6th Georgian – German School and Workshop in Basic Science

Spin-tracking studies for EDM search in storage rings

Andrea Pesce
University and INFN of Ferrara

Tbilisi State University, July 7th 2014

Matter-antimatter asymmetry

Big Bang Theory: initial symmetric configuration of the universe

BARYOGENESIS

Sakharov's conditions (1967):

- $B = n_b - n_{\bar{b}}$ violation
- Departure from thermal equilibrium
- C and CP violation

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Baryon-to-photon ratio n_b/n_γ

Observed (PLANCK) $6.08(14)\times10^{-10}$

SM expected value $\sim 10^{-18}$

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Standard Model (SM):

- Contains the 3 elements
- Does not account for baryon asymmetry
- CP-violation source is too small

CP violation

STANDARD MODEL

- Electro-Weak interaction

Source: CKM matrix (quark-flavor mixing):
Complex phase δ
3 quark flavor mixing angles → Does not explain baryon asymmetry

Observed in K^0 (1964) and B^0 (2001) systems

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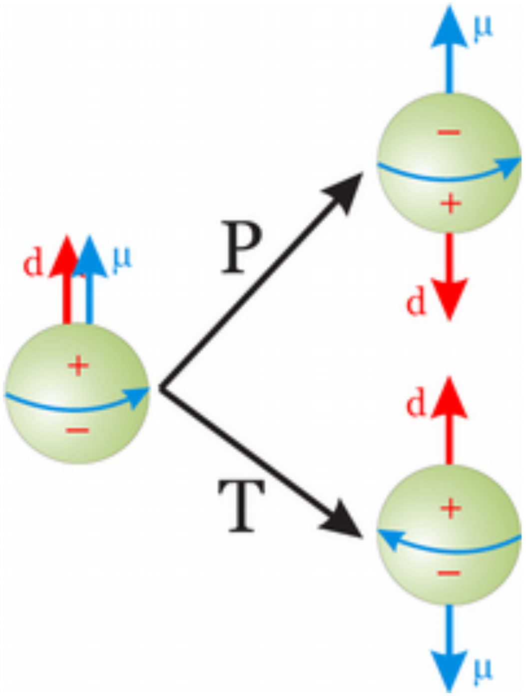
→ EDM search

The Electric Dipole Moment



- Permanent separation of positive and negative electrical charges within the particle volume
- It lies along the spin vector
- It violates both parity P and time reversal T symmetries

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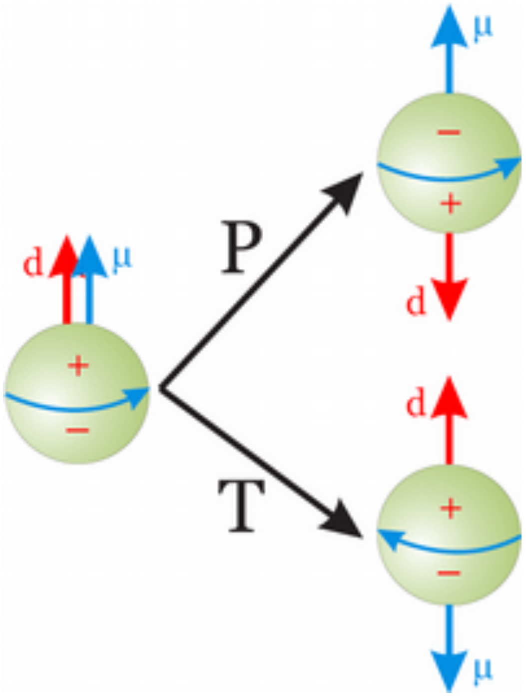

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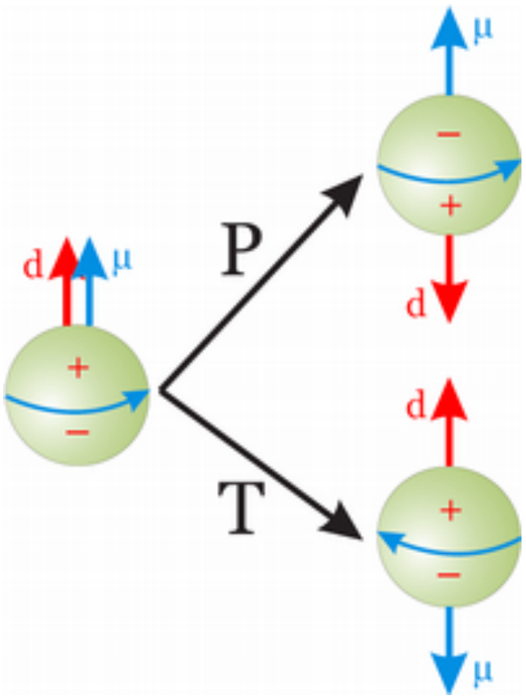

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Theoretical predictions

SM

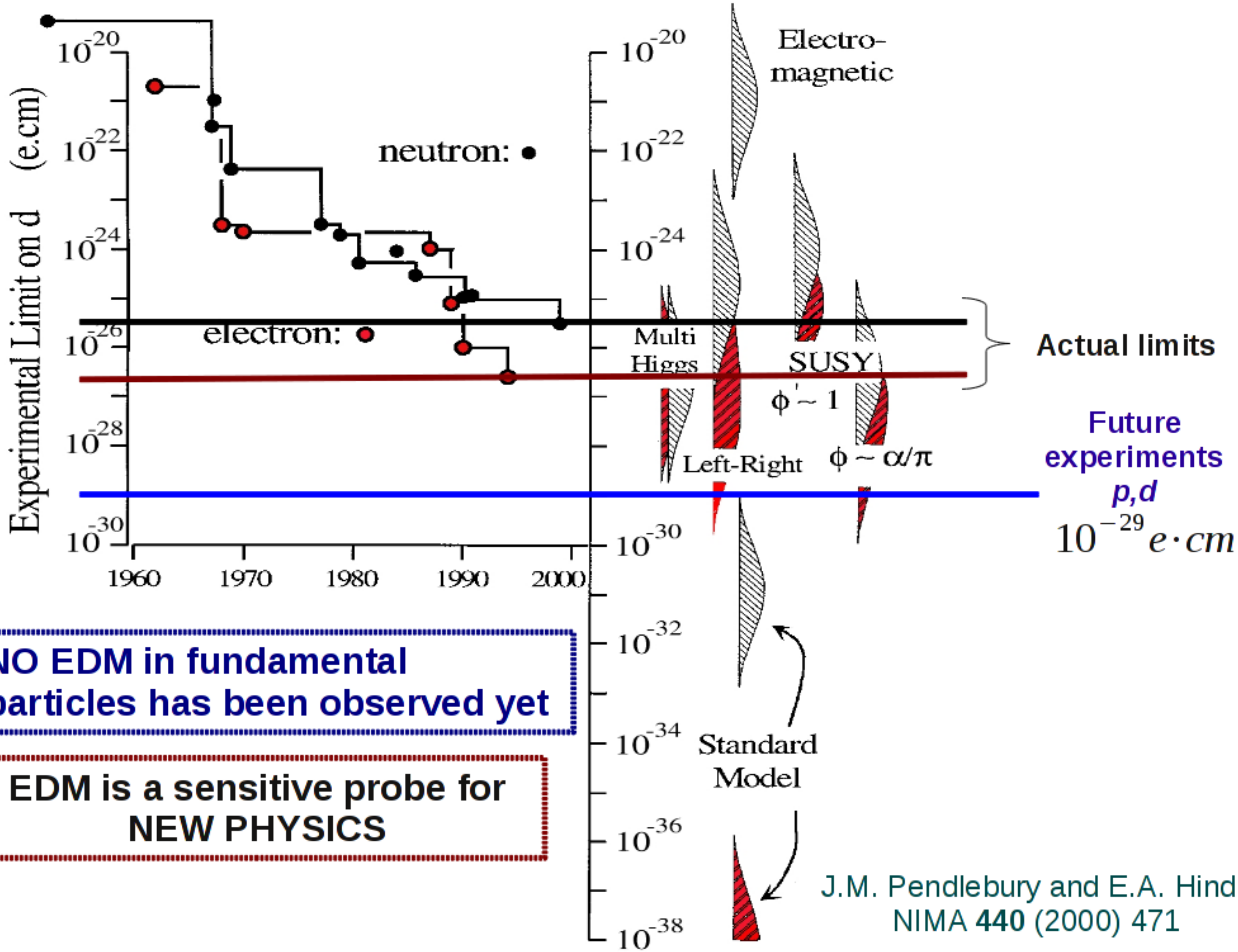
$$|d_e^{SM}| < 10^{-38} e \cdot cm$$

$$|d_N^{SM}| < 10^{-32} e \cdot cm$$

(UNOBSERVABLE)

Models beyond SM

predict EDM values that are close to the sensitivity of current and future experiments



NO EDM in fundamental particles has been observed yet

EDM is a sensitive probe for NEW PHYSICS

J.M. Pendlebury and E.A. Hinds
NIMA **440** (2000) 471

Searching EDM: Neutral systems

Basic idea: apply E-field and look for the energy shift $-\vec{d}\cdot\vec{E}$

- Precession frequency in B and E field (spin ½):

$$\hbar\omega_{\pm} = -2\vec{\mu}\cdot\vec{B} \mp 2\vec{d}\cdot\vec{E}$$

- 2 cases: E parallel and antiparallel to B
- Subtracting the 2 frequencies cancels out the magnetic term: $d = \frac{\hbar\Delta\omega}{4E}$

First experiment: Purcell and Ramsey (1951) searched for neutron EDM

Particle/Atom	Current EDM limit (e·cm)	Future Goal (e·cm)
Neutron	$<2.9\times10^{-26}$	$\sim10^{-28}$
^{199}Hg	$<3.1\times10^{-29}$	$\sim10^{-29}$
^{205}Tl	$<9\times10^{-25}$	$\sim10^{-28}$ - 10^{-31}
Proton	$<7.9\times10^{-25}$	$\sim10^{-29}$
Deuteron		$\sim10^{-29}$

How to measure EDM for charged particles

- Impossible to trap charged particles
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Injection in a *Storage Ring*

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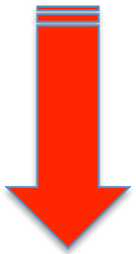

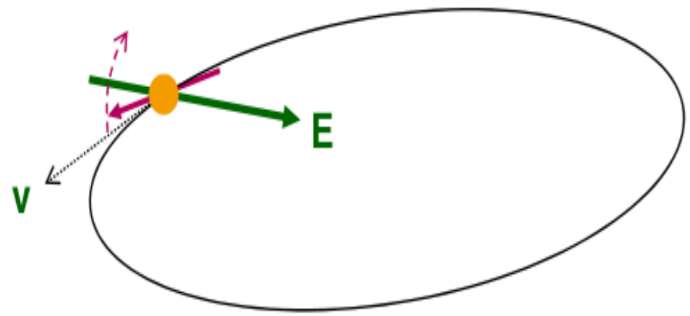

Injection in a ***Storage Ring***

with spin aligned to the velocity (Longitudinal Polarization)

- External E-field produces a torque on the EDM: $\vec{\tau} = \vec{d} \times \vec{E} = \frac{d\vec{S}}{dt}$

- Freeze the horizontal spin precession and watch for the development of a vertical component

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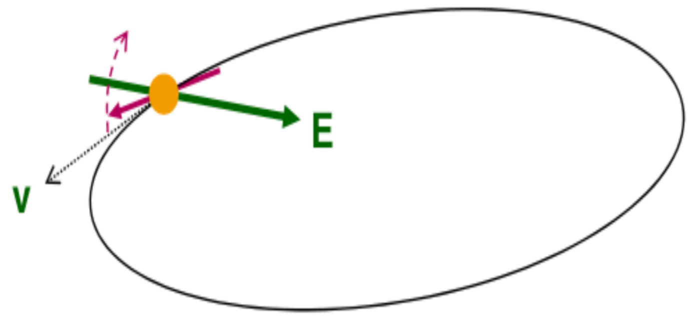

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Spin precession in the vertical plane = **EDM SIGNAL**

The frozen spin method

BMT Equation

$$\vec{\omega}_G = \vec{\omega}_s - \vec{\omega}_c = -\frac{q}{m}\left\{ G\vec{B} + \left[G - \left(\frac{m}{p}\right)^2 \right] \frac{\vec{\beta}\times\vec{E}}{c} \right\}$$

$\vec{\omega}_s$ spin precession frequency in the horizontal plane

$\vec{\omega}_c$ particle revolution frequency

$G = \left(\frac{g-2}{2}\right)$ anomalous magnetic moment

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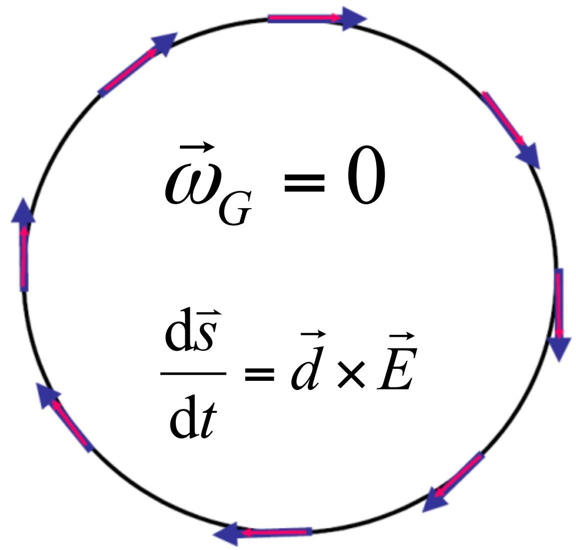
Spin along the momentum vector



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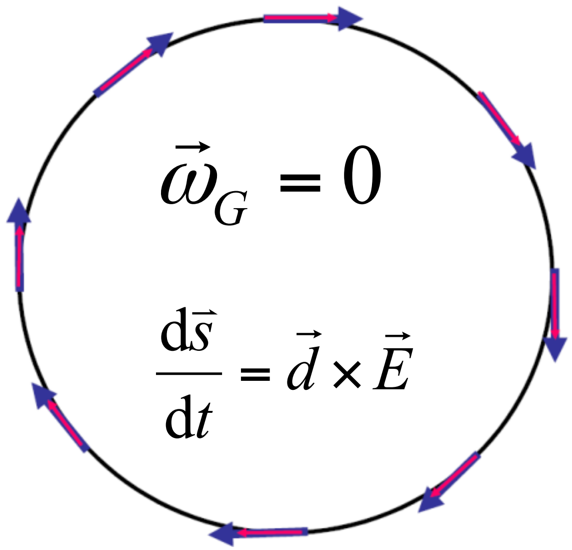
Spin along the momentum vector

- Protons $G = 1.79 > 0 \rightarrow$ magic momentum:

$$G - \left(\frac{m}{p}\right)^2 = 0 \rightarrow p = \frac{m}{\sqrt{G}} = 0.7\frac{GeV}{c}$$

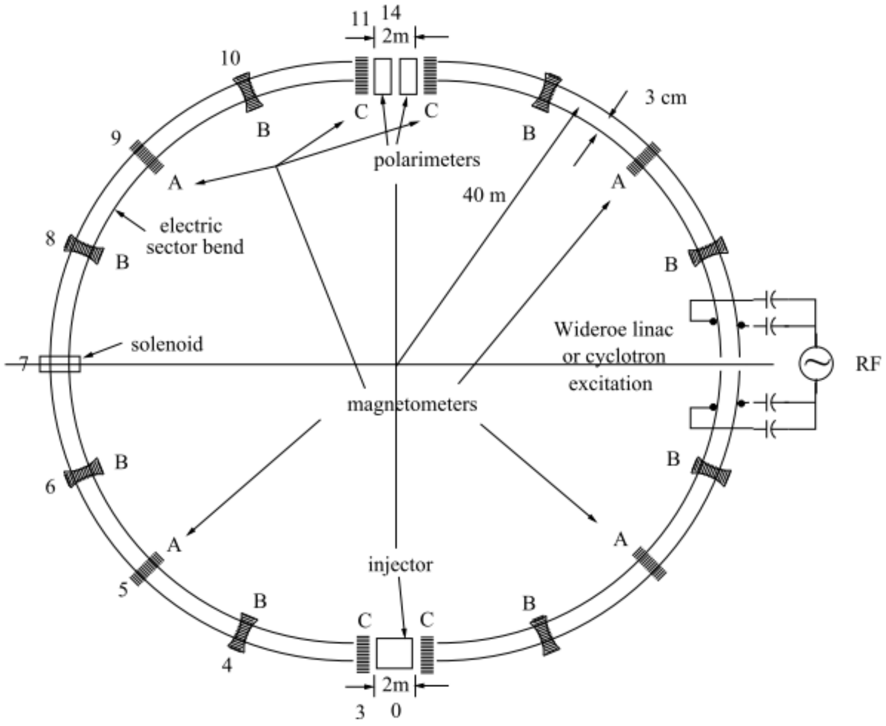
$\vec{B} = 0 \rightarrow$ pure electric ring!



- Deuterons $G = -0.14 < 0 \rightarrow$ no magic momentum: magnetic field with a radial outward electric field

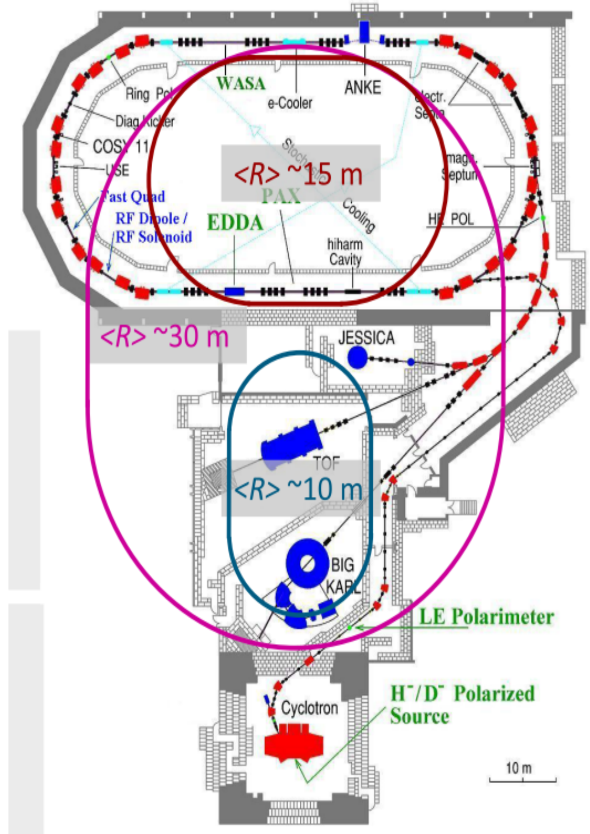
Storage ring projects

BNL all electric ring for protons



R. Talman

EDM with E and B-fields at COSY



A. Lehrach

EDM search and Spin Coherence Time

- The minimal detectable precession angle is $\theta_{EDM} \approx 10^{-6} rad$
- If we assume: $\begin{cases} d \approx 10^{-29} e \cdot cm \\ E = 10 \dfrac{MV}{m} \\ T \approx 10^{-6} s \end{cases}$ ⟹ $\theta_{EDM}(t) \approx 10^{-15} \dfrac{rad}{turn}$

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10^9 turns

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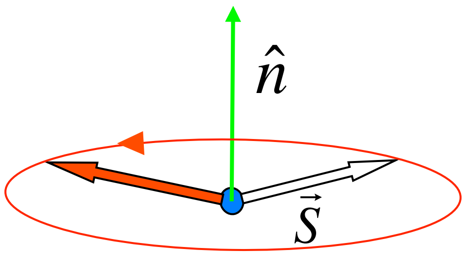

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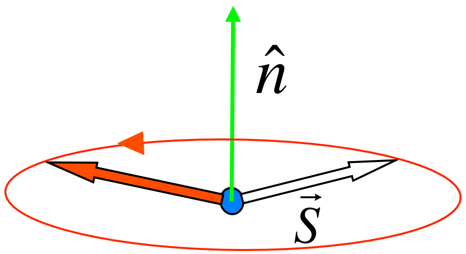

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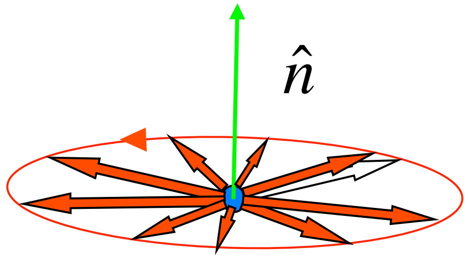

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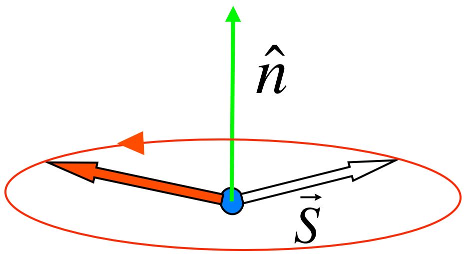

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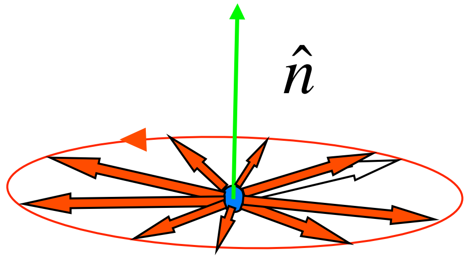

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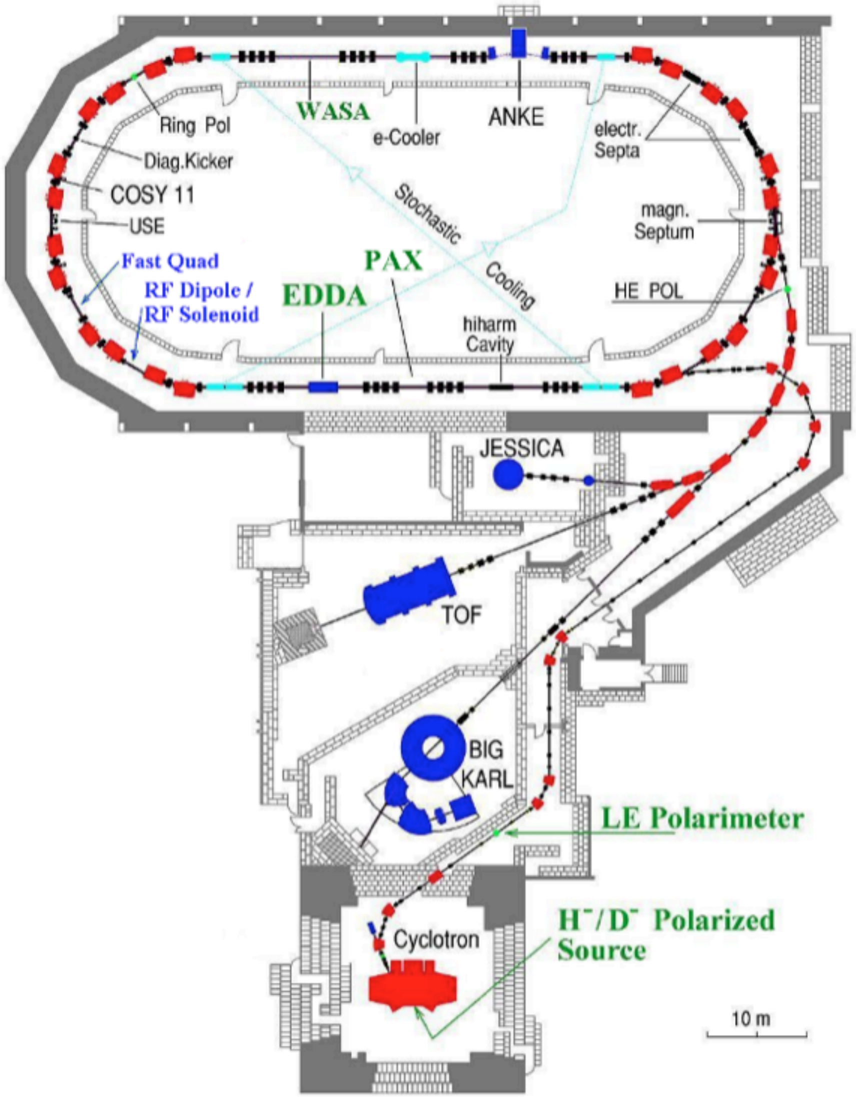
Loss of longitudinal polarization. We have a limited observation time called SCT.

SCT tests at the COoler SYnchrotron (FZJ)



- Momentum p < 3.7 GeV/c
- Circumference: 183 m
- Polarized protons and deuterons
- Manipulation of beam size and polarization

Dedicated SCT studies at the COSY facility

Supported with a spin tracking code: COSY-INFINITY

GOAL:

Benchmark the COSY-INFINITY code against the EDM feasibility tests performed at the COSY storage ring

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WORK PLAN:

Simulation of beam and spin dynamics in the COSY storage ring:

- Spin tune calculation
- Contribution of synchrotron and betatron oscillations to the spin tune spread
- Estimation of the SCT
- RF cavity compensation
- Correction with sextupoles

The COSY-INFINITY code

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- Only after successful benchmarking, the code can be used for designing an innovative dedicated ring for EDM measurements

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SINGLE PARTICLE

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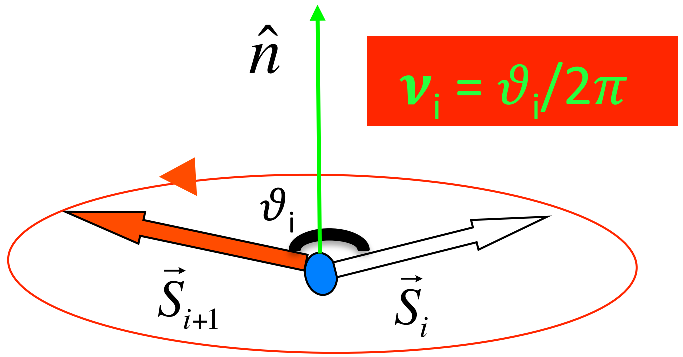
$$\vec{n}_i = \vec{S}_i \times \vec{S}_{i+1}$$

$$\left|\vec{n}_i\right| = \left|\vec{S}_i\right|\left|\vec{S}_{i+1}\right|\sin(\vartheta_i)$$

$$0 \le i \le 2\times 10^5$$

$$\vartheta_i = \arcsin\left(\frac{\left|\vec{n}_i\right|}{\left|\vec{S}_i\right|\left|\vec{S}_{i+1}\right|}\right)$$



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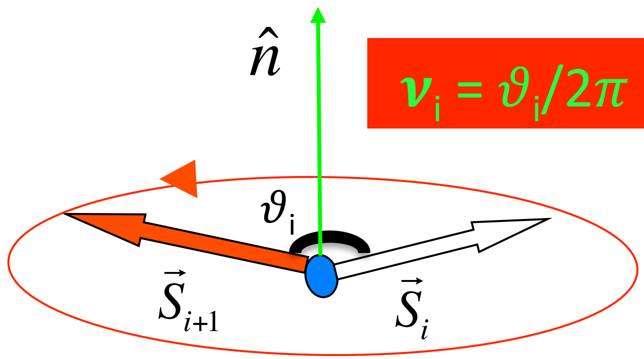


$\boldsymbol{\nu}_i = \vartheta_i/2\pi$

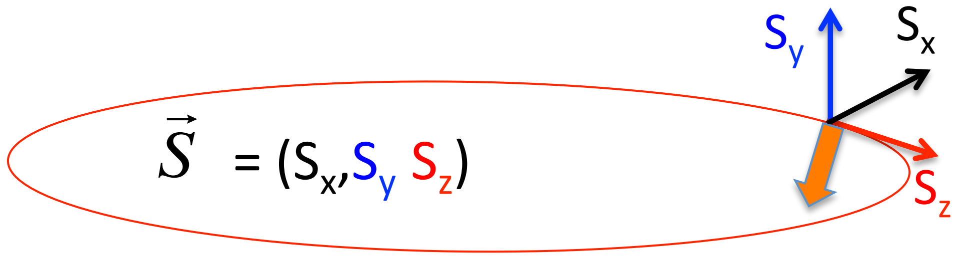
BEAM OF PARTICLES

- Particles with different displacements (Δx, Δy, Δp/p) have different spin tunes ⇒ spin tune spread $\Delta\boldsymbol{\nu}$
- It is related to the spin coherence time:

$$\boldsymbol{\tau}_{SC} \propto 1/|\Delta\boldsymbol{\nu}|$$

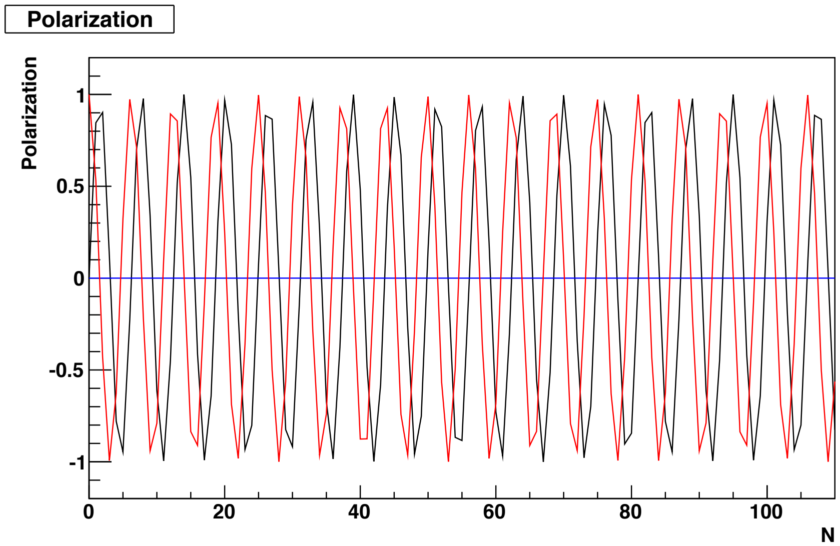
Spin tracking: Reference Particle

- Deuterons with p = 970 MeV/c
- Cyclotron frequency f_{cyc}
- Motion on the reference orbit: it goes through the center of all magnets



$$\Delta x = \Delta y = 0 \quad ; \quad \Delta p/p = 0$$

SPIN TUNE:
$\boldsymbol{\nu}_{RP} = G\Upsilon = 0.1604981$ → 1 spin rotation every ~6.23 turns



Decoherence effects - 1

Longitudinal motion

Momentum dispersion in the beam → Particles with $\Delta p/p = (p' - p)/p \neq 0$

Different velocities ⇒ Different $G\gamma$

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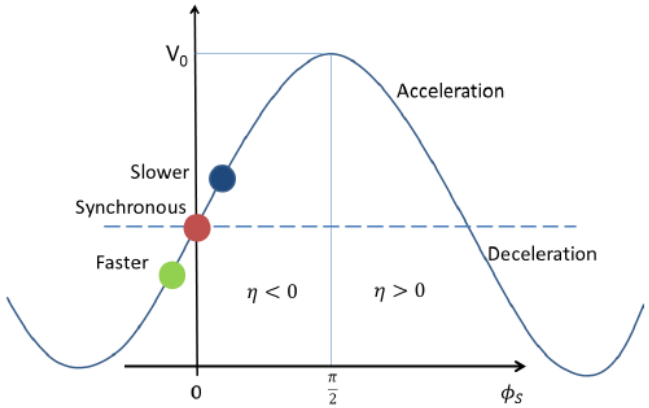

SYNCHROTRON OSCILLATIONS

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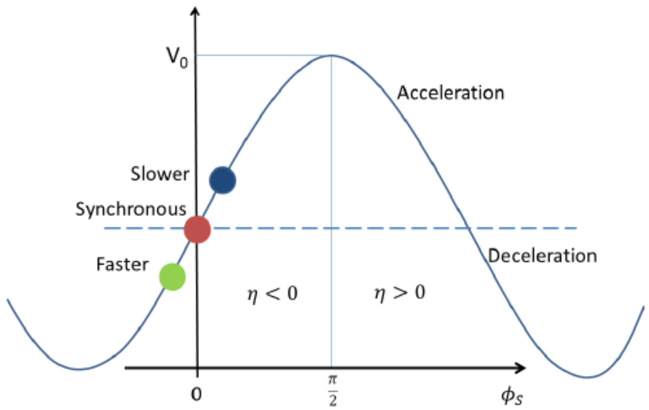
Residual quadratic dependence:

$\Delta\nu \propto (\Delta p/p)^2$



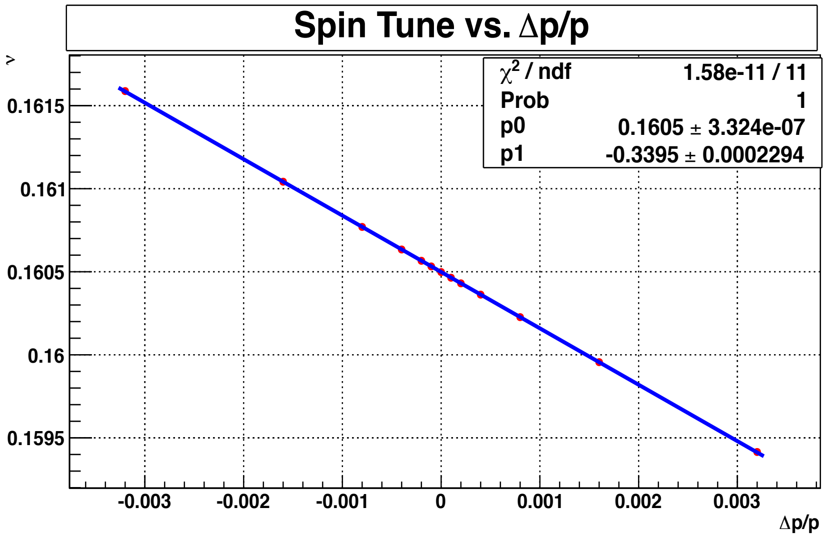
SYNCHROTRON OSCILLATIONS

Simulations

Longitudinal motion

$\Delta\nu = \langle\nu\rangle - \langle\nu_{RP}\rangle$

RF OFF: $\Delta\nu \propto \Delta p/p$



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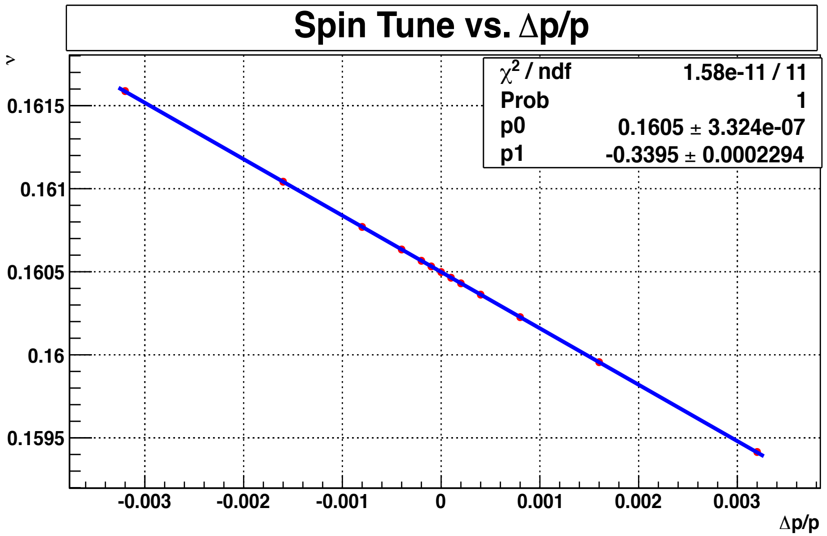

10^{-4} s $\lesssim \tau_{SC} \lesssim 10^{-2}$ s

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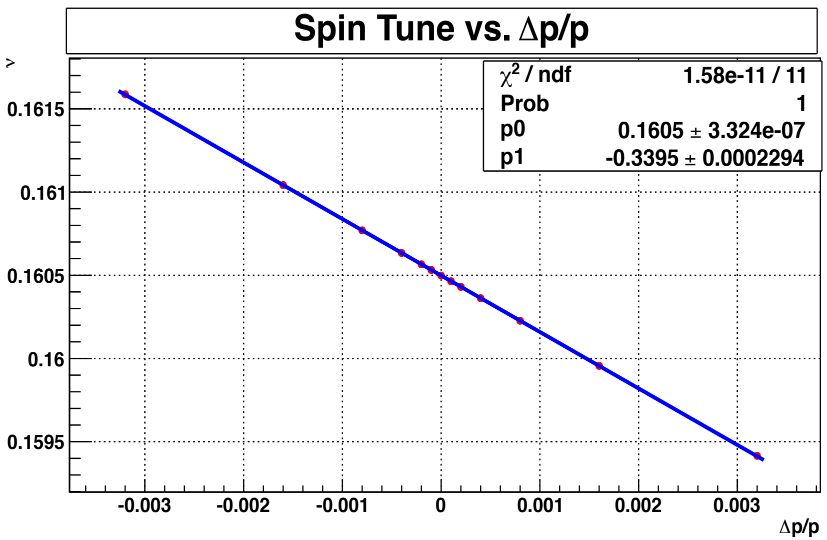

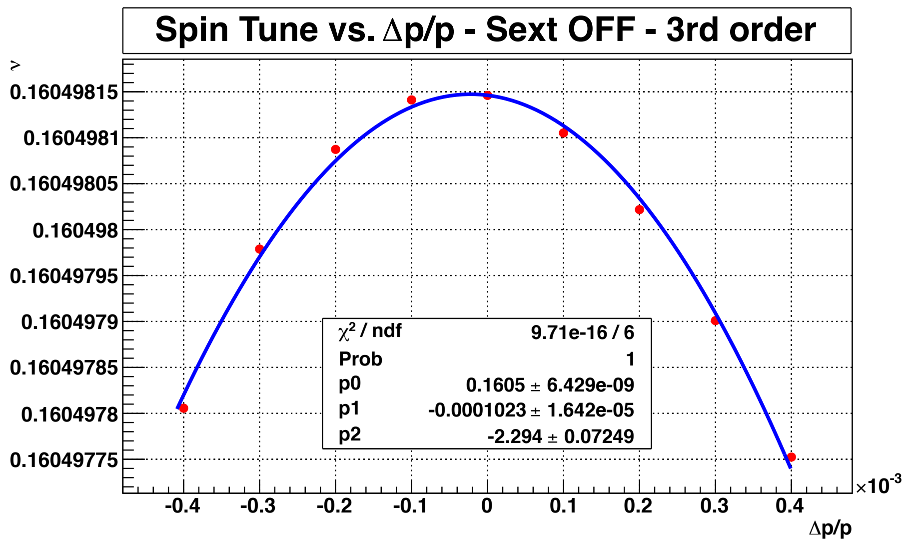

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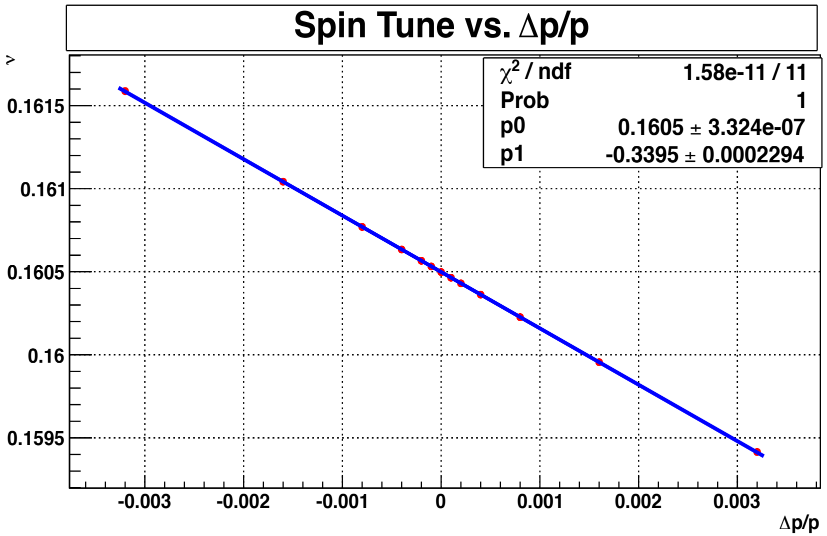
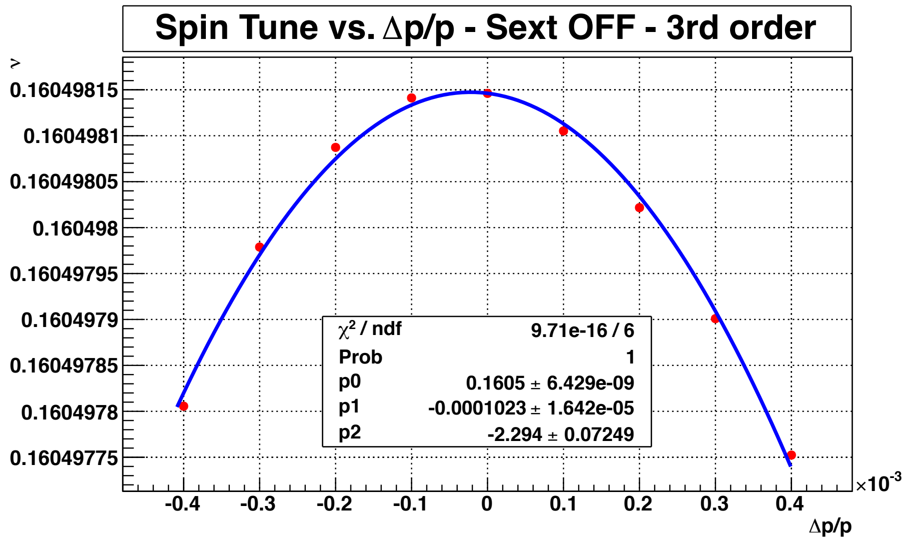




10^{-4} s $\lesssim \tau_{SC} \lesssim 10^{-2}$ s

10^{-1} s $\lesssim \tau_{SC} \lesssim 10$ s

Decoherence effects - 2

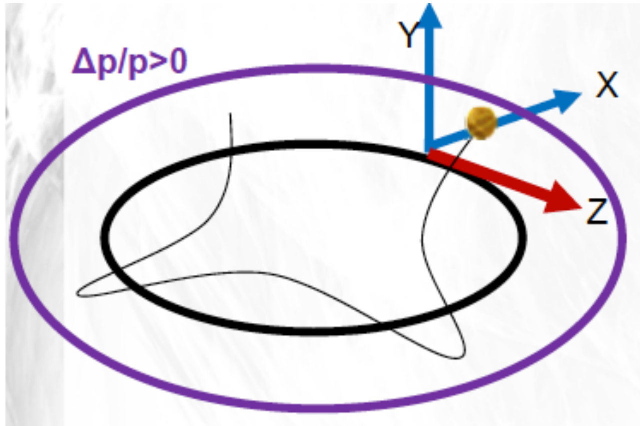
Transverse motion

- Displacement from reference orbit: Δx, Δy

BETATRON OSCILLATIONS

- Particles with Δp/p ≠ 0

$eB\rho = p$ ⟶ Modified orbit



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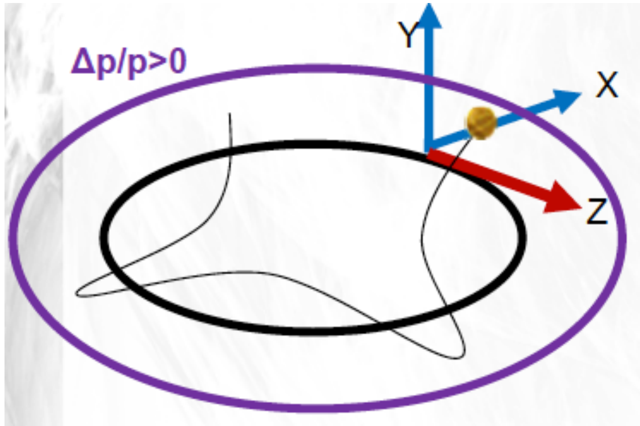

Path lengthening: $$\frac{\Delta L}{L} \approx \frac{(\Delta x')^2 + (\Delta y')^2}{4}$$

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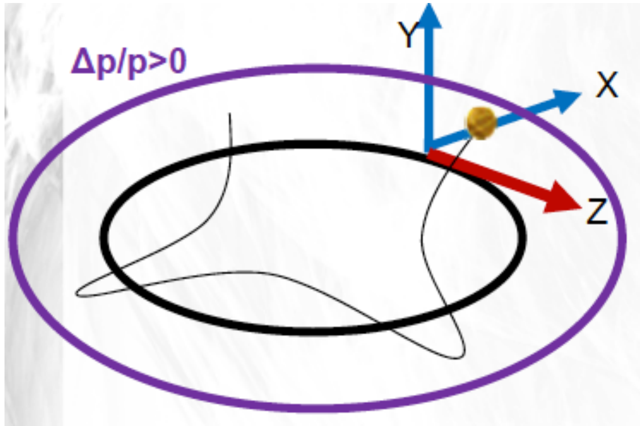

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Same frequency
Different paths → Different velocities → Different Gγ

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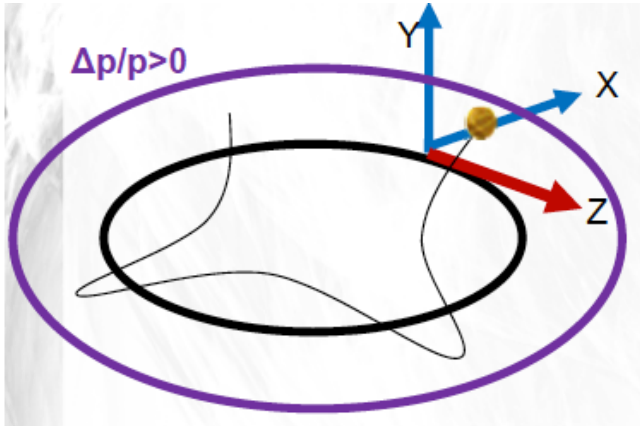

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  Same frequency
  Different paths ➡ Different velocities ➡ Different Gγ

Quadratic effect ⟶ $\Delta\nu \propto A(\Delta x)^2 + B(\Delta y)^2$

Simulations

Transverse motion

$\Delta\nu = \langle\nu\rangle - \langle\nu_{RP}\rangle$

$\Delta\nu \propto (\Delta x)^2$

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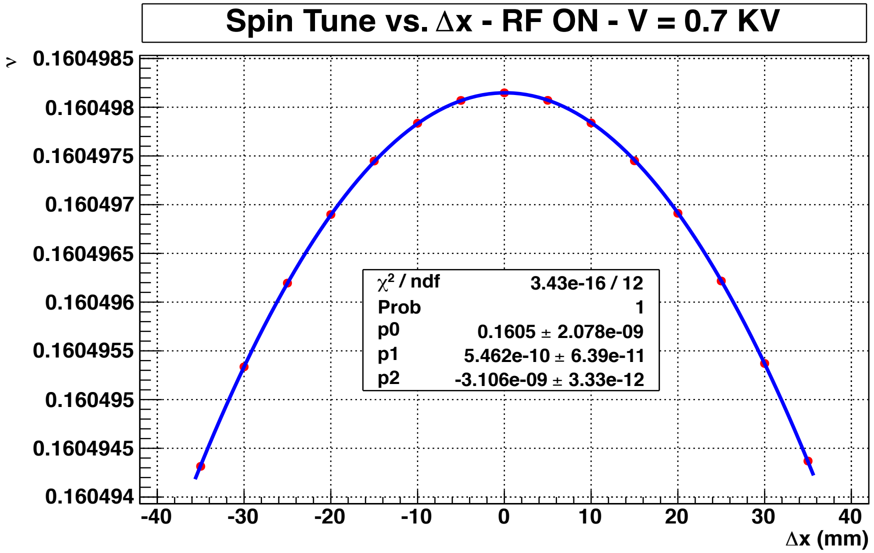

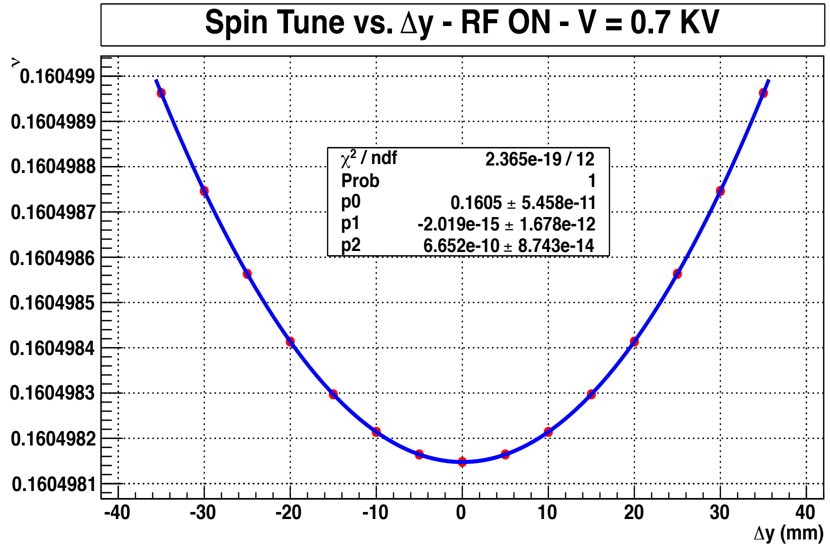

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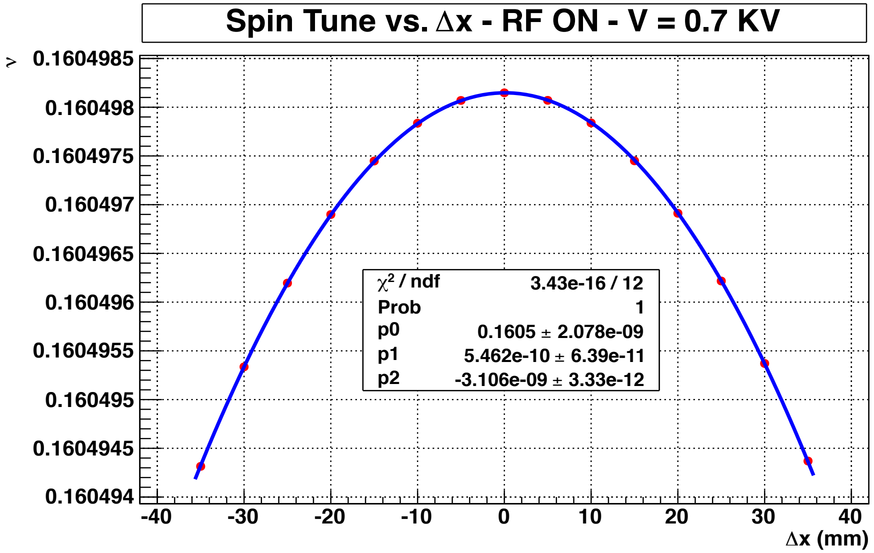
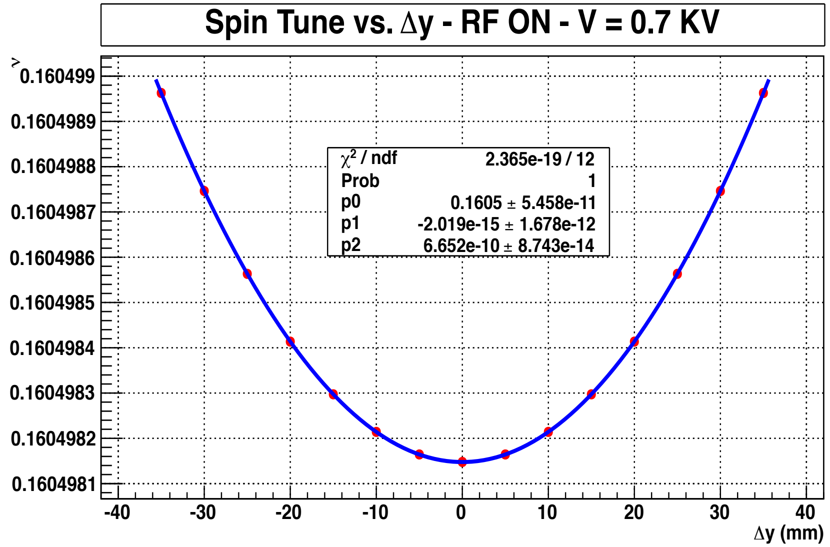
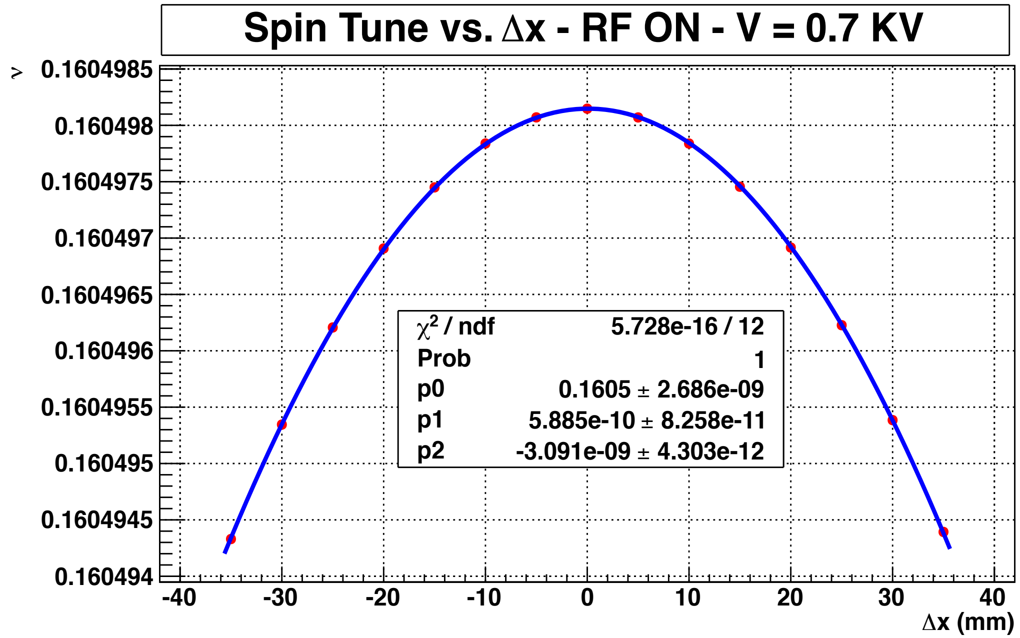




$10^{-1}\ s \lesssim \tau_{SC} \lesssim 10\ s$

Comparison with data

Simulations



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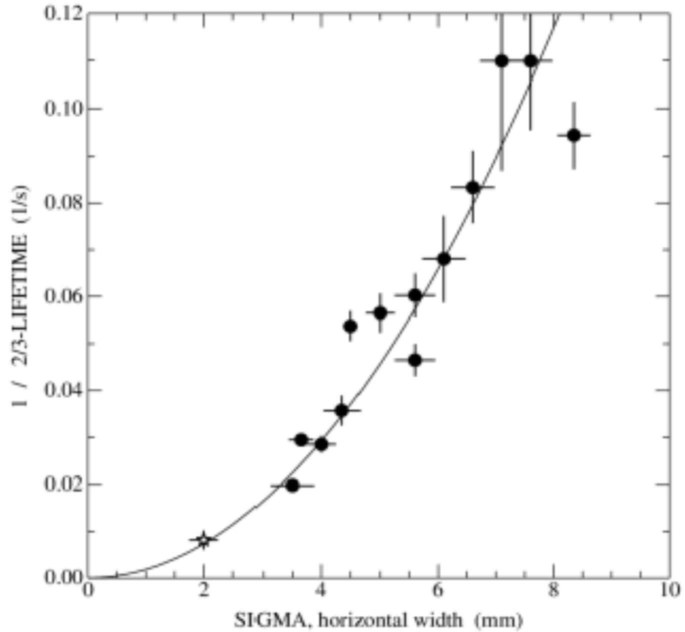

$\Delta x_{exp} = 5$ mm

$\boldsymbol{\tau}_{exp} = 11.4$ s

(Ed Stephenson's note on SCT)

Scaling using the beta functions:

$$\varepsilon\beta_x = (\Delta x)^2 \Rightarrow \Delta x_{COSY} = \sqrt{\frac{\beta_{x(\exp)}}{\beta_{x(COSY)}}}\Delta x_{\exp} = 2.73mm$$

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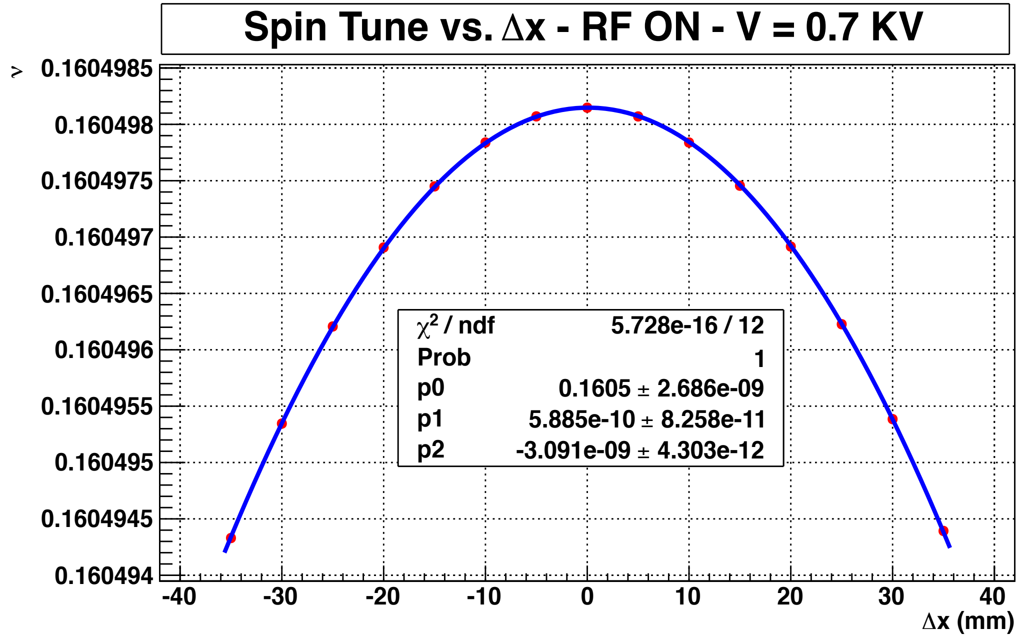

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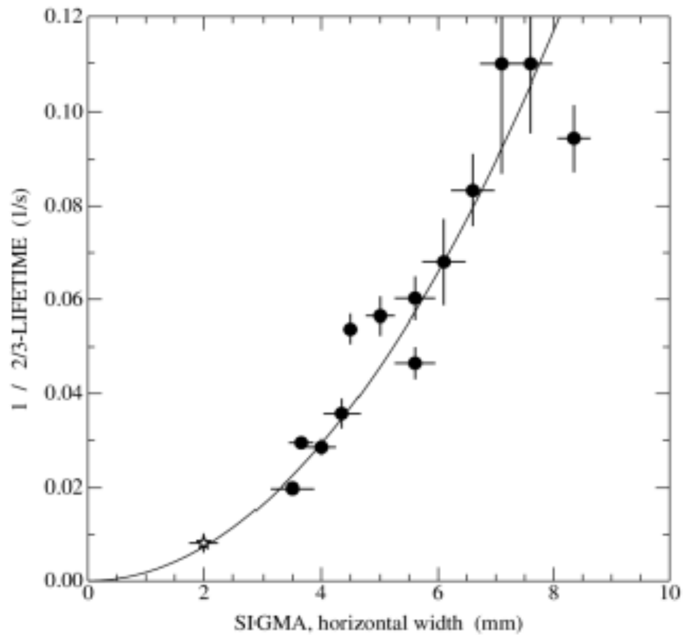

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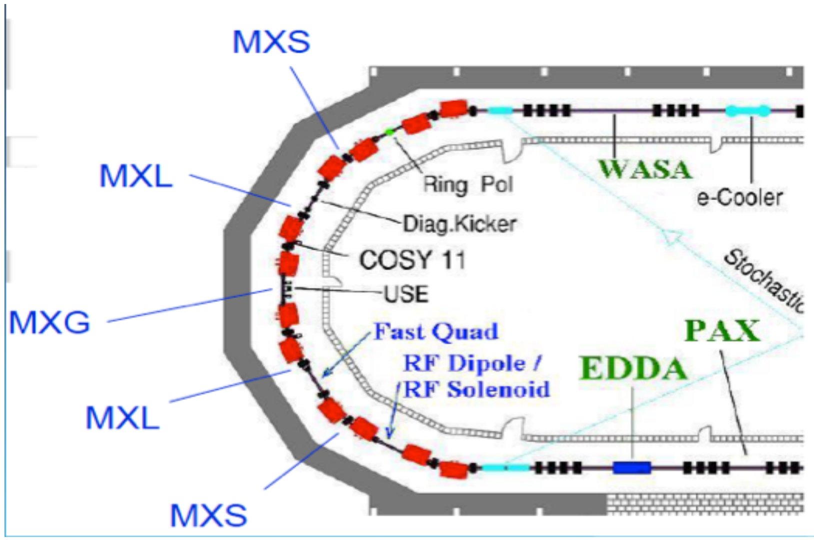
τ_{COSY} = 11.6 s

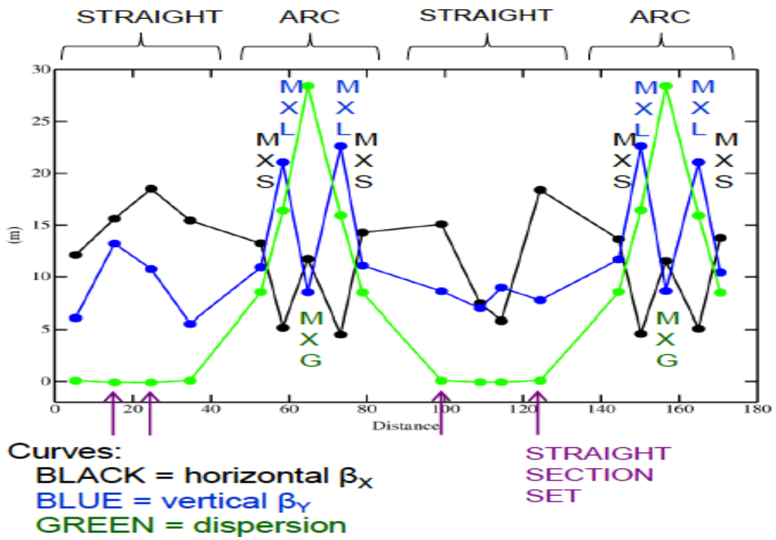
Simulated SCT comparable to the measured one

Compensation of the Betatron Motion

- Use of the sextupoles families in the arcs to cancel the spin tune spread due to the betatron motion

Why sextupoles? → $B \propto r^2$





Simulation of the sextupoles effect

$$\frac{1}{\tau_{SC}} = A\left\langle (\Delta x)^2 \right\rangle + a k_2^{MXS} \left\langle (\Delta x)^2 \right\rangle$$

Sextupole field

Beam emittance term

Simulation of the sextupoles effect

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Need for: $ak_2^{MXS} = -A$

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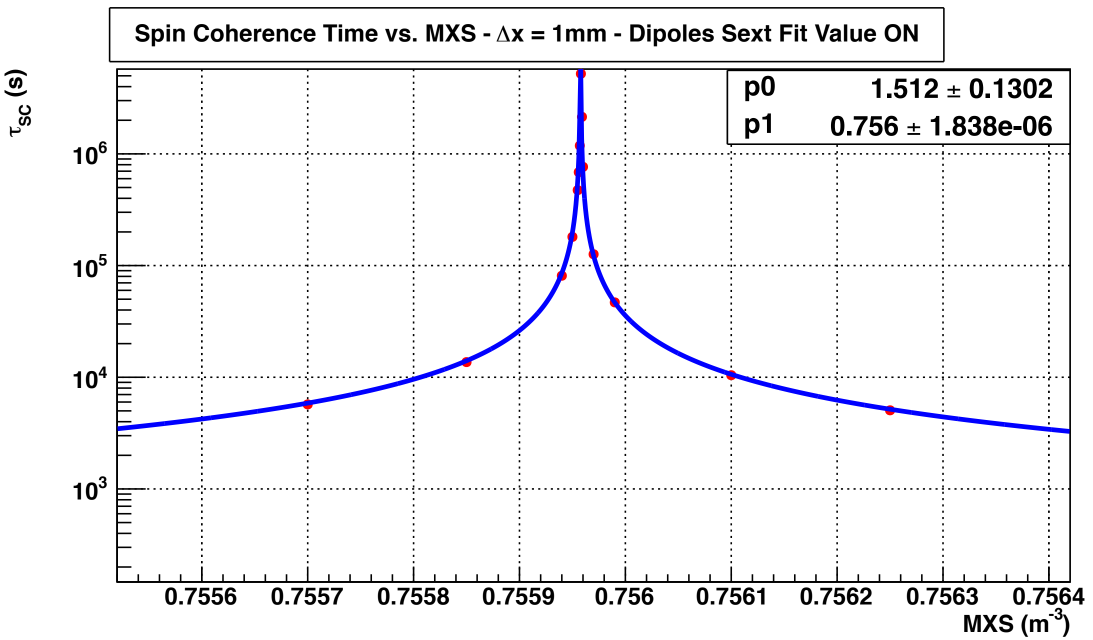

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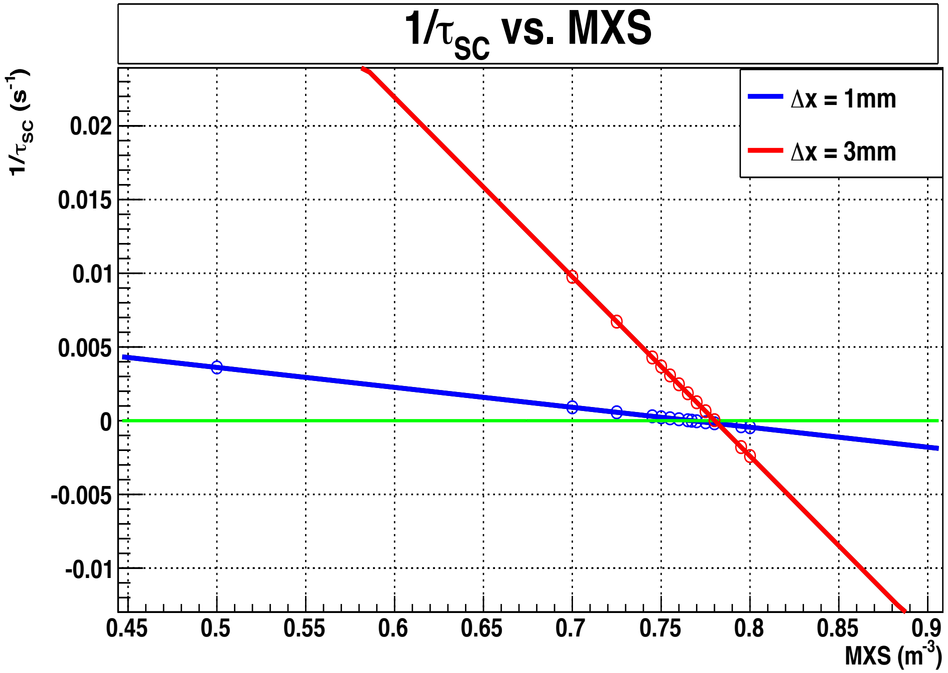

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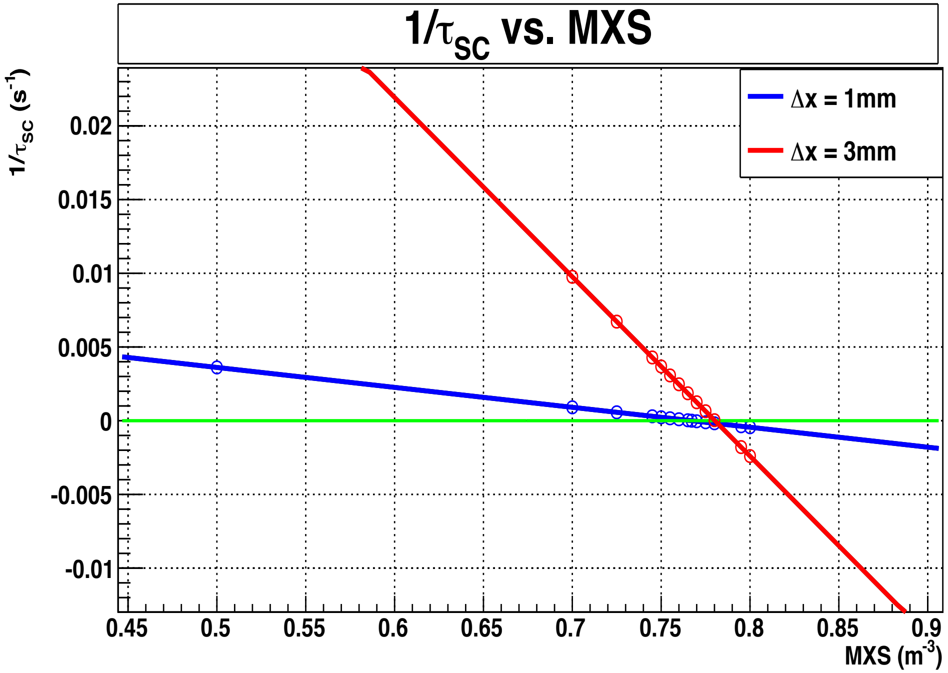

- The zero-crossing point is independent of the chosen Δx value

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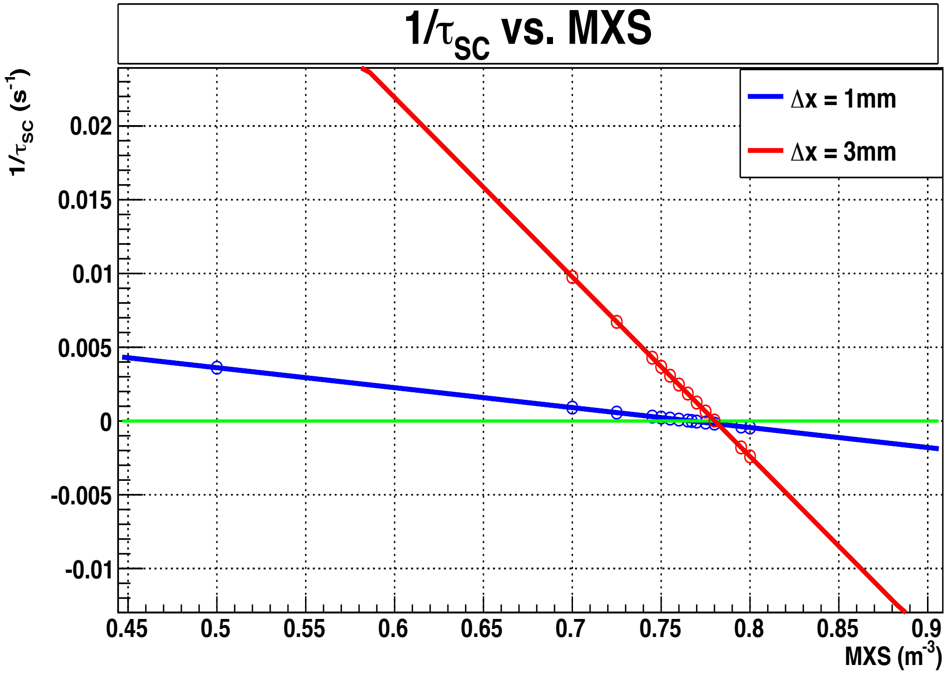

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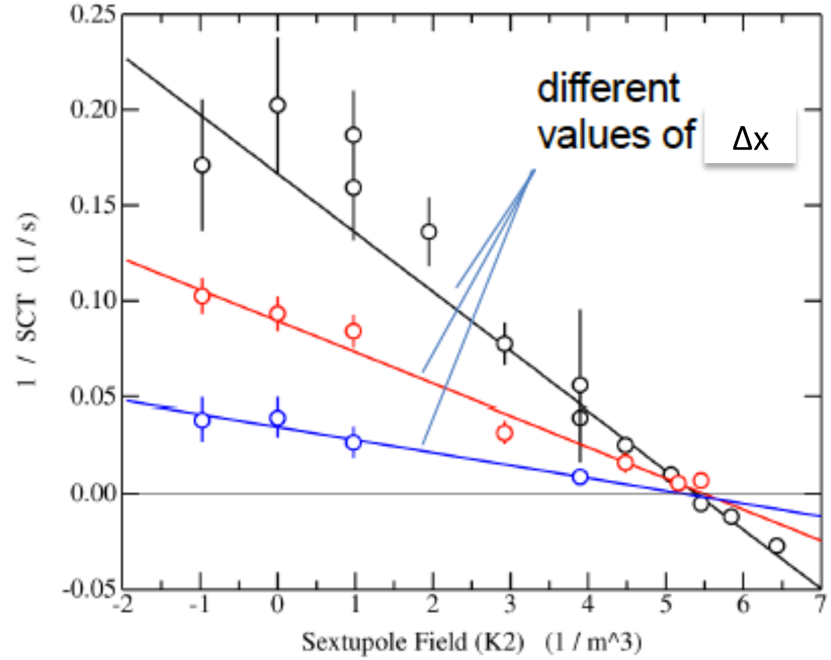

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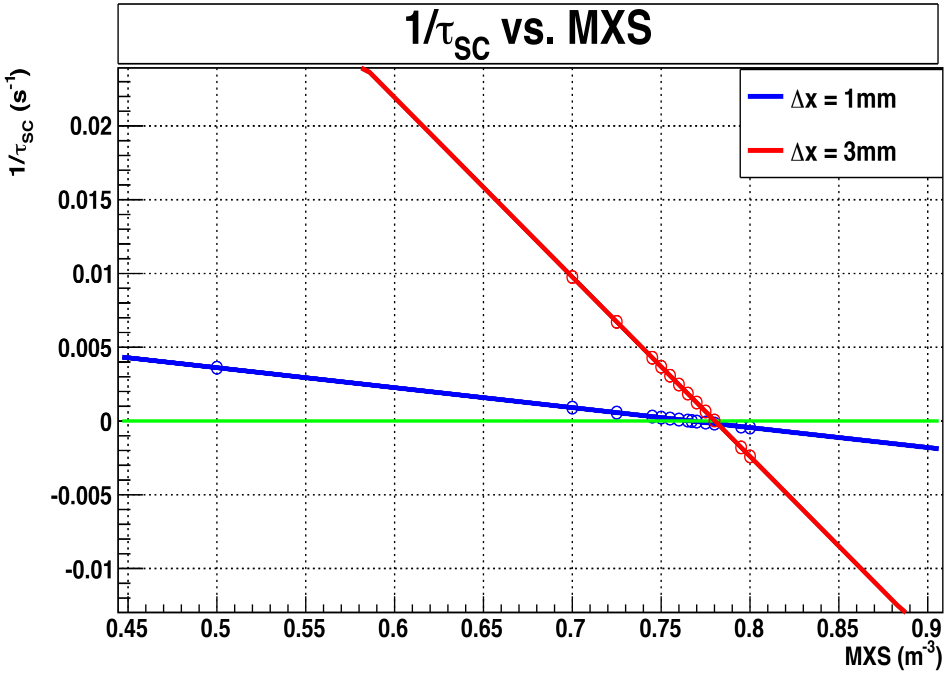

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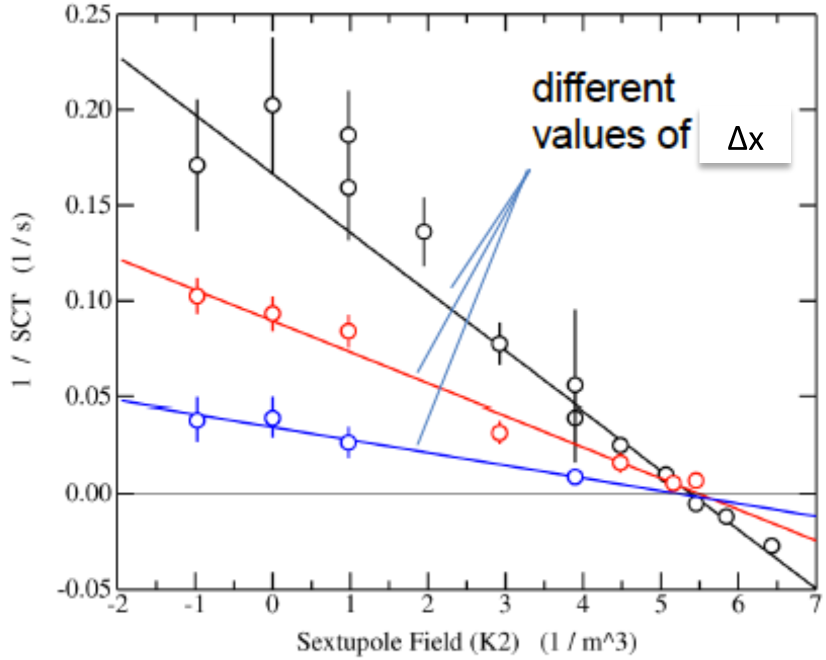

- The zero-crossing point is independent of the chosen Δx value
- Factor ~7 between simulated and measured k_2 values, suggesting the presence of unaccounted-for sextupole components in the ring

Linearity check

Combining two sextupole families it is possible to correct also the vertical offset's effect:

$$K_2(MXL) = C_0 + C_1 * K_2(MXS)$$

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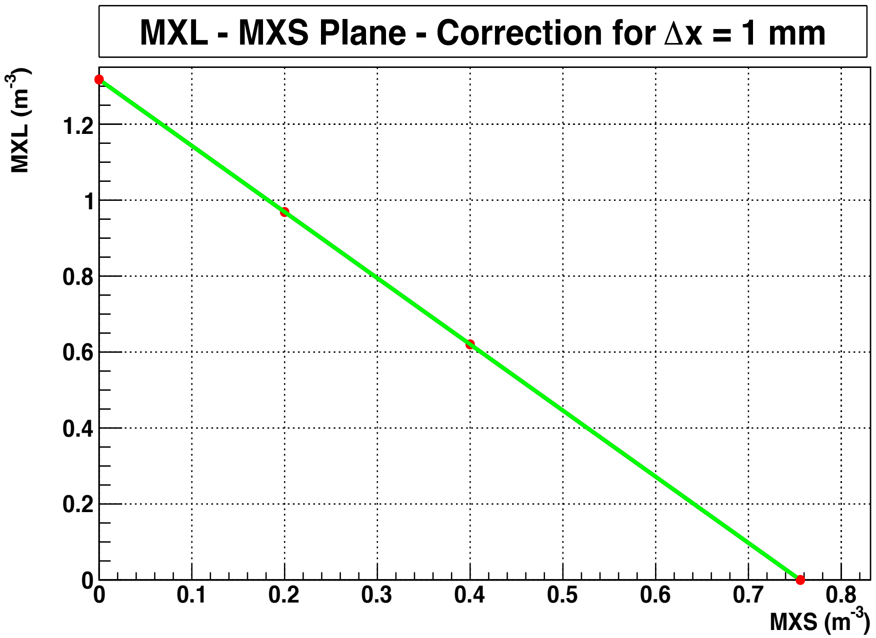

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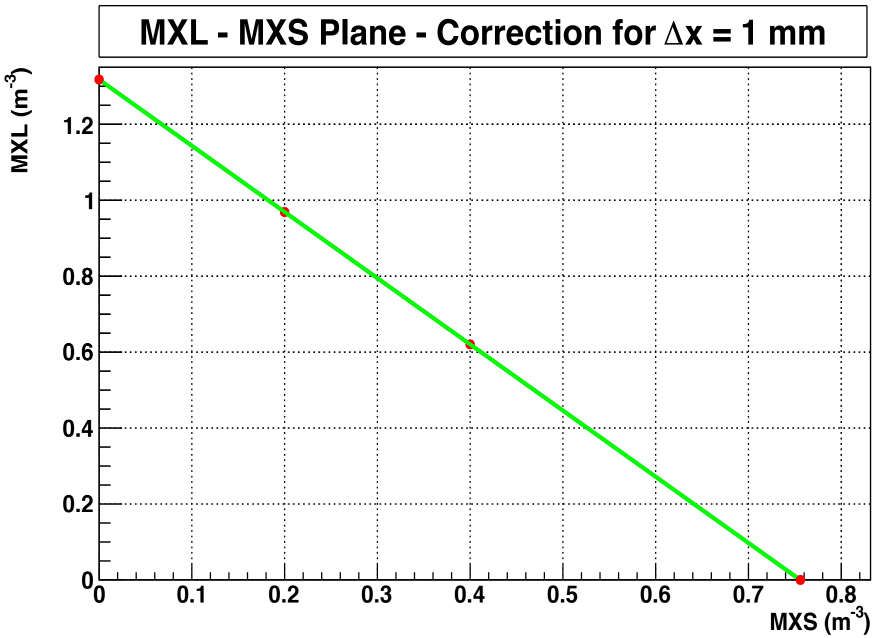

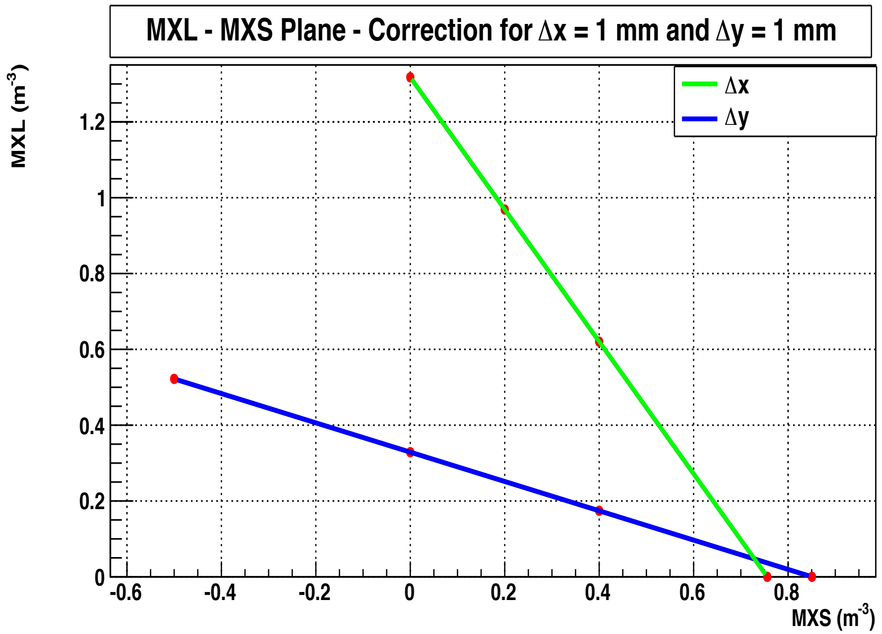

- The two straight lines cross each other → simultaneous compensation is possible
- Due to acceptance problems of the COSY ring, no data for the vertical offset case will be available

Conclusions

- EDM is a high sensitive probe of new physics
- New frontier: search of charged particles EDM in storage rings
- EDM experiment demands SCT > 10^3 s
- Feasibility tests performed at the COSY storage ring
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Promising tool for the design of a new generation of storage rings to be used for EDM search

THANK YOU FOR THE ATTENTION