EDM at Storage Rings: From JEDI@COSY to CPEDM

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DSpin-2019, 2-6 September 2019, JINR, Dubna, Russia

Outlook:

- EDM: why? Fundamental symmetries and baryogenesis
- EDM: how? Spin rotation in electric fields --- storage ring a must for charged particles
- JEDI@COSY: selected record setting results from a unique facility
- Principal evil: false EDM-like signal from MDM in imperfection magnetic fields
- JEDI@COSY: spintune mapping as a tool to quantify, and correct for, the imperfection fields
- JEDI@COSY: RF resonance tune mapping as a tool to quantify, and correct for the imperfection fields
- JEDI@COSY rtsults3: pathways to the dedicated EDM storage rings
- CPEDM initiative → looking forward to the first ever all electric EDM ring
- JEDI publications in

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 JEDI experiment at COSY: dEDM $\sim 10^{-20}$ is within reach?
- **Sequel to JEDI**: **CPEDM** prototype 30 MeV pure electric ring (at CERN? at COSY?...) --- big international effort, 250+ page CERN Yellow Report to be made public in 2019

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

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

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

Summary of upper bounds on the EDM

Particle	Current limit	Goal	d_n equivalent goal	Date [ref]
Electron	$< 8.7 \times 10^{-29}$	$\approx 10^{-29}$		2014 [15]
Muon	$< 1.8 \times 10^{-19}$			2009 [16]
Tau	$< 1 \times 10^{-17}$			2003 [17]
Lambda	$< 3 \times 10^{-17}$			1981 [18]
Neutron	$(-0.21 \pm 1.82) \times 10^{-26}$	$\approx 10^{-28}$	10^{-28}	2015 [8]
$^{199}_{80}$Hg	$< 7.4 \times 10^{-30}$	10^{-30}	$< 1.6 \times 10^{-26}$ [19]	2016 [20]
$^{129}_{54}$Xe	$< 6.0 \times 10^{-27}$	$\approx 10^{-30}$ to 10^{-33}	$\approx 10^{-26}$ to 10^{-29}	2001 [21]
Proton	$< 2 \times 10^{-25}$	$\approx 10^{-29}$	10^{-29}	2016 [20]
Deuteron	not available yet	$\approx 10^{-29}$	$\approx 3 \times 10^{-29}$ to 5×10^{-31}	

Table 2: Current limits, goals and d_n equivalent goals for various particles.

Why charged particles besides neutrons?

- Neutrons are record holders: next generation expts in the pipeline wherever ultracold neutrons are available (PNPI, ILL, ORNL, LANL, 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. in the EFT approach)

- 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

- Not much is known about P-conserving millistrong CP-violation --- entirely BSM
- (TIVOLI@COSY on double polarization pD is under consideration EPJ Tech. Instrum. 6, no. 1, 2 (2019).)

Mitglied der Helmholtz-Gemeinschaft

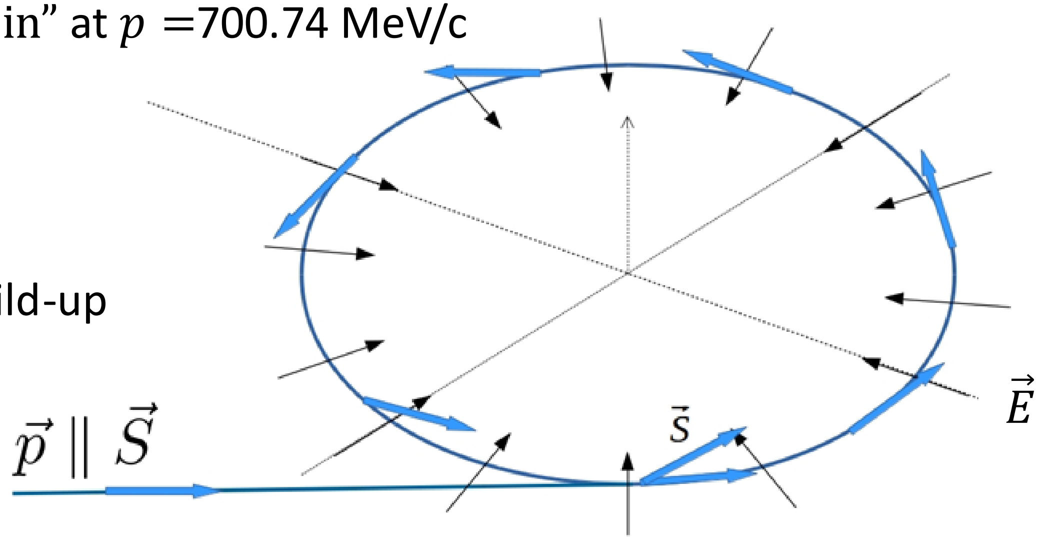
A principle of EDM measurement: spin rotation by EDM-interaction with E-fields

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

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

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 → $\pi\eta$



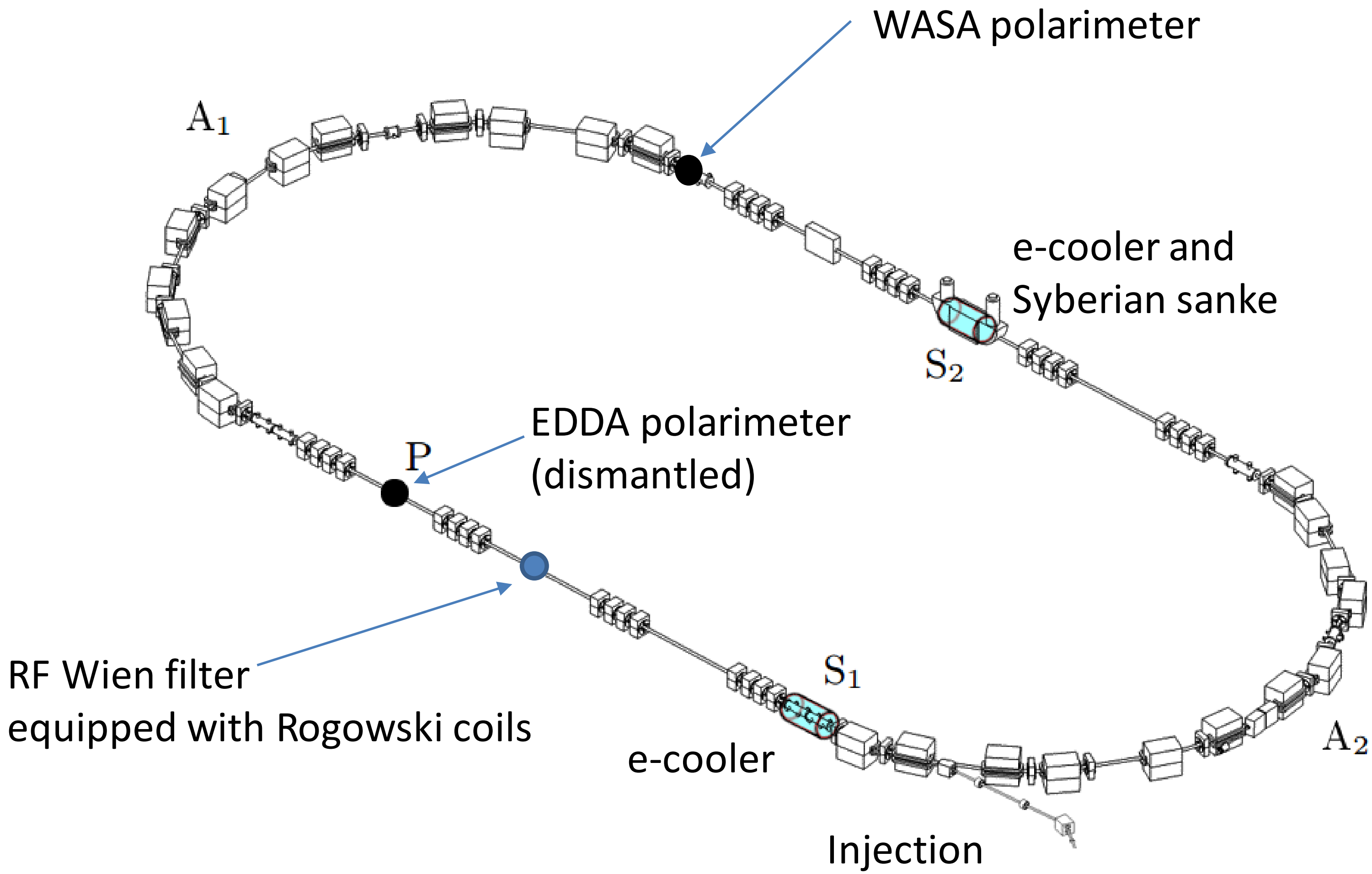
Horizons of an ideal experimental setup

- 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 (τ = 1000 s)
- 1 ppm polarimetry @COSY (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

Yardsale tactics: meanwhile use all-magnetic COSY as a Testing Ground



JEDI: EDM searches at COSY with RF Wien Filter as a spin rotator (2020 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

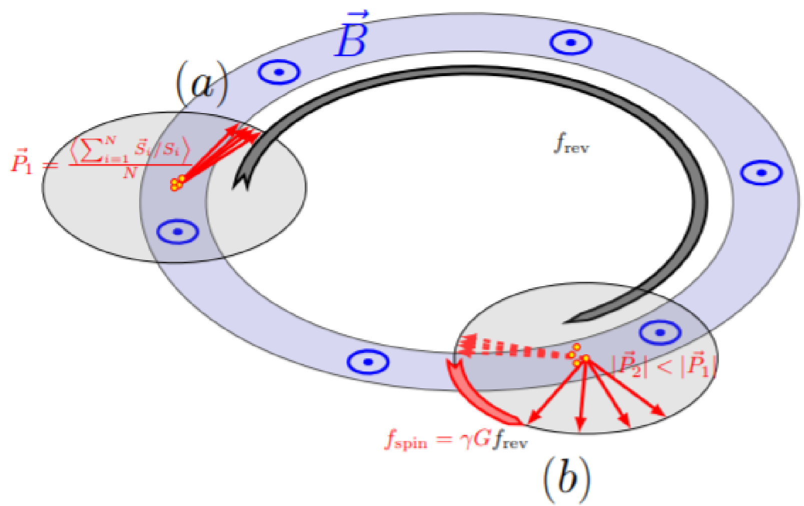
- Systematic effects: horizontal imperfection magnetic fields are evil because MDM >> EDM and MDM rotations give false EDM signal

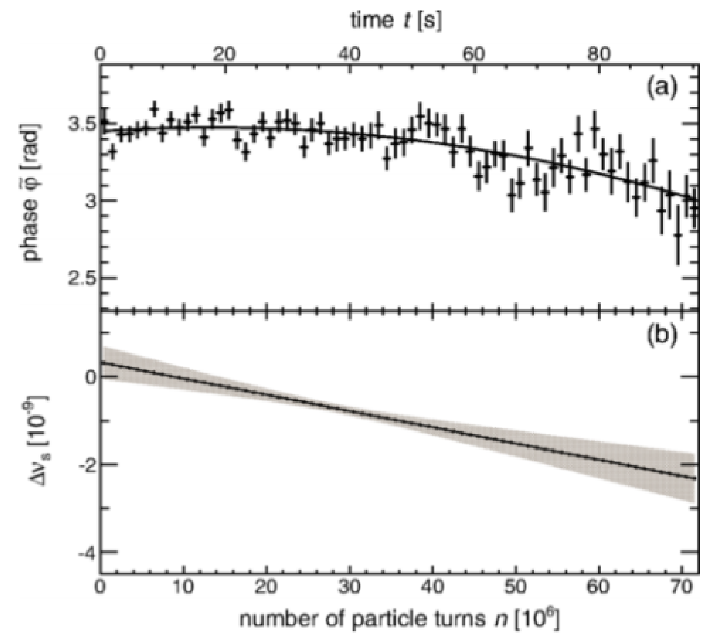
- JEDI experimental studies of imperfections: MDM background can be suppressed to 10^{-6} level. Further suppression of systematics is possible

- COSY as is: EDM $\leq 10^{-6}$MDM $\cong 10^{-20}\ e \cdot cm$ is potential sensitivity limit

JEDI at COSY: record spin tune precision

Achieved by continuous polarimetry of spin precession with time stamp





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

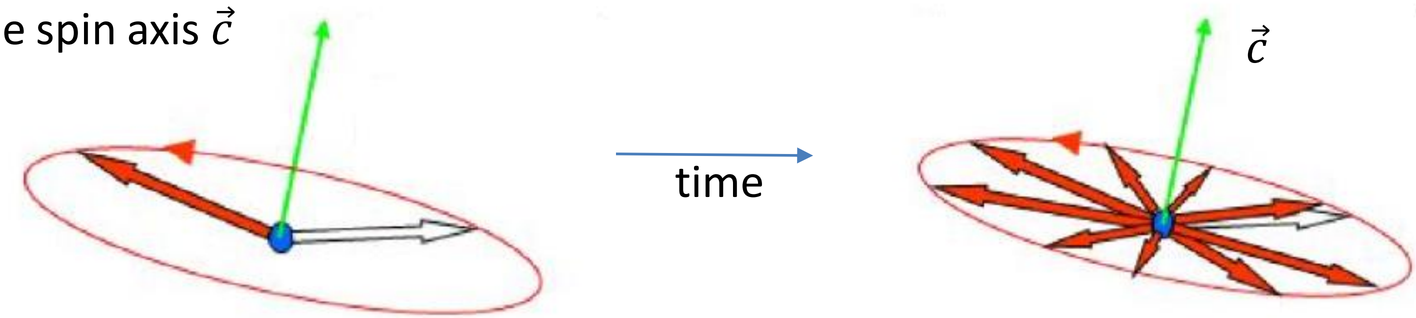
$$\text{Note: } \gamma G = \frac{f_{spin}^{MDM}}{f_{rev}}, \qquad \frac{f_{spin}^{EDM}}{f_{rev}} \approx 10^{-10} \text{ for EDM } d = 10^{-24}\, e\,\mathrm{cm}$$

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

stable spin axis $\vec{c}$



Inititally all spins aligned

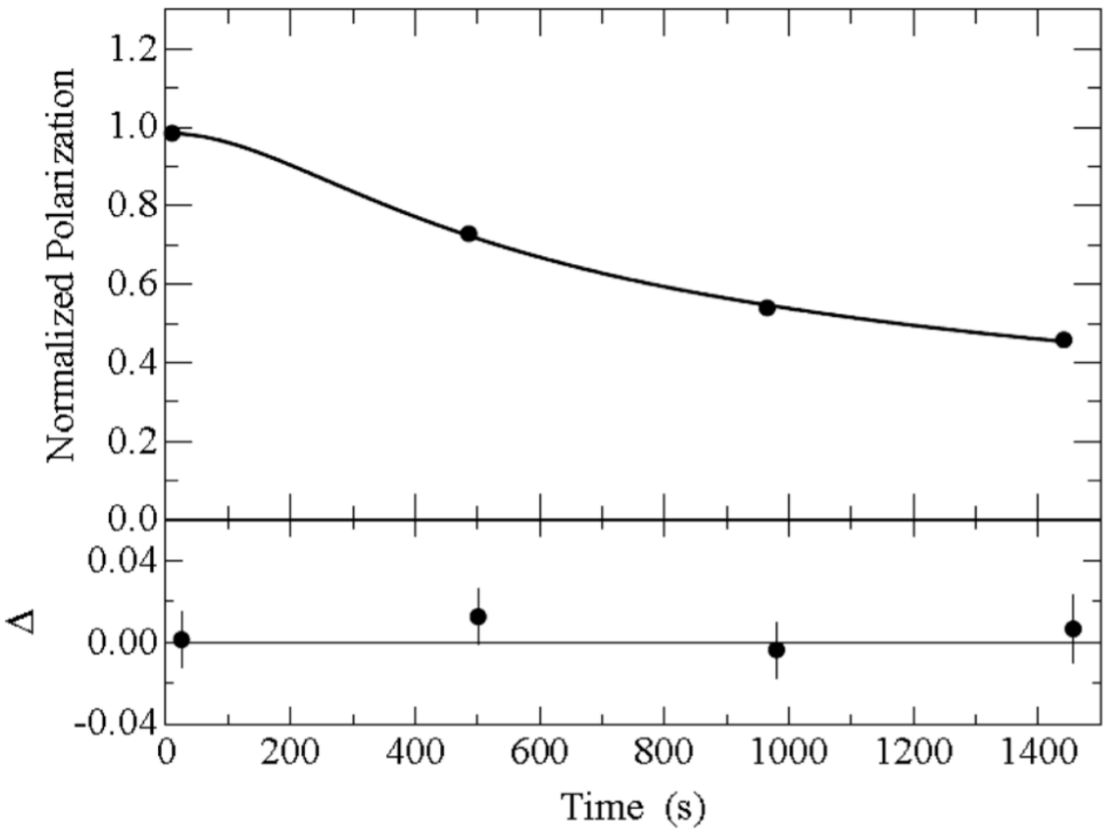
Spins decohered - polarization vanishes

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 with RF Wien Filter

- RF Wien-Filter does not disturb a beam orbit but entails a vanishing EDM term in the FT-BMT eqn.

- 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)

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

- Extract EDM from either stable spin axis or resonance tune?

False EDM-like signal from magnetic imperfections

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

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

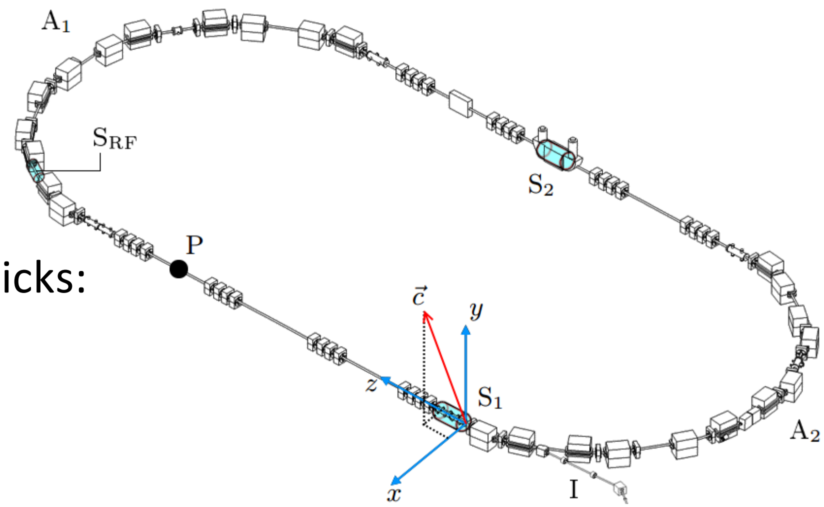
$$\epsilon_0 = \frac{1}{4\pi}\chi_{\mathrm{WF}}|\vec{c}\times\vec{w}|$$

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

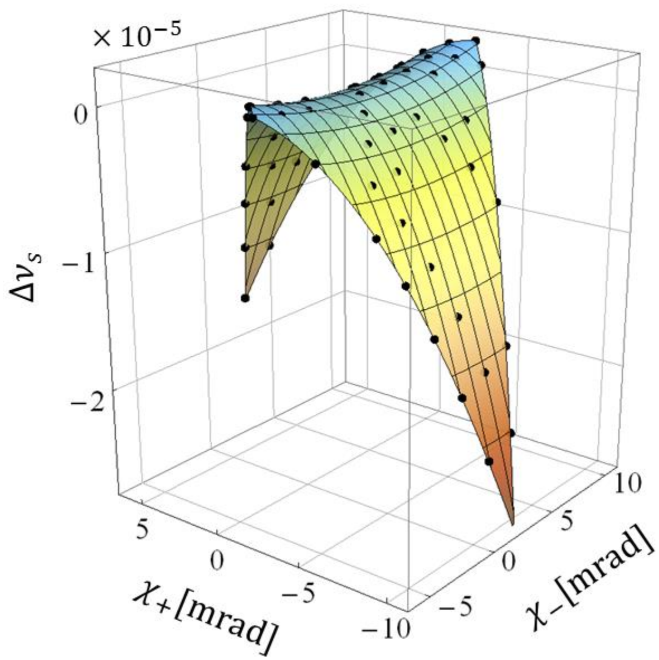
- Spin tune depends on the imperfection fields
- Probe imperfection complementing a ring with artificial in-plane magnetic fields (yardsale approach: take advantage of electron cooler drift colenoids)
- Spin tune mapping: convert a record precision of spin tune to a tool to determine imperfections $c_{\mathrm{x},z}$.
- **Realized experimentally**: JEDI: Phys.Rev. AB 20, 072801 (2017)

JEDI: static spin tune mapping at COSY

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



- Measure spin tune shift vs solenoid spin kicks:



- Position of the theoretically predicted saddle point determines a tilt of stable spin axis by magnetic imperfections: about 3 mrad tilt

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

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

RF WF: no invariant spin orbit anymore

- Spin transfer matrix with running RF WF after Bogolyubov-Krylov-Mitropolsky smoothing of stroboscopic spin motion (one spin kick per revolution)

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

- Axis of driven spin rotation

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

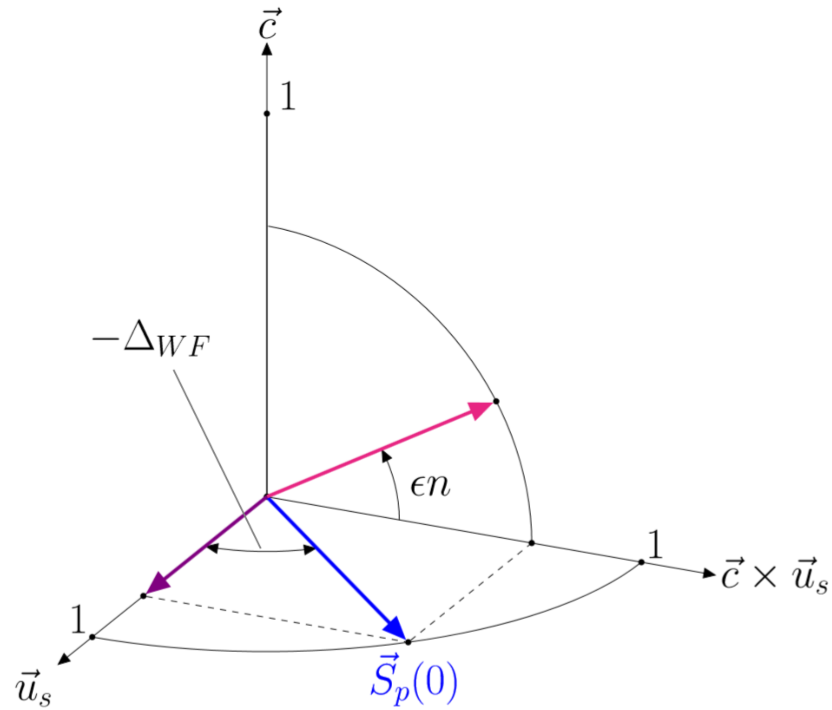
- Δ_{WF} - a phase shift between the spin precession and RF phases

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

- Idle precession

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

Vertical polarization buildup in the idle rotating frame



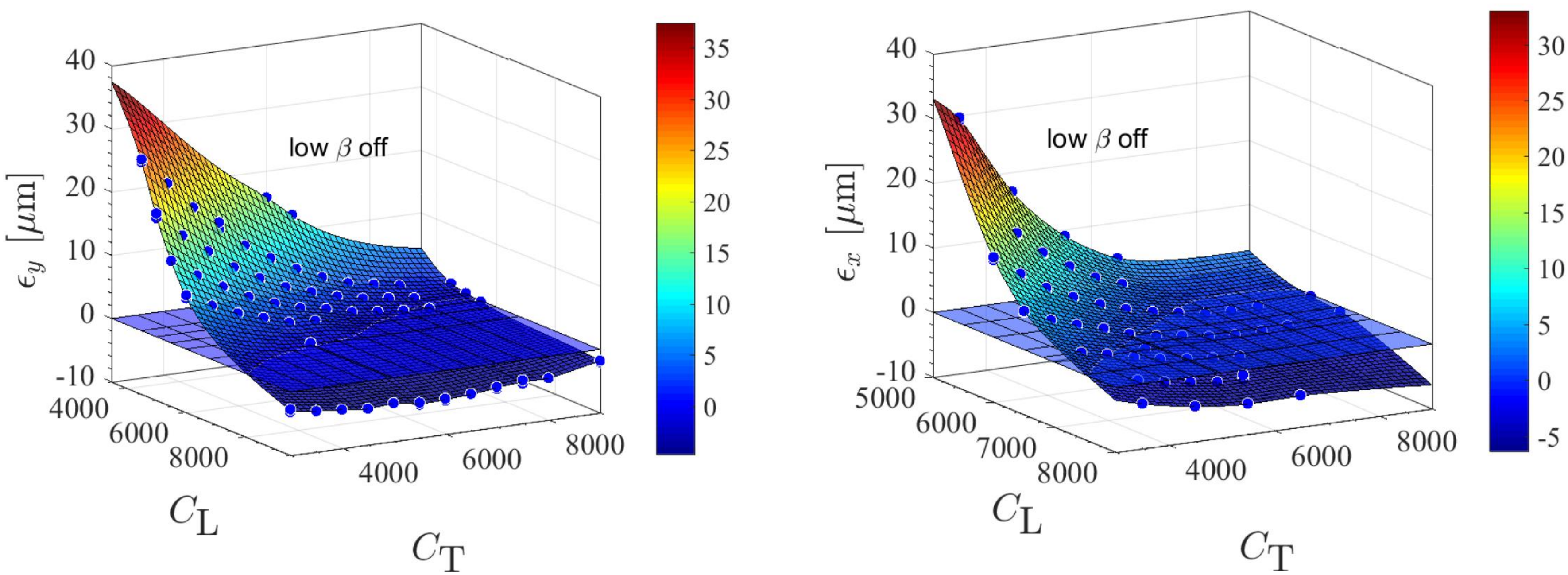
- Rotating frame: one component of the initial in-plane polarization participates the RF WF driven spin resonance
- The second component keeps idle precession
- The initial vertical polarization does not generate the idle precessing component

Comagnetometry with RF WF rotated spin

- Comagnetometry is a principal tool in all searches for the EDM
- In storage rings comagnetometry is imperative to maintain the resonance condition during 1000 s spin coherence time
- JEDI control of the spin tune: continuous time stamp of the idle precession of the horizontal polarization
- **Wouldn't work if the spin is rotated upright out of the horizontal pane**
- Naïve suggestion: make use of the spectator component of the polarization at the price of diminishing the EDM signal
- JEDI: more powerful (?) techniques under consideration and experimental tests
- An example (A. Nass & F.Rathmann & J. Slim): extremely promising multibunch option with different initial polarizations of bunches and the RF WF gated to keep one sterile bunch as a comagnetometer

RF WF in JEDI@COSY: wavegide excerting zero Lorentz force on the beam

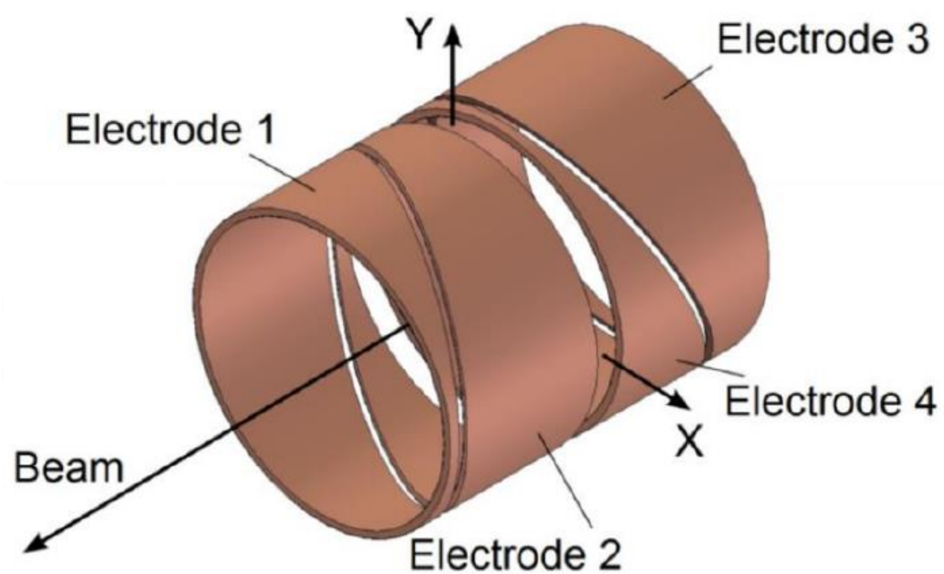
- Control the ratio and relative phase of E- and B-field in the Wien filter by two capacitors CL and CT in RF circuit
- Non-zero Lorentz force in RF WF induces coherent betatron oscillation of the beam - measure the vertical and horizontal kicks:



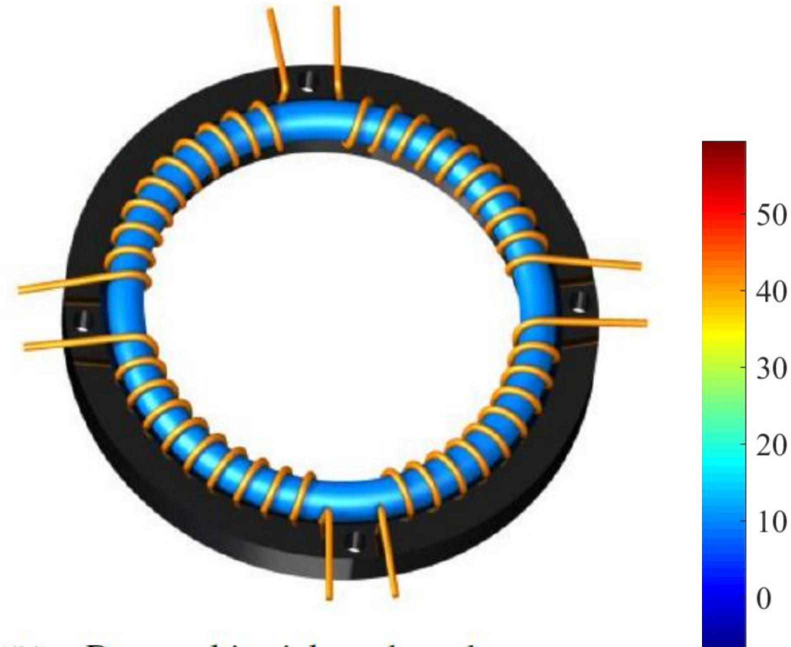
- Effects are different for different RF harmonics, depend on the beta-function

JEDI: Improving beam position monitoring WF

- low-β $\rightarrow$ off-axial trajectories $\rightarrow$ non-zero Lorentz forces are stronger



(a) Conventional split-cylinder beam-position monitor with an installation length of $\approx 20\,\mathrm{cm}$.



(b) Rogowski pickup based on a segmented toroidal coil.

Spin resonance tune mapping: ideal ring, static solenoid & RF WF Rotations

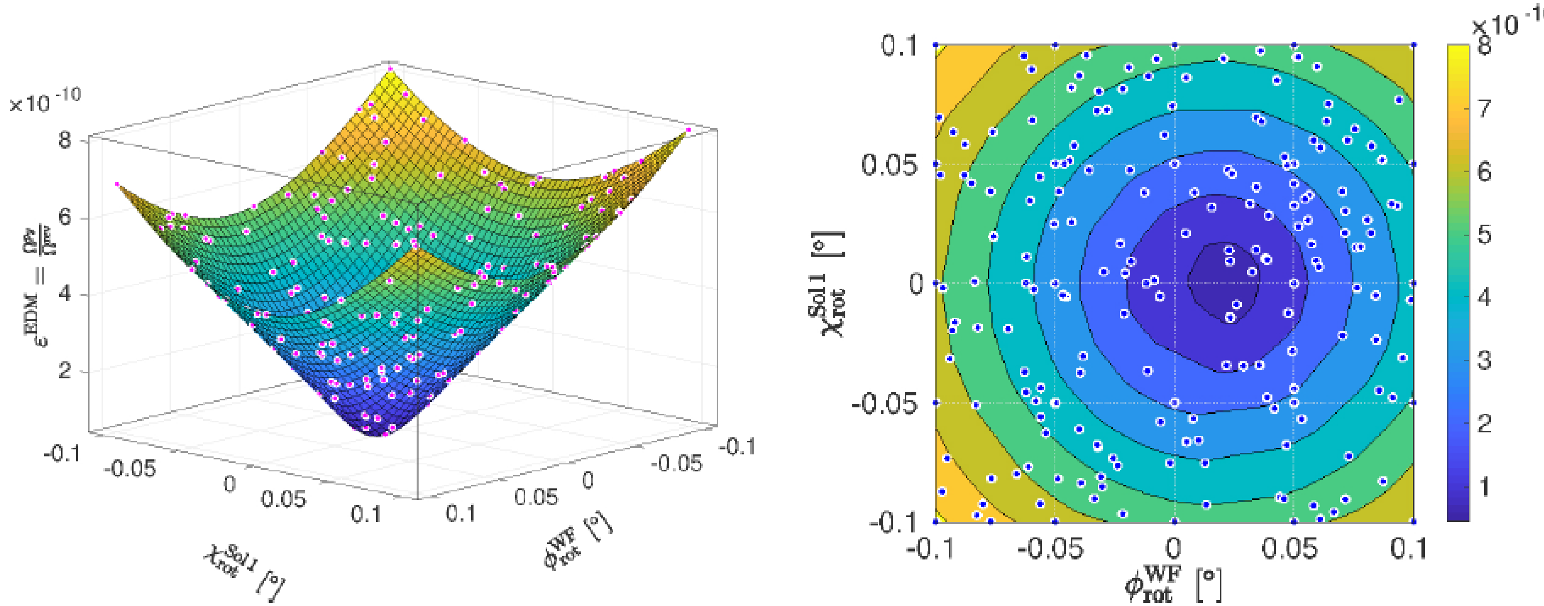
$$\left(\varepsilon^{\mathrm{EDM}}\right)^2 = A \cdot \left(\phi_{\mathrm{rot}}^{\mathrm{WF}} - \phi_0\right)^2 + B \cdot \left(\frac{\chi_{\mathrm{rot}}^{\mathrm{Sol\,1}}}{2\sin \pi \nu_s^{(2)}} + \chi_0\right)^2$$

A = B is predicted by theory in term of the RF WF fields

Numerical simulations for grossly enhanced

$$\phi_0 = \left|\xi_{\mathrm{EDM}}(d = 10^{-18}\,\mathrm{e\,cm})\right| = 0.3054\,\mathrm{mrad}$$

Simulations of the spin resonance tune mapping: ideal ring, static solenoid & RF WF rotations



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

(b) Contour plot of panel (a).

The offset of the contour plot reproduces the input “EDM signal”

The zero longitudinal input imperfection is correctly borne out by simulations

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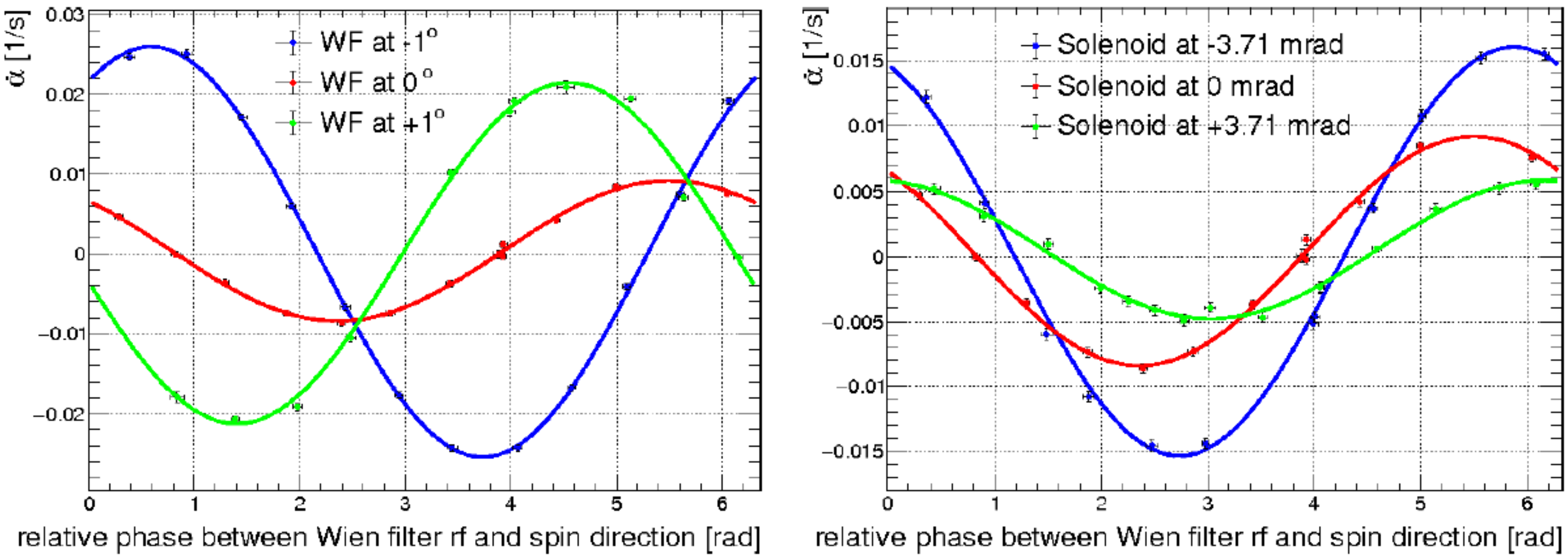
JEDY@COSY: Initial slope of the vertical polarization vs. the RF and spin phase difference



(a) $\dot{\alpha}$ for $\phi_{\text{rot}}^{\text{WF}} = -1°, 0°, +1°$ and $\chi_{\text{rot}}^{\text{Snake}} = 0$.

(b) $\dot{\alpha}$ for $\chi_{\text{rot}}^{\text{Snake}} = -1, 0, +1°$ and $\phi_{\text{rot}}^{\text{WF}} = 0$.

Figure 6: Rate of the out-of-plane rotation angle $\dot{\alpha}(t)|_{t=0}$ as function of the Wien filter RF phase ϕ_{RF} for two situations. In panel (a), only the RF Wien filter is rotated around the beam axis, and in (b) only the Siberian snake solenoid in the opposite straight section of COSY (see Fig. 1) rotates the spins around the beam axis.

CPEDM = Charged Particle Electric Dipole Moments

1st CPEDM presentation: F. Abusaif et al. arXiv: 1812.08535[phys.acc-ph]

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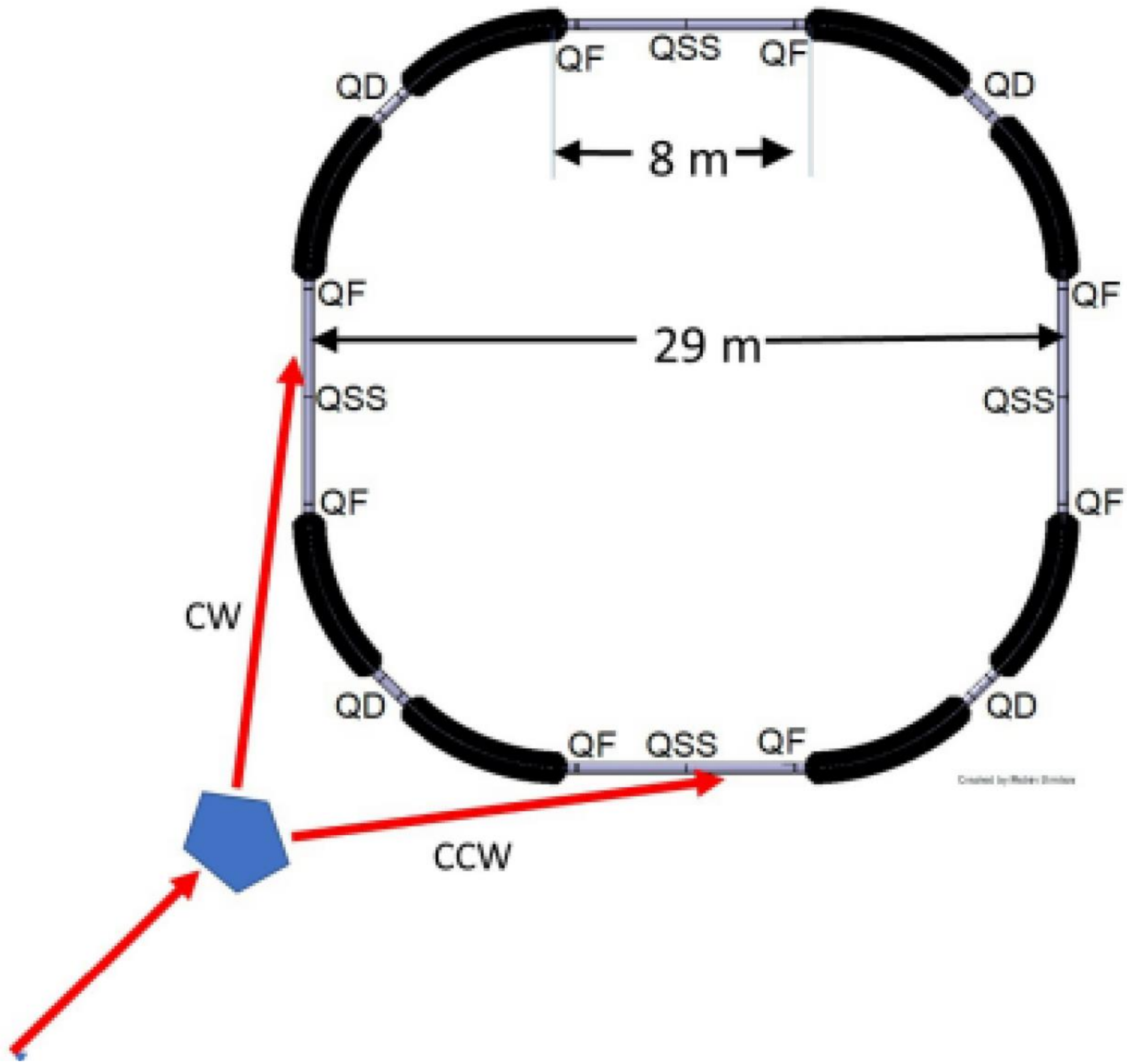
CPEDM: ProtoType Ring Parameters for non-frozen all-electric and hydrid frozen spin options

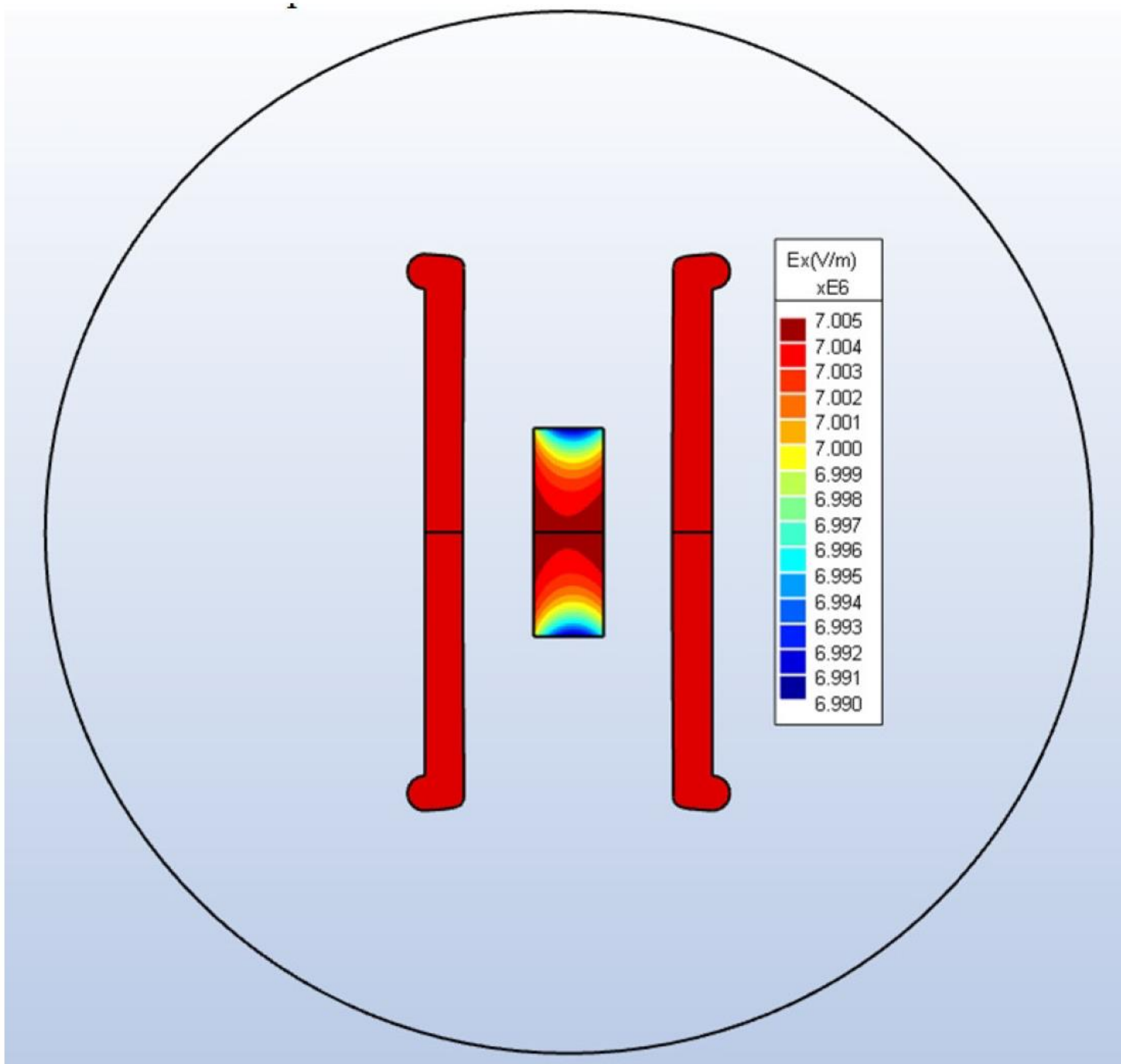
Table 1.1: Basic beam parameters for the PTR ring

	E only	$E,\ B$	unit
Kinetic energy	30	45	MeV
$\beta = v/c$	0.247	0.299	
γ (kinetic)	1.032	1.048	
Momentum	239	294	MeV/c
Magnetic rigidity $B\rho$		0.981	T·cm
Electric field only	6.67		MV/m
Electric field E (frozen spin)		7.00	MV/m
Magnetic field B (frozen spin)		0.0327	T

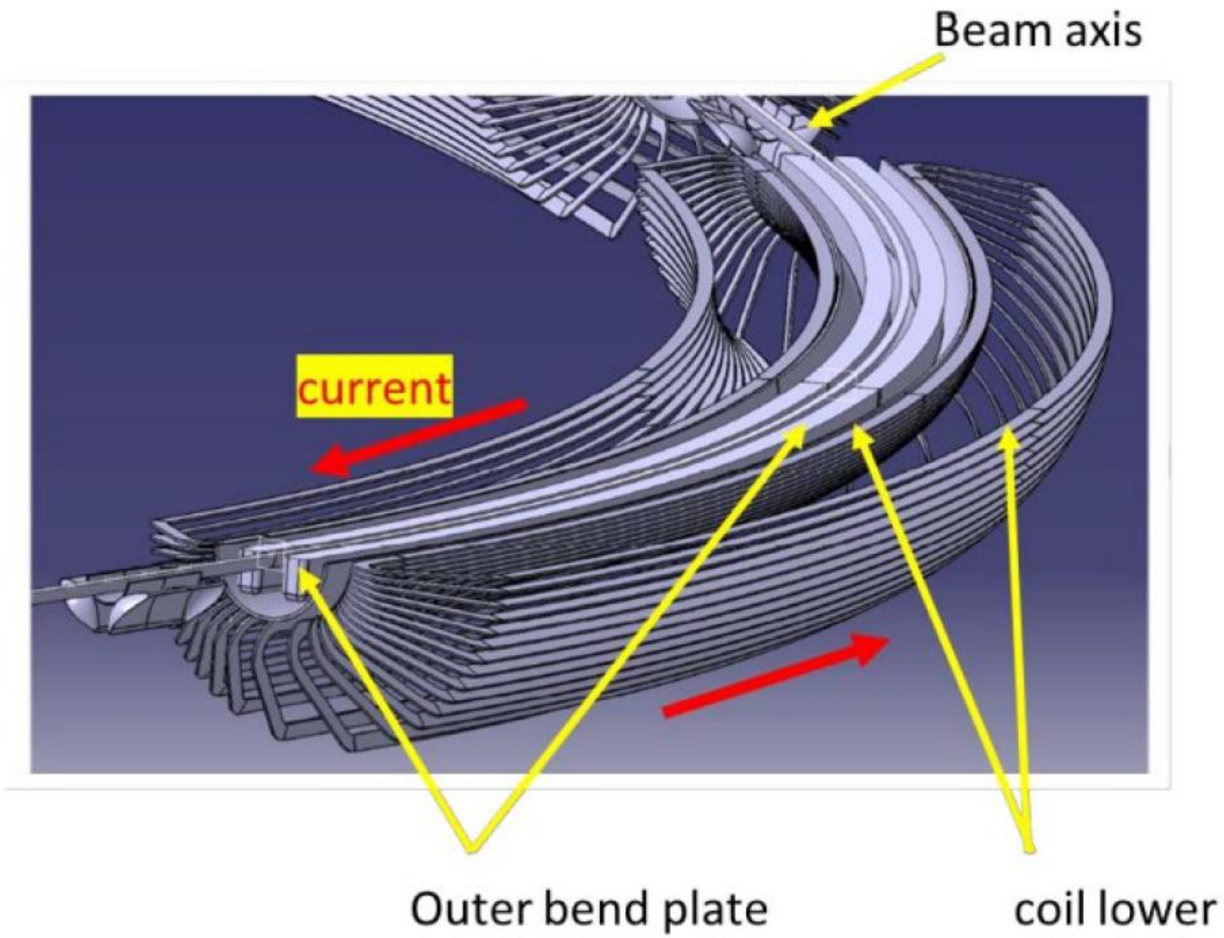
PTR Layout



E-field profile of the PTR capacitor inside the beam tube

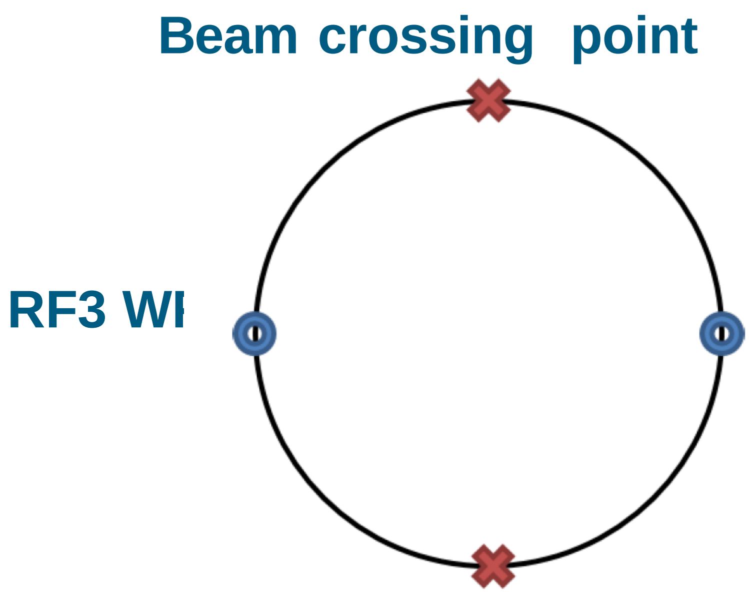


Hybrid ExB frozen spin option



CW and ACW beam in the all-electric PTR with RF WF in a pseudostatic mode

- CW and ACW proton beams in PTR with RF WF run **at ring frequency** with as close to rectangular pulses as possible
- Statistical sensitivity for one year run $\sigma_p \approx 2.2 \cdot 10^{-24} e \cdot \mathrm{cm}$



Spin tune mapping at PTR with RF WF in a pseudostatic mode

(A. Saleev, F. Rathmann & NNN --- one of many options)

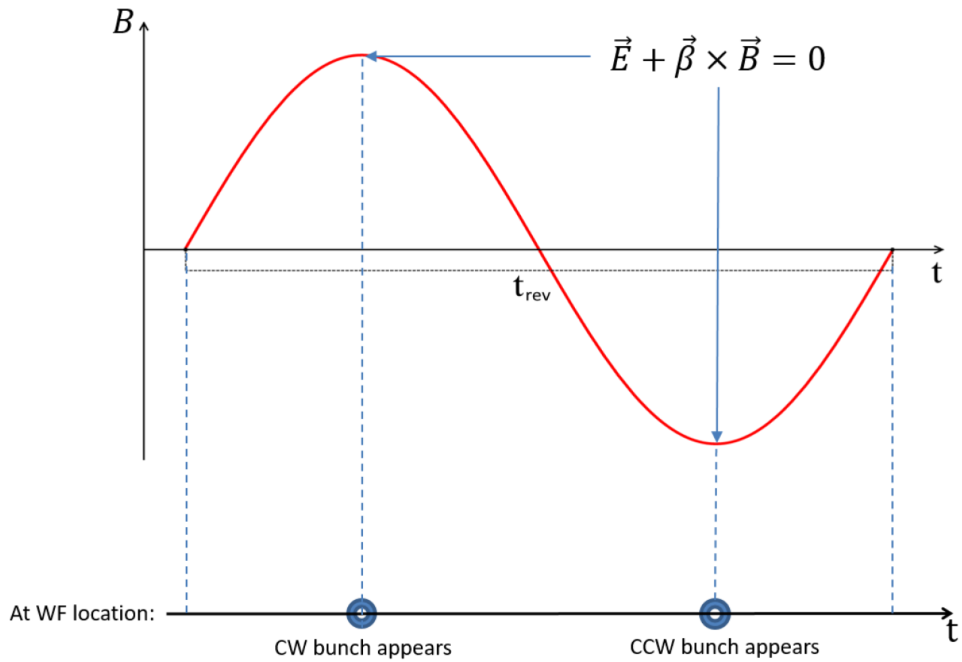


Fig. 1.2: A time-line of Wien filter operation.

Two beams see **static** WF fields → EDM caused imperfections of opposite sign → different spin tunes for the CW and ACW beams

$$\nu_s^{cw} - \nu_s^{ccw} = \frac{1}{\pi}\xi_{\mathrm{EDM}}\psi$$

Koop spin wheel in a frozen spin EDM ring

- Start with frozen spin ring
- Add locally a radial magnetic field
- MDM and EDM rotations add coherently
- Extrapolate to vanishing magnetic field --- superficial similarity to how one proceeds in the neutron and atomic EDM experiments but very different systematics is involved
- Much discussed option for an ultimate frozen spin proton ring
- More on that, on mitigating systematics and comagnetometry options read Koop

Colliding or co-rotating ion beams in storage rings for EDM search

IOP Publishing | Royal Swedish Academy of Sciences

Phys. Scr. **T166** (2015) 014034 (6pp)

- More on Koop spin wheel in Y. Senichev's talk

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 $\Delta p/p$

Synchrotron oscillations

- Spin phase modulation 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 axis vs. 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 $\vec{S}(0) = \vec{c}$

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

- 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

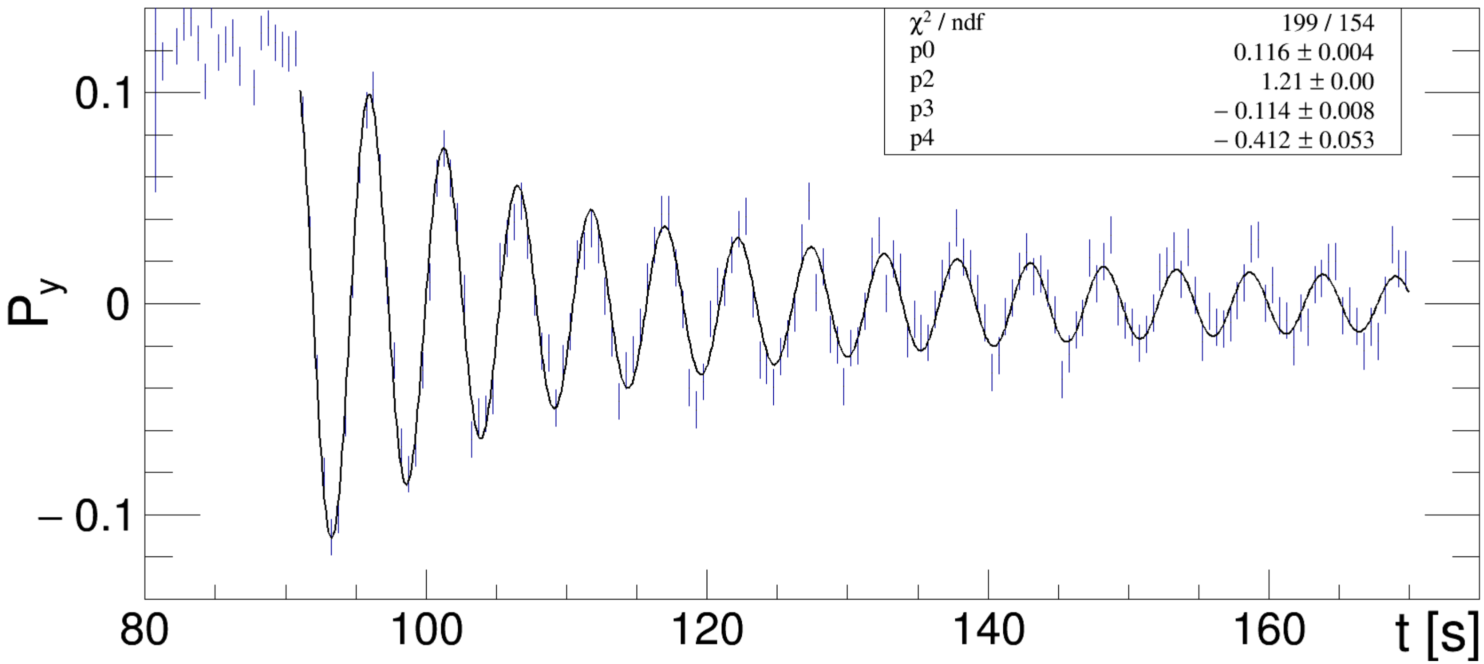
- Extra suppression by $J_0(y) < 1$ of the in-plane polarization from averaging over ensemble of particle-to-particle jittering rotation planes.

- **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

Damping of driven oscillations

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



- Experimental confirmation of non-exponential attenuation

- A word of caution: there is certain sensitivity to the bunch shape

Damping of driven oscillations

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

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

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

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

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

Spin echo in detuned driven spin rotations

- The phase of driven spin rotation: no linear growth of the driven spin phase

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

- Decoherence

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

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

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

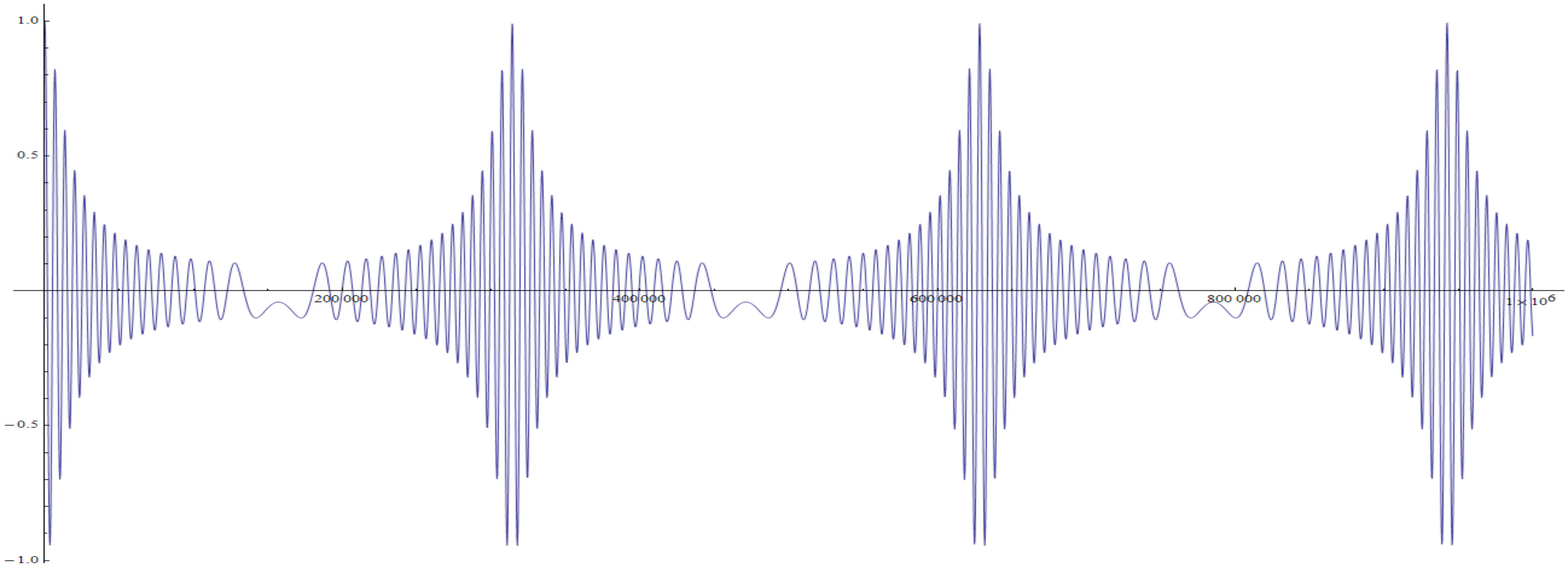
- A **spin echo:** at $\phi = \Phi = 0$, i.e., with the period ,

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

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



- Strong detuning for the sake of illustration of the phenomenon
- Variable driven oscillation frequency $\sim \cos\phi$
- Higher harmonics in the difference of spin and RF frequencies at work

Conclusions

- JEDI: good understanding of the hitherto unexplored ultrahigh precision spin dynamics
- JEDI@COSY precursor RF WF expteriment on the dEDM is scheduled for 2020
- The already obtained JEDI results: sufficiently strong motivation for the **CPEDM** initiative
- CPEDM: more insight into possible systematic effects from both all-electric and ExB options
- Even non-magic all-electric ring will boost tremendously a sensitivity to the pEDM
- More theoretical scrutiny of the relevant spin dynamics is called upon

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

- New interest 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

Synchrotron oscillations

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

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

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

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

- 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 $\sim y^2\tan\Delta_{WF}$

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

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

No real need in full machinery of General Relativity: weak field approximation is OK: it suffices to know the free fall acceleration $\vec{g}$, the Earth rotation is a fairly trivial effect.

Two principal effects:

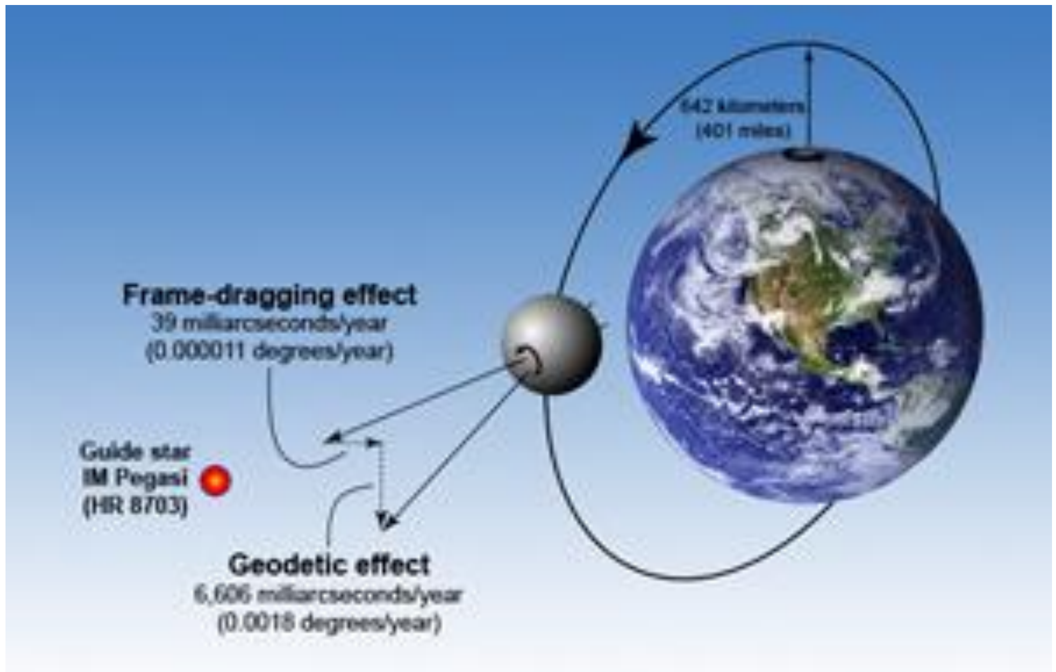
- The spin-orbit interaction in the Earth gravitational field (the de Sitter precession, aka the geodetic effect (1916))
- Focusing EM fields are imperative to impose the closed paricle orbit in a storage ring compensating for the particle weight: first derivation by Silenko & Teryaev (2005) for magnetic 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 otherwise fundamental 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 gravity induced spin precession around **the radial axis --- already a false EDM effect!**

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

Khriplovich-Pomeransky result is fully confirmed by FW analysis (Obukhov, Silenko, Teryyaev (2005,2016))

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
- Compensate free fall 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 GR juggling by Orlov et al (2012))

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

In the commoving frame amounts to he motional radial magnetic field $\propto [\vec{v} \times \vec{g}]$ --- false EDM effect

False EDM from gravity induced imperfection

- 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], Wedn., A11, 17:55
- Orlov et al (2012): gravity under full control , false effects can be cancelled out with counterrotating beams

Magic ring for deuterons

New 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

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

- 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

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

- EM imperfection might prevail for deuterons?

Summary:

The srEDM and JEDI => new exptl and theoretical work on spin dynamics in storage rings (record precision in spin tune, record spin coherence time, spin tune mapping, nonexponential spin decoherence, spin echo…)

COSY@Juelich was, is and will remain a unique facility exploring the frontiers of spin dynamics

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

Still Terra Incognita for all-electric rings despite first forays

Griavity as an example of **surprise imperfection** in all-electric rings: false EDM effects from gravity (first discovered in **1916** !), Orlov-Flanagan-Semertzidis 2012 result is fully vindicated, not an issue for pure electric magic rings

Future: CPEDM (JEDI+CERN) Collaboration in the formative stage

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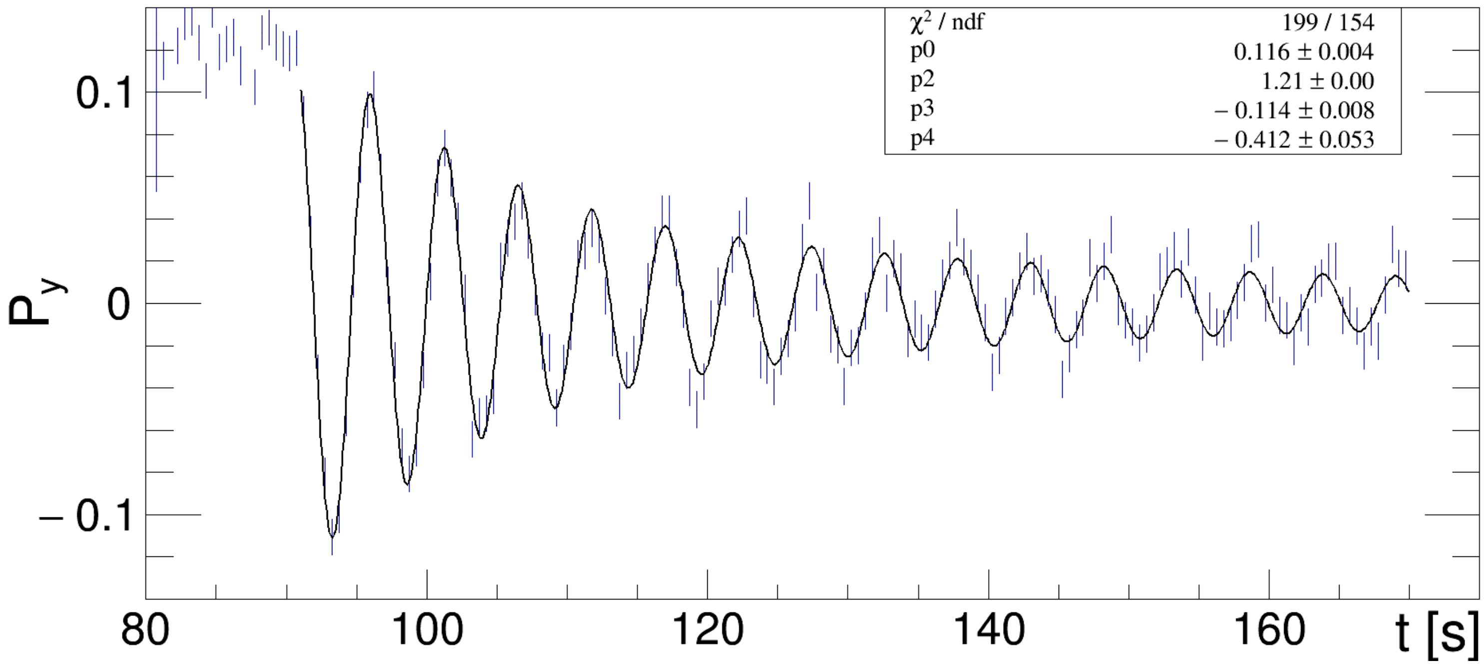


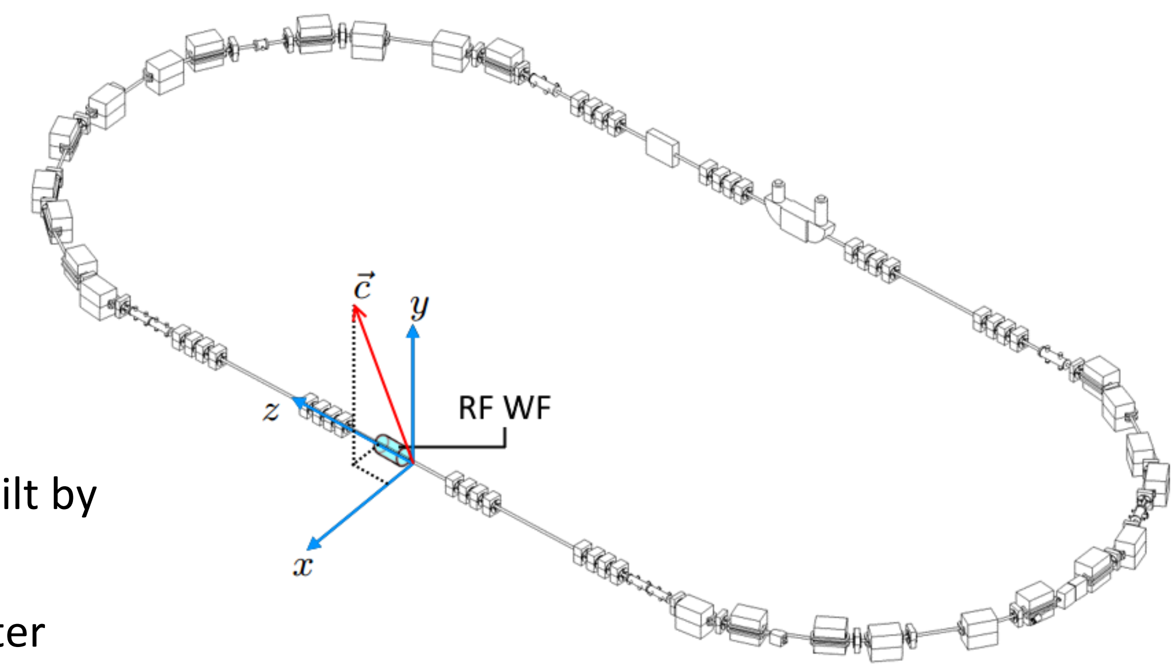
- p0-initial amplitude of oscillation
- p2-oscillation frequency(*2π)
- p3-parameter of damping
- p4 -normalization for running phase function

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

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

- 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



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