JEDI: Towards EDM at COSY: a Status Report

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Outline

- **Introduction**
- Selected Recent Achievements at COSY:
  - *Record spin coherence time*
  - *Record spin tune measurement*
  - *Record measurement of the stable spin axis*

- **Outlook for future**

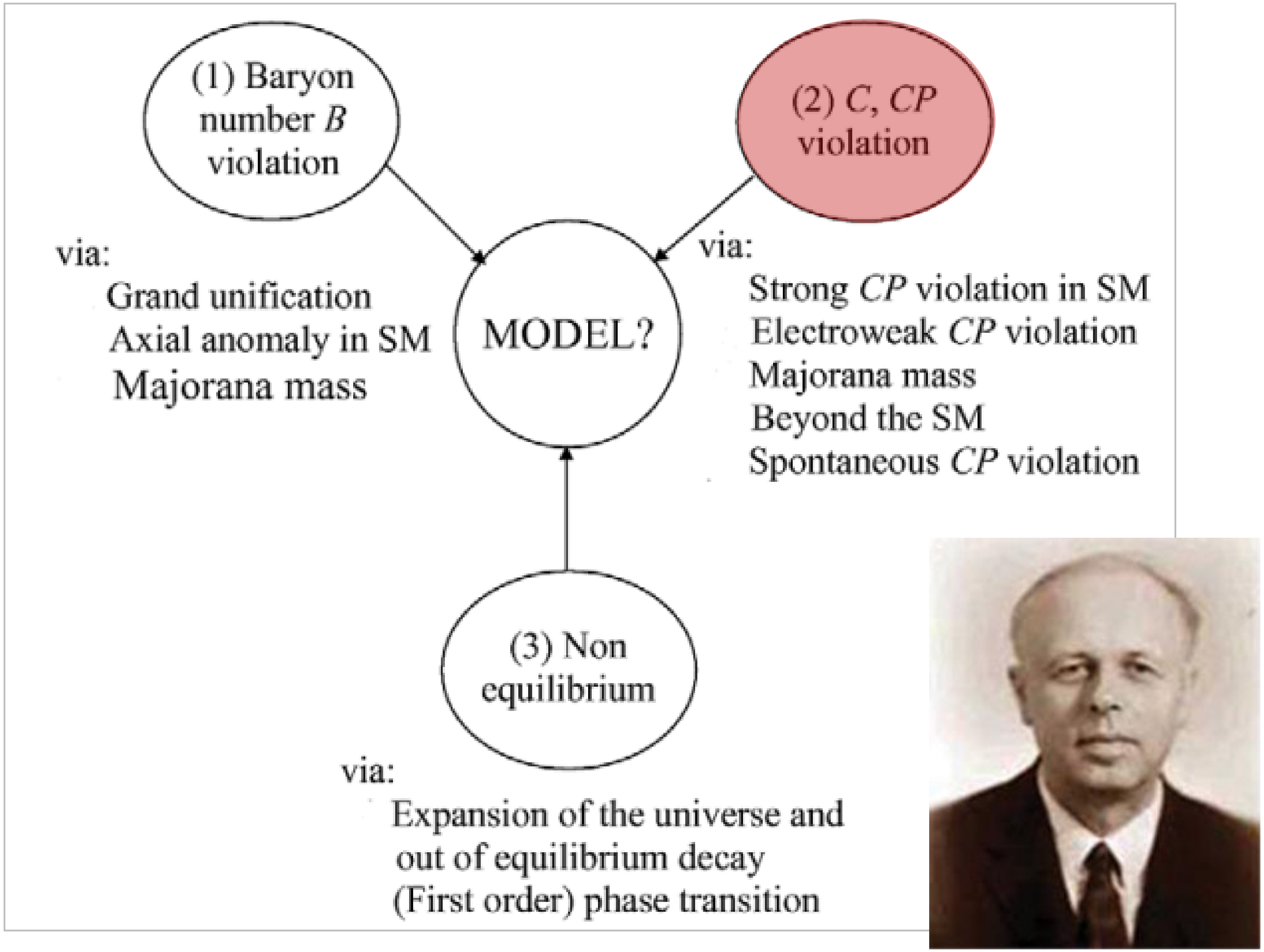
- Clinton to Bush: It's economy, stupid !
- EDM: It's mundane systematics, you the wise ones …

- *To be cont'd by Artem Saleev, next talk*

Why EDM?

1. Sensitive probe of the origin of CP violation
2. Sakharov: CP violation is crucial to generate the net baryon matter in the Universe and, eventually, our biological life
3. The Standard model has all ingredients to generate baryonic asymmetry but is much too feeble by some 9+/- orders in the magnitude
4. The isotopic properties of CP violation beyond the SM are entirely unknown: pEDM and dEDM are a imperative alongside the nEDM

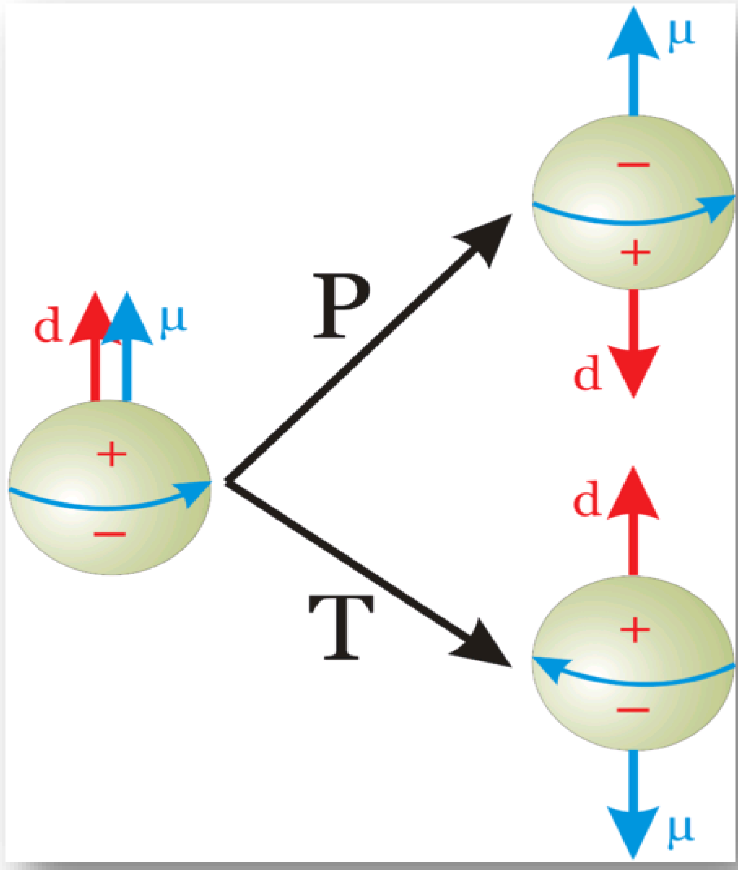
Physics: Baryogenesis



(1967)

Ingredients for baryogenesis: 3 Sakharov conditions

EDMs: Discrete Symmetries



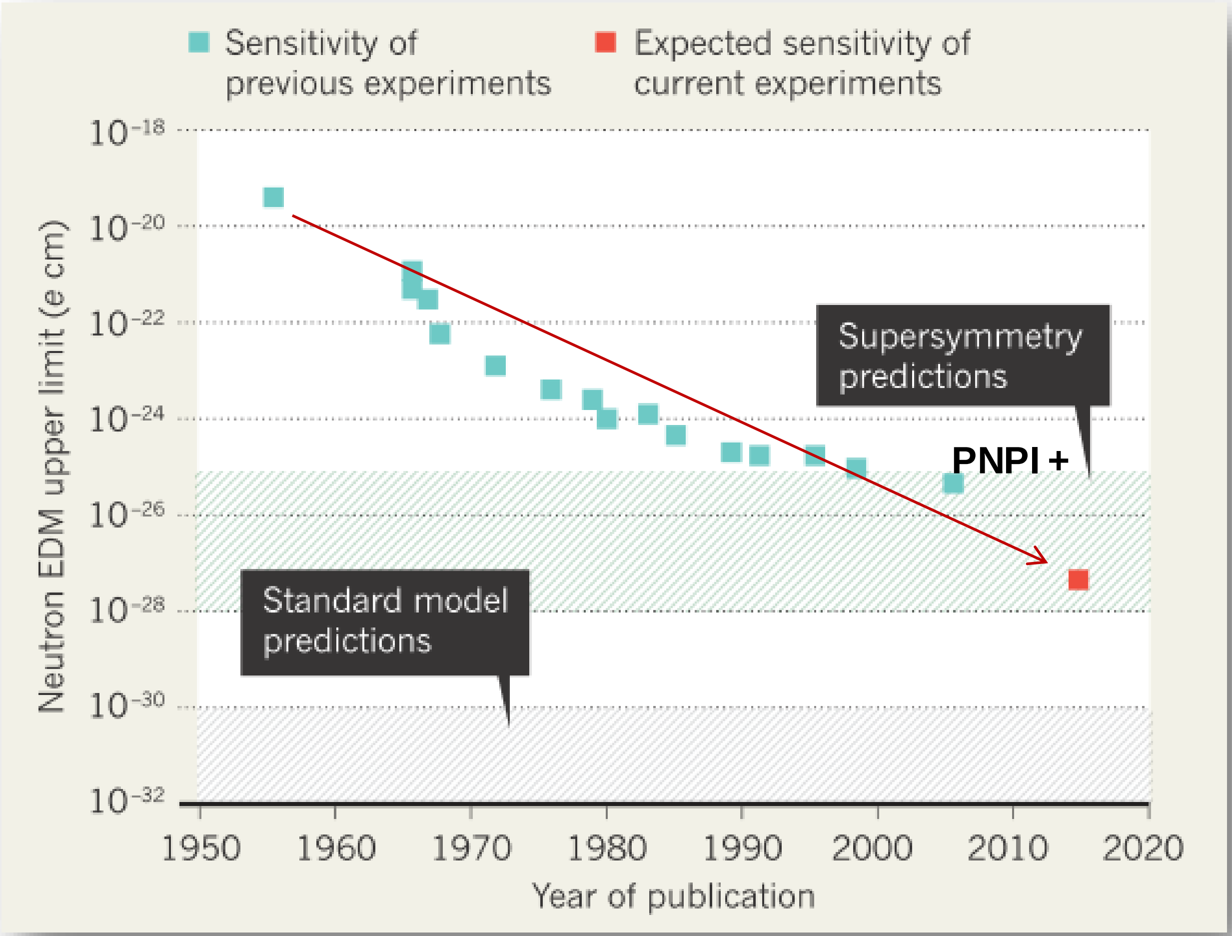
Not Charge symmetric

$\vec{d}$ (aligned w/ spin)

Permanent EDMs violate **P** and **T.**
Assuming **CPT** to hold, **CP** violated also.

EDM: Precision Frontier

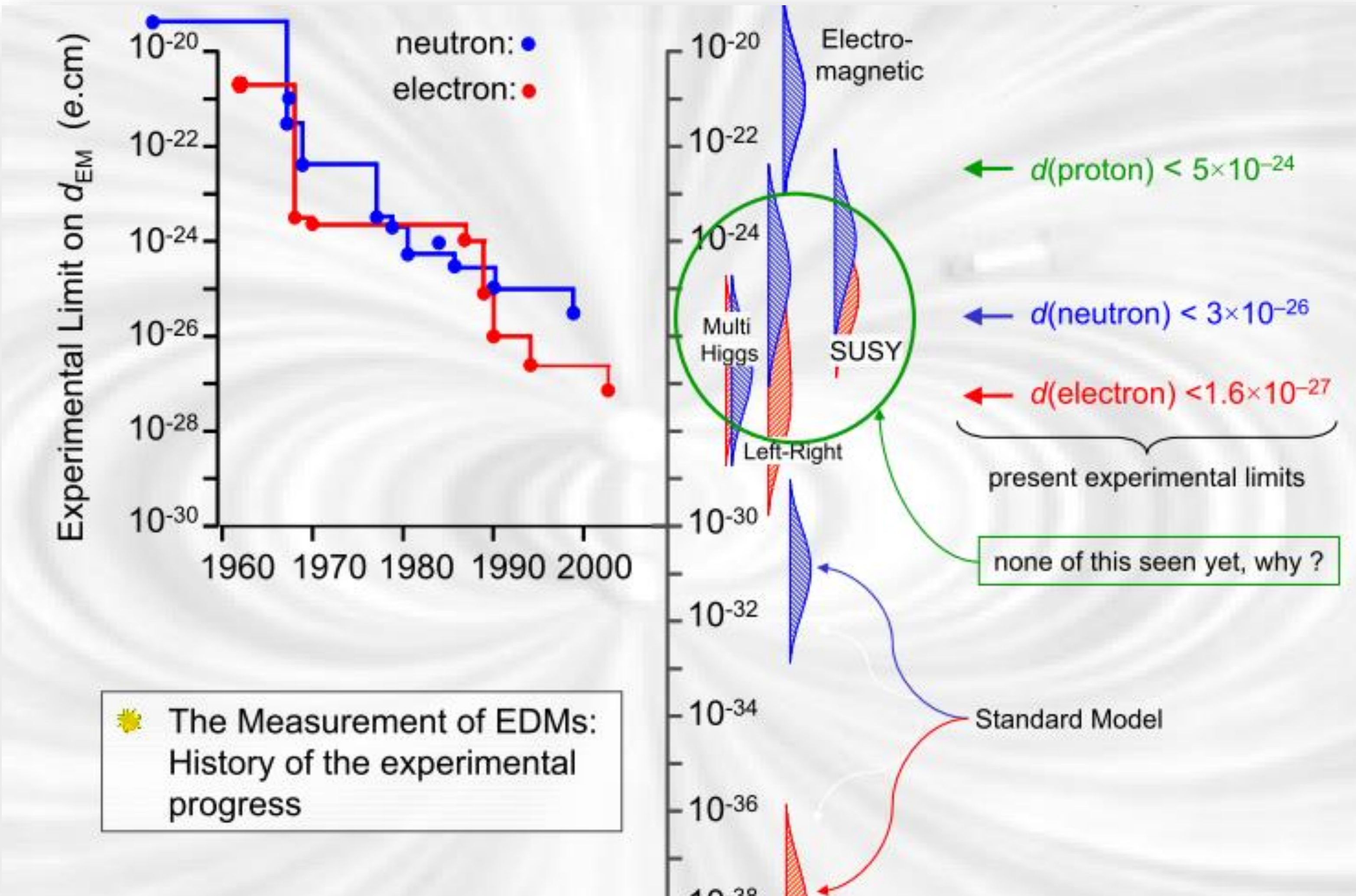
Neutron (nEDM) with ultracold neutrons:



Adapted from: Nature, Vol 482 (2012)

Search for Electric Dipole Moments (EDM) of fundamental particles

Physics: Potential of EDMs



J.M. Pendlebury: „nEDM has killed more theories than any other single expt."

Concept: Experimental requirements

- High precision, primarily electric storage ring
  - Ideal alignment, stability, field homogeneity, and shielding from perturbing magnetic fields
- High beam intensity ($N = 4 \cdot 10^{10}$ per fill)
- Stored polarized hadrons ($P = 0.8$)
- Large electric fields ($E = 10\ \mathrm{MV/m}$)
- Long spin coherence time ($\tau = 1000\ \mathrm{s}$)
- Efficient polarimetry (analyzing power $A_y \approx 0.6, f = 0.005$)

$$\sigma_{\text{stat}} \approx \frac{1}{\sqrt{N \cdot f} \cdot \tau \cdot P \cdot A_y \cdot E} \Rightarrow \sigma_{stat}(1\ \text{year}) = 10^{-29}\ \mathrm{e \cdot cm}$$

Goal: provide σ_{syst} to the same level

Concept: ***EDM rotation from vertical to in-plane and vice versa in the E-filed, eliminate the false MDM rotation in the background B-fields***

Frenkel-Thomas-BMT equation:

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

Magic condition (pioneered at BNL): Spin along momentum vector

1. For any sign of G, in a combined electric and magnetic machine

$$E = \frac{GBc\beta\gamma^2}{1-G\beta^2\gamma^2} \approx GBc\beta\gamma^2, \text{ where } E = E_{\mathrm{radial}} \text{ and } B = B_{\mathrm{vertical}}$$

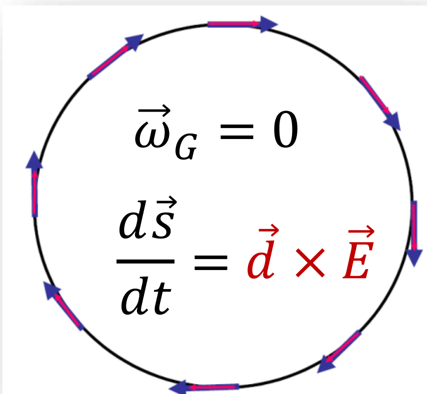
2. For $G > 0$ (protons) in an all electric ring

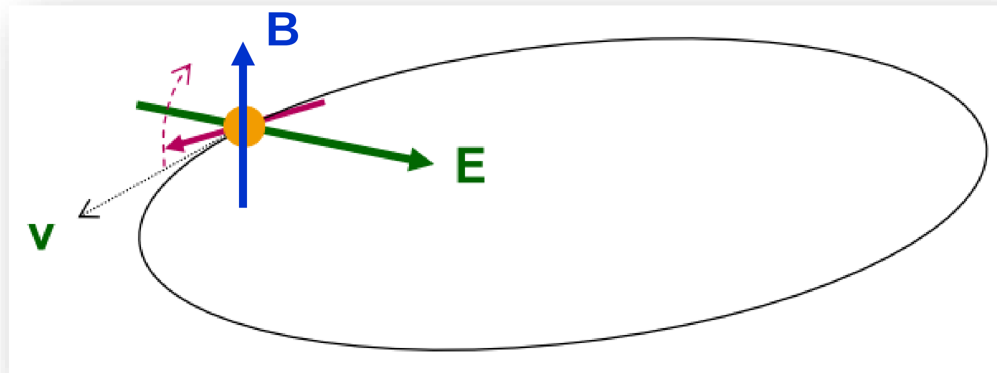
$$G - \left(\frac{m}{p}\right)^2 = 0 \Rightarrow p = \frac{m}{\sqrt{G}} = 700.74\ \mathrm{MeV/c} \quad \text{(magic)}$$

→ Magic rings are optimal ones to measure EDMs of **free** charged particles

Concepts: *Magic* Storage ring

A *magic* storage ring for protons (electrostatic), deuterons, …



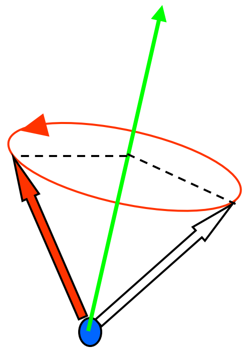


particle	p (MeV/c)	T (MeV)	E (MV/m)	B (T)
proton	701	232.8	16.789	0.000
deuteron	1000	249.9	−3.983	0.160
^{3}He	1285	280.0	17.158	−0.051

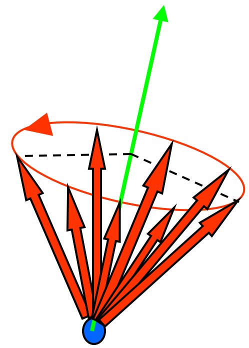
Possible to measure p, d, ^{3}He using **one** machine with $r \sim 25$ m

Challenge: Spin coherence time

We usually don't worry about coherence of spins along $\hat{n}_{co}$



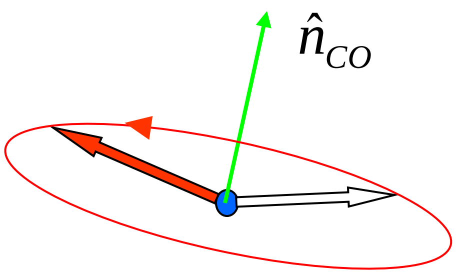
At injection all
spin vectors aligned (coherent)



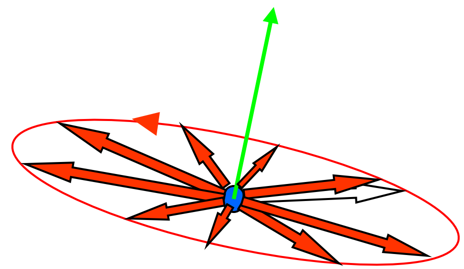
After some time, spin vectors get out of phase and fully
populate the cone but the polarization is preserved

Polarization not affected!

Situation very different for the in-plane $\vec{S} \perp \hat{n}_{co}$ when there is no holding B-field



At injection all spin vectors aligned

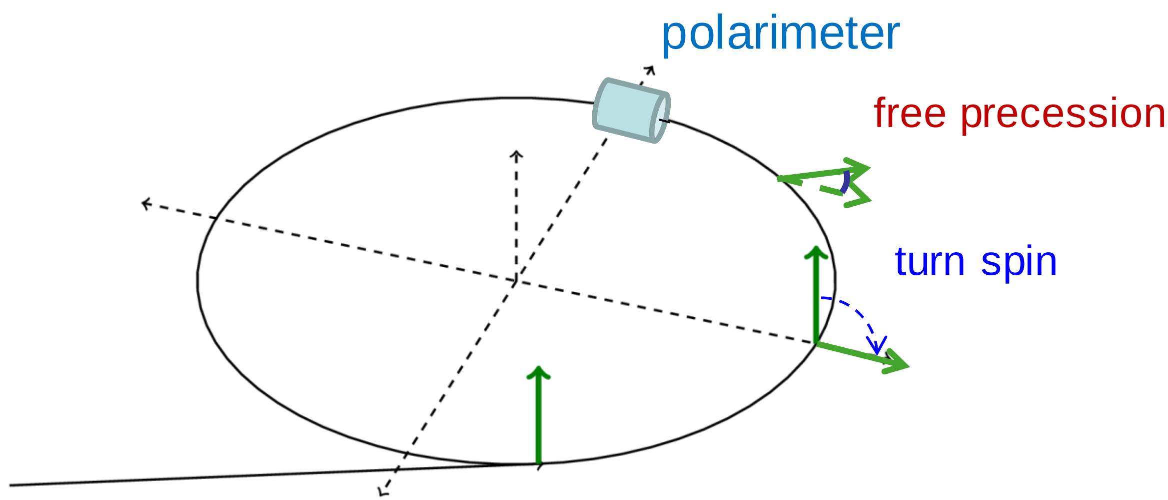


Later, spin vectors are out of
phase in the horizontal plane

Longitudinal polarization vanishes within the spin coherence time!

In an EDM machine with frozen spin, observation time is limited.

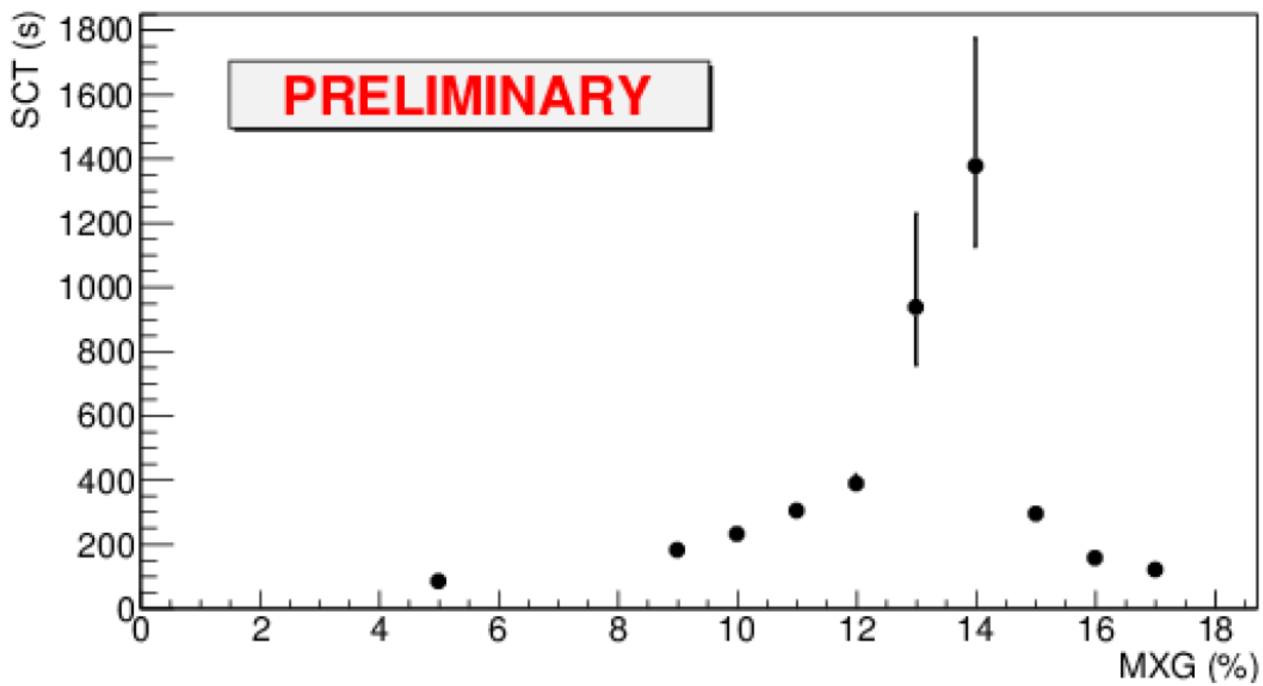
Spin coherence time: Experimental investigation



1. Vertically polarized deuterons stored in COSY at $p \approx 1\,\frac{\mathrm{GeV}}{\mathrm{c}}$.
2. The polarization is flipped into horizontal plane with RF solenoid (takes $\approx 200\ \mathrm{ms}$).
3. Beam slowly extracted on Carbon target by heating the beam.
4. Horizontal (in-plane) polarization determined from Up-Do asymmetry in the detector (EDDA).

Keep track of the event time and revolution time in each turn during a cycle of a few hundred seconds.

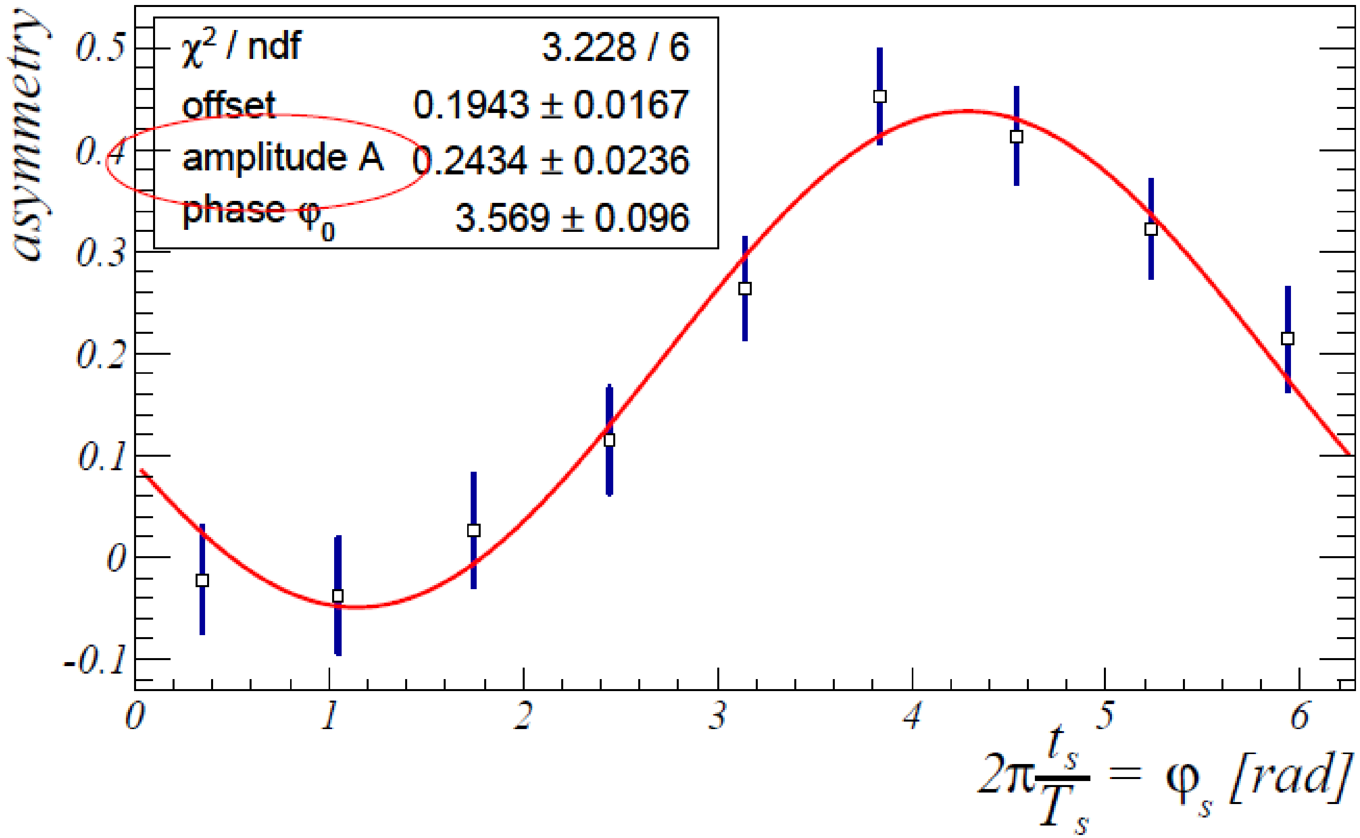
SCT: Optimization



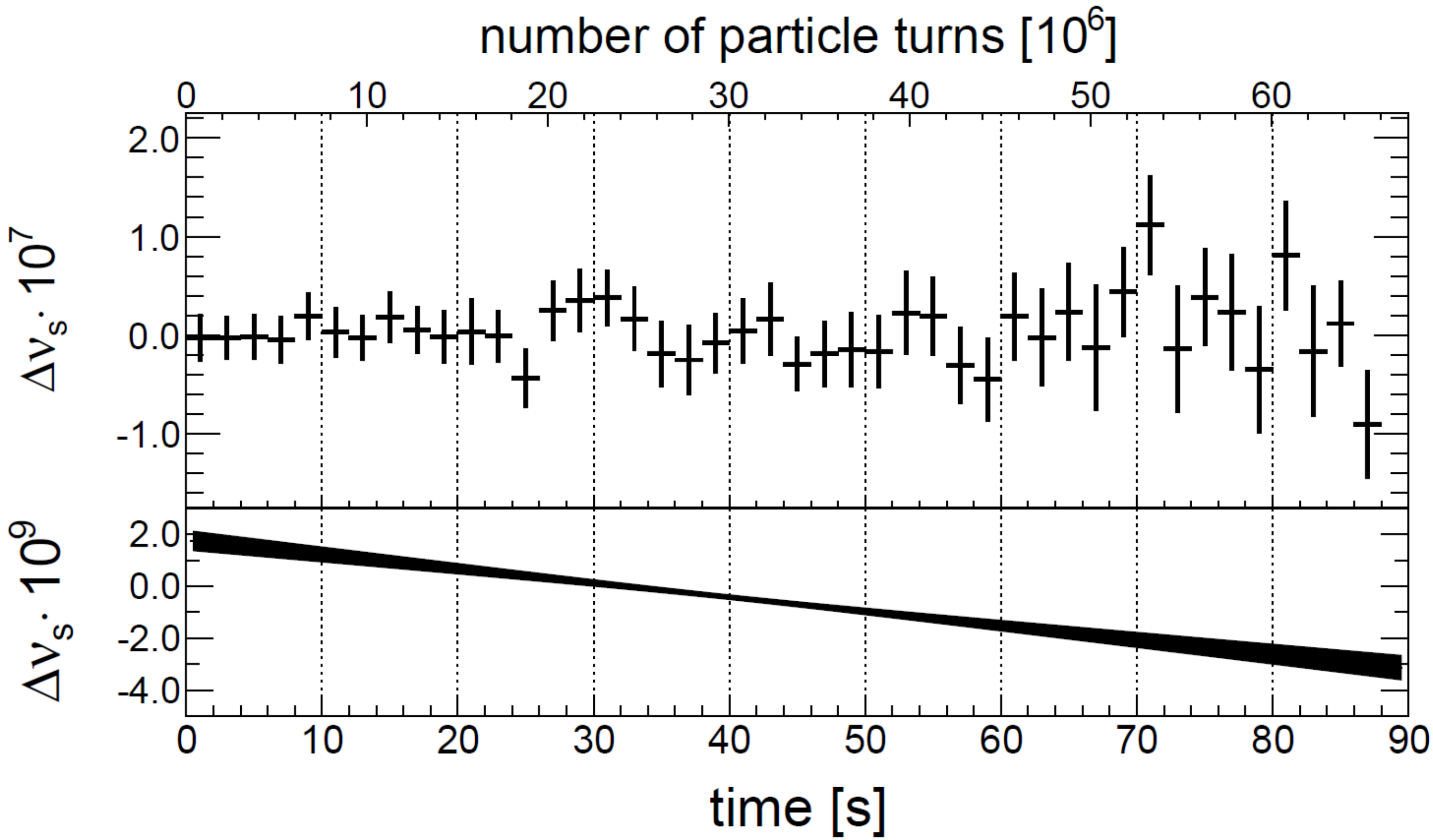
Measurements of the horizontal polarization lifetime as a function of the strength of the MXG sextupole family with MXS set to 10% and MXL set to -1.45% of power supply full scale.

Excellent progress towards the SCT goal for pEDM: $\mathbf{SCT{\sim}1000}$ s

Spin tune: How to find ν_s?



Spin tune: Determination of ν_s



Spin tune ν_s determined to $\approx 10^{-7}$ in 2 s.
$\bar{\upsilon}_s$ in cycle at $t \approx 40\ s$ is determined to $\approx 10^{-10}$.
(PRL, accepted August 26, 2015)

New physics: Option for polarized antiprotons

JEDI is capable to determine the spin tune (number of spin revolutions per turn) $\nu_s = \gamma G$ of deuterons in COSY with a **precision of $\approx 10^{-10}$**.

With a suitable magnetic storage ring (ESR (GSI), AD (CERN)) with CW protons and CCW antiprotons, the ratio $\frac{\nu_s(\bar{p})}{\nu_s(p)}$ could be measured to similar precision.

For the first time a single trapped antiproton ($\bar{p}$) is used to measure the $\bar{p}$ magnetic moment $\boldsymbol{\mu}_{\bar{p}}$. The moment $\boldsymbol{\mu}_{\bar{p}} = \mu_{\bar{p}} \boldsymbol{S}/(\hbar/2)$ is given in terms of its spin $\boldsymbol{S}$ and the nuclear magneton (μ_N) by $\mu_{\bar{p}}/\mu_N = -2.792\,845 \pm 0.000\,012$. The 4.4 parts per million (ppm) uncertainty is 680 times smaller than previously realized. Comparing to the proton moment measured using the same method and trap electrodes gives $\mu_{\bar{p}}/\mu_p = -1.000\,000 \pm 0.000\,005$ to 5 ppm, for a proton moment $\boldsymbol{\mu}_p = \mu_p \boldsymbol{S}/(\hbar/2)$, consistent with the prediction of the *CPT* theorem.

Comparison of spin tunes of protons and antiprotons allows for a CPT test $\approx 10^{-10}$ (publication in prep.)

Precursor: Resonance Method with „magic“ RF Wien filter *(in an ideal all-magnetic ring)*

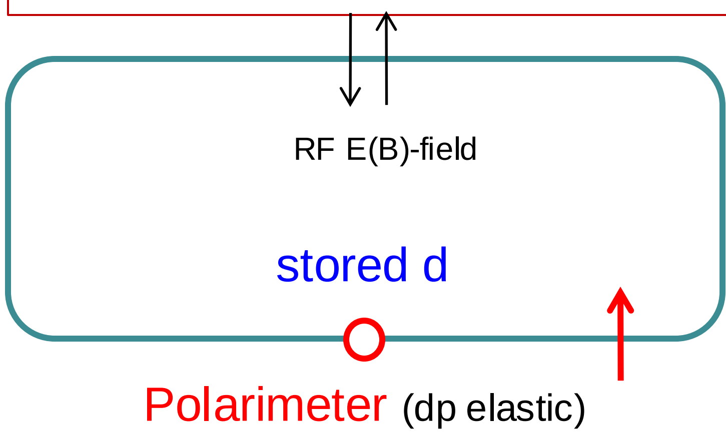
Avoids coherent betatron oscillations of beam.

Radial RF-E and vertical RF-B fields to observe spin rotation due to EDM.

Approach pursued for a first direct measurement at COSY.

$\boldsymbol{E^* = 0 \Rightarrow E_R = -\beta \times B_y}$ **„Magic RF Wien Filter“** no Lorentz force

→ **Indirect** EDM effect



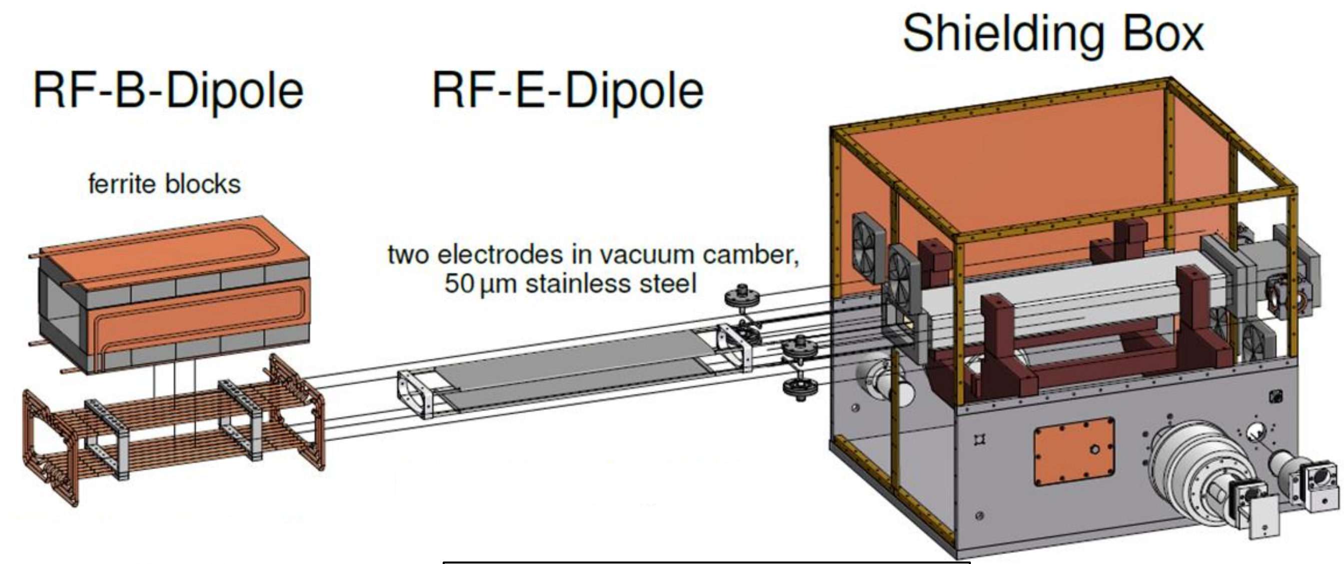
In-plane polarization

Observable:
Accumulation of vertical polarization during spin coherence time

Statistical sensitivity for d_d in the range 10^{-23} to 10^{-24} e·cm range possible.

- Alignment and field stability of ring magnets
- Imperfections of the ring and of the RF-E(B) flipper

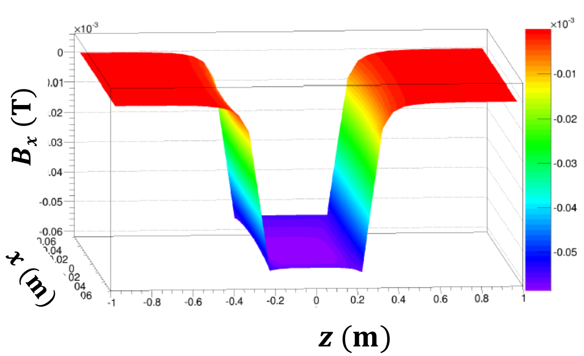
RF $\mathbf{E} \times \mathbf{B}$ Wien Filter: Field calculations

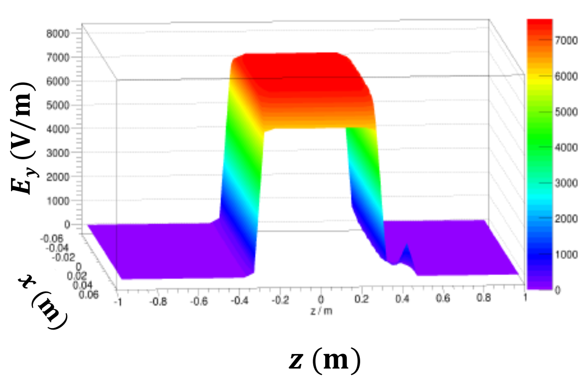


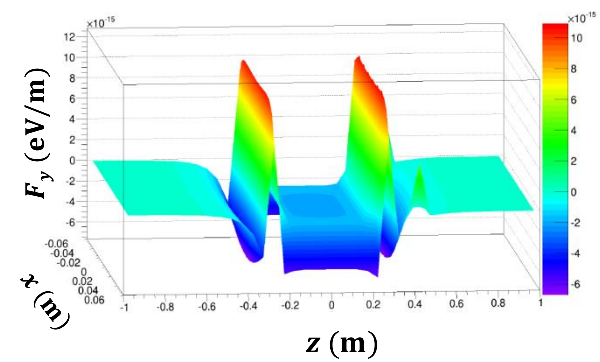
Main field component
$\hat{B}_x = 0.058\,\mathrm{mT}$ at $y = 0,\ \ I = 1\ \mathrm{A}$,
$\int \hat{\boldsymbol{B}}_{\boldsymbol{x}} \boldsymbol{dz} = \mathbf{0.035\ Tmm}$

Main field component
$\hat{E}_y = 7594\ \mathrm{V/m}$ at $\mathrm{y} = 0$,
$\mathrm{U} = 395\ \mathrm{V}, \int \hat{\boldsymbol{E}}_{\boldsymbol{y}} \boldsymbol{dz} = \mathbf{4818\ V}$

Integral compensation of Lorentz force $\int F_y dz = 0$ at $\mathrm{y} = 0$







Why imperfections? COSY is not an ideal ring

- RF Wien Filter: RF modulation of the spin tune couples to the tilt of the stable spin axis by the EDM interaction with the motional radial electric field in the ring.

- The imperfection radial & longitudinal magnetic fields (IMF) do the same job by interaction with much larger MDM

- How large the IMF background to the EDM is?

Systematic study: Machine imperfections using two straight section solenoids

Systematic effects from machine imperfections limit the achievable precision in a precuror experiment using an RF $\mathrm{E} \times \mathrm{B}$ Wien filter.

Idea: The precise determination of the spin tune $\left(\frac{\Delta \nu_s}{\nu_s} \approx 10^{-10} \text{ in one cycle}\right)$ can be exploited to map out the imperfections of COSY.

COSY provides two solenoids in opposite straight sections:

1. one of the compensation solenoids of the 70 kV cooler: $\int \boldsymbol{B_z dz} \approx \mathbf{0.15\ Tm}$,
2. The main solenoid of the 2 MV cooler: $\int \boldsymbol{B_z dz} \approx \mathbf{0.54\ Tm}$.

Both are available dynamically in the cycle, *i.e.*, their strength can be adjusted on flattop.

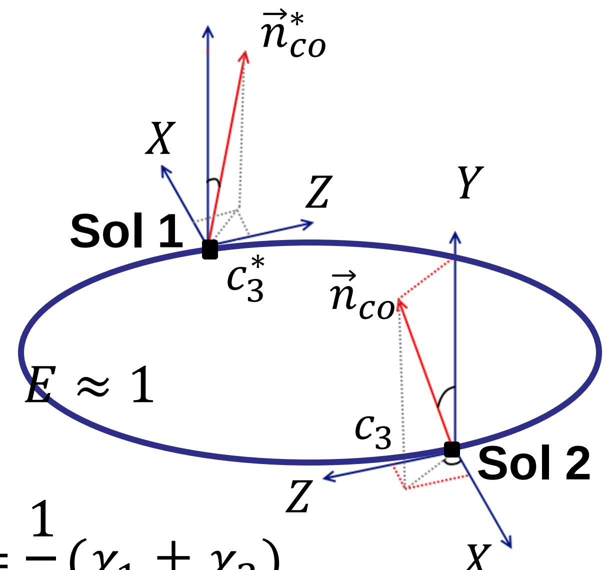
Two solenoids probe $\vec{n}_{co}$ at 2 points

When 2 solenoids turned on simultaneously:

$$\cos\pi(\nu_s + \Delta\nu_s) = \cos\pi\nu_s \cos\frac{1}{2}\chi_1 \cos\frac{1}{2}\chi_2 - \sin\pi\nu_s\, c_3^* \sin\frac{1}{2}\chi_1 \cos\frac{1}{2}\chi_2 - E\sin\frac{1}{2}\chi_1 \sin\frac{1}{2}\chi_2 - \sin\pi\nu_s\, c_3 \sin\frac{1}{2}\chi_2 \cos\frac{1}{2}\chi_1$$

ν_s - base spin tune

$\Delta\nu_s$ - a spin tune shift

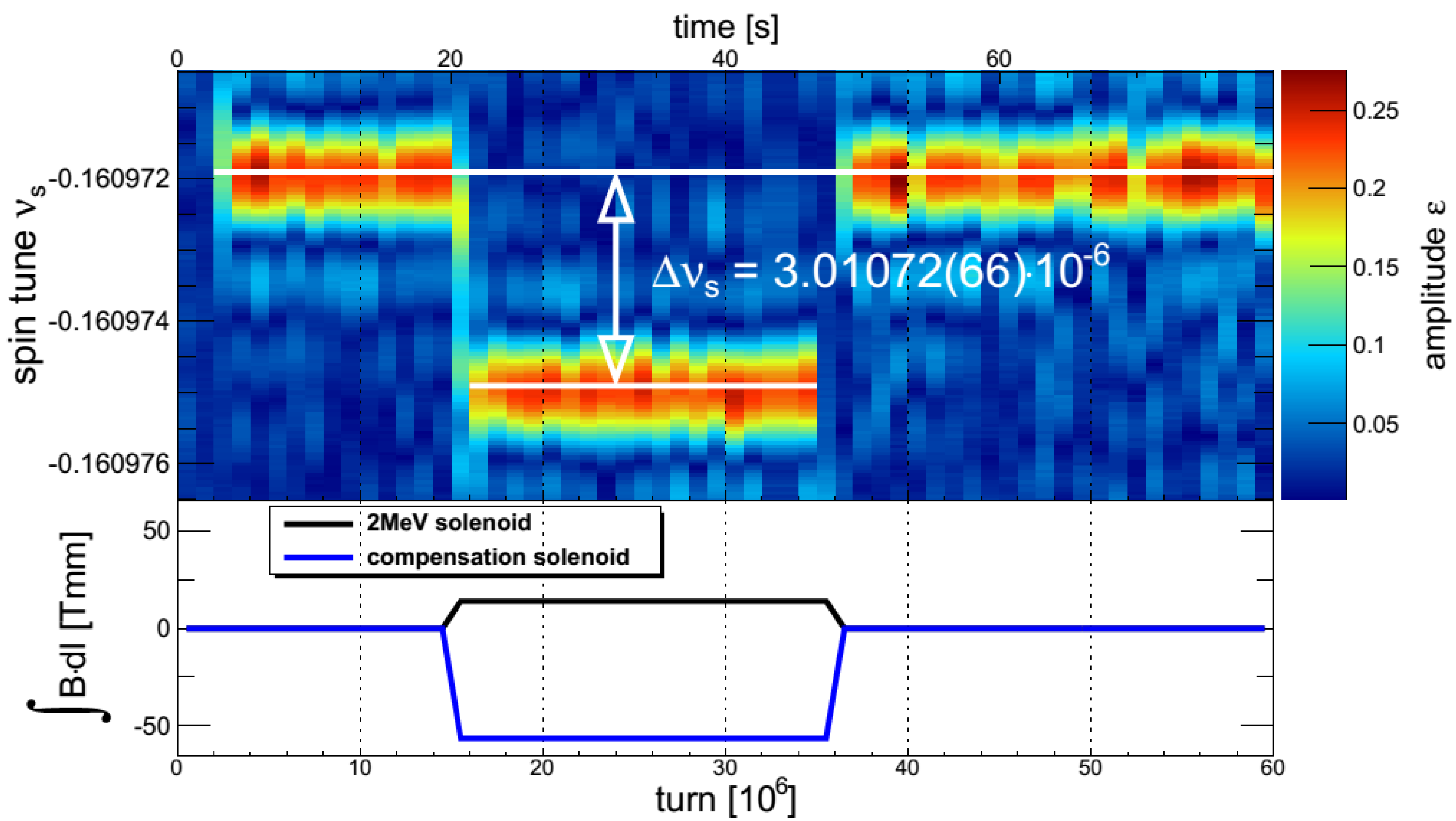


$$y_\pm = \frac{1}{2}(\chi_1 \pm \chi_2)$$

In $y_\pm$-dimension, $\Delta\nu_s \sim y_\pm^2$

Measurement of Spin Tune Shift

Spin tune shift registered in the data analysis:

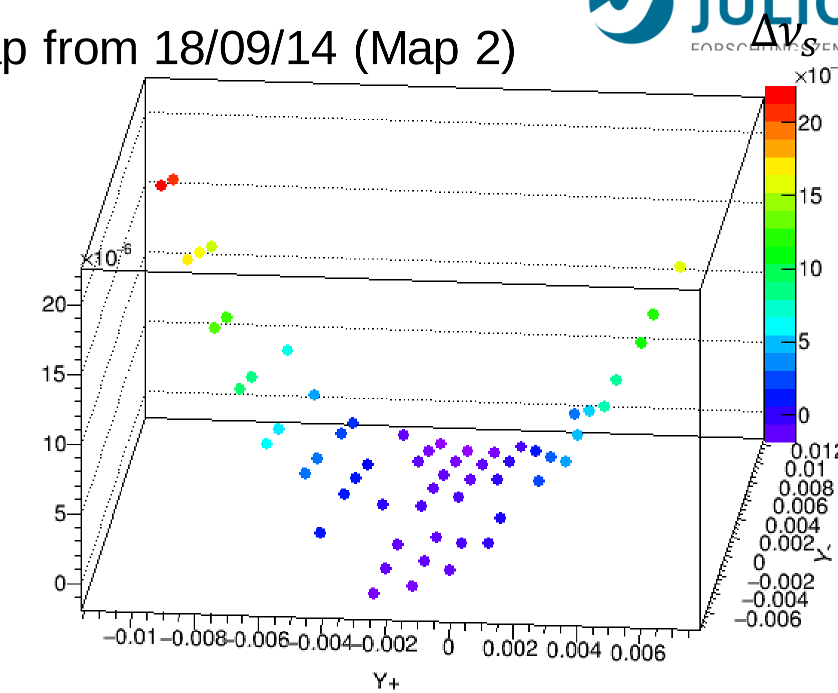


The spin tune shift was observed at $t = [20, 45]\ s$

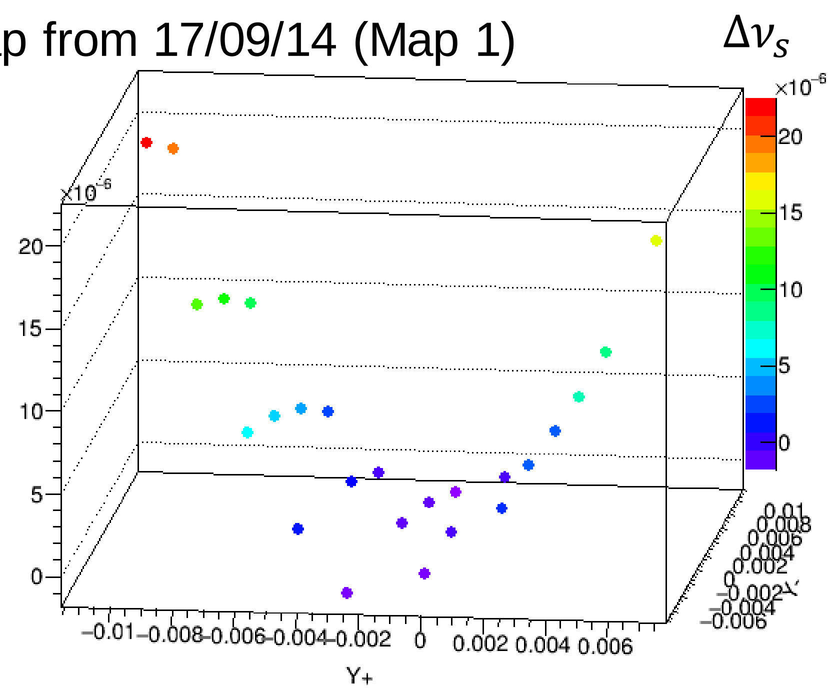
$$y_{\pm} = \frac{1}{2}(\chi_1 \pm \chi_2)$$

In $y_{\pm}$-dimension, $\Delta\nu_s \sim y_{\pm}^2$

Map from 18/09/14 (Map 2)



Map from 17/09/14 (Map 1)



Location of the saddle point depends on c_3, c_3^*

The first unexpected proof of the power of the spin tune technique from the Ionization Profile Measurements during spin tune mapping

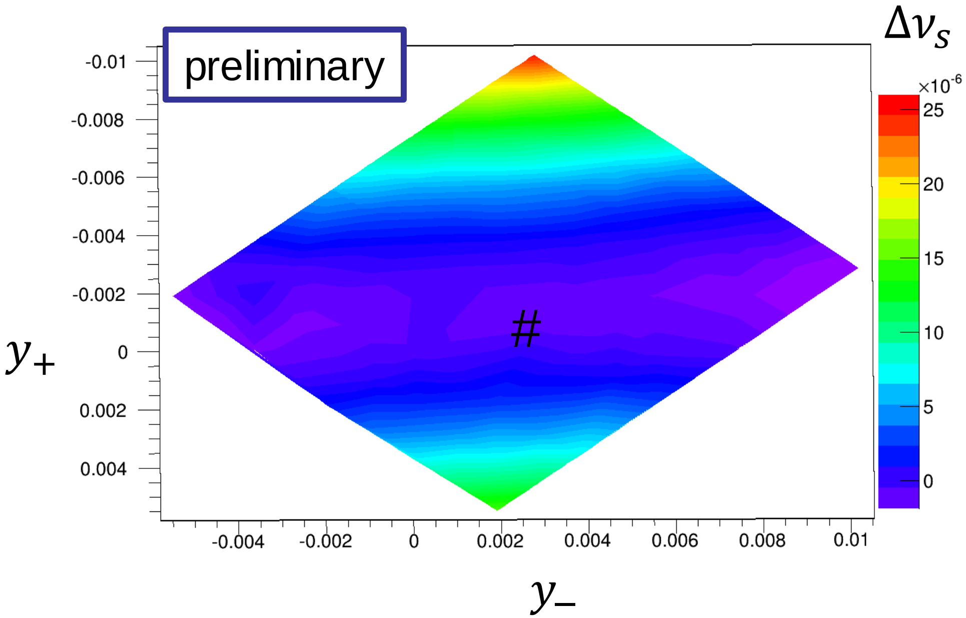
IPM was found to produce a very large spin tune shift $\backsimeq 10^{-6}$

Orbit perturbation by IPM was less than orbit perturbation by weakest solenoid field

Runs 3845-3860 (in Map 1, 17/09/2014), 3913-3923 (in Map 2, 18/09/2014) have an indication of IPM measurements.

These points are excluded from the current analysis.

Imperfection Strength



The fitted saddle point at #:

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

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

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

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

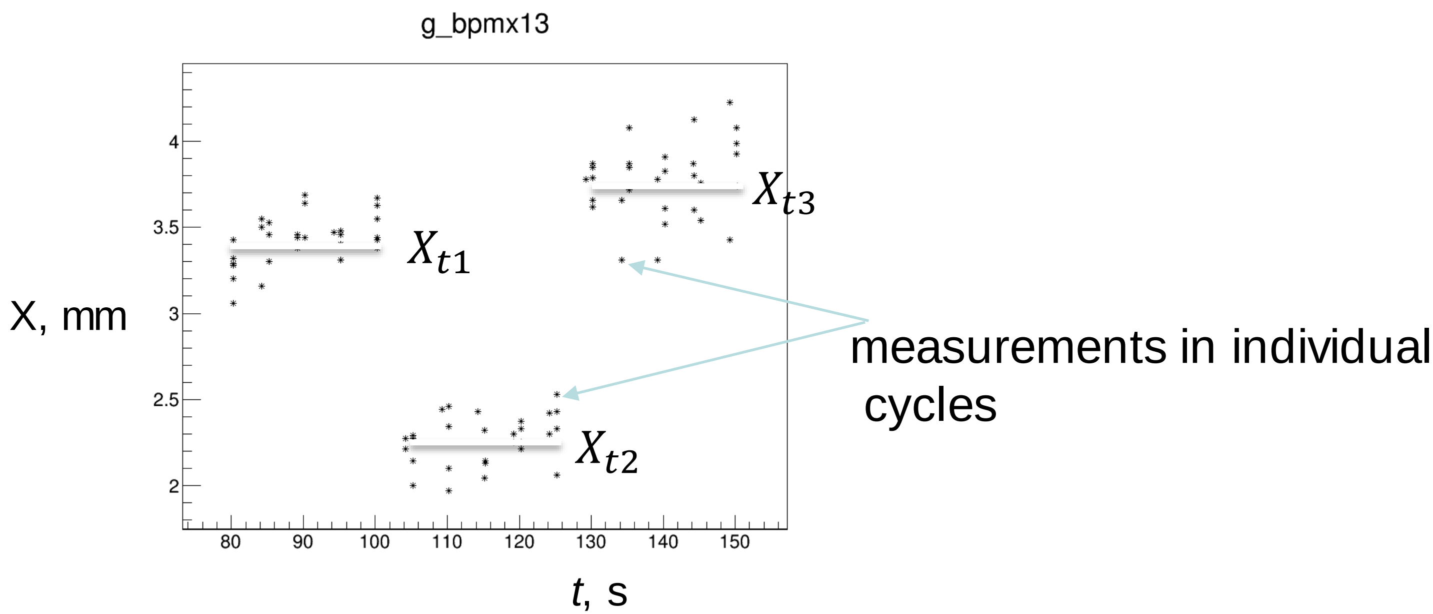
- Position of the saddle point measures projections of SCO for two arcs, c_3 and c_3^*
- Strength of imperfection fields in the ring is at the level of $\approx 3\, Tmm$
- For an ideal ring, the saddle point would be at $a_\pm = 0$

Stability of orbit during the run

Beam position was measured multiple times during the cycle

6 cycles in each run

Run 3825:



- The betatron velocity and orbit kicks have an origin in the spiraling trajectory of non-coaxial particles inside a solenoid
- A temporal drift similar to that in the spin tune measurements
- High precision BPMs are crucial!

Poor mans simulation of the orbit distorions

calibration of the field integral, b, and nonlinearity, a, of the spin kick vs. the solenoid currents: $\chi_{1,2} \rightarrow (b_{1,2} + a_{1,2}\chi_{1,2})\chi_{1,2}$:

	Map 1		Map 2	
Chi2	1790,110		578,269	
NDf	53		14	
		+/-		+/-
ν_s	-0,16097200		-0,16097197	
E	0,99884911	2,45E-05	0,99910627	4,83E-05
c_3^*	-0,00268672	1,57E-07	-0,00269191	3,52E-07
c_3	-0,00224142	1,50E-07	-0,00224553	3,31E-07
b_1	0,99634211	1,60E-05	0,99644492	2,72E-05
b_2	0,99480173	3,32E-05	0,99490906	7,05E-05
a_1	0,11598673	2,14E-03	0,10965885	5,81E-03
a_2	0,00357409	2,33E-03	0,02813882	4,53E-03
location of the saddle point				
χ_1^{ext}	0,00046525	1,07E-07	0,00046364	2,60E-07
χ_2^{ext}	-0,00301352	5,17E-08	-0,00301637	9,28E-08

Challenges: Overview

Charged particle EDM searches require the development of a **new class of high-precision machines** with mainly electric fields for bending and focussing.

Issues are:

- **Electric field gradients** $\left(\sim 17\ \frac{\mathrm{MV}}{\mathrm{m}}\right)$ at $\sim 2\ \mathrm{cm}$ plate distance
- **Spin coherence time** $(\geq 1000\ \mathrm{s})$
- **Continuous polarimetry** $(< 1\ \mathrm{ppm})$
- **Beam position monitoring** $(10\ \mathrm{nm})$
- **Spin tracking**

These issues must be addressed *experimentally* at existing facilities

Conclusions on the EDM at COSY as is

- JEDI is making a rapid progress in unprecedently high precision spin dynamics at COSY and systematic studies --- developing new technique has at the moment a higher priority than setting stringent bounds on pEDM and dEDM at COSY as is
- Sensitivity to EDM ~

  (precision in the IMF tilt of the closed spin orbit) x MDM
- Extra systematics of the artificial imperfections as a probe of IMF

  = accuracy of the solenoid axis angular alignement
- Extra systematics from the RF WF

  = accuracy of the WF axis angular alignement
- Align those gadgets better than the statistical precision of the spin closed orbit!
- A power of analytic approaches is limited --- developing complementary high precision beam and spin tracking is an urgent issue

Conclusions for more distant future with more resources

- EDMs offer new window to disentangle sources of CP violation, and to explain matter-antimatter asymmetry of the universe.
- First direct EDM measurements of $\boldsymbol{p}$ and $\boldsymbol{d}$ at an upgraded COSY $(10^{-24}\ \mathrm{e \cdot cm})$
- Development of a dedicated EDM storage ring $(10^{-29}\ \mathrm{e \cdot cm})$
- Development of high precision spin tracking tools, incl. RF structures.
- Electrostatic deflector development based on FNAL equipment.

Very challenging …, but the physics is fantastic.

Timeline for JEDI at COSY

Item	2015	2016	2017	2018	2019
EDM R&D	RF ExB Polarimetry	RF ExB Data Base (WASA) Systematics	RF ExB Systematics	Deflect., Squid Review Polarimeter	CDR PoF-4 Evaluation
EDM Precursor	Concept for precursor measurement	Beam based alignment	Precursor experiment		
	COSY beam time approx. 5000 hours per year				
Installation at COSY	Strip line RF ExB	90° Rotation of conv. RF ExB	FNAL deflector Prototype SQUID-BPM	Prototype Polarimeter	
COSY Upgrade	Shunts Rogowski Coils	Readout electronics Backleg winding	Upgrade finalized		

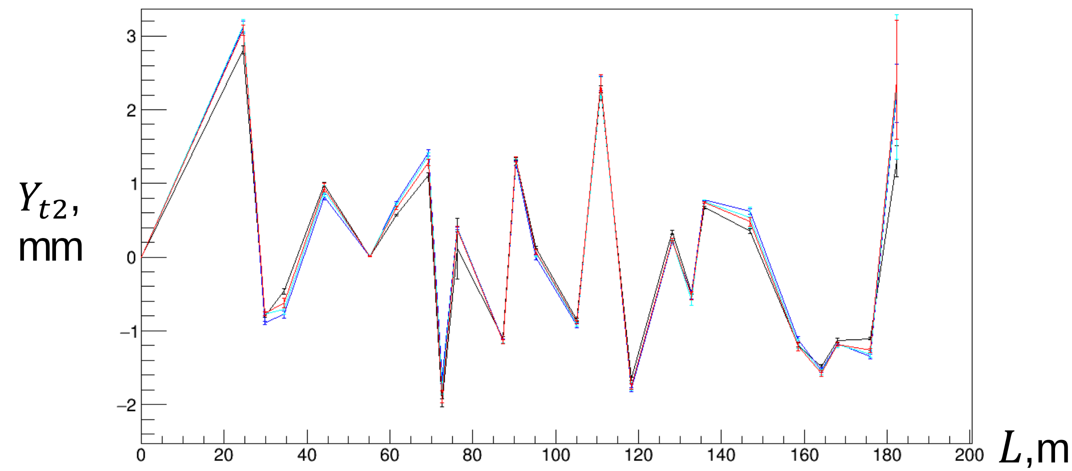
Orbit perturbation by solenoids

Perturbation of the orbit for each BPM calculated as

$$\Delta_Y = Y_{t2} - \frac{Y_{t1} + Y_{t3}}{2}$$

Perturbation of the Y orbit by 100 KeV e-cooler compensation solenoids

At $\chi_1 = 0$
(2MeV-ecooler comp. solenoid is switched OFF)



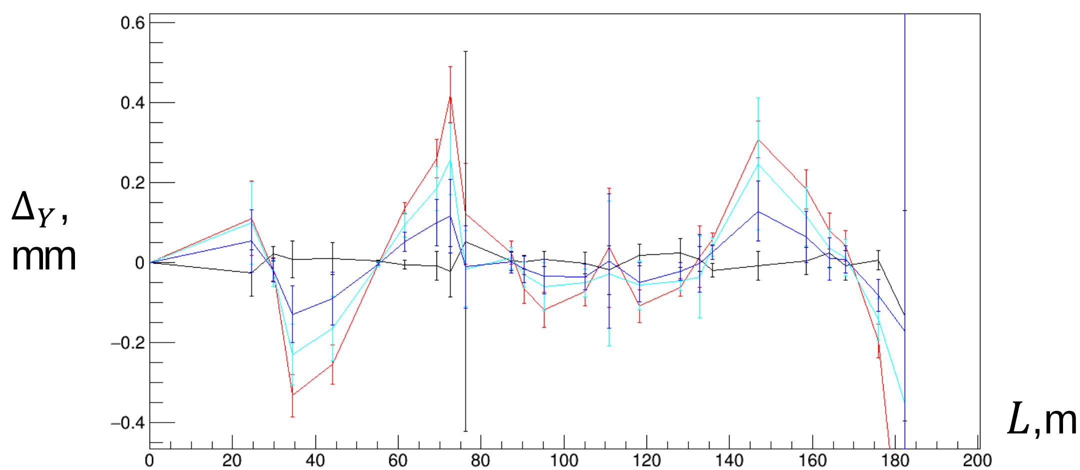
Color code:

$\color{red}{\chi_2 = -13}$ mrad

$\color{cyan}{\chi_2 = -9}$ mrad

$\color{blue}{\chi_2 = -5}$ mrad

$\chi_2 = 0$ mrad



Challenges: Overview

Additional items to be adressed:

- The measured difference of the CW-CCW beam orbits depends also on the space-charge distribution in the beam.
  → ideal would be a **phase-space detector** for (x, x') and (y, y'), but how to do that?
- Magnetic machines can be trimmed and shimmed after construction. The design of an electric machine has to be „correct“ from the start, fields are generated by the plate geometry.
- Therefore, high **precision spin tracking calculations** have to be carried out in order to validate a design. This involves keeping track of some 10^{10} particles for the duration of about $1000\ s$, i.e., for some 10^9 turns.

Timeline: Stepwise approach towards all-in-one machine

Step	Aim / Scientific goal	Device / Tool	Storage ring
1	Spin coherence time studies	Horizontal RF-B spin flipper	COSY
	Systematic error studies	Vertical RF-B spin flipper	COSY
2	COSY upgrade	Orbit control, magnets, …	COSY
	First direct EDM measurement at $\mathbf{10^{-24} e\cdot cm}$	RF-E(B) spin flipper	Modified COSY
3	Built dedicated all-in-one ring for p, d, $^3\mathrm{He}$	Common magnetic-electrostatic deflectors	Dedicated ring
4	EDM measurement of p, d, $^3\mathrm{He}$ at $\mathbf{10^{-29} e\cdot cm}$		Dedicated ring

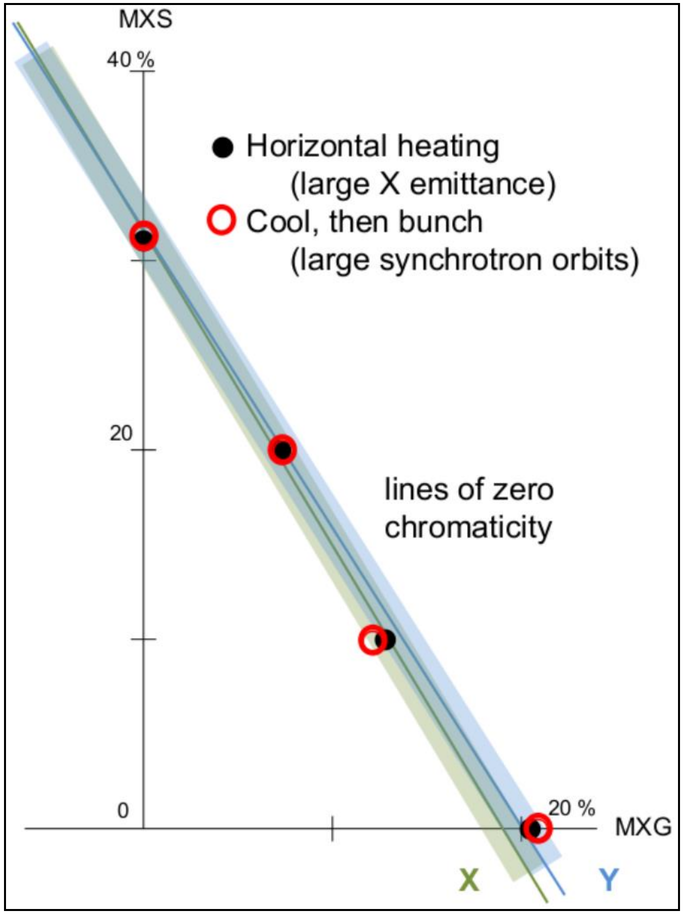
Time scale: **Steps 1 and 2: $<$ 5 years (i.e., in POF 3)**
Steps 3 and 4: $>$ 5 years

SCT: Chromaticity studies

Chromaticity ξ defines the tune change with respect to momentum deviation

$$\frac{\Delta Q_{x,y}}{Q_{x,y}} = \xi_{x,y} \cdot \frac{\Delta p}{p}$$

- Strong connection between $\xi_{x,y}$ and τ_{SC} observed.
- COSY Infinity based model predicts negative natural chromaticities ξ_x and ξ_y.
- Measured natural chromaticity: $\xi_y > 0$ and $\xi_x < 0$.



Maximal horizontal polarization lifetimes from scans with a horizontally wide or a long beam agree well with the lines of $\xi_{x,y} \approx 0$.

Crucial for achieving a large τ_{SC} is careful adjustment of $\xi_{x,y}$.

Publications

Experiment:

1. A. Lehrach, B. Lorentz, W. Morse, N.N. Nikolaev, F. Rathmann, ***Precursor Experiments to Search for Permanent Electric Dipole Moments (EDMs) of Protons and Deuterons at COSY***, e-Print: arXiv:1201.5773 (2012).
2. N.P.M. Brantjes et al., ***Correcting systematic errors in high-sensitivity deuteron polarization measurements,*** Nucl. Instrum. Meth. A664, 49 (2012), DOI: 10.1016/j.nima.2011.09.055
3. P. Benati et al., ***Synchrotron oscillation effects on an rf-solenoid spin resonance***, Phys. Rev. ST Accel. Beams 15 (2012) 124202, DOI: 10.1103/PhysRevSTAB.15.124202.
4. Frank Rathmann, Artem Saleev, N.N. Nikolaev [JEDI and srEDM Collaborations], ***The search for electric dipole moments of light ions in storage rings*** **J. Phys. Conf. Ser. 447 (2013) 012011,** DOI: 10.1088/1742-6596/447/1/012011.
5. Z. Bagdasarian et al., ***Measuring the Polarization of a Rapidly Precessing Deuteron Beam***, Phys. Rev. ST Accel. Beams 17 (2014) 052803, DOI: 10.1103/PhysRevSTAB.17.052803.
6. F. Rathmann et al. [JEDI and srEDM Collaborations], ***Search for electric dipole moments of light ions in storage rings,*** Phys. Part. Nucl. 45 (2014) 229, DOI: 10.1134/S1063779614010869.

Theory:

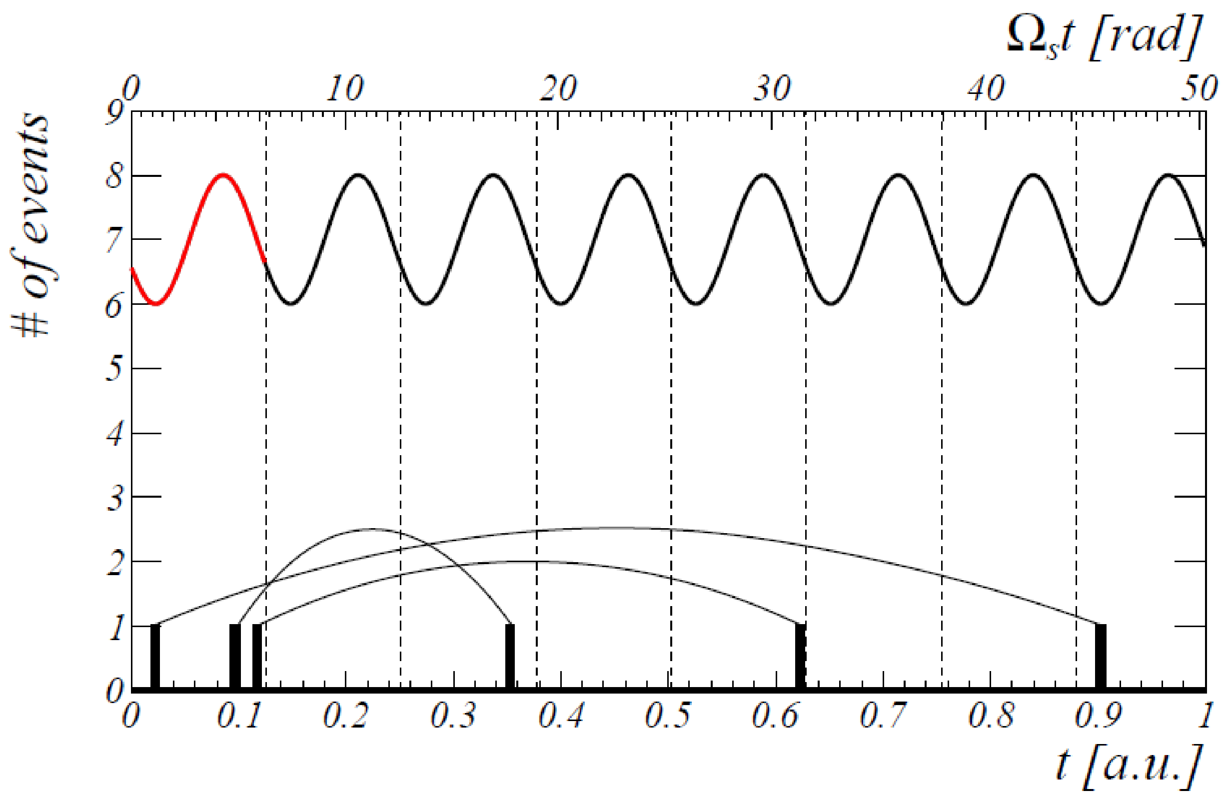
J. Bsaisou, J. de Vries, C. Hanhart, S. Liebig, Ulf-G. Meißner, D. Minossi, A. Nogga, A. Wirzba, ***Nuclear Electric Dipole Moments in Chiral Effective Field Theory,*** e-Print: arXiv:1411.5804 (2014).

Spin tune: How to find ν_s?

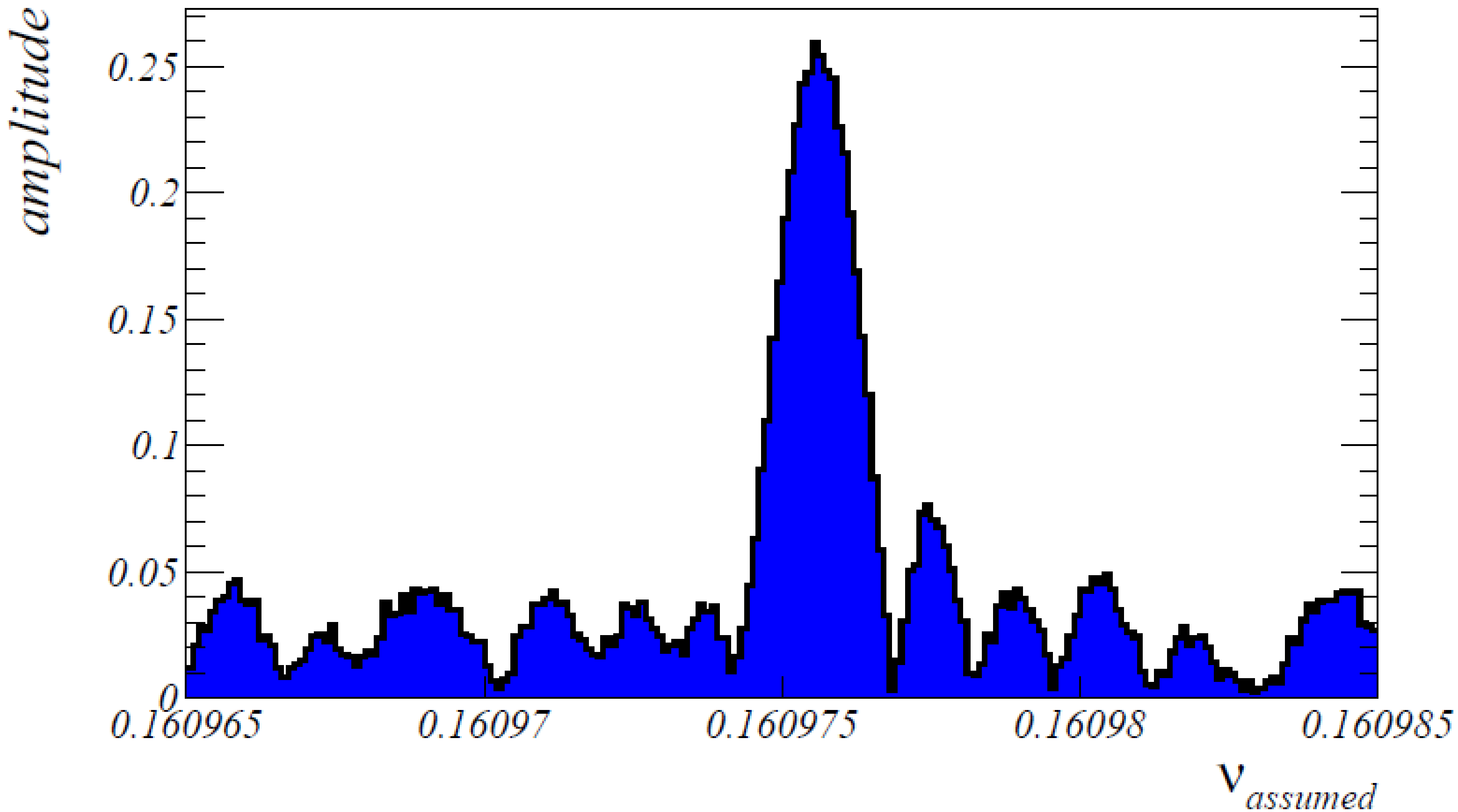
Spin tune ν_s : Number of spin precessions per turn

Detector rate is $\approx 5\ \mathrm{kHz}$, while $f_{\mathrm{rev}} = 781\ \mathrm{kHz} \rightarrow$ one hit in detector per 25 beam revolutions.

Solution: Map all events into first spin oscillation period.



Spin tune: Scan of ν_s



Pick ν_s with maximum amplitude of asymmetry.