Measurement of Electric Dipole Moments of Charged Particles at Storage Rings

- Research and Development at COSY -

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on behalf of the JEDI Collaboration

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R&D at COSY

- maximizing spin coherence time
- precise spin tune determination
  (monitoring, study of imperfections, feedback systems, ..)
- rf-Wien filter
- development of high precision beam position monitors
  (e.g. SQUID based, final goal ≈ nm per cycle)
- electrostatic deflectors (goal: field strength > 10 MV/m)
- polarimeter development
- spin tracking in storage rings
- …

see also: http://collaborations.fz-juelich.de/ikp/jedi

How to measure EDMs?

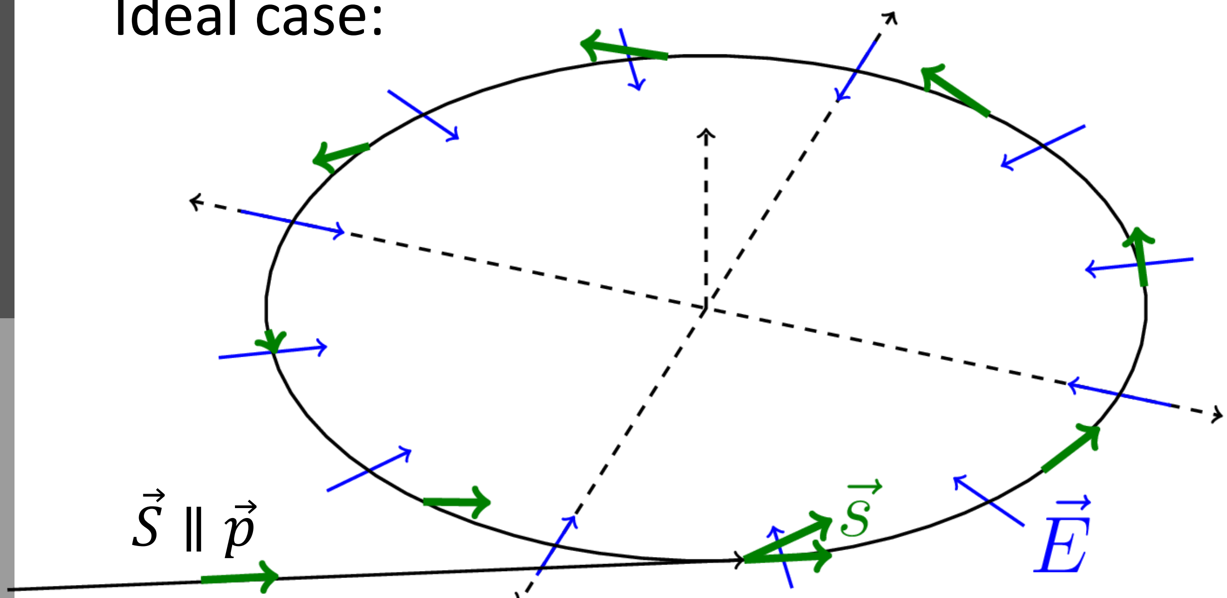
Common strategy for all EDM measurements:

$\longrightarrow$ measure interaction of $\vec{d}$ with electric field $\vec{E}$

For charged particles:

$\longrightarrow$ apply electric field in a storage ring

Ideal case:



$$\frac{d\vec{S}}{dt} \propto d\vec{E} \times \vec{S}$$

$\Downarrow$

Build-up of vertical polarisation

$s_\perp \propto |d|$

General case: spin motion

Thomas-BMT equation:

MDM EDM

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = -\frac{q}{m_0}\left\{ G\vec{B} + \left(\frac{1}{\gamma^2 - 1} - G\right)\frac{\vec{\beta} \times \vec{E}}{c} + d\,\frac{m_0 c}{q\hbar S}\left(\frac{\vec{E}}{c} + \vec{\beta} \times \vec{B}\right)\right\} \times \vec{S}$$

Ω: angular precession frequency

G: anomalous magnetic moment

d: electric dipole moment

γ: Lorentz factor

In general:

magnetic moment causes fast spin precession

"frozen spin": chose $\gamma, \vec{B}, \vec{E}$ such that $\Omega_{\mathrm{MDM}} = 0$

Mitglied der Helmholtz-Gemeinschaft

COSY: pure magnetic ring

Thomas-BMT equation:

MDM EDM

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- polarized protons and deuterons up to 3.7 GeV/c available
- access to EDM via motional electric field $\vec{\beta} \times \vec{B}$
- requires additional means (e.g. rf E and B fields) to compensate $G\vec{B}$ contribution

Ideal starting place for R&D and a proof-of-principle experiment

R&D at COSY

Thomas-BMT equation:

MDM | neglect EDM

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = -\frac{q}{m_0}\left\{G\vec{B} + \left(\frac{1}{\gamma^2 - 1} - G\right)\frac{\vec{\beta} \times \vec{E}}{c} + d\,\frac{m_0 c}{q\hbar S}\left(\frac{\vec{E}}{c} + \vec{\beta} \times \vec{B}\right)\right\} \times \vec{S}$$

study spin tune $\upsilon_s = \frac{|\vec{\Omega}|}{|\vec{\omega}_{\mathrm{cycl}}|} = \gamma G$

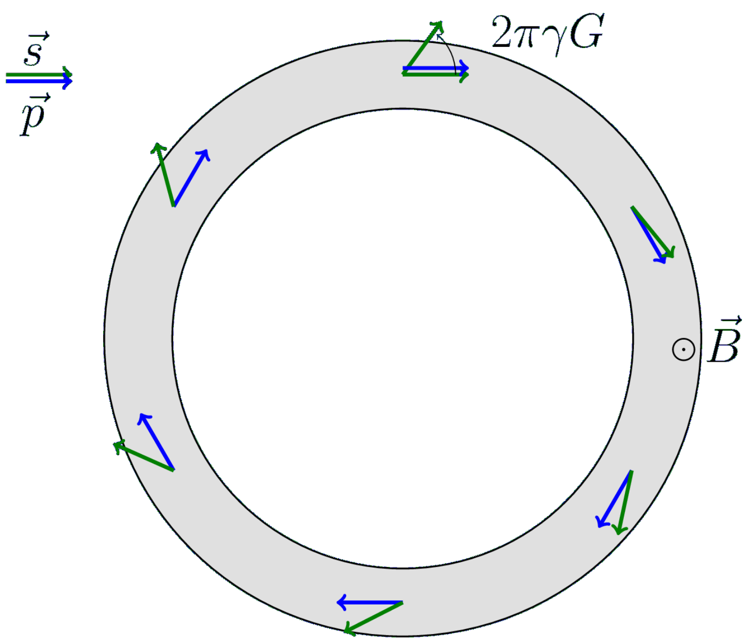
$\rightarrow 2\pi\upsilon_s$: phase advance per turn

R&D with deuterons

p = 1 GeV/c

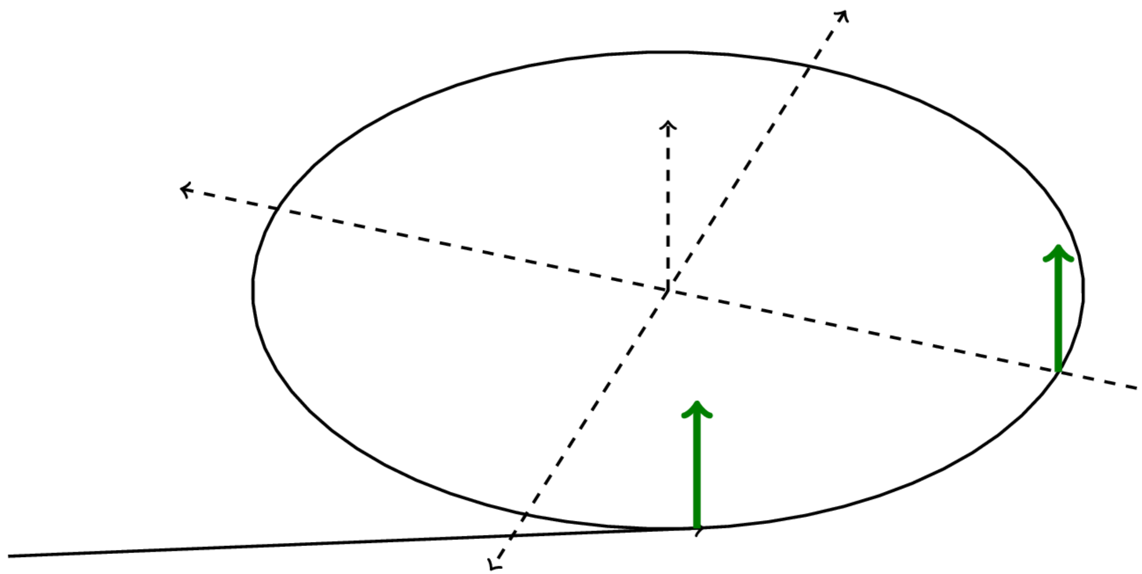
G = -0.14256177(72)

$\nu_s \approx -0.161 \longrightarrow f_s \approx 120$ kHz



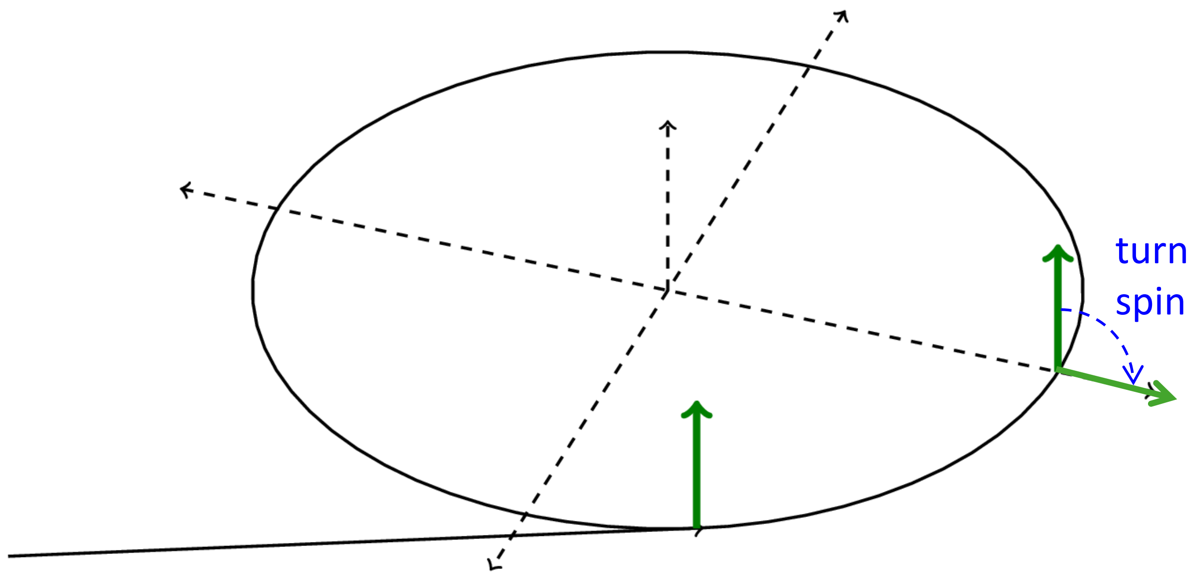
Experimental setup

1. inject and accelerate vertically polarized deuterons to p = 1 GeV/c



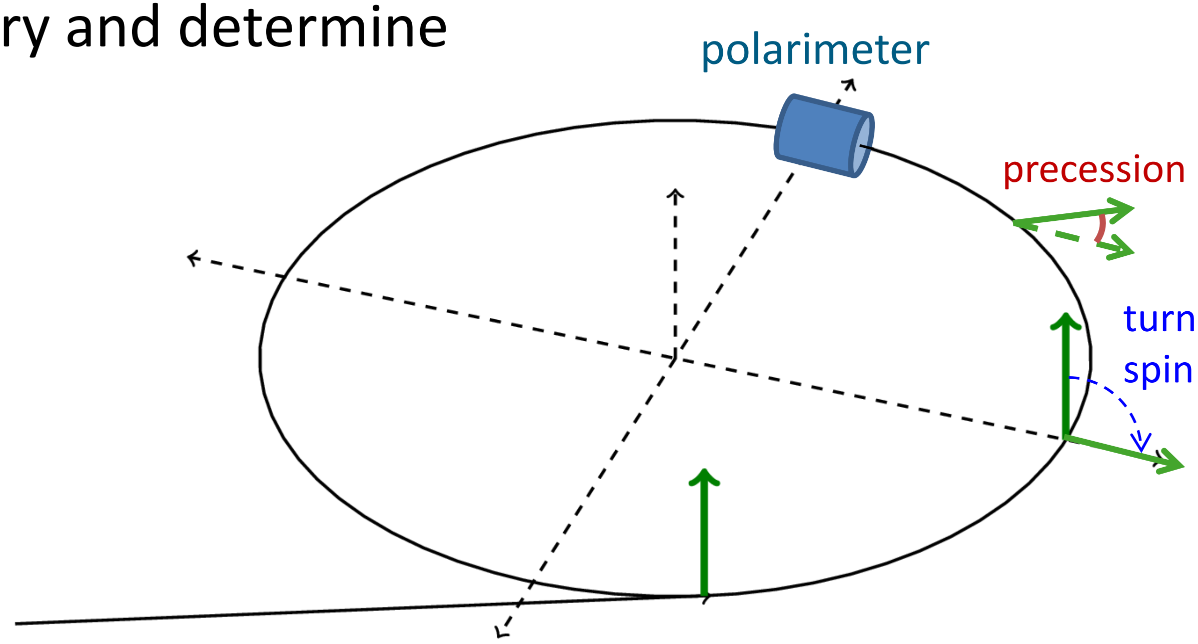
Experimental setup

1. inject and accelerate vertically polarized deuterons to p = 1 GeV/c
2. turn spin with help of a RF solenoid into horizontal plane



Experimental setup

1. inject and accelerate vertically polarized deuterons to p = 1 GeV/c
2. turn spin with help of a RF solenoid into horizontal plane
3. extract beam slowly (within 100 s) onto a carbon target measure asymmetry and determine spin precession



Asymmetry measurement

Detector signal

$$N^{up,down} \propto 1 \pm PA\sin(2\pi \cdot f_s t) = 1 \pm PA\sin(2\pi \cdot \upsilon_s\, n_{\mathrm{turns}})$$

P: polarisation, A: analysing power

Asymmetry

$$\varepsilon = \frac{N^{up} - N^{down}}{N^{up} + N^{down}} = PA\sin(2\pi \cdot \upsilon_s\, n_{\mathrm{turns}})$$

Challenges

- precession frequency $f_s \approx 120$ kHz
- $\nu_s \approx -0.161$ → 6 turns / precession
- event rate ≈ 5000 s^{-1} → 1 hit / 25 precessions
  → no direct fit of the rates

Asymmetry measurement

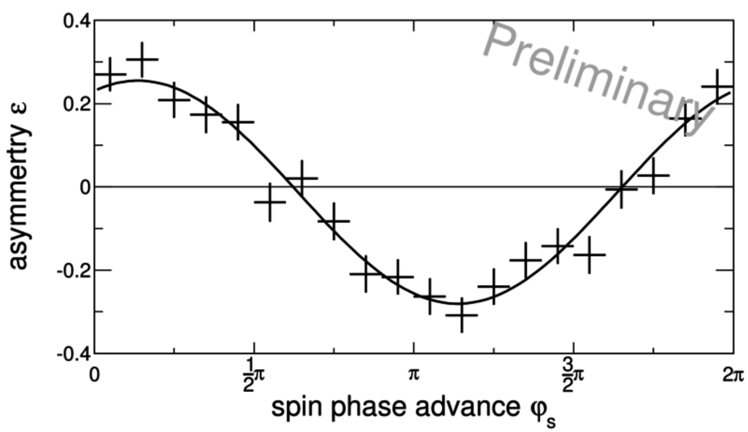
COSY rf → **T D C** → beam revolutions: counting turn number *n*

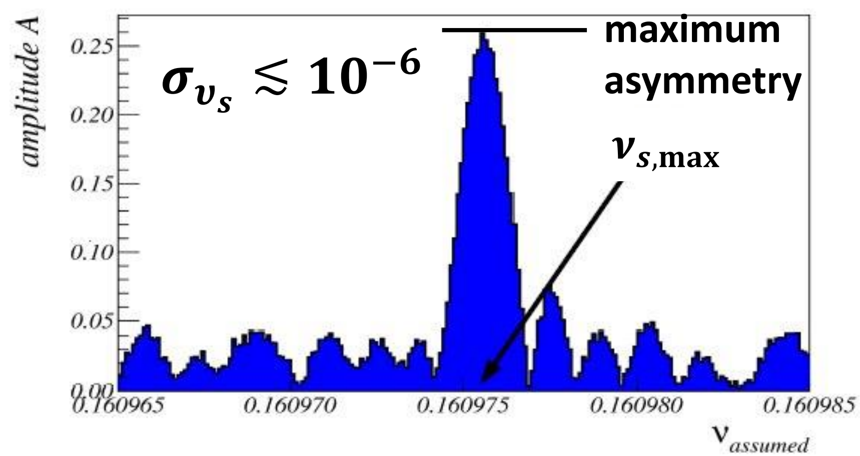
detector events → **T D C** → assign turn number *n* → phase advance $\varphi_s = 2\pi\nu_s n$

for intervals of $\Delta n = 10^6$ turns: $\varphi_s \rightarrow \varphi_s \bmod 2\pi$

scan ν_s in some interval around $\nu_s = \gamma G$

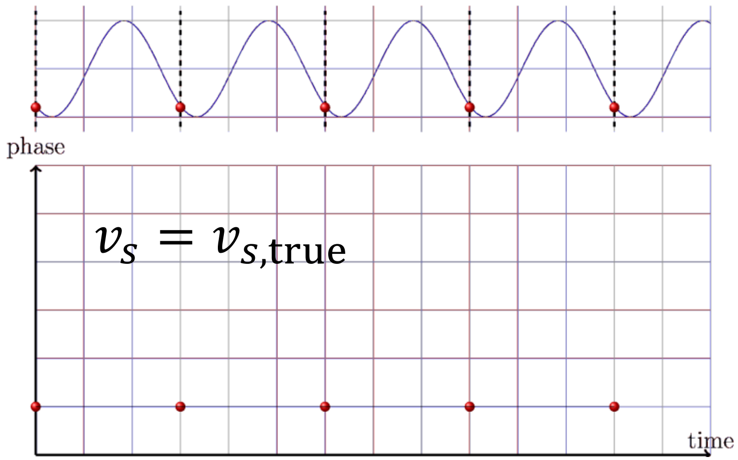
true ν_s *a priori* not known

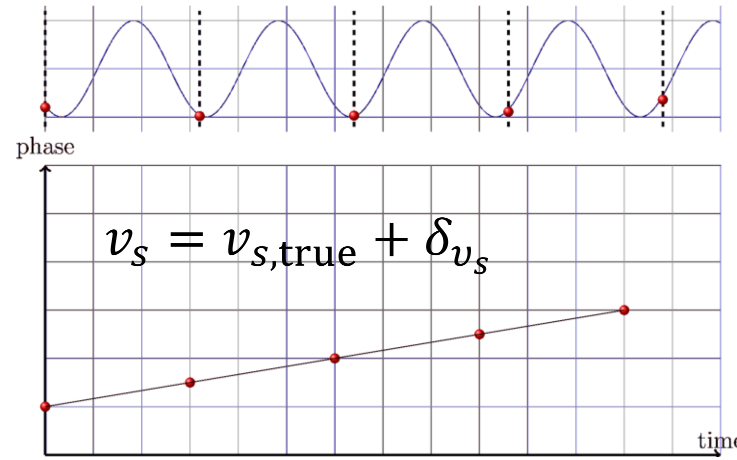




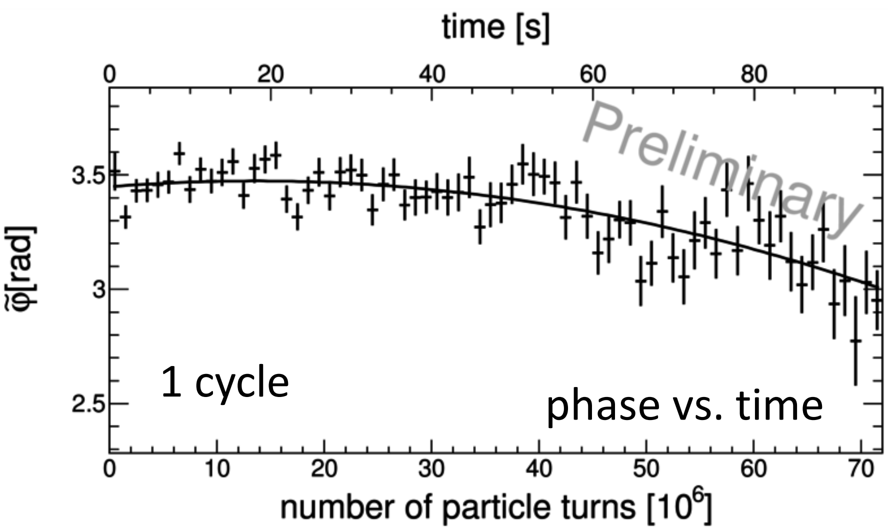
Improvement of σ_{ν_s}

Monitoring phase of asymmetry (ν_s fixed):

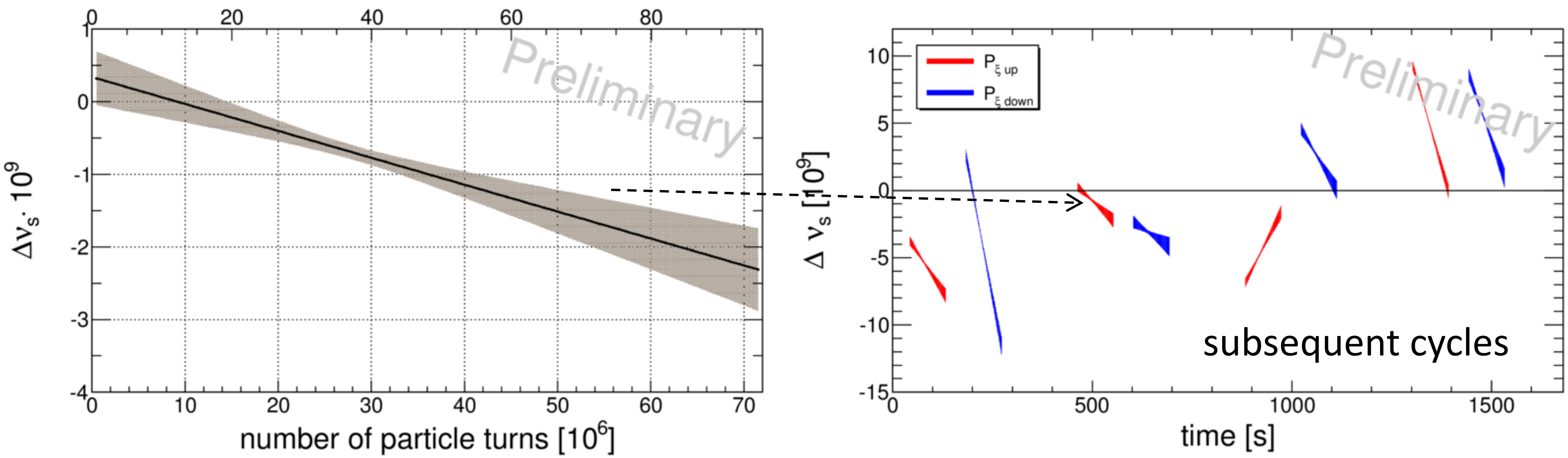




first derivative gives deviation from assumed spin tune ν_s



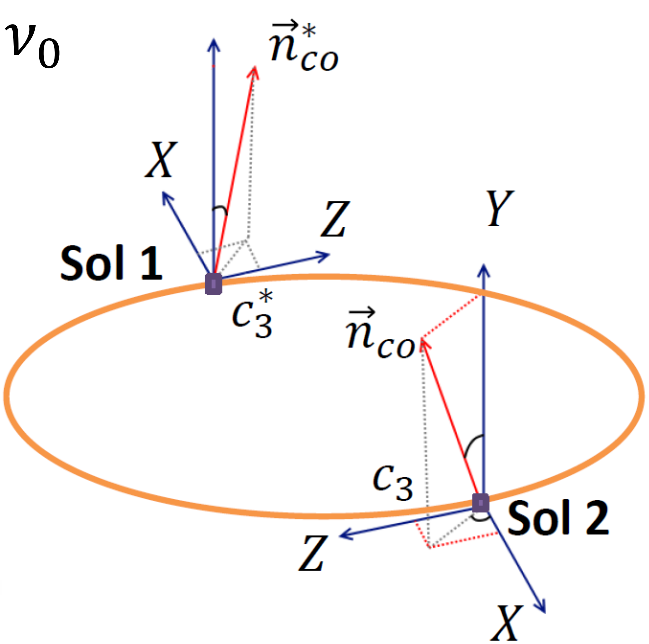
Results: spin tune ν_s



- spin tune ν_s can be determined to $\sigma_{\nu_s} \approx 10^{-8}$ in $\Delta t \approx 2s$
- average $\overline{\nu_s}$ in 1 cycle ($\approx$ 100s) determined to $\sigma_{\nu_s} \approx 10^{-10}$
- one application: study long term stability of the ring
- future application: dedicated online feedback systems

Spin tune: probing ring imperfections

- spin tune is perturbed by small kicks $\sim a$ by ring imperfections
$$\nu_0 = \gamma G + O(a^2)$$
- idea: probe imperfections by adding artificial imperfections
  spin kicks χ_1, χ_2 by means of e-cooler solenoids
- measure spin tune change
$$\Delta\nu_s = \nu_s(\chi_1, \chi_2) - \nu_0$$
- expectation
  $\Delta\nu_s \propto (y_\pm - a_\pm)^2$
  $y_\pm = \frac{1}{2}(\chi_1 \pm \chi_2)$
  $a_\pm$: in-plane ring imperfections



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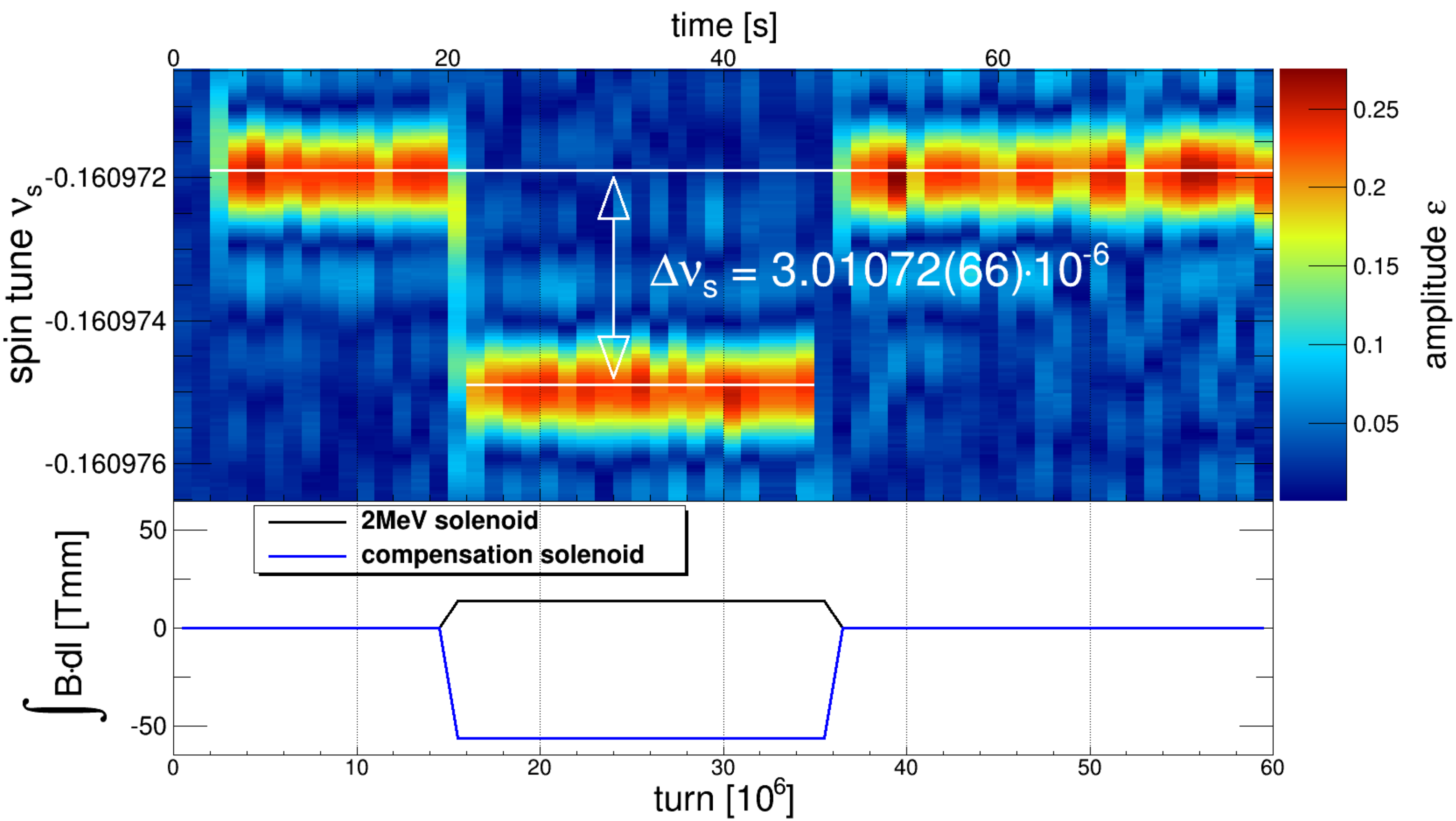
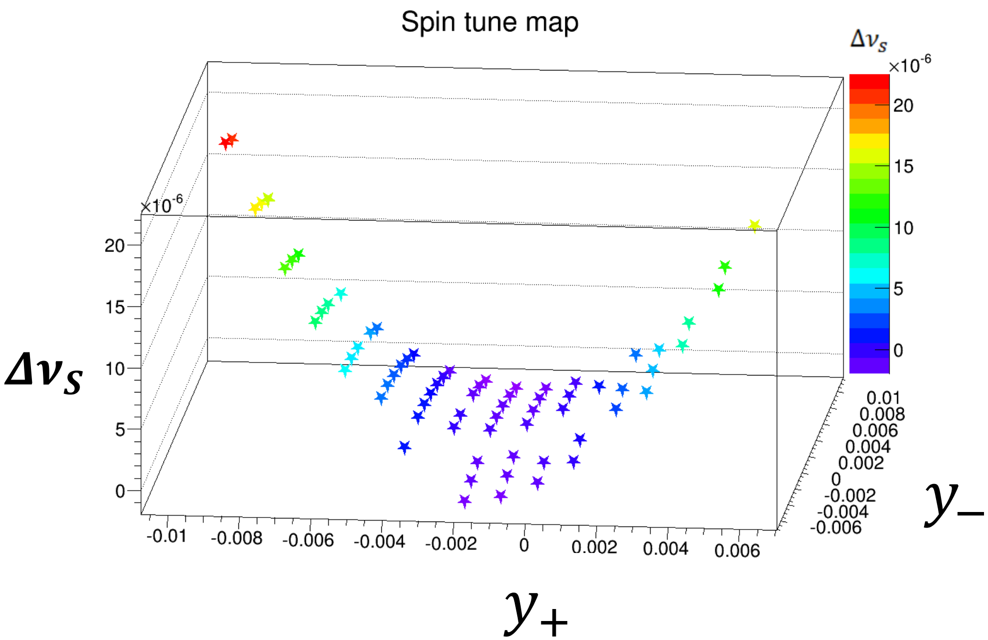
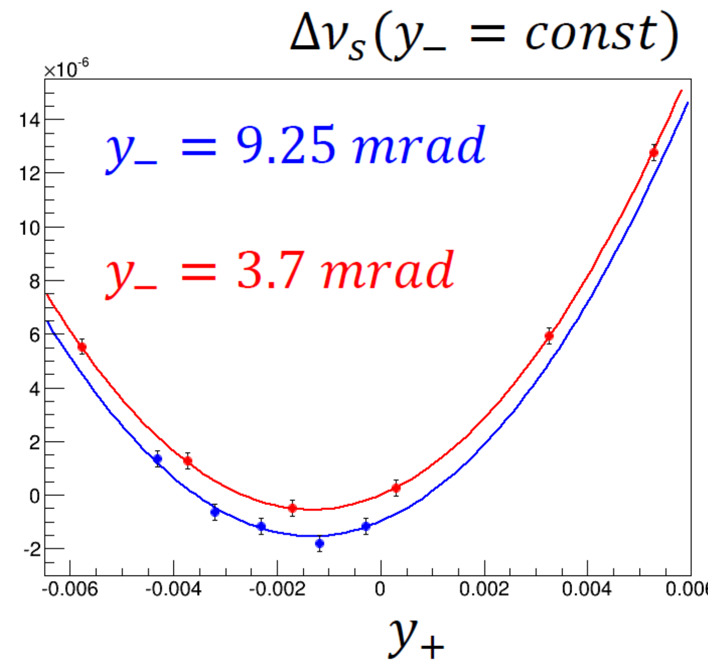


Spin tune: probing ring imperfections

spin tune map:





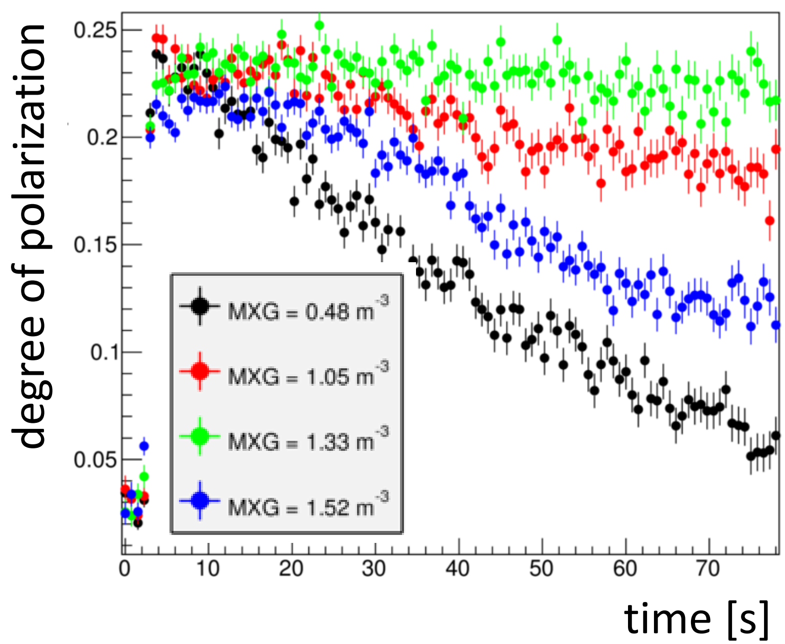
- parabolic behavior confirmed
- saddle point provides information on ring imperfections

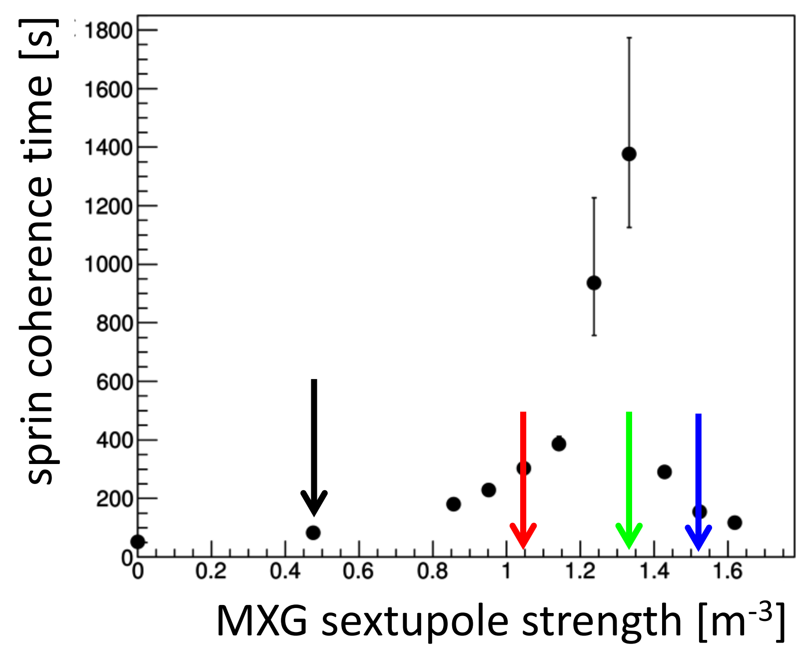
further information: HK 72.2 (Fabian Trinkel), HK 72.4 (Dennis Eversmann)

Spin coherence time (SCT)

Ensemble of ≈ 10^9 deuterons: coherent precession needed!

- unbunched beam: $\frac{\Delta\gamma}{\gamma} \approx 10^{-5} \implies$ decoherence in < 1s
- bunching: eliminate effects on $\frac{\Delta p}{p}$ in 1st order → $\tau \approx 20$ s
- correcting higher order effects using sextupoles → $\tau \approx 1000$ s





SCT vs chromaticity

chromaticity: $\Delta Q_{x,y}/\Delta p$

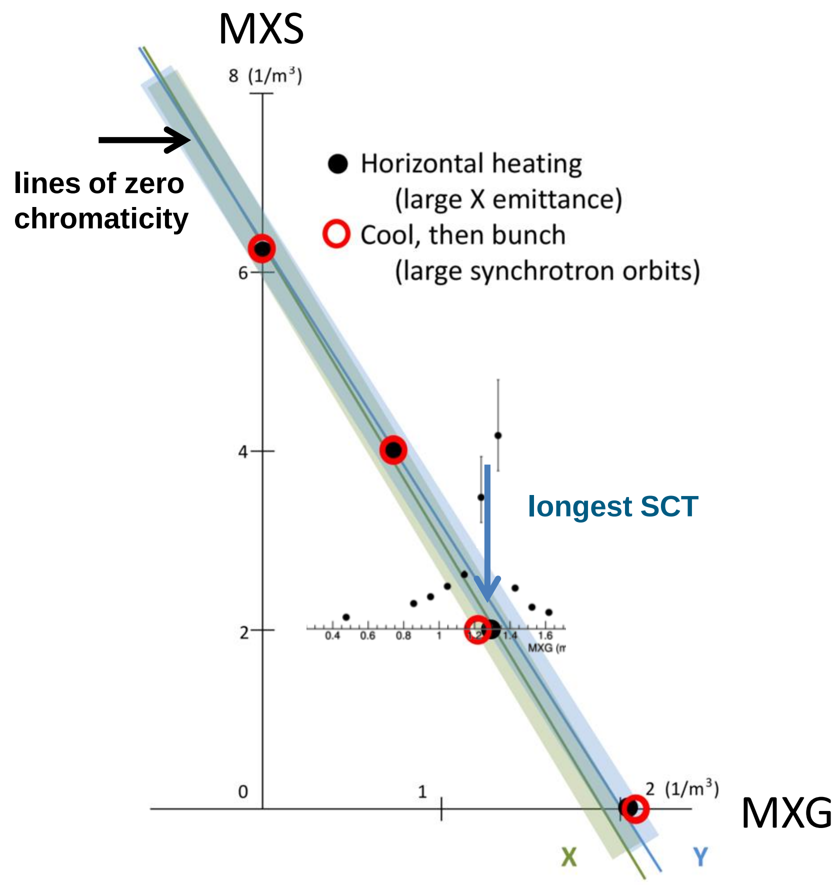
($Q_{x,y}$: betatron tunes, p : momentum)

- also controlled by sextupoles (here: MXS, MXG)
- compare:
  points of zero chromaticity

  $\updownarrow$

  points of longest SCT

settings for zero chromaticity and longest SCT coincide!



rf Wien filter: magnetic ring

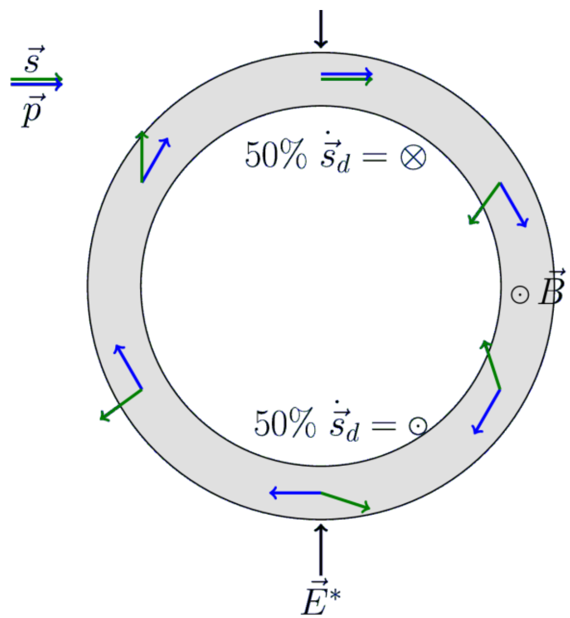
$$\vec{\Omega} \propto G\vec{B} + d\,\frac{m}{q\hbar S}\left(\vec{v}\times\vec{B}\right)$$

Due to horizontal precession caused by magnetic moment:

$$\int d\left[\left(\vec{\beta}\times\vec{B}\right)\times\vec{S}\right]\mathrm{d}t = 0$$

$\longrightarrow$ no net EDM effect

$\vec{E}^* = \vec{v}\times\vec{B}$



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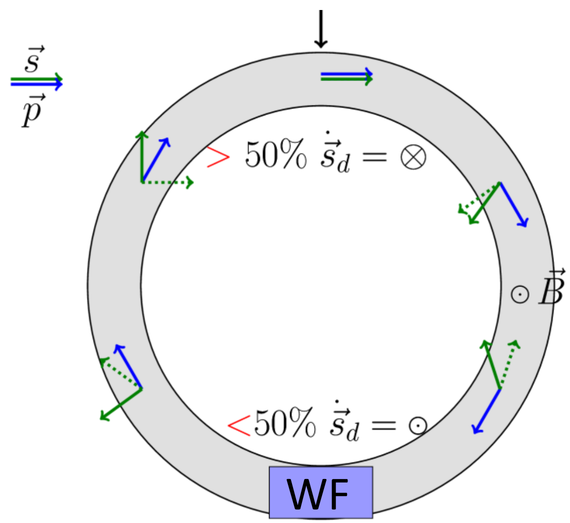


$$\vec{\boldsymbol{E}}^* = \vec{\boldsymbol{E}}_W + \vec{\boldsymbol{v}}\times\vec{\boldsymbol{B}}_W$$

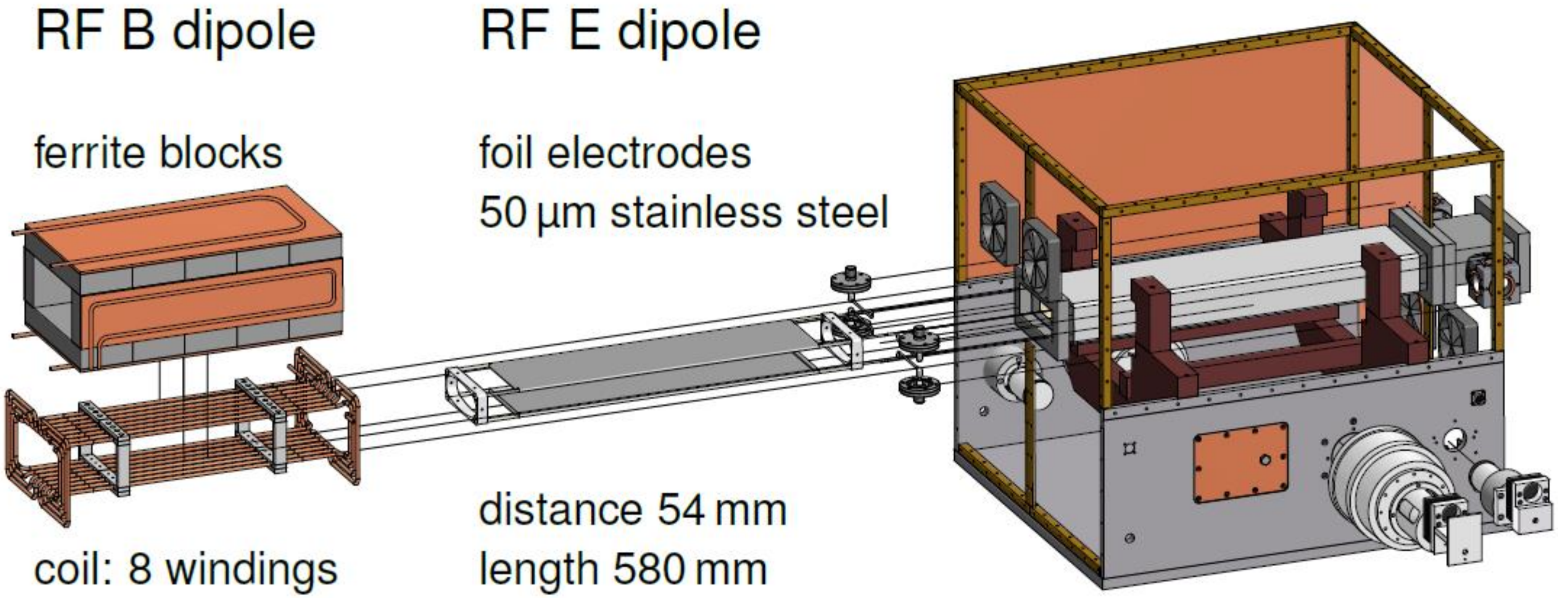
Use resonant “magic Wien-Filter”

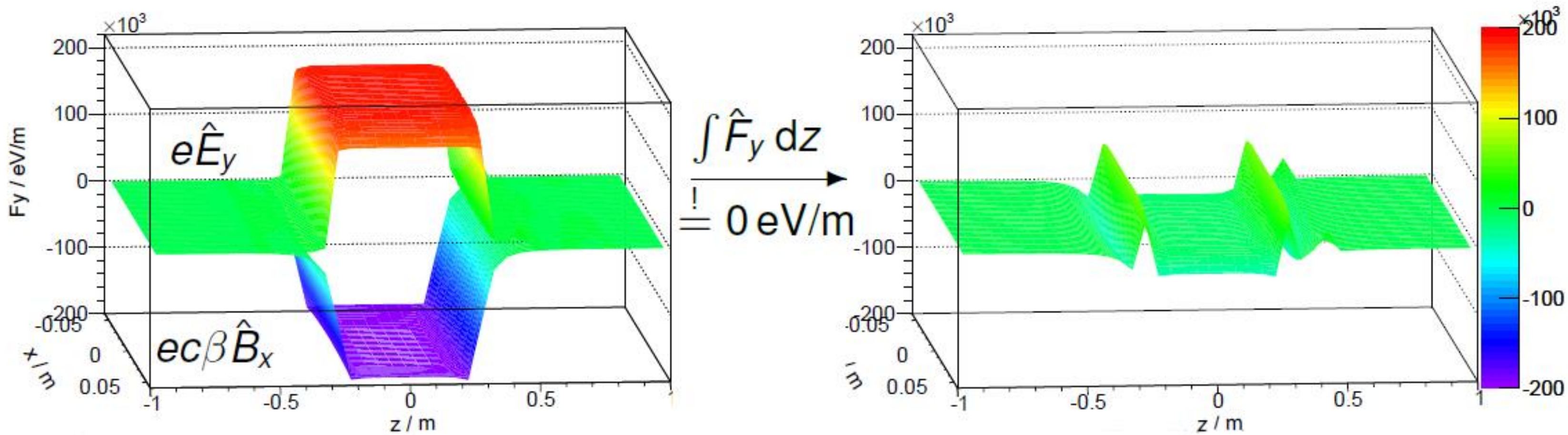
$$\vec{E}^* = \vec{E}_W + \vec{v}\times\vec{B}_W = 0$$

- affects only magnetic moment
- introduces „EDM free“ phase advance in horizontal precession

$\longrightarrow$ net EDM effect can be observed

rf Wien filter: design



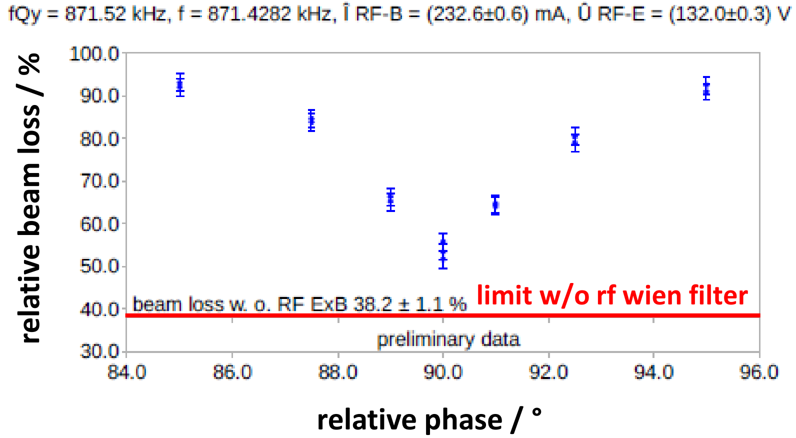


rf Wien filter: first tests in beam

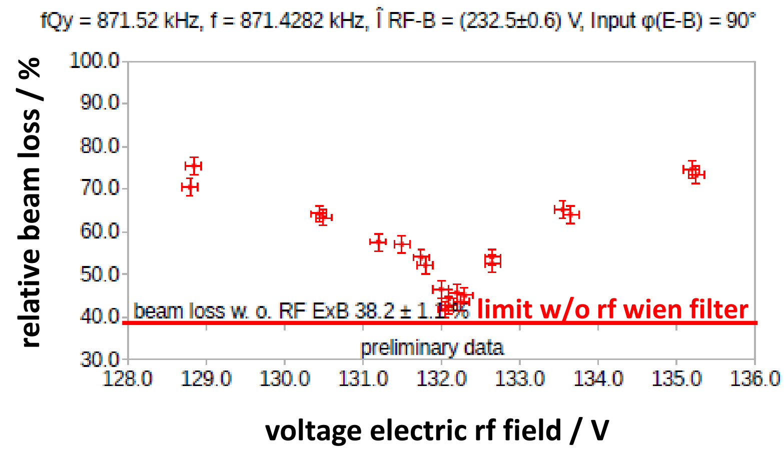
Lorentz force compensation

- Amplitude and phase matching of rf E- and B-fields
- move betatron sideband onto RF frequency for max. sensitivity
- exited part of beam is removed (beam loss)
- determination of matching amplitudes and phase down to 10^{-3}

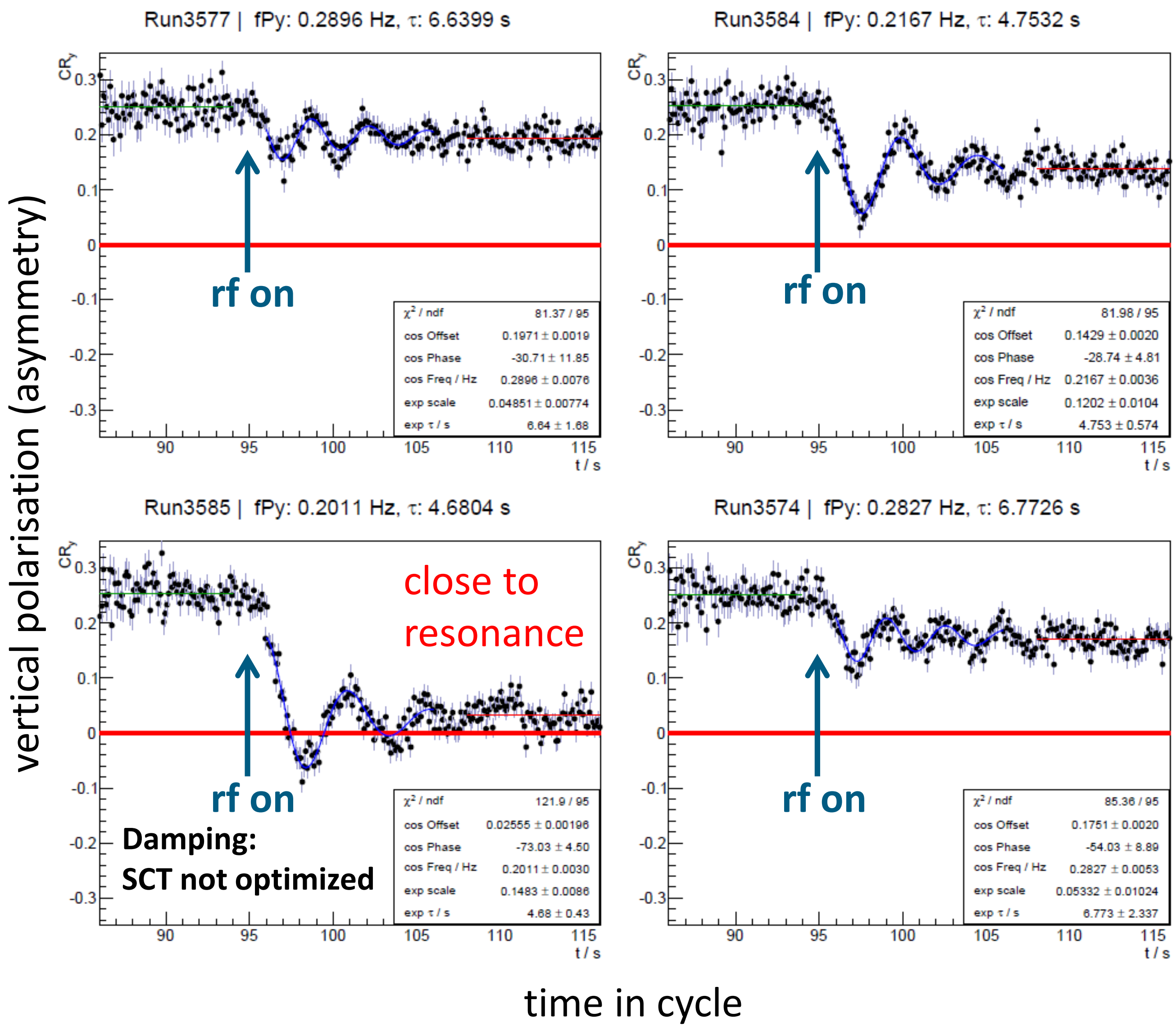
phase scan



amplitude scan



rf Wien filter: frequency scan



Summary

- COSY: ideal starting point for R&D and a pre-cursor experiment
- spin coherence time of several hundred seconds reached
- precise spin tune determination tool for understand storage ring parameters (future option: phase lock for rf devices)
- new equipment: rf Wien filter, BPMs, deflectors, ...

Outlook

- pre-cursor experiment at COSY:
  proof of principle with lower sensitivity planned for < 2019
- dedicated storage ring:
  different options are currently under investigation
  goal: conceptual design report 2019

JEDI

Jülich **E**lectric **D**ipole Moment **I**nvestigations:

- ≈ 100 members:
  Aachen, Daejeon, Dubna, Ferrara, Grenoble, Indiana, Ithaca, Jülich, Krakau, Michigan, Minsk, Novosibirsk, St. Petersburg, Stockholm, Tbilisi, …

- see
  http://collaborations.fz-juelich.de/ikp/jedi