}\sin(2J_0(y)\pi\epsilon_0 n)\,[\vec{c}\times\vec{u}_s(n)]$$

- The $\cos(2J_0(y)\pi\epsilon_0 n)$ and $\sin(2J_0(y)\pi\epsilon_0 n)$ are spin envelopes from RF driven spin resonance
- Extra suppression by $\boldsymbol{J_0(y) < 1}$ of the in-plane polarization from averaging over ensemble of particle-to-particle jittering rotation planes.
- **Spin echo**: while the in-plane polarization decoheres, the amplitude of the vertical polarization stays put at unity
- No idle precessing in-plane component is generated from vertical polarization

Synchrotron oscillations

- The initial in-plane polarization $\vec{S}_p(0)$:

$$\vec{S}(\vec{S}_p; n) = J_0(y) \cos\Delta_{WF} \sin(J_0(y)\Phi)\, \vec{c}$$

$$+\frac{1}{2}\cos(J_0(y)\Phi)\,\{\cos\Delta_{WF}\left(1 - J_0(2y)\right)\vec{u}_s(n) - \sin\Delta_{WF}\left(1 + J_0(2y)\right)[\vec{c}\times\vec{u}_s(n)]\}_{\boldsymbol{driven}}$$

$$+\frac{1}{2}\{\sin\Delta_{WF}\left(1 + J_0(2y)\right)\vec{u}_s(n) - \sin\Delta_{WF}\left(1 - J_0(2y)\right)[\vec{c}\times\vec{u}_s(n)]\}_{\boldsymbol{idle}}$$

- Reminder of the spin echo: in-plane polarization decoheres stronger than the vertical one

- Driven rotation plane and the idle precession are axis rotated by an angle $\sim y^2 \tan\Delta_{WF}$

Damping of driven oscillations

- One-particle resonance strength $\epsilon(\xi) = \epsilon_0 J_0(C_{WF}\psi_s\xi)$

- Spread of driven resonance tunes → decoherence of polarization of an ensemble of particles

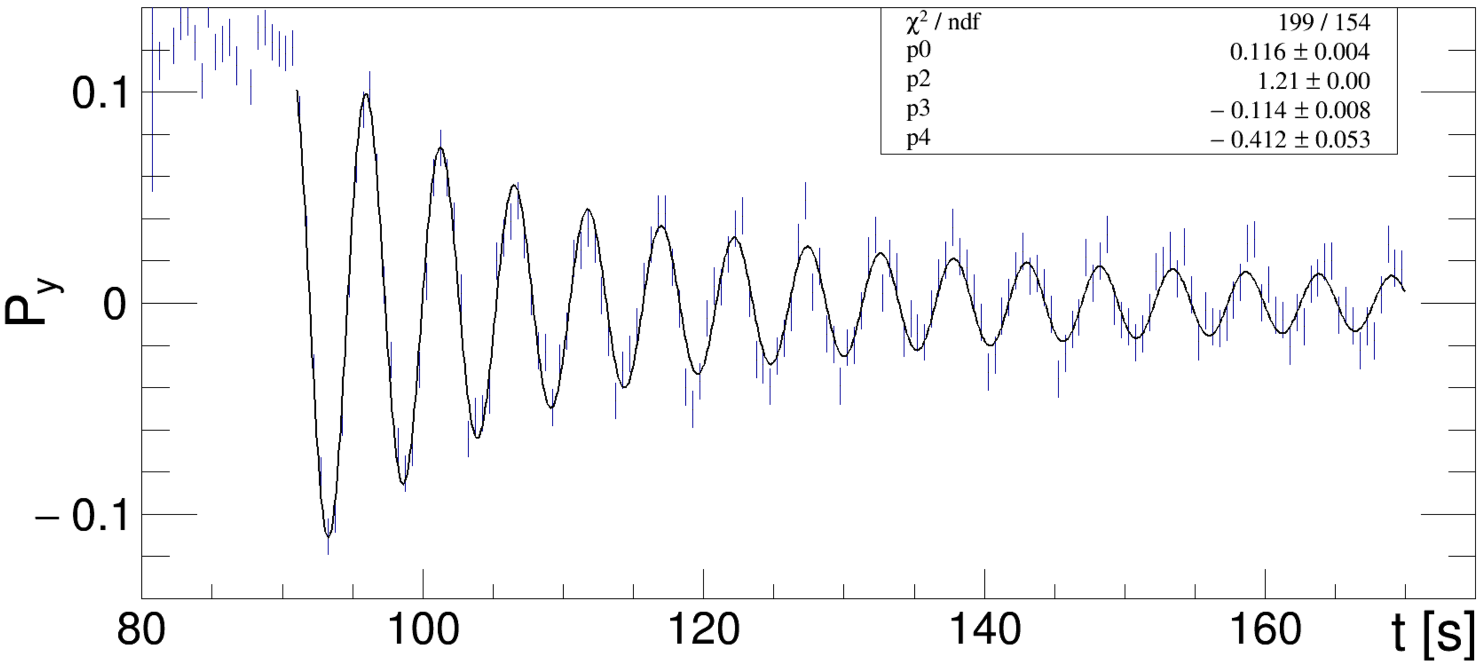
$$
\begin{aligned}
S_y &= \Re\langle \exp[-in\epsilon(\xi)]\rangle_\xi \\
&= \Re\left\langle \exp\left\{-in\epsilon_0\left[1-\frac{1}{4}C_{rf}^2\psi_s^2\xi^2\right]\right\}\right\rangle_\xi \\
&= \frac{1}{\sqrt{1+\rho^2n^2}}\cos[\epsilon_0 n-\kappa(n)]\,,
\end{aligned}
$$

- Damping parameter $\rho = \frac{1}{4}\epsilon_0 C_{WF}^2\psi_s^2$

- Phase walk $\kappa(n) = \arctan(\rho n)$

Damping of driven oscillations

- An example of damping of oscillations driven by RF Wien Filter (JEDI, November 2017, very preliminary):



- Exptl confirmation of non-exponential attenuation
- Phase walk is confirmed
- Analysis of much more data is in progress

Detuned driven spin rotations

- The phase of driven spin rotation

$$\epsilon n \Rightarrow \phi = \epsilon_0 \frac{\sin \delta_{WF} n}{\delta_{WF}} \qquad \epsilon(\xi) = \epsilon_0 J_0(C_{WF}\psi_s \xi)$$

- Decoherence

$$S_y = \frac{1}{\sqrt{1+\Phi^2}} \cos[\phi - \kappa(n)]$$

$$\kappa(n) = \arctan(\Phi)\,,$$

$$\rho n \Rightarrow \Phi = \frac{1}{4} C_{WF}^2 \psi_s^2 \phi$$

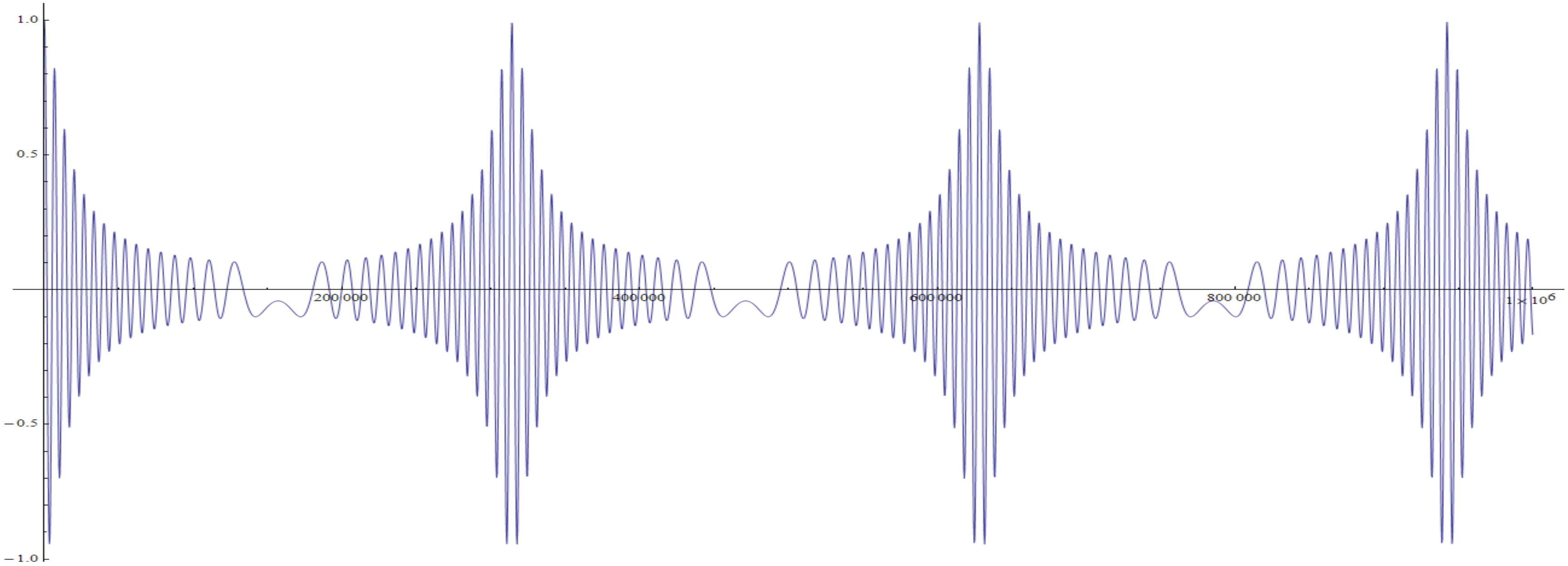
- A **spin echo:** at $\phi = \Phi = 0$, i.e., with the period ,

$$n = \frac{\pi}{\delta_{WF}}$$

spin decoherence and phase walk vanish!

- Similar spin echo in the in-plane polarization (formulas are too lengthy)

Spin echo in vertical polarization under detuning



- Artificially strong detuning for the sake of illustration of the phenomenon
- Variable driven oscillation frequency ~ cos ϕ
- Higher harmonics of detuning frequency at work

Spin in curved space-time and gravity induced false EDM effects

- New interest (and much to much noise) inspired by misleading e-prints by T. Morishima et al. PTEP (2018) no.6, 063B07 and references therein

- Promptly refuted by several authors. Good summary in arXiv:1805.01944 [hep-ph] by J. P. Miller and B. Lee Roberts

- My principal task: historical overview and vindication of early results by

A. Silenko and O. Teryaev, Phys. Rev. D71 (2005) 064016; Phys.Rev. D76 (2007) 061101;

Y. Orlov Y, E. Flanagan E and Y. Semertzidis. Phys.Lett. A376 (2012) 2822

Spin in curved space-time and gravity induced false EDM effects

The Earth as a laboratory: storage rings rests on the terrestrial surface.

No real need in full complexity of General Relativity: weak field approximation is OK, it suffices to know the free fall acceleration $\vec{g}$

Two principal effects:

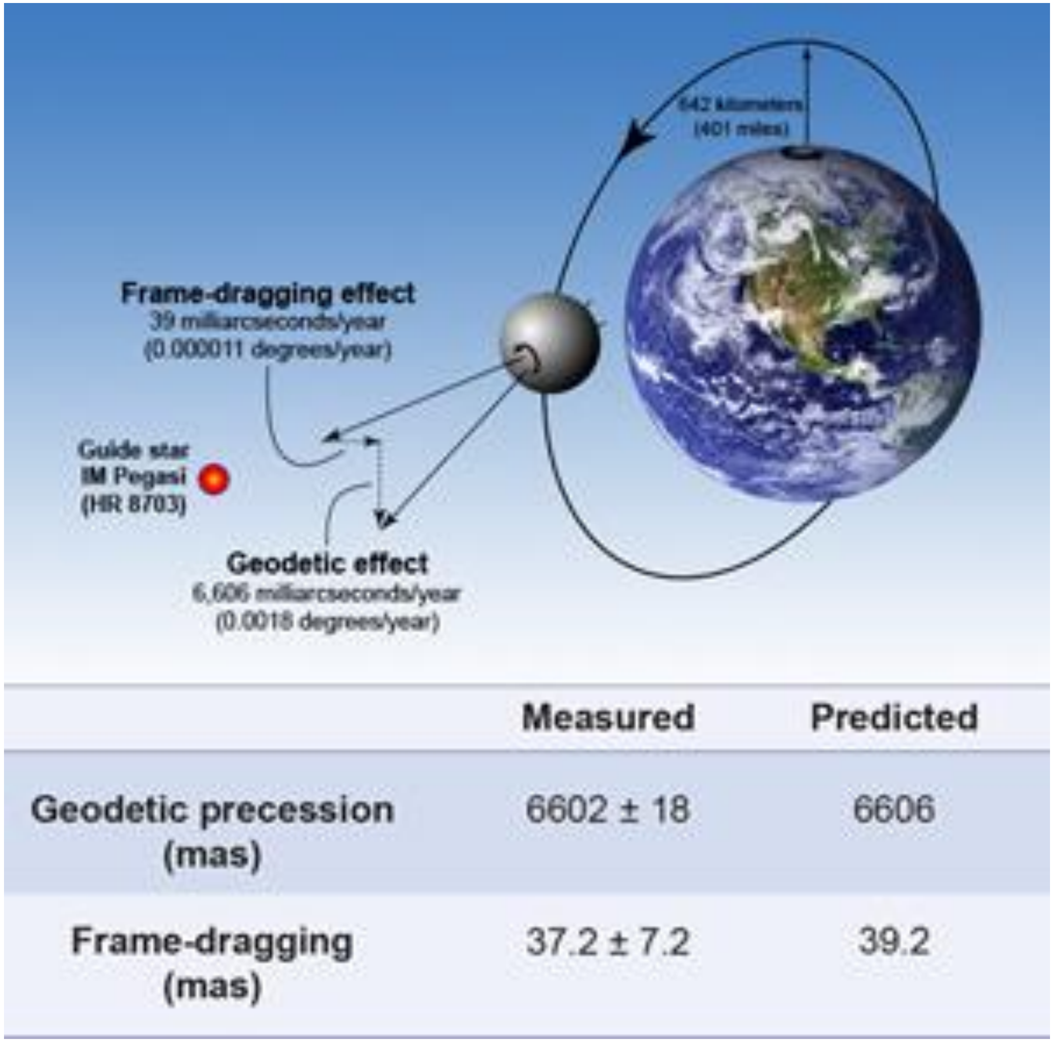
- The spin-orbit interaction in the Earth gravitational field (the de Sitter-Fokker effect, aka the geodetic effect (**1916, 1921**))
- Focusing EM fields are imperative to impose the closed paricle orbit in a storage ring compensating for the particle weight: Silenko & Teryaev (2005) for magnetic case
- The both effects have similar structure and both produce false EDM signal in frozen spin pure electric ring

- No explicit separation of the two in Orlov et al. (2012)

The spin-orbit interaction

Has been tested experimentally by Gravity Probe B

C.W.F Everitt et al. Phys.Rev.Lett. 106 (2011) 221101



	Measured	Predicted
Geodetic precession (mas)	6602 ± 18	6606
Frame-dragging (mas)	37.2 ± 7.2	39.2

De Siiter in relativistic case

The relativistic extension of the spin-orbit interaction result: .

- I.B. Khriplovich, A.A. Pomeransky, J.Exp.Theor.Phys. 86 (1998) 839-849
- A.A. Pomeransky, R.A. Senkov, I.B. Khriplovich, Phys.Usp. 43 (2000) 1055-1066

The precession frequency equals

$$\vec{\Omega}_{LS} = -\frac{2\gamma + 1}{\gamma + 1}[\vec{v} \times \vec{g}]$$

As $\vec{g}$ is normal to the storage ring plane, $\vec{\Omega}_{LS}$ describes spin precession around the radial axis.

The spin is not quite a classical object. Study the Dirac eqn. in a static gravitational field invoking the Foldy-Wouthuysen representation.

Khriplovich-Pomeransky result is fully confirmed (Obukhov, Silenko, Teryaev (2005,2016))

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Closed orbit in a storage ring

Gravity force

$$\vec{F}_g = \frac{2\gamma^2 - 1}{\gamma} m\vec{g}$$

displaces the orbit w.r.t. the electromagnetic equilibrium one.

- Never has been of any concern to accelerator builders

- Compensation by radial focusing magnetic field (Silenko, Teryaev (2005))

$$\vec{B}_r = \frac{2\gamma^2 - 1}{\gamma v^2} \cdot \frac{m}{e} \, [\vec{v} \times \vec{g}]$$

- Compensation by vertical focusing electric field (Obukhov et al. (2016), can be digged out also from the earlier work by Orlov et al (2012))

$$\vec{E}_y = -\frac{2\gamma^2 - 1}{\gamma} \cdot \frac{m}{e} \, \vec{g}$$

Amounts to the motional **imperfection radial magnetic field** $\propto [\vec{v} \times \vec{g}]$

False EDM from gravity

Gravity acts as an imperfection radial magnetic field.

- Absolute evil in an all electric EDM ring - false EDM signal

- Obukhov et al. (2016))

$$\vec{\Omega}_{gE} = \frac{1 - G(2\gamma^2 - 1)}{\gamma c^2}[\vec{v} \times \vec{g}]$$

- Upon the frozen spin constraint $v^2 = \frac{1}{1+G}$

$$\vec{\Omega}_{gE} = \frac{g\sqrt{G}}{c}\vec{e}_r$$

- First derived by Orlov et al. (2012) by brute force solution of GR equations without explicit separation of the spin-orbit and focusing effects.

- Similar derivation by Laszlo et al. arXiv: 1803.01395 [gr-qc]

- Gravity effect (a) can be cancelled out with counterrotating beams, (b) can be used as a candle to control the systematics

Magic ring for deuterons

New simple result for $G < 0$: frozen spin with crossed E- and B-fields

- Pure magnetic field (Silenko, Teryaev (2005)

$$\vec{\Omega}_{gM} = -\frac{1}{\gamma v^2}\{1 + G(2\gamma^2 - 1)\}[\vec{v} \times \vec{g}]$$

- Frozen spin condition in the E × B ring

$$\left[\vec{v} \times \vec{B}_y\right] = \frac{1}{G}\{1 - v^2(1 + G)\}\vec{E}_r$$

- Focusing forces are propto a dispacement from the EM equilibrium orbit

$$\kappa = \frac{vB_r}{E_y} \approx const$$

Depends on the ring design

- Frequency of gravity induced false EDM signal

$$\vec{\Omega}_g = -\frac{1}{1 + \kappa}(\vec{\Omega}_{gE} + \kappa\vec{\Omega}_{gM})$$

Summary:

The srEDM and JEDI experimental plans have motivated new interesting results on spin dynamics in storage rings (spin tune mapping, RF Wien Filter, nonexponential spin decoherence, spin echo…)

COSY@Juelich is and will remain a unique facility for such studies

Systematic backgrounds from ring imperfection effects are and will remain of the major concern: only the first scratch of all-magnetic case (NICA?)

Still Terra Incognita for all-electric rings despite first forays

Example of unexpected imperfection in all-electric rings: systematic false EDM effect from gravity (first discovered in **1916 !**) is fully understood & Orlov-Flanagan-Semertzidis result vindicated

Future: CPEDM in the formative stage. **A good piece of physics for NICA.**

Talks by Yuri Filatov and Anatoly Kondratenko at this meeting

Summary and outlook

The srEDM and JEDI experimental plans have motivated new interesting results on spin dynamics in storage rings (spin tune mapping, nonexponential spin decoherence, spin echo…)

COSY@Juelich is and will remain a unique facility for such studies (**don’t miss a chance at NICA! --- accelerator and spin dynamics studies are imperative)**

Systematic backgrounds from ring imperfection effects are and will remain the major concern: only the first scratch off all-magnetic case

Still Terra Incognita for all-electric rings despite first forays

Exsmple of imperfection in all-electric rings: systematic false EDM effect from gravity (first discovered in 1916 !) is fully understood & Orlov-Flanagan-Semertzidis result vindicated

Future: CPEDM in the formative stage

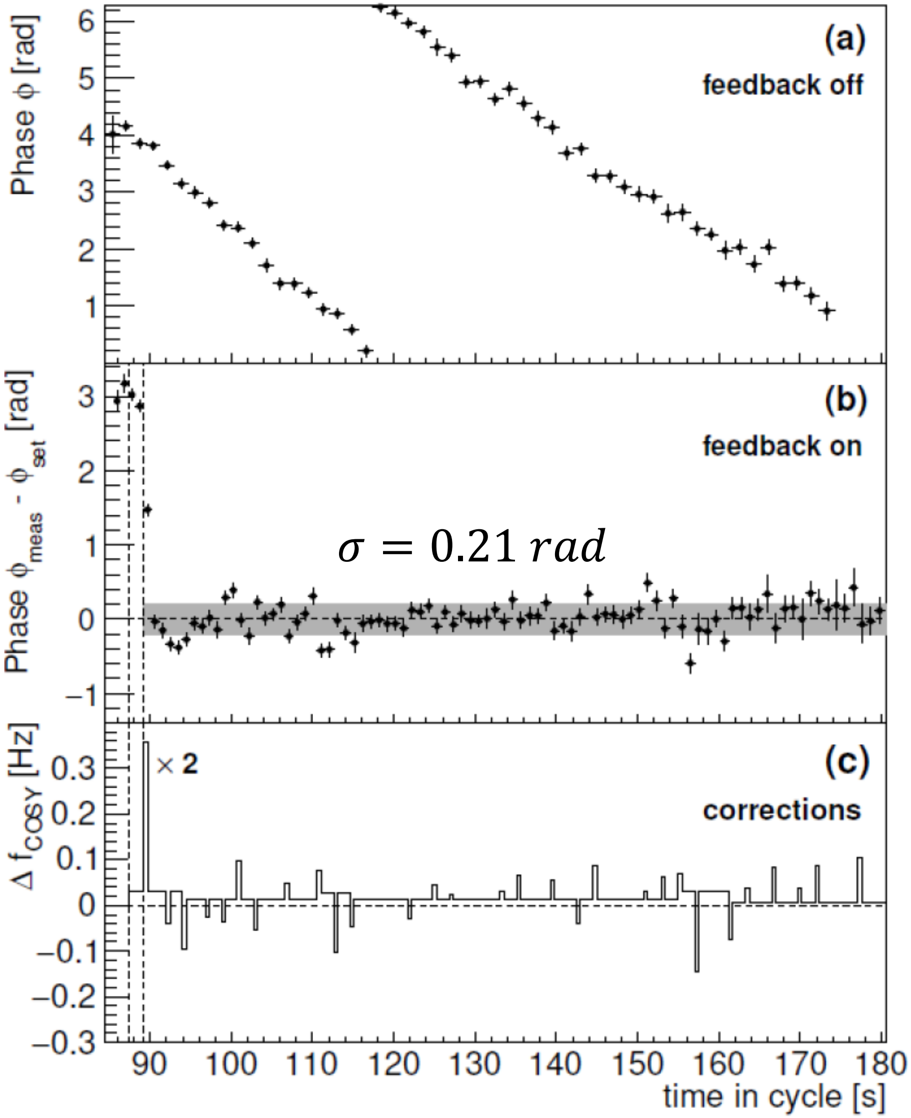
JEDI: Phase lock to maintain resonance condition

- 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}

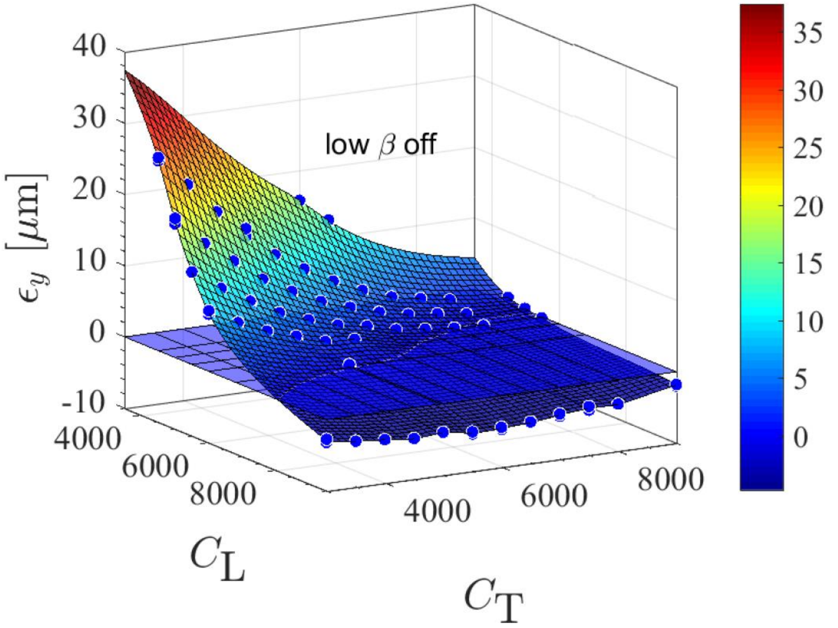
- Early tests conducted rather varying spin tune at fixed RF by changing RF cavity frequency (revolution freq. changes) →

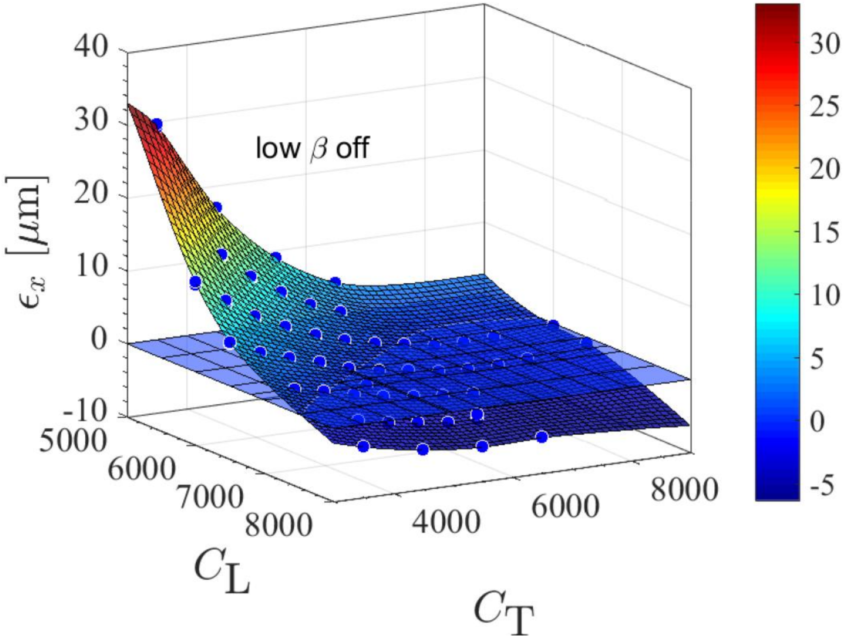
- Spin phase was maintained constant within 0.21 rad



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:



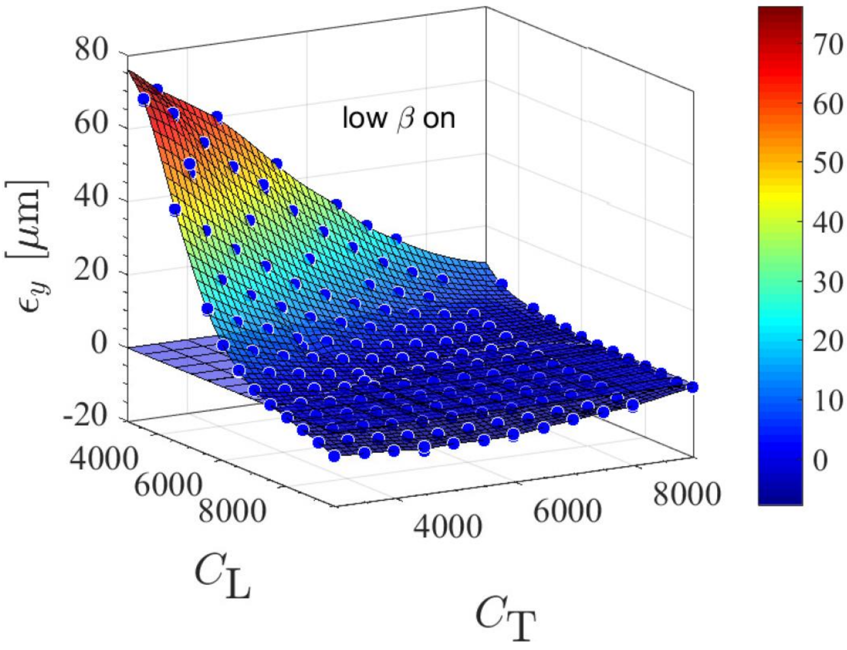


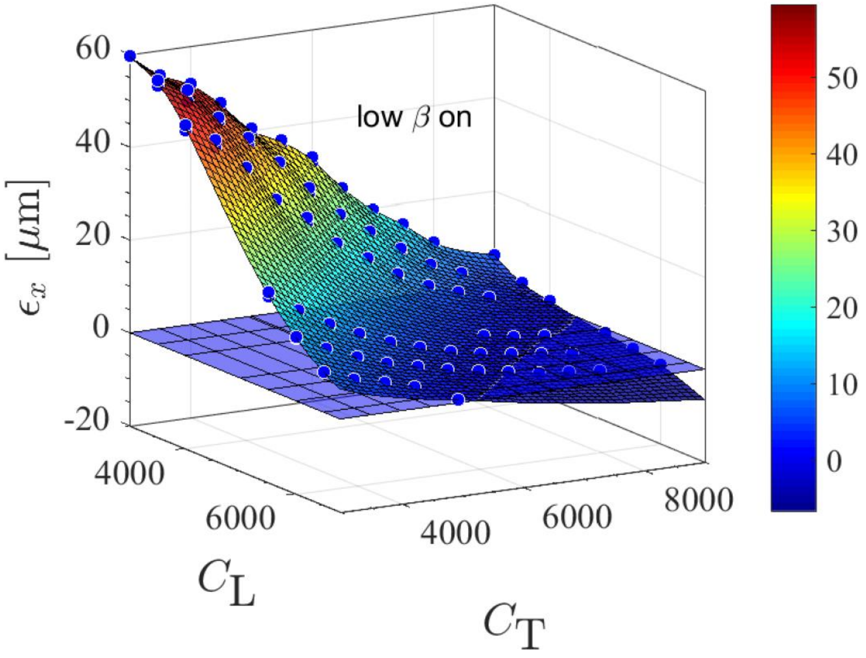
- Effects are different for different RF harmonics

JEDI: Lorentz force properties of RF WF

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

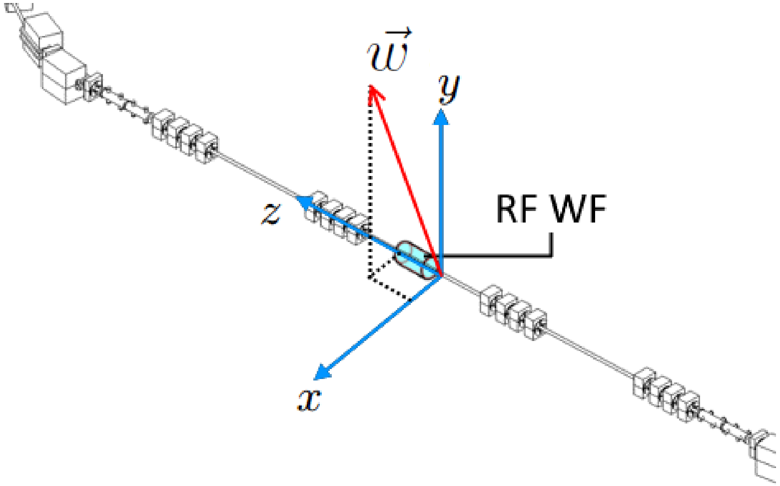
- Orbit effects are amplified at low-β :





JEDI: controlling alignment of RF WF

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



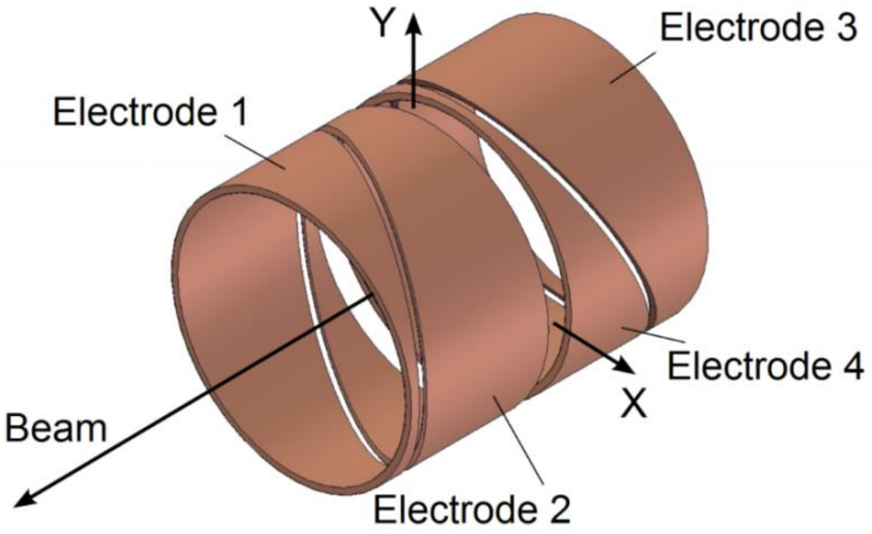
- New electronic levels implemented to set WF rotation angle with accuracy of at least 170 μrad:

- 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

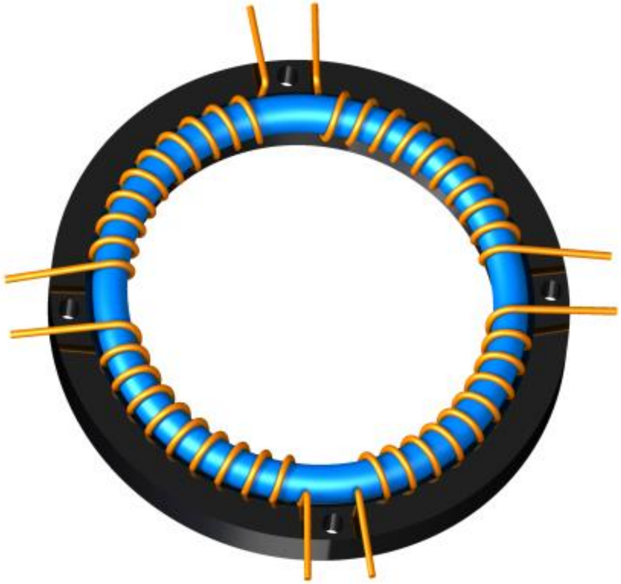
JEDI: Rogowski coil beam position monitors

Conventional BPM



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

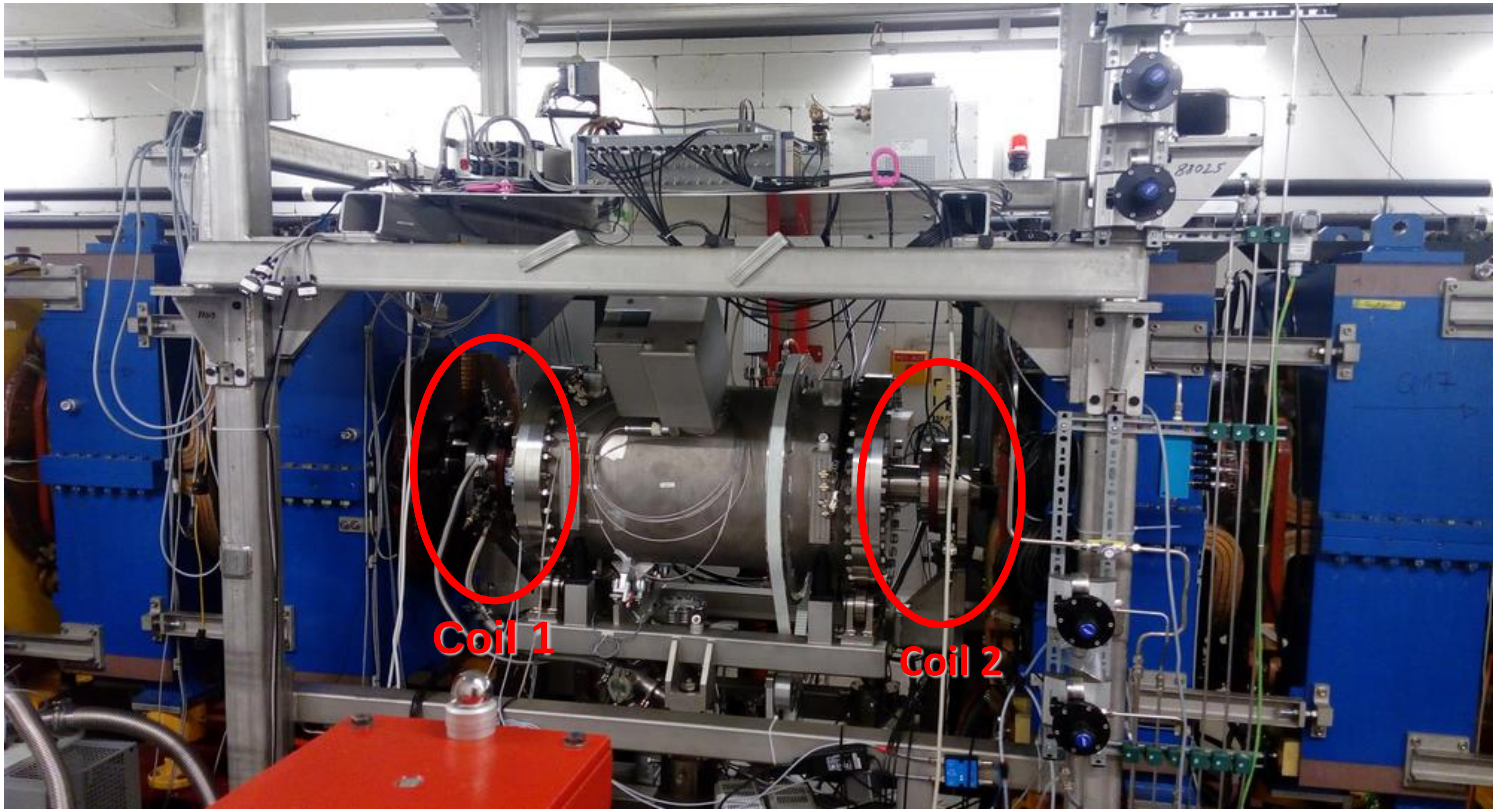
Rogowski coil BPM



- 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

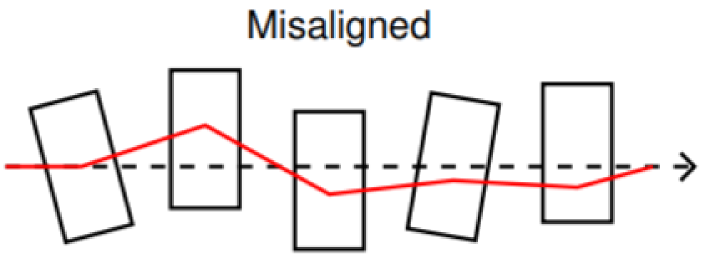
- Two Rogowski coils installed at entrance and exit of RF Wien filter



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



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Driven oscillations off-resonance

- Spin echo for vertical polarization

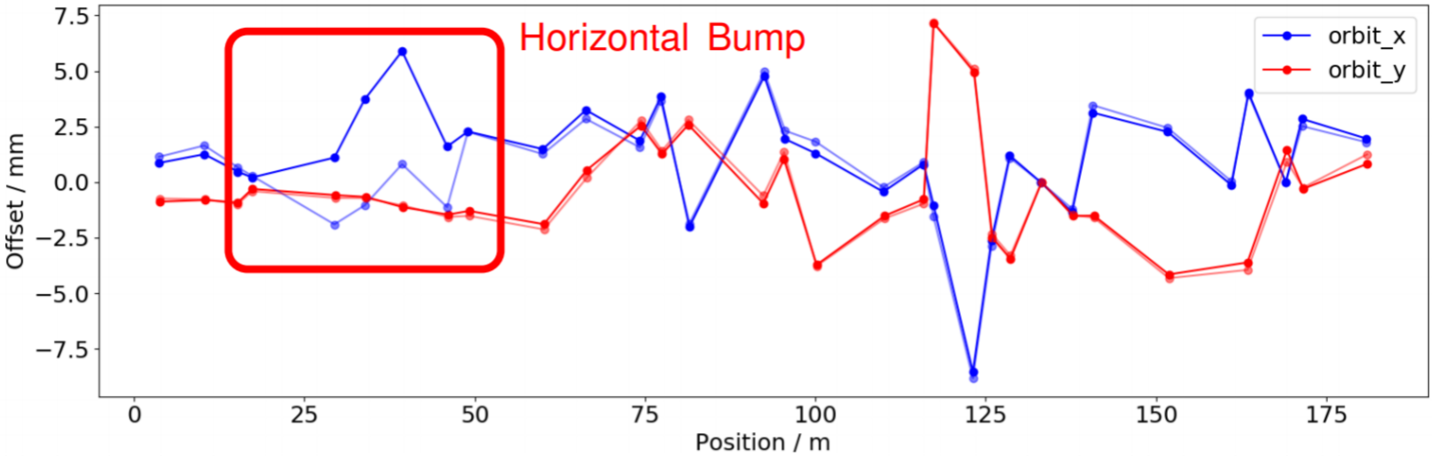
$$S_y = \frac{1}{\sqrt{1+\Phi^2}}\cos[\phi - \kappa(n)]$$

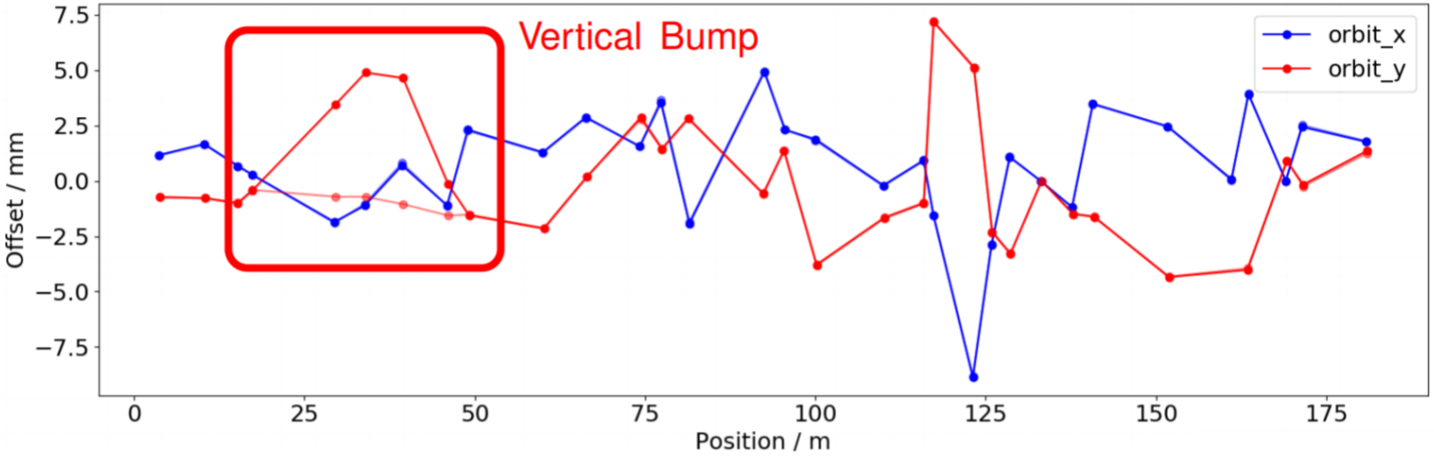
$$\kappa(n) = \arctan(\Phi)\,,$$

- At $\phi = \Phi = 0$.e., $n = \frac{\pi}{\delta_{WF}}$ enuation and phase walk vanish: a **"spin echo"** !

Beam-based alignment at COSY

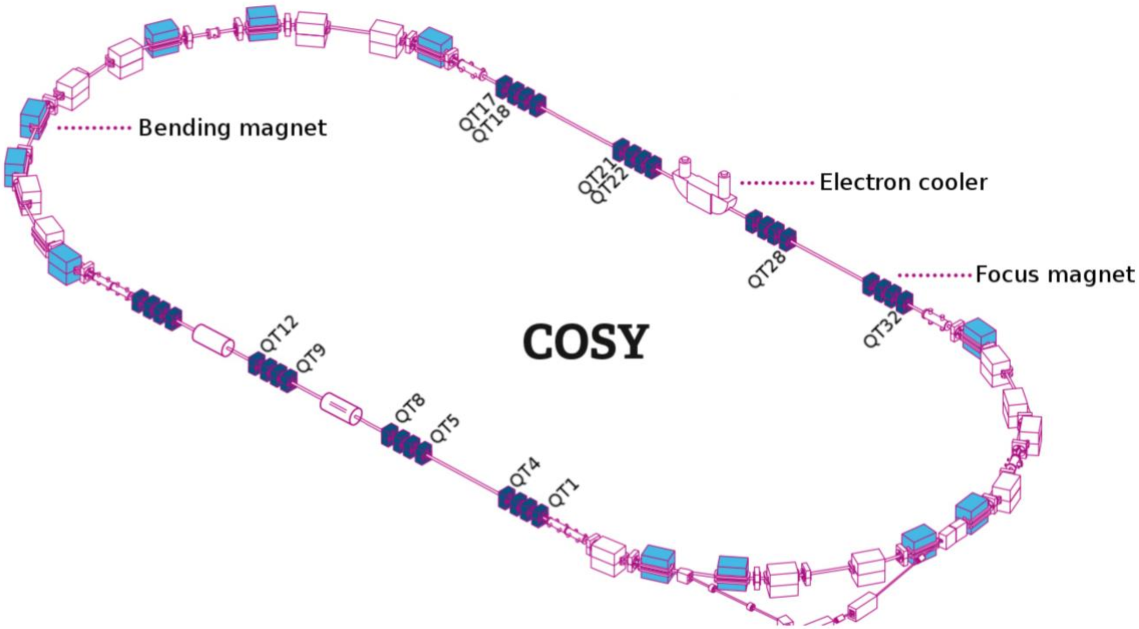
- Steerers around the quadrupole QT12 (located at 30 m) are varied to adjust the beam position inside the quadrupole





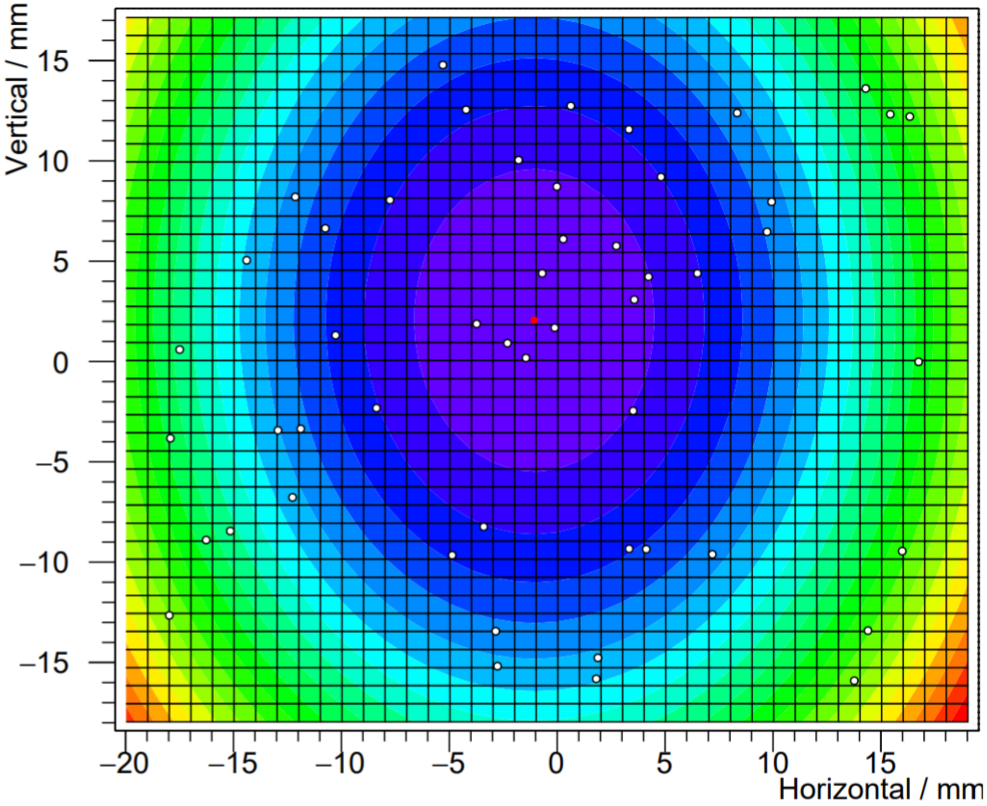
Beam-based alignment at COSY cont’d

- 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:



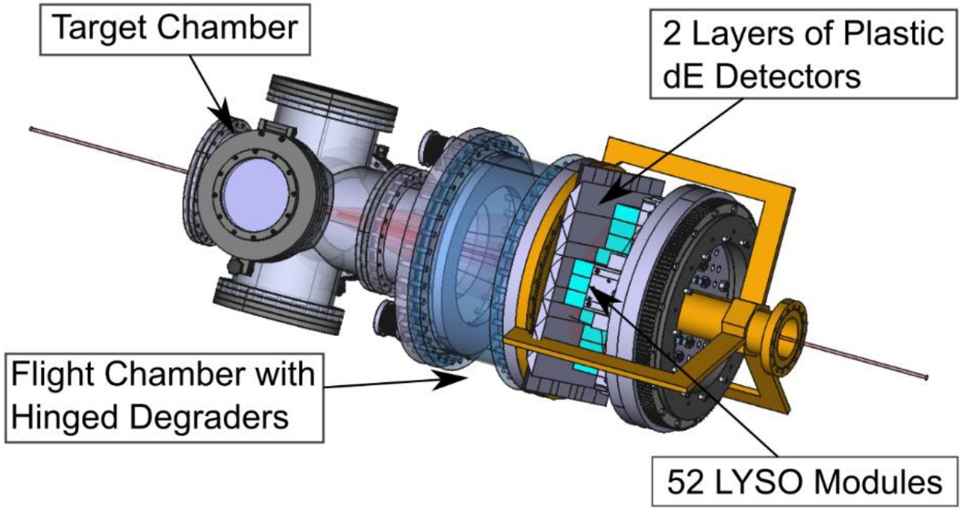
X = −1.14 ± 0.02 mm
Y =   2.08 ± 0.03 mm

Outlook:
All quadrupole magnets to be controlled

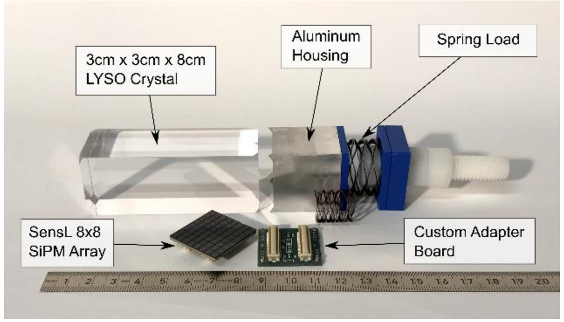
JEDI: from EDDA to WASA to dedicated LYSO polarimetry

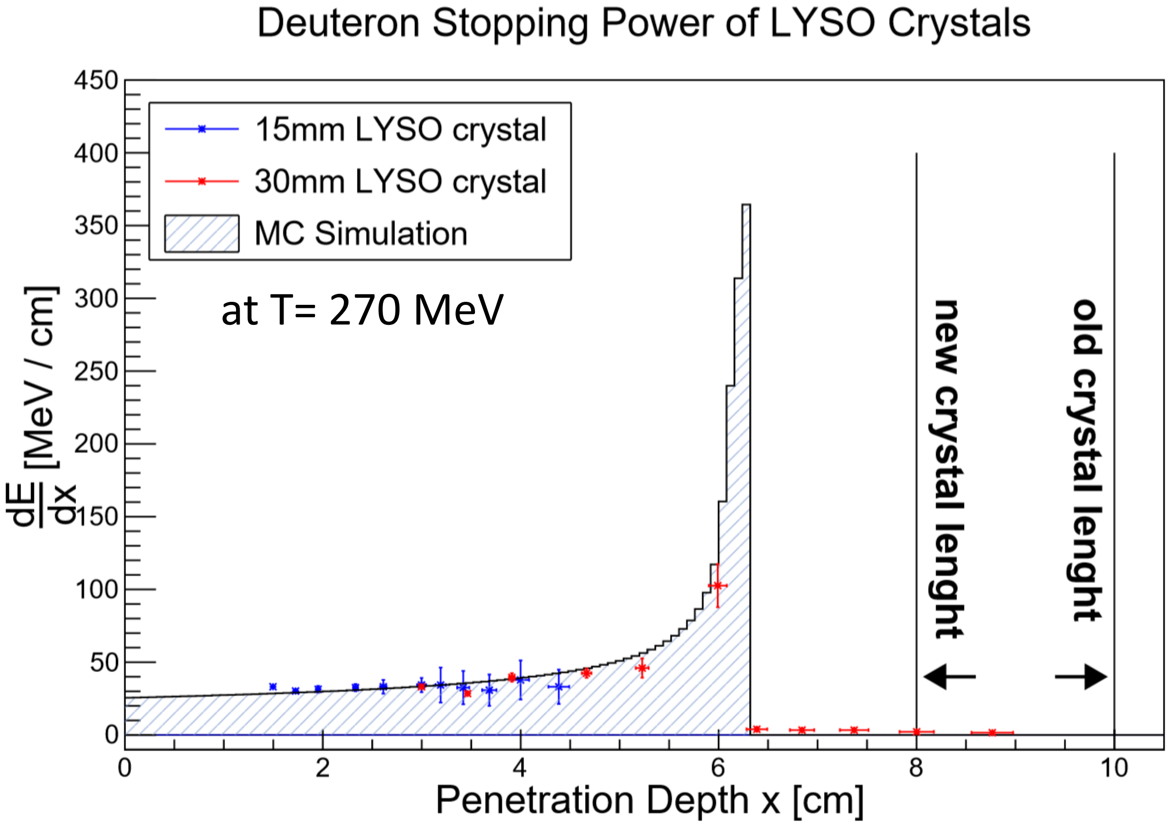
- Early studies were based on EDDA polarimeter
- Present studies: WASA is a polarimeter

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

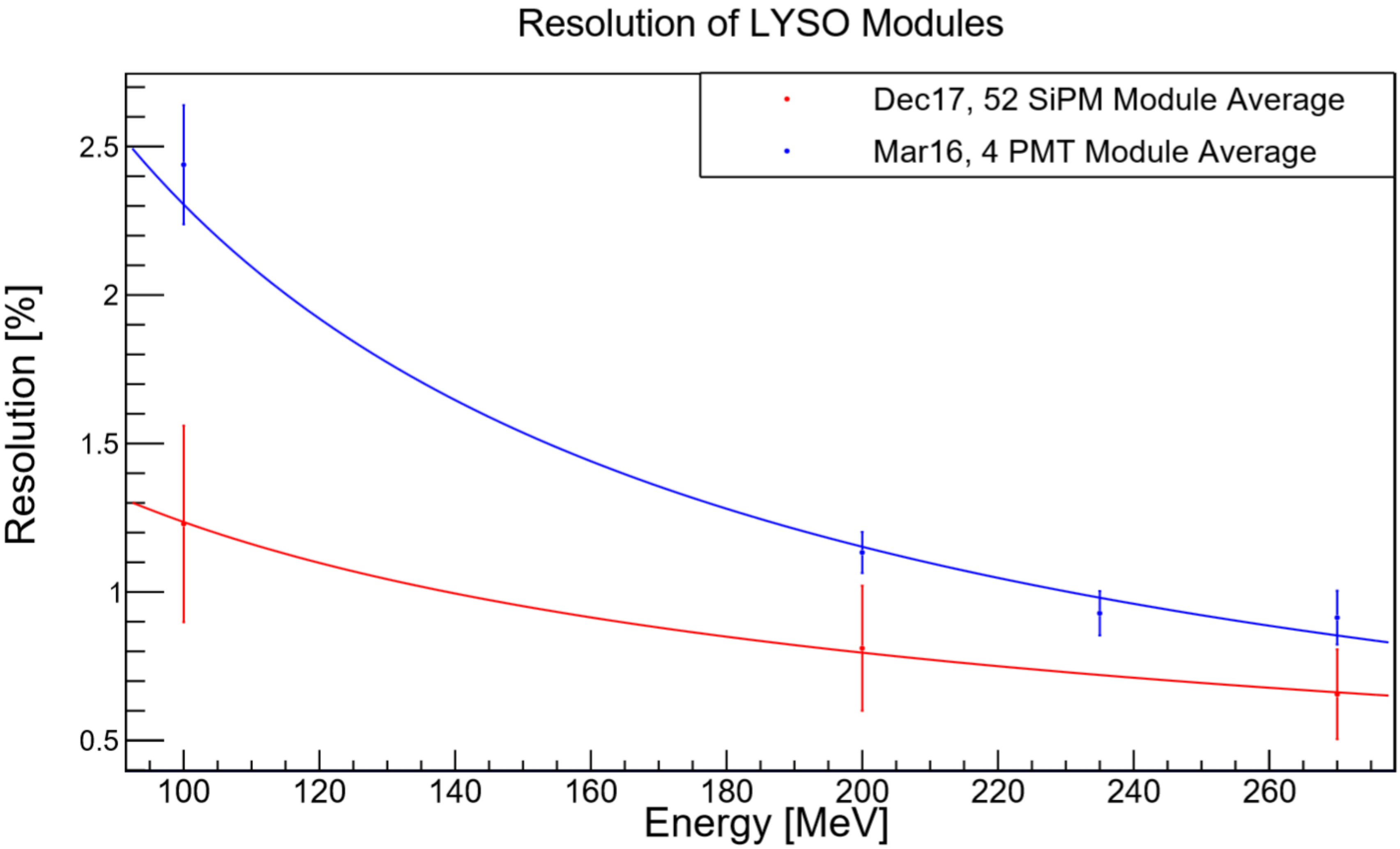


JEDI polarimeter based on LYSO calorimetry





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
- dσ/dΩ 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: (Py,Pyy) = (0,0), (-⅔,0), (⅔,0), (½, -½), (-1, 1)
- Targets: C and CH2

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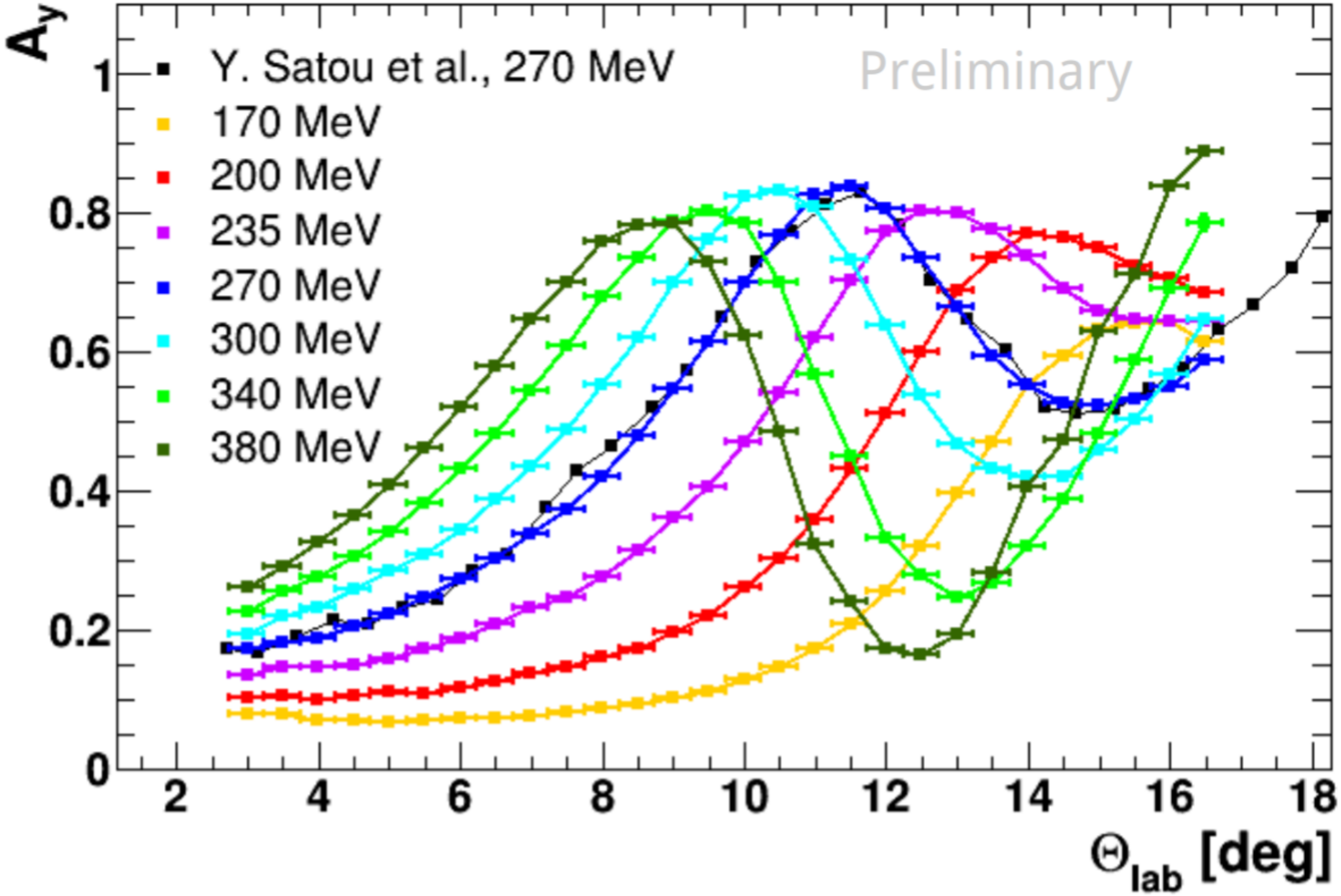
JEDI: database experiment at WASA

- Vector Analyzing power for elastic dC scattering



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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? --- part of the Physics Beyond the Standard Model and Beyond LHC: CDR to be prepared for fall 2018)
- Crossed ExB field prototype EDM storage ring might be an option before going to TDR for ultimate EDM machine

Damping of driven oscillations

- One-particle resonance strength $\epsilon(\xi) = \epsilon_0 J_0(C_{WF}\psi_s\xi)$

- Spread of resonance strengths --→ decoherence of polarization of an ensemble of particles

$$S_y = \Re\langle\exp[-in\epsilon(\xi)]\rangle_\xi$$

$$= \Re\left\langle\exp\left\{-in\epsilon_0\left[1-\frac{1}{4}C_{rf}^2\psi_s^2\xi^2\right]\right\}\right\rangle_\xi$$

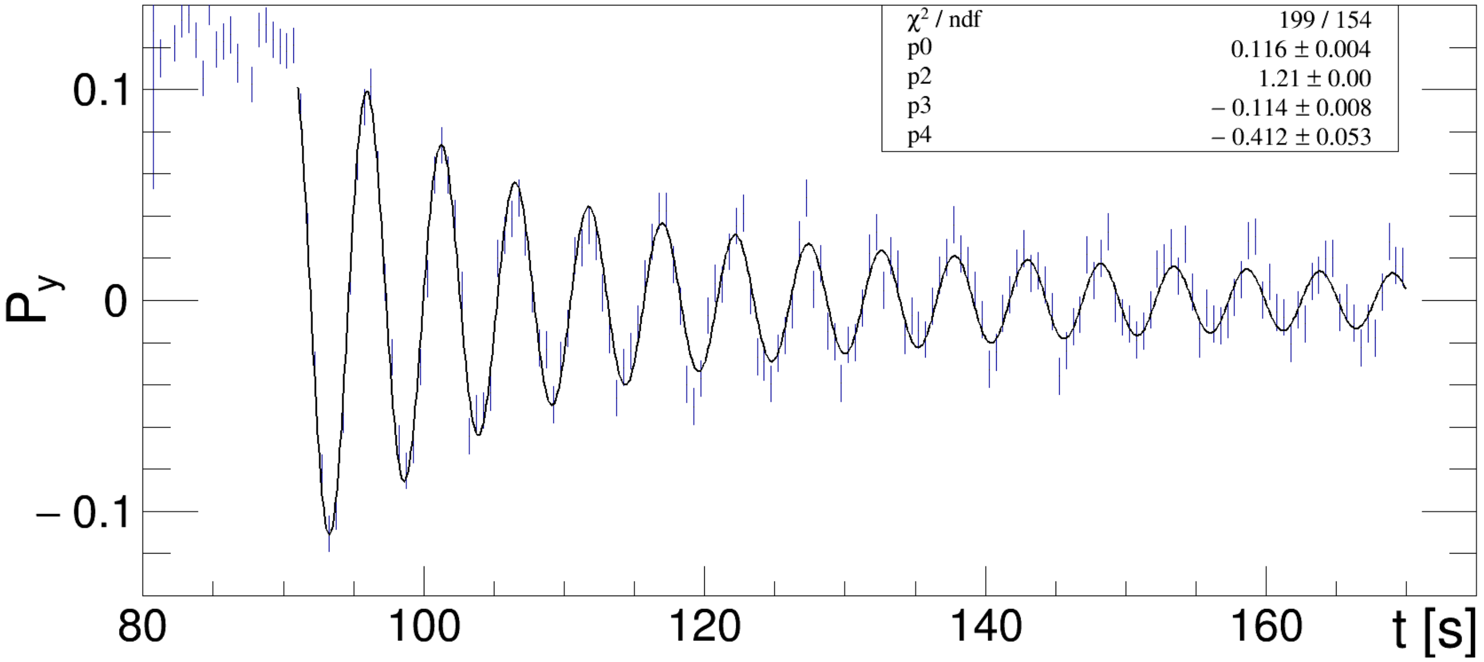
$$= \frac{1}{\sqrt{1+\rho^2n^2}}\cos[\epsilon_0 n - \kappa(n)] \,,$$

- Damping parameter $\rho = \frac{1}{4}\epsilon_0 C_{WF}^2\psi_s^2$

- Phase walk $\kappa(n) = \arctan(\rho n)$

Damping of driven oscillations

- An example of damping of oscillations driven by , RF Wien (JEDI, November 2017, very preliminary):



- p0-initial amplitude of oscillation
- p2-oscillation frequency(*2π)
- p3-parameter of damping
- p4 -normalization for running phase function

Summary and outlook

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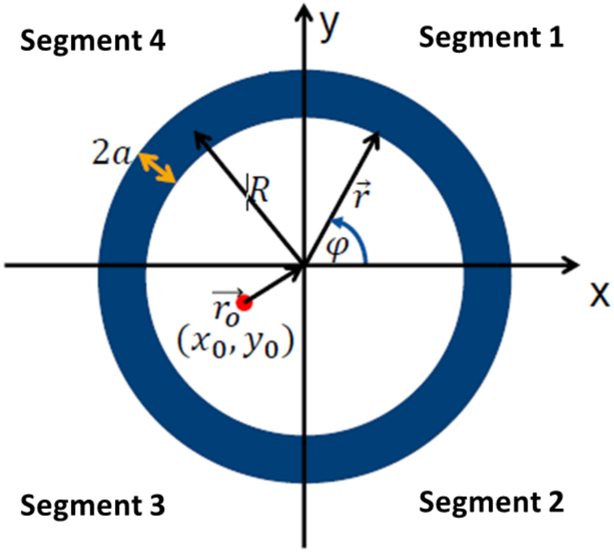
Position determination



$$\frac{\Delta \mathrm{U}_{\mathrm{hor}}}{\Sigma \mathrm{U}_i} = \frac{(\mathrm{U}_1 + \mathrm{U}_2) - (\mathrm{U}_3 + \mathrm{U}_4)}{\mathrm{U}_1 + \mathrm{U}_2 + \mathrm{U}_3 + \mathrm{U}_4} \qquad \frac{\Delta \mathrm{U}_{\mathrm{ver}}}{\Sigma \mathrm{U}_i} = \frac{(\mathrm{U}_1 + \mathrm{U}_4) - (\mathrm{U}_2 + \mathrm{U}_3)}{\mathrm{U}_1 + \mathrm{U}_2 + \mathrm{U}_3 + \mathrm{U}_4}$$

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

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

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

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

Coil parameters

R = 58.625 mm

a = 6.375 mm

n = 434

s = 0.15 mm

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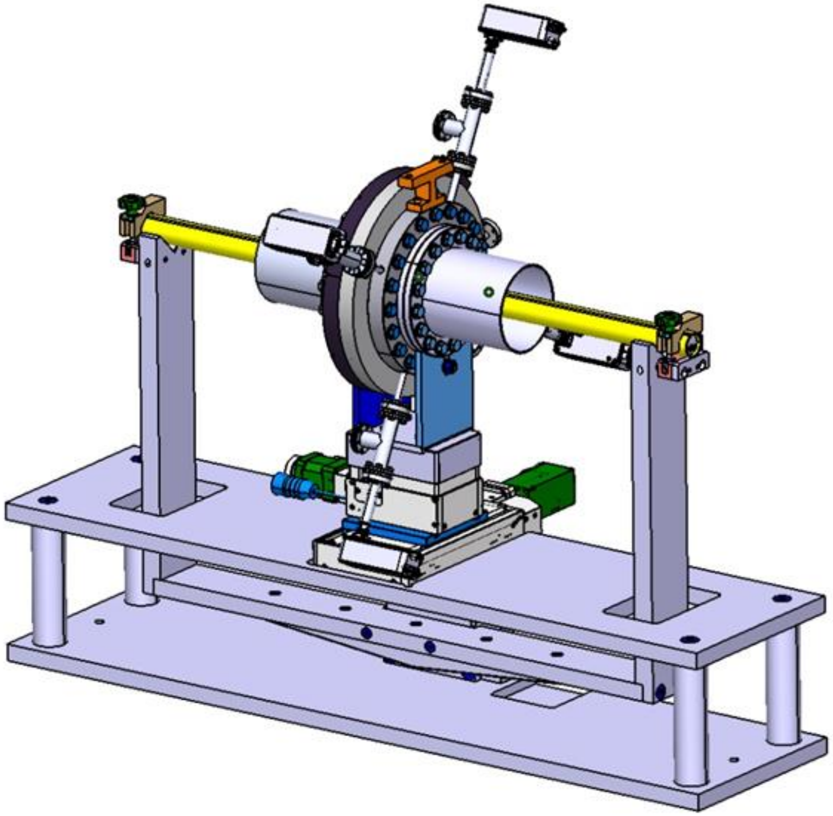
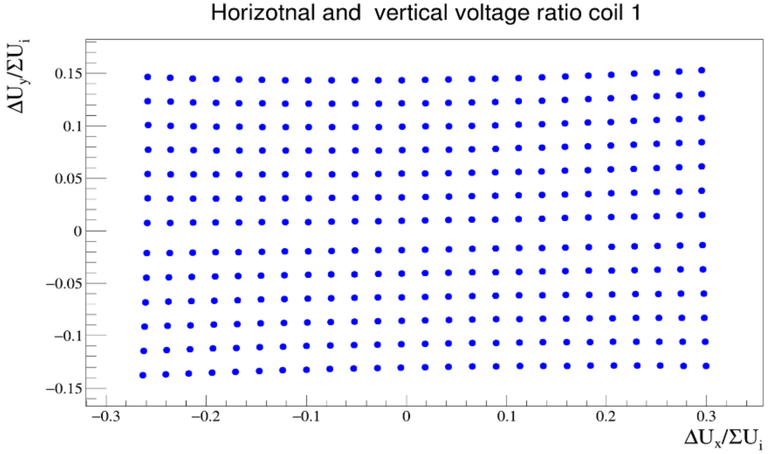
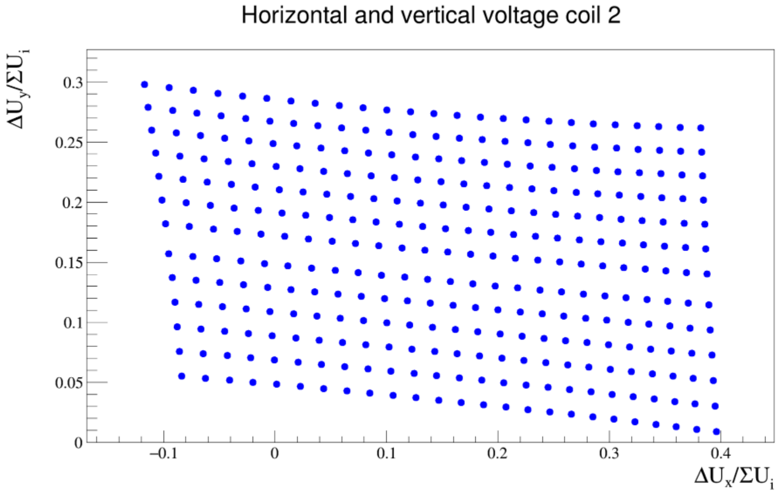
Calibration




Horizotnal and vertical voltage ratio coil 1


Horizontal and vertical voltage coil 2

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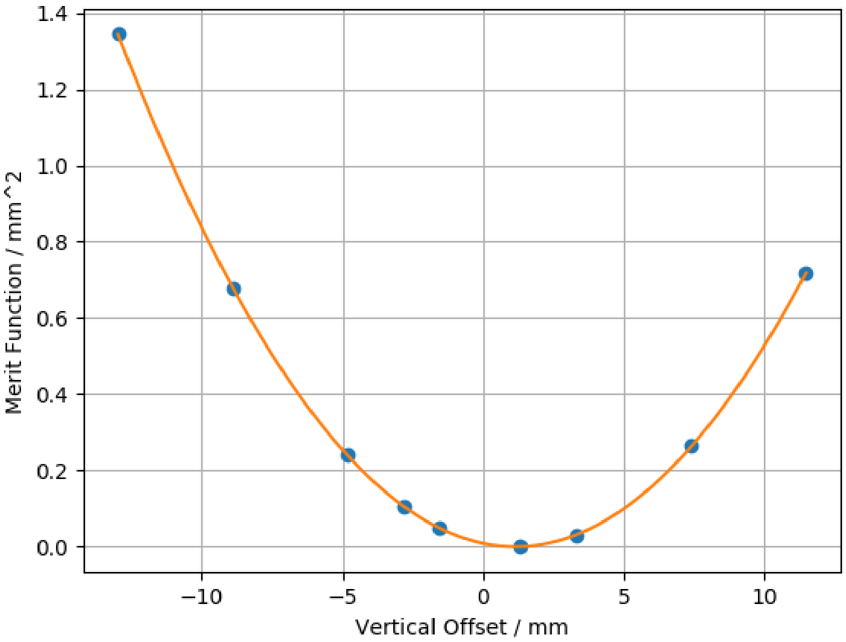
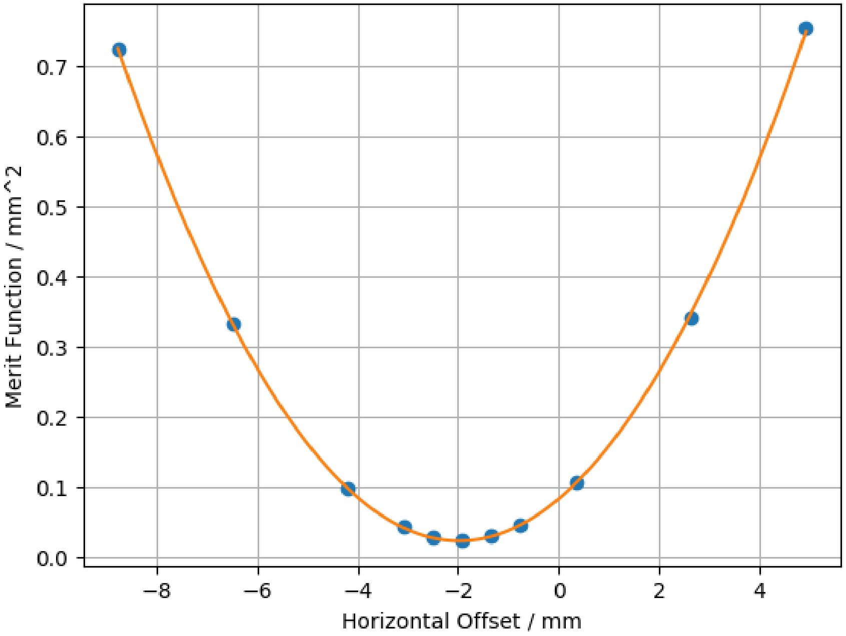
Beam-based alignment

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

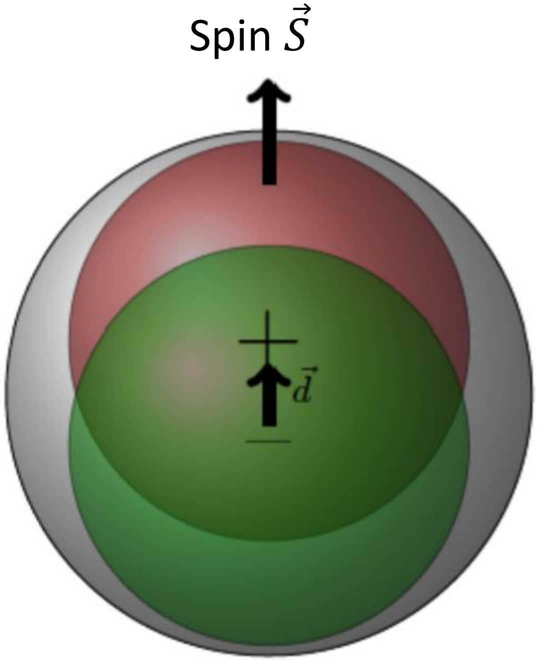
$$f \propto (\Delta x)^2 \propto (x(\bar{s}))^2$$

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





Electric dipole moment and fundamental symmetries



- Permanent separation of + and - charges
- EDM $\vec{d}$ and MDM $\vec{\mu}$ of particle are aligned along spin $\vec{S}$
- Possible only if P and T-symmetries are broken

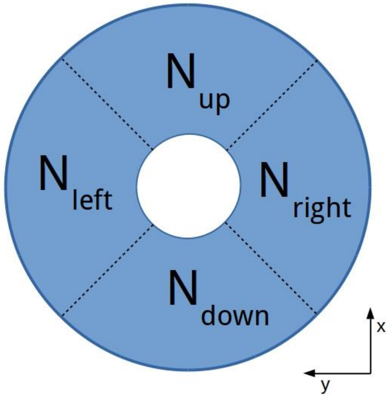
JEDI Collaboration at IKP FZJ

- Based at COSY in Juelich: unique facility for EDM-related spin dynamics
- About 120 participants
- Belarus – France – Georgia – Germany – JEDI – JINR Dubna – Italy – Poland - Republick of Korea – Russia – Sweden – United Kingdom – USA
- http://collaborations.fz-juelich.de/ikp/jedi/documents/colpapers.shtml

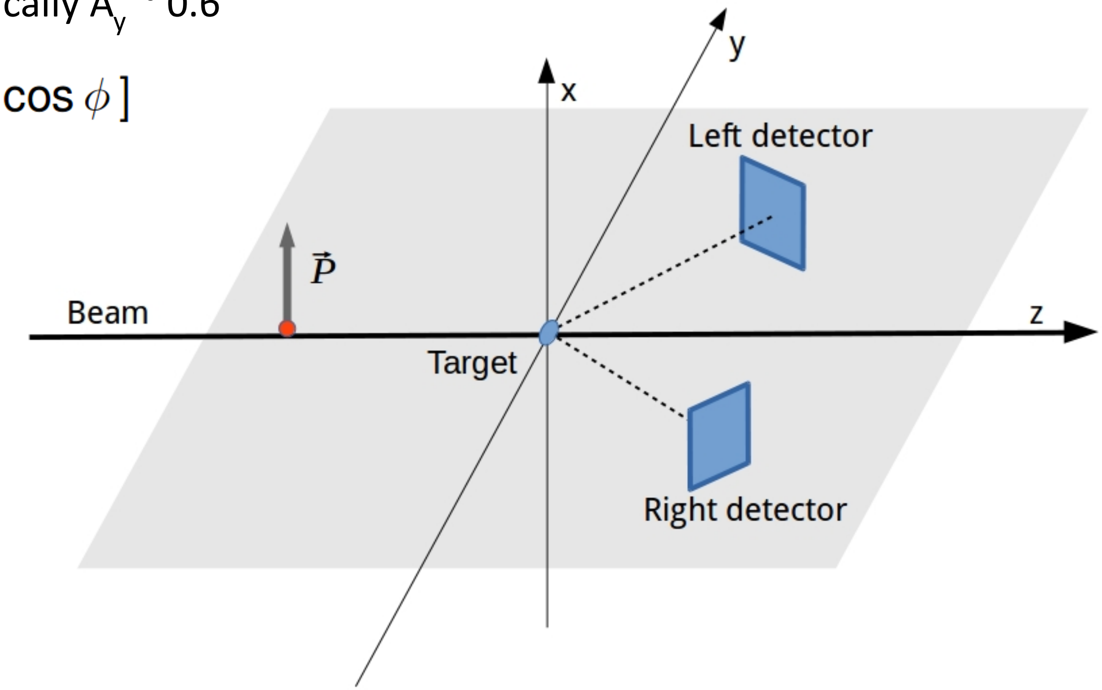
How to measure beam polarization?

- Scattering from Carbon target, typically A_y ~ 0.6

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



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

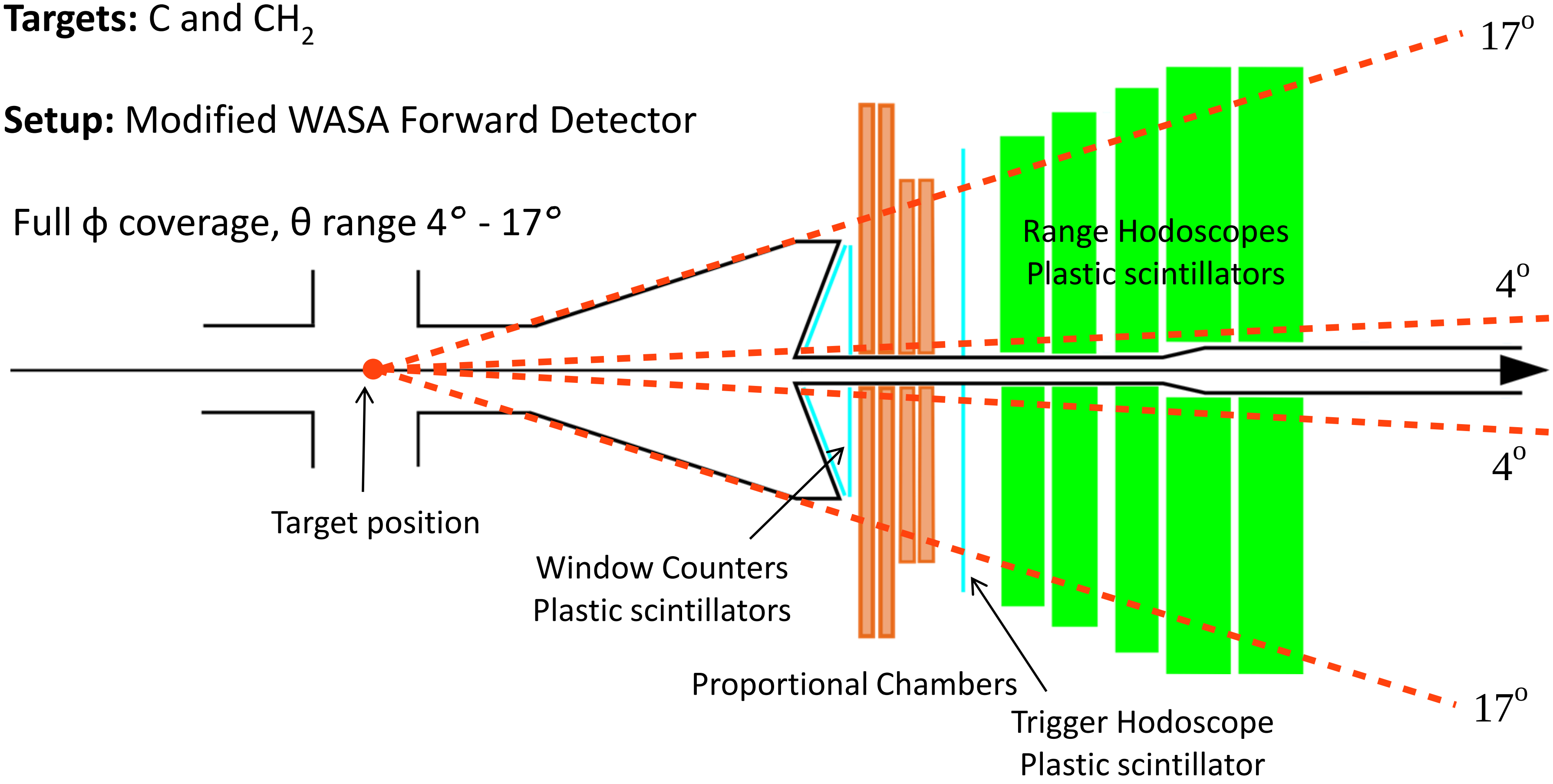
JEDI: polarimetry at COSY (so far a junkyard approach)

- 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°



Range Hodoscopes
Plastic scintillators

Target position

Window Counters
Plastic scintillators

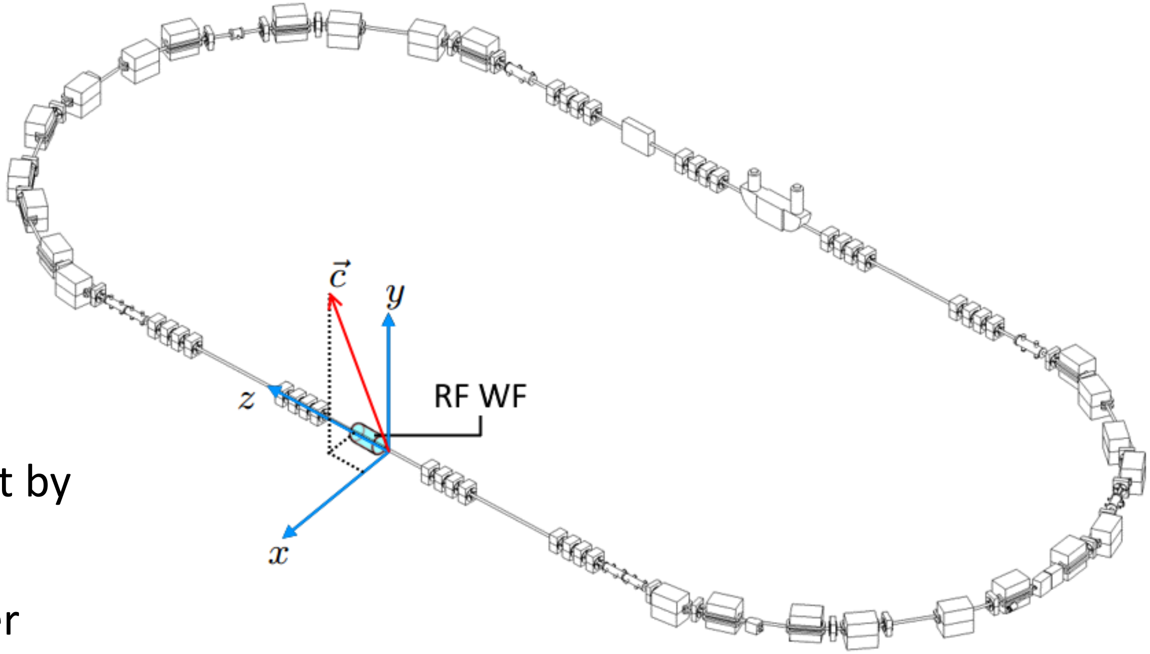
Proportional Chambers

Trigger Hodoscope
Plastic scintillator

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

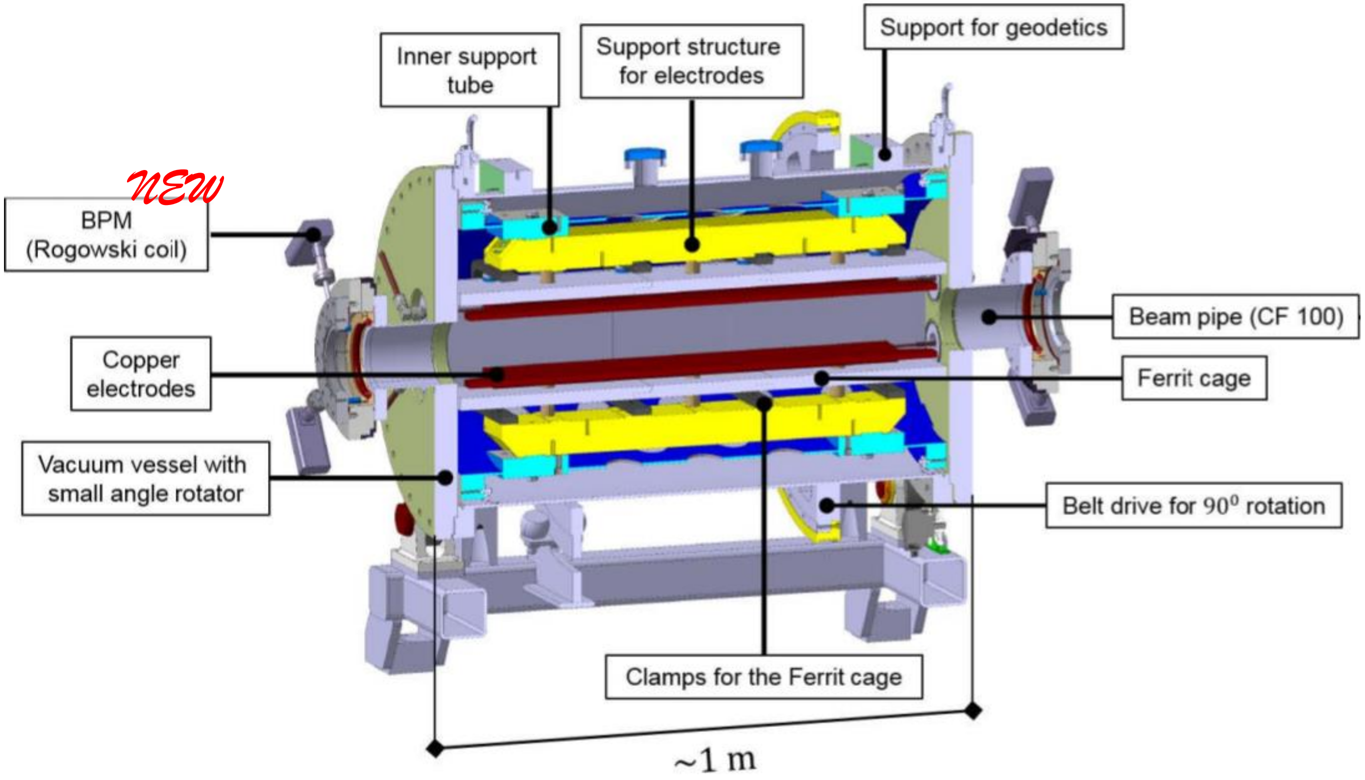
- In pure magnetic storage ring, T-BMT eq.:
- $\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S}(t) = -\frac{q}{m}\left(G\vec{B} + \frac{1}{2}\eta(\vec{E} + \vec{\beta} \times \vec{B})\right) \times \vec{S}(t)$
- EDM effect in the stable spin axis: $\vec{c} = \vec{e}_x \sin \xi_{\mathrm{EDM}} + \vec{e}_y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

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



- 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



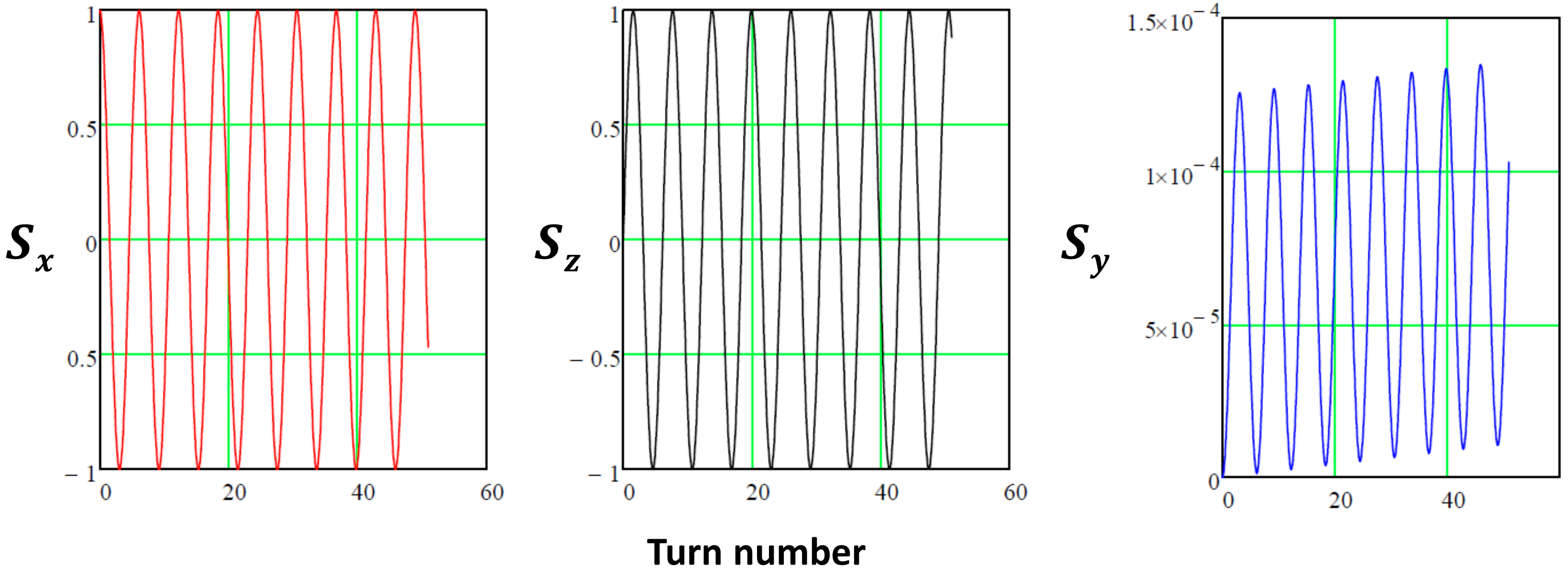
- RF spin rotation by radial E and vertical B fields without orbit distortions
- Developed at FZJ in collaboration with RWTH-Aachen
- Installed in the PAX low-β section at COSY

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

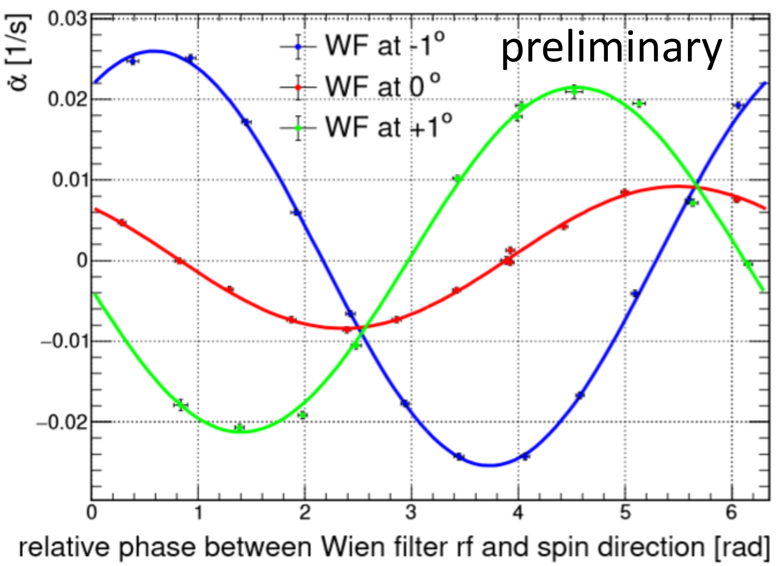
$$\theta_{\mathrm{RF}}(n) = \theta_{\mathrm{s}}(n) + \Delta_{\mathrm{RF}}$$

- 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 $d_{\mathrm{d}} = 10^{-19} e \cdot cm$:



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

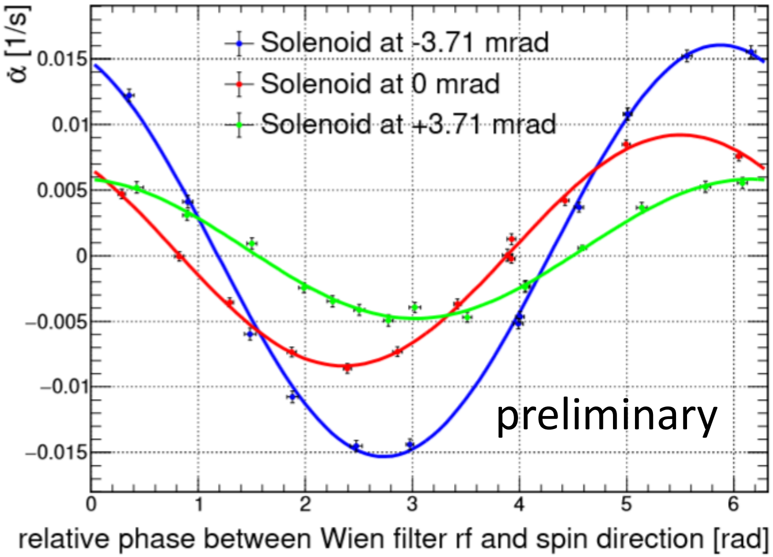


- Rotate Wien filter by small angle ξ_z around Z-axis

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

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

Synchrotron oscillations

Synchrotron oscillations: Nikolaev, Saleev, Rathmann, JETP Lett. 106(4), 213-216 (2017)

- Individual spin doesn't decohere, polarization decoherence comes from averaging over an ensemble.

- Bunch density and synchrotron amplitude, a_z, distributions are related by the Abel transform.

- A Gaussian bunch as an working approximation:

$$N_z \propto \exp(-z^2/B^2)$$

$$F\left(\xi = \frac{a_z}{B}\right) = 2\xi \exp(-\xi^2)$$

- Bunch length is related to $\Delta p/p$

Spin rotation with RF Wien filter

- With RF WF, spin resonance strength is

$$\epsilon = \frac{1}{2}\chi_{\rm WF}\,|\vec{c}\times\vec{w}|$$

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

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

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

- Slope of the vertical polarization build-up

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

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

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