Mitglied der Helmholtz-Gemeinschaft

Jefferson Lab
EXPLORING THE NATURE OF MATTER

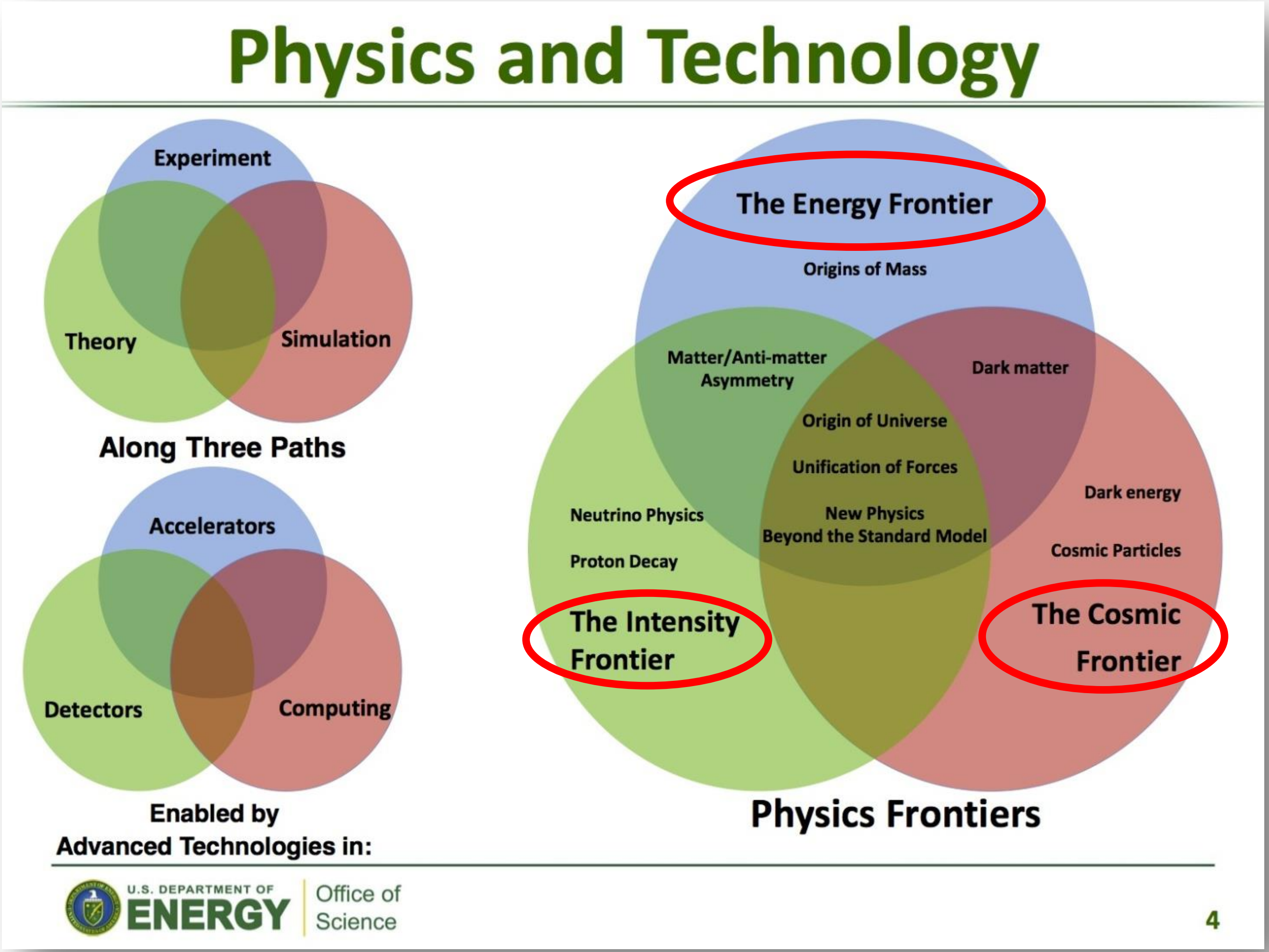
JÜLICH
FORSCHUNGSZENTRUM

Search for permanent electric dipole moments of protons and deuterons using storage rings

February 4, 2016

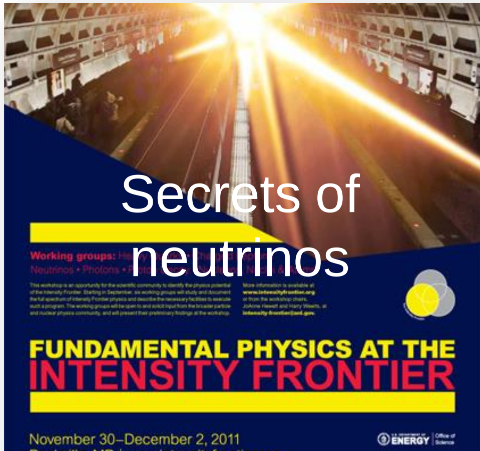
Frank Rathmann (on behalf of JEDI)
Accelerator Seminar, Jefferson Lab

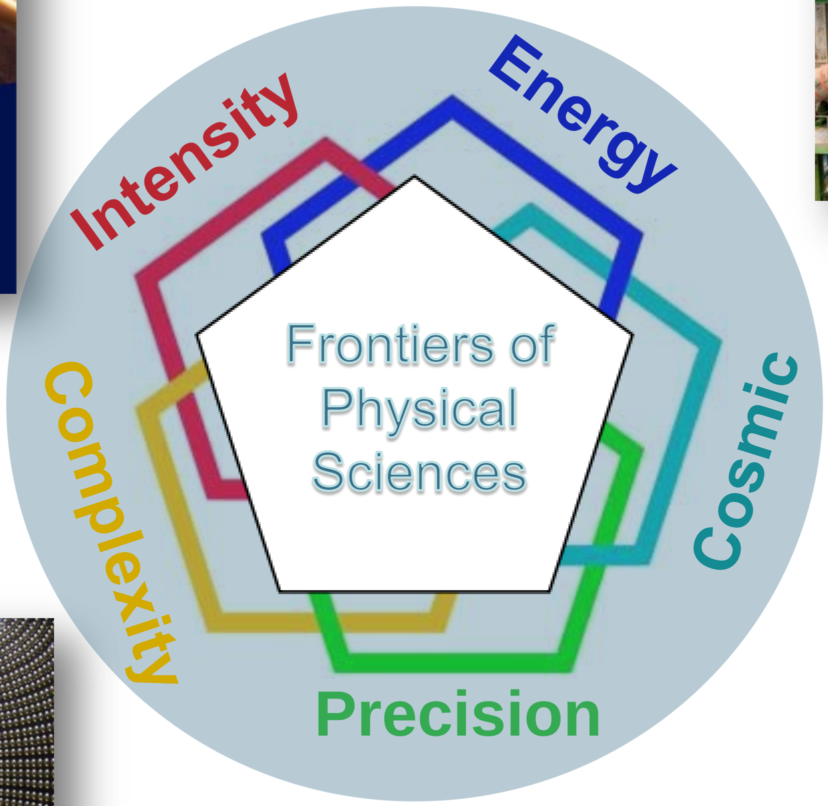
Preamble: The big challenges

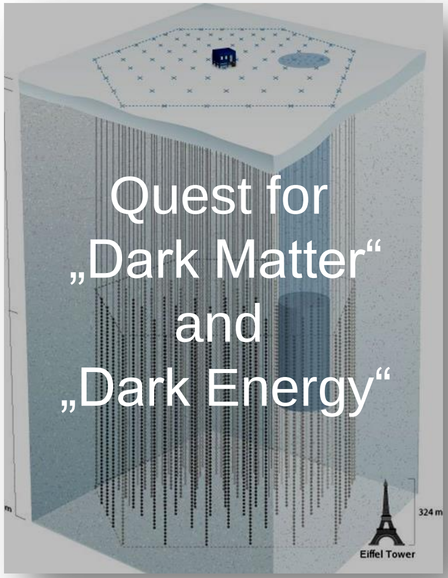


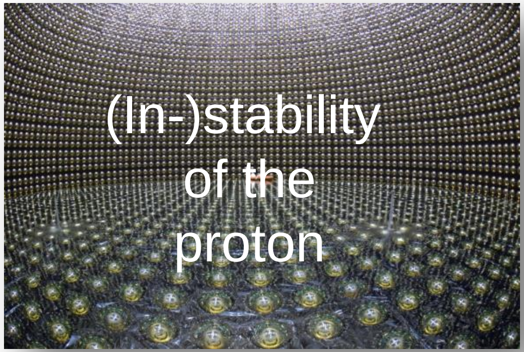
This is the conventional HEP wisdom, but there is more than that …

Preamble: Physics Frontiers









Preamble: Precision Frontier

CERN Courier November 2012

Viewpoint

Charting the future of European particle physics

Tatsuya Nakada considers what the updated European Strategy for Particle Physics needs to address.

for carrying out the research programme, such as accelerator science, detector R&D, computing and infrastructure for large detector construction, were also addressed. The meeting demonstrated that there is an emerging consensus that new physics must be studied both by direct searches at the highest-energy accelerator possible, as well as by precision experiments with and without accelerators.

The Preparatory Group is in the process of producing a summary document on the

ESPP, Cracow, September 2012

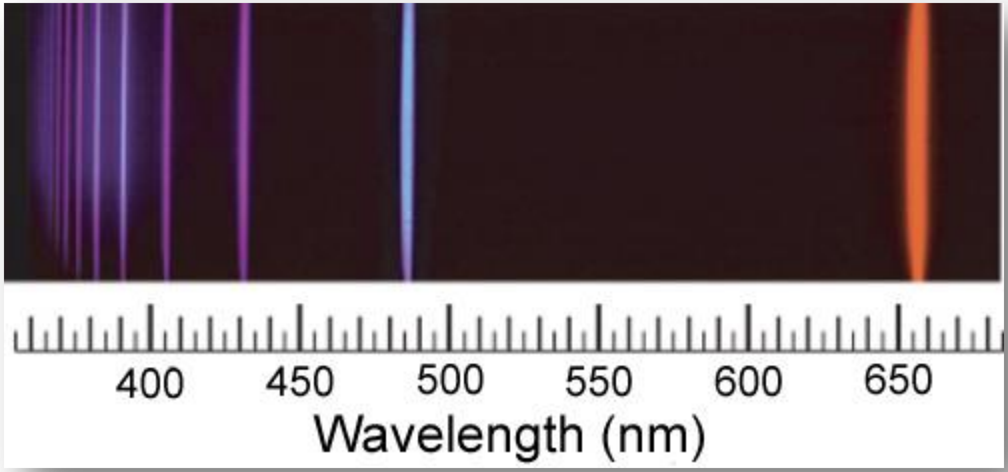
A most promising **additional** frontier: *Precision*

Outline

- **Introduction**
- Recent Achievements
  - Spin coherence time
  - Spin tune measurement
  - Study of magnetic machine imperfections
- Technical challenges
- Toward a first direct p, d EDM measurement
- Conclusion

Introduction: Precision Frontier

Johann
Jakob
Balmer
(1885)

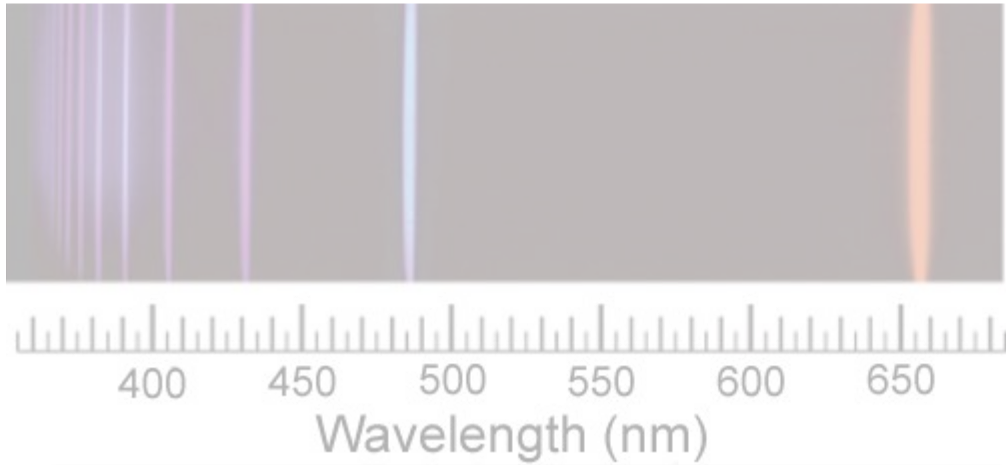


Balmer Series
→ H-atom

Striving for the ultimate precision/sensitivity: **example hydrogen**

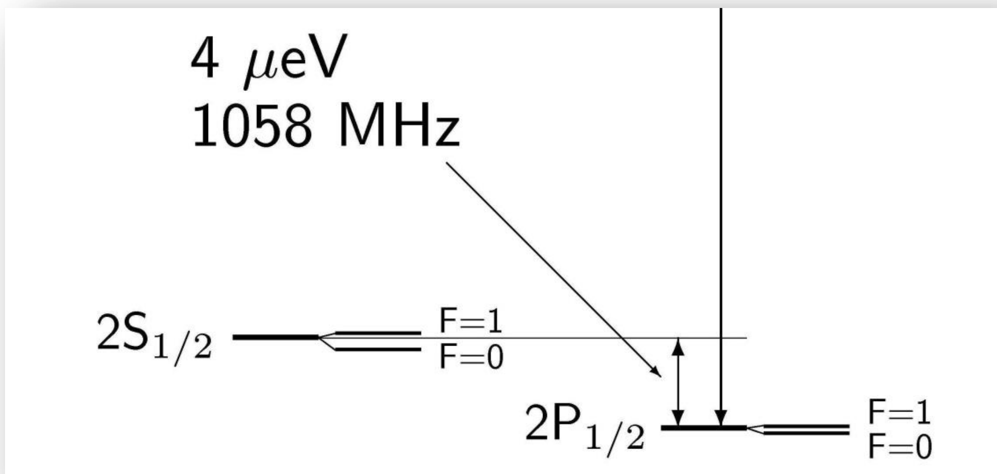
Introduction: Precision Frontier

Johann Jakob Balmer (1885)



Balmer Series
→ **H-atom**

Willis E. Lamb (1947)



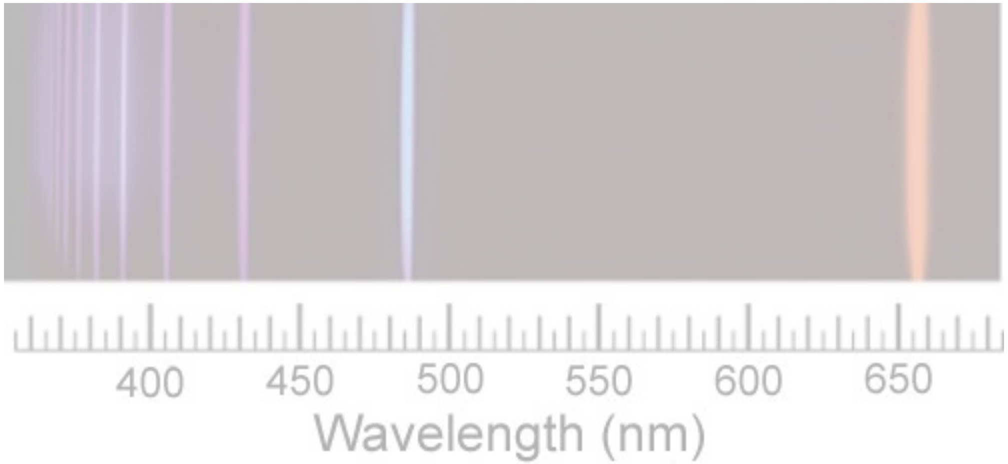
Lamb-shift
(NP 1955)
→ **QED**

$g/2 = 1 + \alpha/2\pi$
~ 1.00116

Striving for the **ultimate precision/sensitivity**

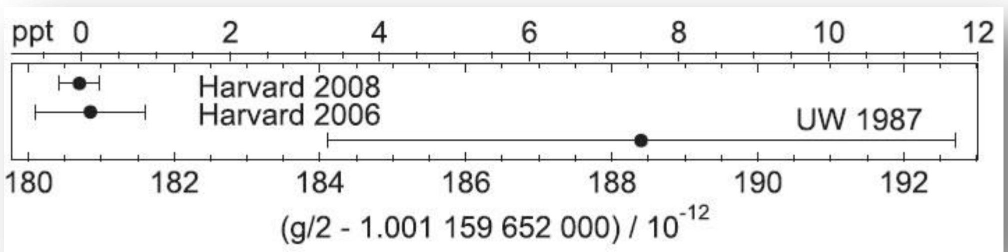
Introduction: Precision Frontier

Johann Jakob Balmer (1885)



Balmer Series
→ H-atom

G. Gabrielse et al. (2008)



$$g/2 = 1.001\,159\,652\,180\,73(28) \quad [0.28\ \text{ppt}].$$

Electron MDM
→ SM test

(…)

V. Weisskopf: „To **understand hydrogen** is to understand all of physics“

Five questions:

1. Why do we observe matter and almost no antimatter if we believe there is a symmetry between the two in the universe?
2. What is this "dark matter" that we can't see that has visible gravitational effects in the cosmos?
3. Why can't the Standard Model predict a particle's mass?
4. Are quarks and leptons actually fundamental, or made up of even more fundamental particles?
5. Why are there exactly three generations of quarks and leptons? How does gravity fit into all of this?

From http://particleadventure.org/beyond_start.html

Physics: Baryogenesis

Big
Bang

↓

Early
Universe

Symmetry

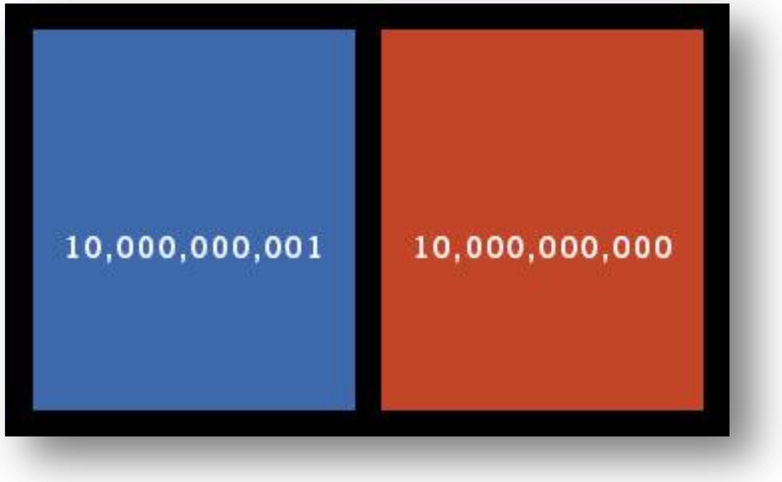
Matter **Anti-matter**

Assertion: Universe „started“ with **equal amounts** of matter and antimatter !

Physics: Baryogenesis

Big
Bang

Early
Universe



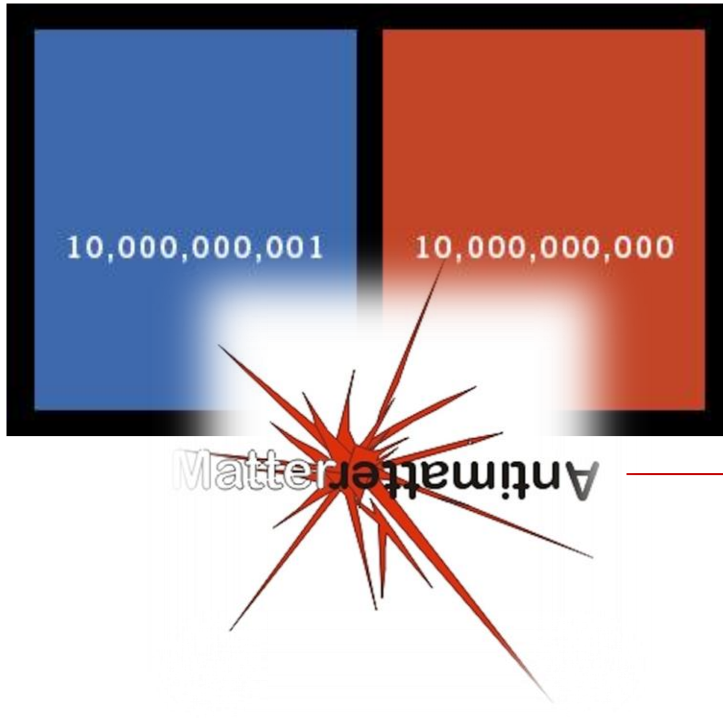
Matter **Anti-matter**

Very soon, a slight **asymmetry developed** (CP / T violation)

Physics: Baryogenesis

Big
Bang

Early
Universe



Matter
anti-matter
annihilation
→ photons

Matter **Anti-matter**

All the **anti-matter annihilated** with matter

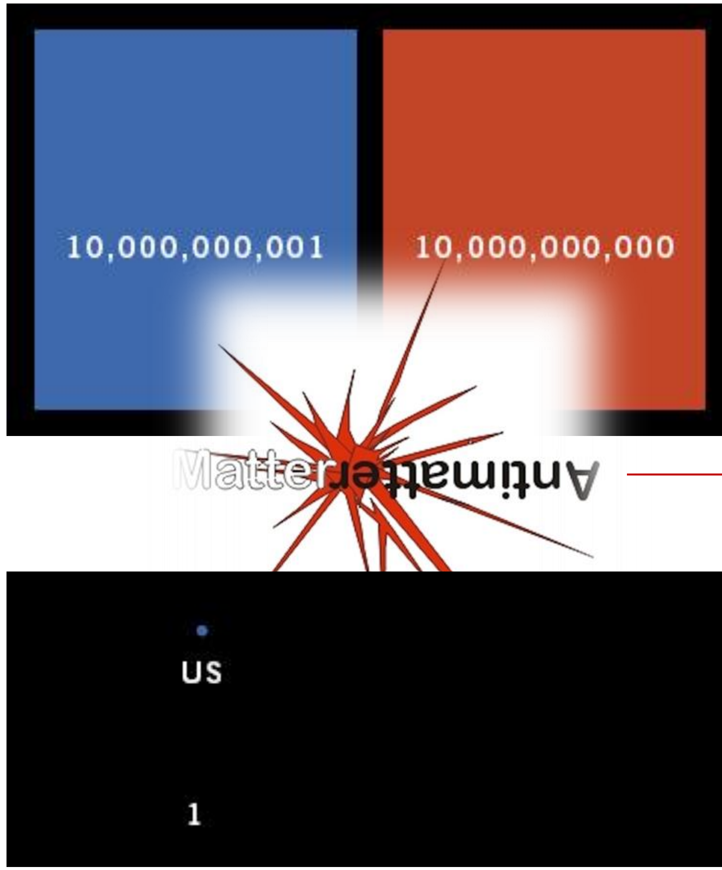
Physics: Baryogenesis

Big Bang

~~CP~~

Early Universe

Today

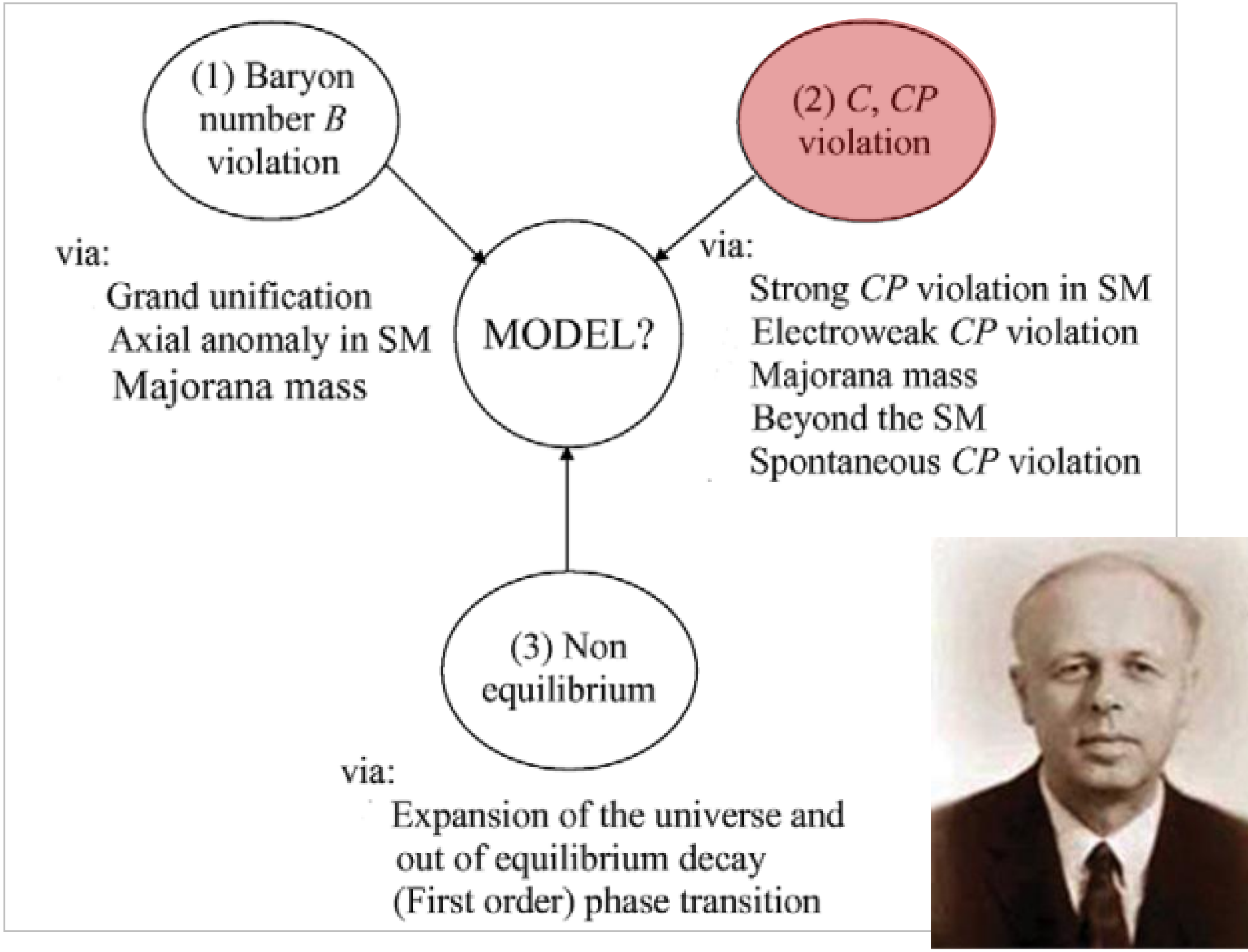


Matter **Anti-matter**

Matter anti-matter annihilation → photons

Now, only **matter** is **left over** !

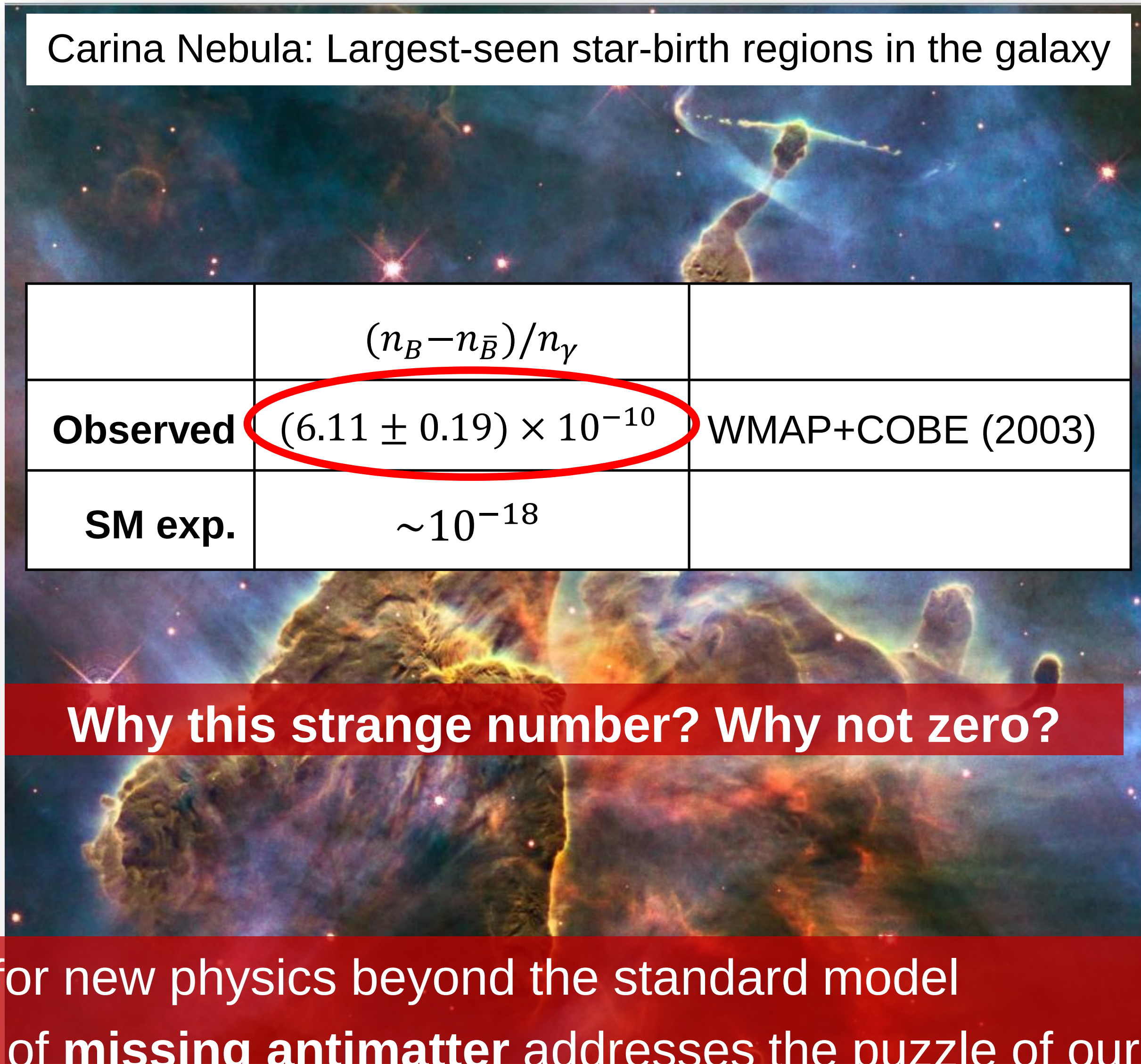
Physics: Baryogenesis



(1967)

Ingredients for baryogenesis: **3 Sakharov conditions**

Physics: Observed Baryon Asymmetry



Carina Nebula: Largest-seen star-birth regions in the galaxy

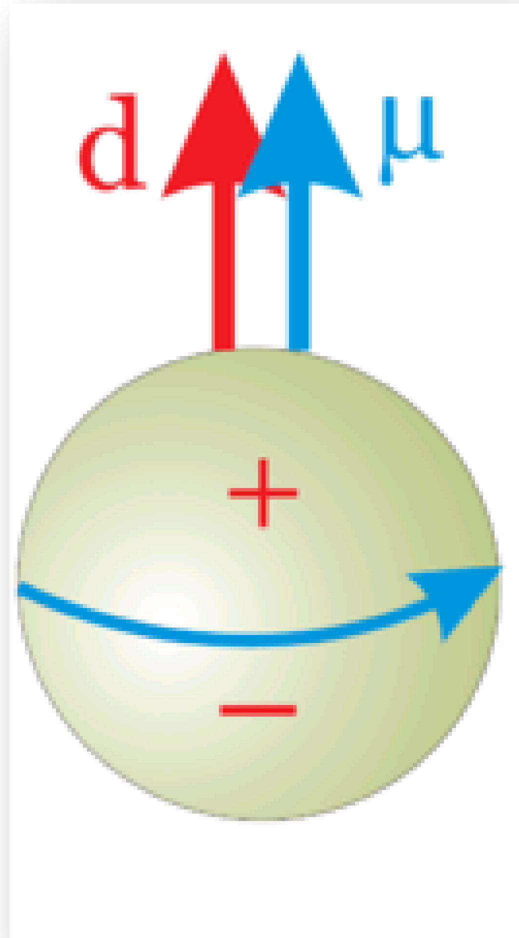
	$(n_B - n_{\bar{B}})/n_\gamma$	
Observed	$(6.11 \pm 0.19) \times 10^{-10}$	WMAP+COBE (2003)
SM exp.	$\sim 10^{-18}$	

Why this strange number? Why not zero?

- Search for new physics beyond the standard model
- Mystery of **missing antimatter** addresses the puzzle of our existence

Physics: Fundamental Particles

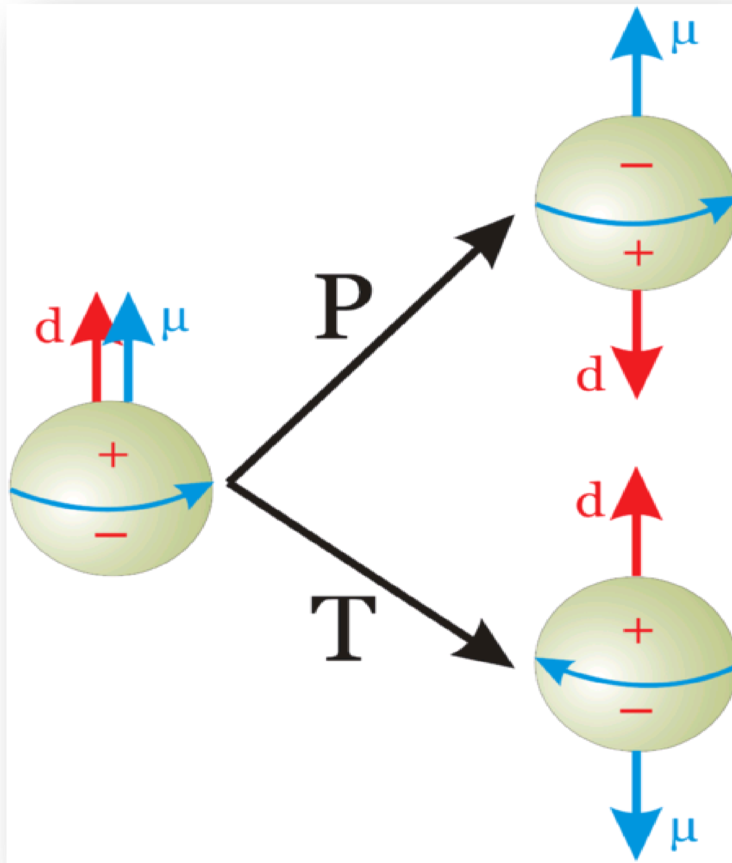
Charge symmetric
$\rightarrow$ No EDM ($d = 0$)



$\vec{\mu}$: **MDM**
$\vec{d}$: **EDM**

Do particles (e.g., electron, nucleon) have an EDM?

EDMs: Discrete Symmetries



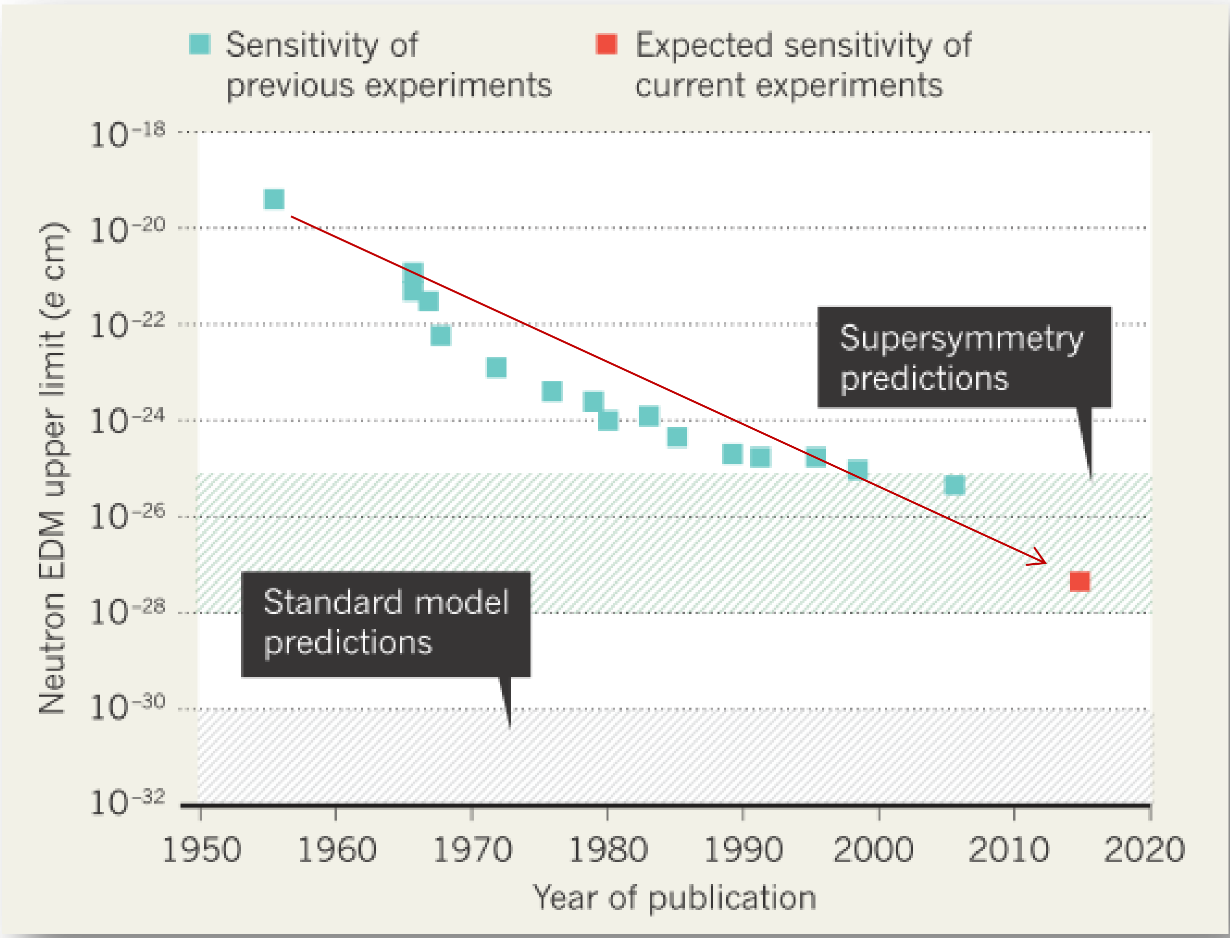
Not Charge symmetric

$\vec{d}$
(aligned with spin)

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

Introduction: Precision Frontier

Example: Neutron (nEDM)

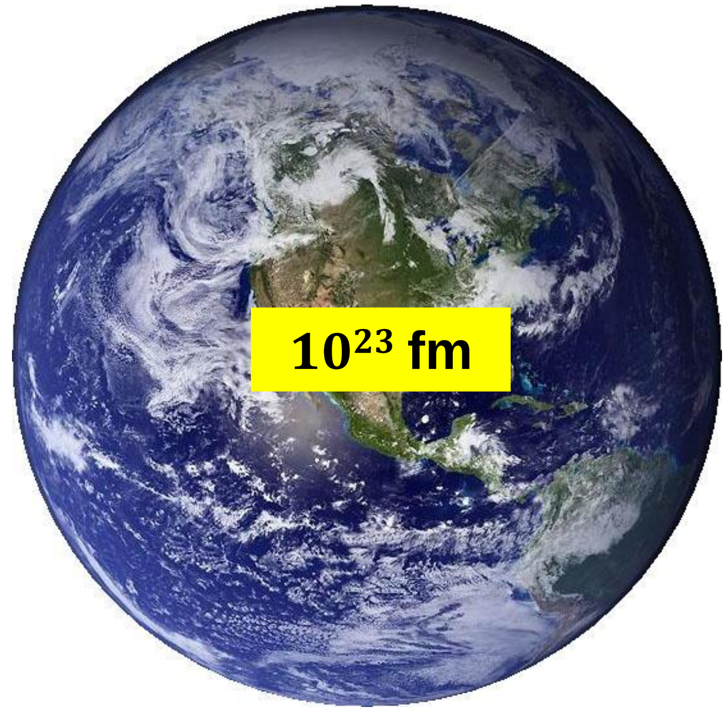


Adapted from: Nature, Vol 482 (2012)

Search for **Electric Dipole Moments** (EDM) of fundamental particles

Introduction: Precision Frontier

Nucleon → Earth

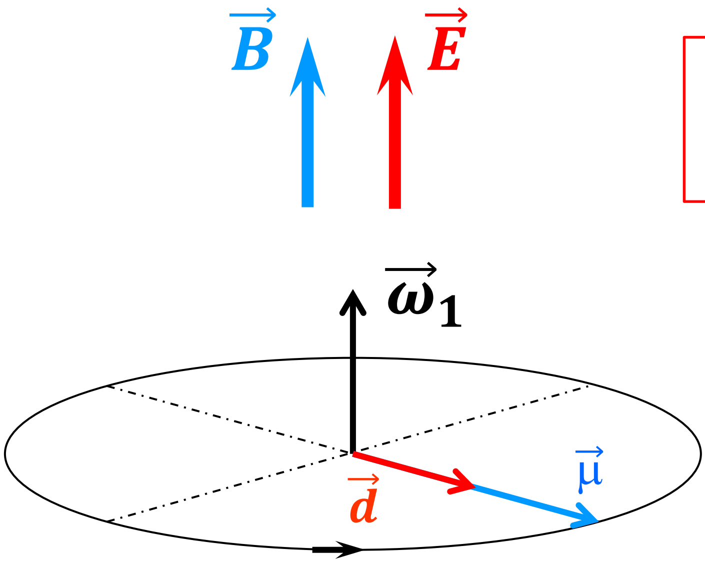


Current **upper limit** →
separation ≈ size of a hair

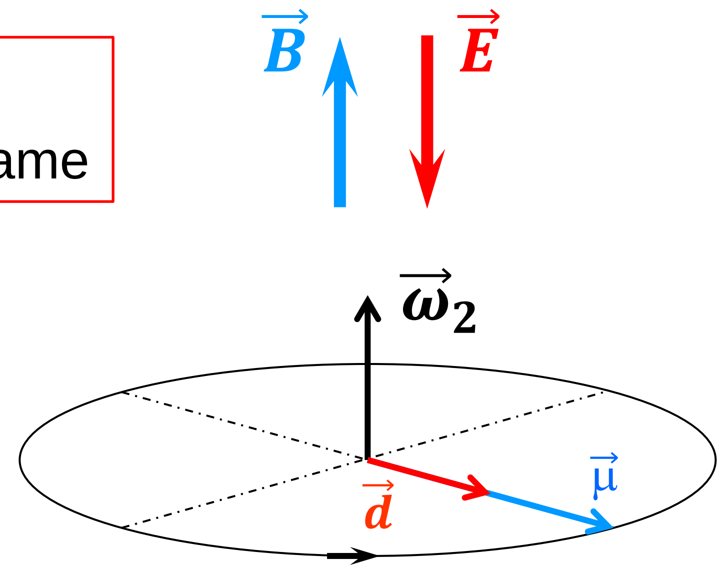
An EDM is **VERY** small !!

Measurement principle: Neutral particle EDM

Particle in ground state: $\boldsymbol{s} = \frac{\mathbf{1}}{\mathbf{2}}$



1. Reverse $\vec{E}$
2. Keep $\vec{B}$ the same



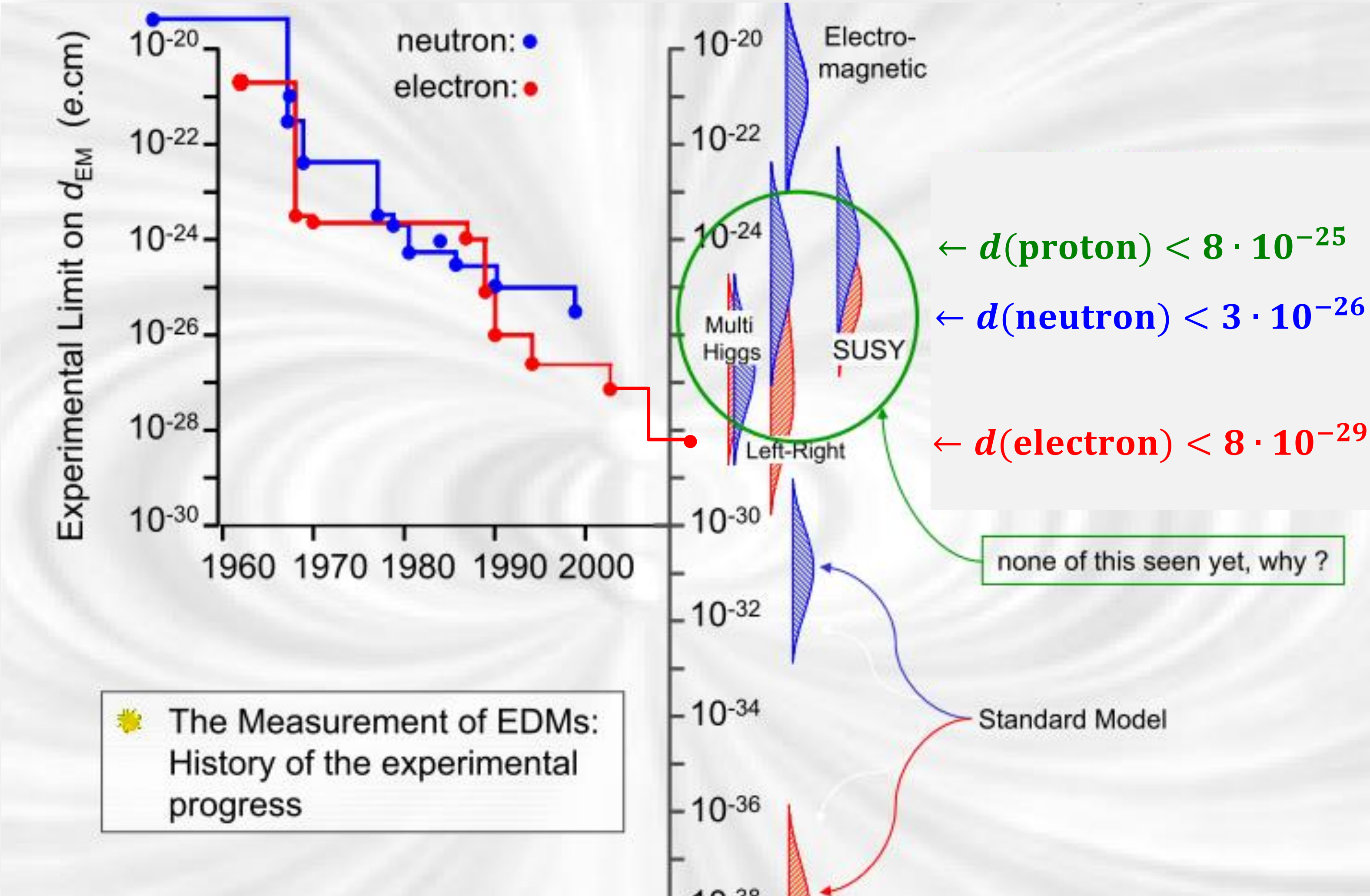
$$\omega_1 = \frac{2\mu B + 2dE}{h}$$

$$\boxed{\Rightarrow \omega_1 - \omega_2 = \frac{4dE}{h}}$$

$$\omega_2 = \frac{2\mu B - 2dE}{h}$$

One challenge: Shield external sources of B to levels $|B_{\mathrm{ext}}| < 1\,\mathrm{nT}$.

Physics Potential of EDMs



$\leftarrow d(\text{proton}) < 8 \cdot 10^{-25}$

$\leftarrow d(\text{neutron}) < 3 \cdot 10^{-26}$

$\leftarrow d(\text{electron}) < 8 \cdot 10^{-29}$

J.M. Pendlebury: „nEDM has killed more theories than any other single exp‘t“

Introduction: Why charged particle EDMs?

- No direct measurements of charged hadron EDMs
- Potentially higher sensitivity than neutrons
  - longer life time
  - more stored polarized protons/deuterons
  - larger electric fields
- Approach complimentary to neutron EDM
- $d_d \stackrel{?}{=} d_p + d_n \Rightarrow$ access to θ_{QCD}
- EDM of a single particle not sufficient to identify CP-violating source

Charged particle EDM experiments can potentially provide a higher sensitivity than nEDM

EDMs: Naive estimate of the nucleon EDM scale

Khriplovich & Lamoreux (1997); Nikolaev (2012)

- $\boldsymbol{CP}$ & $\boldsymbol{P}$ conserving magnetic moment ≈ nuclear magneton $\boldsymbol{\mu_N}$

$$\mu_N = \frac{e}{2m_p} \sim 10^{-14}\text{e cm}$$

- A non-zero EDM requires
  - P violation: the price to pay is $\approx 10^{-7}$, and
  - CP violation (from K-decays): the price to pay is $\approx 10^{-3}$
- In summary: $\boxed{|\boldsymbol{d_N}| \approx \mathbf{10^{-7}} \times \mathbf{10^{-3}} \times \boldsymbol{\mu_N} \approx \mathbf{10^{-24}}\ \mathbf{e\ cm}}$
- In SM (without θ term): $\boxed{\left|\boldsymbol{d_N}^{\mathbf{SM}}\right| \approx \mathbf{10^{-7}} \times \mathbf{10^{-24}} \approx \mathbf{10^{-31}}\ \mathbf{e\ cm}}$

⇒ Region to search for BSM physics $\left(\theta_{\text{QCD}} = 0\right)$ using nucleon EDMs:
$\mathbf{10^{-24}}\mathbf{e\ cm} > |\boldsymbol{d_N}| > \mathbf{10^{-31}}\ \mathbf{e\ cm}$

Physics: Present limits of EDMs

EDM searches: Up to now only upper limits (in e·cm)

Particle/Atom	Current EDM Limit	Future Goal
Electron	$< 8.7 \cdot 10^{-29}$	
Muon	$< 1.8 \cdot 10^{-19}$	
Neutron	$< 3 \cdot 10^{-26}$	$\sim 10^{-28}$
^{199}Hg	$< 3.1 \cdot 10^{-29}$	$\sim 10^{-29}$
^{129}Xe	$< 6 \cdot 10^{-27}$	$\sim 10^{-30} - 10^{-33}$
Proton	$< 7.9 \cdot 10^{-25}$	$\sim 10^{-29}$
Deuteron	?	$\sim 10^{-29}$

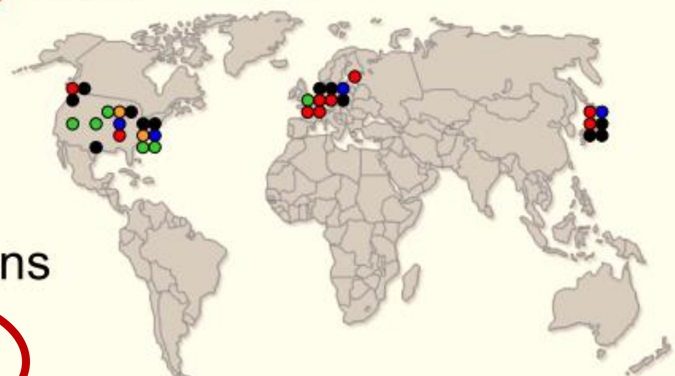
- No direct measurements of electron (ThO molecule) or proton (^{199}Hg) EDMs
- No measurement at all of deuteron EDM

Large effort on worldwide scale to improve limits and to find EDMs

Physics: Ongoing/planned Searches

Rough estimate of numbers of researchers, in total ~500 (with some overlap)

- Neutrons ~200
  - @ILL
  - @ILL,@PNPI
  - @PSI
  - @FRM-2
  - @RCNP,@TRIUMF
  - @SNS
  - @J-PARC
- Molecules ~50
  - YbF@Imperial
  - PbO@Yale
  - ThO@Harvard
  - HfF+@JILA
  - WC@UMich
  - PbF@Oklahoma
- Atoms ~100
  - Hg@UWash
  - Xe@Princeton
  - Xe@TokyoTech
  - Xe@TUM
  - Xe@Mainz
  - Cs@Penn
  - Cs@Texas
  - Fr@RCNP/CYRIC
  - Rn@TRIUMF
  - Ra@ANL
  - Ra@KVI
  - Yb@Kyoto



- Ions-Muons ~200
  - @BNL
  - @FZJ
  - @FNAL
  - @JPARC

new

- Solids ~10
  - GGG@Indiana
  - ferroelectrics@Yale

P. Harris, K. Kirch … A large worldwide effort

Concept: Experimental requirements

- High precision, primarily electric storage ring
  - 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 ($\tau_{\mathrm{SCT}} = 1000\ \mathrm{s}$)
- Efficient polarimetry (analyzing power $A_y \approx 0.6, f = 0.005$)

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

Goal: provide σ_{syst} to the same level

Concept: Frozen spin Method

For transverse electric and magnetic fields in a ring, the ***anomalous*** spin precession is described by Thomas-BMT equation:

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

Magic condition: Spin along momentum vector

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

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

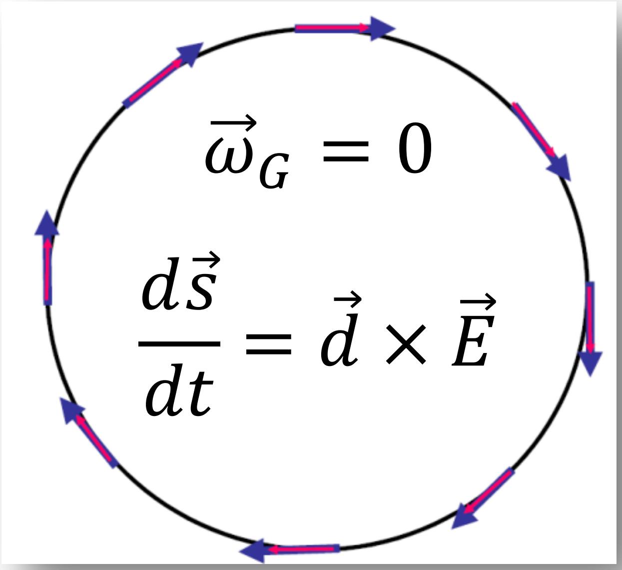
2. For $G > 0$ (protons) in an all electric ring

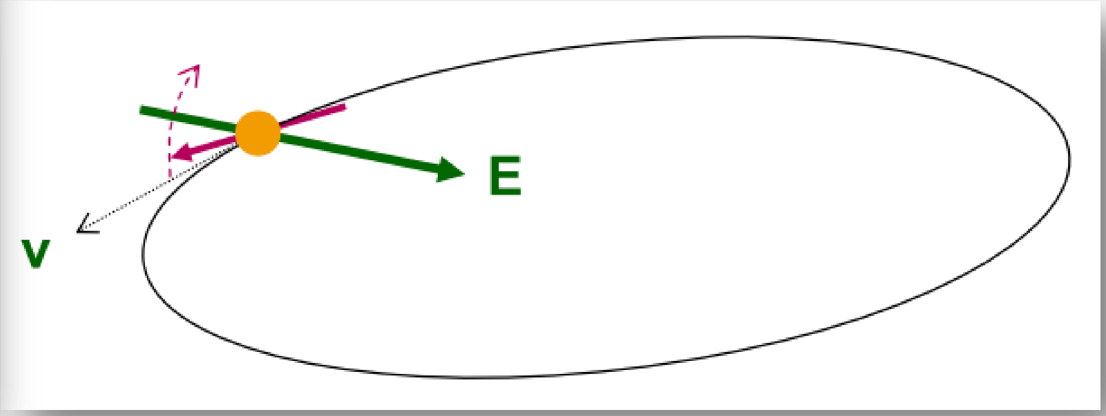
$$G - \left(\frac{m}{p}\right)^2 = 0 \;\Rightarrow p = \frac{m}{\sqrt{G}} = 700.74\ \mathrm{MeV/c}$$ (magic)

→ Magic rings to measure EDMs of **free** charge particles

Concept: Rings for EDM searches

- **Place particles in a storage ring**
- **Align spin along** momentum („freeze“ horizontal spin precession)
- **Search for time development of vertical polarization**



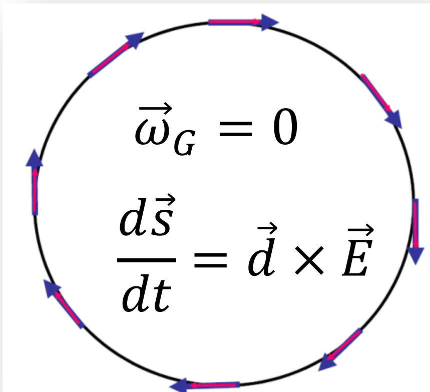


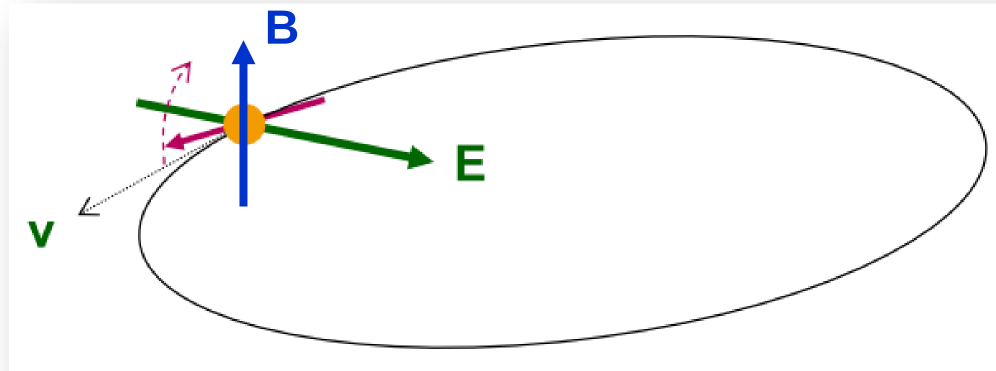
New Method to measure EDMs of charged particles:

- **Magic rings with spin frozen along momentum**
- **Polarization buildup $P_y(t) \sim d$**

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

Concept: Systematics

Magnetic fields:

- Radial field B_r mimics EDM effect when $\mu \times B_r \approx d \times E_r$
- With $d = 10^{-29}\ \mathrm{e \cdot cm}$ in a field of $E = 10\ \mathrm{MV/m}$,

$$B_r = \frac{dE_r}{\mu_n} = \frac{10^{-31} \cdot 10^{7}\,\mathrm{eV}}{3.152 \cdot 10^{-8}\ \mathrm{eV/T}} = 3.1 \cdot 10^{-17}\ \mathrm{T}$$

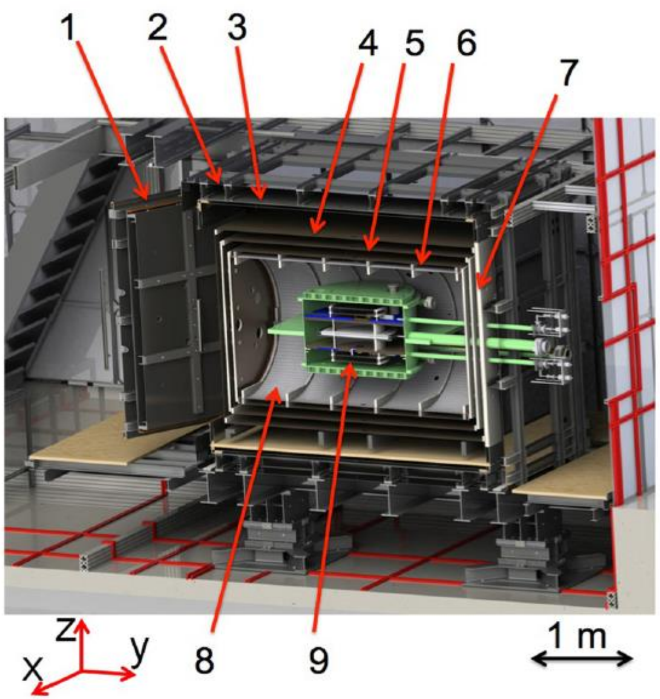
- **Solution:** Use two beams *simultanously*, clockwise (CW) and counter-clockwise (CCW), the vertical separation of the beam orbits is sensitive to B_r.

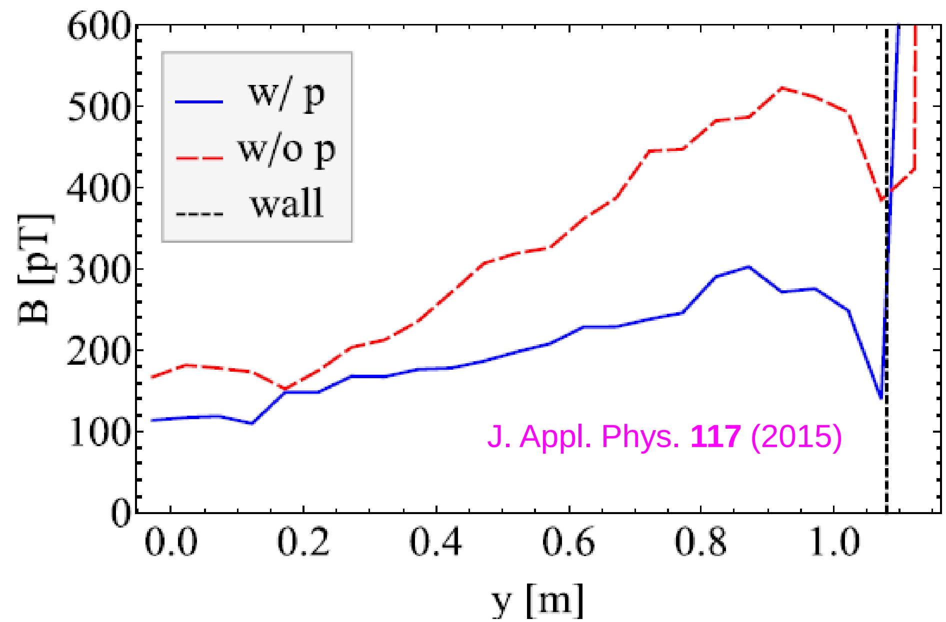
Use CW and CCW beams to tackle systematics

Recent Progress: Magnetic shielding

Next generation nEDM experiment under development at TUM (FRM II):

- **Goal:** Improve present nEDM limit by factor 100.
- Experiment shall use multi-layer shield.
- Applied magnetic field: $\mathrm{B} \approx 1\text{–}2.5\ \mu\mathrm{T}$.





At mHz frequencies, damping of $|B_{\mathrm{ext}}| \approx 1 \cdot 10^6$ achieved

Concept: Systematics, Orbit splitting (Dave Kawall)

- Splitting of beam orbits: $\delta y = \pm \frac{\beta c R_0 B_r}{E_r {Q_y}^2} = \pm 1 \cdot 10^{-12}\ \mathrm{m}$
- $Q_y \approx 0.1$ denotes the vertical betatron tune
- Modulate $Q_y = {Q_y}^0[1 - m\cos(\omega_m t)]$, with $m \approx 0.1$
- Splitting corresponds to $B \approx 0.4 \cdot 10^{-3}\ \mathrm{fT}$
- In one year of measurement: 10^4 fills of $1000\ s$ each

  $\Rightarrow\ \sigma_B = 0.4 \cdot 10^{-1}\mathrm{fT}$ per fill

Required sensitivity $\approx 1.25\ \mathrm{fT}/\sqrt{\mathrm{Hz}}$, achievable with state-of-the-art SQUID magnetometers.

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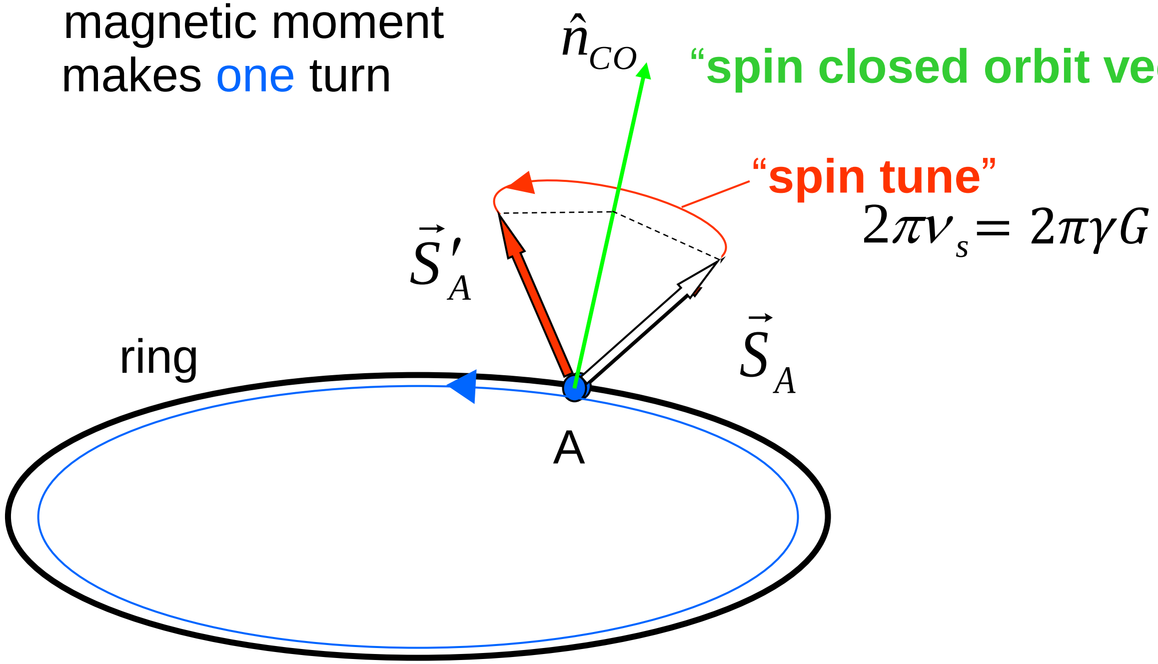
Insert: Spin closed orbit and spin tune

Spin closed orbit

one particle with
magnetic moment
makes one turn

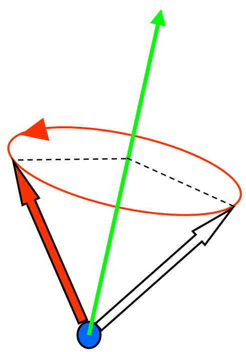


stable polarization
if $\vec{S} \parallel \hat{n}_{CO}$

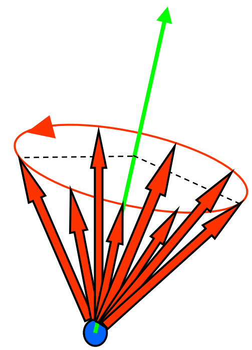
The number of spin precessions per turn is called spin tune ν_s

Challenge: Spin coherence time (SCT)

We usually don‘t worry about coherence of spins along $\hat{n}_{co}$



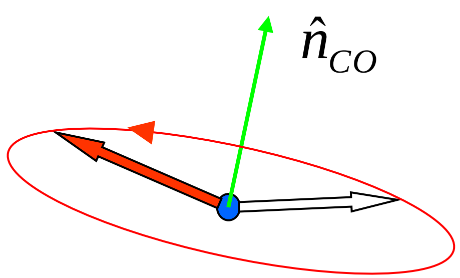
At injection all
spin vectors aligned (coherent)



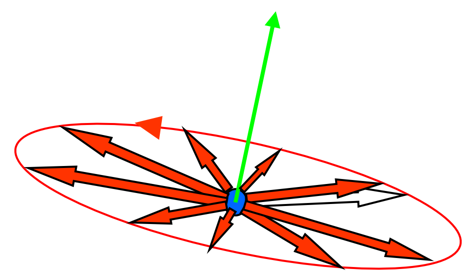
After some time, spin vectors get out of
phase and fully populate the cone

Polarization along
$\hat{n}_{co}$ not affected!

Situation very different, when you deal with $\vec{S} \perp \hat{n}_{co}$ machines with frozen spin.



At injection all spin vectors aligned



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

Longitudinal polarization
vanishes!

In a machine with frozen spins the buildup time
to observe a polarization $P_y(t)$ is limited by τ_{SCT}.

EDM at COSY: COoler SYnchrotron

Cooler and storage ring for (polarized) protons and deuterons

$p = 0.3 - 3.7\ \mathrm{GeV/c}$

Phase space cooled internal & extracted beams

… an ideal starting point for EDM search

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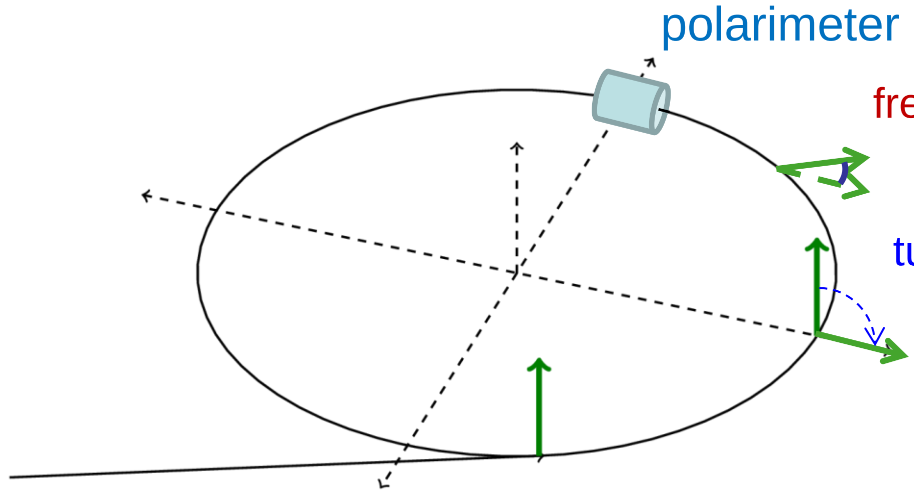
Spin coherence time: Experimental investigation



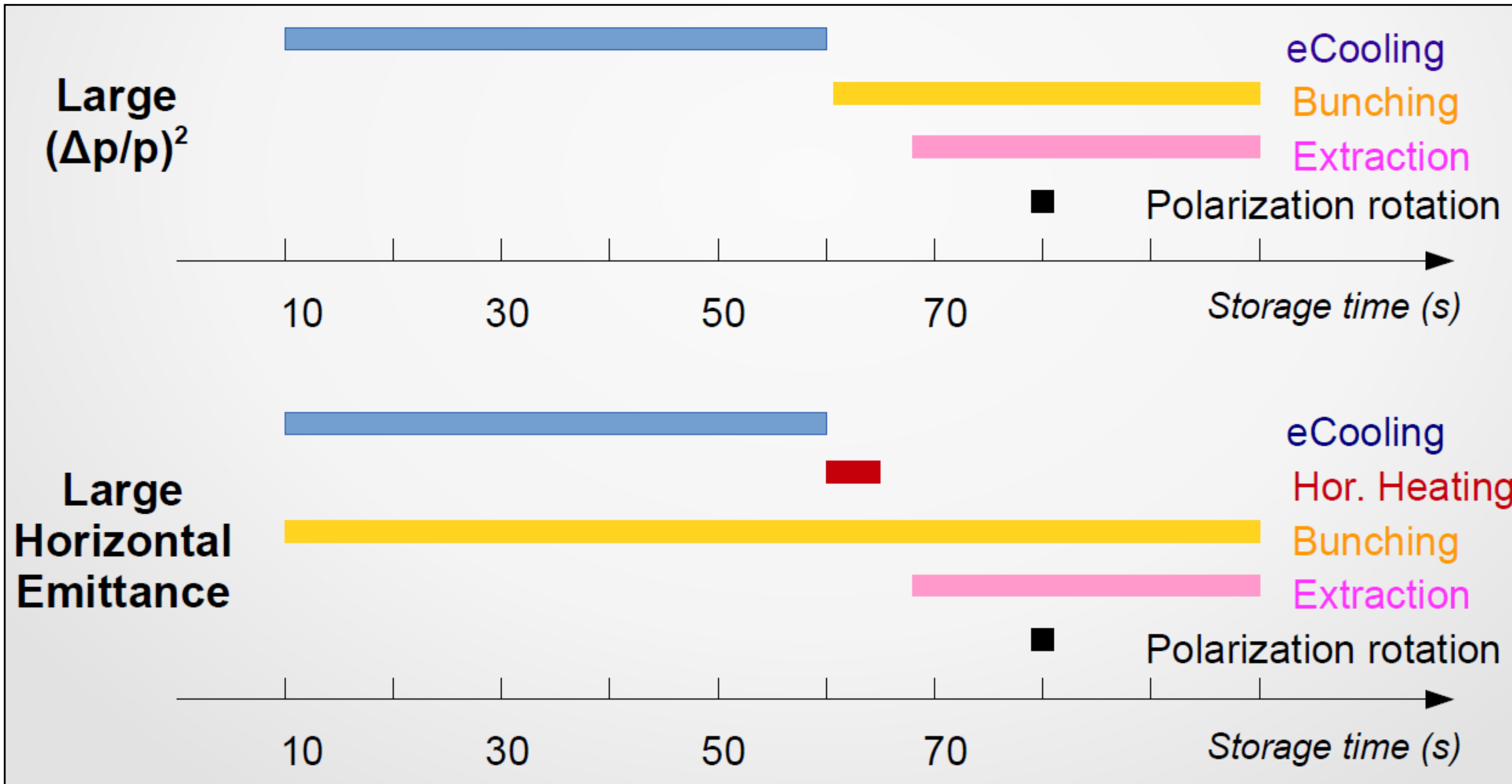
1. Vertically polarized deuterons stored in COSY at $p \approx 1\,\frac{\mathrm{GeV}}{\mathrm{c}}$.
2. The polarization is flipped into horizontal plane with RF solenoid (takes $\approx 200\ \mathrm{ms}$).
3. Beam slowly extracted on Carbon target with ramped bump or by heating the beam.
4. Horizontal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

Experimental investigations of SCT in storage ring: Keep track of the event time and revolution time in each turn during a cycle of a few hundred seconds.

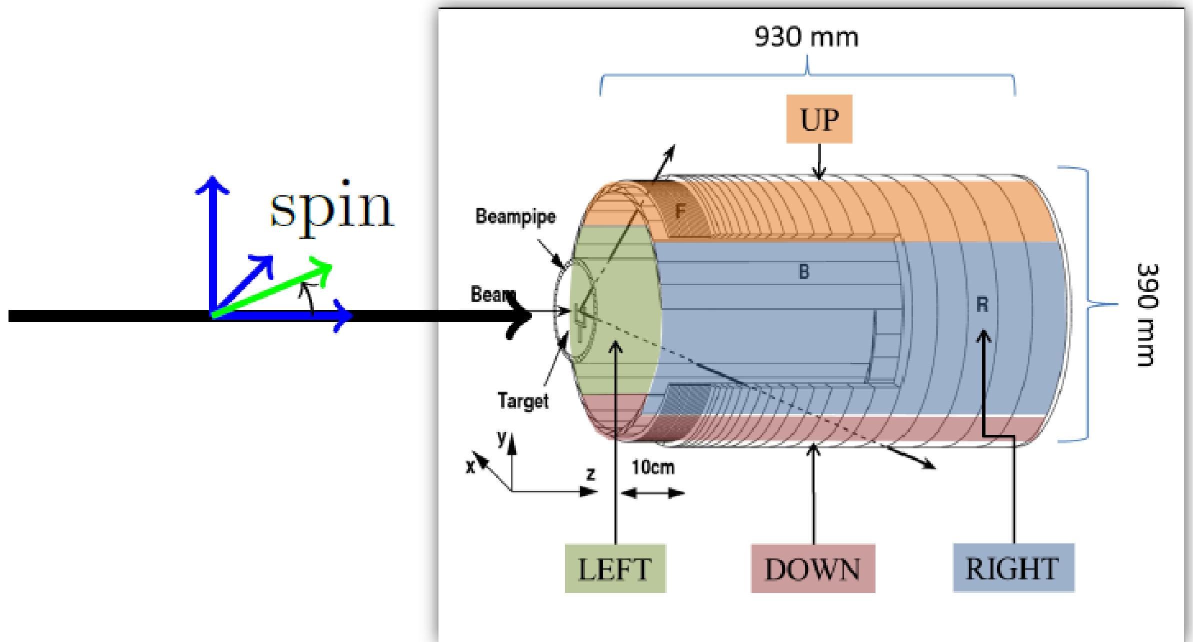
Spin coherence time: Beam setups

Two different beam setups were used:

1. Large $\frac{\Delta p}{p}$, and
2. large horizontal beam emittance.



Polarimeter: Experimental investigation of SCT

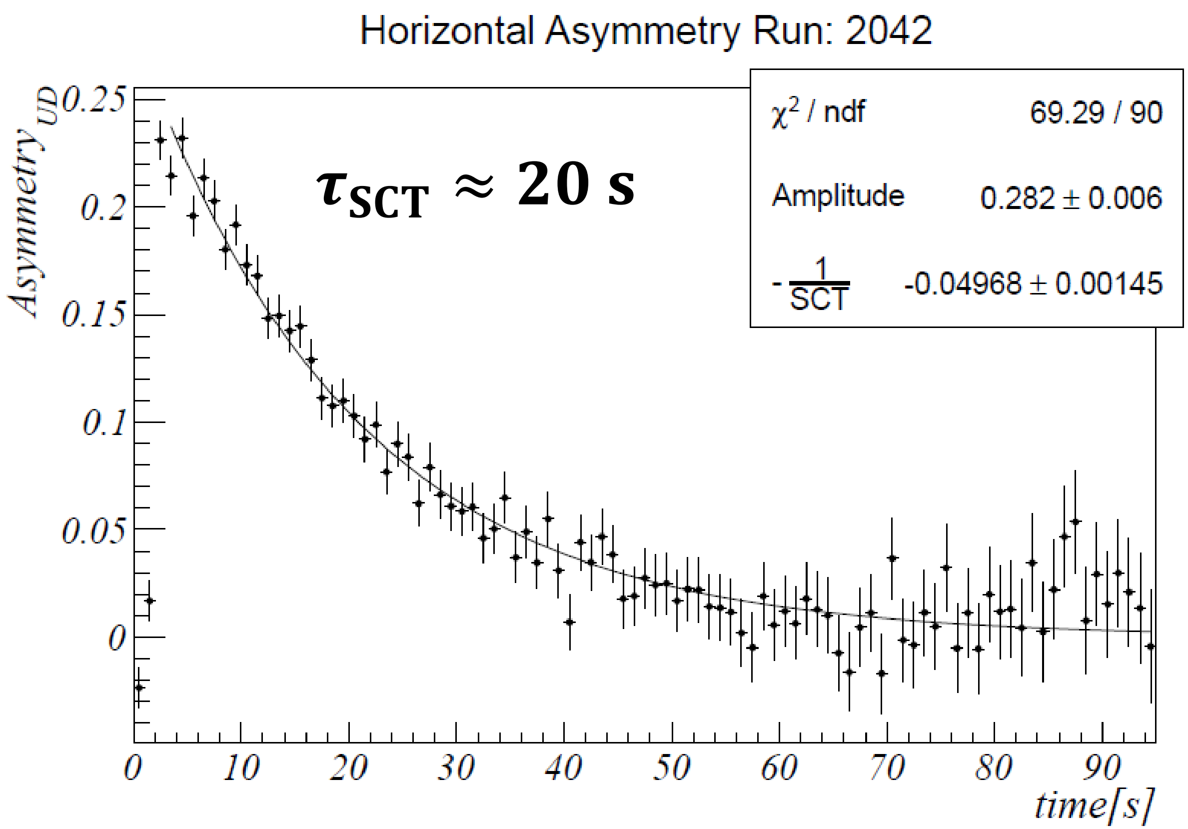


Deuterons at $p \approx 1$ GeV/c, $\gamma = 1.13$ and $\nu_s = \gamma \cdot G = -0.161$

$$N_{U,D} \propto 1 \pm \frac{3}{2} p \cdot A_y \cdot \sin(\nu_s f_{\mathrm{rev}} t), \text{ where } f_{\mathrm{rev}} \approx 781\ kHz$$

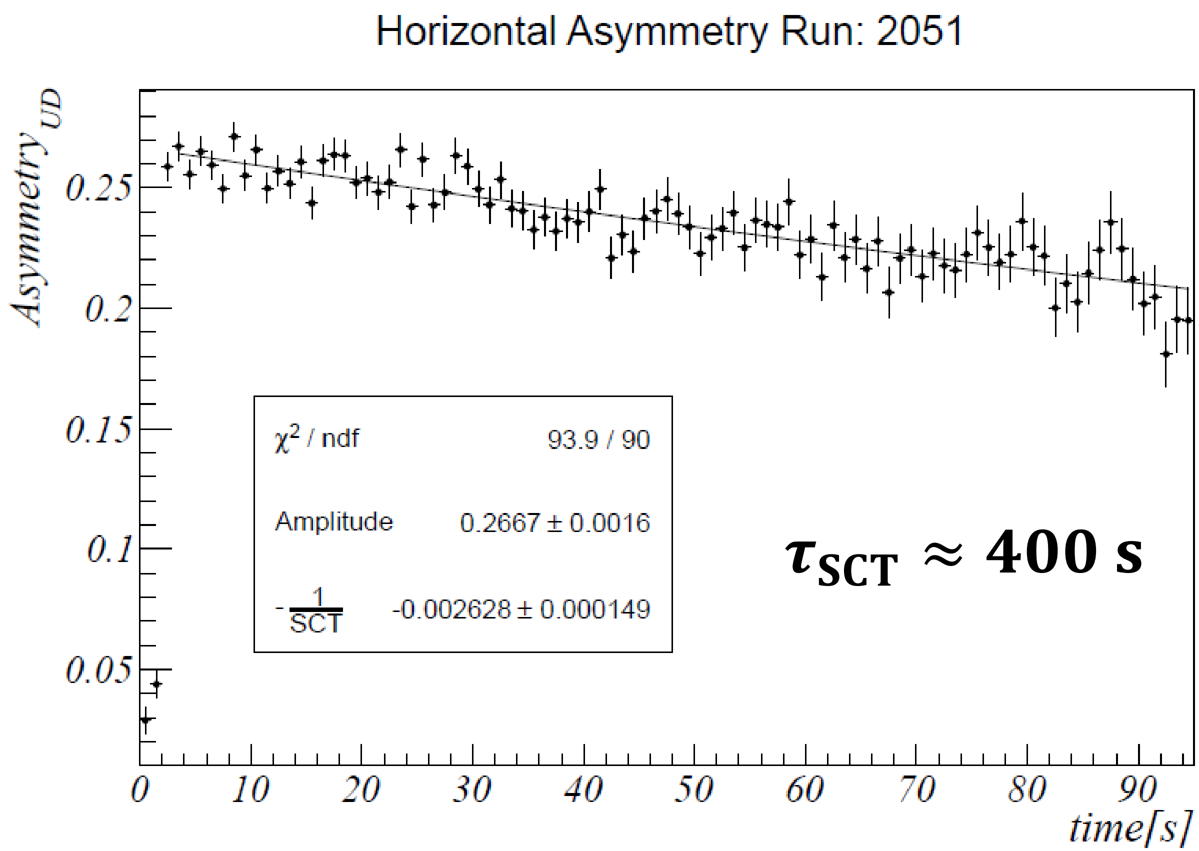
Polarimeter: Determination of SCT

Observed experimental decay of the asymmetry $\varepsilon_{UD} = \frac{N_D - N_U}{N_D + N_U}$ as function of time, $\varepsilon_{UD}(t) \approx P(t)$.



Polarimeter: Optimization of SCT

Using sextupole magnets in the machine, higher order effects can be corrected, and the SCT is substantially increased



$\tau_{\mathrm{SCT}} \approx 400\ \mathrm{s}$

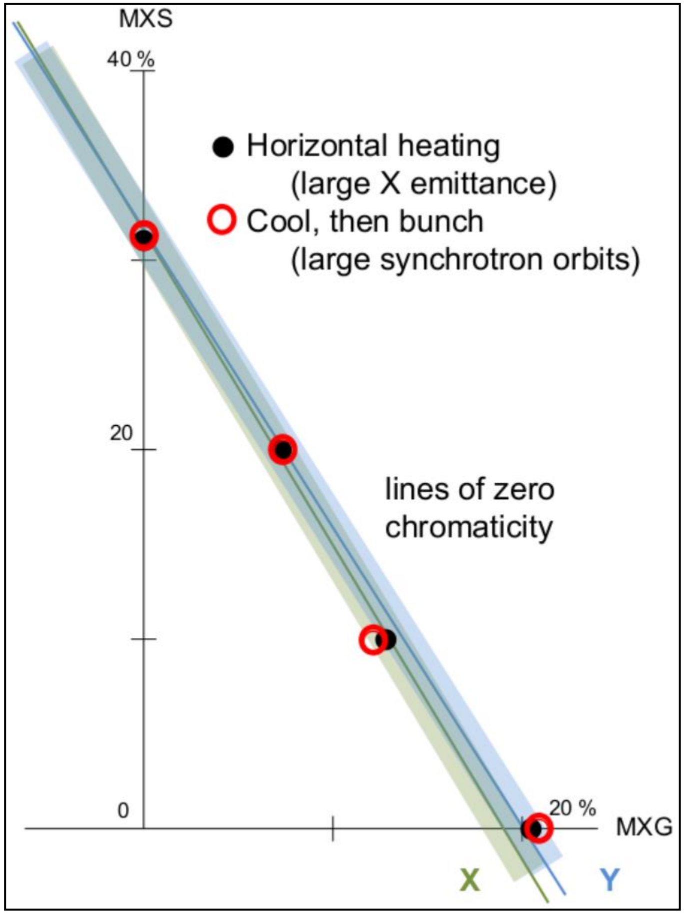
SCT: Chromaticity studies

Chromaticity ξ defines the betatron tune change with respect to the momentum deviation

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

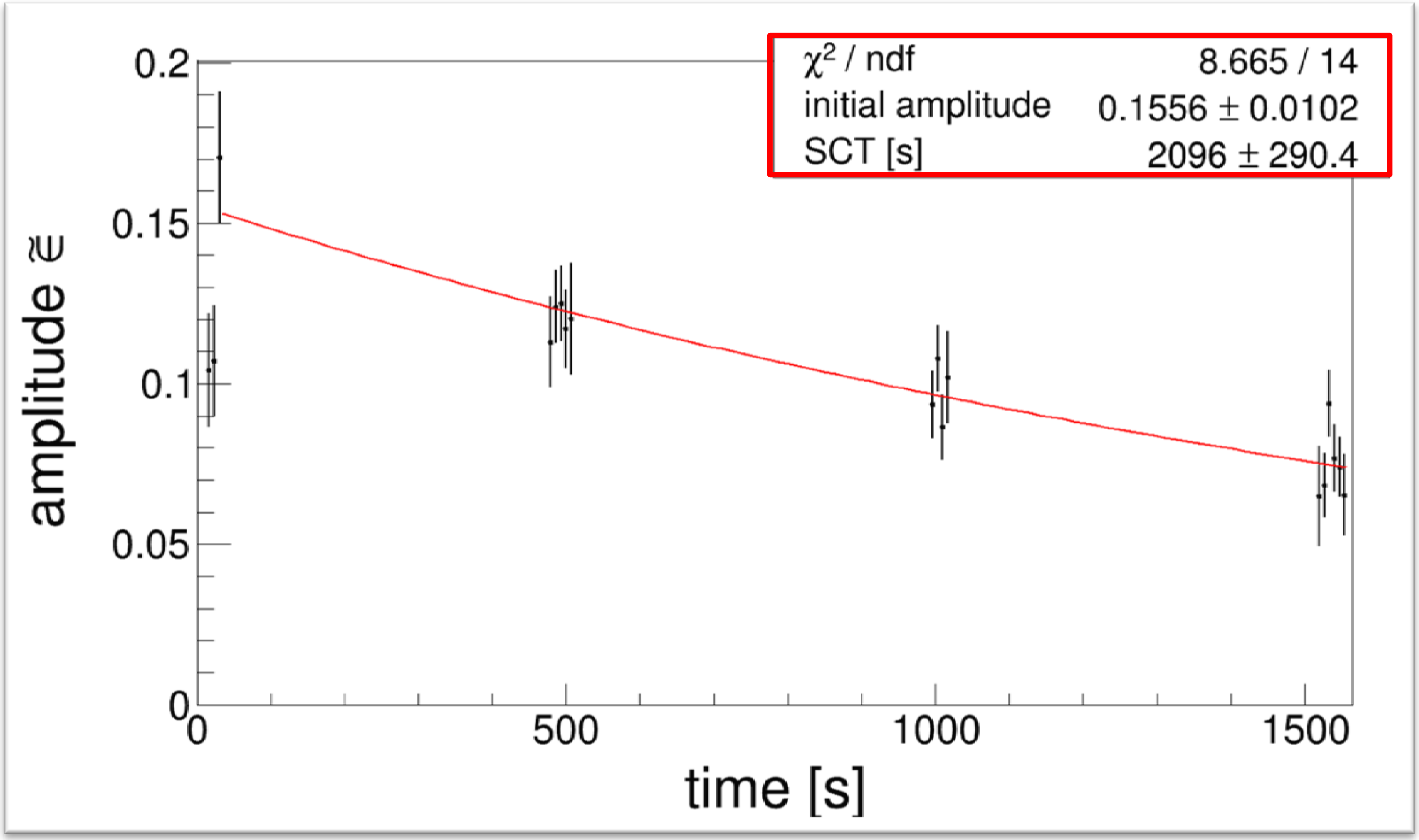
- Strong connection between $\xi_{x,y}$ and τ_{SC} observed.
- COSY Infinity based model predicts negative natural chromaticities ξ_x and ξ_y.
- Measured natural chromaticity: $\xi_y > 0$ and $\xi_x < 0$.

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 $\xi_{x,y}$.

More progress on τ_{SCT}: Spring 2015



Way beyond anybody's expectations $\rightarrow \sigma_{stat} \approx \tau_{SCT}^{-1}$

Outline

- Introduction
- Recent Achievements
  - Spin coherence time
  - **Spin tune measurement**
  - Study of magnetic machine imperfections
- Technical challenges
- Toward a first direct p, d EDM measurement
- Conclusion

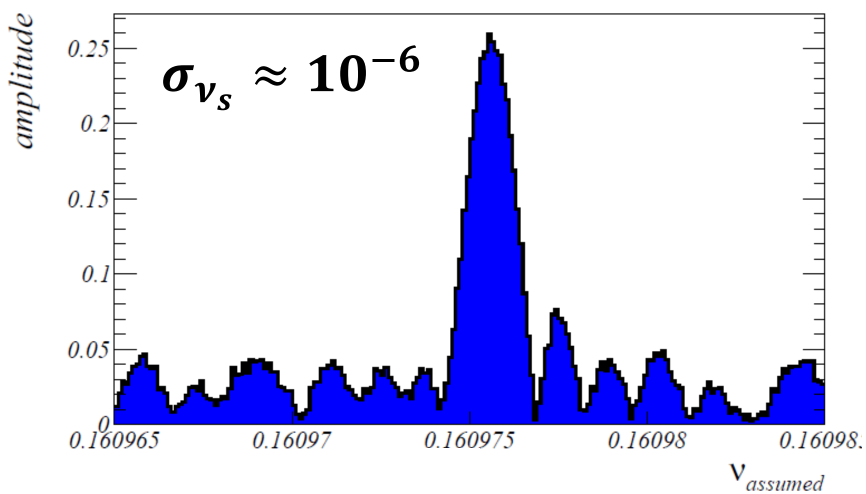
Spin tune ν_s: How to measure it?

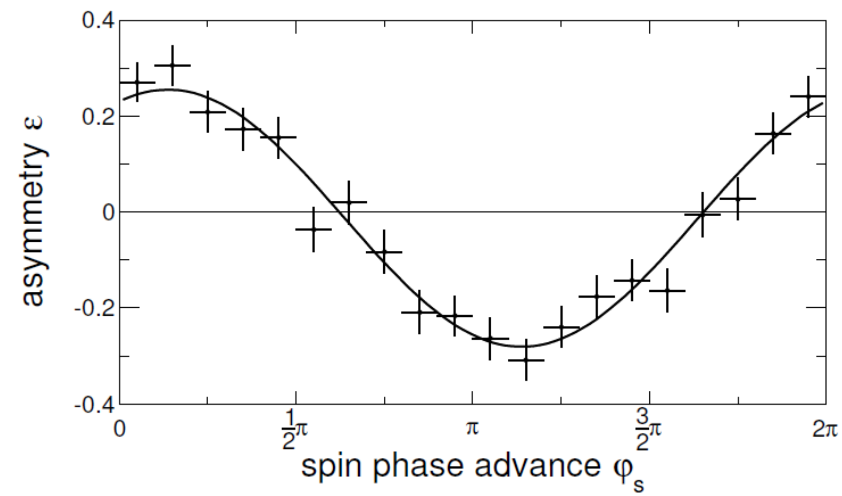
$\nu_s \equiv$ Number of spin precessions revolution, a priori not known ($\approx \gamma G$)

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

Scan ν_s in an interval around γG and find maximum of asymmetry ε_{UD}

COSY rf $\rightarrow$ $\boxed{\mathrm{T}}$ $\rightarrow$ beam revolutions: counting turn number *n*



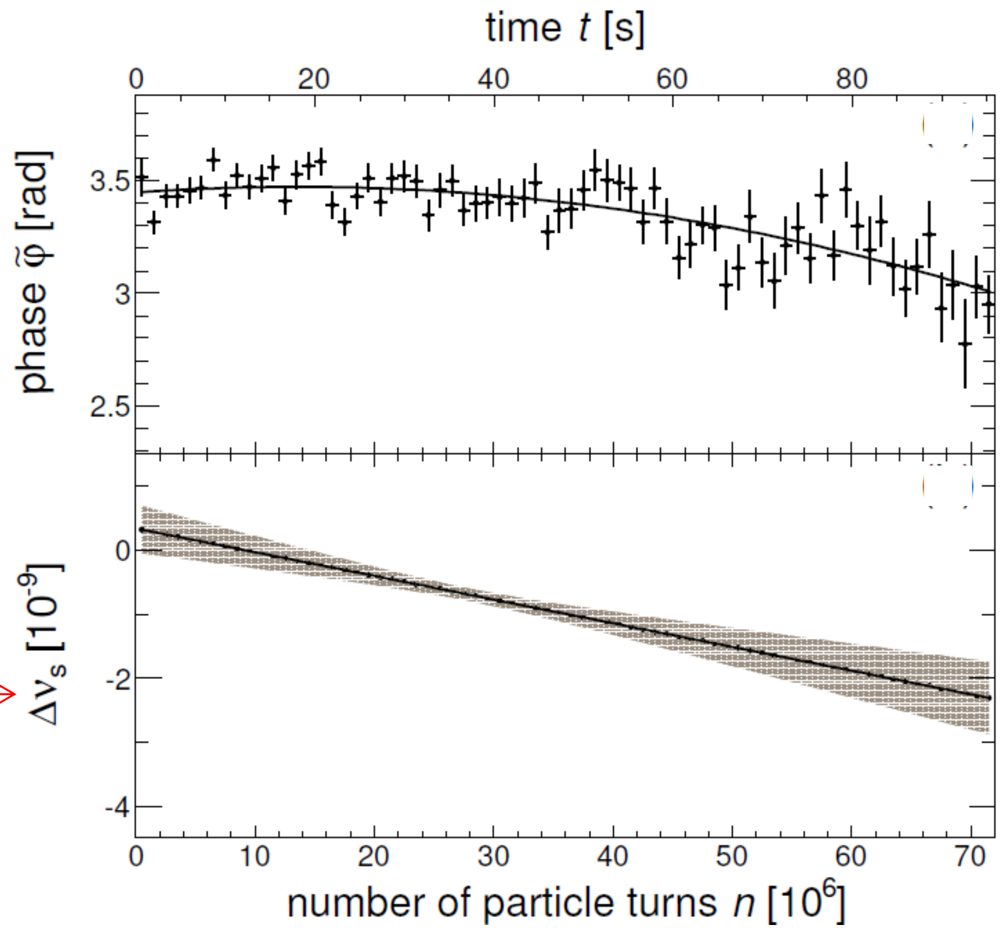


Solution: Map all events into one spin oscillation period

Spin tune: Determination of ν_s

Monitor phase of asymmetry with fixed ν_s in a 100 s cycle.

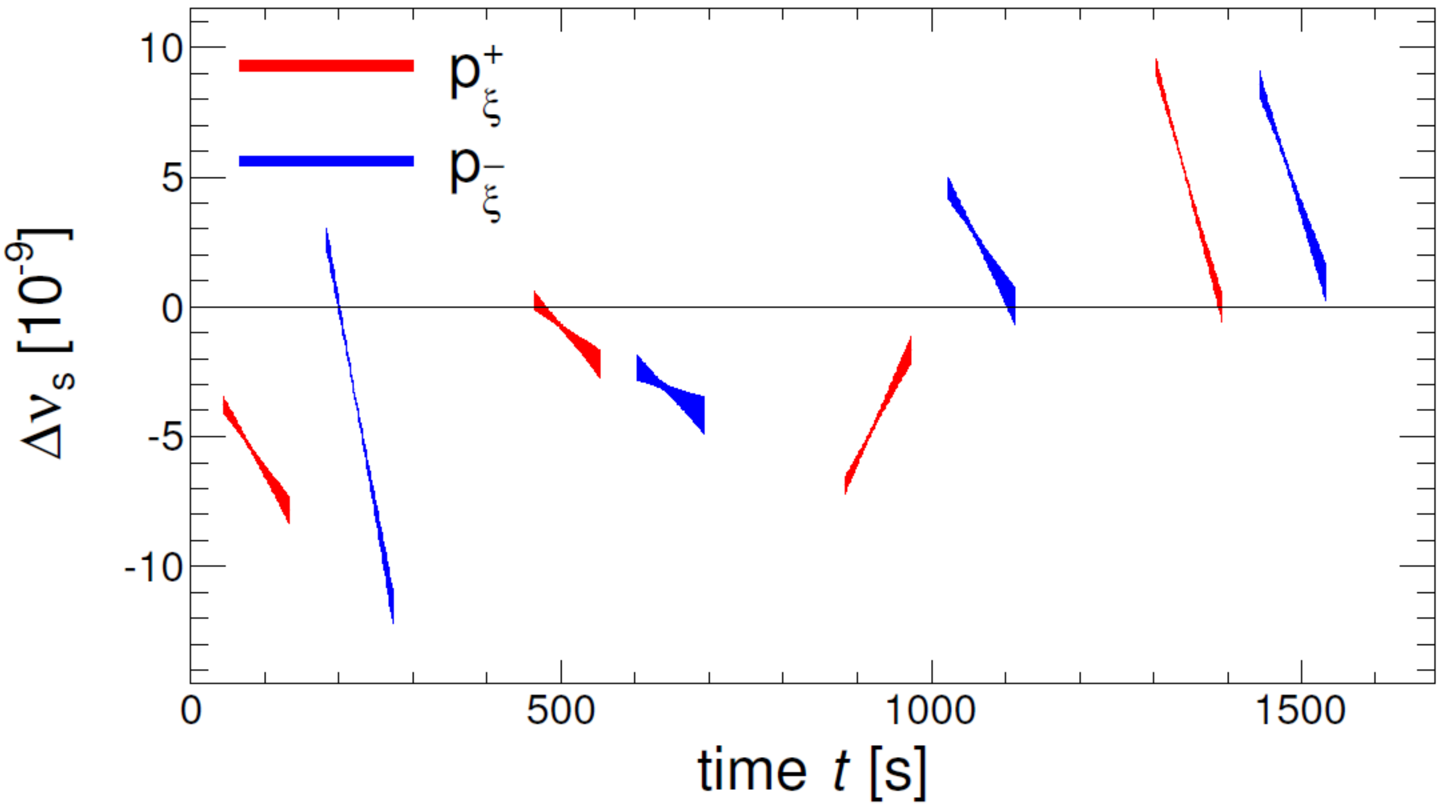
$$\nu_s(n) = \nu_s^{\text{fix}} + \frac{1}{2\pi}\frac{\mathrm{d}\tilde{\varphi}(n)}{\mathrm{d}n}$$
$$= \nu_s^{\text{fix}} + \Delta\nu_s(n)$$



Spin tune ν_s determined to $\approx 10^{-8}$ in 2 s time interval, and in a $100\ s$ cycle at $t \approx 40\ s$ to $\approx 10^{-10}$ (PRL 115, 094801 (2015)

New precision tool: Spin tune determination

Observed behavior of subsequent cycles



- Study long term stability of an accelerator
- Develop feedback systems to minimize variations
- Phase-locking the spin precession to RF devices possible

Outline

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Systematic study: Machine imperfections using two straight section solenoids

Systematic effects from machine imperfections limit the achievable precision in an EDM 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 magnetic imperfections of COSY.

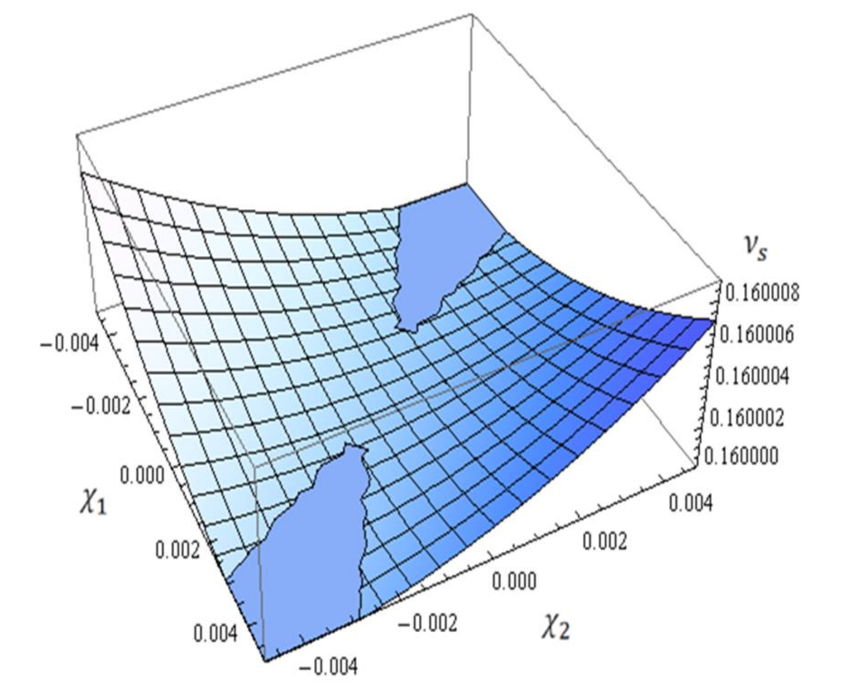
COSY provides two solenoids in opposite straight sections:

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 flat top.

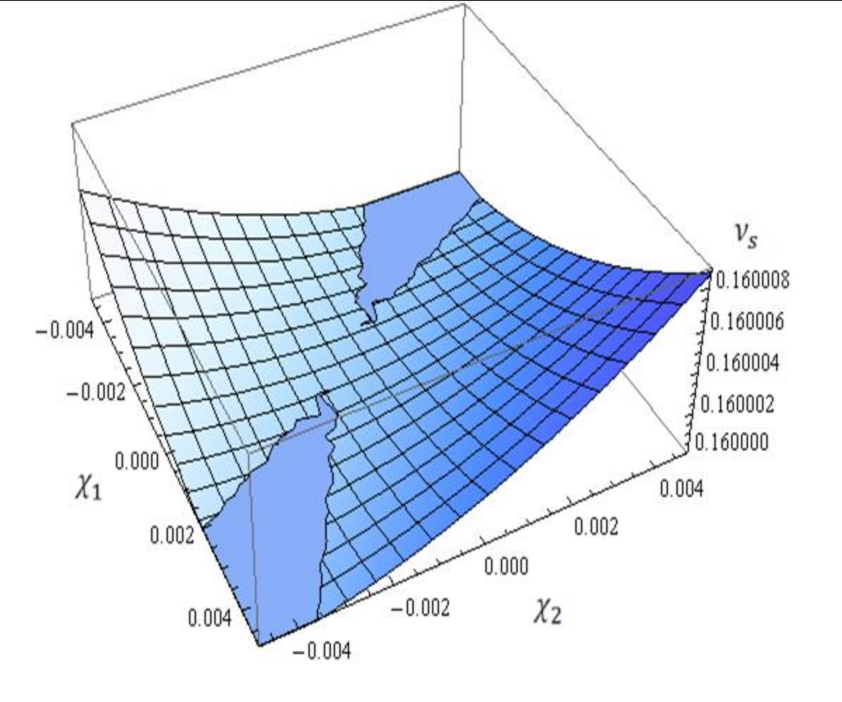
Systematic study: Simulation of one imperfection spin kick for deuterons at 970 MeV/c

Ideal machine with vanishing static imperfections: **Saddle point at the origin**



sea level at $G\gamma\ (= 0.16) - 5\ \cdot 10^{-7}$

Intrinsic imperfection kick $\alpha_x\ =\ 0.001$ **shifts saddle point** away from origin



Location of imperfection: $\Theta^* = \pi/3$

Systematic study: Thomas-BMT eq. $(d \neq 0)$ in magnetic machine

Goal: explore dynamics and systematic limitations of EDM searches in magnetic ring

$$\boxed{\frac{d\vec{s}}{dt} = \vec{s} \times \left(\vec{\Omega}_{\mathrm{MDM}} + \vec{\Omega}_{\mathrm{EDM}}\right)}$$

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

$$\vec{\mu} = g\frac{q\hbar}{2m}\vec{s} = (G+1)\frac{q\hbar}{m}\vec{s}, \text{ and } \vec{d} = \frac{\eta q\hbar}{2m}\vec{s}$$

$$\vec{\Omega}_{\mathrm{EDM}} = \frac{\eta q}{2mc}\left\{\vec{E} - \frac{\gamma}{\gamma+1}\vec{\beta}(\vec{\beta}\cdot\vec{E}) + c\vec{\beta}\times\vec{B}\right\}$$

BMT for magnetic machine with $d \neq 0$:

$$\boxed{\frac{d\vec{s}}{dt} = \frac{q}{m}\left\{G\cdot\vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right\}}$$

Interaction of EDM with motional E-field $(\vec{\beta}\times\vec{B})$ tilts stable spin axis:

$$\vec{n}_{co} = \vec{e}_x \sin\xi + \vec{e}_y \cos\xi \qquad \tan\xi = \frac{\eta}{2G}\beta \qquad \eta = 2d\frac{m}{q}$$

Misalignment of magnetic elements produces in-plane imperfection magnetic fields:

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

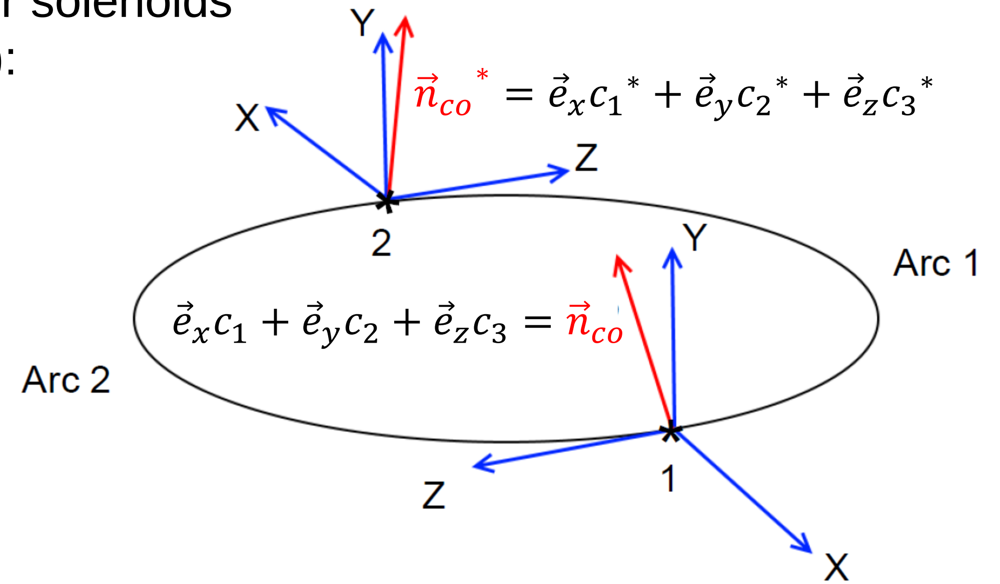
Non-vanishing c_1 and c_3 generate background to the EDM-signal of an ideal imperfection-free machine ($c_1 = \sin\xi$, $c_2 = \cos\xi$ and $c_3 = 0$).

The challenge is to control this background:
An accuracy $\Delta c_{1,3} \approx 10^{-6}\ \mathrm{rad}$ amounts to a sensitivity $d = 10^{-20}\ \mathrm{e\cdot cm}$.

Systematic study: Imperfection measurement

Probing the in-plane imperfection fields by introducing artificial imperfections and looking for the spin tune response

Use the compensation and e-cooler solenoids in straight sections (points 1 and 2): spin kicks χ_1 and χ_2.

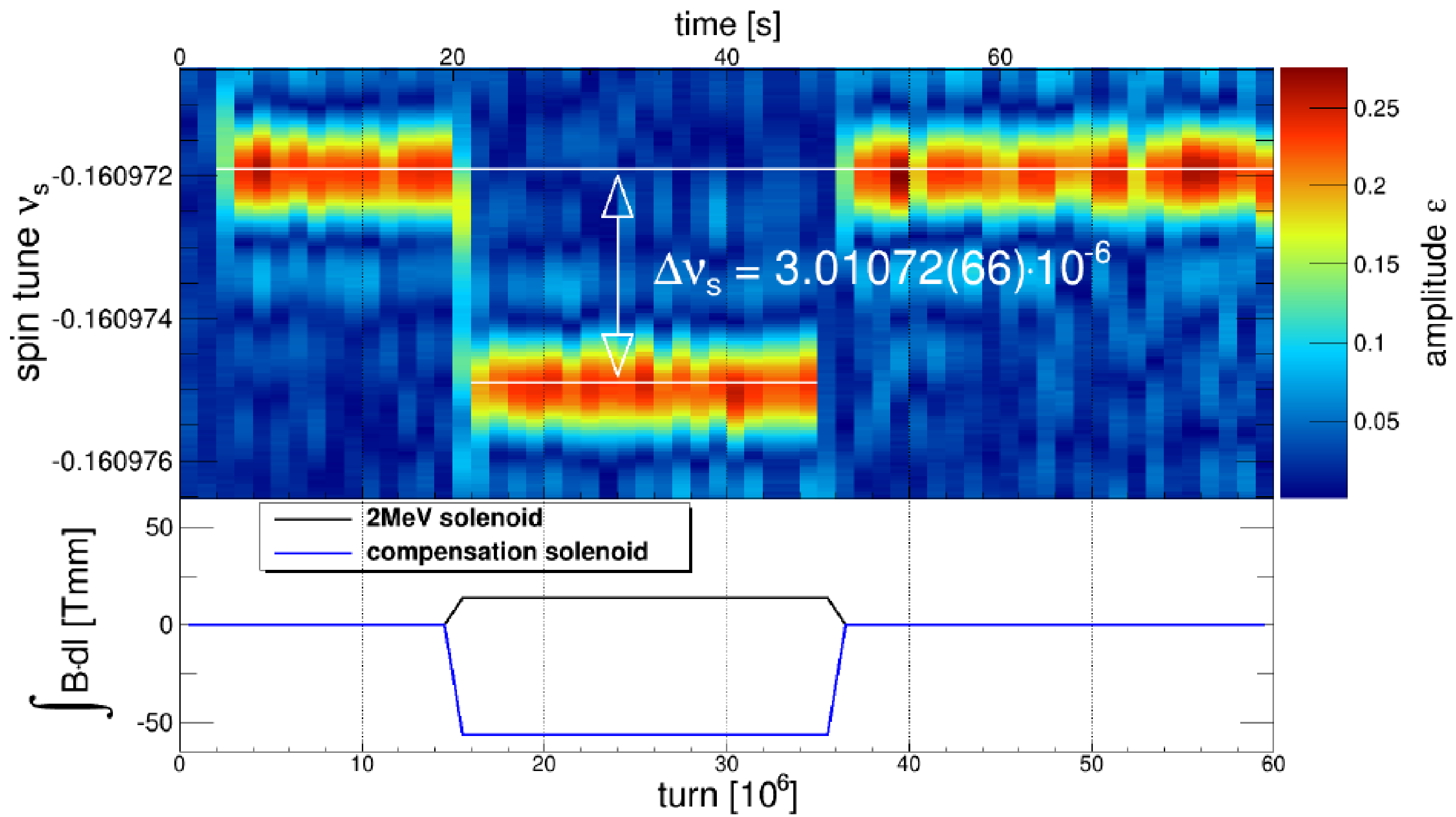


The values of (c_1, c_2), and $(c_3, c_3{}^{*})$ depend of spin kicks in non-vertical imperfection fields in the arcs → spin tune perturbed:

$$\nu_s = G\gamma + O(c_1{}^2, c_3{}^2, c_1{}^{*2}, c_3{}^{*2})$$

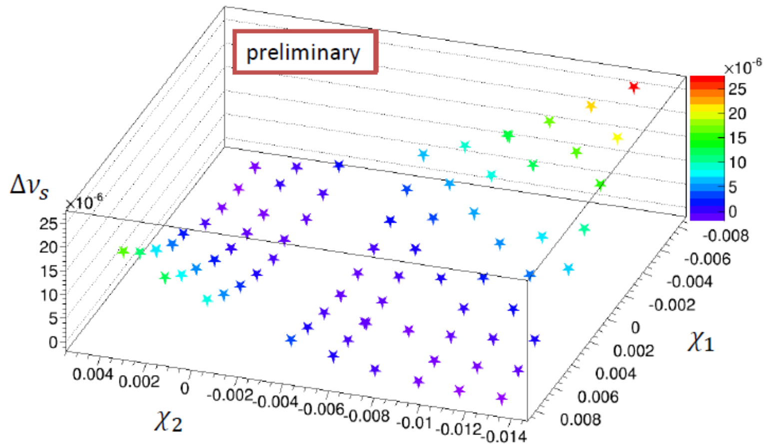
Probe the in-plane imperfection fields by introducing well-known artificial imperfections χ_1 and χ_2.

Systematic study: Measurement of spin tune shift



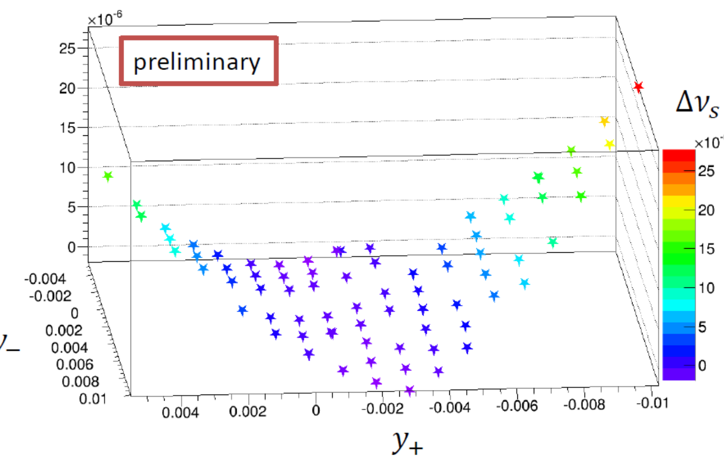
Take multiple measurements with different χ_1, χ_2, build a spin tune map $\Delta\nu_s(\chi_1, \chi_2)$

Systematic study: Mapping machine imperfections

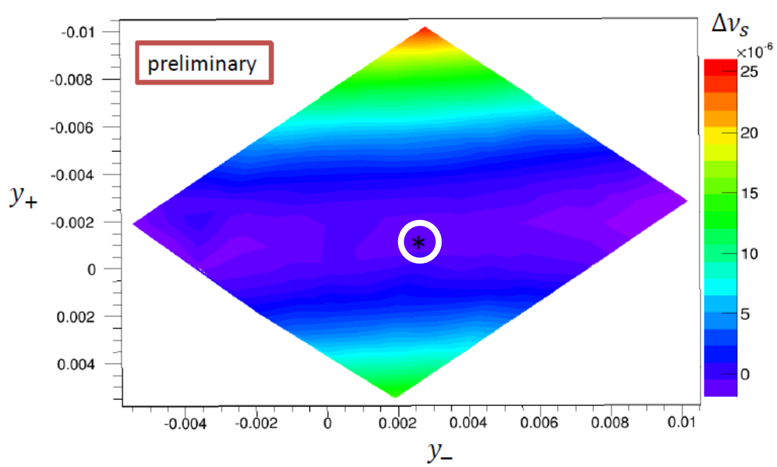


Map translated to

$$y_+ = \frac{\chi_1 + \chi_2}{2} \qquad y_- = \frac{\chi_1 - \chi_2}{2} \quad \Rightarrow \quad \Delta\nu_s \approx {y_+}^2, {y_-}^2$$



Fit map to locate saddle point

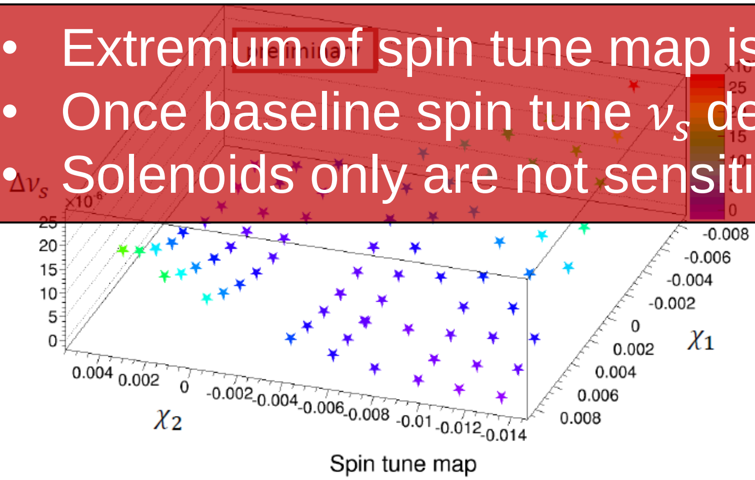


From the map taken on 18+19.09.2014, with the baseline spin tune at $\upsilon_s = -0.160971917$, one finds:

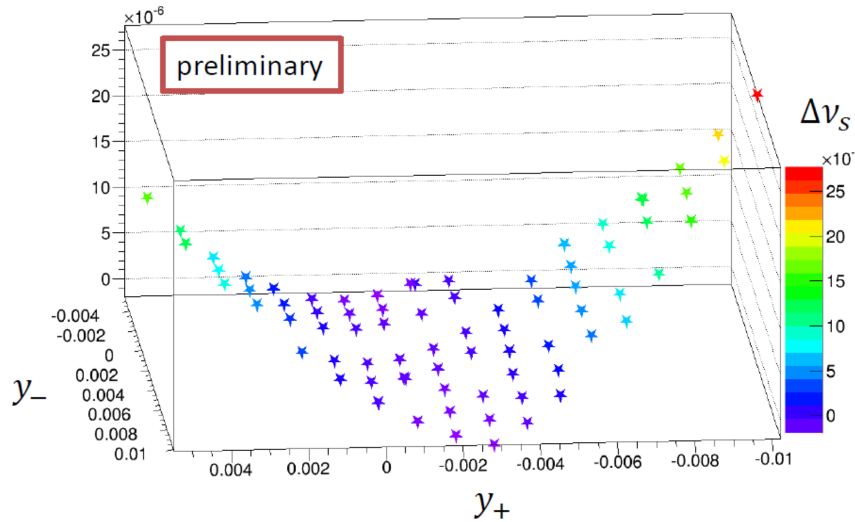
$$c_3 = -0.0034 \pm 2 \cdot 10^{-7}$$
$${c_3}^* = -0.0021 \pm 6 \cdot 10^{-8}.$$

Systematic study: Mapping imperfections

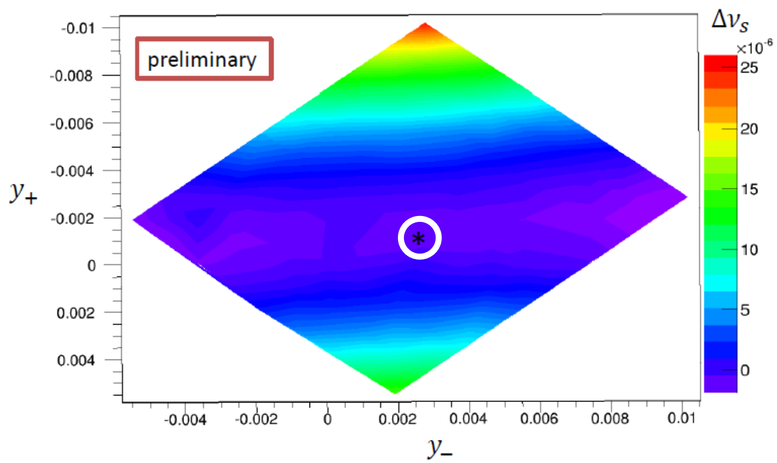
- Extremum of spin tune map is saddle point at $y_+, y_- = O(c_3, c_3^*)$.
- Once baseline spin tune ν_s determined, (c_3, c_3^*) are only fit parameters.
- Solenoids only are not sensitive to c_1, c_1^* ($\rightarrow$ static WF with B_x and E_y).



$\Downarrow$



$\Leftarrow$



New technique allows one to experimentally reconstruct the components of the spin closed orbit $\vec{n}_{co}$ in a storage ring with unprededented precision (not achievable from polarization measurements alone).

Outline

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- Recent Achievements
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- **Technical challenges**
  - Beam position monitors
  - Electrostatic deflectors
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- Conclusion

Technical 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** ☒

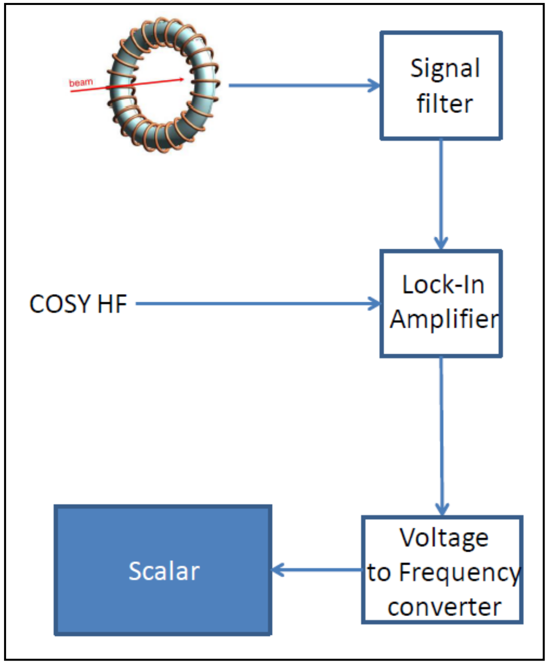
These issues must be addressed *experimentally* at existing facilities

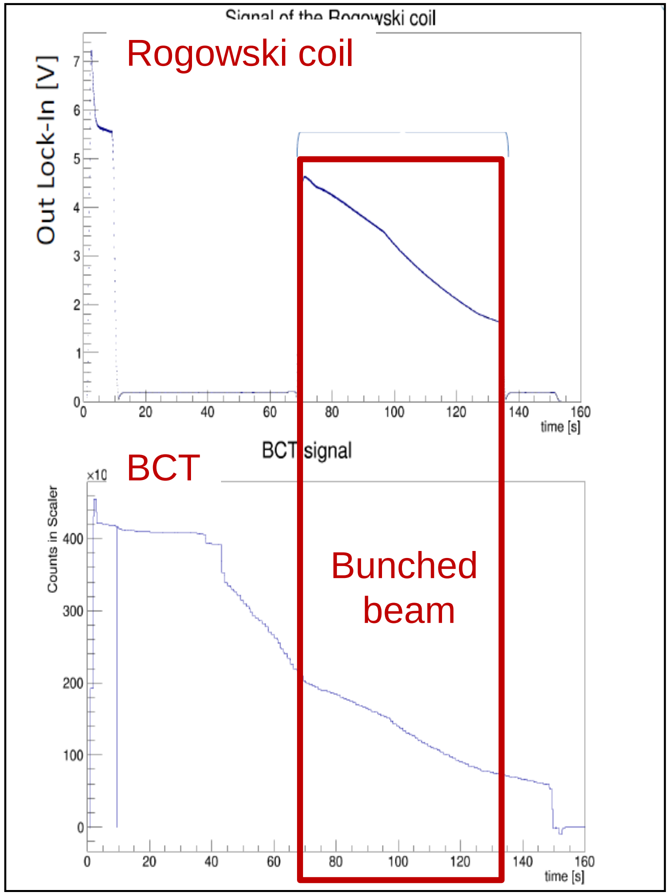
Challenge BPMs: Rogowski coil

- **Integral signal measures beam current**
- Quadrant signals sensitive to position

Installed in ANKE target chamber

Readout



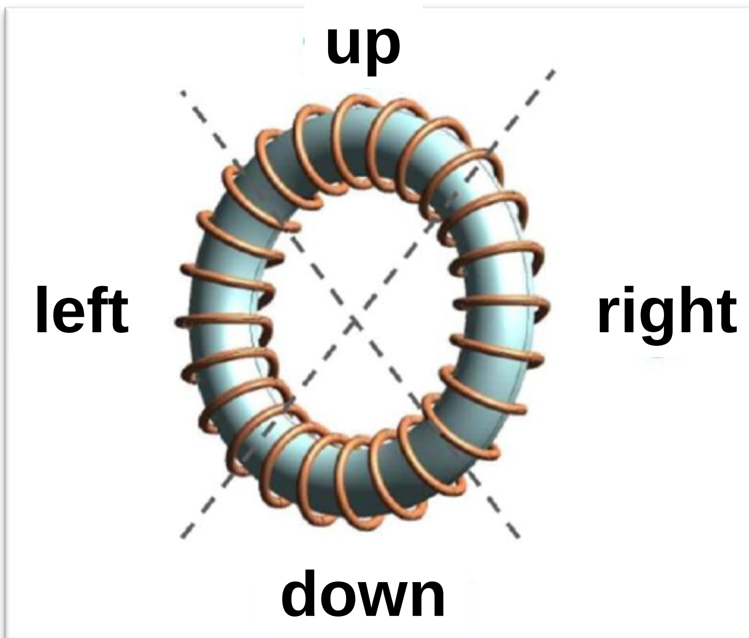


For bunched beams, sum signal of Rogowski coil can be used as a beam current monitor.

Challenge BPMs: Rogowski coil

- Integral signal measures beam current
- **Quadrant signals sensitive to position**

EDM experiments use bunched beams:
- Rogowski coil system well-suited.
- Small size allows for flexible installation (→ Stripline RF Wien filter)



$$x = \frac{\text{left} - \text{right}}{\text{left} + \text{right}}$$

$$y = \frac{\text{up} - \text{down}}{\text{up} + \text{down}}$$

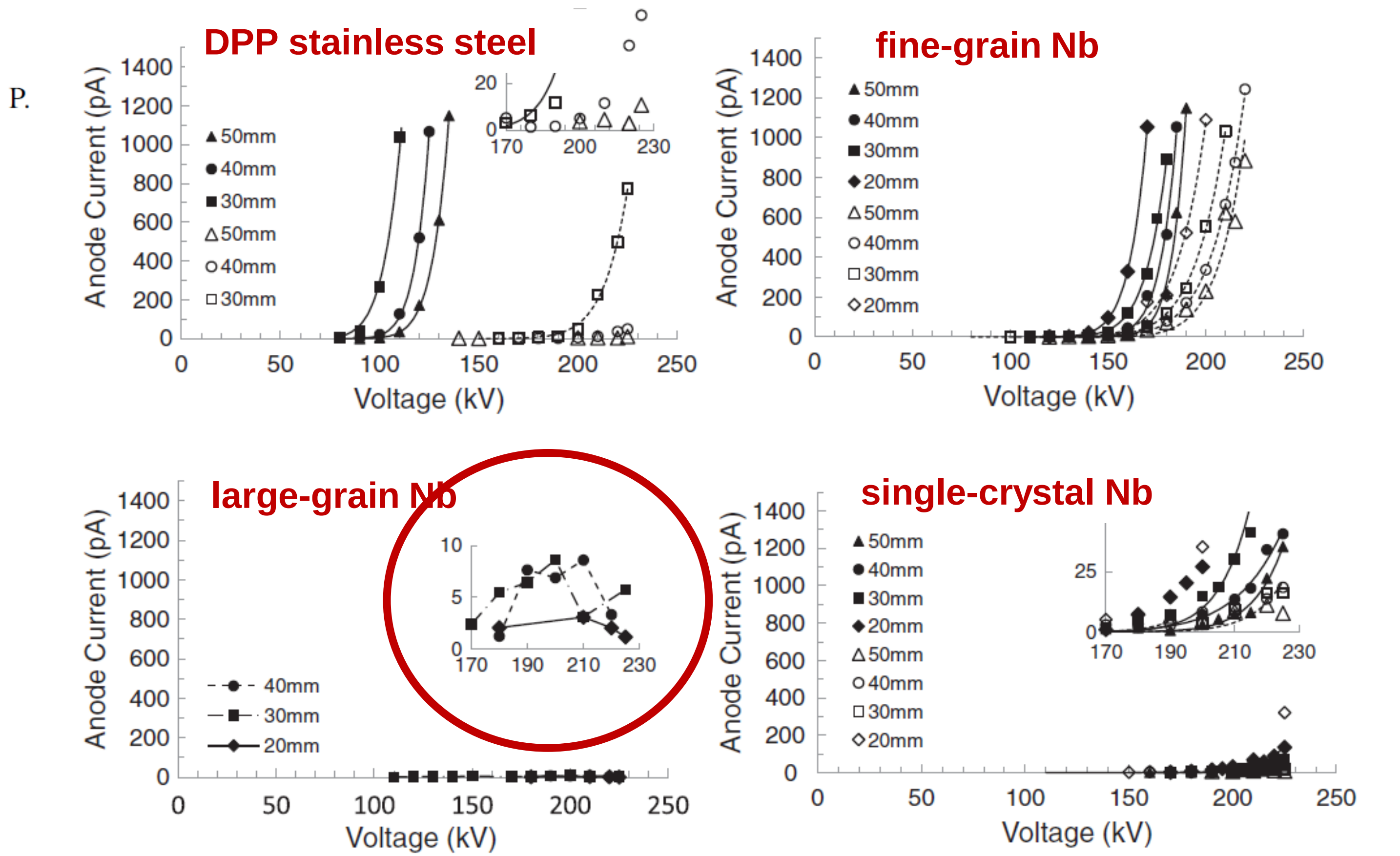
Dynamic range
- $10^8 - 10^{11}$ particles
- Maximum deviation from axis $\approx 40\ \text{mm}$
- Resolution: $10\ \text{nm}$

Quadrant signals of Rogowski coil sensitive to beam position.
Tests at COSY can be carried out parasitically.

Challenge: Niobium electrodes

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **15**, 083502 (2012)

Evaluation of niobium as candidate electrode material for dc high voltage photoelectron guns



Large-grain Nb at plate separation of a few cm yields ~20 MV/m

Challenge: Electric deflectors for magic rings

Electrostatic separators at Tevatron were used to avoid unwanted $\bar{p}p$ interactions - electrodes made from stainless steel

Routine operation at $1\ \mathrm{spark/year}$ at $6\ \mathrm{MV/m}$

May 2014: Transfer of separator unit plus equipment from FNAL to Jülich

Need to develop new electrode materials and surface treatments

Challenge: Electric deflectors for magic rings

1. Deflector development will use scaled models $\sim 1:10$
   - Electric fields are the same, but voltages $< 20\ \mathrm{kV}$
   - Avoids shielding of x-rays
   - Allows tests to be done in usual lab environment

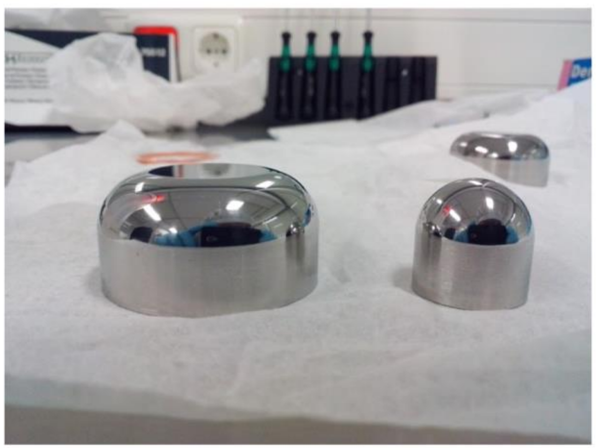
2. Development of real size combined elements (E & B)
   - Begin EDM search with deuterons
   - Use existing dipole magnet of internal ANKE spectrometer
   - Allows for tests with beam

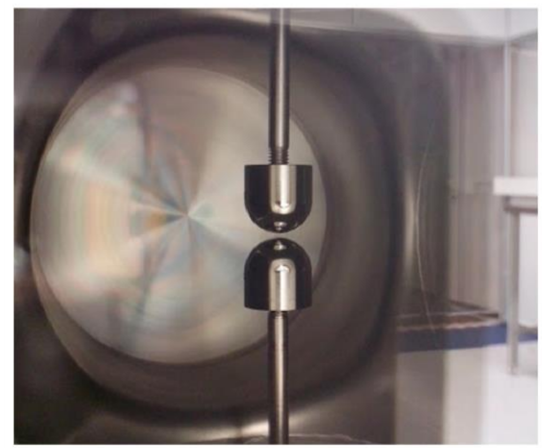
Development of new deflector materials, treatment methods towards high fields $E \sim 20\ \mathrm{MV/m}$, and combined E-B deflectors

Electrostatic deflectors: Clean room at RWTH

Prof. Marquardt chairman of FZJ directors board and
Prof. Schmachtenberg Rektor of RWTH Aachen

Test bench at RWTH Aachen





Development of mall scale deflector elements in cooperation with RWTH (Kirill Grigoriev).
But: Result need to be verified using 1:1 deflector models (Jülich)

Electrostatic deflectors: Some results

JÜLICH FORSCHUNGSZENTRUM

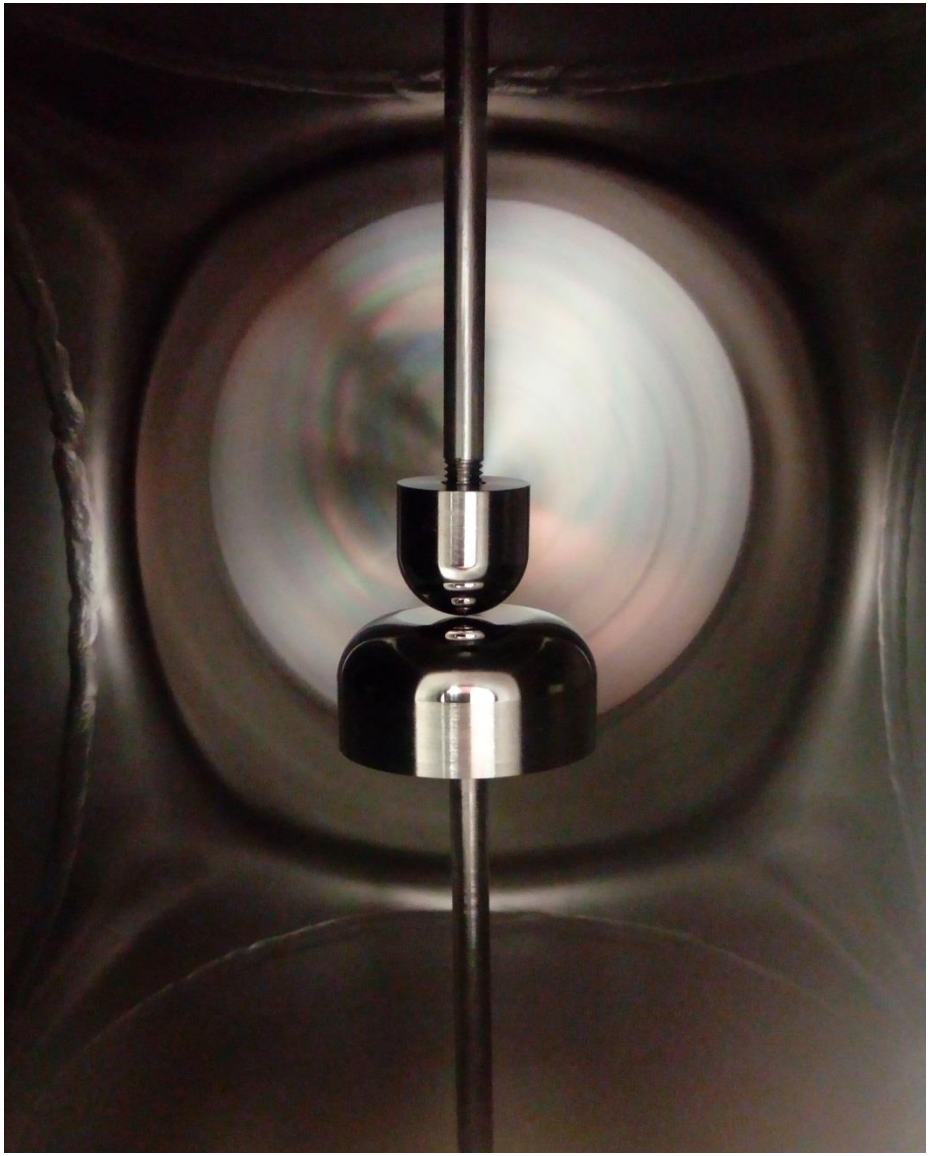
Different shape of the electrodes

Material : Stainless steel, Aluminum
Mechanical polished and cleaned

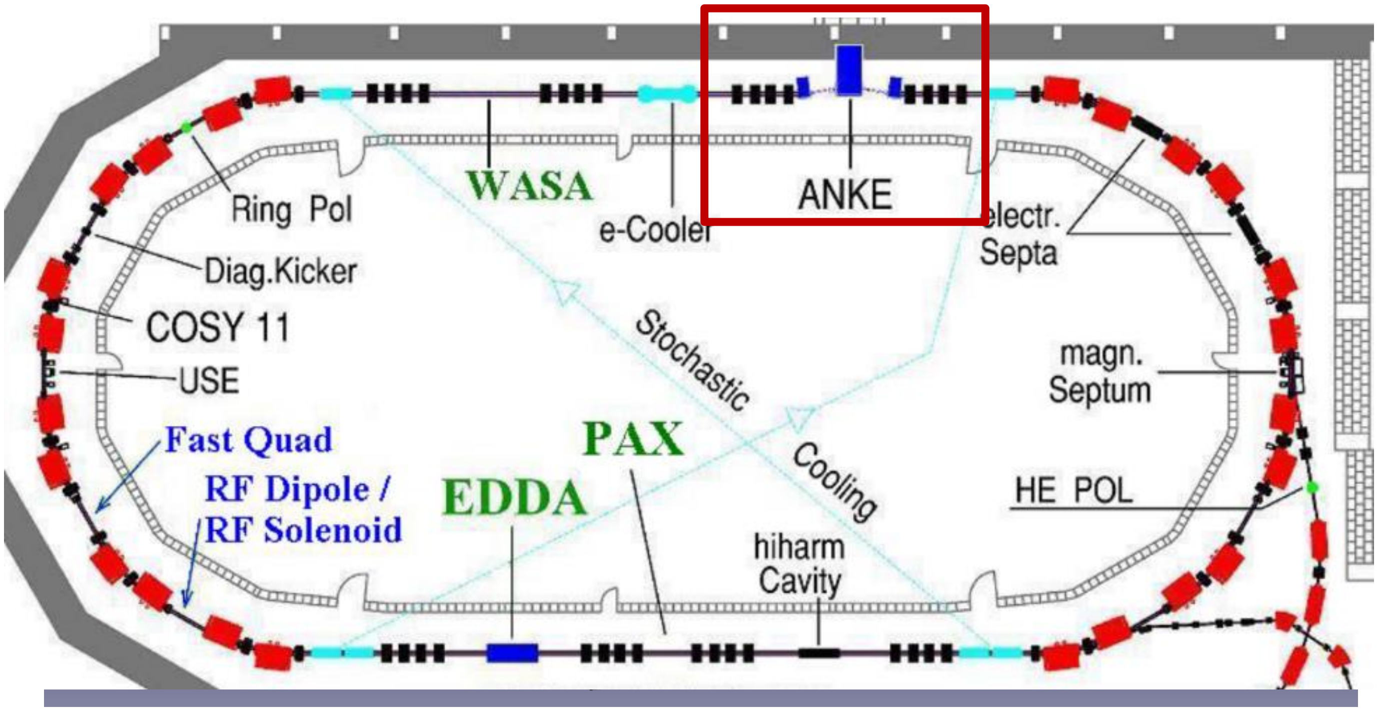
Stainless steel
Two small half-spheres (R = 10mm)
17kV at 1mm distance → **17 MV/m**

Half-sphere vs. flat surface
12kV at 0.05 mm distance → **240 MV/m**

Aluminum
Two small half-spheres (R = 10mm)
3kV at 0.1mm distance → **30 MV/m**



Large scale elements: ANKE chicane at COSY

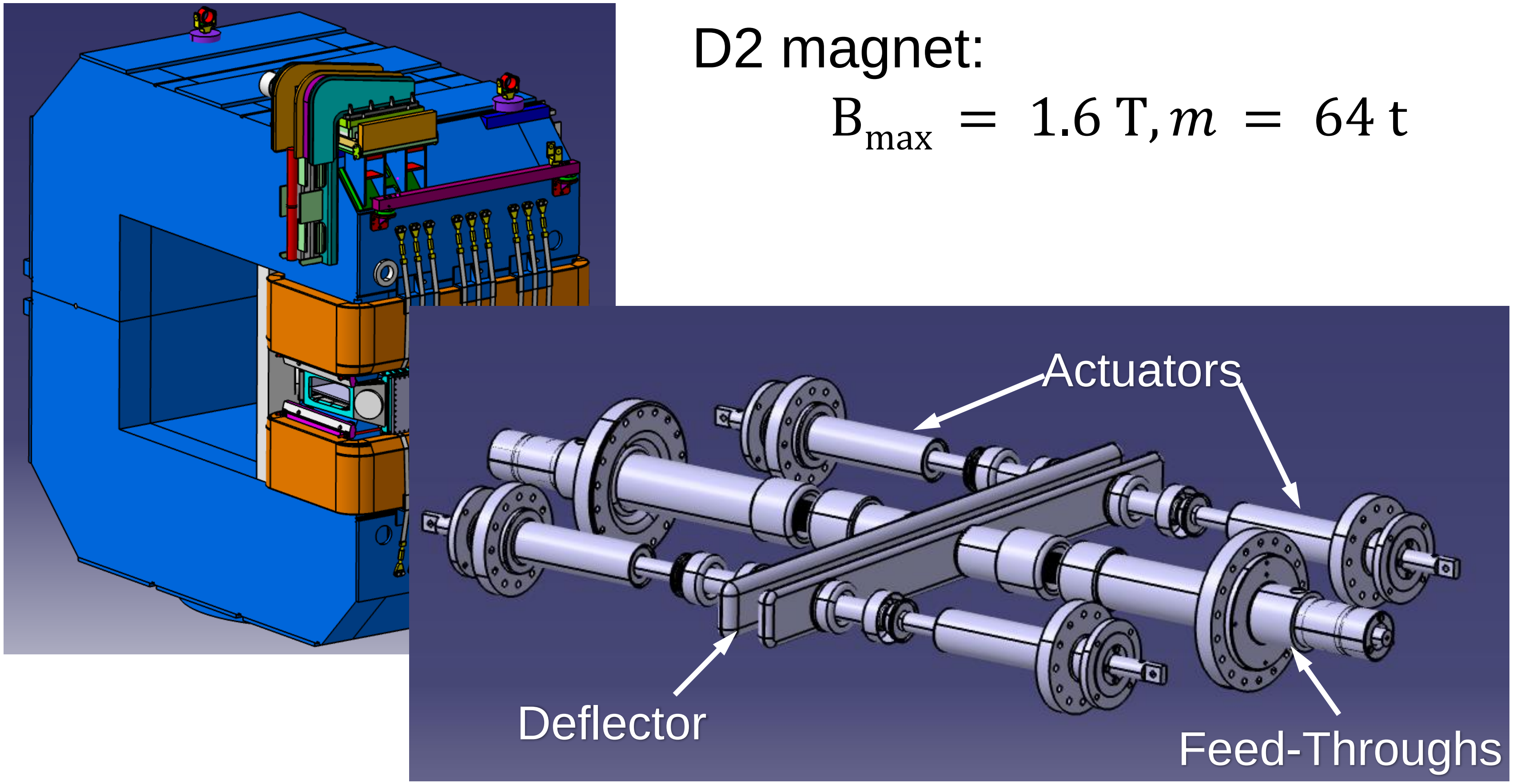


Idea (Jürgen Böker): Produce E-B deflector by insertion of deflector element into D2 magnet chamber.

Large-scale E-B deflector development

D2 magnet:

$$B_{\max} = 1.6\,\mathrm{T}, m = 64\,\mathrm{t}$$



Deflector: Length: $1020\,\mathrm{mm}$, Height: $90\,\mathrm{mm}$, Gap: $40 - 80\,\mathrm{mm}$

Begin development with straight elements

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Idea for proof-of-principle srEDM experiment

Use an RF technique:

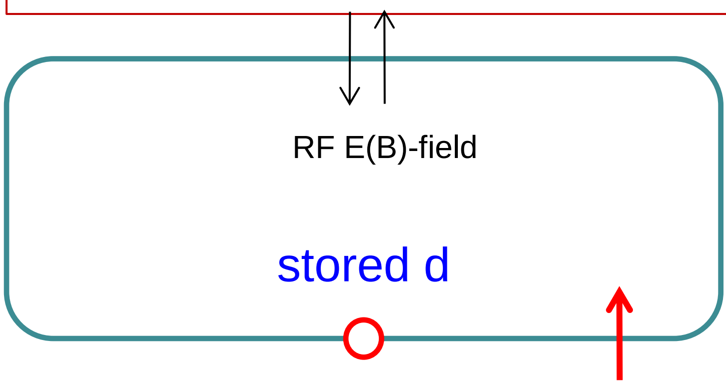
- **RF device operates on some harmonic of the spin precession frequency**
- **accumulate EDM signal with time**

Use COSY for a first direct p and d EDM measurement

Direct EDM measurement :
Resonance Method with „magic" RF Wien filter

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.

$\boldsymbol{E}^* = \mathbf{0} \Rightarrow \boldsymbol{E}_R = -\beta \times \boldsymbol{B}_y$ **„Magic RF Wien Filter"** no Lorentz force
→ **Indirect** EDM effect



Polarimeter (dp elastic)

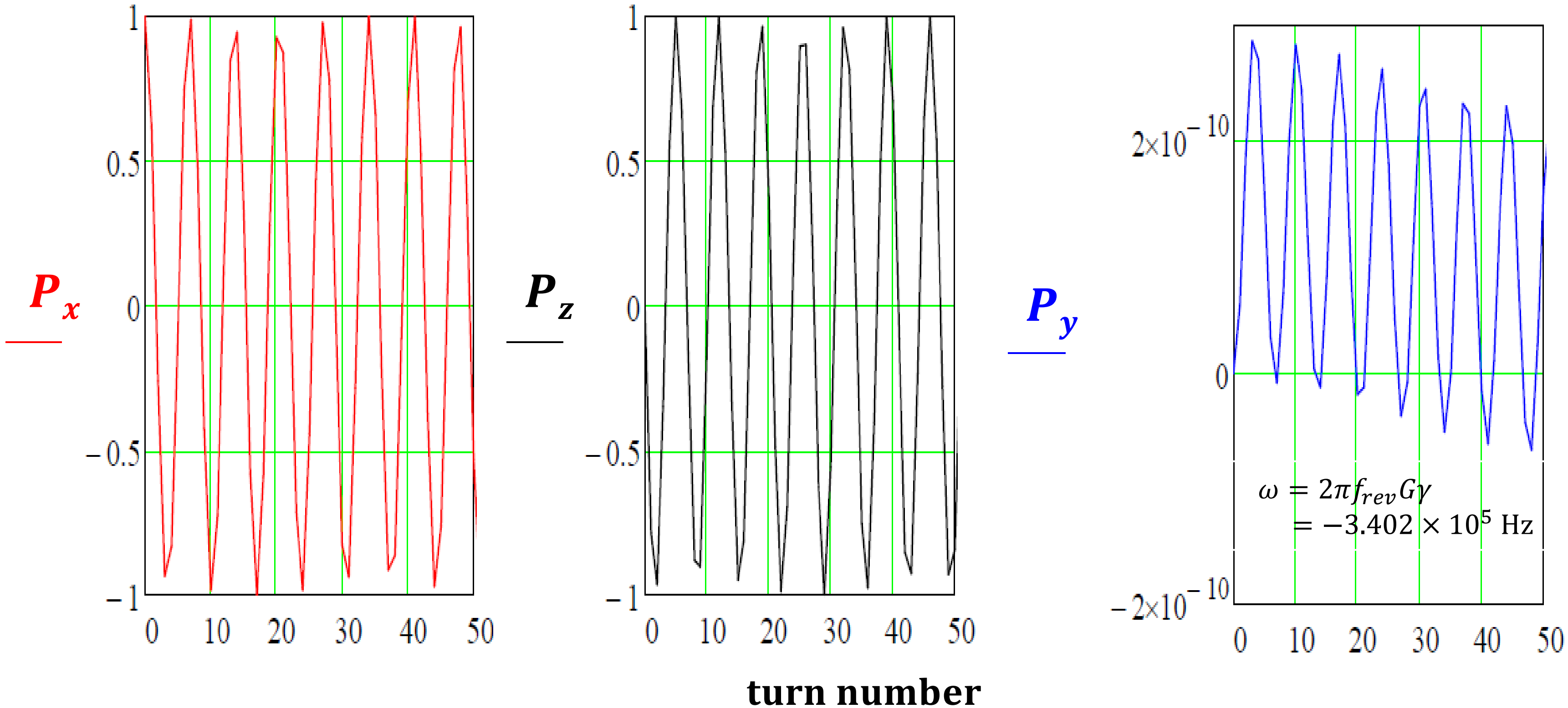
In-plane polarization

Observable:
Accumulation of vertical polarization during spin coherence time

Statistical sensitivity for d_d in the range 10^{-23} to 10^{-24} $\mathrm{e{\cdot}cm}$ range possible.
- Alignment and field stability of ring magnets
- Imperfection of RF-E(B) flipper

First direct EDM measurement:
Resonance Method for deuterons

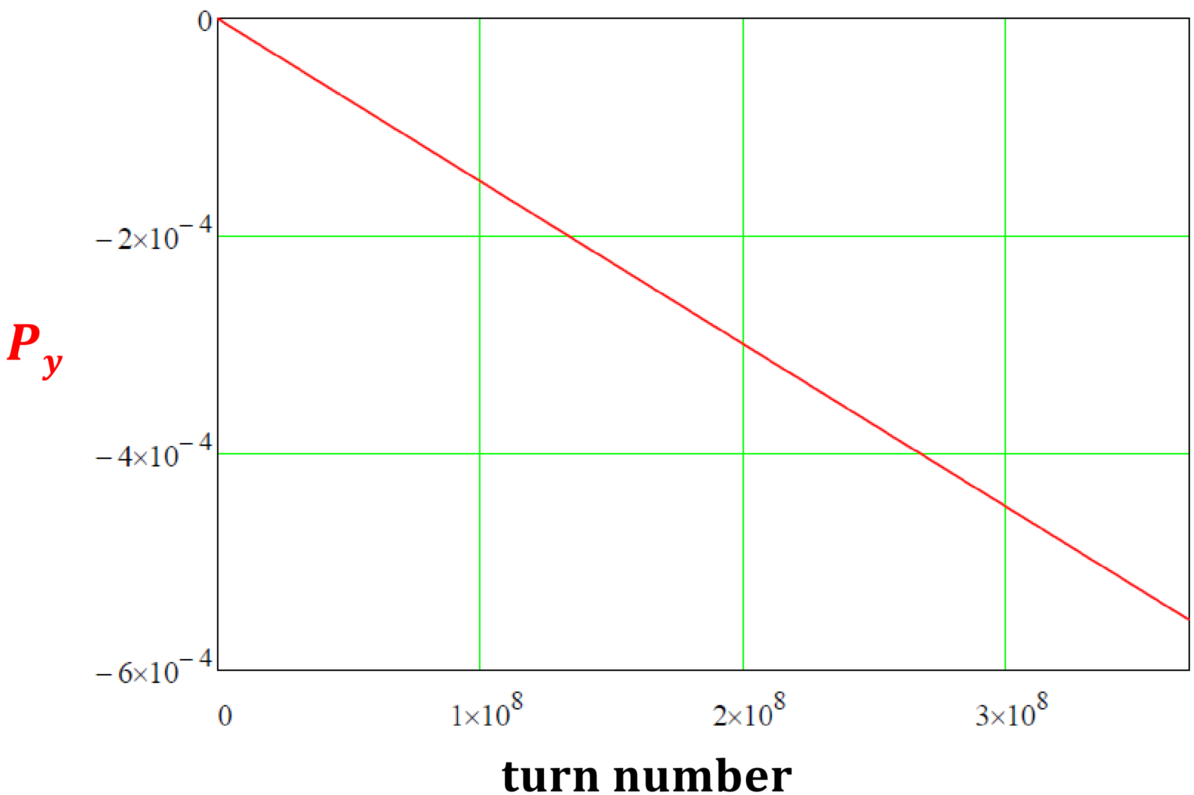
Parameters:	beam energy	$T_d = 50$ MeV	$L_{\mathrm{RF}} = 1$ m
	assumed EDM	$d_d = 10^{-24}$ e·cm	
	E-field	30 kV/cm	



EDM effect accumulates in P_y (see Phys. Rev. ST AB 16, 114001 (2013))

First direct Edm measurement:
Resonance Method for deuterons

Parameters:	beam energy	$T_d = 50$ MeV	$L_{\mathrm{RF}} = 1$ m
	assumed EDM	$d_d = 10^{-24}$ e·cm	
	E-field	30 kV/cm	



Linear extrapolation of P_y for a time period of $\tau_{sc} = 1000$ s ($= 3.7\cdot 10^8$ turns) yields a sizeable $P_y \sim 10^{-3}$.

RF $\mathbf{E} \times \mathbf{B}$ Wien Filter: Resonance condition

Deuterons at 970 MeV/c: $\beta = 0.459$; $\gamma = 1.126$; $G = -0.142\,987$

$$\boxed{f_{RF} = f_{\text{rev}}(\gamma G \pm K),\ K \in \mathbb{Z}}$$

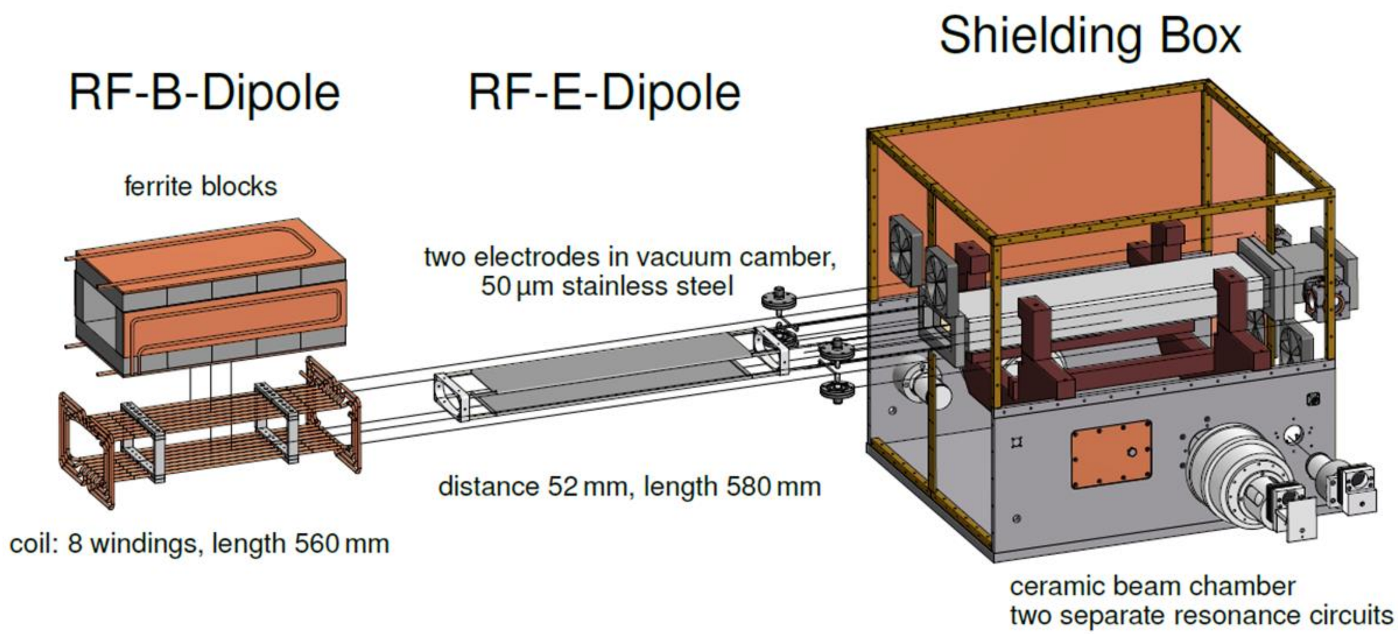
$f_{\text{rev}} \approx 750$ kHz
$\nu_s = \gamma G = -0.16098$

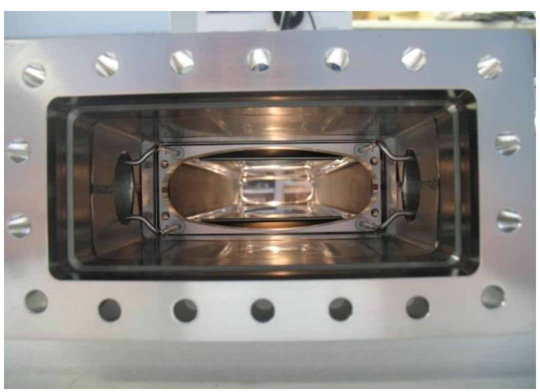
K	0	1	-1	2	-2
f_{RF}/kHz	120	629	871	1380	1621

Frequency range RF Wien filter prototype

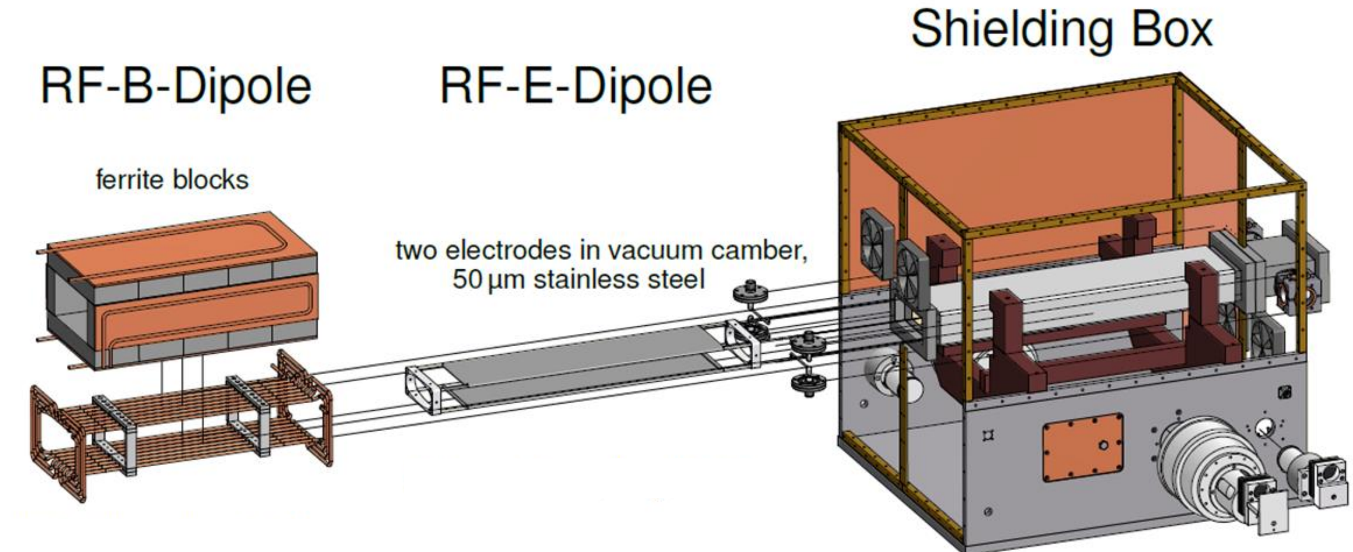
RF $\mathbf{E} \times \mathbf{B}$ Wien Filter: Prototype commissioning

EDM measurement concept: **RF Wien filter to accumulate EDM signal**





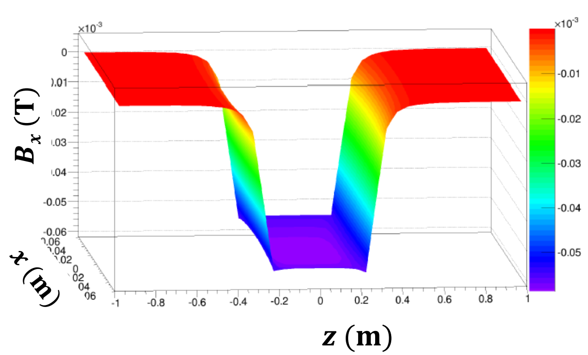
RF E × B Wien Filter: Field calculations

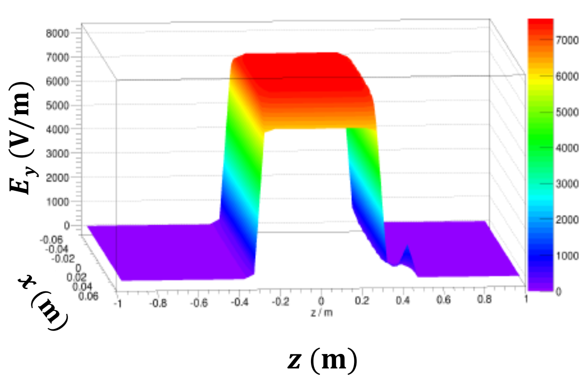


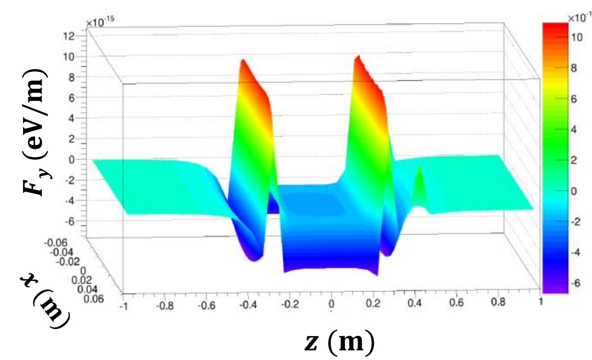
Main field component
$\hat{B}_x = 0.058\ \mathrm{mT}$ at $y = 0,\ \ I = 1\ \mathrm{A}$,
$\int \hat{\boldsymbol{B}}_x d\boldsymbol{z} = \mathbf{0.035\ Tmm}$

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

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



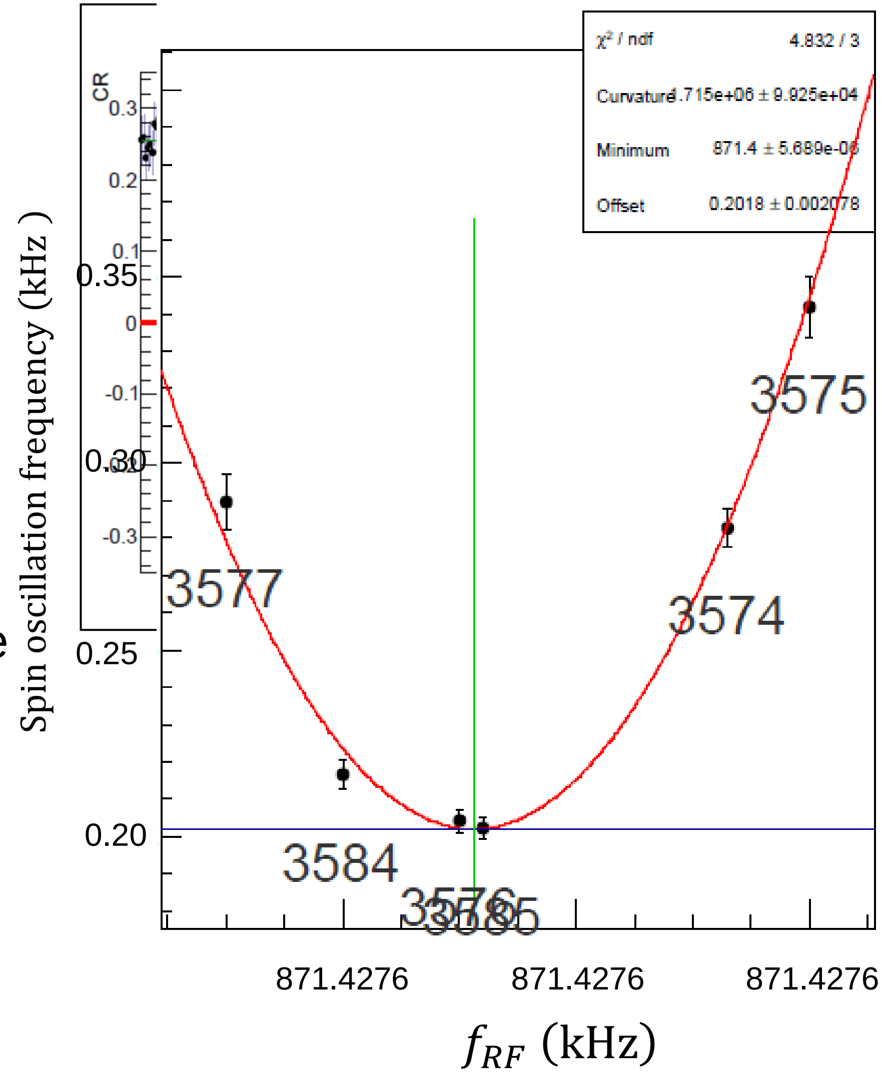




RF Wien Filter: Measurement of Resonance Strengths

- **Continuous polarimetry**: Fixed frequency scans for resonance determination
- Damping due to decoherence
- Cross-ratio of UD-asymmetries used.
- Minimum vertical polarization oscillation frequency gives resonance strength:

$$\epsilon = \frac{f_{P_{y,\min}}}{f_{\mathrm{rev}}}$$



RF $\mathbf{E} \times \mathbf{B}$ Wien Filter: Preliminary Results

RF solenoid:

$$f_{P_y} \approx \frac{1+G}{4\pi} \int \frac{\hat{B}_{\parallel} dl}{B\rho}$$

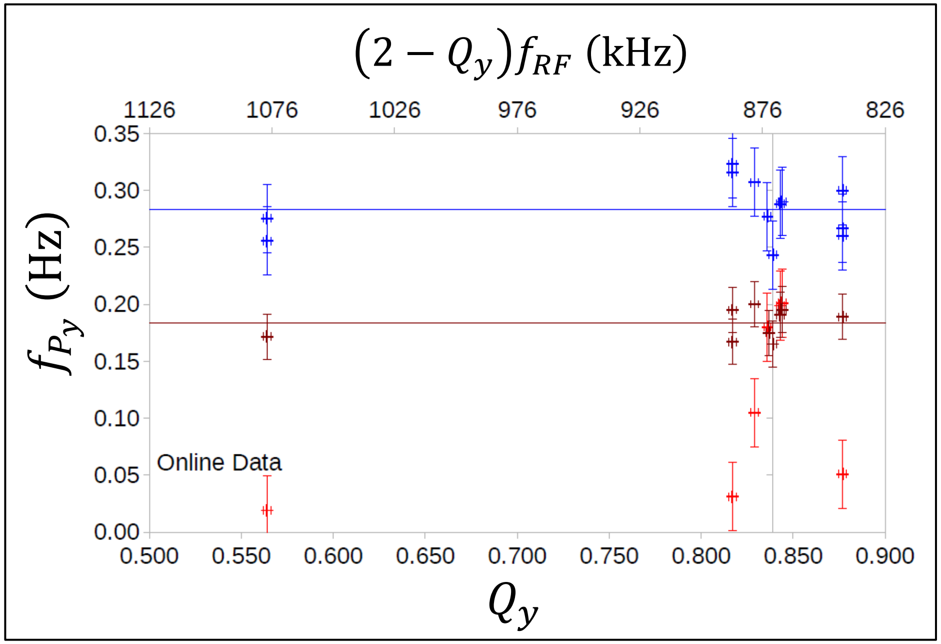
RF Wien filter:

$$f_{P_y} \approx \frac{1+G}{4\pi\gamma} \int \frac{\hat{B}_{\perp} dl}{B\rho}$$

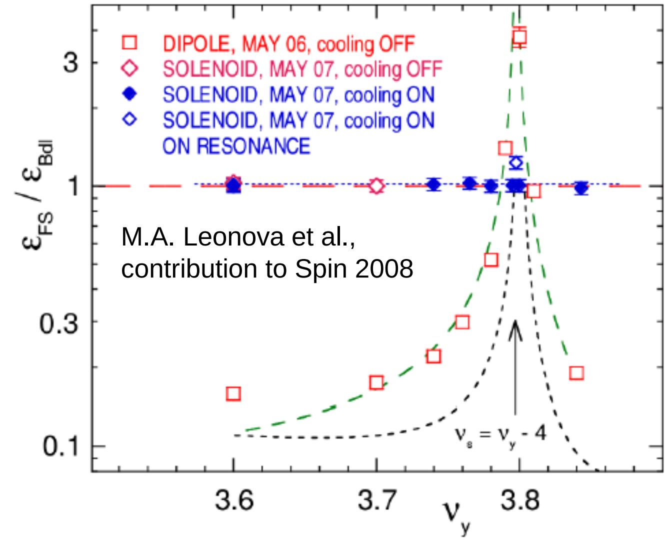
RF dipole:

$$f_{P_y} \approx \frac{1+\gamma G}{4\pi} \int \frac{\hat{B}_{\perp} dl}{B\rho}$$

From driven vertical oscillation at fixed frequency



From froissart-Stora scans

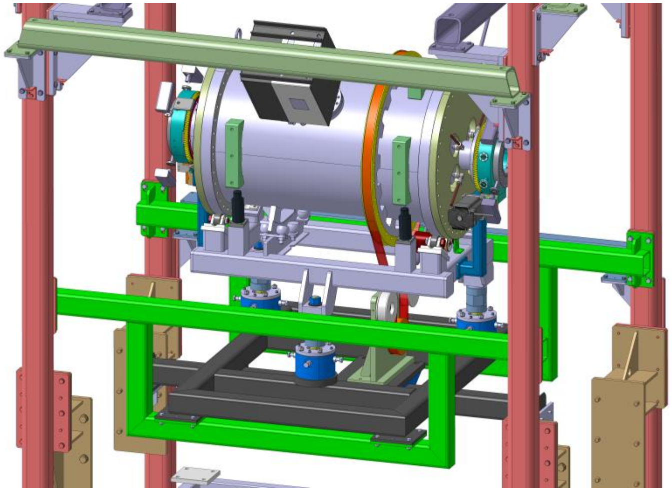


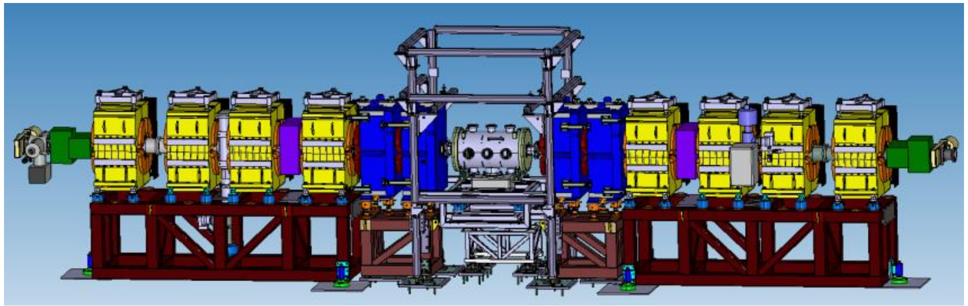
RF $\mathbf{E}\times\mathbf{B}$ Wien filter protoype performs like an RF solenoid

Development of waveguide RF Wien Filter

Device developed at IKP in cooperation with:

- **RWTH Aachen, Institute of High Frequency Technology**:
  - Dirk Heberling, Dominik Hölscher, and PhD Student **Jamal Slim**
- **ZEA-1 of Jülich**:
  - Helmut Soltner, **Lars Reifferscheidt, Heidi Straatmann**

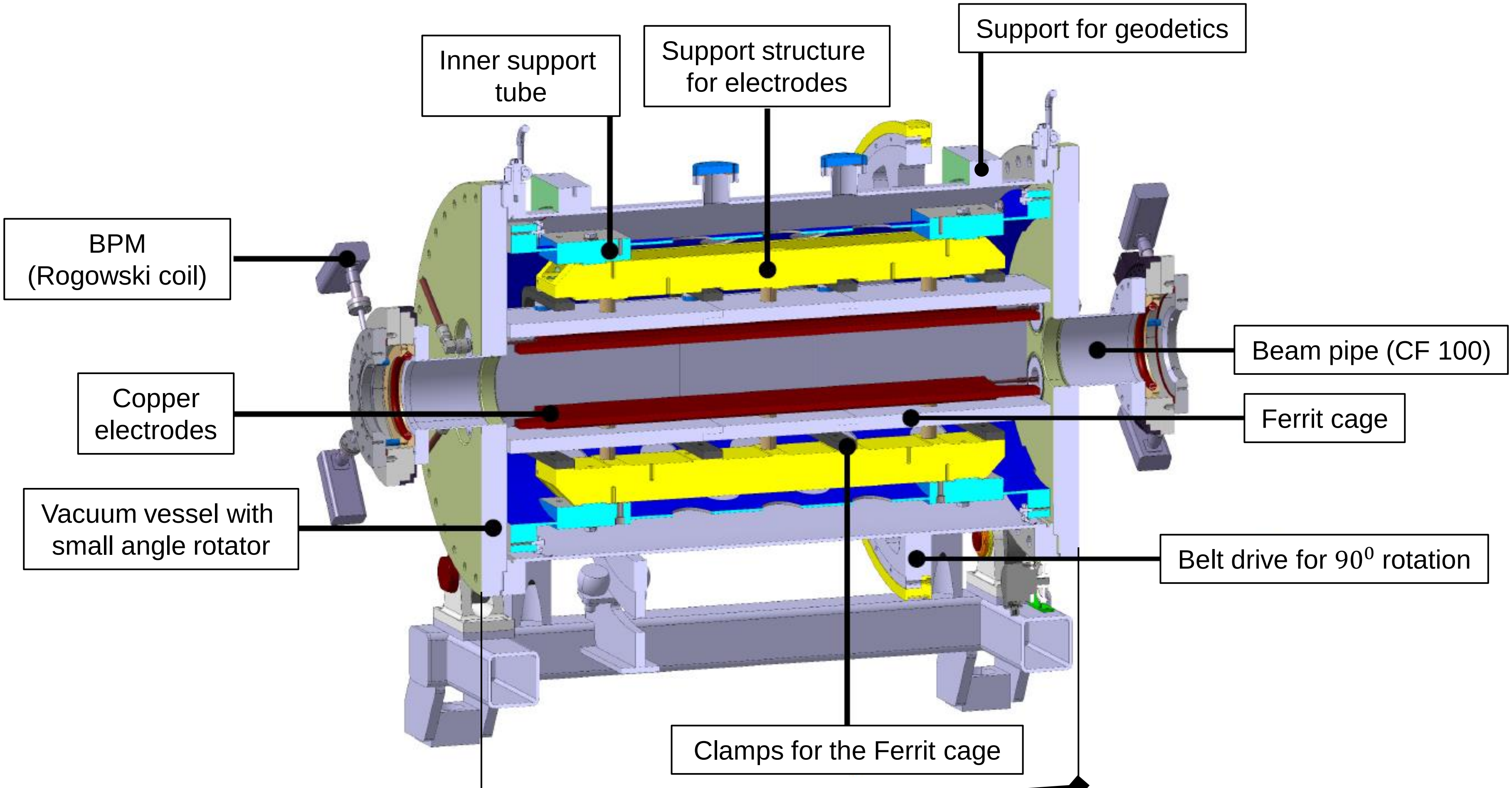




Device will be installed in PAX low-β section

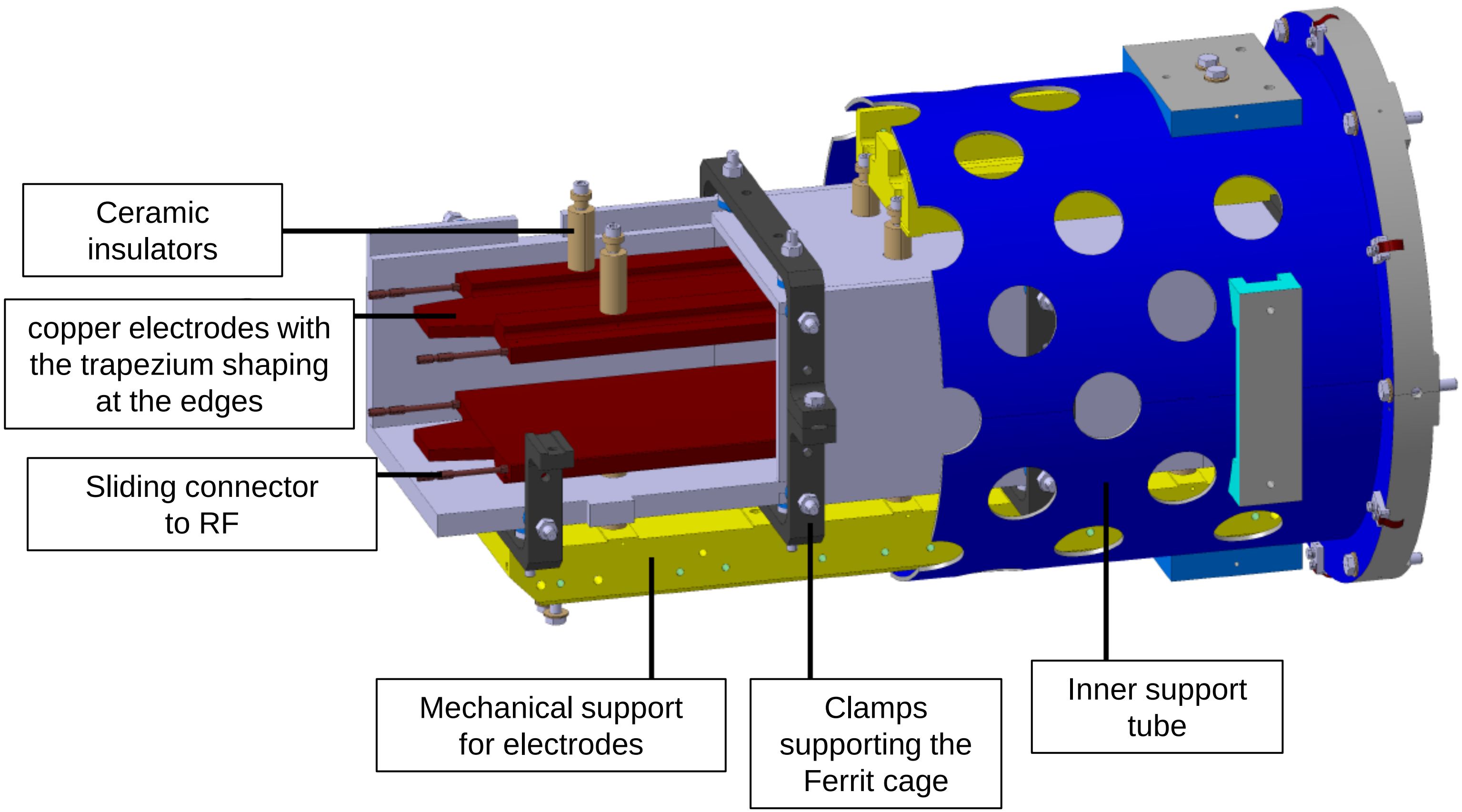
Some features of the new RF Wien filter

Waveguide provides $\vec{E} \times \vec{B}$ by design.



Aim is to build the best possible device with respect to electromagnetic performance, mechanical tolerances, etc.

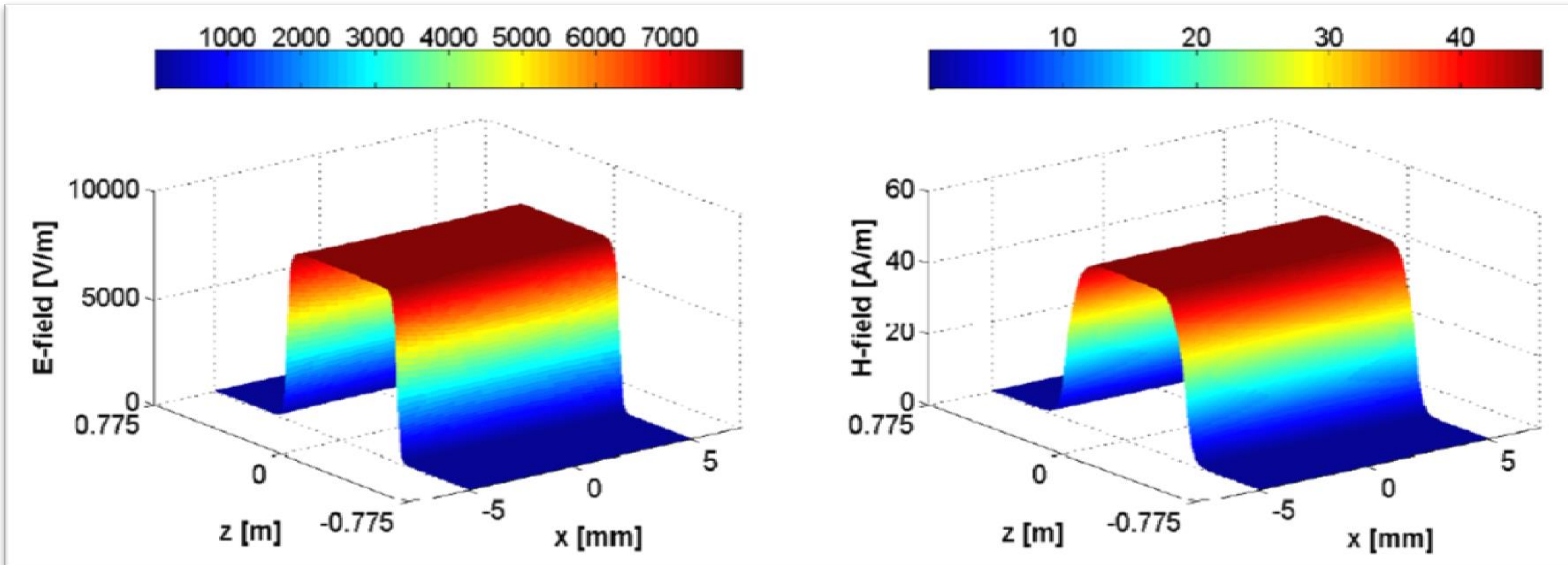
Internal structure of the device



Design completed, production started, device available in fall 2016.

Electromagnetic field simulations

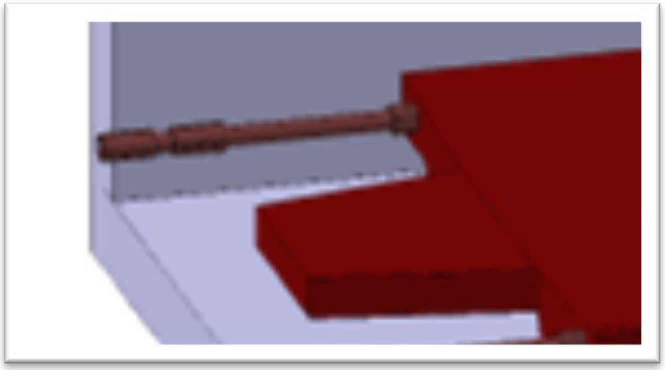
- Full-wave simulation with CST Microwave Studio
- Each simulation required ~12 hours of computer time

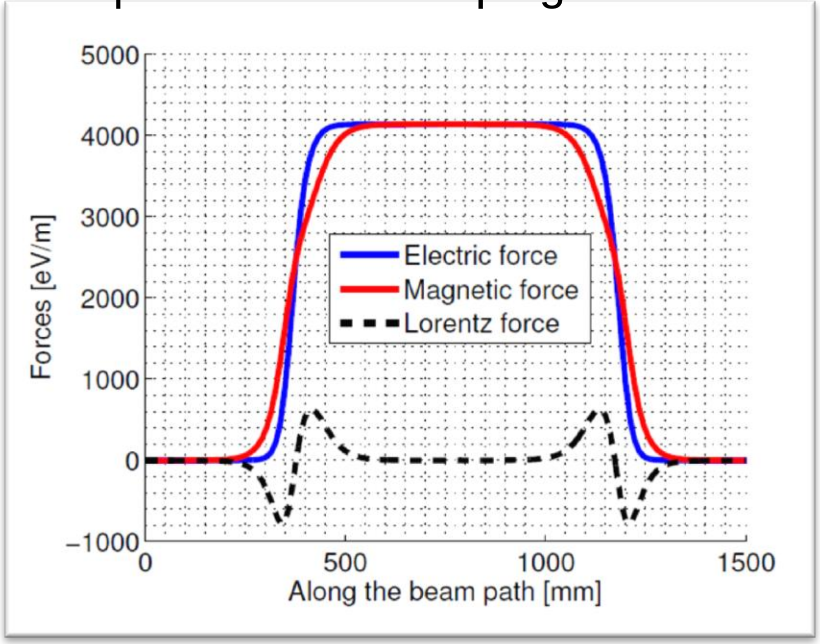


Excellent cooperation with RWTH and ZEA

Lorentz force compensation

Providing minimal integral Lorentz force requires careful shaping of electrodes and all other components





$$\vec{F}_L = q(\vec{E} + \vec{v} \times \vec{B})$$

Lorentz force integral with $\vec{v}$ along Wien filter axis

$$\frac{q}{\ell}\int_{-\ell/2}^{\ell/2}\begin{pmatrix} E_x - c\beta B_y \\ E_y + c\beta B_x \\ E_z \end{pmatrix} dz = \begin{pmatrix} 5.97\times 10^{-3} \\ 7.97\times 10^{-3} \\ 1.27\times 10^{-21} \end{pmatrix} \mathrm{eV/m}$$

$$\int_{-\ell/2}^{\ell/2}\vec{B}dz = \begin{pmatrix} 2.73\times 10^{-9} \\ 0.047 \\ 6.96\times 10^{-7} \end{pmatrix} \mathrm{T\,mm}$$

**Mechanical design completed. Continued work on RF driving circuit.
Goal is to reach $\int Bdl \sim 0.5\ \mathrm{Tmm}$ possible.**

RF $\mathbf{E} \times \mathbf{B}$ Wien Filter: Resonance conditions

JÜLICH FORSCHUNGSZENTRUM

$$f_{RF} = f_{\text{rev}}(\gamma G \pm K),\ K \in \mathbb{Z}$$

	p	$f_{\text{rev}}/\text{kHz}$	G	β	γ	γG
d	970.0	750.2	-0.143	0.459	1.126	-0.161
p	521.1	752.6	1.793	0.486	1.144	2.051

K		-4	-3	-2	-1	0	$+1$	$+2$
$\lvert f_{RF}\rvert/\text{kHz}$	d			1621.2	871.0	120.8	629.4	1379.6
	p	1545.6	752.6	40.3	833.2	1626.2		

Frequency range RF Wien filter prototype (Gebel/Mey)

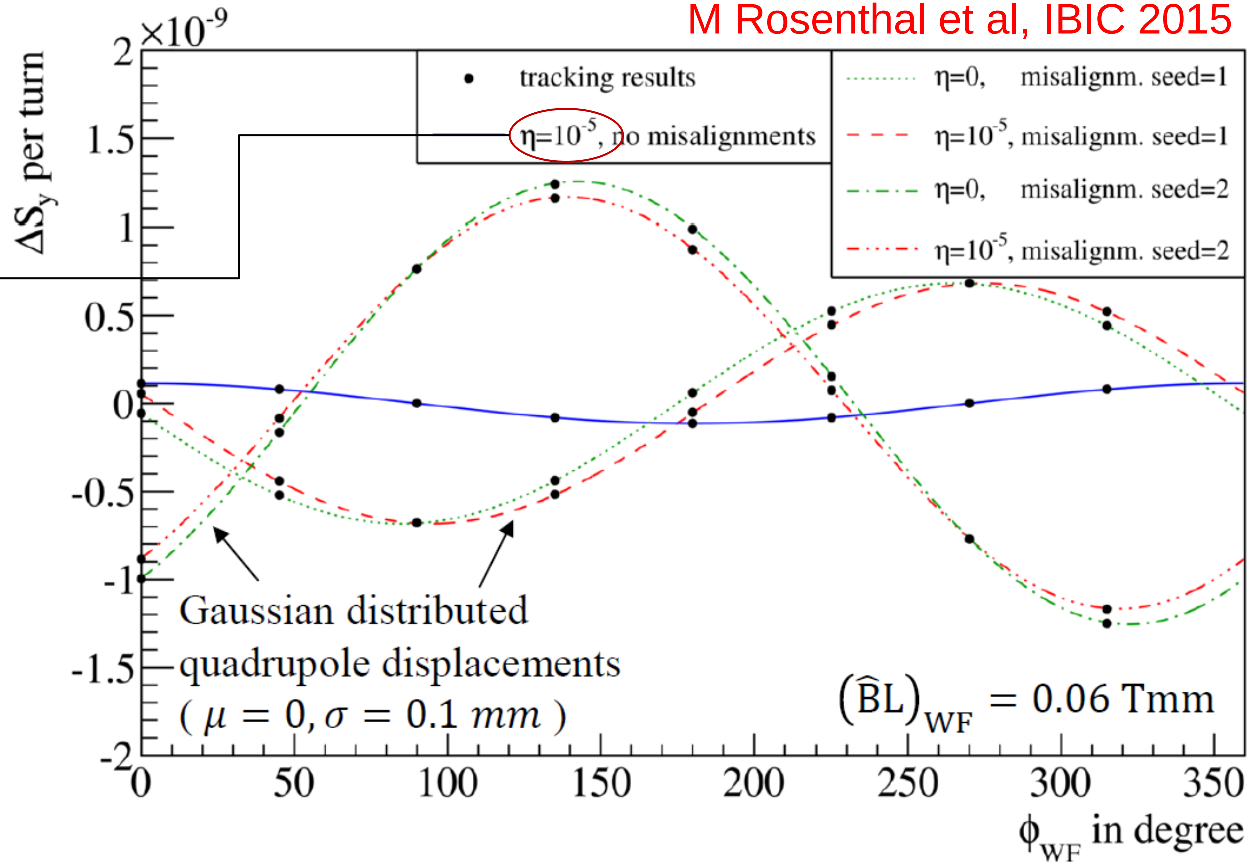
New waveguide RF Wien filter will provide resonance conditions for deuterons and protons for a number harmonics K.

Concept for first measurements

Simulations with COSY-INF. and RF Wien filter (E_x, B_y) in EDM buildup mode.

M Rosenthal et al, IBIC 2015

$$\vec{d} = \frac{\eta q \hbar}{2mc} \vec{S}$$
$$d = 5 \cdot 10^{-20}\ \text{e cm}$$

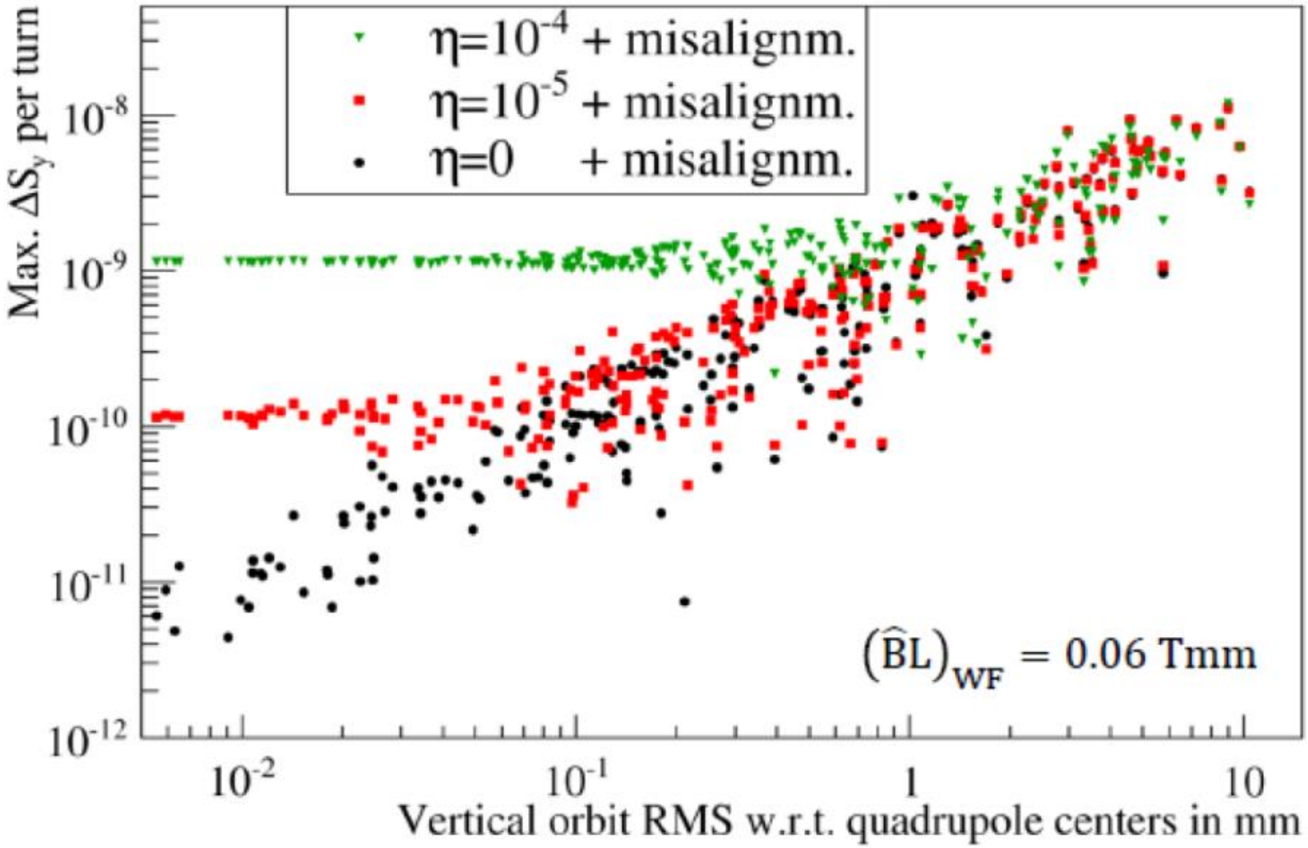


EDM hidden underneath imperfections from magnet misalignments.

Concept for first measurements

- With an RF Wien filter of $\int Bdl = 0.05\ \mathrm{Tmm}$, $\sigma_{stat} \sim 2 \cdot 10^{-22}\ \mathrm{e\ cm}$ can be reached in 1000 s.

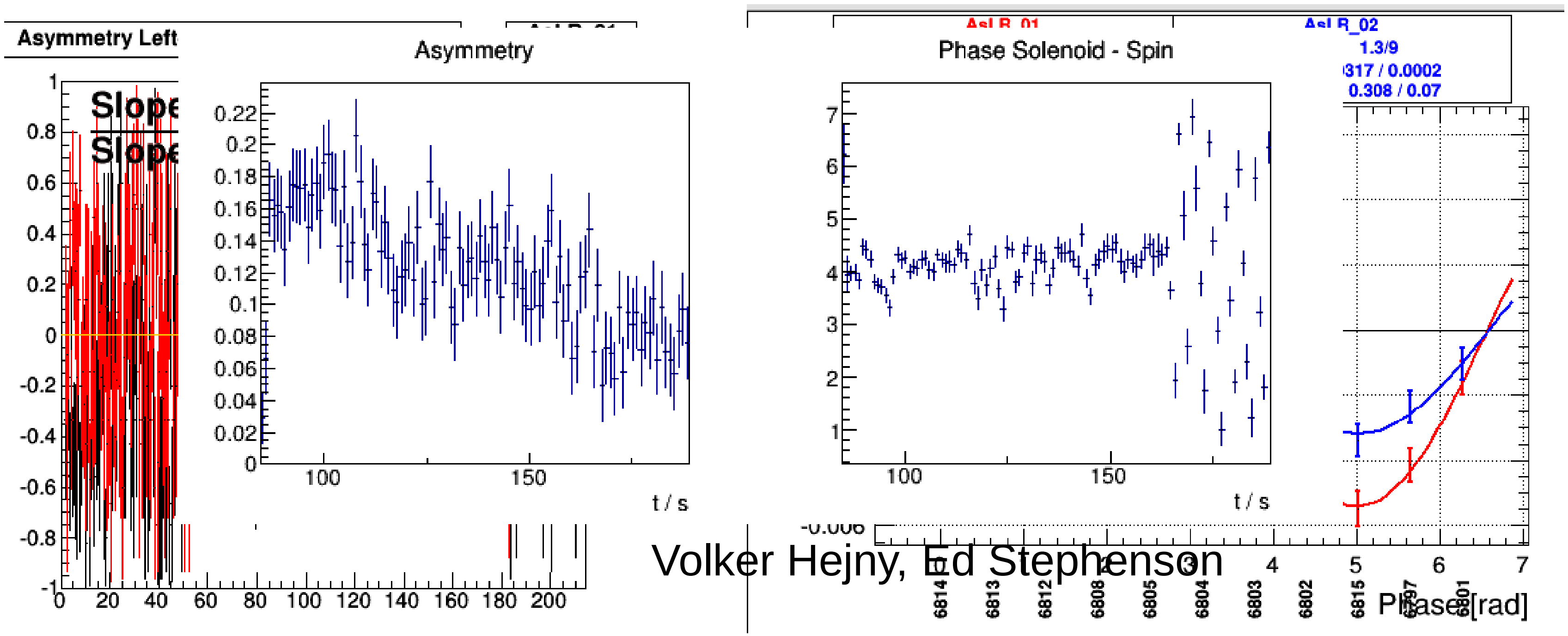
M Rosenthal et al, IBIC 2015



Randomized error standard deviation of $0.1\ \mathrm{mm} \rightarrow$ RMS displacements $\sim 1\mathrm{mm}$.
Contribution to buildup from misalignments similar to EDM for $\eta = 10^{-4}$,
$d = 5 \cdot 10^{-19}\ \mathrm{e\ cm}$.

Results from the December 2015 run at COSY

1. Rotate deuteron spins into ring plane and let them freely precess.
2. Lock the solenoid RF phase to the polarization direction of the ensemble
3. Use small RF solenoid amplitude to mimic polarization buildup



Volker Hejny, Ed Stephenson

- During commissioning, waveguide RF Wien filter will be rotated to observe RF phase-dependence with small amplitudes

Phase-locking now works via changing of the COSY RF (first try). Later, we will phase-lock to RF Wien filter RF.

Outline

- Introduction
- Recent Achievements
  - Spin coherence time
  - Spin tune measurement
  - Study of magnetic machine imperfections
- Technical challenges
- Toward a first direct p, d EDM measurement
- **Conclusion**

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 $\mathbf{10^{-2?}\,e{\cdot}cm}$	RF $\vec{E} \times \vec{B}$ Wien filter	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**

Steps 3 and 4: $>$ 5 years

JEDI Collaboration

- **JEDI** = **J**ülich **E**lectric **D**ipole Moment **I**nvestigations

May the force be with us!

- ~100 members (Aachen, Dubna, Ferrara, Indiana, Ithaka, Jülich, Krakow, Michigan, Minsk, Novosibirsk, St Petersburg, Stockholm, Tbilisi, … http://collaborations.fz-juelich.de/ikp/jedi/)
- ~ 10 PhD students

Conclusion

- EDMs offer new window to disentangle sources of CP violation, and to explain matter-antimatter asymmetry of the universe.
- First direct EDM measurements (p, d) at COSY $(10^{-2?}\ \mathrm{e} \cdot \mathrm{cm}) < 2019$
- Development of a dedicated EDM storage ring $(10^{-29}\ \mathrm{e} \cdot \mathrm{cm})$
  - Conceptual design report 2019
- Spin tune determination is a new precision tool for accelerator studies
  - Map out magnetic imperfections in a machine
- Successful phase-locking of spin precession to solenoid RF
- Development of high-precision spin tracking tools, incl. RF structures.
- Development of electrostatic deflectors (also $E_r \times B_y$), BPMs etc.

Very challenging …, but the physics is fantastic.

Georg Christoph Lichtenberg (1742-1799)

"Man muß etwas Neues machen, um etwas Neues zu sehen."

"You have to make (create) something new, if you want to see something new"

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.
7. D. Eversmann et al. [JEDI Collaboration], **New method for a continuous determination of the spin tune in storage rings and implications for precision experiments,** Phys. Rev. Lett. 115, 094801 (2015), DOI: 10.1103/PhysRevLett.115.094801

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,*** Journal of High Energy Physics 3, 104 (2015), DOI:10.1007/JHEP03(2015)104