# Towards JEDI@COSY: systematic studies of spin dynamics in preparation for the EDM searches

March 10, 2015 | DPG | Artem Saleev for the JEDI Collaboration

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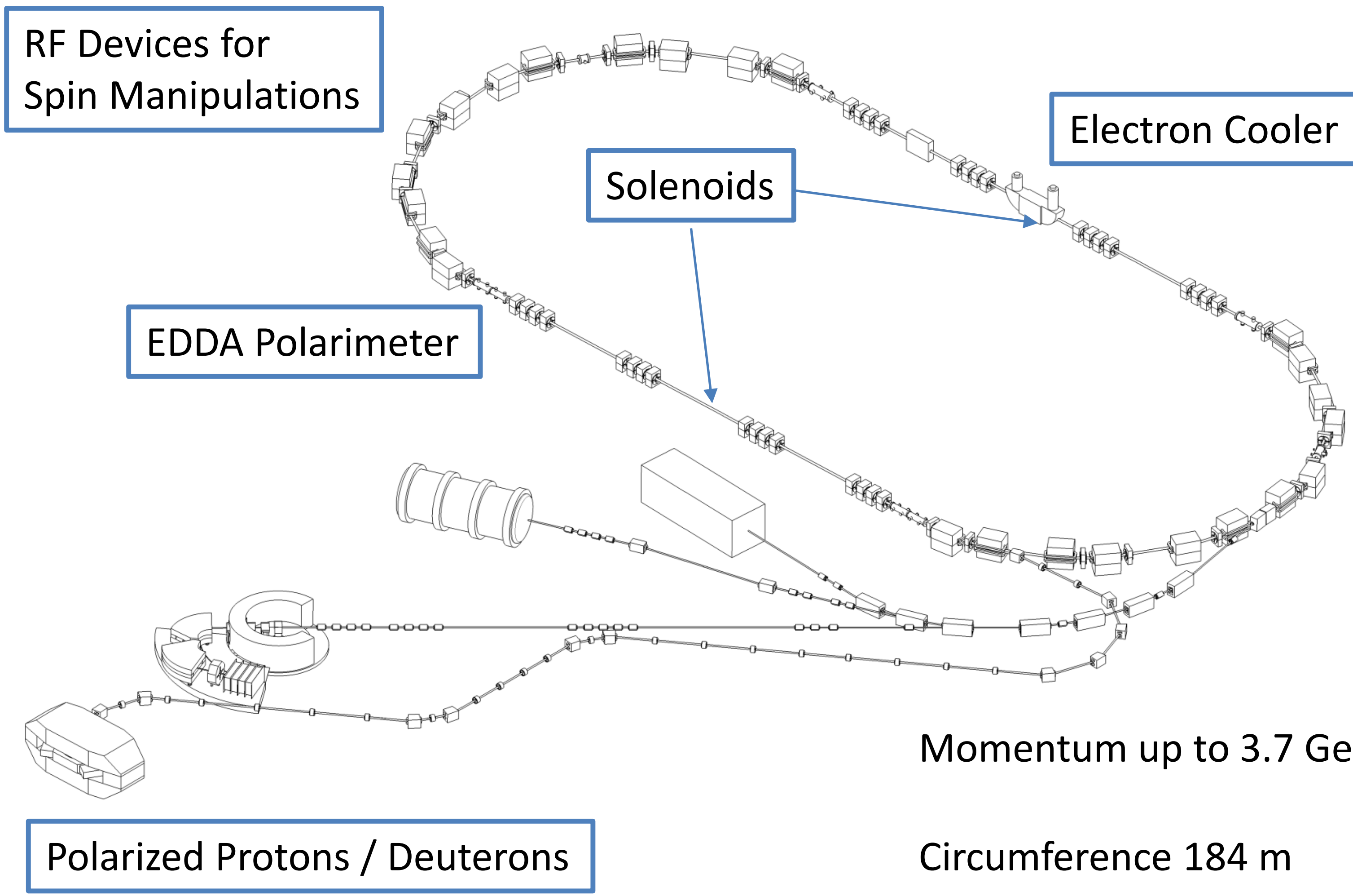
# Outline

- Exploring the COSY ring for Electric Dipole Moment (EDM) studies (JEDI - Jülich Electric Dipole moment Investigations)
- 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)*

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

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

**<u>Spintune</u>** ≔ Number of spin turns relative to particle turns, for the ideal pure magnetic ring like COSY:

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

Mitglied der Helmholtz-Gemeinschaft

# Spin Precession by EDM in Pure Magnetic Ring

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

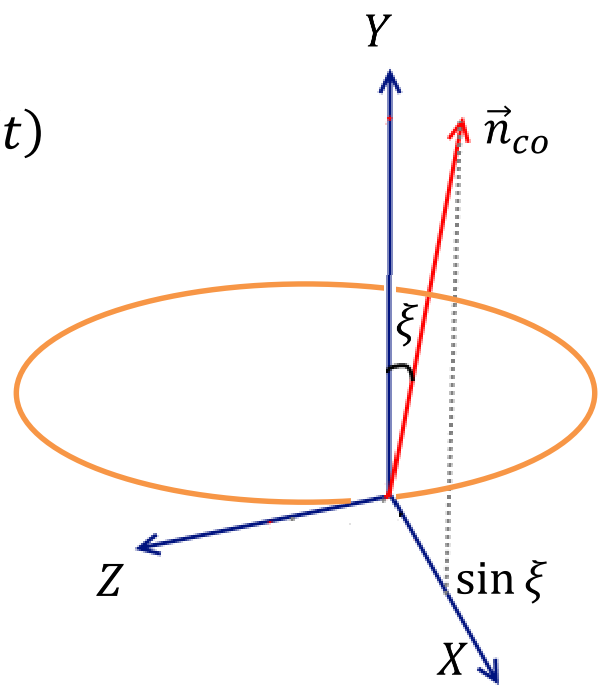
$$\frac{d\vec{S}}{dt} = -\frac{q}{m}\left(G\vec{B} + \eta(\vec{\beta} \times \vec{B})\right) \times \vec{S}(t)$$

- Interaction of the EDM with the motional E-field

  tilts the stable spin axis:

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

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




- The JEDI Collaboration aims at a first direct measurement
  of the deuteron and proton Electric Dipole Moment (EDM) at COSY
- JEDI looks forward to the RF E-field induced EDM rotation without excitation of the coherent betatron oscillations. Example: RF Wien-Filter, EDM signal comes from ring

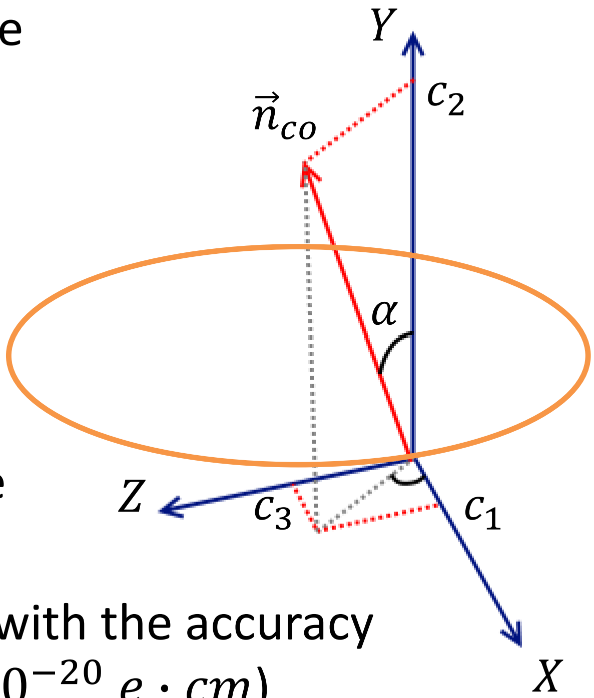
«RF Wien filter in an electric dipole moment storage ring: The “partially frozen spin” effect». William M. Morse, Yuri F. Orlov, Yannis K. Semertzidis. Phys.Rev.ST Accel.Beams 16 (2013) 11, 114001

# Imperfection In-plane Fields

- A current task for JEDI: exploring the EDM dynamics and systematic limitations of the EDM searches at all magnetic rings

- Misalignment of any magnetic elements produces the in-plane imperfection magnetic fields
- Imperfection spin kicks perturb $\vec{n}_{co}$:

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




- 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 $d = 10^{-20}\ e \cdot cm$)

# EDDA Polarimeter

- ***Left-Right*** asymmetry

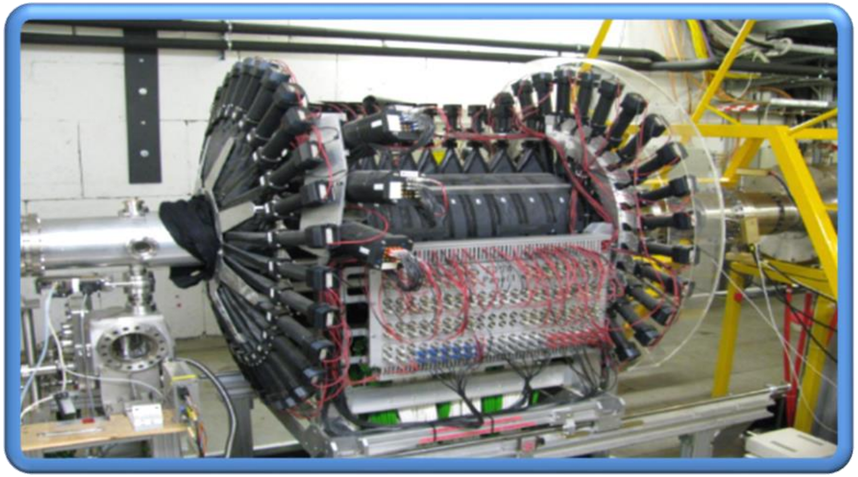
  ⇒ ***vertical*** polarization

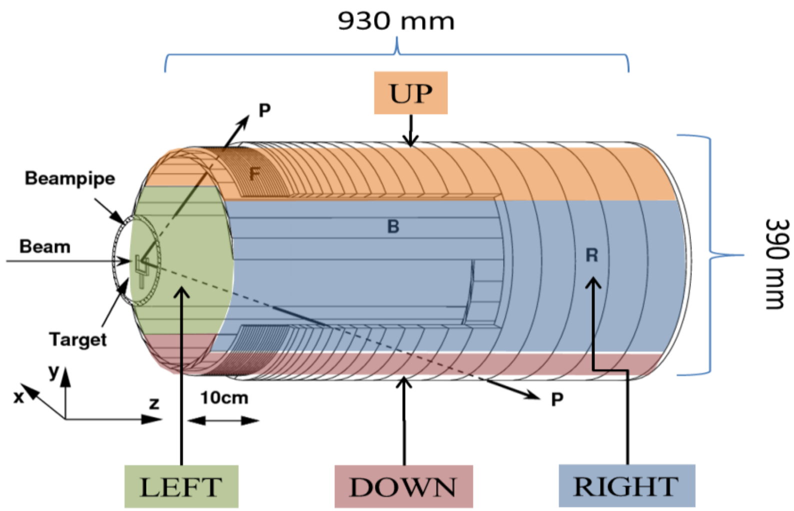
$$P_V \propto \epsilon_{ver} = \frac{N_l - N_r}{N_l + N_r}$$

- ***Up-Down*** asymmetry

  ⇒ ***horizontal*** polarization

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





# Spin Tune Measurement

- Spin vector precesses with $f_{\text{Spin}} = \nu_s f_{rev}$ in the horizontal plane around spin closed orbit

- 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, $p = 0.97$ GeV/c)

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

- Spin precession frequency: $\nu_s \cdot f_{rev} \approx 120 \text{ kHz}$

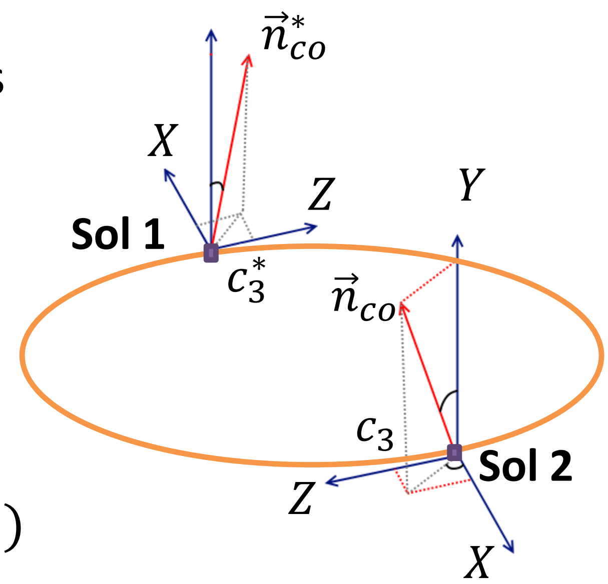
- Special spin tune analysis software resolves $\nu_s$ with an accuracy $10^{-8}$ in 1-second interval

# Spin Tune Response to the Artificial Imperfections

- The spin tune is perturbed by small spin kicks $\sim a$ in the ring imperfection fields:

$$\nu_0 = G\gamma + O(a^2)$$

- The idea is to probe the in-plane imperfection fields by introducing well-known *artificial imperfections.*




- Apply artificial imperfections: spin kicks $\chi_1$ and $\chi_2$ by the compensation solenoids in e-coolers, located in both straight sections,

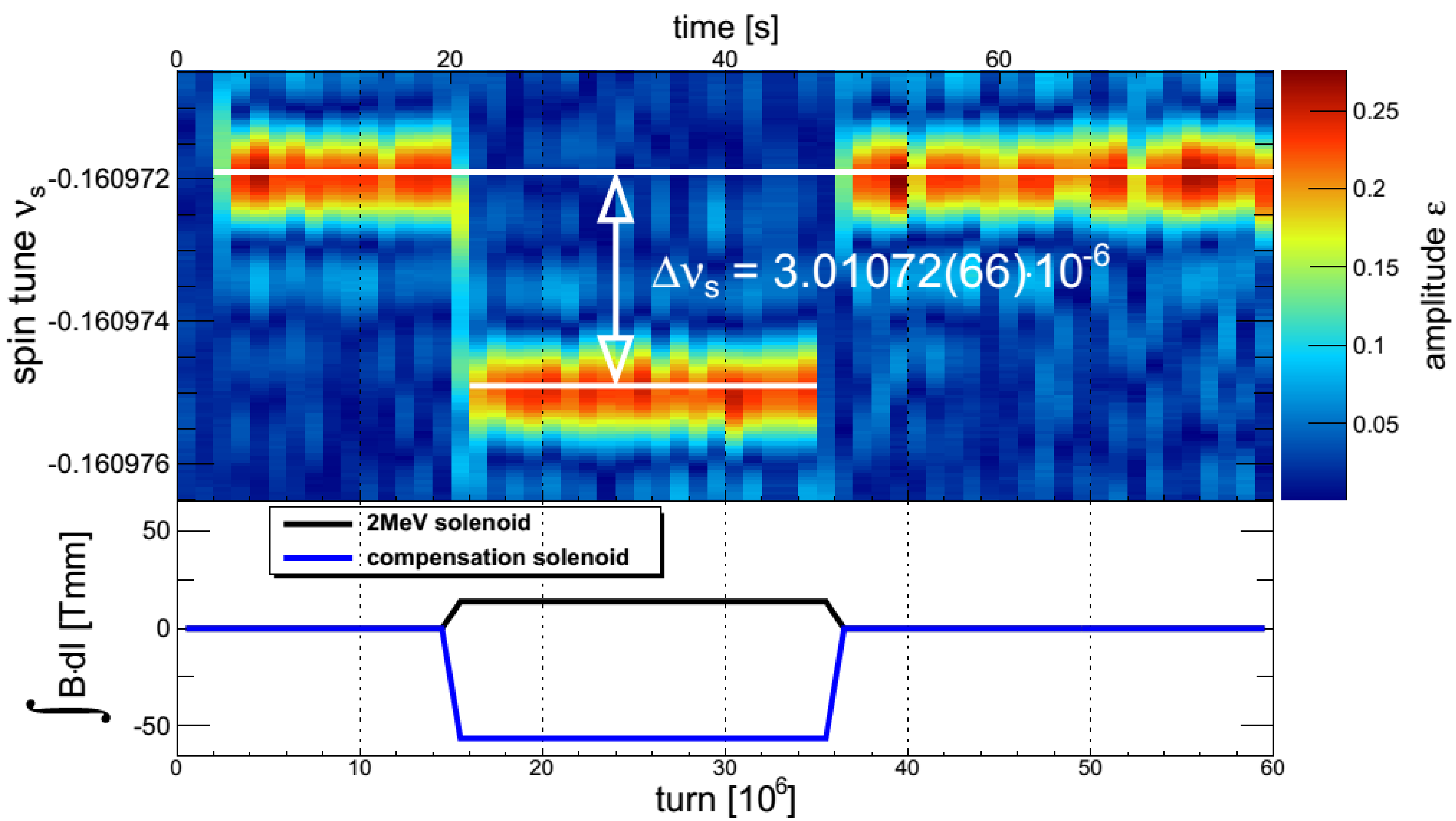
$$\nu_s = \nu_0 + O(c_3^2, (c_3^*)^2, \chi_1^2, \chi_2^2)$$

- Measure the spin tune shift w.r.t. applied spin kicks,

$$\Delta\nu_s(\chi_1, \chi_2) = \nu_s(\chi_1, \chi_2) - \nu_0$$

# Measurement of Spin Tune Shift

- Spin tune shift registered in the data analysis:

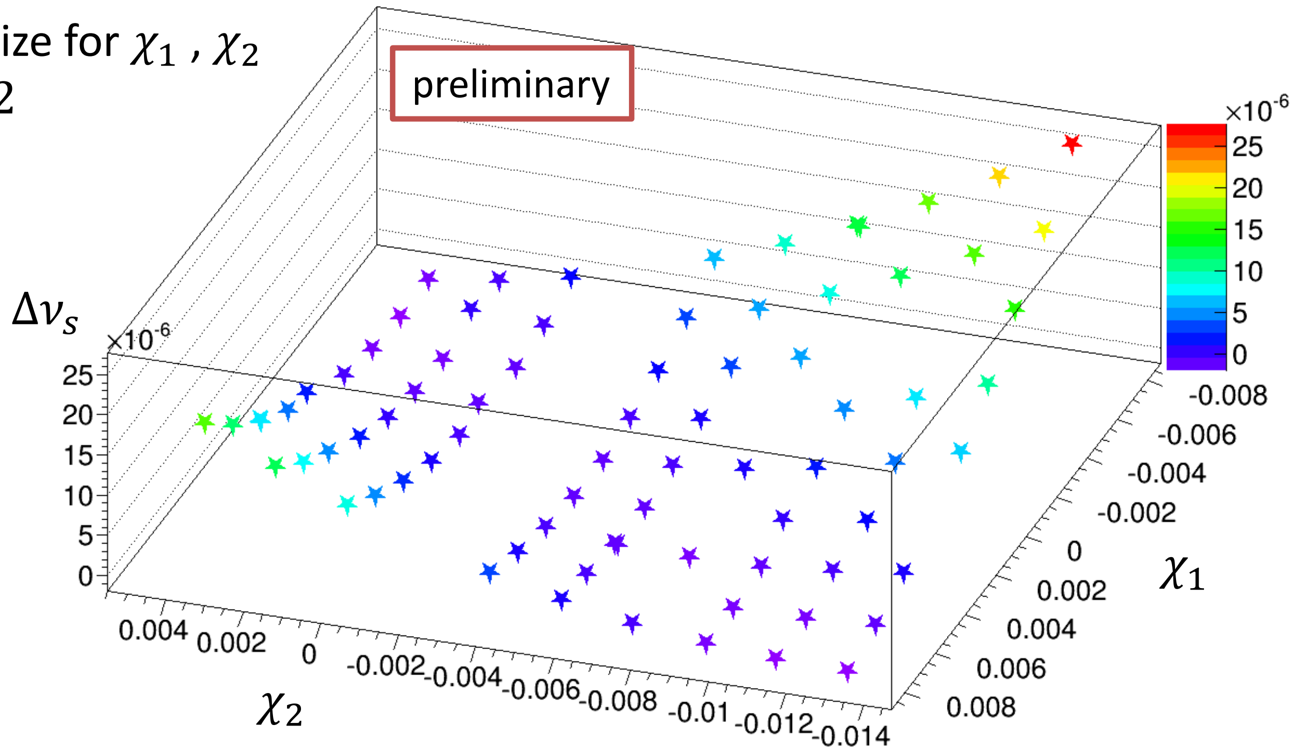



- The spin tune shift was observed at $t = [20, 45]\ s$

# The Spin Tune Mapping

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

Equal step size for $\chi_1$ , $\chi_2$
$\Delta\chi = 0.002$




- 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

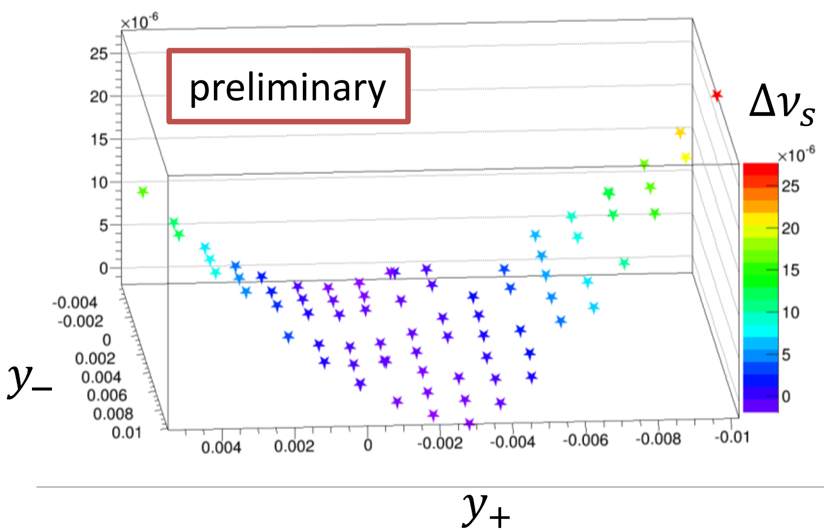
- If the kicks are translated to:

$$y_+ = \frac{1}{2}(\chi_1 + \chi_2) \qquad y_- = \frac{1}{2}(\chi_1 - \chi_2)$$

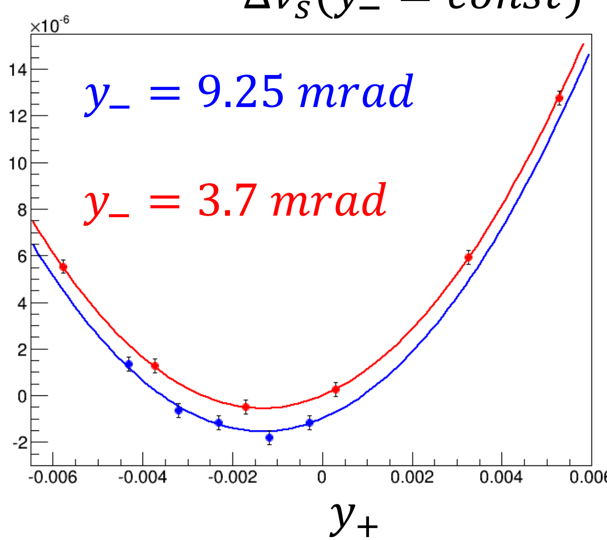
- then

$$\Delta\nu_s \propto -(y_- - a_-)^2, \qquad \Delta\nu_s \propto (y_+ - a_+)^2$$

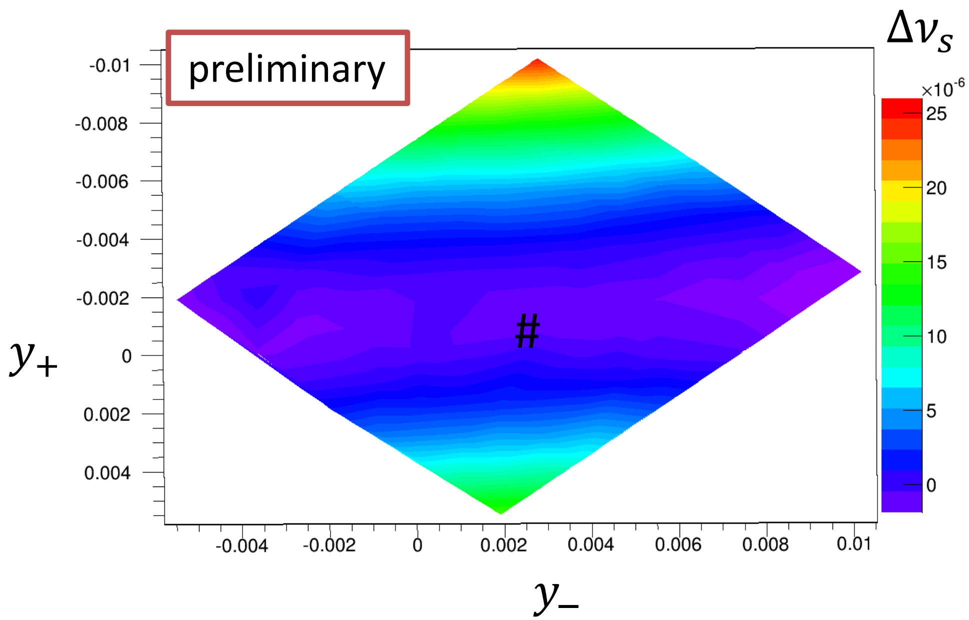
- The distributions of the data points in $y_\pm$ dimension share common parabolic features : equal curvature and extremum $a_\pm$
- It is a sign that the solenoids work as anticipated:




$\Delta\nu_s(y_- = const)$



# Imperfection Strength




The fitted saddle point at #:

$$a_+ = -0.00111077 \pm 6.1 * 10^{-8} \text{ rad}$$

$$a_- = 0.00244326 \pm 2.1 * 10^{-7} \text{ rad}$$

$$c_3 = -0.00299124 \pm 1.8 * 10^{-7}$$

$$c_3^* = -0.00163653 \pm 7.1 * 10^{-8}$$

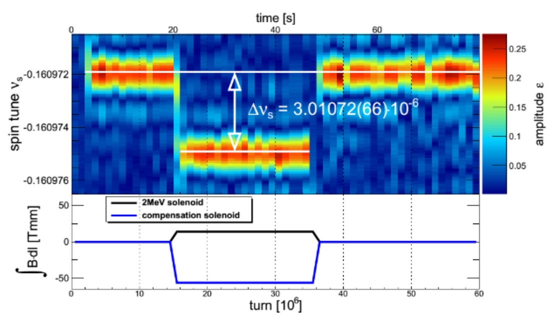
- Position of the saddle point measures projections of SCO, $c_3$ and $c_3^*$
- Strength of imperfection fields in the ring is at the level of $\approx 3\, Tmm$

- For an ideal ring, the saddle point would be at $a_\pm = 0$

# Summary

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

- First high precision measurement of the imperfection fields at COSY

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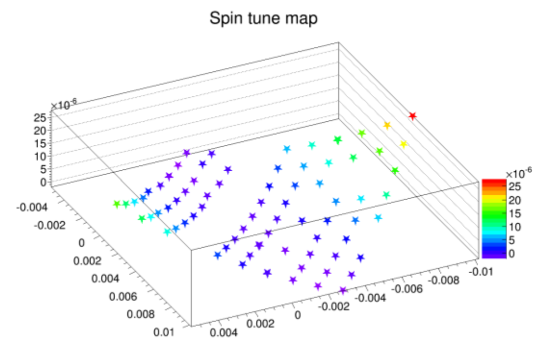



❖ The ultimate goal of the JEDI: to understand the EDM dynamics in storage rings as a prerequsite to the construction of the dedicated storage ring for the EDM searches

# More Details About Spin Tune Analysis

# Mapping the Events

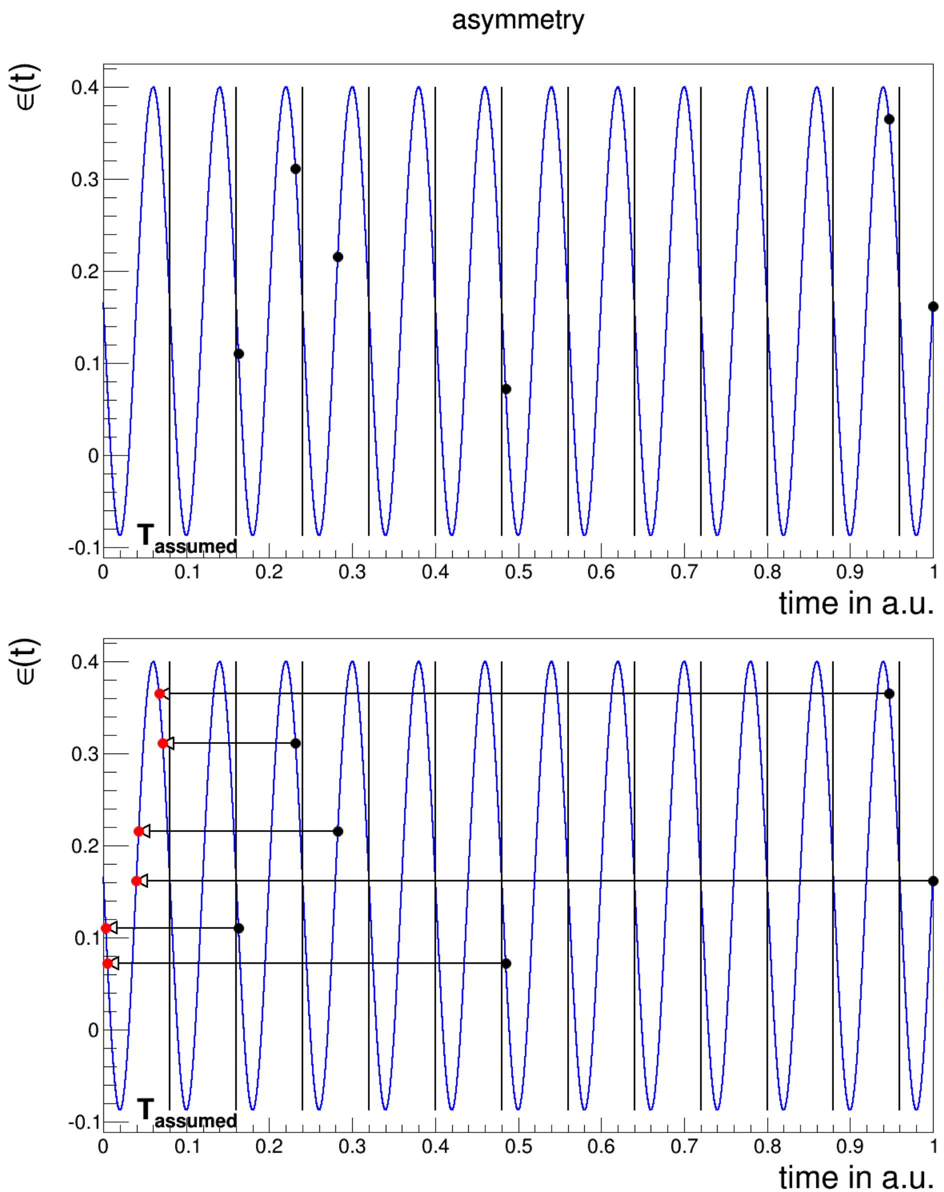
1. Assume Spin Tune $\nu_{assumed}$

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

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

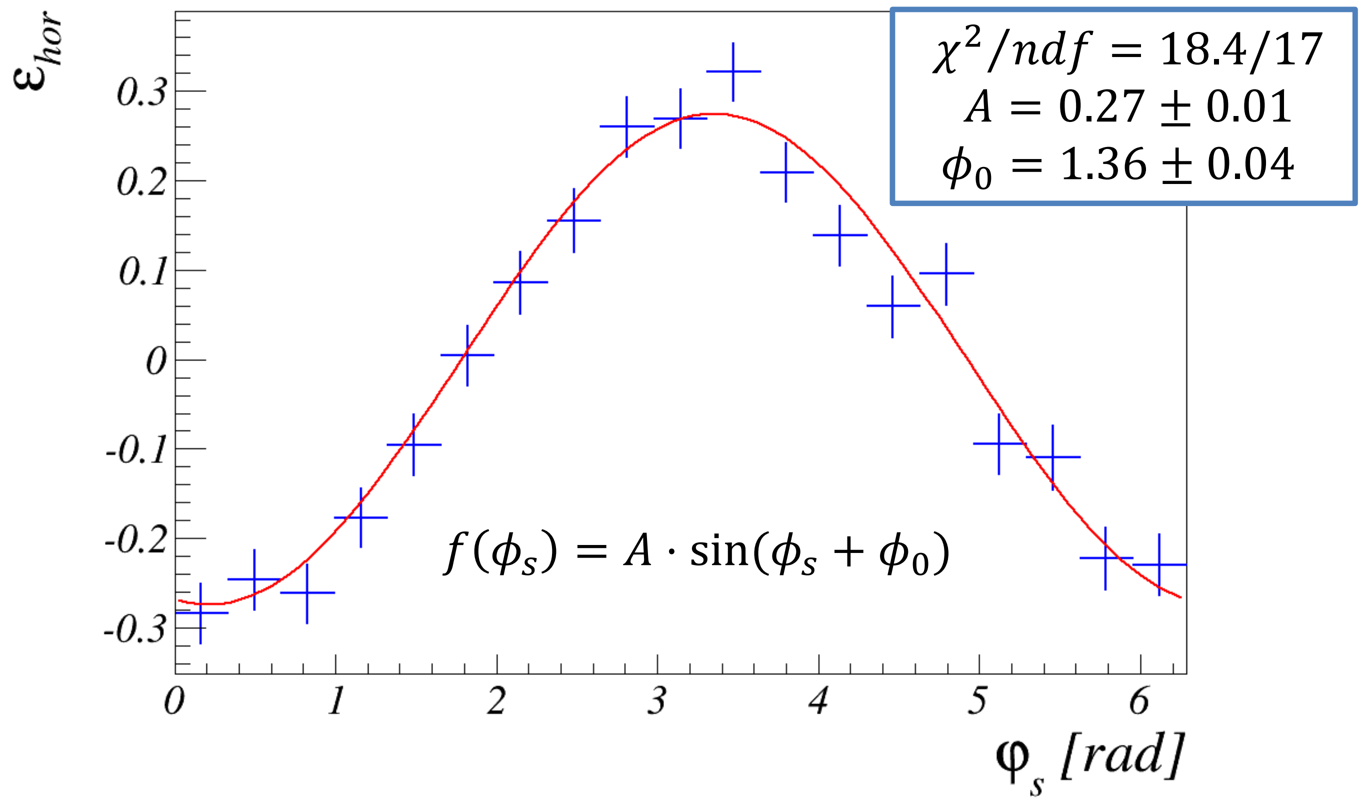
   $$t' = mod(t, T_{assumed})$$

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 $A \propto Polarisation$

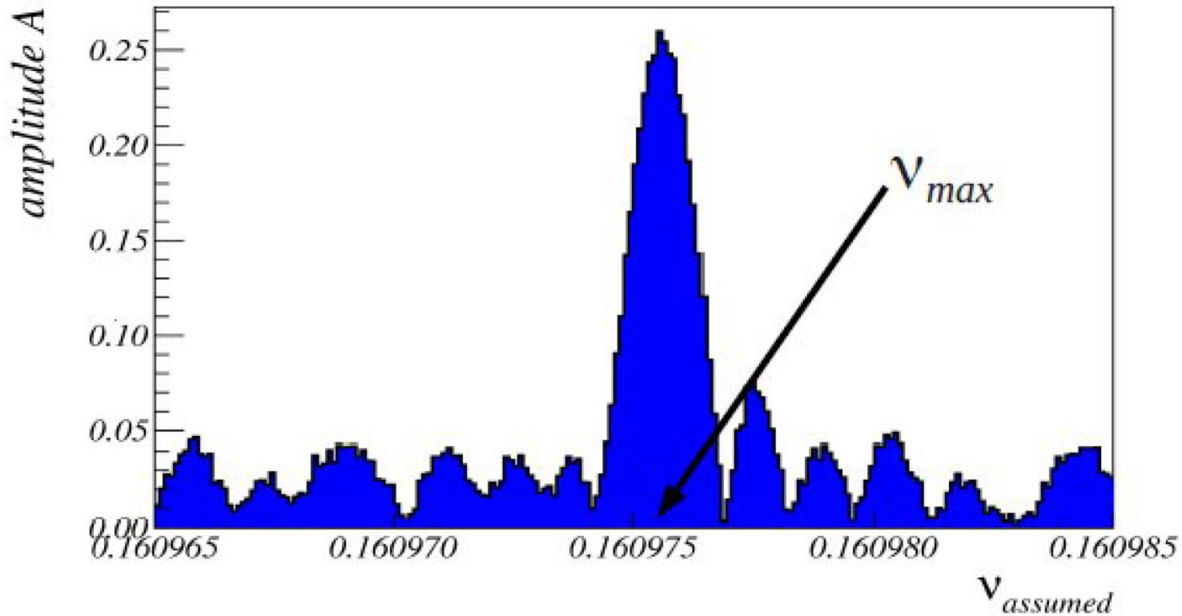
# Find Correct Spin Tune

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 $\nu_{assumed}$




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

- $c_3$ 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 $\Phi$ 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 $\nu_0$ has been determined, only $c_3$ and $c_3^*$ are the fit parameters