Physics Institute III B

RWTH AACHEN UNIVERSITY

JEDI

JÜLICH FORSCHUNGSZENTRUM

Spin Tracking with COSY INFINITY and its Benchmarking

2015-05-05 | Marcel Rosenthal for the JEDI collaboration

Outline

- **Methods**
  - Simulation toolbox
  - New extension: Transfer maps for time-varying fields
- **Application I : RF-B Solenoid Driven Oscillations**
  - Induced RF field spin resonance
  - Benchmarking of measurement, analytical estimation and tracking
- **Application II: RF-E×B Wien filter Driven Oscillations**
  - EDM method based on RF fields
  - Benchmarking of tracking and analytical estimation
  - Systematic limitations
- **Conclusion**

Thomas-BMT-Equation

- Equation of spin motion for relativistic particles in electromagnetic fields:

$$\frac{d\vec{S}}{dt} = \vec{S} \times \vec{\Omega}_{MDM} + \vec{S} \times \vec{\Omega}_{EDM}$$

$$\vec{\Omega}_{MDM} = \frac{e}{\gamma m}\left[(1 + G\gamma)\vec{B} + \left(G\gamma + \frac{\gamma}{1+\gamma}\right)\frac{\vec{E} \times \vec{\beta}}{c} - \frac{G\gamma^2}{\gamma + 1}\vec{\beta}(\vec{\beta} \cdot \vec{B})\right]$$

$$\vec{\Omega}_{EDM} = \frac{e}{m}\frac{\eta}{2}\left[\frac{\vec{E}}{c} + \vec{\beta} \times \vec{B} - \frac{\gamma}{\gamma + 1}\vec{\beta}\left(\vec{\beta} \cdot \frac{\vec{E}}{c}\right)\right]$$

$$\vec{\mu} = 2(G + 1) \cdot \frac{e}{2m}\vec{S}$$

	G
Proton	1.792847357
Deuteron	-0.142561769

$$\vec{d} = \eta \cdot \frac{e}{2mc}\vec{S}$$

d	η
10^{-24} e cm	$\sim 10^{-9}$
10^{-29} e cm	$\sim 10^{-14}$

COSY Toolbox

COSY Lattice → COSY Toolbox

COSY INFINITY ↔ COSY Toolbox ↔ Armadillo

COSY Toolbox → ROOT

COSY INFINITY

M. Berz, K. Makino et al.

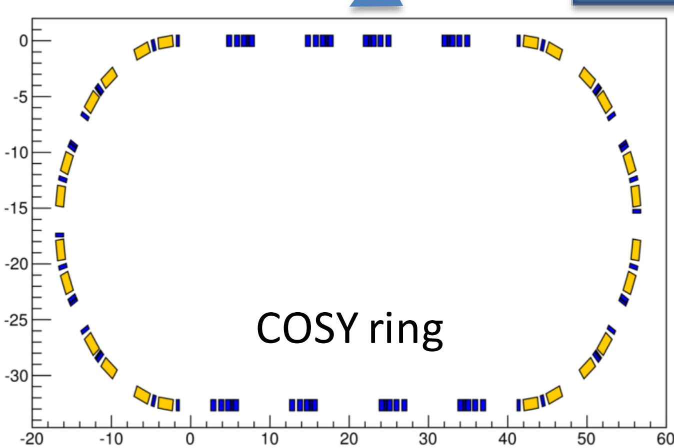
- Calculator:
  - Optical functions
  - Closed orbit
  - Spin tune
- Tracker:
  - Static maps
  - RF maps

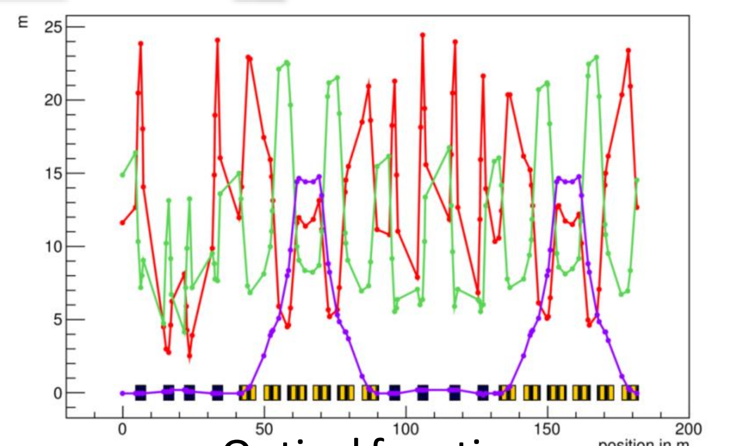
Armadillo

- linear algebra operations
- SVD, pseudo-inverse

ROOT

- plotting
- storage (ROOT files/trees)



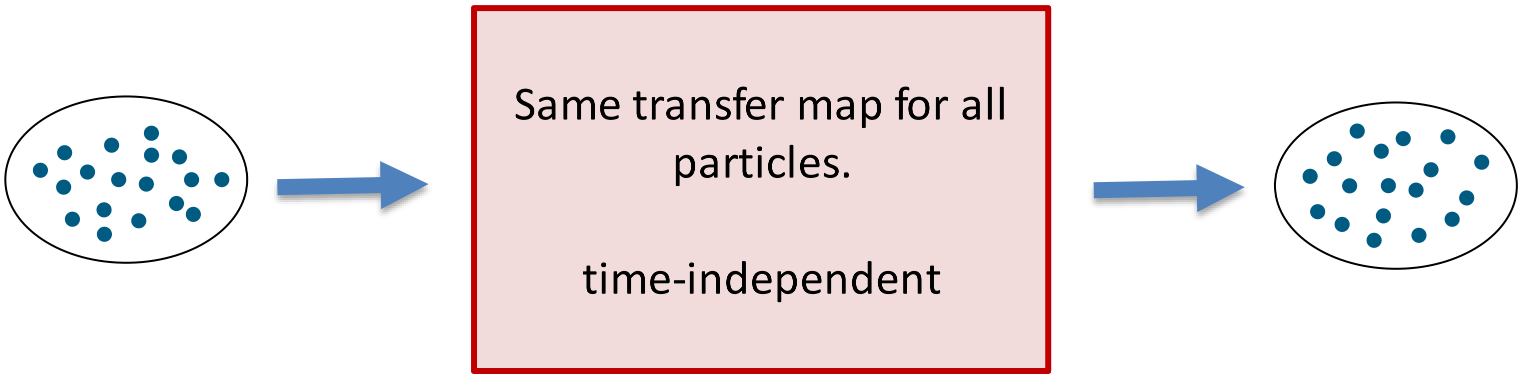


Optical functions

Transfer Maps

- Solutions for equations of motion to arbitrary order: $\mathcal{M}(\vec{z}_0)$, $\mathcal{A}(\vec{z}_0)$
- Relate phase space and spin coordinates before and after element

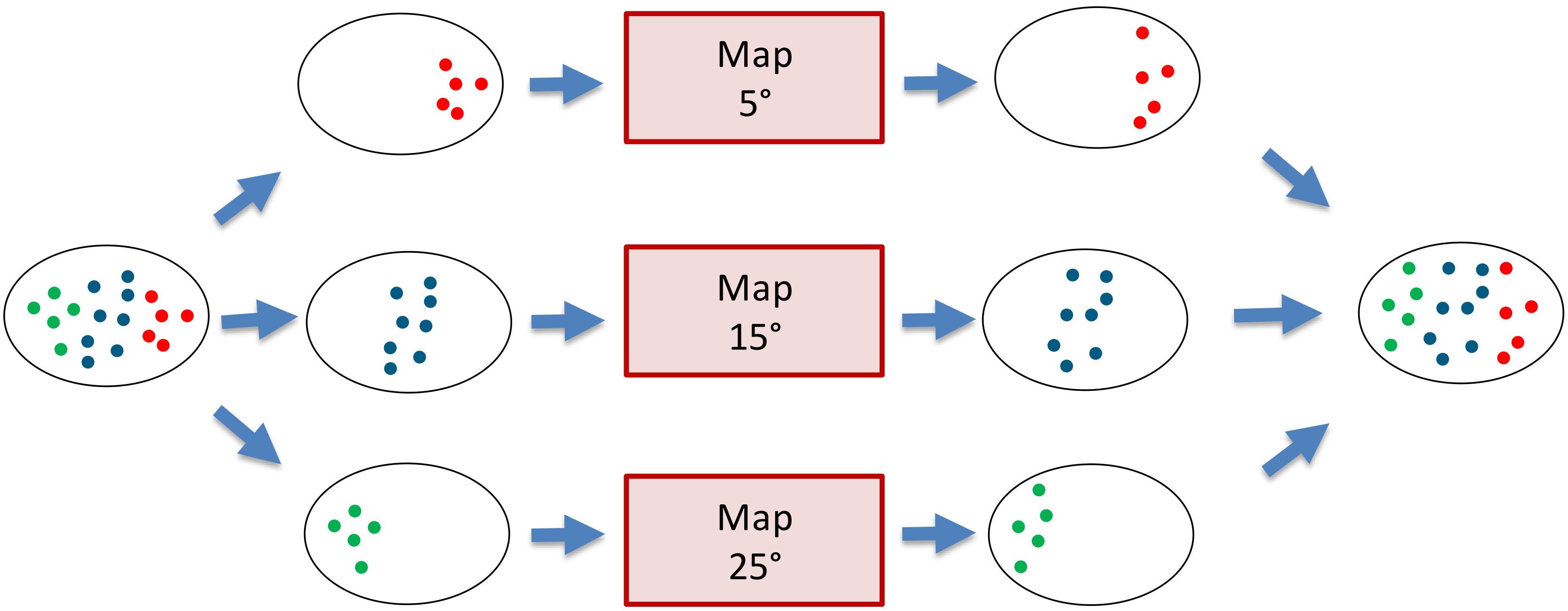
- Static fields:



- What about time-varying fields?

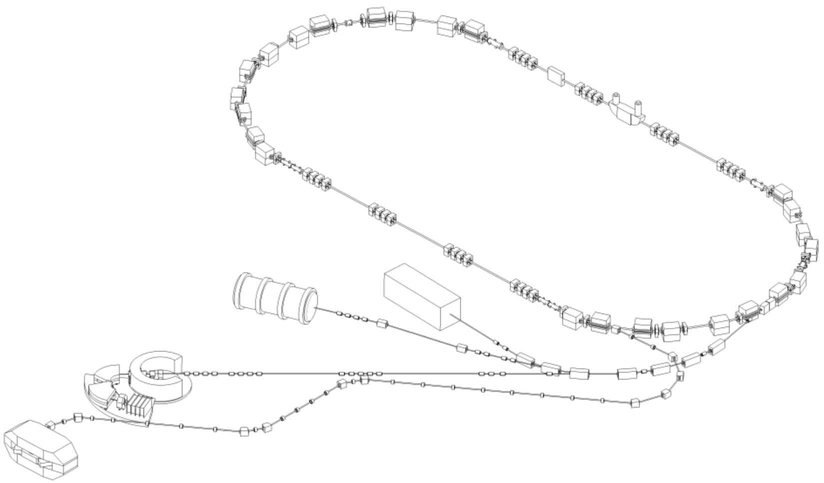
Transfer Maps for RF fields

- Radiofrequency fields:
  - Split element into N maps covering the $360°$ phase interval of the time-varying field (currently $N = 36$).

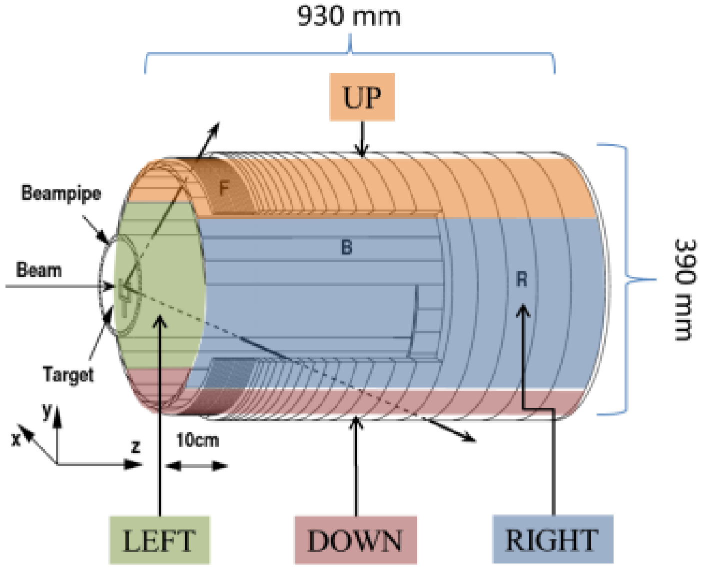


Experimental Setup for Studies

- Beam setup:
  - Polarized deuterons, 970 MeV/c
  - Electron cooled and bunched
  - Optimized Spin Coherence Time



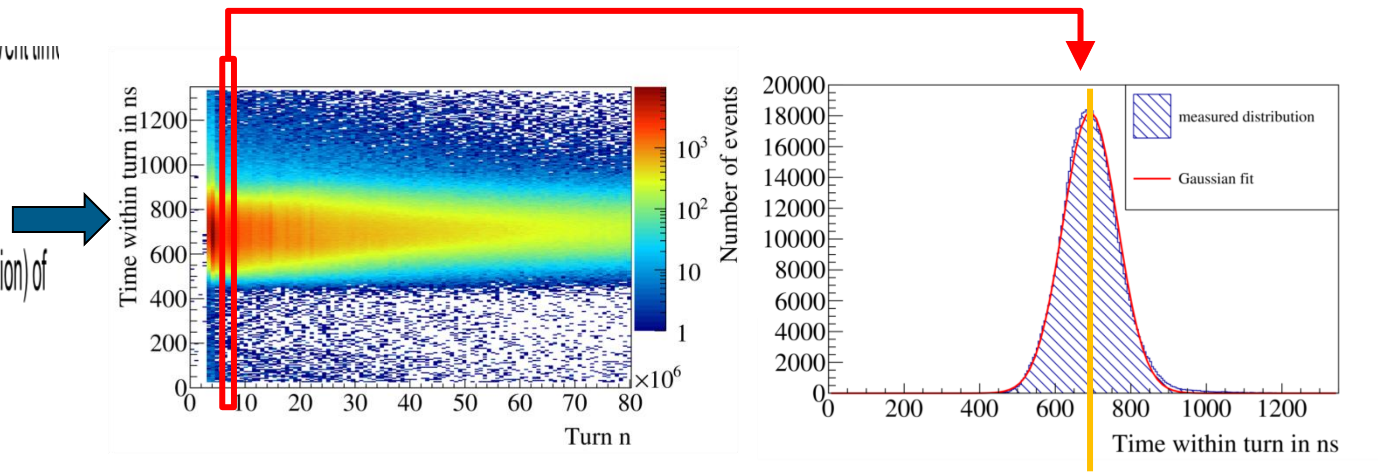
- Idea:
  - Induce spin resonance by RF-B solenoid and measure characteristica of vertical polarization oscillations



Measured time distribution

Time marking system allows for determination of event time with respect to RF cavity

Extraction of measured time distribution (τ-distribution) of particles in the bunch is possible.



Bunch center: $\tau = 0$

- Time marking system allows for determination of event time with respect to RF cavity
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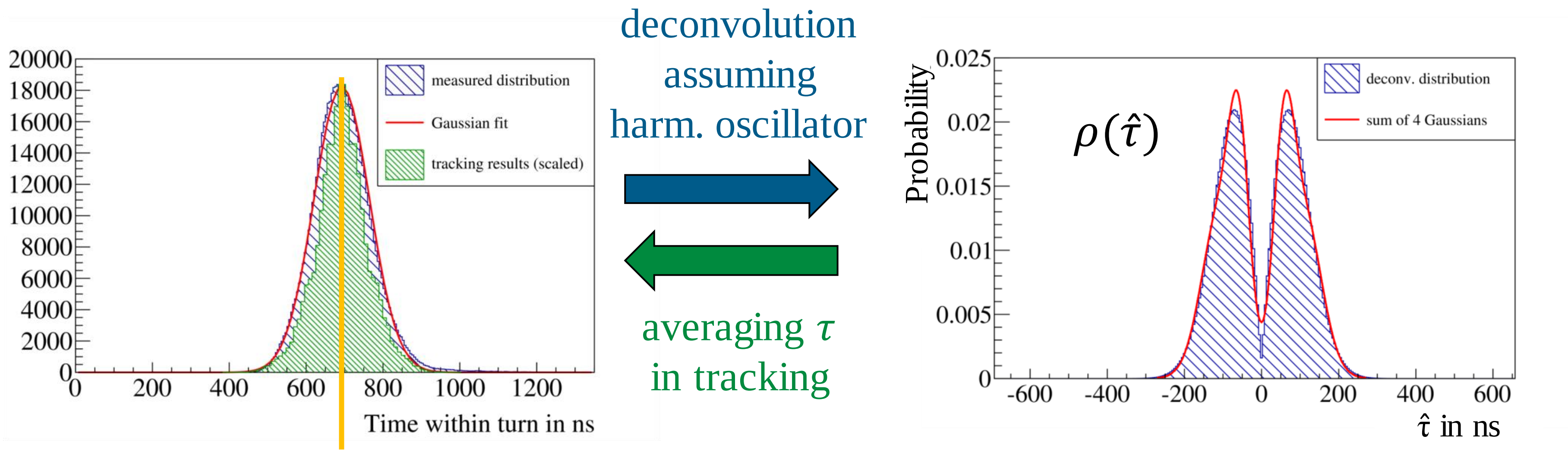
Deconvolved amplitude distribution

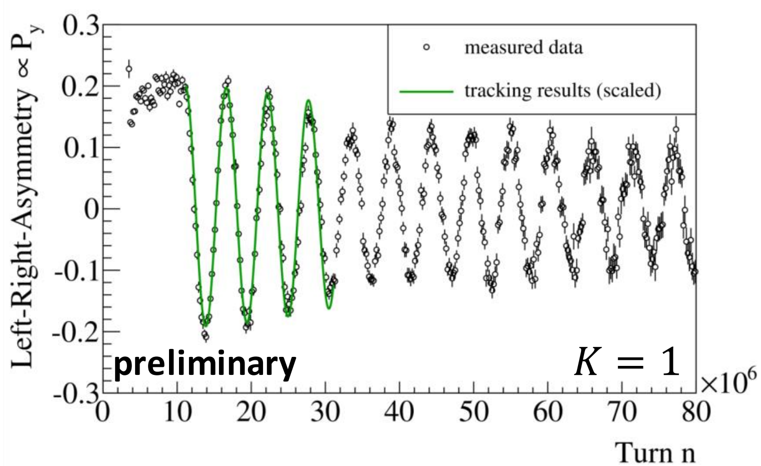


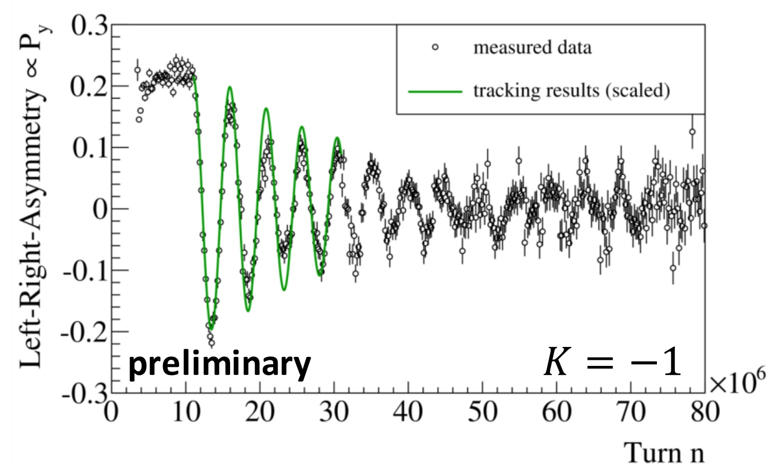
Bunch center: $\tau = 0$

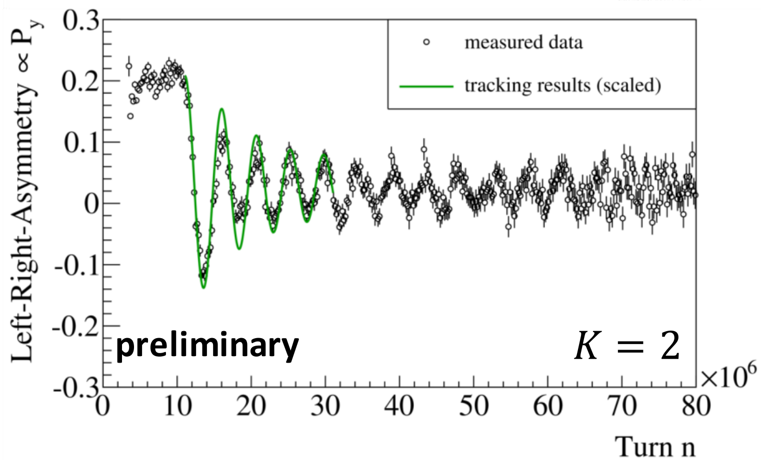
- Initial longitudinal amplitude distribution required for analytical estimations and for tracking simulations.
- Assuming solution for an harmonic oscillator $\tau \approx \hat{\tau} \cdot \cos(2\pi\nu_{\mathrm{sync}} n + \phi_{\mathrm{sync}})$, the deconvolution results in the longitudinal synchrotron amplitude $\hat{\tau}$-distribution.

Benchmarking Results

- Radiofrequency field: $B_{sol} = \hat{B}_{sol} \cdot \cos(2\pi\nu_{sol} \cdot n + \phi_{sol})$ turned on at ~11 mio. turns.
- resonance condition: $\nu_{sol} = G\gamma + K,\ K \in \mathbb{Z}$







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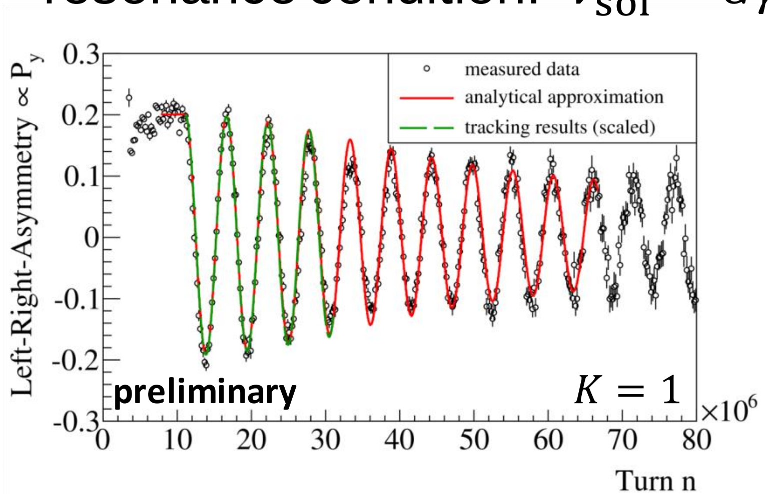
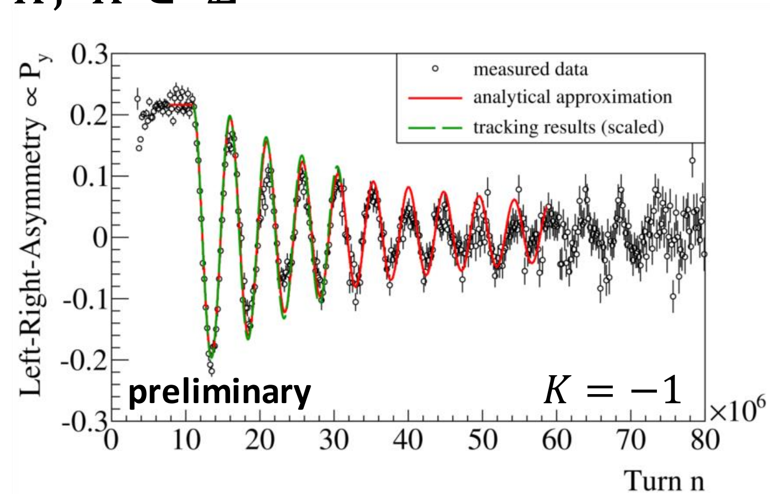
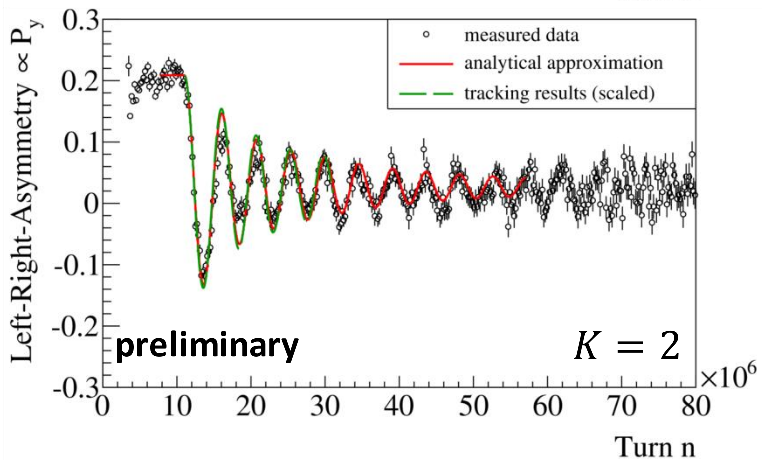






Analytical estimation:

$$P_y(n) = \int_{-\infty}^{\infty} \rho(\hat{\tau}) S_y(n, \hat{\tau})\, \mathrm{d}\hat{\tau}$$

RF Wien filter induced spin resonance

- Idea:
  - RF-E×B Wien filter with $\vec{\mathrm{B}} \parallel \vec{\mathrm{e}}_{\mathrm{y}}$ on resonance induces buildup of vertical spin component for non-vanishing EDM.
  - Minimized impact on beam, but interaction on spin
- Analytical estimation for closed orbit and $S_z(0) = 1$:

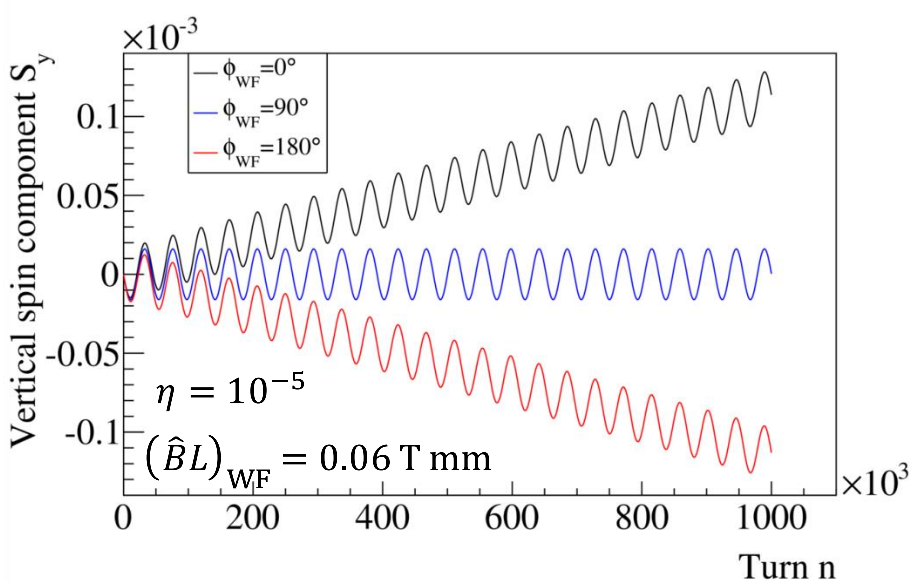
$$\frac{\mathrm{d}S_y}{\mathrm{d}n} \approx -\frac{\alpha_0}{2}\left(n_y^2 \cdot n_z \cdot \sin(\phi_{\mathrm{WF}}) + n_y \cdot n_x \cdot \cos(\phi_{\mathrm{WF}})\right) + \text{fast osc. terms}$$

$$\alpha_0 = \frac{(1+G)}{\gamma}\,\frac{q}{p}\,(\hat{B} \cdot L)_{\mathrm{WF}}$$

$$B_{\mathrm{WF}}(n) = \hat{B}_{\mathrm{WF}} \cdot \cos(2\pi\nu_{\mathrm{WF}} \cdot n + \phi_{\mathrm{WF}})$$

$$E_{\mathrm{WF}}(n) = \beta c \cdot B_{\mathrm{WF}}(n)$$

(n_x, n_y, n_z):
spin closed orbit of static ring
@ RF Wien filter location



Buildup for different EDM magnitudes

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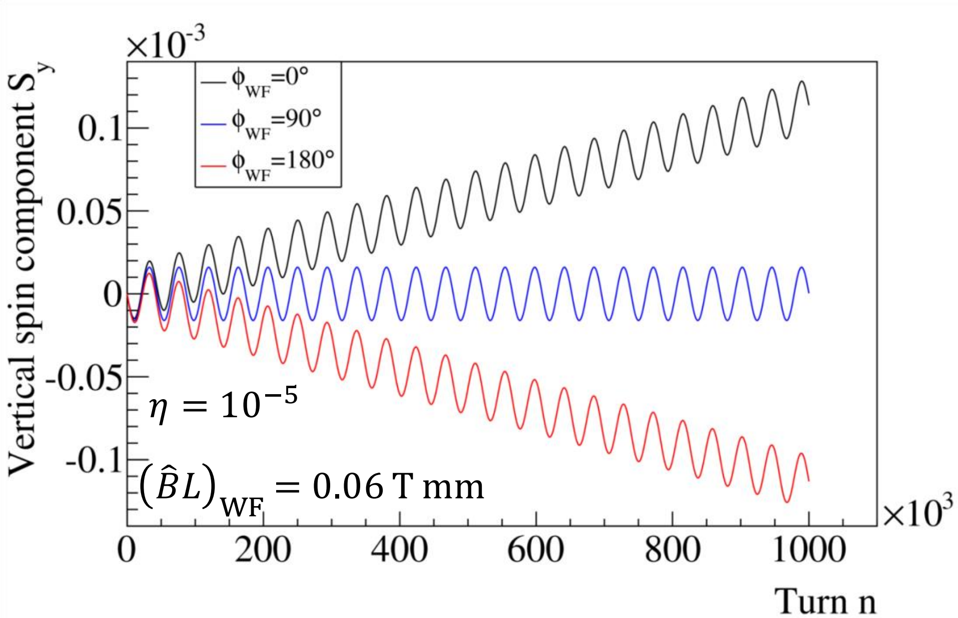
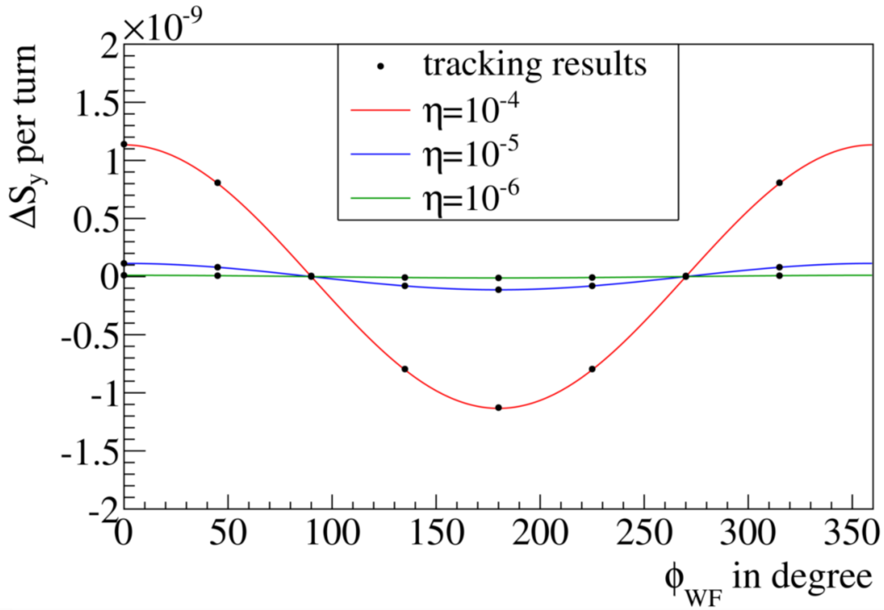
- Buildup scales linearly with EDM magnitude and depends on initial RF Wien filter phase





- Good agreement between analytical estimates and tracking results

Buildup for Misalignments

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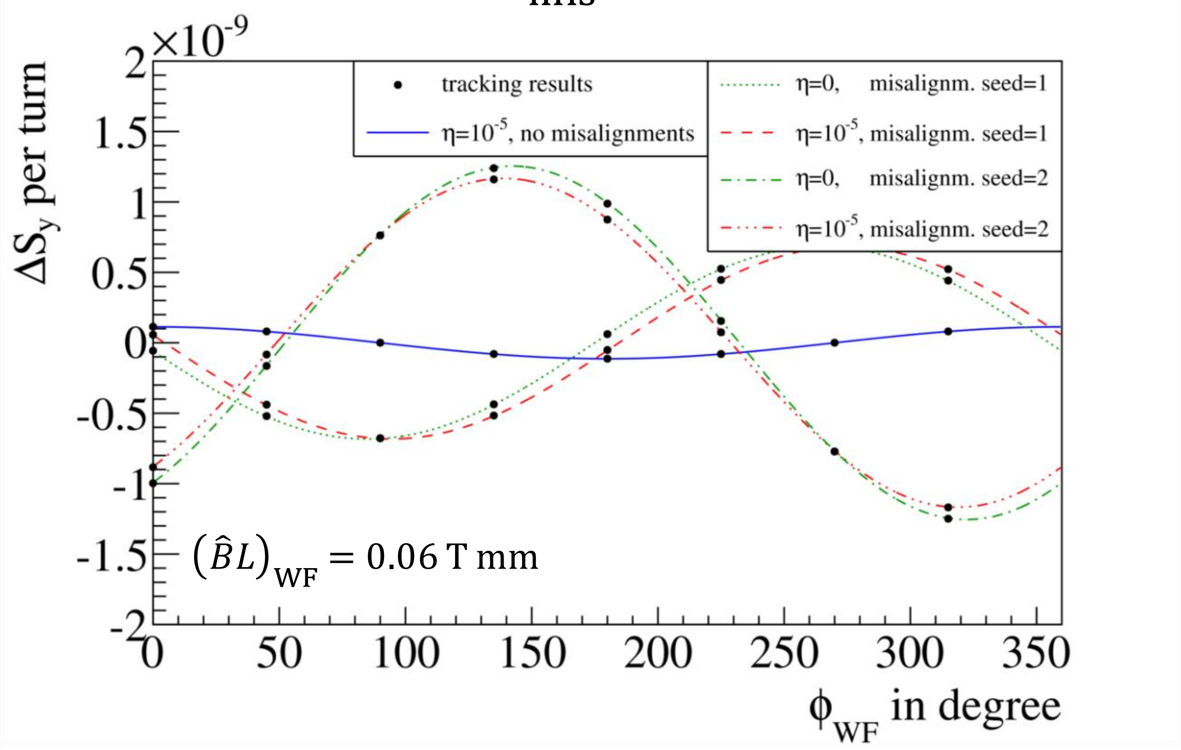
- Introduce misalignments of the 56 lattice quadrupoles
- Gaussian distributed with $\sigma_{\text{mis}} = 0.1\ \text{mm}$

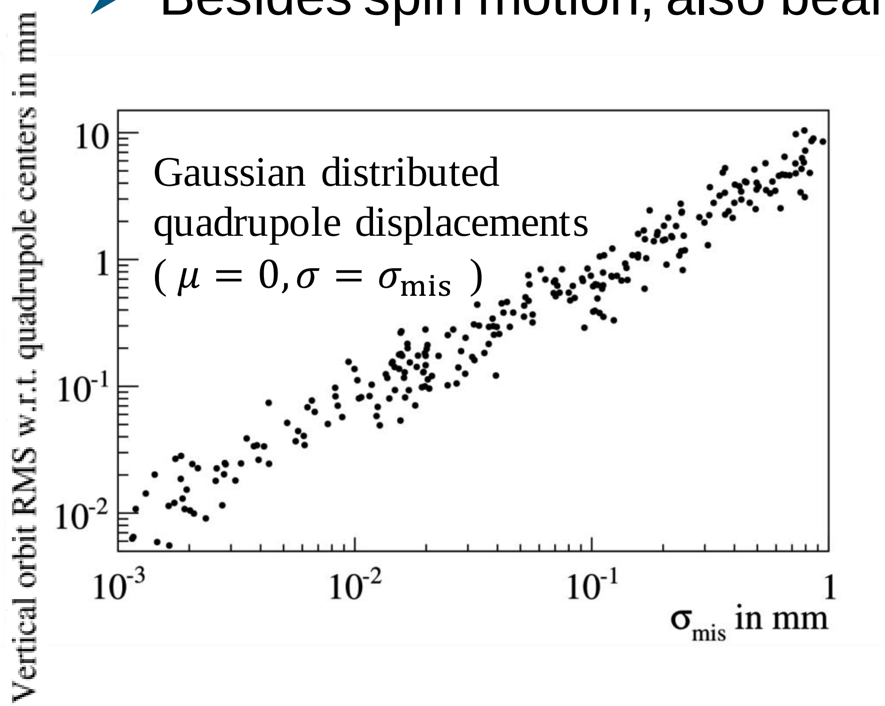


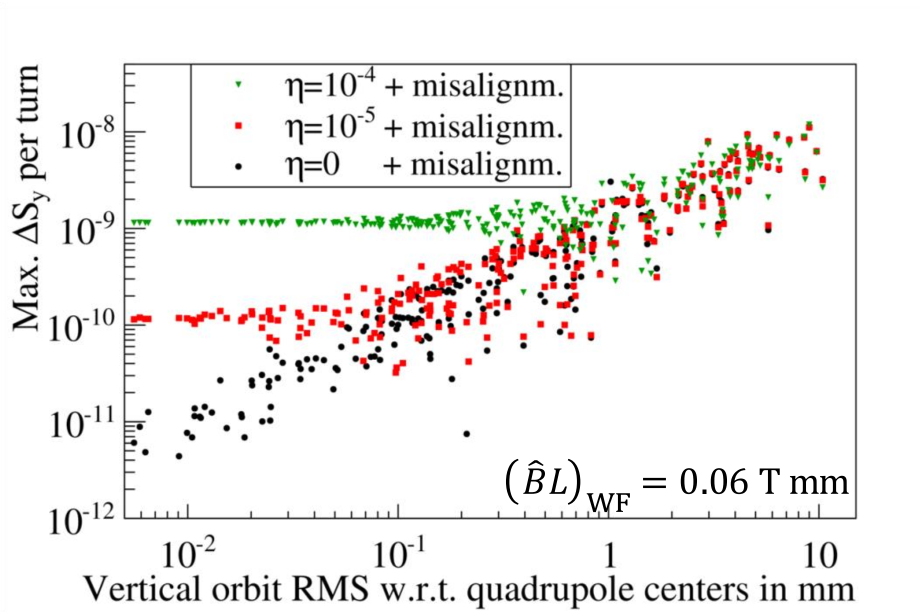
$$\frac{\mathrm{d}S_y}{\mathrm{d}n} \approx -\frac{\alpha_0}{2}\left(n_y^2 \cdot n_z \cdot \sin(\phi_{\text{WF}}) + n_y \cdot n_x \cdot \cos(\phi_{\text{WF}})\right) + \text{fast osc. terms}$$

- Pure EDM: $n_x \neq 0$, misalignments: $n_x \neq 0$ and $n_z \neq 0$

Connection to Orbit RMS

- Main contribution from additional radial magnetic fields
- Besides spin motion, also beam motion is affected





- Vertical buildup ΔS_y per turn for RMS of 1 mm similar to $\eta = 10^{-4}$ $(d = 5 \cdot 10^{-19} \text{e cm})$

Summary

- **Method:**
  - Calculation of maps for time-varying elements implemented into COSY INFINITY extension
- **Application I: RF-B Solenoid**
  - Successfully benchmarked with analytical estimates and measured data for RF-B solenoid induced resonance
  - Dependence of oscillation damping on solenoid frequency has been reproduced
- **Application II: RF-E×B Wien filter**
  - Tracking results for EDM related buildup match with analytical calculations.
  - Gaussian distributed quadrupole displacements which introduce an vertical orbit RMS of $1\ \mathrm{mm}$ lead to a buildup similar to an EDM of $d \approx 5 \cdot 10^{-19}\ \mathrm{e\ cm}$

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