Studies of systematic limitations in the EDM searches at storage rings

The spin tune mapping at COSY

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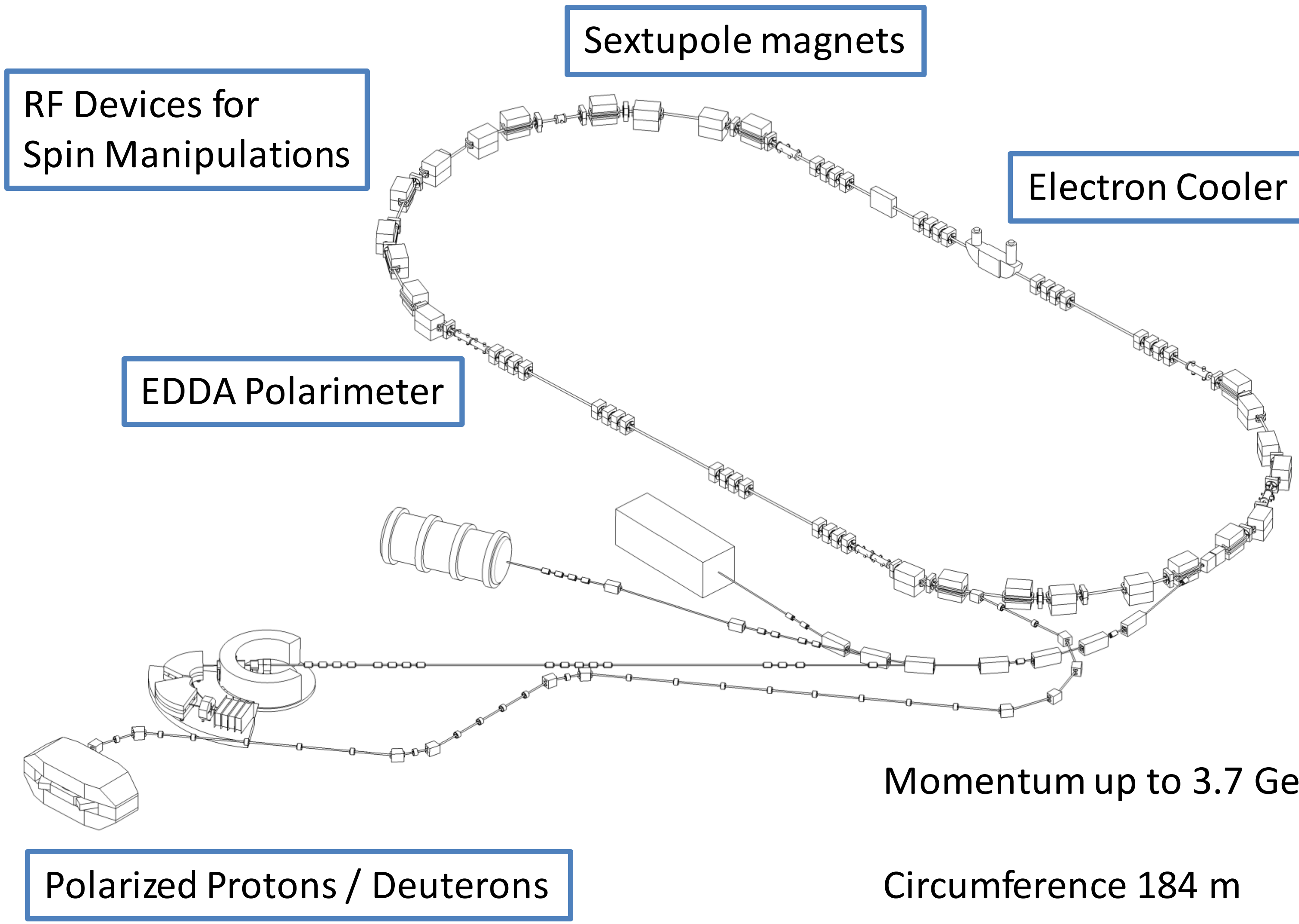
Outline

- Exploring the COSY ring for EDM studies (JEDI)
- Imperfection background to EDM spin precession
- Mapping the spin tune with static solenoids
- Summary

Cooler Synchrotron COSY in Jülich



Momentum up to 3.7 GeV/c,

Circumference 184 m

Spin Motion in Storage Ring

- *Thomas BMT eqn. for the Magnetic Dipole Moment (MDM)*

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

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

Spintune ≔ Number of spin turns relative to particle turns, for the ideal pure magnetic ring like COSY:

$$\nu_s := \frac{|\vec{\Omega}_{MDM}|}{\omega_{rev}} = \frac{\frac{q}{m}GB}{\frac{q}{m\gamma}B} = \gamma G$$

Spin Precession by EDM in Pure Magnetic Ring

- The JEDI Collaboration aims at a first direct measurement of the deuteron and proton Electric Dipole Moment (EDM) at COSY
- A current task: exploring the EDM dynamics and systematic limitations of the EDM searches at all magnetic rings

- If particle has $d \neq 0$, T-BMT equation takes form

$$\frac{d\vec{S}}{dt} = -\frac{q}{m}\left(G\vec{B} + \eta(\vec{\beta} \times \vec{B})\right) \times \vec{S}(t)$$

- Interaction of the EDM with the motional E-field tilts the stable spin axis:

$$\vec{n}_{co} = \left(\vec{e}_x \sin\xi + \vec{e}_y \cos\xi\right)$$

- where

$$\tan\xi = -\frac{\eta}{G}\beta \qquad \eta = d\frac{m}{q}$$

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Imperfection In-plane Fields

- JEDI looks forward to the RF E-field induced EDM rotation without excitation of the coherent betatron oscillations
- RF Wien-Filter as an example: generates the RF modulation of the spin tune, the EDM signal comes from the motional E-field in the ring*
- Misalignment of any magnetic elements produces the in-plane imperfection magnetic fields, so that in general case

$$\vec{n}_{co} = \left(\vec{e}_x c_1 + \vec{e}_y c_2 + \vec{e}_z c_3\right)$$

- The nonvanishing c_1 and c_3 generate a background to the EDM-signal of the ideal imperfection-free case

$$c_1 = \sin\xi\,, \qquad c_3 = 0$$

- The challenge is to control background (for example with the accuracy $c_1 \sim 10^{-6}\ rad$ would amount to sensitivity for $d = 10^{-20}\ e \cdot cm$)

*«RF Wien filter in an electric dipole moment storage ring: The "partially frozen spin" effect». William M. Morse, Yuri F. Orlov, Yannis K. Semertzidis. Phys.Rev.ST Accel.Beams 16 (2013) 11, 114001

EDDA Polarimeter

- ***Left-Right*** asymmetry

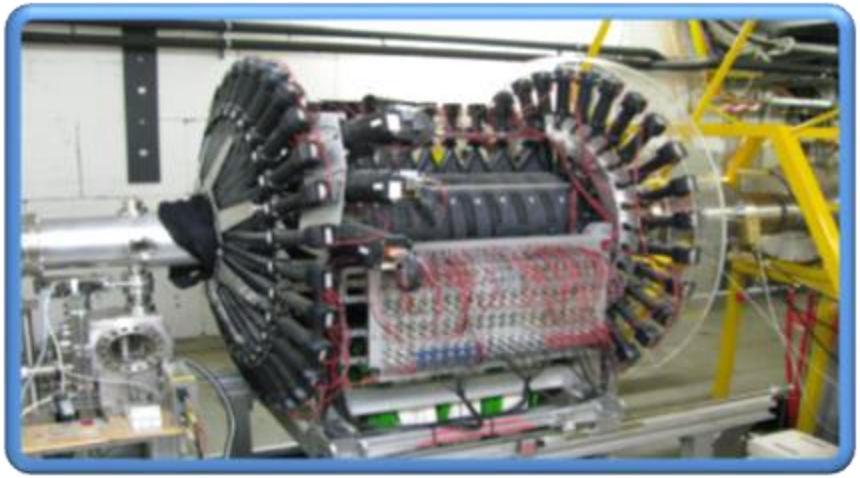
  ⇒ ***vertical*** polarization

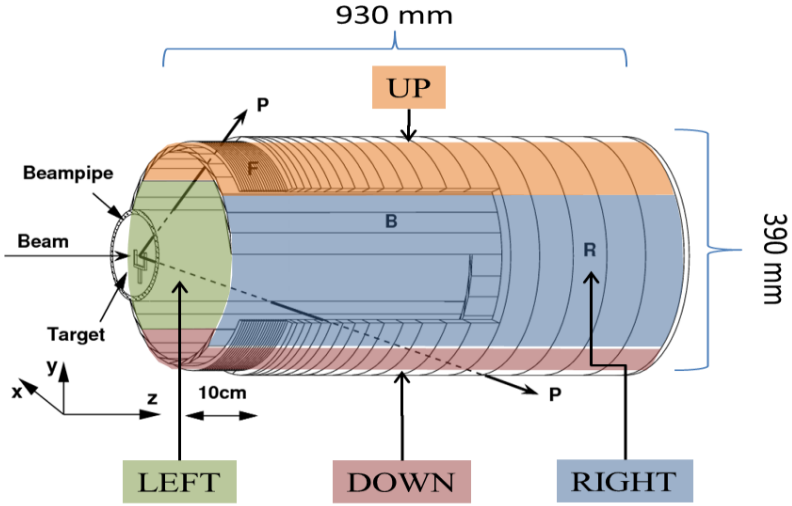
$$P_V \propto \epsilon_{ver} = \frac{N_l - N_r}{N_l + N_r}$$

- ***Up-Down*** asymmetry

  ⇒ ***horizontal*** polarization

$$P_H \propto \epsilon_{hor} = \frac{N_{up} - N_{dn}}{N_{up} + N_{dn}}$$





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Spin Tune Measurement

Spin vector precesses with $f_{\mathrm{Spin}} = \nu_s f_{rev}$ in the horizontal plane

Asymmetry is given by:

$$\epsilon_{hor}(t) = \frac{N_{up} - N_{dn}}{N_{up} + N_{dn}} \approx AP(t)\sin(2\pi\nu_s f_{rev} t + \phi)$$

What do we expect? (Deuterons, $p = 0.97\ \mathrm{GeV/c}$)

$$\nu_s \approx 0.16, \qquad f_{rev} = 750\ \mathrm{kHz}$$

Spin precession frequency: $\nu_s \cdot f_{rev} \approx 125\ \mathrm{kHz}$

Detector rates: $5\ \mathrm{kHz}$ (only every 25$^{\mathrm{th}}$ spin revolution is detected)

Special spin tune analysis software resolves ν_s with an accuracy 10^{-8} in 1-second interval

Spin Tune Response to the Artificial Imperfections

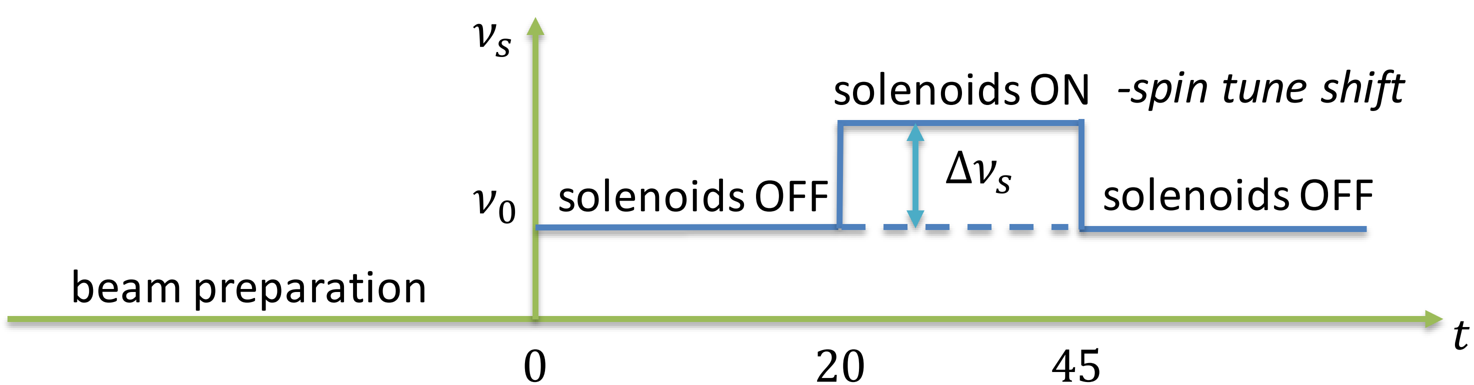
- The spin tune is perturbed by spin kicks in the ring imperfection fields:

$$\nu_0 = G\gamma + O(c_1^2, c_3^2)$$

- The idea is to probe the in-plane imperfection fields by introducing well-known *artificial imperfections.*
- Artificial imperfections: spin kicks χ_1 and χ_2 by compensation solenoids from e-coolers in straight sections

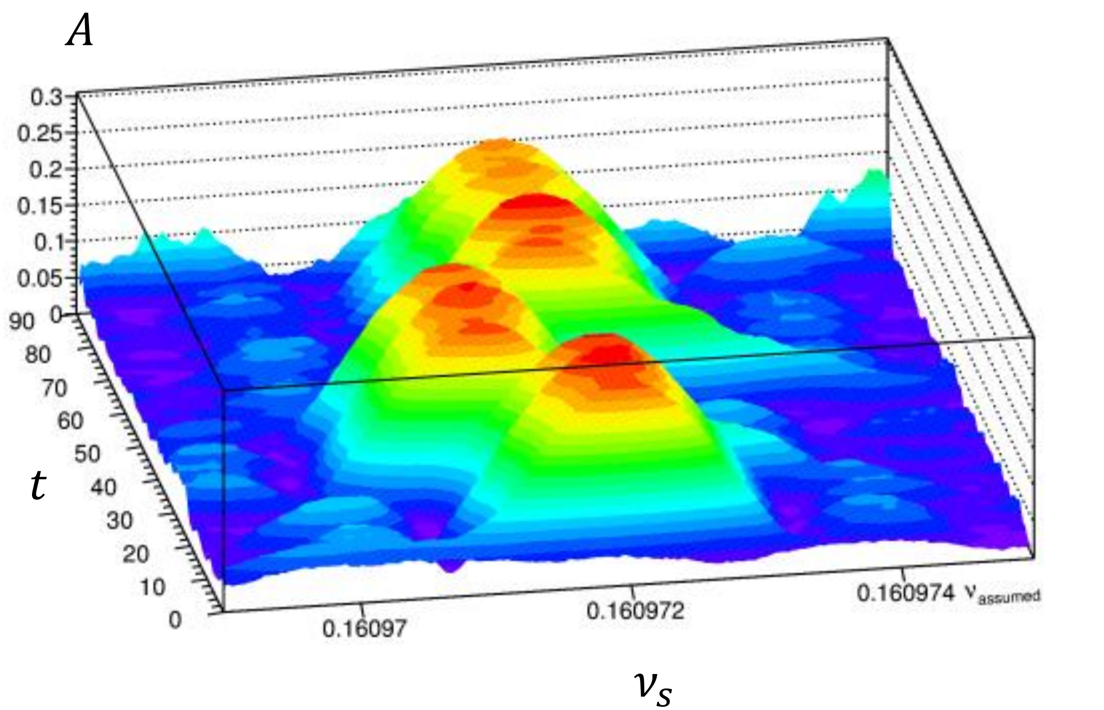
$$\nu_s = G\gamma + O(c_1^2, c_3^2, \chi_1^2, \chi_2^2)$$

- Perform the measurement:



Measurement of Spin Tune Shift

- Spin tune shift registered in the data analysis:

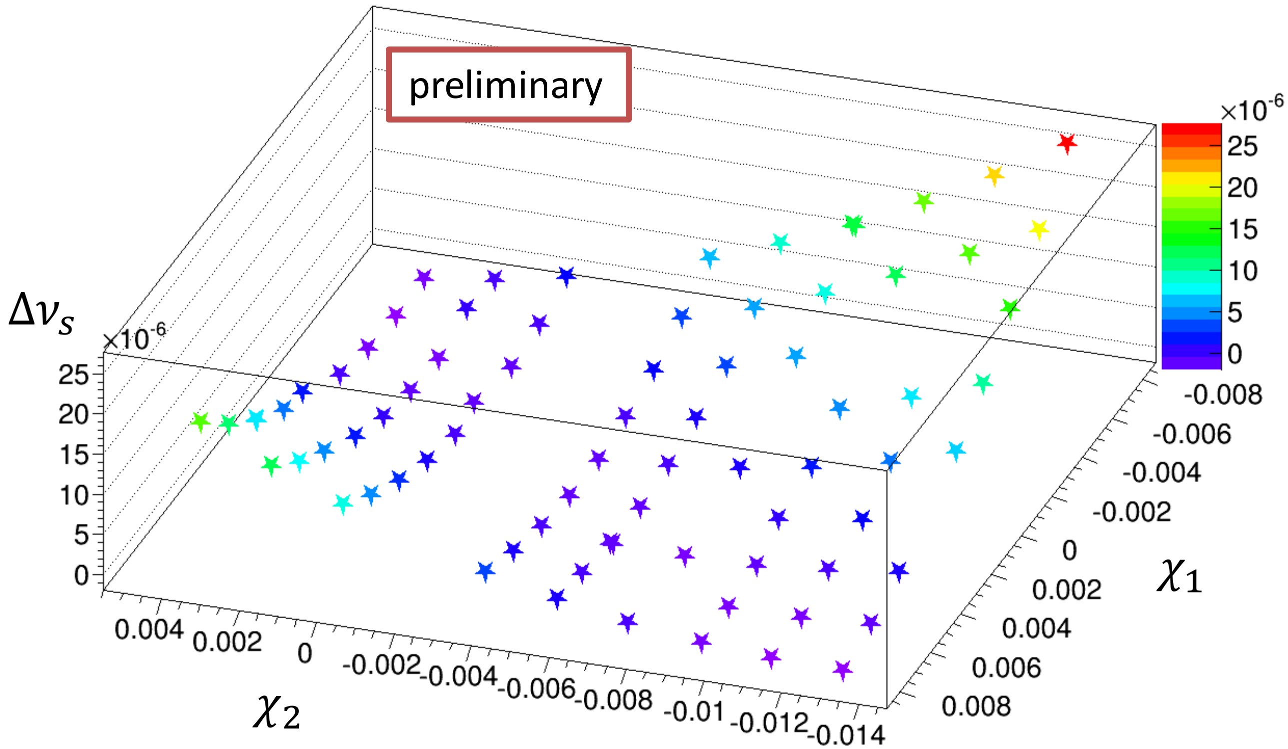


The highest amplitudes of the asymmetry fit correspond to real spin tune values

- The spin tune shift was observed at $t = [20, 45]\ s$

The Spin Tune Mapping

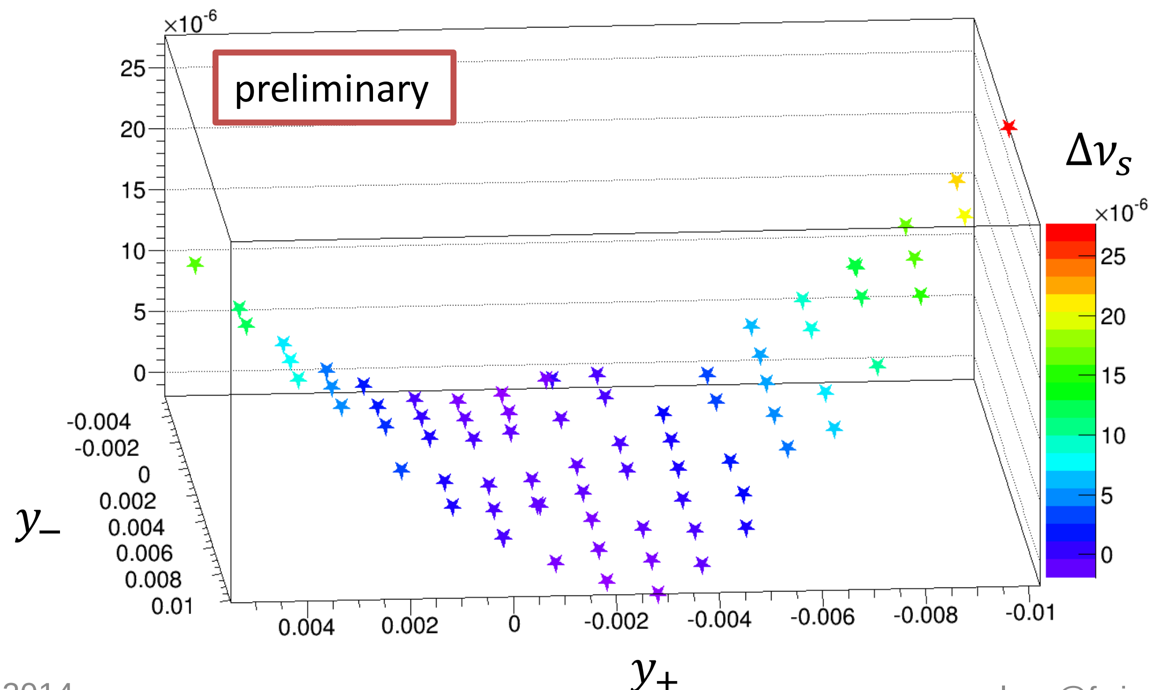
Take multiple measurements with different χ_1 , χ_2 and build a spin tune map $\Delta\nu_s(\chi_1, \chi_2)$:



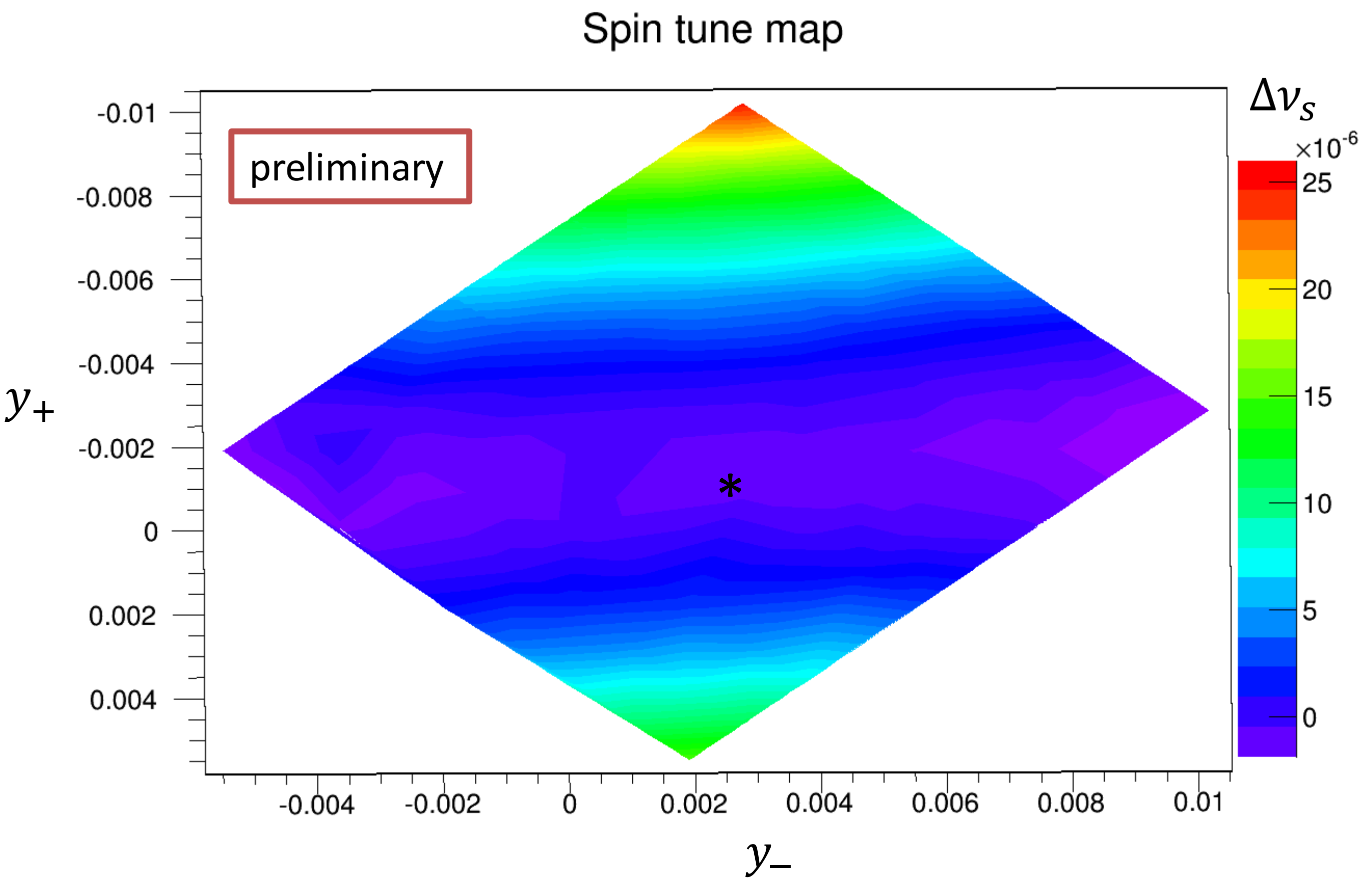
- Spin tune shift w.r.t. the solenoid spin kicks, $\Delta\nu_s \sim \chi_1^2$, $\Delta\nu_s \sim \chi_2^2$

The Spin Tune Mapping

- If the kicks are translated to: $y_+ = \frac{\chi_1+\chi_2}{2}$ $y_- = \frac{\chi_1-\chi_2}{2}$
- then $\Delta\nu_s \propto y_+^2, y_-^2$
- The distributions of the data points in $y_\pm$ dimension share common parabolic features : equal curvature and extremum
- It is a sign that the solenoids work as anticipated



Imperfection Strength



The fitted saddle point *:

$y_+ = -0.0011$ rad

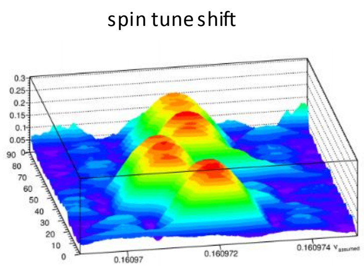
$y_- = -0.0024$ rad

- The theory predicts a saddle point, its position measures the integrated imperfection strength. For an ideal ring, the saddle point would be at $y_\pm = 0$

Summary

- The technique of spin tune measurement appears as a precision tool for the systematic analysis of the ring imperfections

- First measurement of the imperfection fields at COSY



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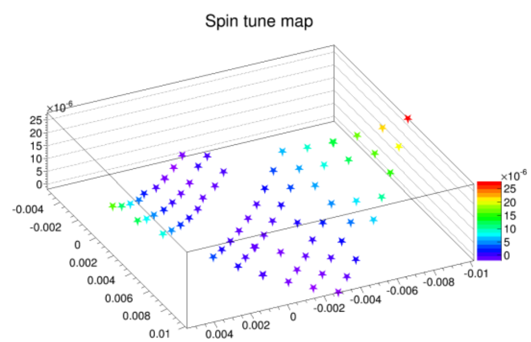


❖ The ultimate goal of the JEDI: to understand the EDM dynamics in storage rings as a prerequsite to the construction of the dedicated storage ring for the EDM searches

More Details About Spin Tune Analysis

Mapping the Events

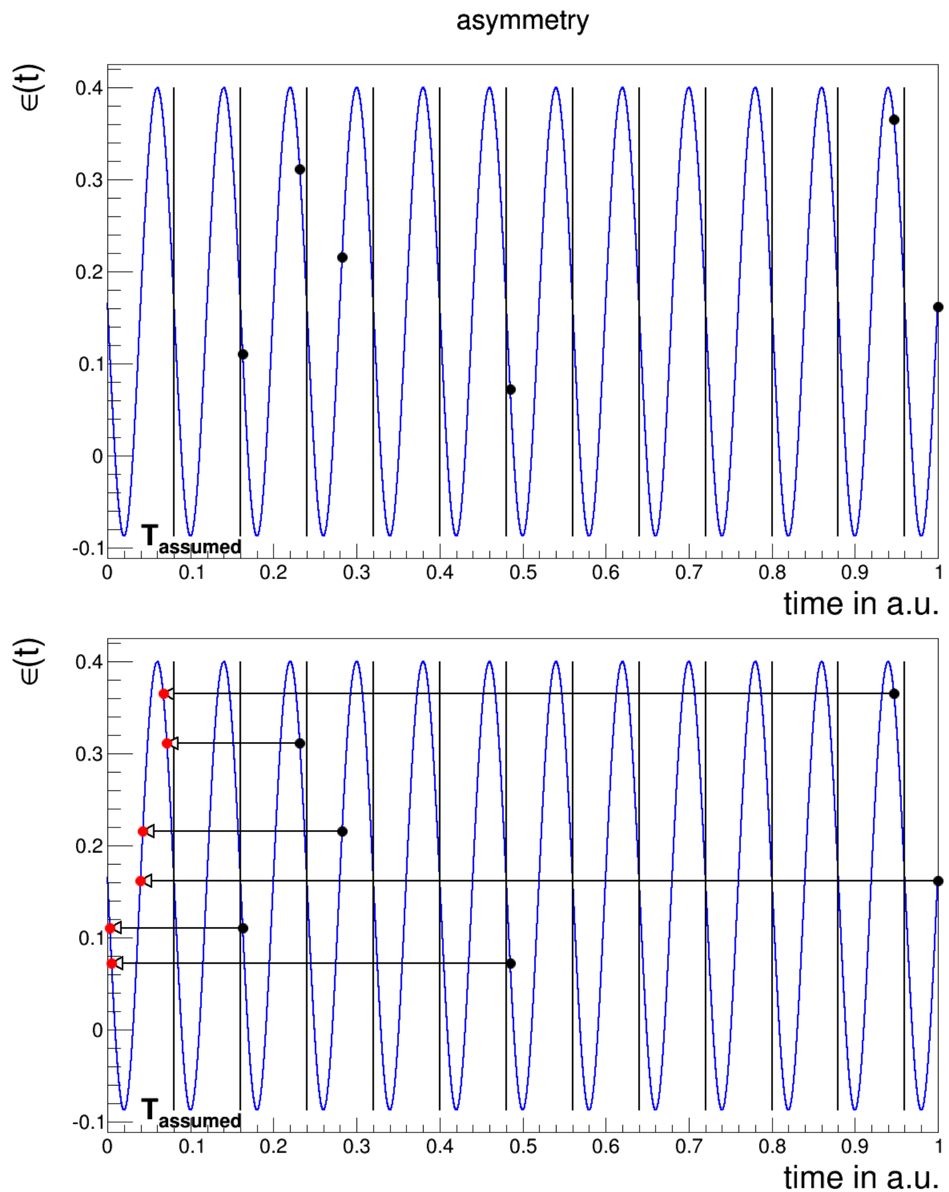
1. Assume Spin Tune $\nu_{assumed}$

$$T_{assumed} = \frac{2\pi}{\nu_{assumed} f_{rev}}$$

2. Map all events of a macroscopic time interval (2s) in first period:

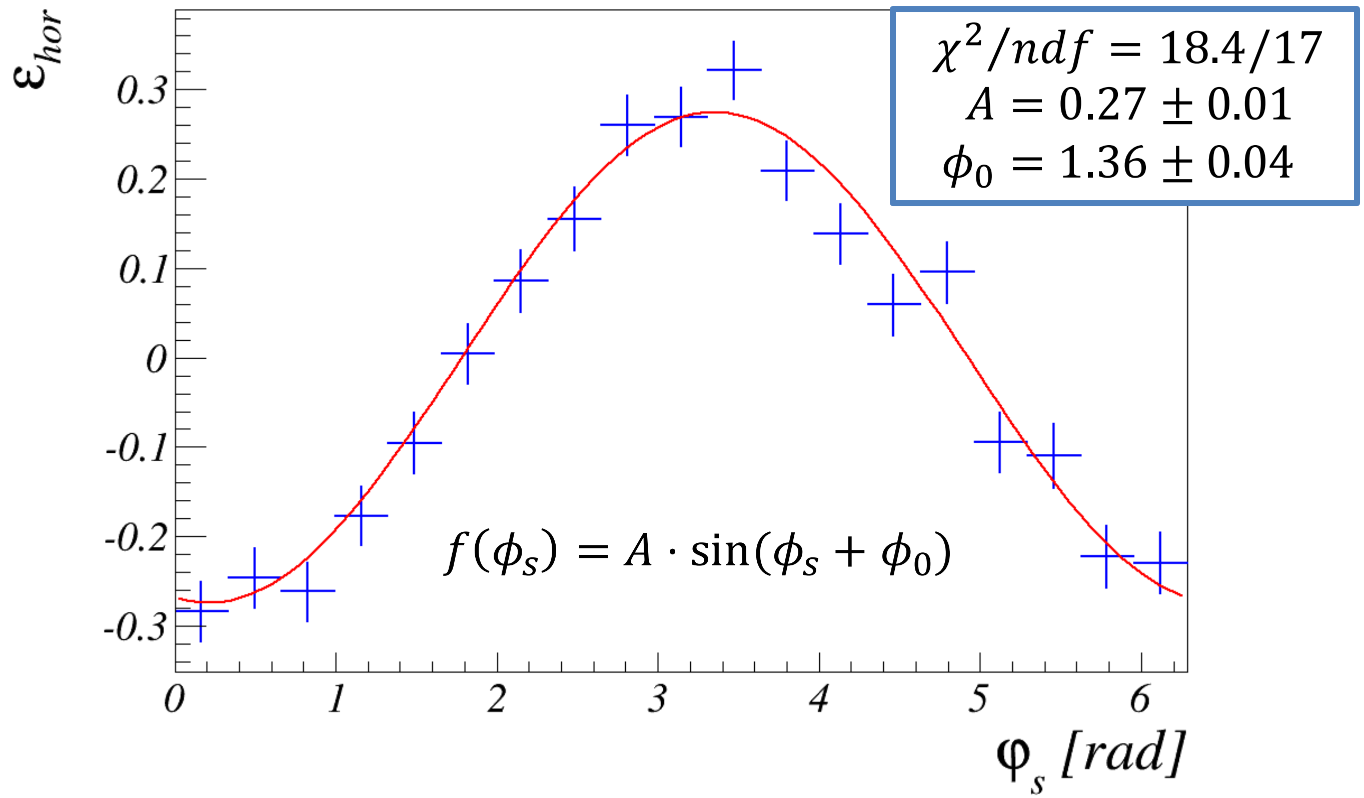
$$t' = mod(t, T_{assumed})$$

3. Fit asymmetry to first period



Fit Asymmetry to First Period

1. $T_{assumed}$
2. Mapping events
3. Fit asymmetry to first period

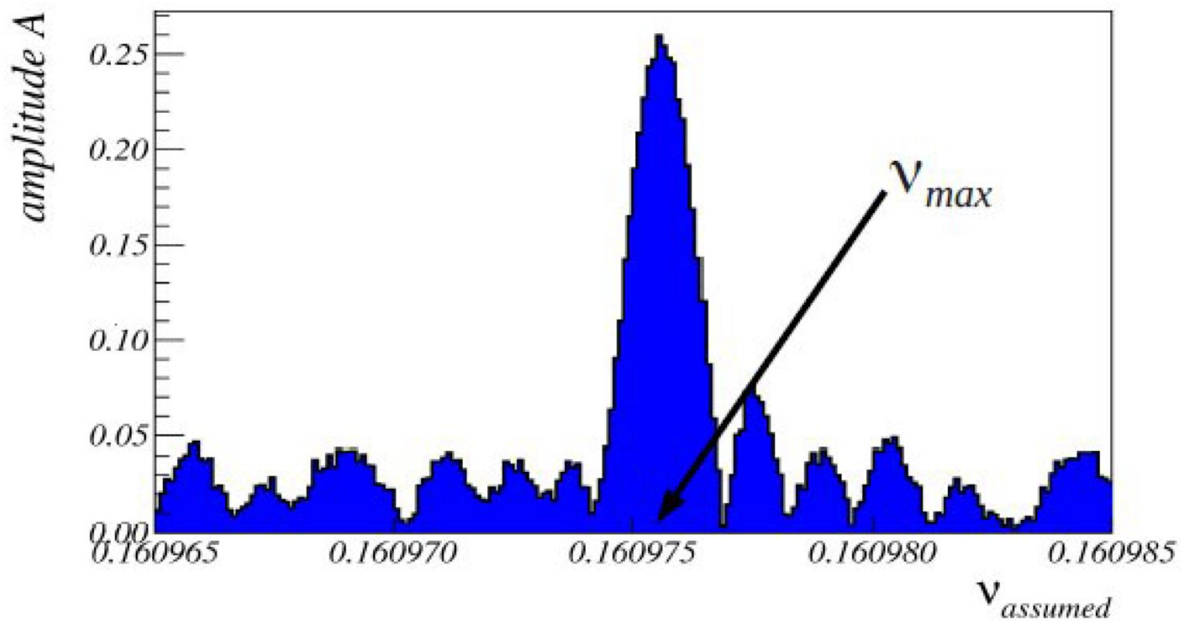


Extract amplitude $A \propto Polarisation$

Find Correct Spin Tune

1. $T_{assumed}$
2. Mapping events
3. Fit asymmetry to first period

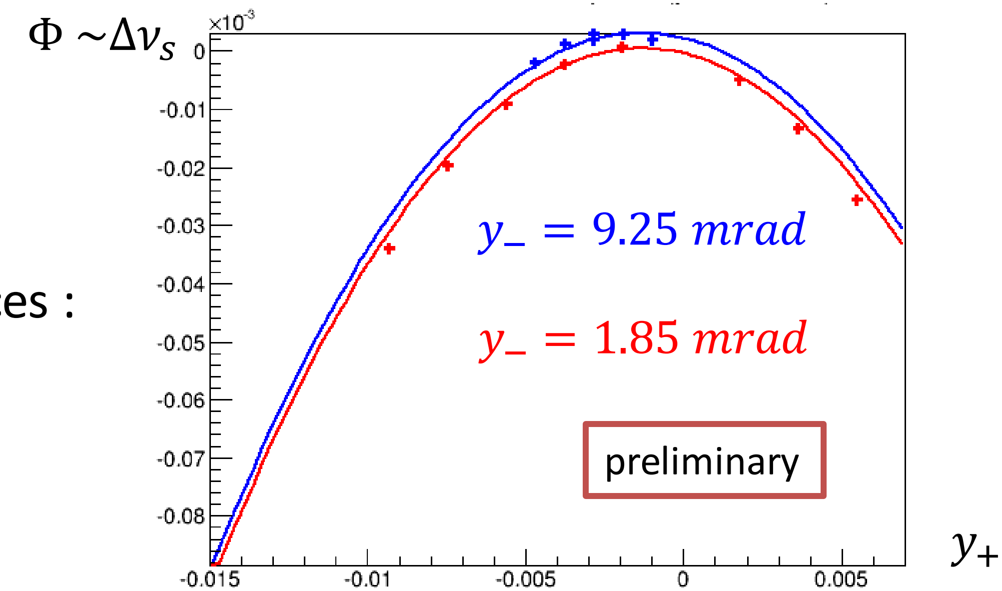
- Vary $T_{assumed}$ and repeat steps 1 to 3
- Plot extracted parameter A vs $\nu_{assumed}$



- ν_{max} is correct spine tune in macroscopic time interval $(2\ s)$
- $\nu_{max} = 0.160975 \pm 10^{-6}$

The Features of the Spin Tune Maps

- Using equal step size $\Delta\chi_1 = \Delta\chi_2$, translate the kicks to: $y_\pm = \frac{1}{2}(\chi_1 \pm \chi_2)$
- Fit to Φ
- Spin tune map slices :



- The theoretical analysis: depending on the value of y_- the parabola shifts up/down & the extremum stays constant

- Solenoids interact with $\vec{e}_z$ projections of $\vec{n}_{co}$
- c_3 is given after one of the solenoid, and c_3^* after another

- Model function:

$$\Phi = \cos\pi(\nu_0 + \Delta\nu_s(y_+, y_-)) - \cos\pi\nu_0 =$$
$$-\Big[(E + \cos\pi\nu_0)\sin^2\left(\frac{y_+}{2}\right) + \frac{1}{2}\sin\pi\nu_0\,(c_3 + c_3^*)\sin y_+ +$$
$$(E - \cos\pi\nu_0)\sin^2\left(\frac{y_-}{2}\right) + \frac{1}{2}\sin\pi\nu_0\,(c_3 - c_3^*)\sin y_-\Big]$$

- for a guidance:

$$\Phi \backsimeq -\pi\Delta\nu_s \sin\pi\nu_0 \propto y_+^2, y_-^2$$

- $E \approx \cos\frac{\pi(\nu_1-\nu_2)}{2} \approx 1$ is related to the difference of horizontal spin phase advances in the arcs
- The theory tells

$$\nu_1 - \nu_2 \sim O(c^2)$$

- The extremum of Φ is a saddle point at

$$y_+, y_- = O(c_3, c_3^*)$$

- With solenoids only we are not sensitive to c_1 , c_1^*

- Once ν_0 has been determined, only c_3 and c_3^* are the fit parameters