SPIN TUNE DETERMINATION AND FEEDBACK

2025/03/11 VOLKER HEJNY

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Forschungszentrum

OUTLINE

This talk covers more than 10 years of R&D by the JEDI collaboration at COSY, Jülich

1. (Online) determination of spin tune and in-plane polarization

- Measuring the polarization of a rapidly precessing deuteron beam, PRAB 17, 052803 (2014).
- New Method for a Continuous Determination of the Spin Tune in Storage Rings and Implications for Precision Experiments, PRL 115, 094801 (2015).

2. How to reach large spin coherence times

- How to Reach a 1000s in-Plane Polarization Lifetime with 0.97-GeV/c d in a Storage Ring, PRL 117, 054801 (2016).
- Connection between zero chromaticity and long in-plane polarization lifetime in a magnetic storage ring, PRAB 21, 024201 (2018).
- Influence of e-cooling on the polarization lifetime of a horizontally polarized storage ring beam, NIM A 987, 164797 (2021)

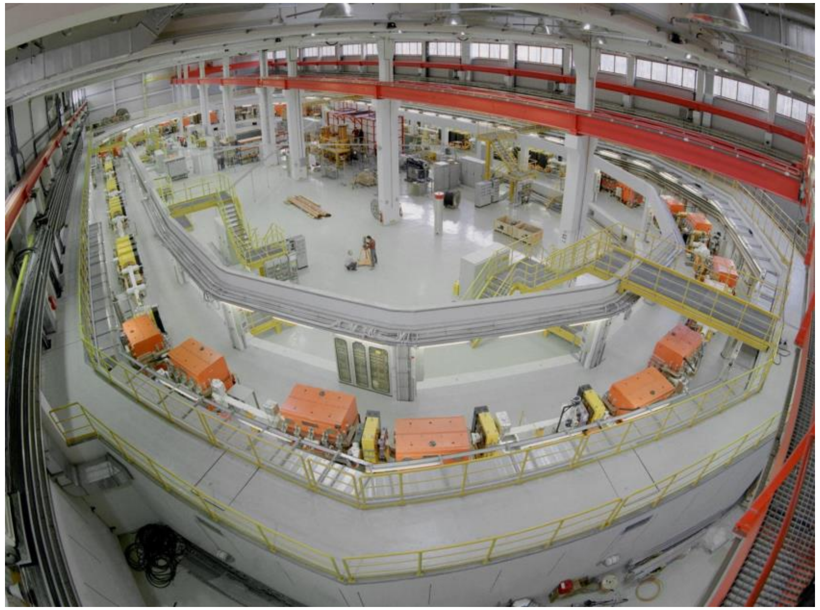
3. Phase-lock feedback: synchronizing spin precession and rf devices

- Phase Locking the Spin Precession in a Storage Ring, PRL 119, 014801 (2017).
- Phase measurement for driven spin oscillations in a storage ring, PRAB 21, 042002 (2018).
- Maintaining a Resonance Condition of an RF Spin Rotator Through a Feedback Loop in a Storage Ring, arXiv:2501.19123

INTRODUCTION

Physics case:

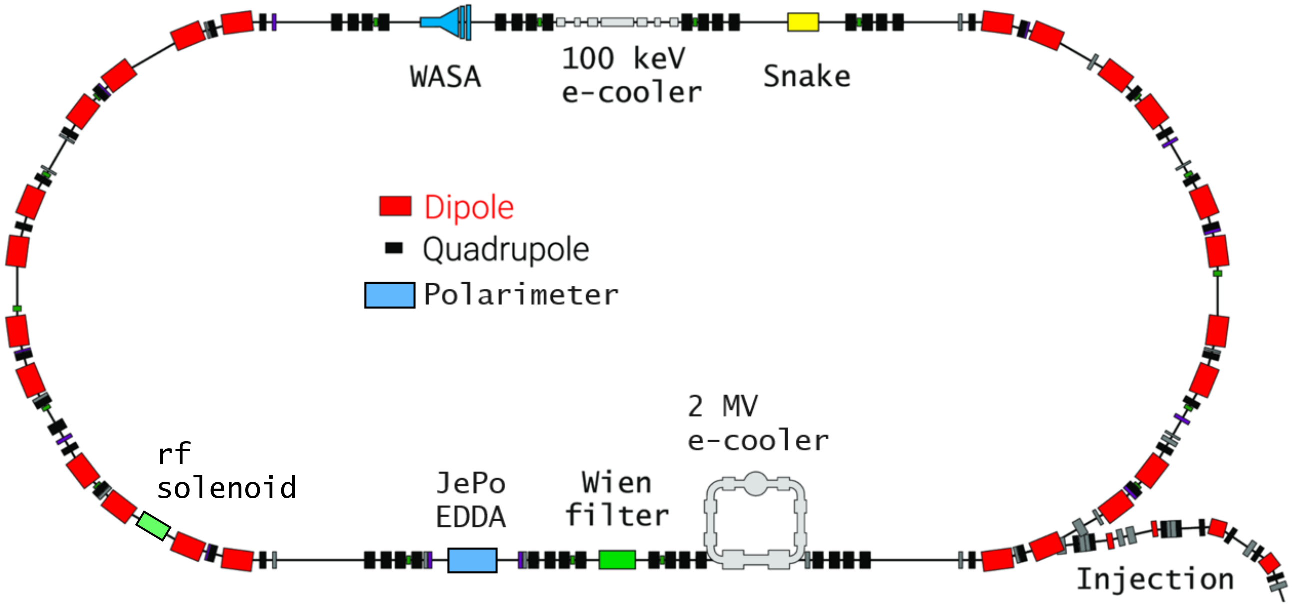
- R&D for precision experiments on EDMs of charged particles in storage rings
  Storage Ring to Search for Electric Dipole Moments of Charged Particles: Feasibility Study (CERN, 2021), doi: 10.23731/CYRM-2021-003, arXiv:1912.07881
- First measurement of the deuteron EDM at COSY ("precursor experiment")
  2 runs, 2018 and 2021, analysis and systematics currently being finalized



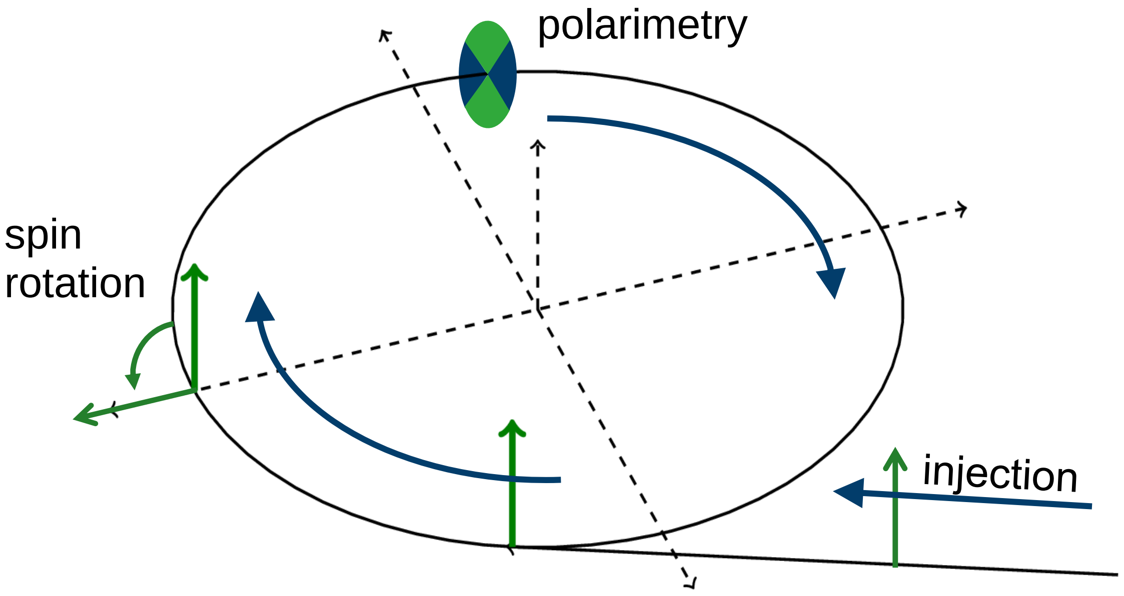
All experiments were carried out at the Cooler Synchrotron COSY,
Institut für Kernphysik,
Forschungszentrum Jülich,
Germany

INTRODUCTION: COSY

- Circumference 184m
- Protons and deuterons up to 3.7 GeV/c
- Unpolarized and polarized
- Electron cooling
- Stochastic cooling
- Up to 10^{10} – 10^{11} particles / fill (typically 10^9 for polarized fill)
- Instrumentation used by JEDI:
  - various detectors as polarimeters
  - snake, static e-cooler solenoids, rf solenoid, rf Wien filter for spin manipulation
  - sextupoles for optimizing spin coherence times



INTRODUCTION: TYPICAL EXPERIMENTAL SETUP



Beam:

- (Vector-) polarized deut. @ 0.97 GeV/c
- Phase-space cooled and bunched

Accelerator / measurement cycle:

1. Injection & acceleration
2. Electron cooling
3. Switching off all e-cooler magnets
4. Orbit correction and adjustment of tune / chromaticity (steerer, quadrupoles, sextupoles)
5. Spin rotation into the horizontal plane by means of an rf solenoid
6. Start of the measurement cycle (typically @90s after injection)

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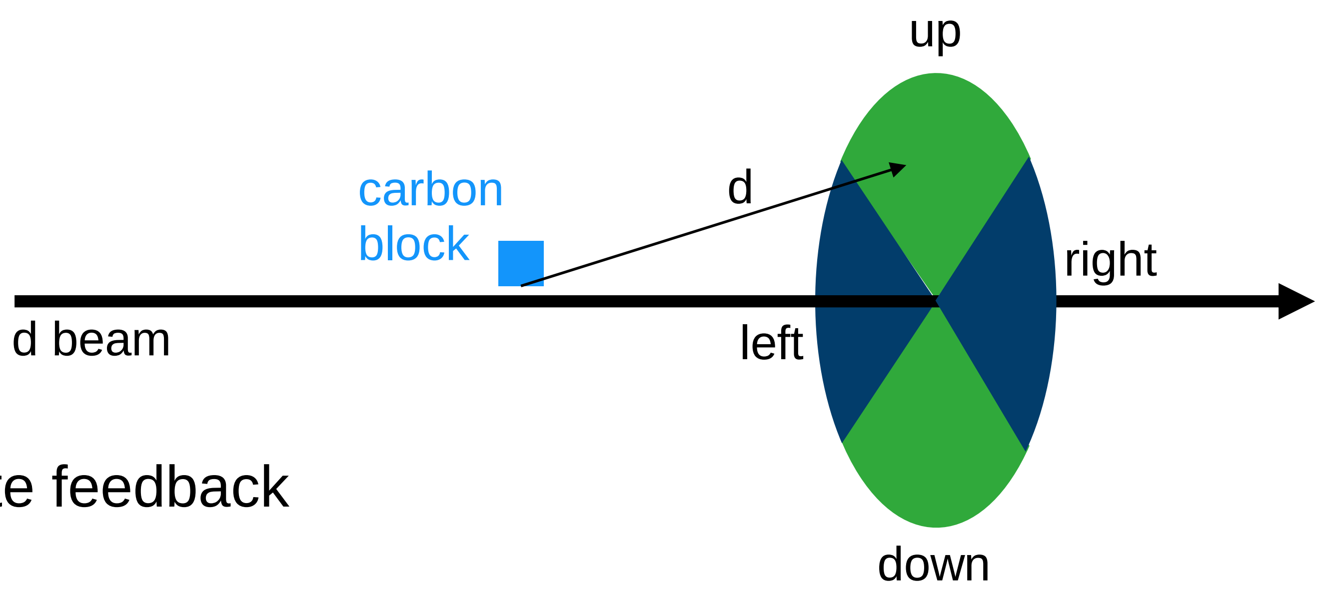
INTRODUCTION: CONTINOUS POLARIMETRY

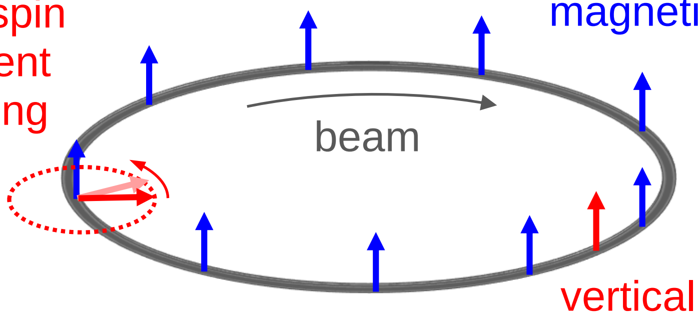
General setup:

- beam excitation in a narrow band around a betatron resonance
  → outermost particles hit target



- excitation amplitude controlled by rate feedback
  → constant detector rates
- dC elastic scattering, asymmetries: $\frac{N_{\text{left}}-N_{\text{right}}}{N_{\text{left}}+N_{\text{right}}} \propto p_{\text{vertical}}$, $\frac{N_{\text{up}}-N_{\text{down}}}{N_{\text{up}}+N_{\text{down}}} \propto p_{\text{radial}}$
- various detectors used (EDDA, WASA, JePo), same principal
- beam momentum was selected to match hight analysing power and e-cooler options.

1. SPIN TUNE / IN-PLANE POLARISATION



Situation:

- In-plane spin vector precesses with
  $f_s = 2\pi\nu f_c \approx 120\ \mathrm{kHz}\ (\nu = \gamma G \approx 0.16,\ f_c \approx 750\ \mathrm{kHz})$
  event rate ≈ 10000 s^{-1}

Solution:

- Events are time-stamped using a long-range TDC in continuous mode ($\Delta t_{\mathrm{bin}} = 90\mathrm{ps}$, $\Delta T_{\mathrm{TDC}} \approx 6\mathrm{s}$, longer ranges by software overflows)
- Cavity rf is recorded by the same TDC (same clock) → allows clock-independent turn-based analysis
- Data are analyzed in time interval of 1-2s by a Fourier-analysis based sorting algorithm
  → amplitude (=asymmetry) @ maximum is a measure of the in-plane polarization
  → frequency @ maximum is a measure of the precession frequency / spin tune

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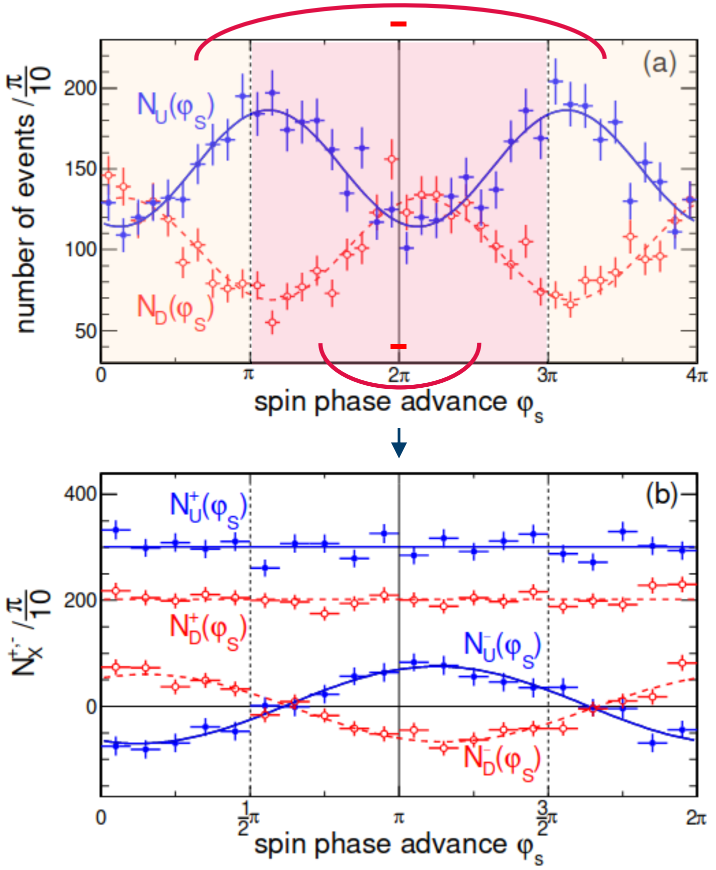
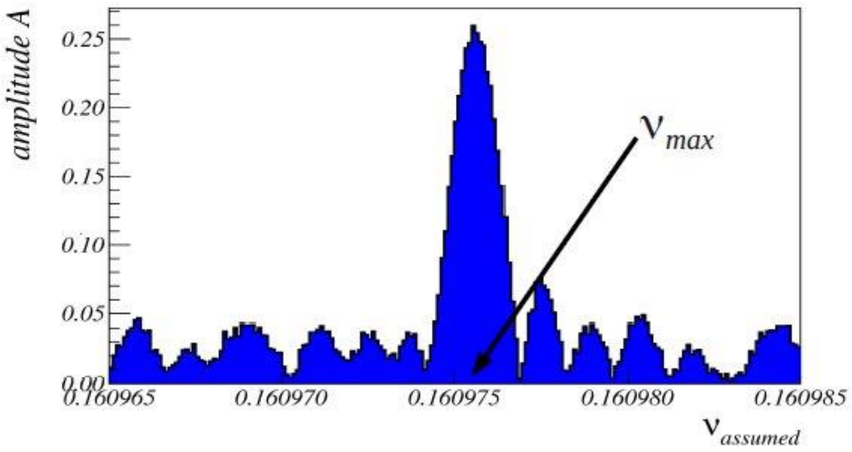
EXAMPLE: SINGLE INTERVAL

assumed spin tune ν: $\varphi_s = 2\pi\nu_{\text{assumed}}\,\mathrm{N}_{\text{turn}}$



range scan

ν_{assumed}



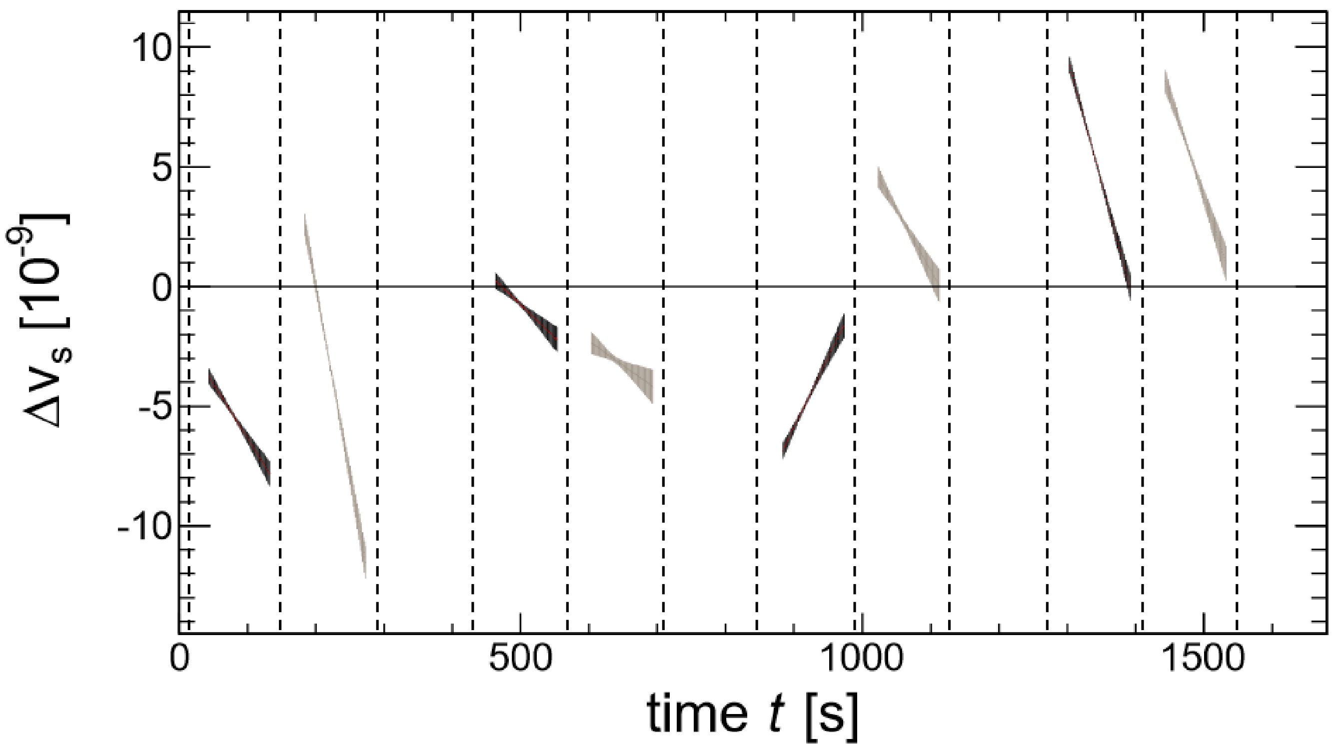
Improving precision:

Phase walk from internal to interval

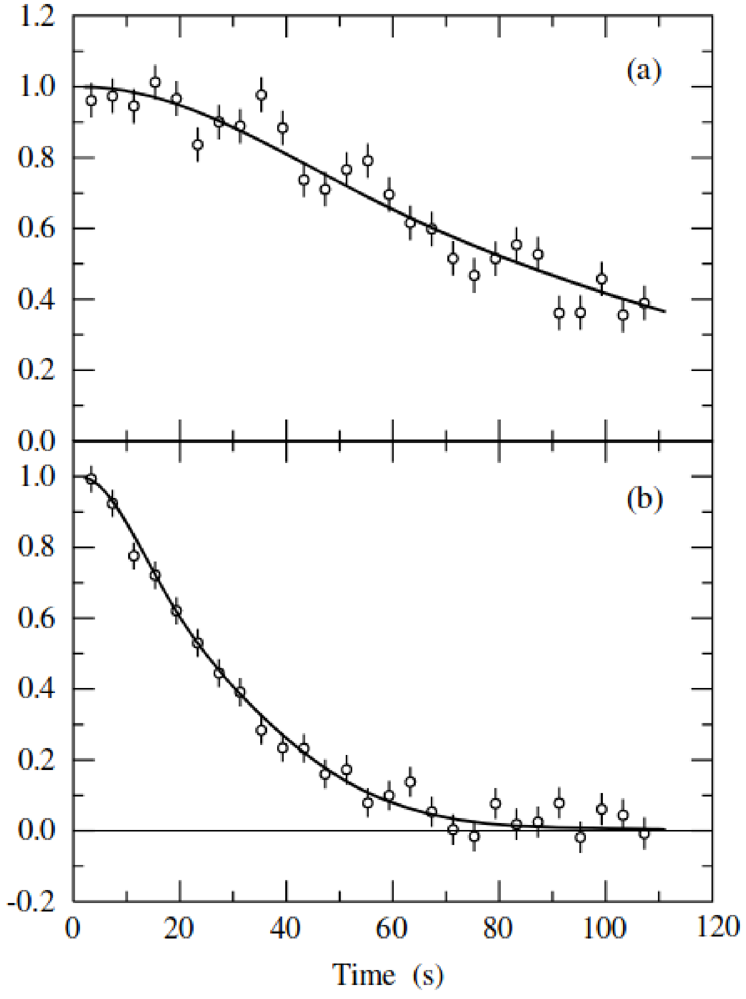
$$\Delta\nu(t) = \frac{1}{2\pi}\,\Delta\varphi(t)$$

EXAMPLE: TIME DEPENDANCE

spin tune stability ($\nu \approx 0.16$)



normalized
in-plane polarisation



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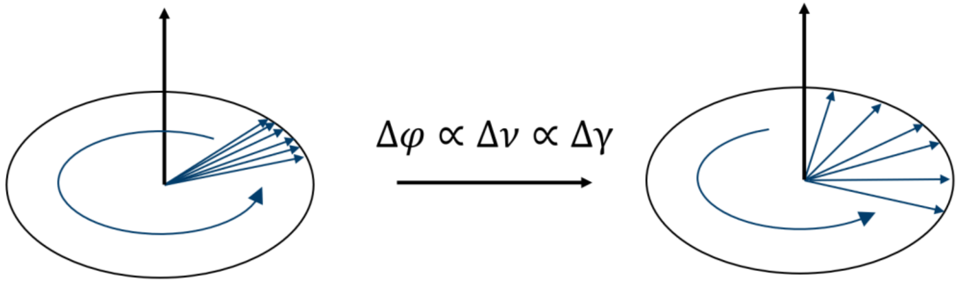
2. SPIN COHERENCE TIME

- transverse and longitudinal phase-space distribution effects SCT

  $\rightarrow$ minimize $\Delta\nu_s = f\left(\Theta_x, \Theta_y, \Theta_x^2, \Theta_y^2, \frac{\Delta p}{p}, \left(\frac{\Delta p}{p}\right)^2, \ldots\right)$



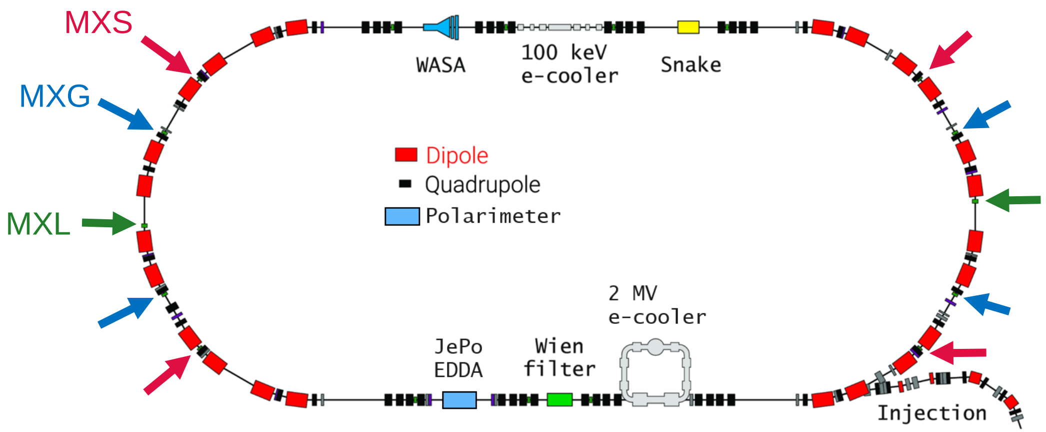
Θ_x, Θ_y: angles of particle's motion $\rightarrow$ different path lengthening

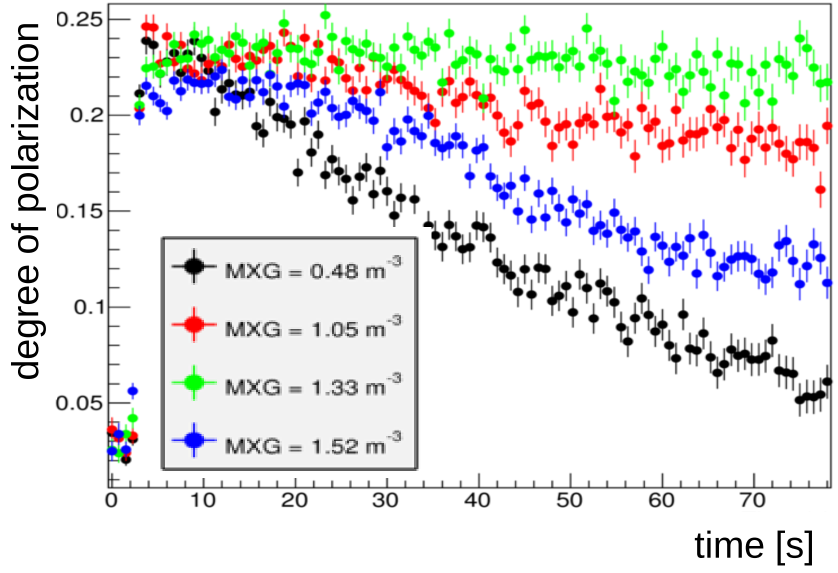
$\frac{\Delta p}{p}$: momentum spread $\rightarrow$ spin tune spread $\Delta\nu_s$

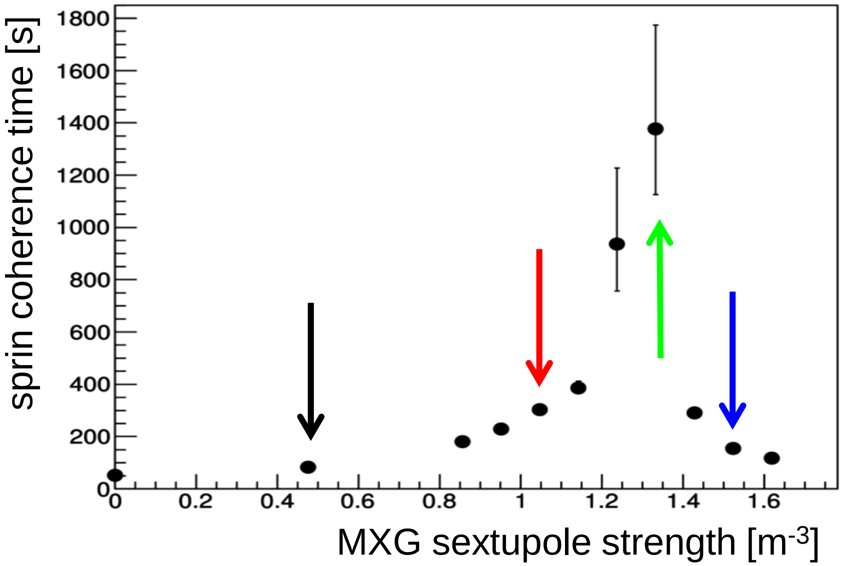
- measures to reach long spin coherence (>1000s for deuterons, PRL 117 (2016) 054801)
  - beam bunching to remove the first order Δp/p contribution
  - (electron) cooling to shrink transverse and longitudinal beam emittance
  - sextupole field corrections to decrease different path lengthening of particles

SEXTUPOLE SETTINGS

Optimization of spin coherence time using 3 sextupole families







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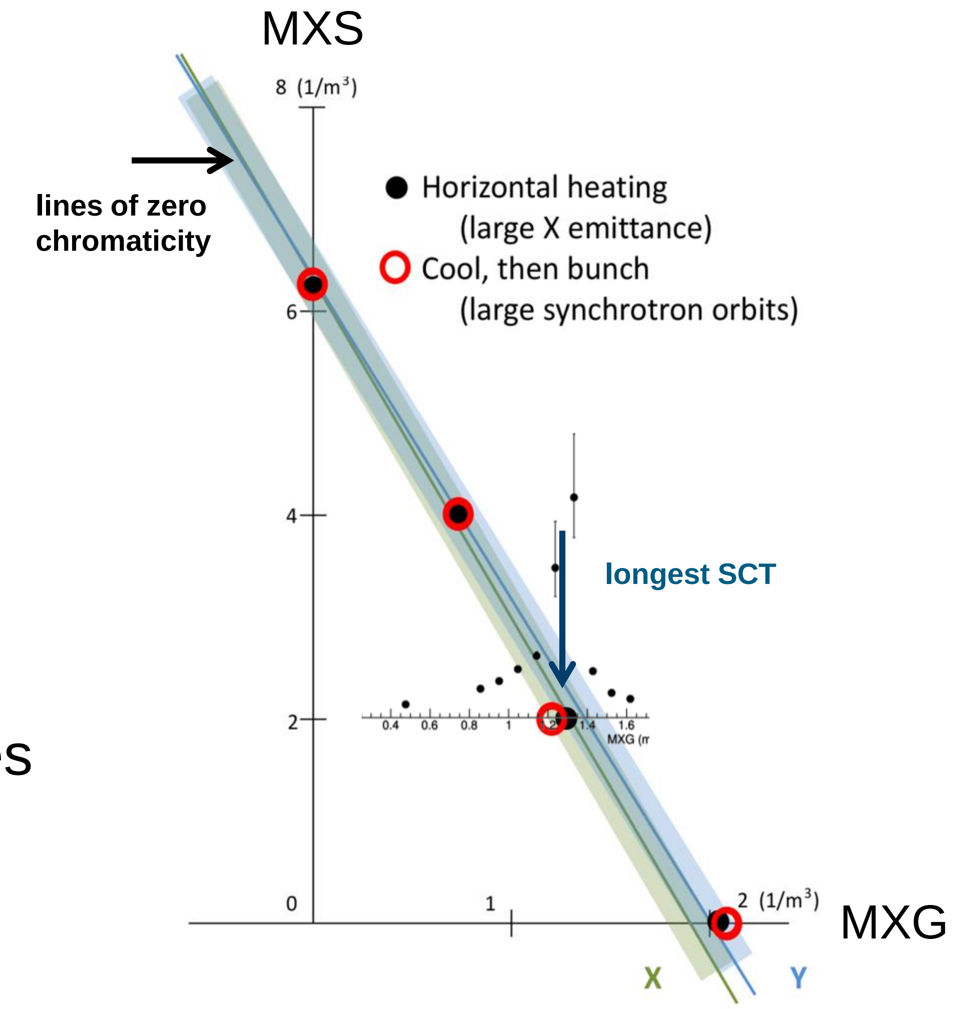
SPIN COHERENCE TIME VS CHROMATICITY

Sextupoles control chromaticity:

- We compared chromaticity settings with points of large spin coherence time

settings for zero chromaticity and longest SCT coincide!

- However: this is for the case where no spin resonances are near-by:
  Large spin-tune deviations close to spin resonances

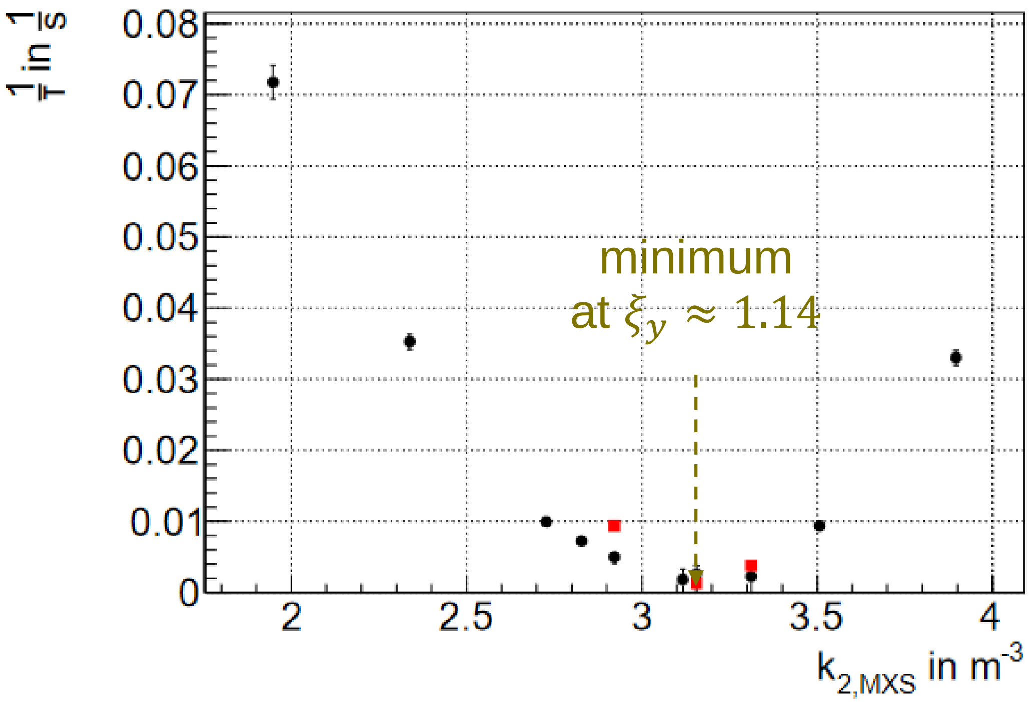


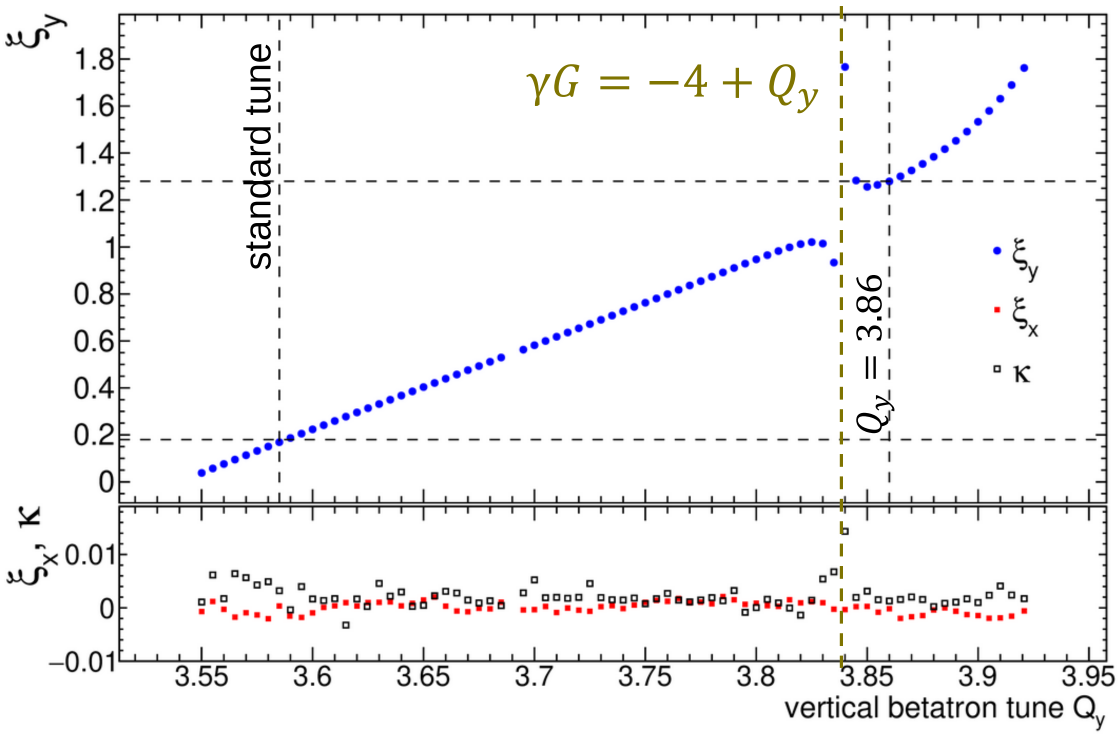
BEHVIOUR CLOSE TO A RESONANCE

Normally no spin resonances in the COSY momentum range for deuterons

- move vertical tune close to resonance ($Q_y = 3.86$)
- compensate effect with simulated chromaticities

(PhD theses M. Rosenthal)





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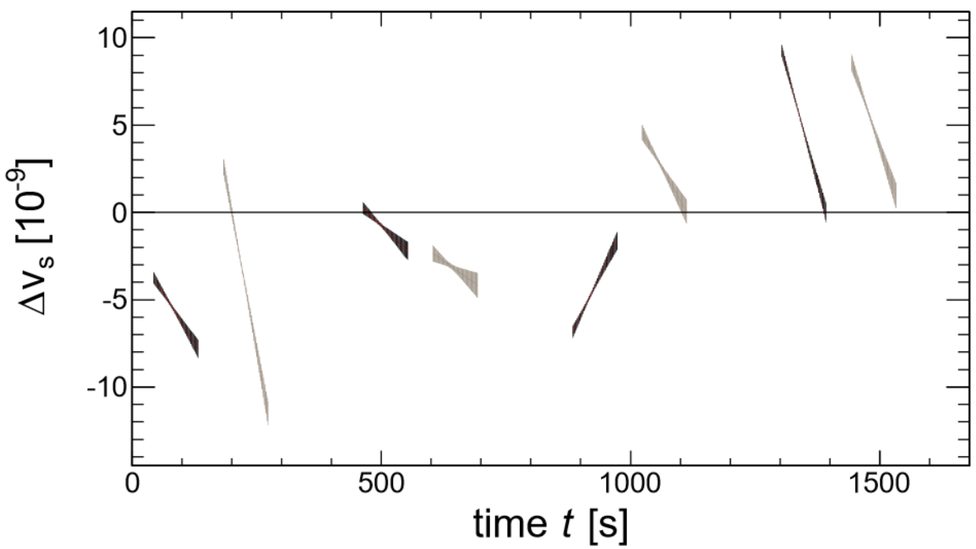
3. PHASE-LOCK FEEDBACK

For the EDM measurements the rf Wien filter had to run on resonance with the spin precession:

$$f_{\mathrm{WF}} = (n + \gamma G) f_{\mathrm{COSY}}, \qquad n \in \mathbb{Z}$$

A variation of $\Delta\nu \approx 10^{-8}$ means a phase shift of $\Delta\varphi \approx 2\pi\Delta\nu\, f_{\mathrm{COSY}} t > 2\pi$ for one cycle

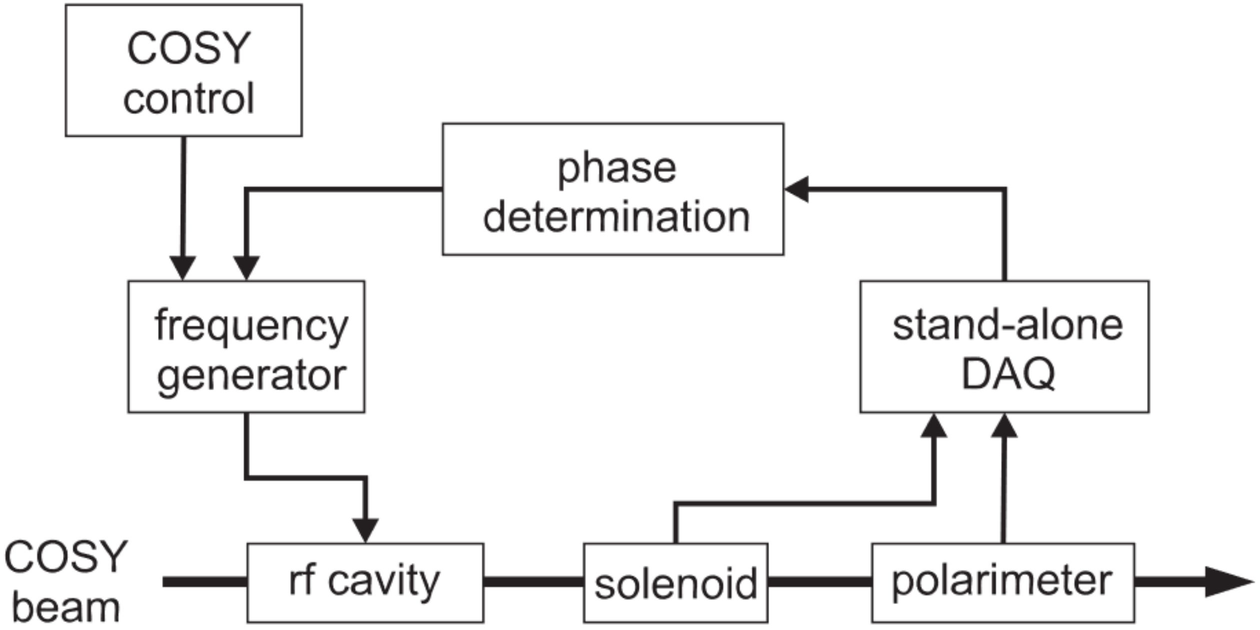


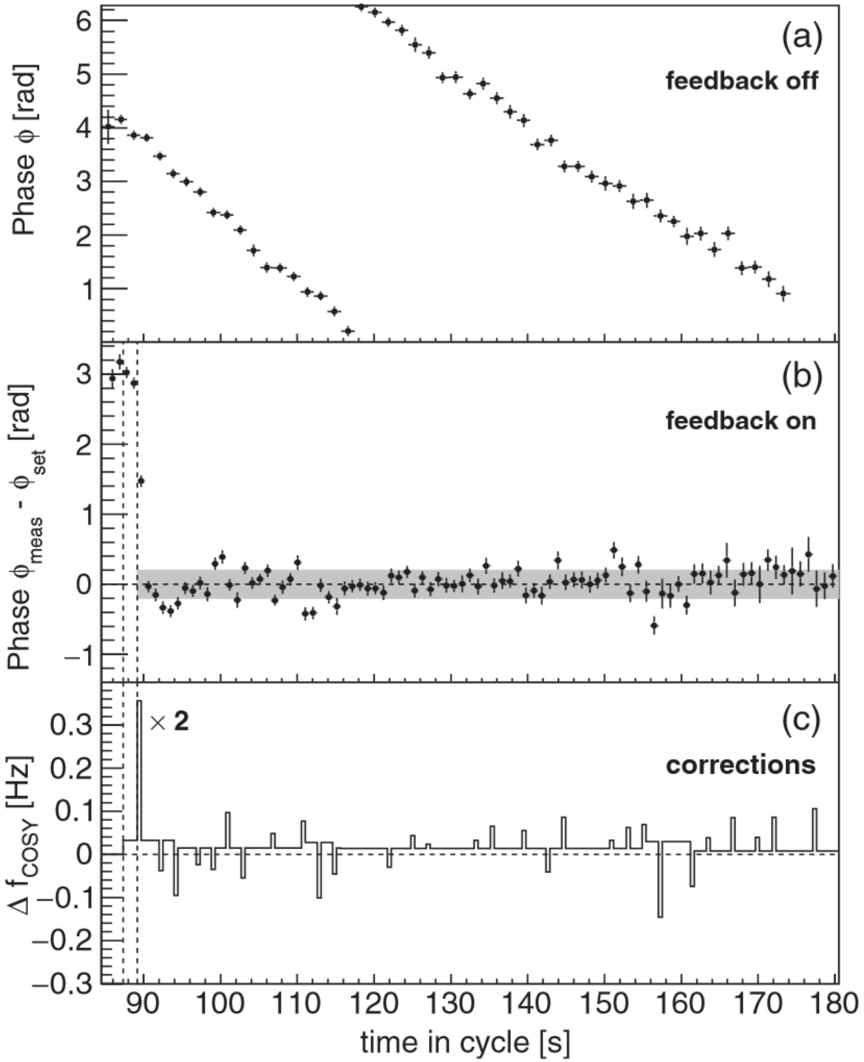
Two options:

- Stabilization of the spin tune
- Adjustment of f_{WF}

SPIN TUNE MANIPULATION (2017, PRL 119, 014801)

Based on the continuous spin tune measurement, the COSY frequency generator was modified to apply miniscule frequency changes during flat top ($\Delta f_{\text{min}} = 3.7\ \text{mHz}$)





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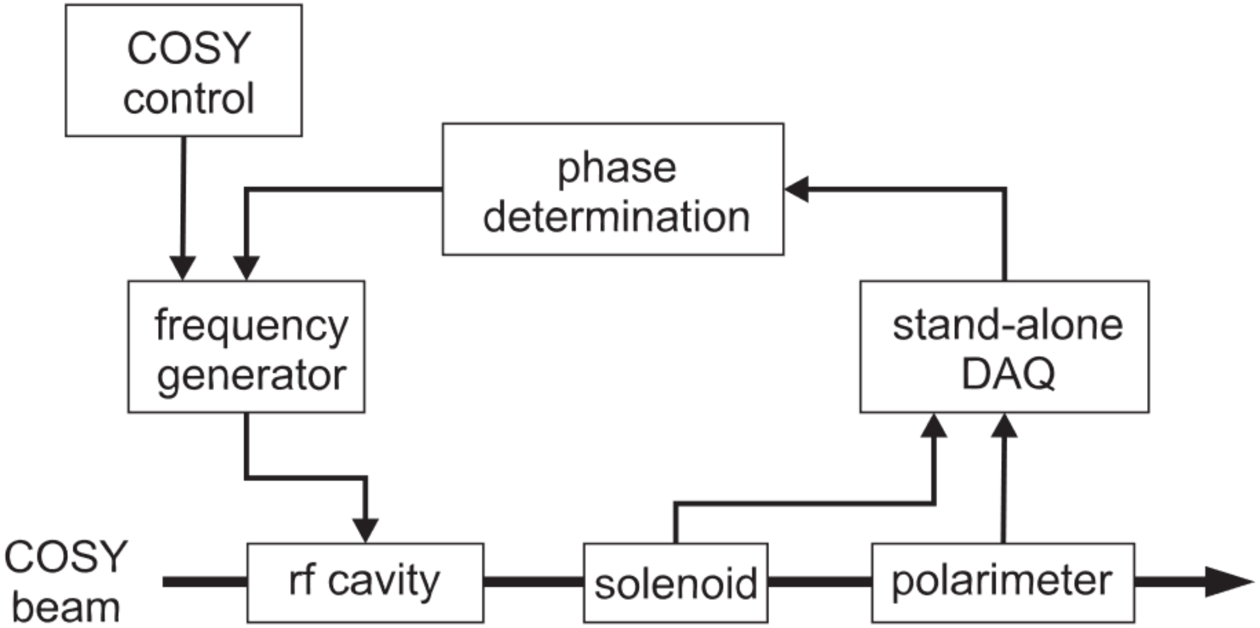
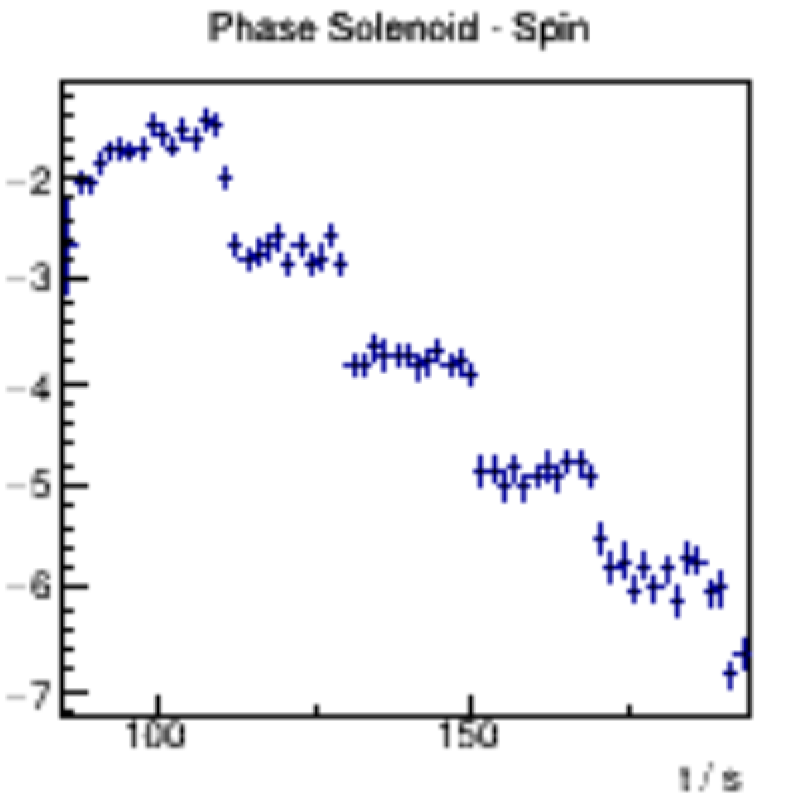


From elog:
induced phase jumps



PHASE FEEDBACK ON RF WIEN FILTER

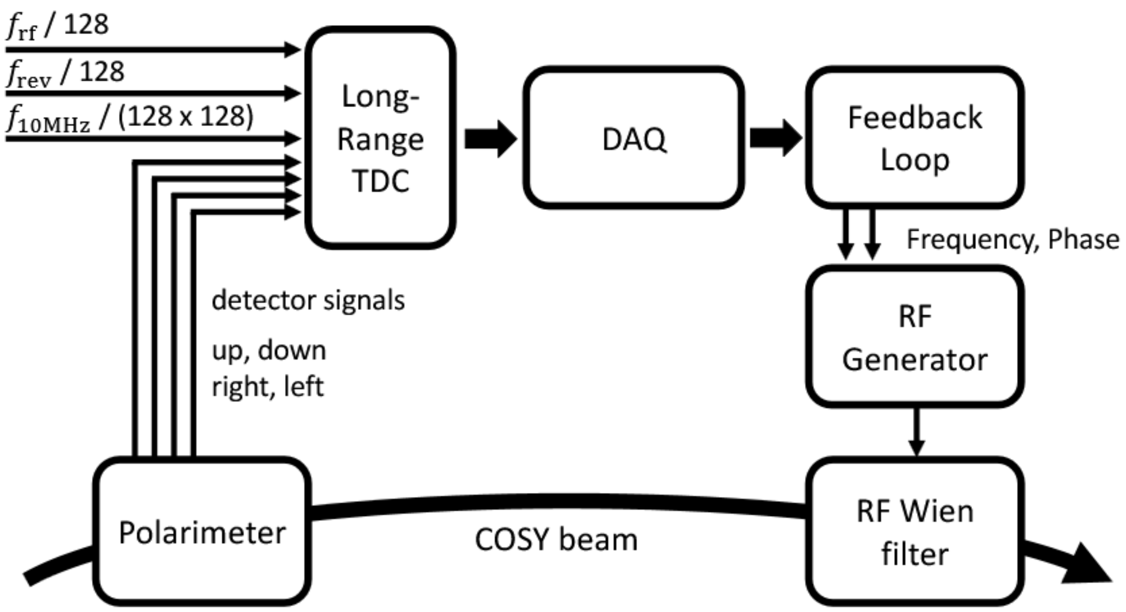
Changing the rf of COSY might change other parameters

Modified approach:

Keep spin precession and WF rf sync‘ed in phase

Two settings:

1. Use bunch affected by the Wien filter
2. Use pilot bunch (unaffected bunch used as comagnetometer)



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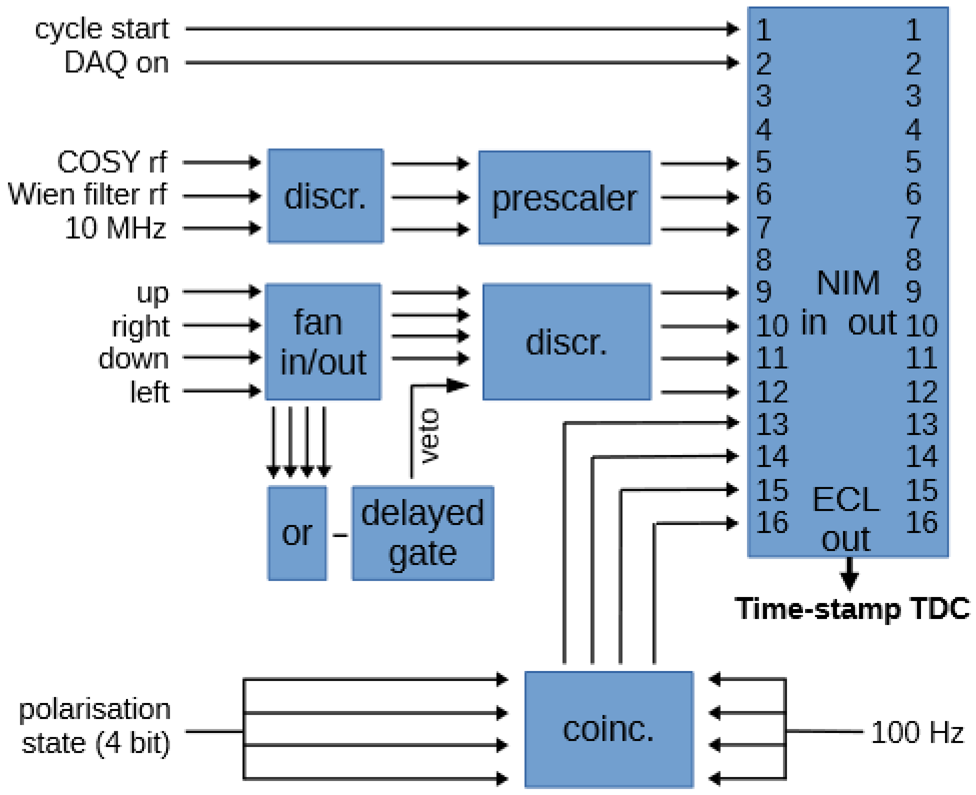
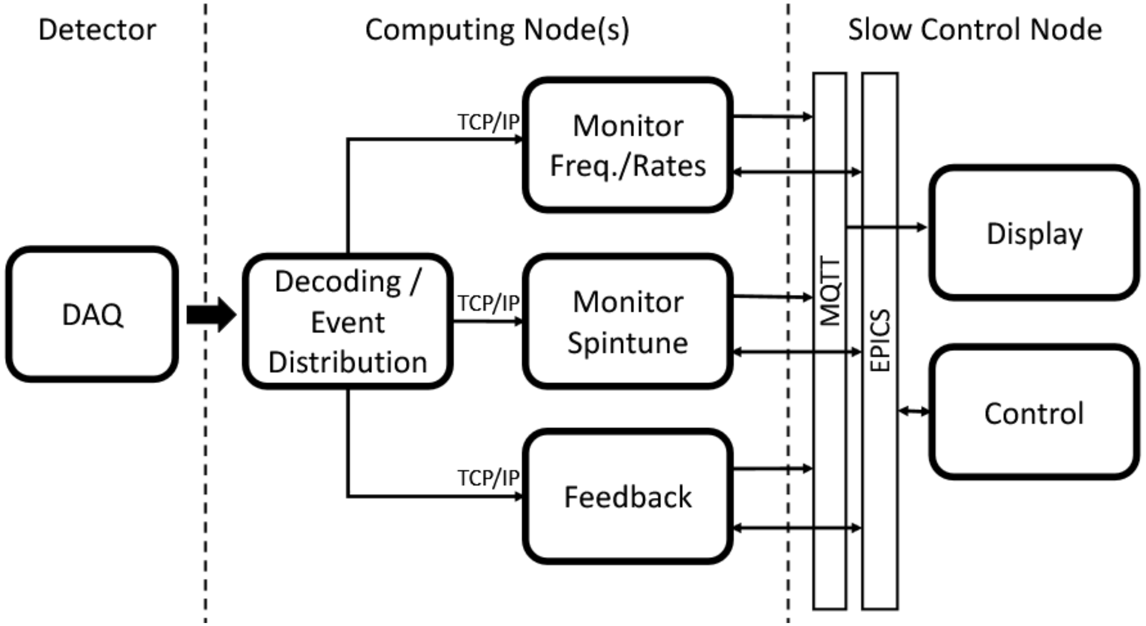
BASIC SETUP





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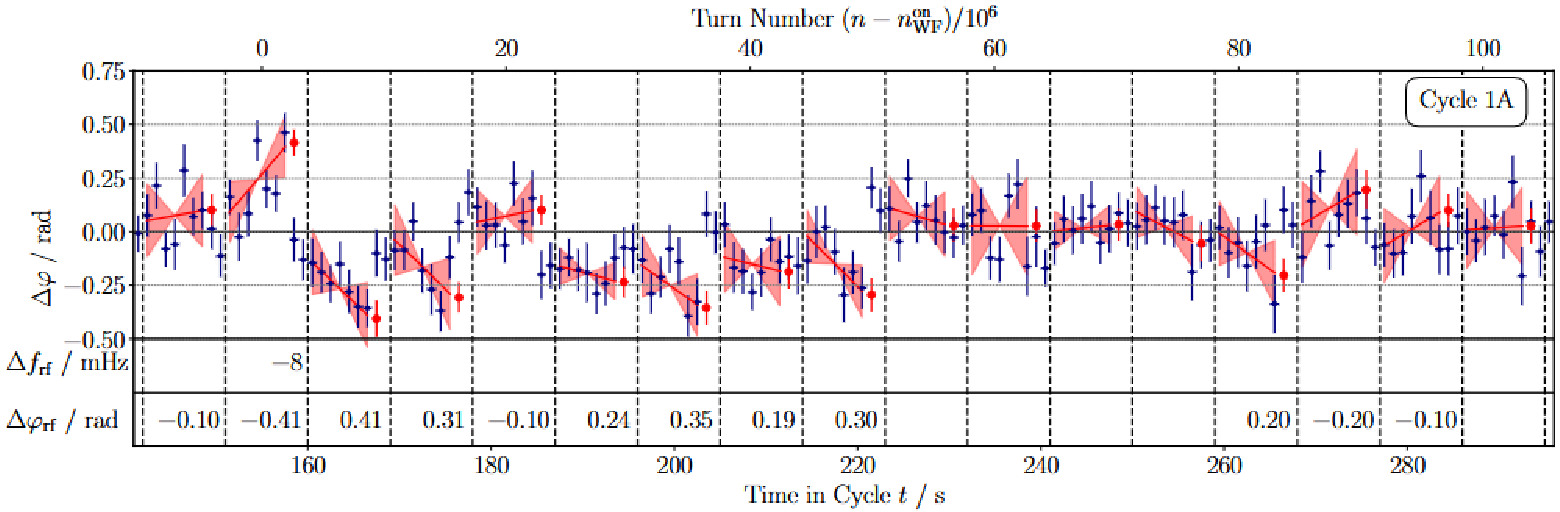
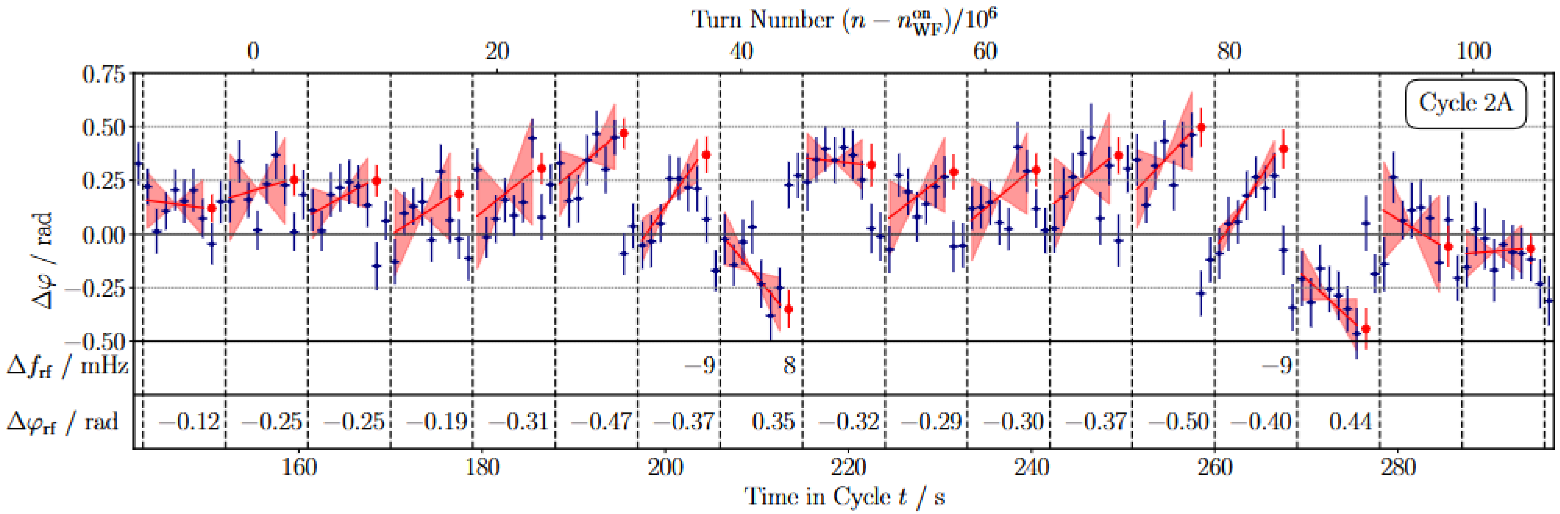
PRECURSOR FEEDBACK: CONTROL





$$\varphi_{meas} = \varphi_{WF} - \varphi_s$$

$$\varphi = m \cdot \Delta t \cdot \left(i - \frac{N}{2}\right) + \Delta\varphi_c$$

Corrections are applied if m and/or $\Delta\varphi_c$ are outside of a 2σ window from the demand value.

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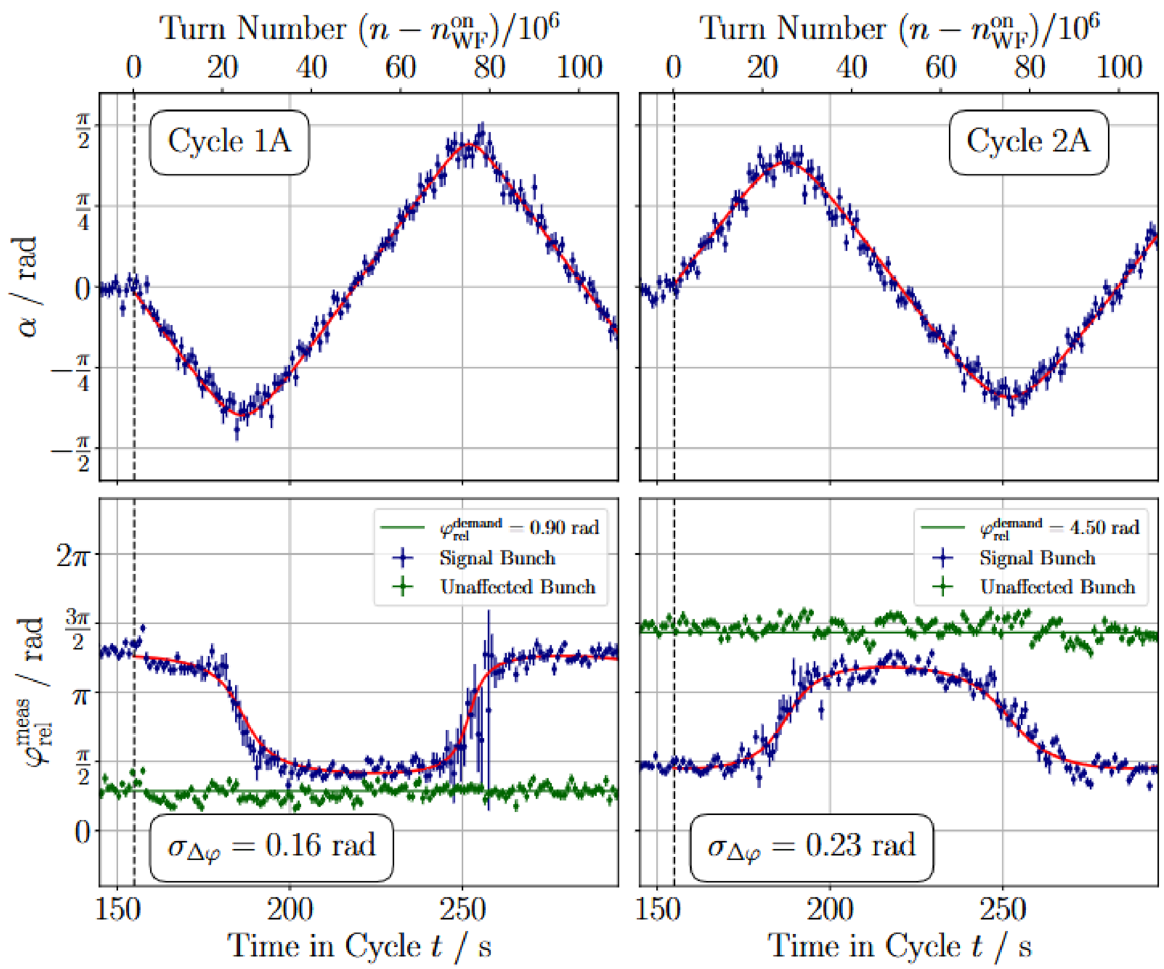
PRECURSOR FEEDBACK: EXAMPLE

Two bunches:

- pilot bunch (WF fields off when passing): remains in-plane, monitors spin-tune changes
- signal bunch on resonance with a defined phase relation (amplitude $A \propto \cos\varphi$)

→ guarantees well defined conditions for spin manipulation using the Wien filter



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