III. Physikalisches Institut B

Simulation of Spin Dynamics to measure Electric Dipole Moments in Storage Rings

2013-10-16| Marcel Rosenthal on behalf of the JEDI collaboration

JÜLICH
FORSCHUNGSZENTRUM

Outline

- Introduction to EDMs in storage rings
- Methods for measuring EDMs in storage rings
- First test measurements and simulations of:
  - Driven Spin Oscillations
  - Spin Coherence Time

The fate of antimatter

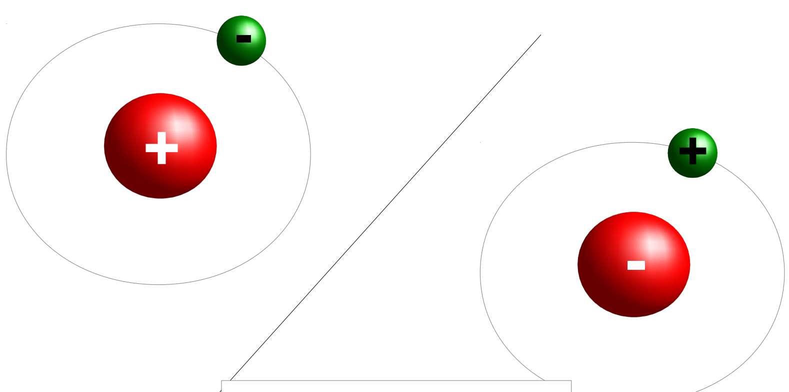
- Observed baryon density: $(n_B - n_{\bar{B}})/n_\gamma = 6 \cdot 10^{-10}$
- SM expectation: $\sim 10^{-18}$

many orders of magnitude difference

?

still a great amount of antimatter in universe

- separated matter- & antimatter-galaxies



antimatter annihilated

- Sakharov conditions (1967):
  - Baryon number conservation violated
  - Violation of C-symmetry and CP-symmetry
  - Interactions during evolution of universe out of thermal equilibrium

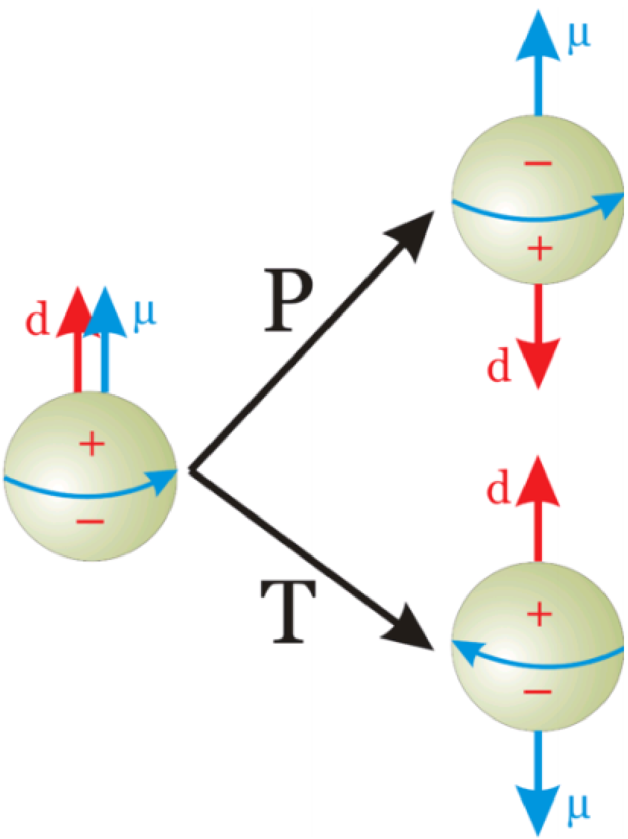
AMS-Experiment → **JARA-FAME** ← **JEDI-Experiment**

Electric Dipole Moments (EDMs)

- Permanent EDMs violate parity and time reversal symmetry
- CPT-theorem valid:

➡ CP-violation

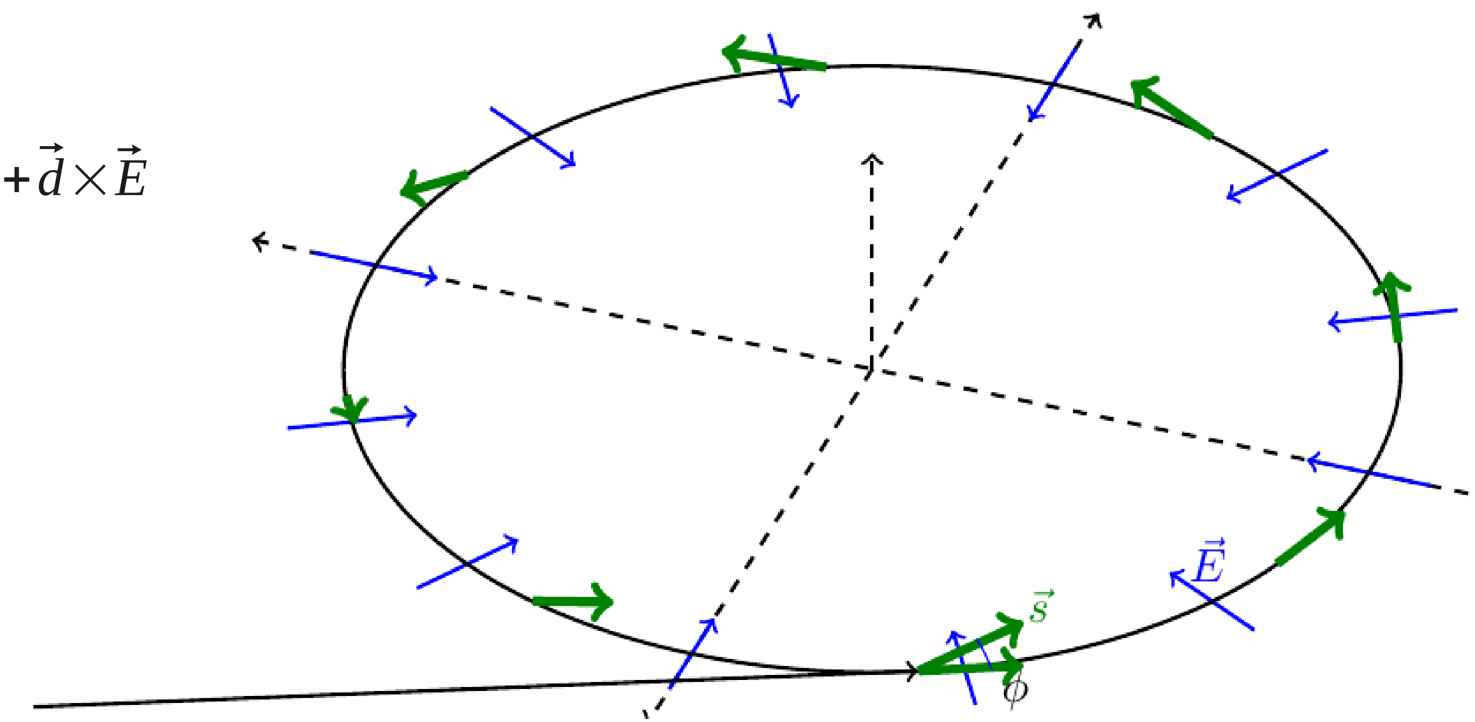
➡ **Possibility to explain the matter-antimatter-asymmetry**



Search for EDMs in storage rings

- General idea:

$$\frac{d\vec{S}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$



Initially longitudinal polarised particles interact with transversal electric field

⇒ build-up of vertical polarisation

⇒ measurement with polarimeter

Thomas-BMT-equation

- Equation for spin motion of relativistic particles in EM-fields.
- For $\vec{\beta}\cdot\vec{B} = \vec{\beta}\cdot\vec{E} = 0$ the spin precession relative to the momentum direction is given by:

$$\frac{d\vec{S}^*}{dt} = \vec{\Omega}\times\vec{S}^*$$

Magnetic moment

Electric Dipole Moment

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

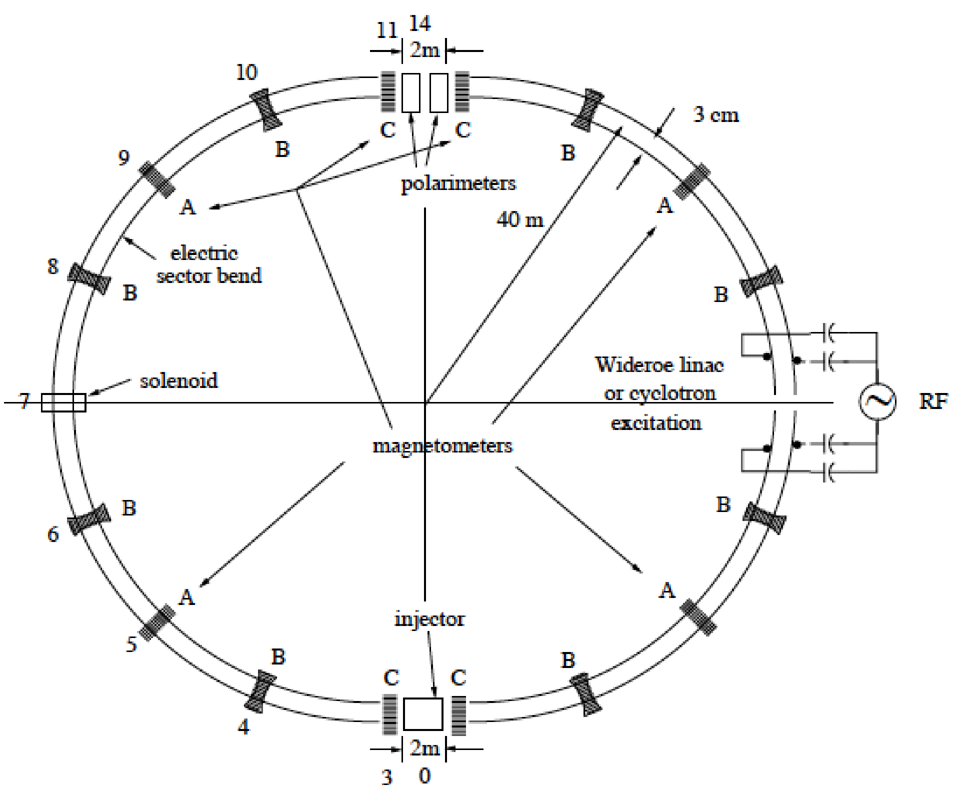
$\vec{B}^*$ $\quad$ $\vec{E}^*$

$$G = \frac{g-2}{2},\quad \vec{\mu} = 2(G+1)\frac{e}{2m}\vec{S},\quad \vec{d} = \eta\frac{e}{2mc}\vec{S}$$

Method 1: pure electric ring

$$\vec{\Omega} = -\frac{e}{m}\left(G\vec{B} + \underbrace{\left(\frac{1}{\gamma^2 - 1} - G\right)}_{=0}\left(\frac{\vec{\beta}\times\vec{E}}{c}\right) + \frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\right)$$

➡ "Frozen spin method", only possible for G > 0



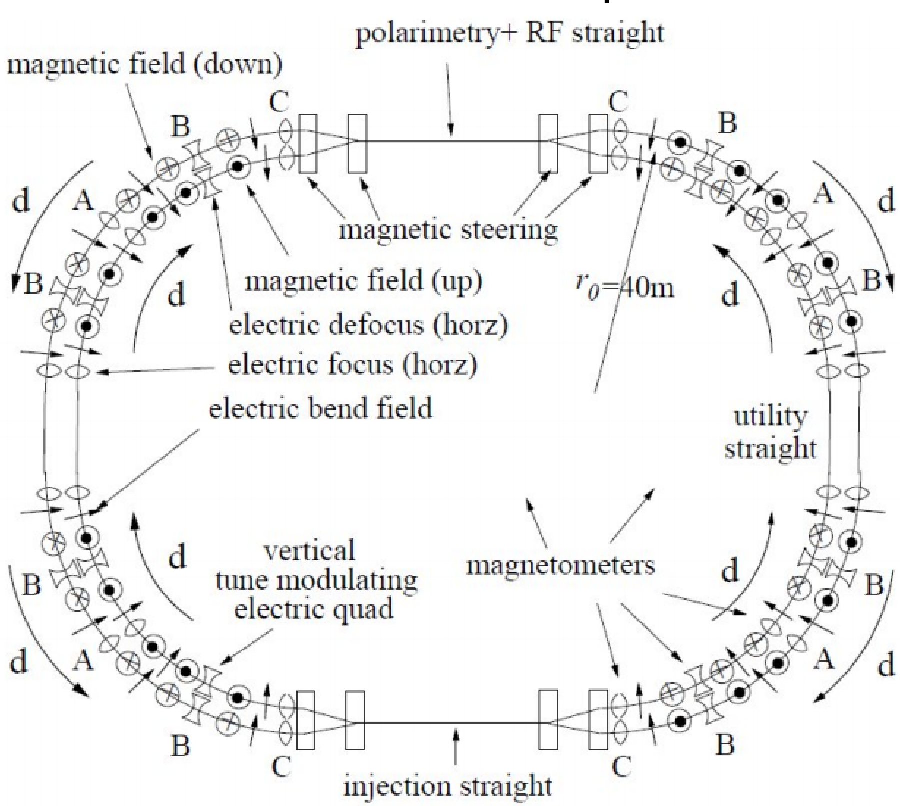
Particle	G
proton	1.7928473565
deuteron	-0.14298727202
^{3}He	-4.1839627399

- Advantage:
  no magnetic field, which interacts with anomalous magnetic moment
- Disadvantage:
  not possible for deuterons (G < 0)

Method 2: combined electric/magnetic ring

$$\vec{\Omega} = -\frac{e}{m}\left(\underbrace{G\vec{B} + \left(\frac{1}{\gamma^2-1} - G\right)\left(\frac{\vec{\beta}\times\vec{E}}{c}\right)}_{=\,0} + \frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\right)$$

➡ “Frozen spin method”



Particle	G
proton	1.7928473565
deuteron	-0.14298727202
^{3}He	-4.1839627399

- Advantage:
  works for protons, deuterons & ^{3}He
- Disadvantage:
  requires a magnetic field

Method 3: pure magnetic ring

$$\vec{\Omega} = -\frac{e}{m}\left(G\vec{B} + \cancel{\left(\frac{1}{\gamma^2-1} - G\right)\left(\frac{\vec{\beta}\times\vec{E}}{c}\right)} + \frac{\eta}{2}\left(\cancel{\frac{\vec{E}}{c}} + \vec{\beta}\times\vec{B}\right)\right)$$

precession in horizontal plane (MDM)

Influence on vertical spin component (EDM)

→ tilt of invariant spin axis

- Advantage:
  existing COSY accelerator
  → precursor experiment
- Disadvantage:
  lower sensitivity

Method 3: pure magnetic ring

$$\vec{\Omega} = -\frac{e}{m}\left(G\vec{B} + \cancel{\left(\frac{1}{\gamma^2-1} - G\right)\left(\frac{\vec{\beta}\times\vec{E}}{c}\right)} + \frac{\eta}{2}\left(\cancel{\frac{\vec{E}}{c}} + \vec{\beta}\times\vec{B}\right)\right)$$

precession in horizontal plane (MDM)

Influence on vertical spin component (EDM)

→ tilt of invariant spin axis

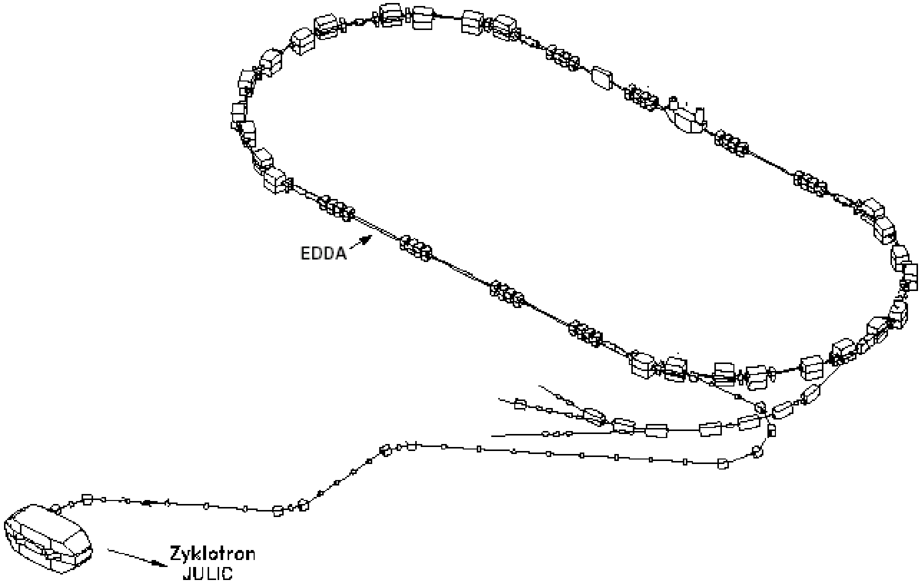
First direct measurement of charged hadron EDMs

Advantage: existing COSY accelerator → precursor experiment

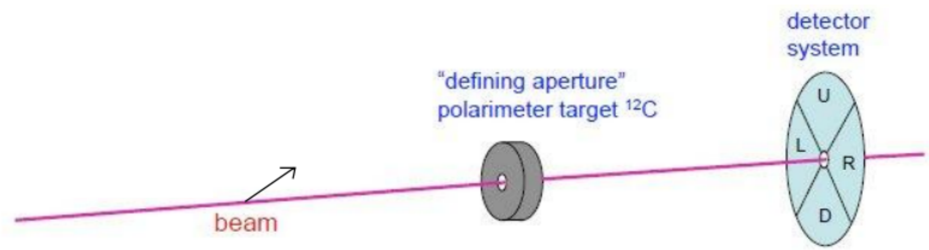
Disadvantage: lower sensitivity

The Cooler Synchrotron COSY

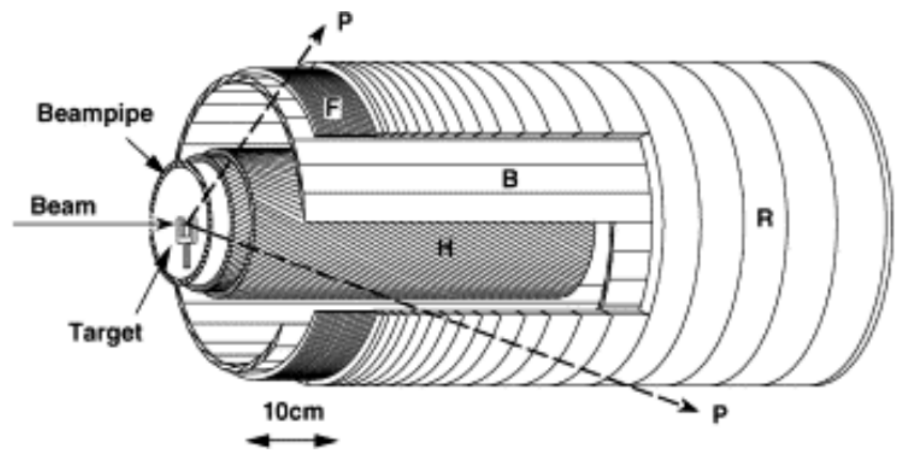
- Storage ring for polarised protons and deuterons
- Momentum range: $p = (0.3 - 3.7)\frac{GeV}{c}$
- Electron and stochastic cooling to reduce occupied phase space
- Ideal place (unique!) to study storage ring EDMs



Polarimetry



- White noise or orbit bump extraction
- Single particles of beam hit target
- Polarisation-dependent cross-section:
- Vertical Polarisation → Left-Right-Asymmetry
- Horizontal Polarisation → Up-Down-Asymmetry



Spin tune

- Assume $\vec{E}=0 \wedge \eta=0:$

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

- Compare to momentum precession frequency in lab frame

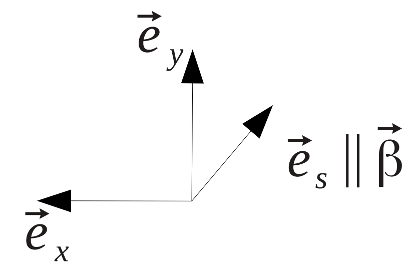
$$\vec{\Omega}_L=-\frac{e\vec{B}}{\gamma m}$$

➡ Each turn the spin vector precesses an additional angle $G\gamma\cdot 2\pi$ with respect to the momentum vector

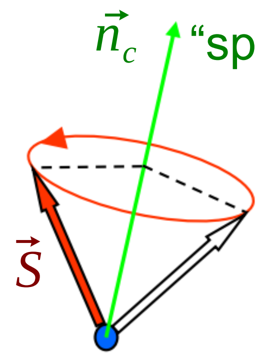
➡ $\nu_s=G\gamma$ "spin tune"

Spin coherence time (SCT)

$\vec{B} \parallel \vec{e}_y \Rightarrow \vec{n}_c \parallel \vec{e}_y$

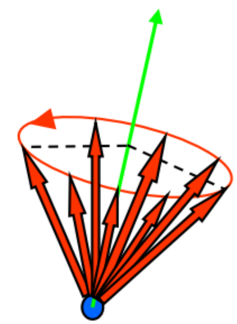


- Polarisation $\parallel \vec{n}_c$:



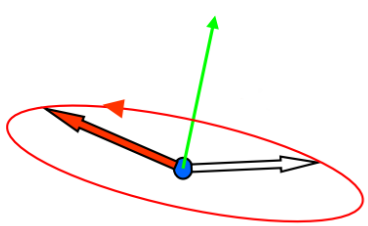
"spin closed orbit vector"

spin tune spread

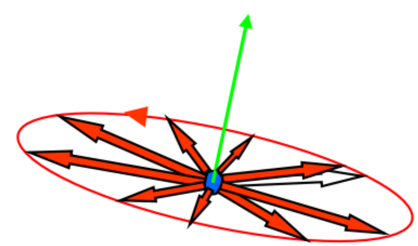


No negative effect on polarisation parallel to $\vec{n}_c$

- Polarisation $\perp \vec{n}_c$:



spin tune spread

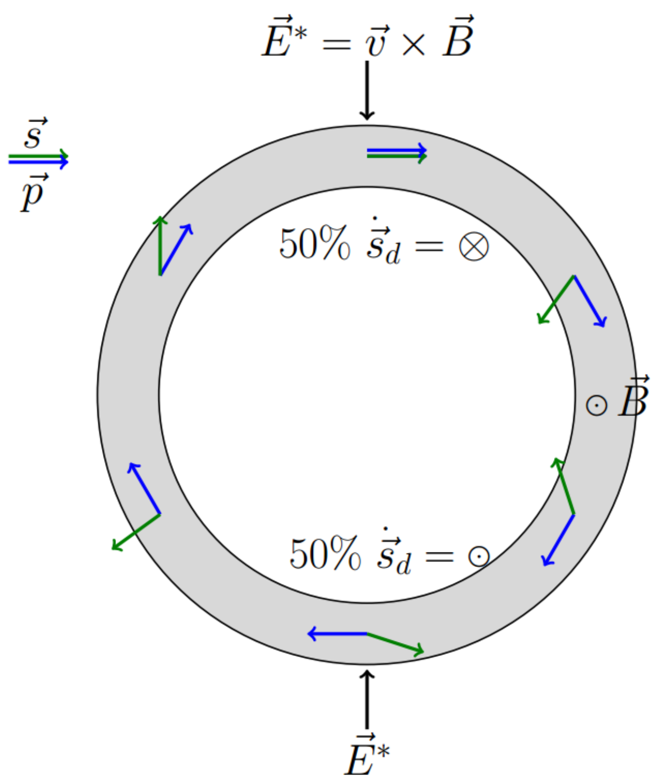


Polarisation loss perpendicular to $\vec{n}_c$

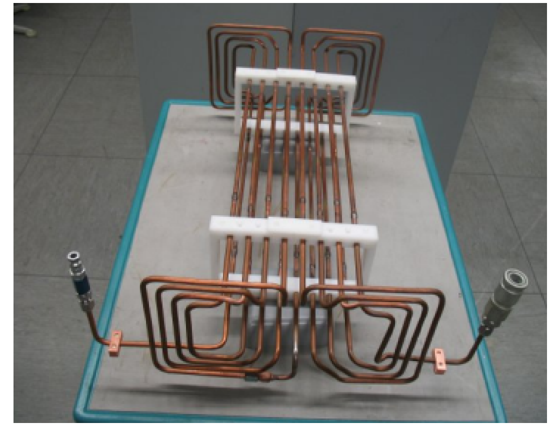
Statistical sensitivity for single cycle $\sigma \propto \frac{1}{\tau_{SCT}}$ $\Rightarrow$ **τ_{SCT} = crucial parameter**

Pure magnetic ring issue

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



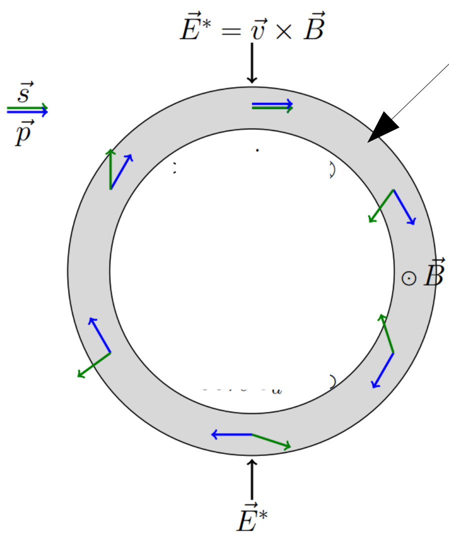
- Precession around stable spin axis
  - ➡ $<\Omega_x \cdot S_z^* > = 0$
  - ➡ No rising signal, only tiny oscillations
- Solution:
  Equip ring with “special” element:
  1. (RF)-E-Dipole
  2. (RF)-Wien-Filter



magnetic part

RF-Wien-Filter

- Two ingredients:
  - Ring: $\vec{\Omega} = -\frac{e}{m}\left(G\vec{B} + \cancel{\left(\frac{1}{\gamma^2-1} - G\right)\left(\frac{\vec{\beta}\times\vec{E}}{c}\right)} + \frac{\eta}{2}\left(\cancel{\frac{\vec{E}}{c}} + \vec{\beta}\times\vec{B}\right)\right)$
  - RF-Wien-Filter: $\vec{\Omega} = -\frac{e}{m}\left(G\vec{B}(t) + \left(\frac{1}{\gamma^2-1} - G\right)\left(\frac{\vec{\beta}\times\vec{E}(t)}{c}\right) + \frac{\eta}{2}\underbrace{\left(\frac{\vec{E}(t)}{c} + \vec{\beta}\times\vec{B}(t)\right)}_{=0}\right)$



- Wien-Filter condition: $\frac{\vec{E}(t)}{c} = -\vec{\beta}\times\vec{B}(t)$

➡ No excitation of beam, but also EDM transparent

➡ Resonant spin interaction: $f_r = f_c(K + G\gamma)$

➡ build-up of EDM signal

Investigation of RF-induced driven spin oscillations

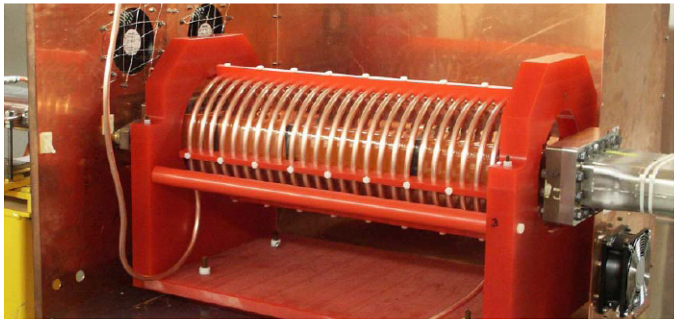
Idea

- RF solenoid to drive polarisation oscillations
- Investigate different resonance frequencies:

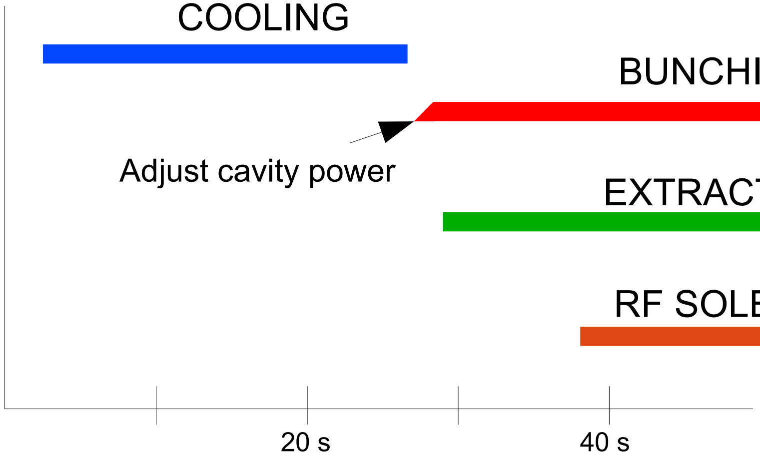
$$f_r = f_c(K + G\gamma)$$

$$deuterons,\ p = 970\ MeV/c$$
$$\rightarrow\ f_c = 750\ kHz,\ G\gamma \approx -0.16$$

- Accessible frequencies:
  - K=1: 630 kHz
  - K=-1: 871 kHz
  - K=2: 1380 kHz
  - K=-2: 1622 kHz

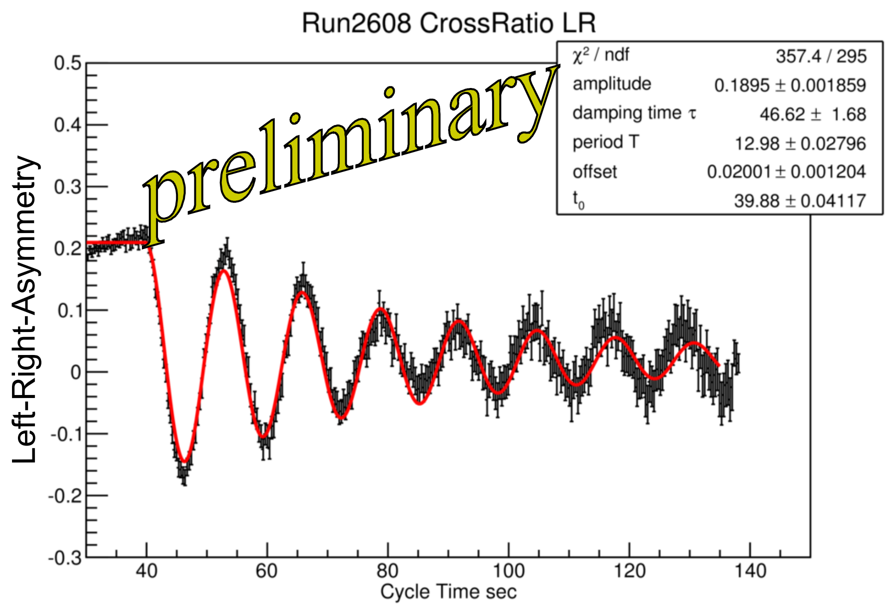


water-cooled copper-coil in ferrite box:
- Length: 0.6m
- Integrated field up to ~1 T·mm

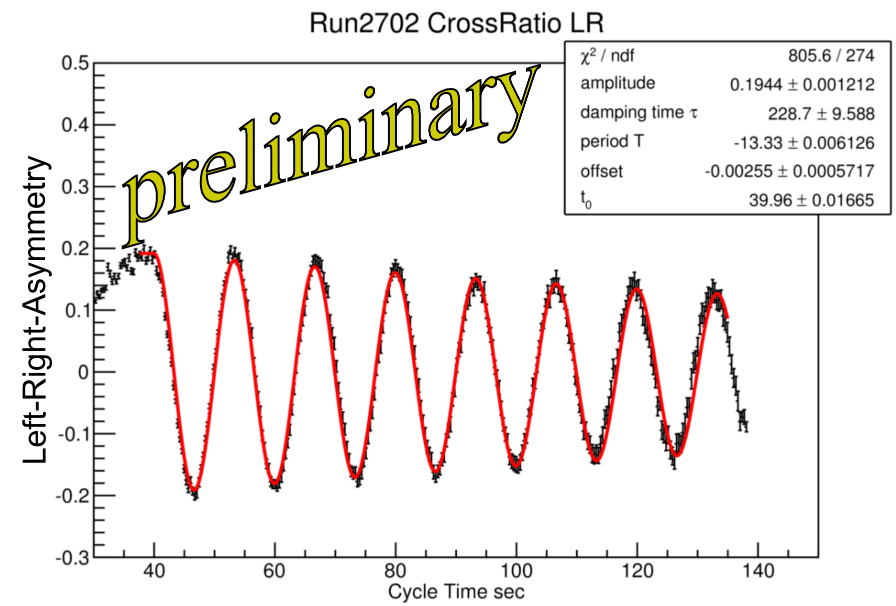


Measurements

K=-1 (871 kHz)

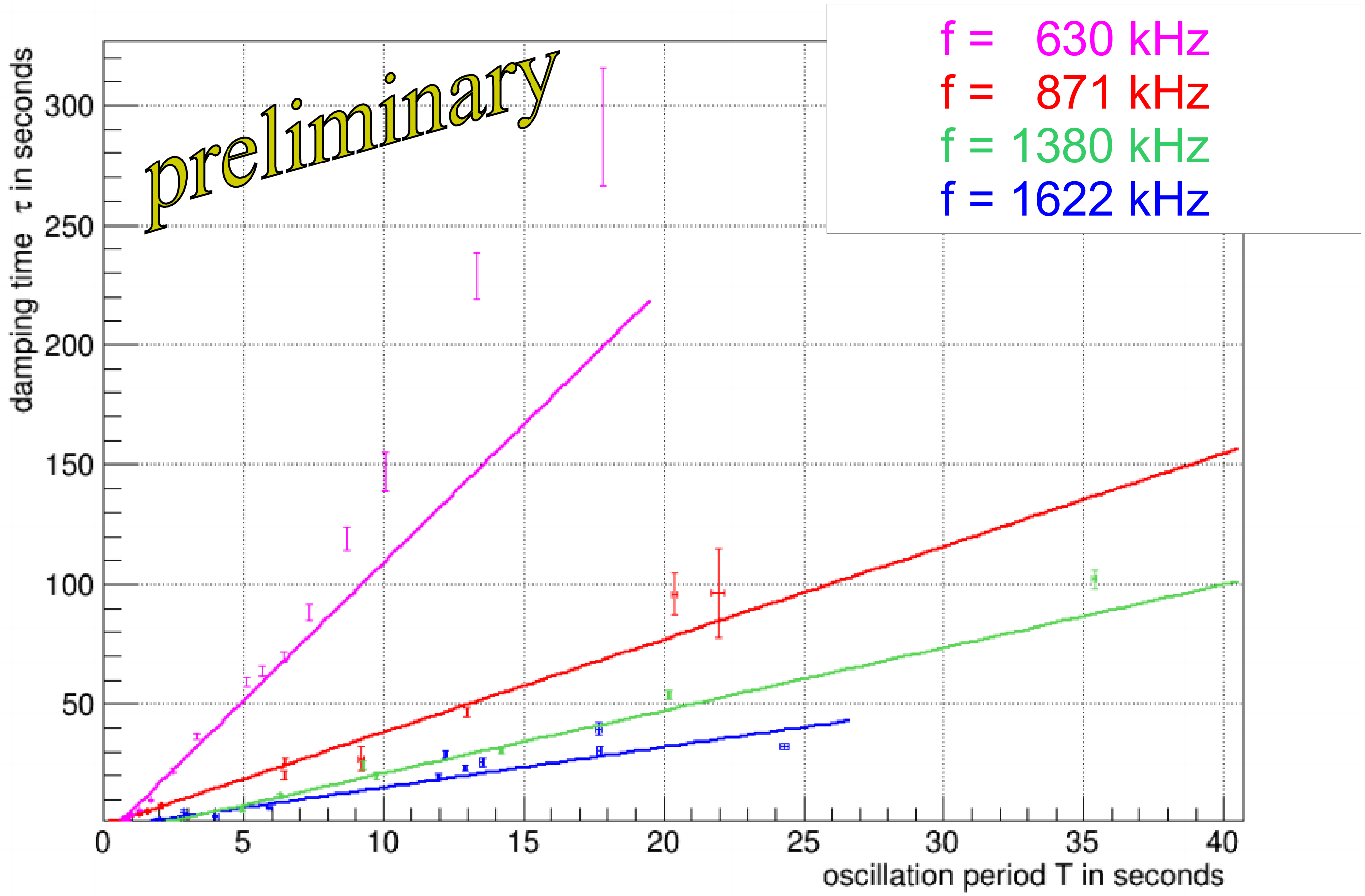


K=1 (630 kHz)



- A set of measurements with different RF solenoid strengths and frequencies were taken.
- Polarisation lifetime depends on these solenoid parameters.

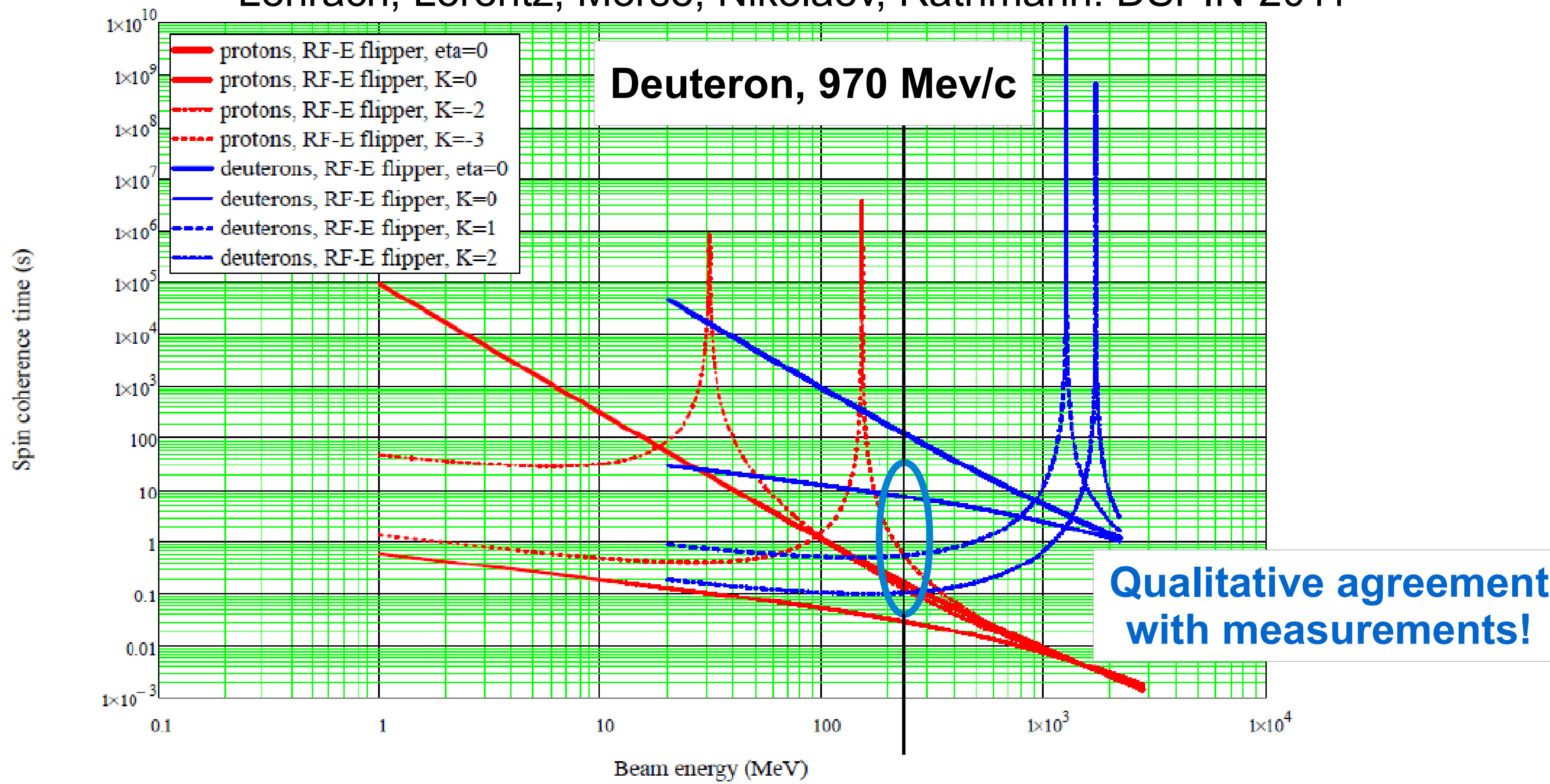
Measurements



- Rough pre-analysis of data clearly shows this dependency

Prediction

Lehrach, Lorentz, Morse, Nikolaev, Rathmann: DSPIN-2011



- Effect of particle motion in longitudinal phase space
- huge differences of polarisation lifetimes (several orders of magnitude!)

Simulations with simple model

- Simple model based on spin rotation matrices:
  - Spin rotation in ring around vertical axis:

$$R_y(2\pi G\gamma)=\begin{pmatrix}\cos(2\pi G\gamma) & 0 & \sin(2\pi G\gamma)\\ 0 & 1 & 0\\ -\sin(2\pi G\gamma) & 0 & \cos(2\pi G\gamma)\end{pmatrix}$$

  - Spin rotation in rf solenoid around longitudinal axis:

$$R_z(2\pi\epsilon\cos(2\pi f t))$$

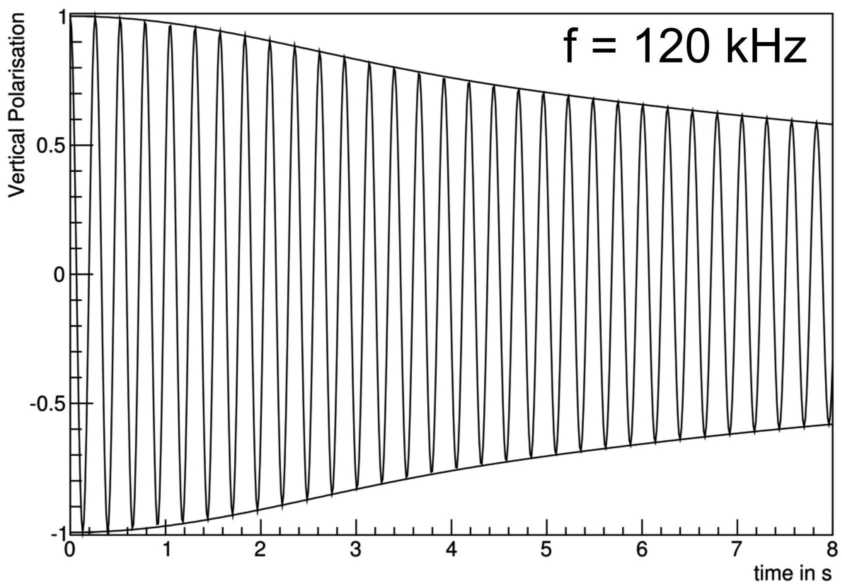
Change in time of arrival for every particle
→ different solenoidal field

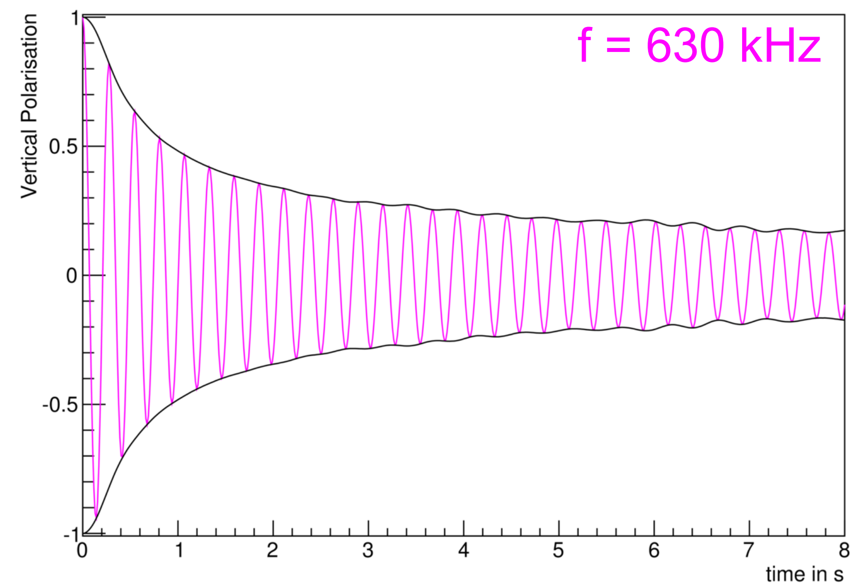
Synchrotron Oscillations:

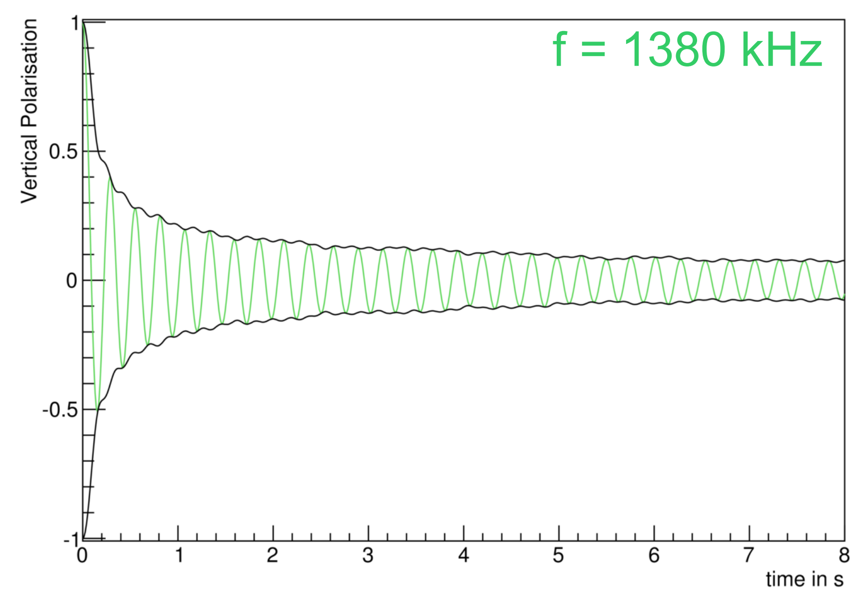
$$\frac{\Delta p}{p}=\left(\frac{\Delta p}{p}\right)_{max}\cdot\cos(2\pi f_{sync} t)$$

→ Revolution time changes!

Results (simple model)





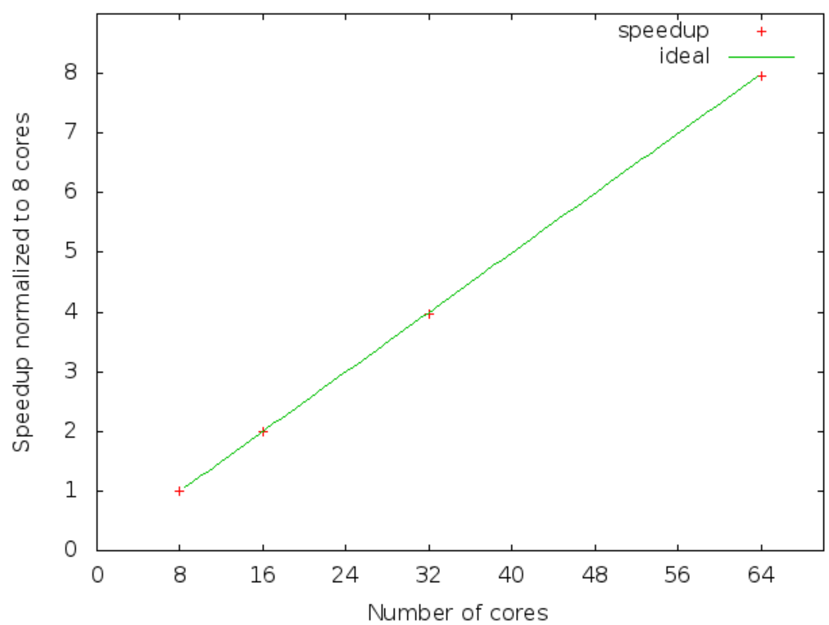


- Averaged over 500 deuterons, Gaussian distributed momentum deviation with $\sigma = 5 \cdot 10^{-4}$
- Simulation in simple model in qualitative agreement with measurements
-

Full lattice spin tracking simulations

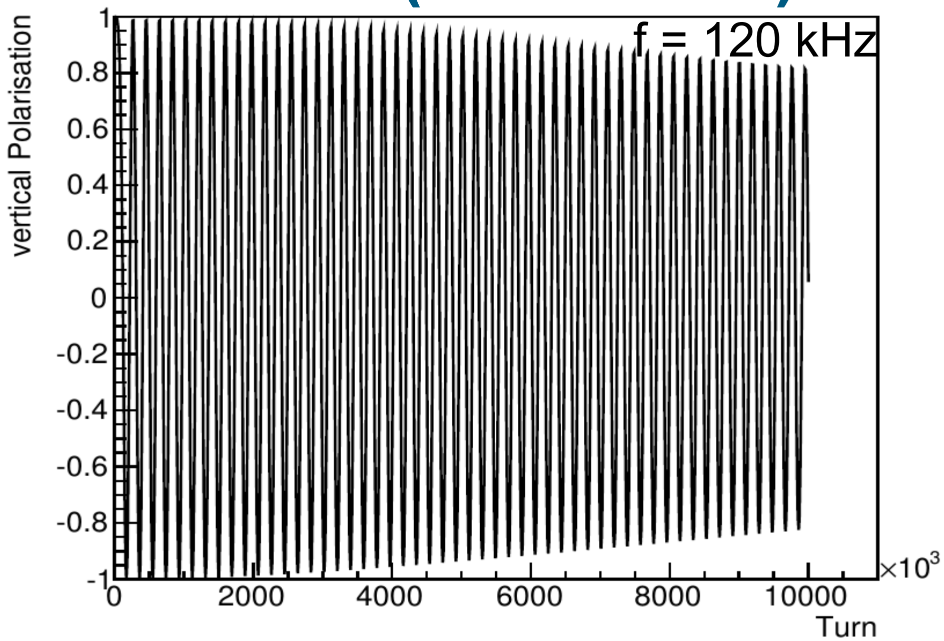
- COSY INFINITY: (credits to M. Berz, http://bt.pa.msu.edu/index_cosy.htm)
  - Solves equation of motion using differential algebraic techniques
  - Taylor expansions to arbitrary order
  - Generates transfer maps to allow fast particle motion and spin tracking
  - Also allows multi-threaded tracking using Message Passing Interface (MPI)

→ significant speed-up of simulations

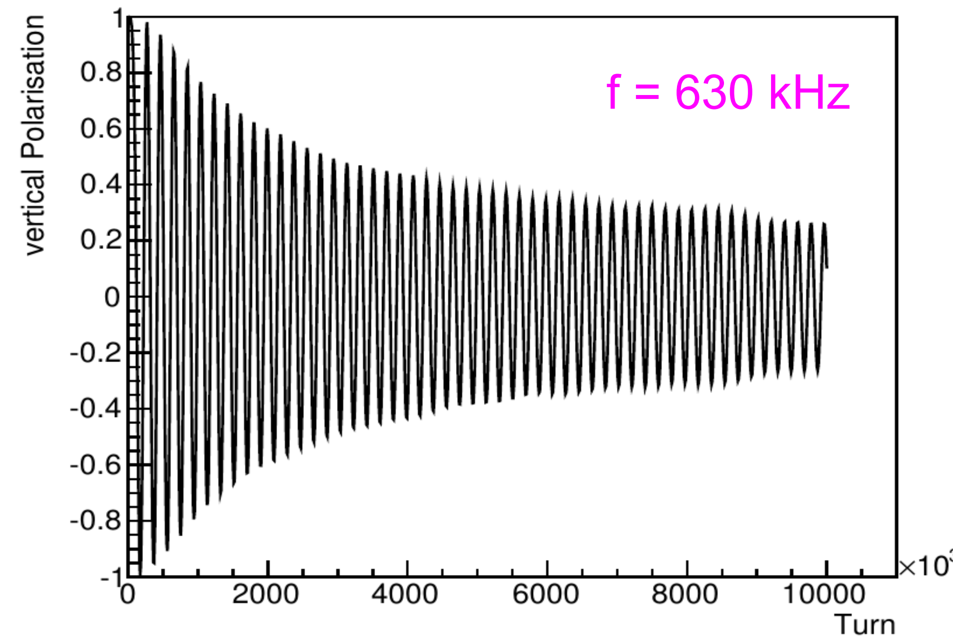


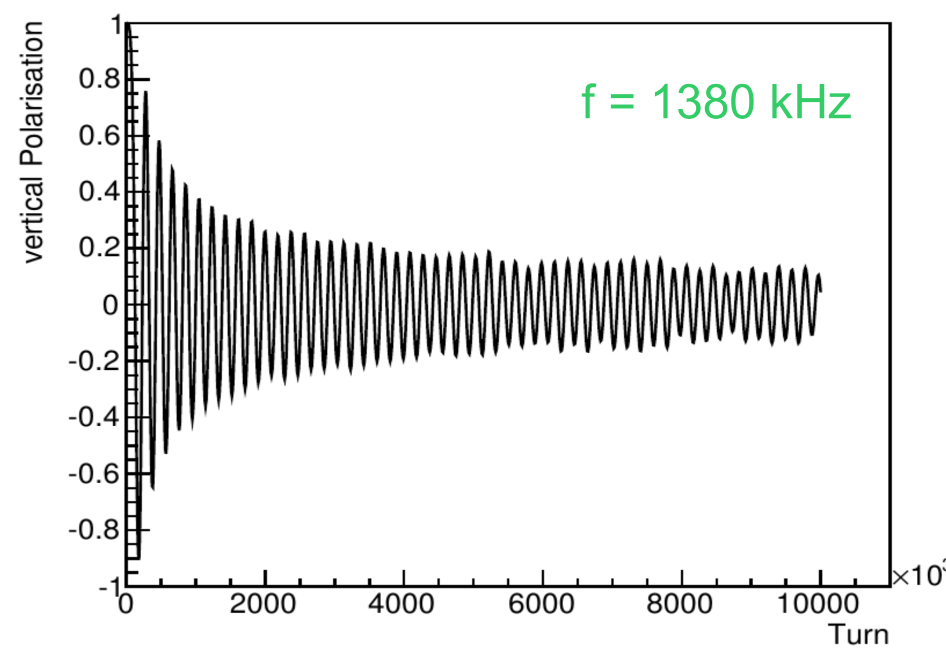
- Computing time estimations:
  - 10^6 particles, 10^9 turns → ~7.5 mio. cpu-h (3rd order non-linearities)
  - Already used on JUROPA super-computer
  - Applied for using it on JARA-HPC

Results (full model)



- Averaged over 640 deuterons, Gaussian distributed initial particle coordinates, momentum deviation: $\sigma = 2\cdot 10^{-4}$, normalized emittances: $\varepsilon = 0.2$ mm mrad
- Same qualitative agreement
- **PLAN**: benchmark simulation codes with measurements

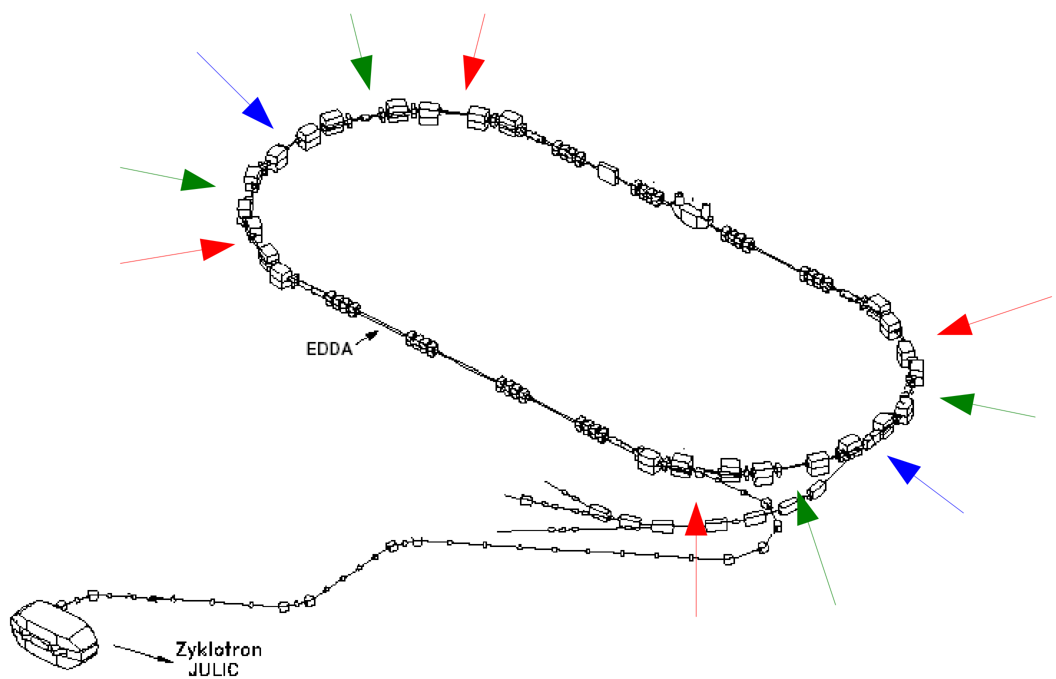




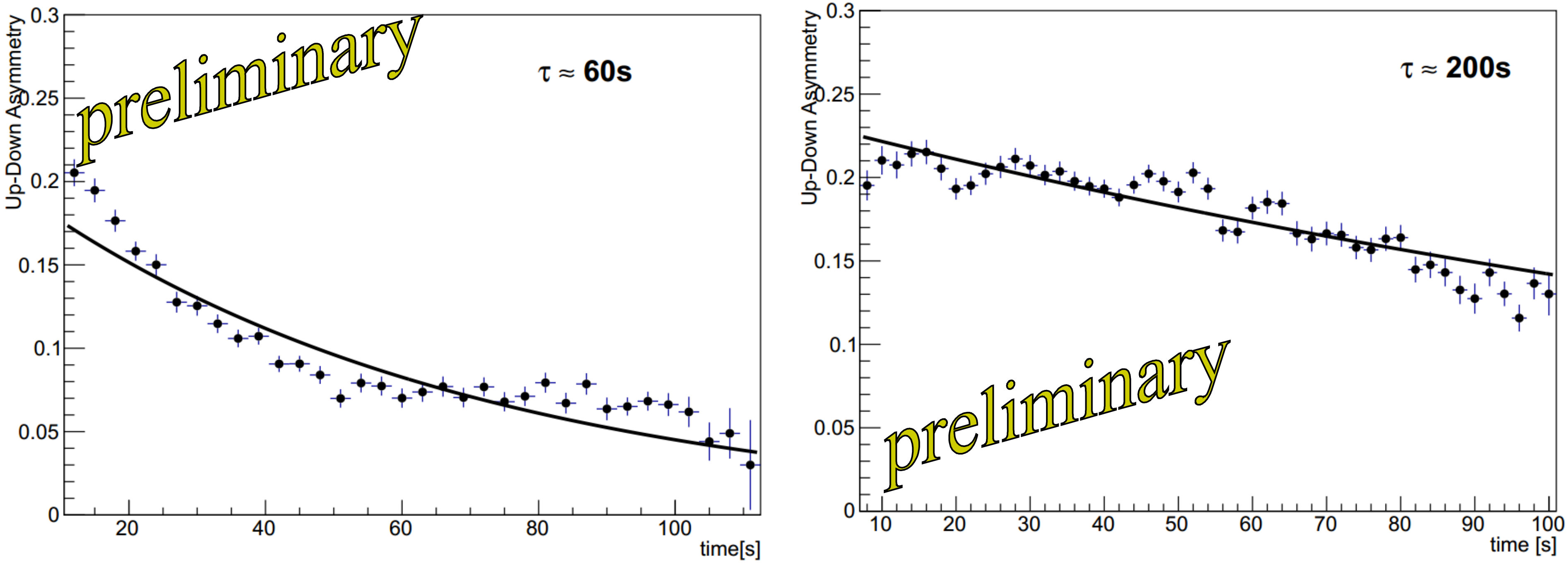
Investigation of Spin Coherence Time

SCT & Sextupoles

- Try to decrease spin tune spread and increase spin coherence time with correct setup of sextupole strengths
- COSY has 3 sextupole families in the arcs
- Vary strengths and investigate their influence on SCT



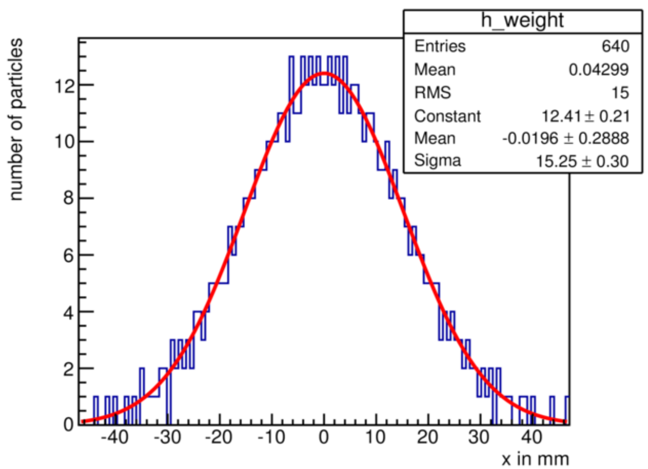
Measurements

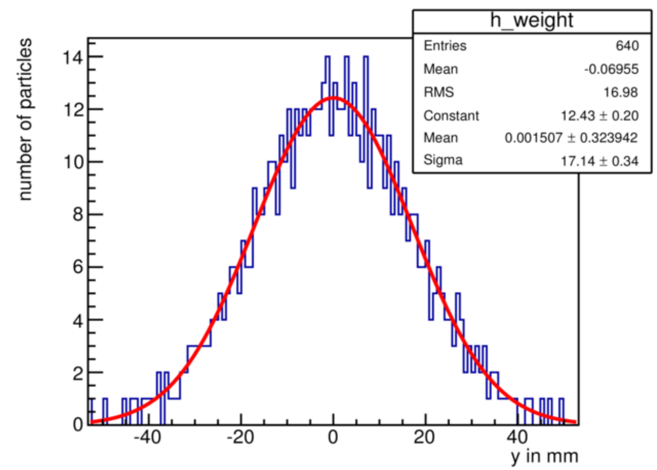


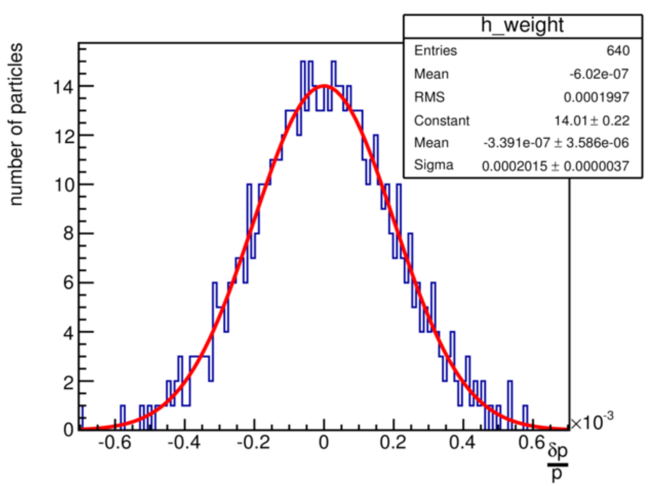
- Different settings of sextupole strength have large influence on spin coherence time.
- Last beamtime August/September 2013 a large amount of data with different sextupole settings was taken, which waits to be fully analyzed

Simulation: Initial Setup of Beam

- Ensemble: ε_x=10 mm mrad, ε_y=10 mm mrad, $\delta p/p = 2\cdot 10^{-4}$

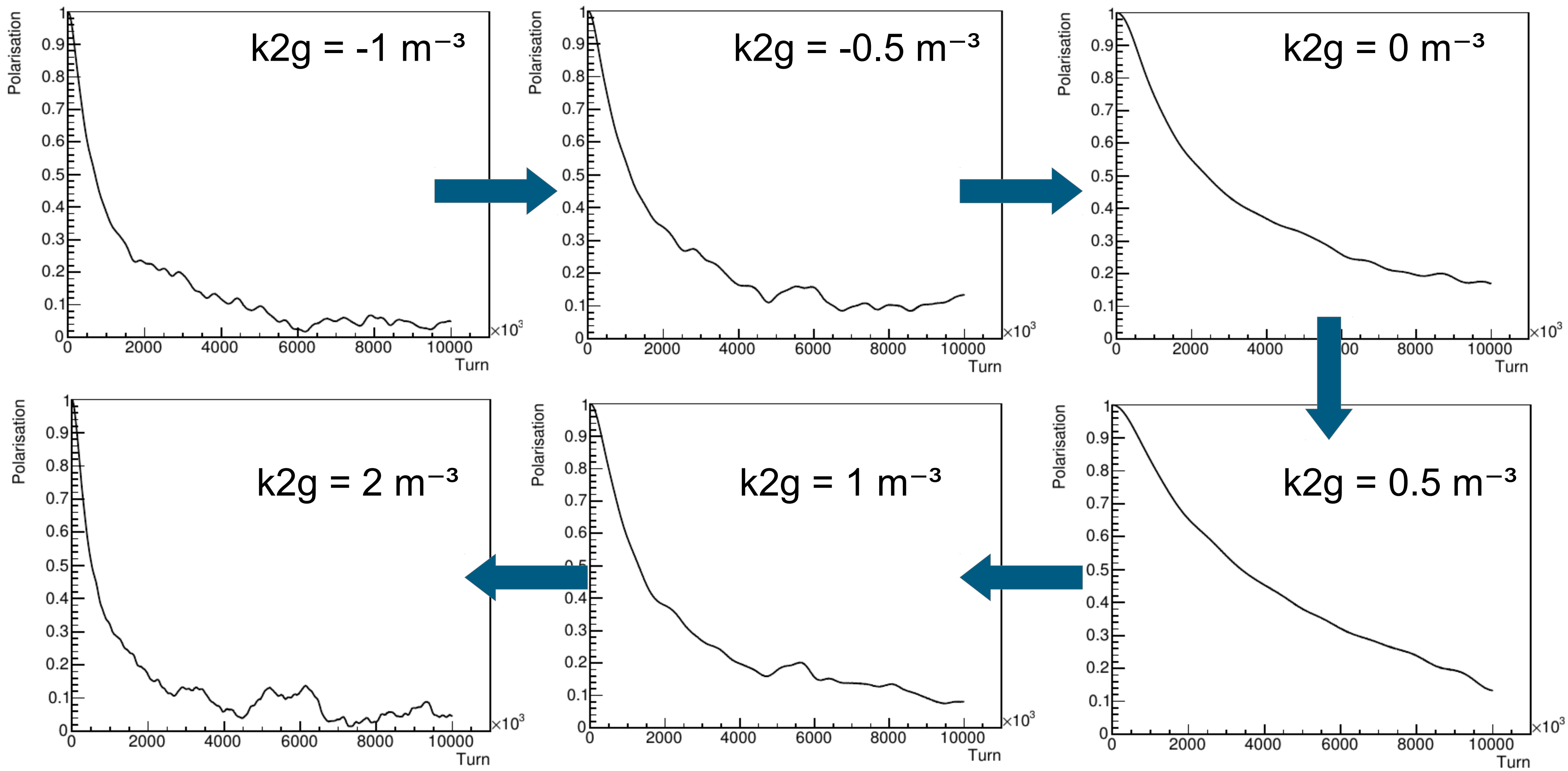






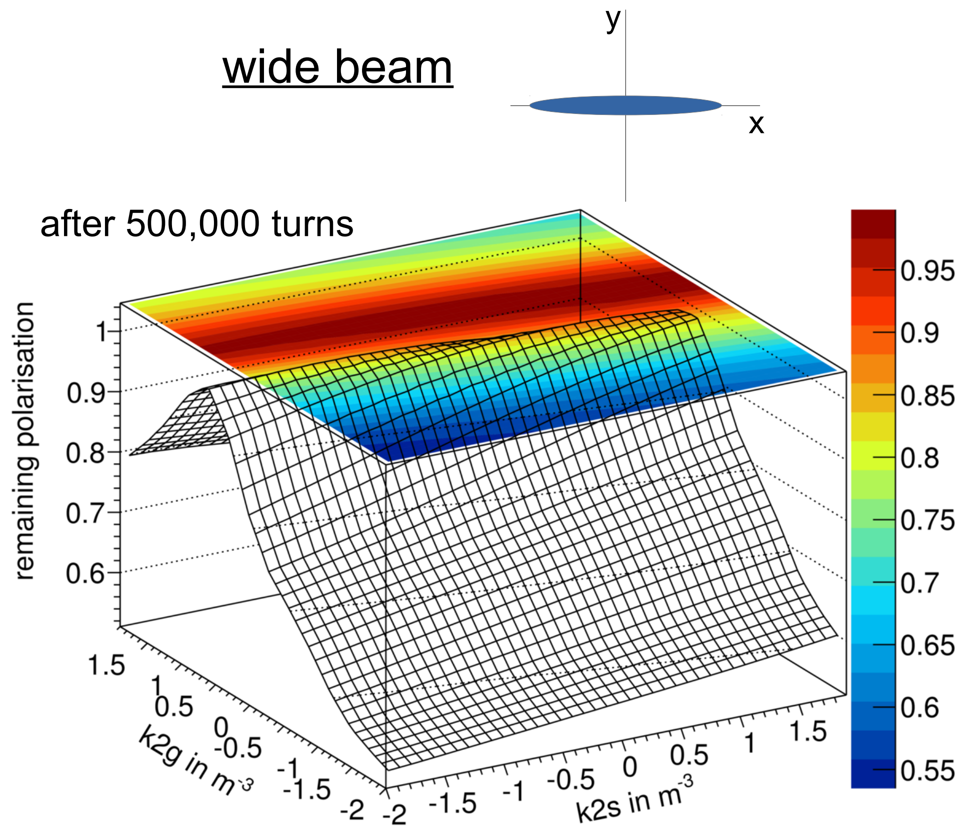
- 640 particles (deuterons), p=970 MeV/c
- $\beta\gamma$=0.52
- Gaussian distribution in x, y, and δp/p, other coordinates set to zero.
- Fully longitudinal polarized

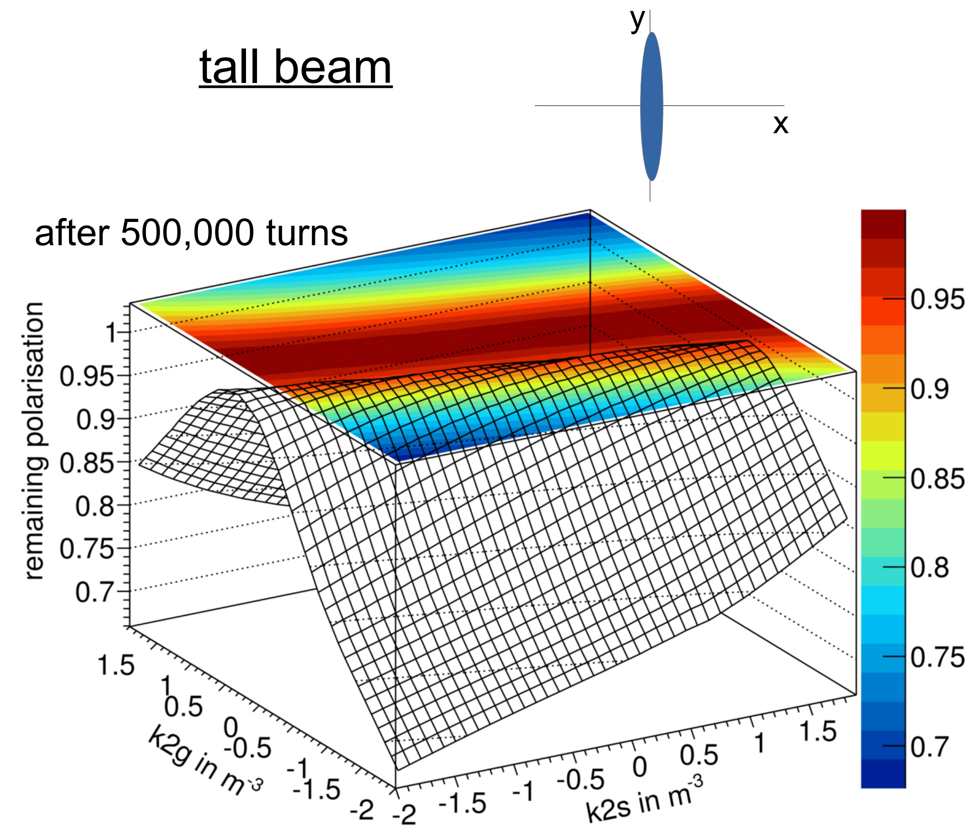
Simulation: Spin coherence



- Without correction polarisation is lost very fast.
  → No signal build-up possible!

Simulation: 2D-scans in sextupole space

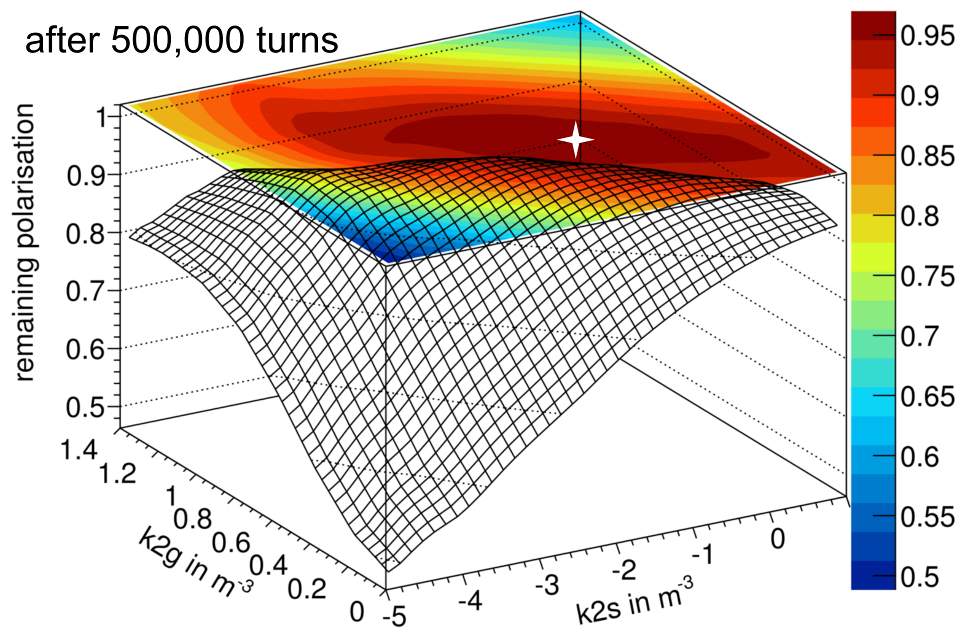




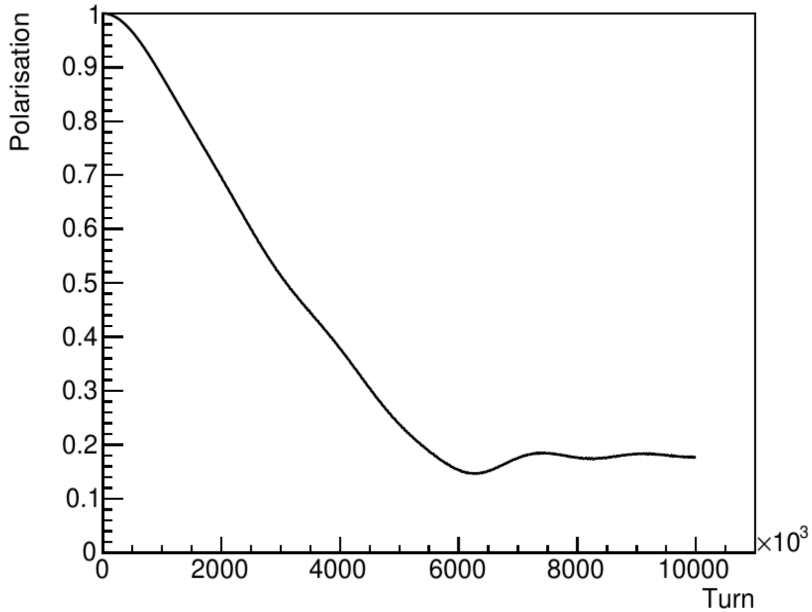
- 1D-toy beams to examine phasespace dependency separately
- Cancellation of spin tune spread for oscillating particles in transversal space at crossing point

Simulation: 2D-scans in sextupole space II

round beam



polarisation



- Reduction of spin tune spread for particles occupying transversal phasespace with two sextupole families

➡ Increase of spin coherence time, but very sensitive

- **PLAN:** Improve modelling the accelerator and benchmark the simulation with performed measurements

Summary

- EDMs are important quantity to search for physics beyond the standard model and explanation of matter-antimatter-asymmetry
- The feasibility of different methods for measuring EDMs in storage rings has to examined.

➡ Powerful simulation tools (e.g. COSY Infinity) are absolutely mandatory!

- First measurements of rf-induced driven oscillations give hint for frequency dependency of polarisation lifetime
- Measurements and simulations show strong influence of sextupoles on spin coherence time

➡ New data has to be analyzed

➡ Simulations have to improved and benchmarked to allow future predictions

Spares

Statistical Sensitivity for electric/combined-ring

$$\sigma \approx \frac{\hbar}{\sqrt{NfT\tau_p PEA}}$$

P	beam polarization	0.8
τ_p	Spin coherence time/s	1000
E	Electric field/MV/m	10
A	Analyzing Power	0.6
N	nb. of stored particles/cycle	4×10^7
f	detection efficiency	0.005
T	running time per year/s	10^7

$\Rightarrow \sigma \approx 10^{-29} e{\cdot}\text{cm/year}$ (for magnetic ring $\approx 10^{-24} e{\cdot}\text{cm/year}$)
Expected signal $\approx$ 3nrad/s (for $d = 10^{-29} e{\cdot}\text{cm}$)
(BNL proposal)

Statistical Sensitivity for magnetic ring (COSY)

$$\sigma \approx \frac{\hbar}{2} \frac{G\gamma^2}{G+1} \frac{U}{E \cdot L} \frac{1}{\sqrt{NfT\tau_p PA}}$$

G	anomalous magnetic moment	
γ	relativistic factor p =1GeV/c	1.13
U	circumference of COSY	180 m
$E \cdot L$	integrated electric field	$0.1 \cdot 10^6$ V
N	nb. of stored particles/cycle	$2 \cdot 10^9$

$\Rightarrow \sigma \approx 10^{-25} e \cdot$cm/year

JÜLICH
FORSCHUNGSZENTRUM

Systematics

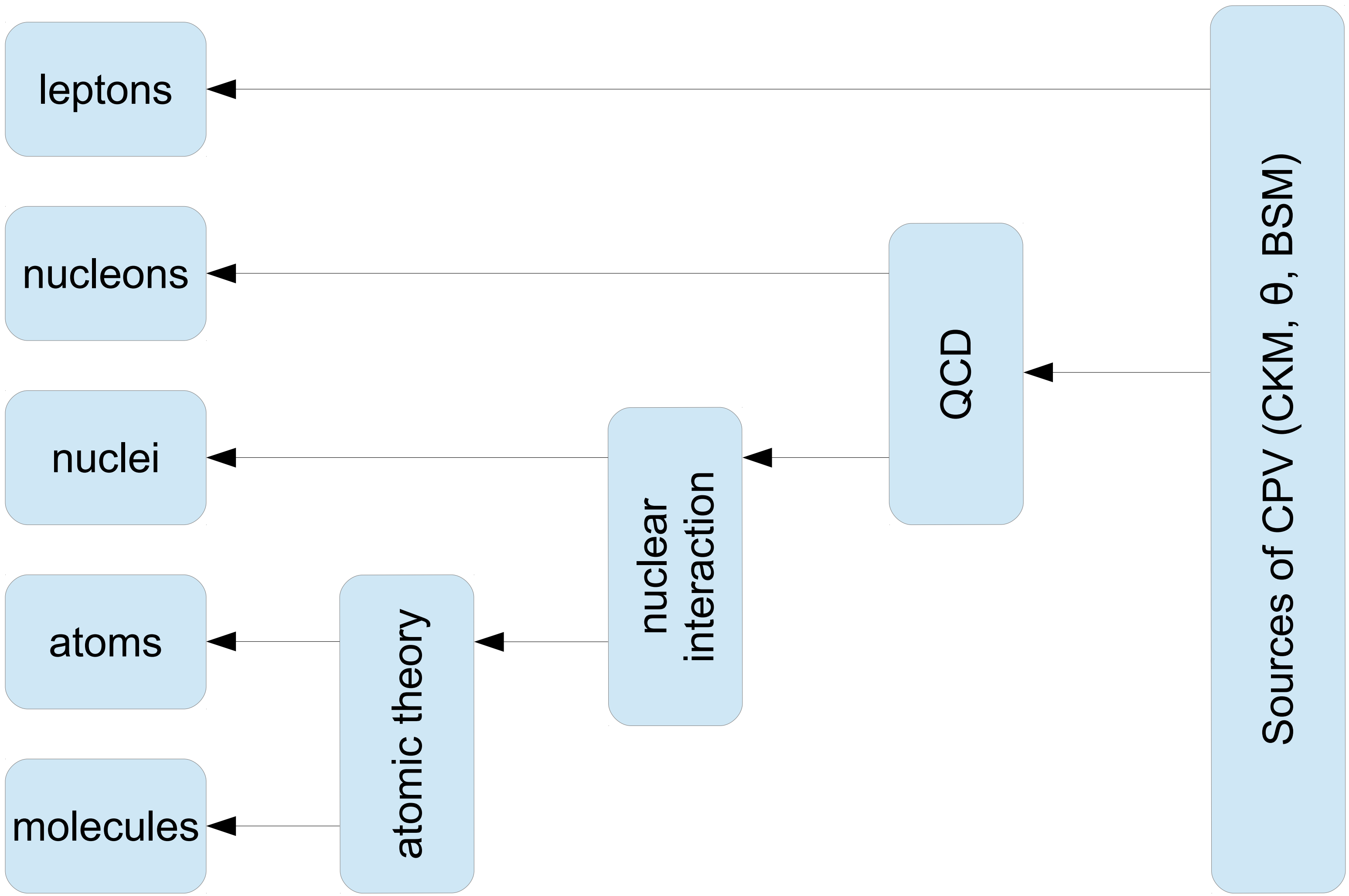
One major source:
Radial B field mimics an EDM effect:

- Difficulty: even small radial magnetic field, B_r can mimic EDM effect if :$\mu B_r \approx dE_r$
- Suppose $d = 10^{-29} e{\cdot}\mathrm{cm}$ in a field of $E = 10\mathrm{MV/m}$
- This corresponds to a magnetic field:
  $$B_r = \frac{dE_r}{\mu_N} = \frac{10^{-22}e\mathrm{V}}{3.1 \cdot 10^{-8}e\mathrm{V/T}} \approx 3 \cdot 10^{-17}\mathrm{T}$$
  (Earth Magnetic field $\approx 5 \cdot 10^{-5}$ T)

Solution: Use two beams running clockwise and counter clockwise, separation of the two beams is sensitive to B_r

Mitglied der Helmholtz-Gemeinschaft

Sources of CP-Violation



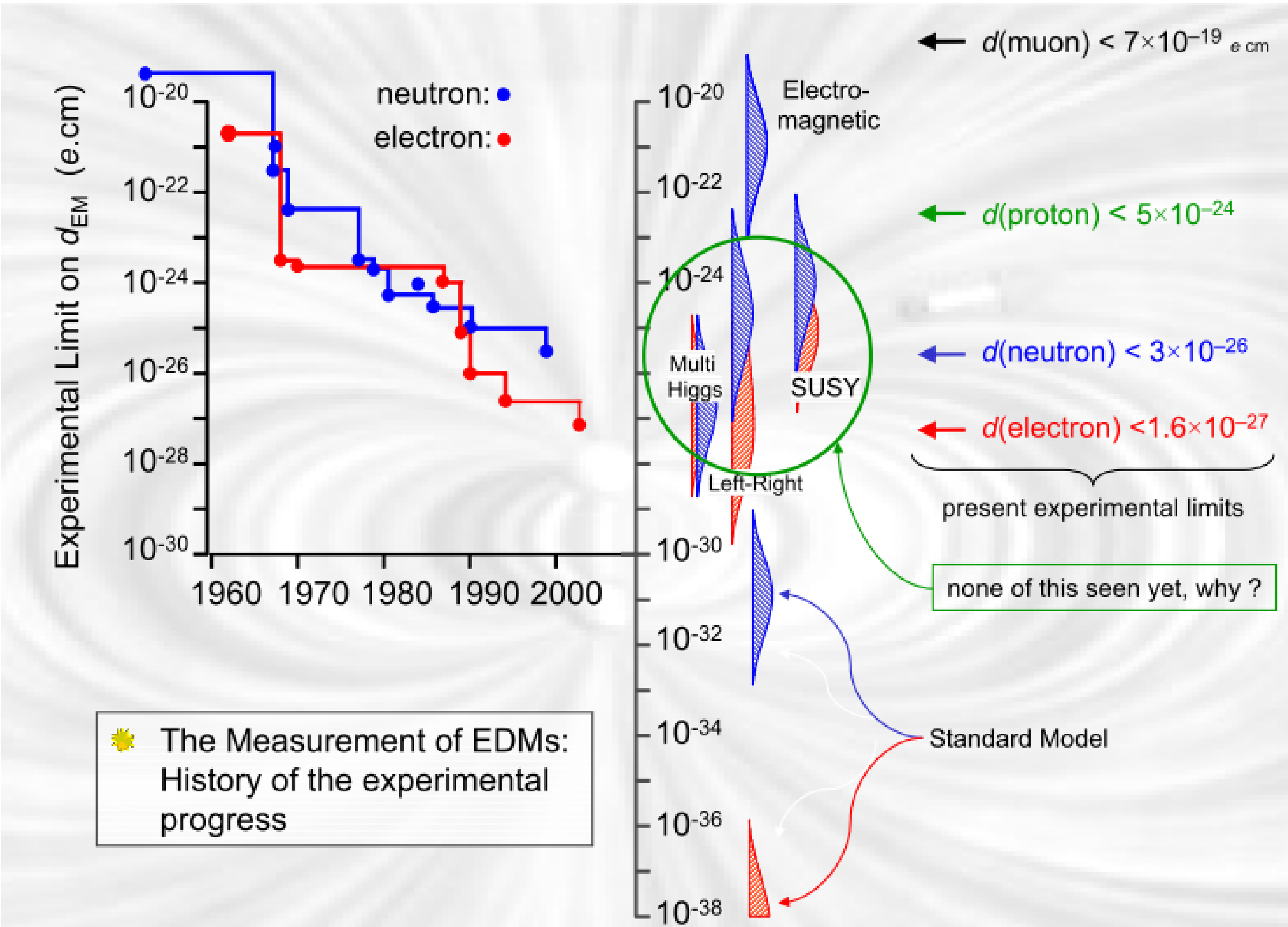
Disentanglement of different sources of CP violation needs various measurements

Limits on hadron EDMs

Particle / Atom	Current EDM Limit / e·cm
Neutron	$< 3 \cdot 10^{-26}$
^{199}Hg → Proton	$< 3.1 \cdot 10^{-29}$ $< 7.9 \cdot 10^{-25}$
Deuteron	?
^{3}He	?

- Proton limit deduced from atomic EDM limit
- No direct measurements for protons or deuterons yet

Limits on neutron and electron EDMs



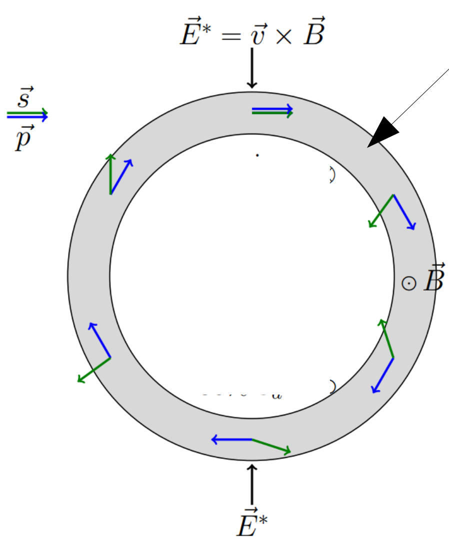
Solution 1: “RF-E-Dipole”

- Two ingredients:
  - Ring:

$$\vec{\Omega} = -\frac{e}{m}\left(G\vec{B} + \cancel{\left(\frac{1}{\gamma^2-1} - G\right)\left(\frac{\vec{\beta}\times\vec{E}}{c}\right)} + \frac{\eta}{2}\left(\cancel{\frac{\vec{E}}{c}} + \vec{\beta}\times\vec{B}\right)\right)$$

  - RF-E-Dipole:

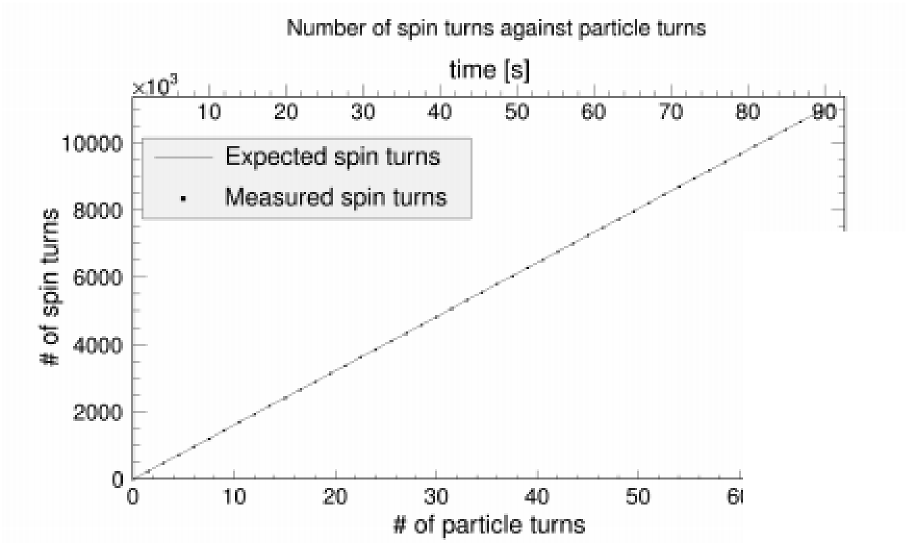
$$\vec{\Omega} = -\frac{e}{m}\left(\cancel{G\vec{B}} + \underbrace{\left(\frac{1}{\gamma^2-1} - G\right)}_{=0}\left(\frac{\vec{\beta}\times\vec{E}(t)}{c}\right) + \frac{\eta}{2}\left(\frac{\vec{E}(t)}{c} + \cancel{\vec{\beta}\times\vec{B}}\right)\right)$$



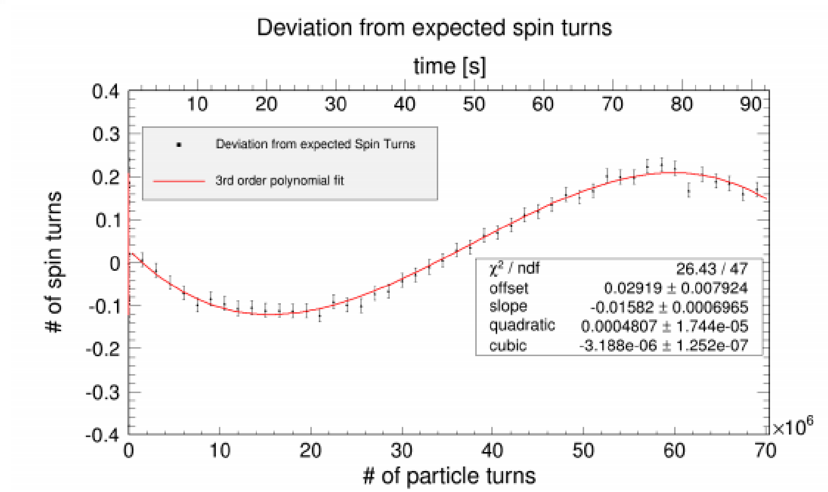
→ Idea:
lock phase of RF electric field to phase of spin precession

Disadvantage:
excites transversal motion of beam
→ Wien-Filter concept

Spin Tune measurements

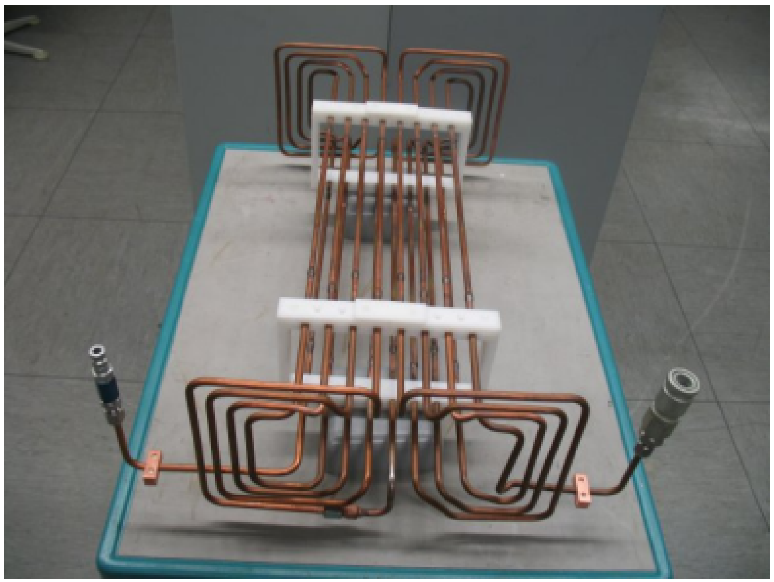


Slope equals $\nu = \gamma G$

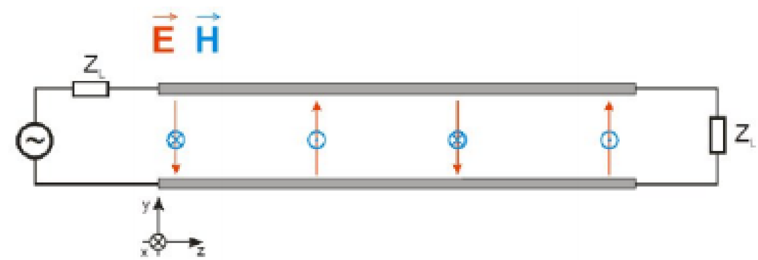


- We are sensitive to spin tune changes of the order of 10^{-9} in a single cycle ($\approx$ 100s)
- reason for varying spin tune is still under investigation
- powerful to keep spin aligned with momentum vector (vital for frozen spin method)

Wien-Filter-methods



Conventional design
R. Gebel, S. Mey (FZ Jülich)

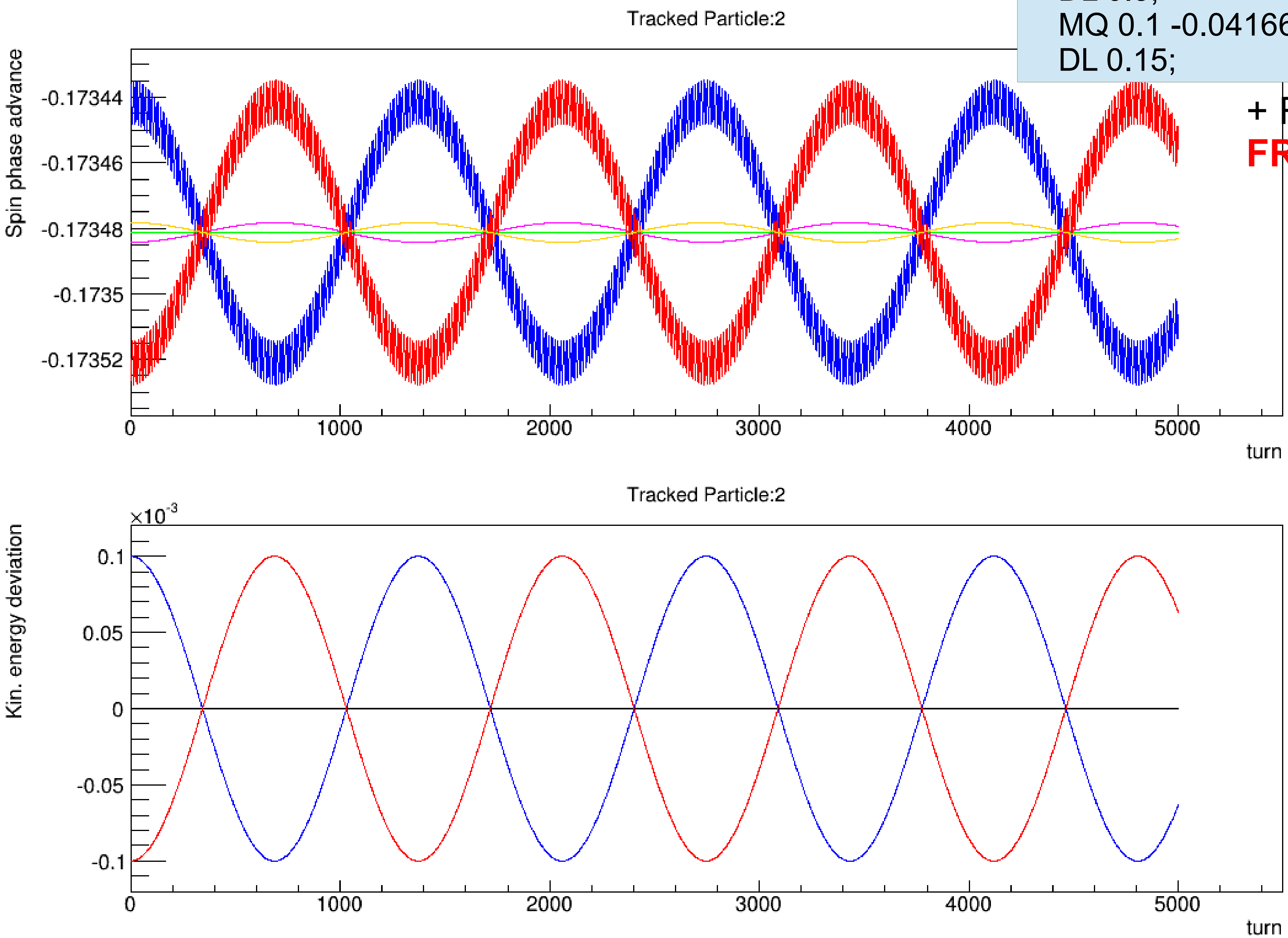


stripline design
D. Hölscher, J. Slim
(IHF RWTH Aachen)

FODO (RF) rectangular Dipoles

DL 0.15;
DP 2.546479 22.5 0.1;
DL 0.3;
MQ 0.1 0.04166 0.05;
DL 0.3;
MS 2.546479 22.5 0.1 0 0 0 0 0;
DL 0.3;
MQ 0.1 -0.04166 0.05;
DL 0.15;

+ RF command
FR 0;



FODO (RF) rectangular Dipoles

```
DL 0.15;
DP 2.546479 22.5 0.1;
DL 0.3;
MQ 0.1 0.04166 0.05;
DL 0.3;
MS 2.546479 22.5 0.1 0 0 0 0 0;
DL 0.3;
MQ 0.1 -0.04166 0.05;
DL 0.15;
```

+ RF command

FR 3;