Mitglied der Helmholtz-Gemeinschaft

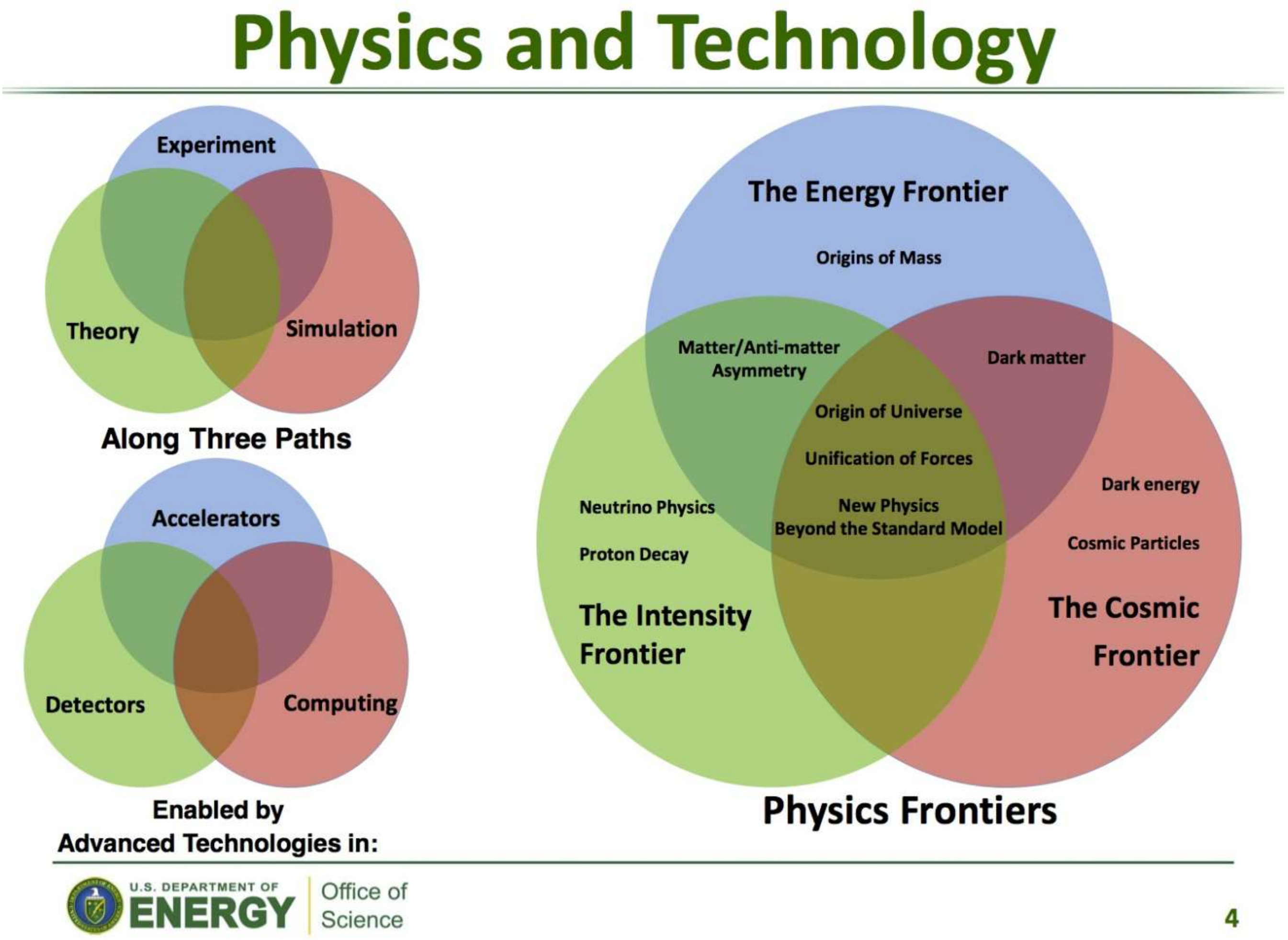
Niccolò Cabeo School 2014
Vacuum and broken symmetries:
from the quantum to the cosmos

Search for Electric Dipole Moments in Storage Rings

May 21, 2014

Frank Rathmann on behalf of JEDI
Cabeo School of Physics, Ferrara, Italy

Preamble: The big challenges



Physics and Technology

Experiment

Theory

Simulation

Along Three Paths

Accelerators

Detectors

Computing

Enabled by
Advanced Technologies in:

The Energy Frontier

Origins of Mass

Matter/Anti-matter Asymmetry

Dark matter

Origin of Universe

Unification of Forces

New Physics Beyond the Standard Model

Neutrino Physics

Proton Decay

Dark energy

Cosmic Particles

The Intensity Frontier

The Cosmic Frontier

Physics Frontiers

U.S. DEPARTMENT OF ENERGY | Office of Science

4

Conventional HEP wisdom, but there is more than that …

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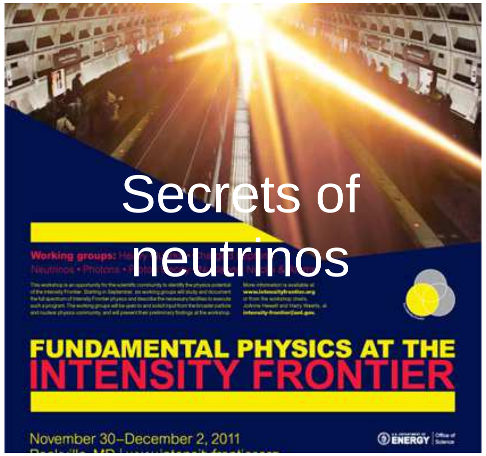
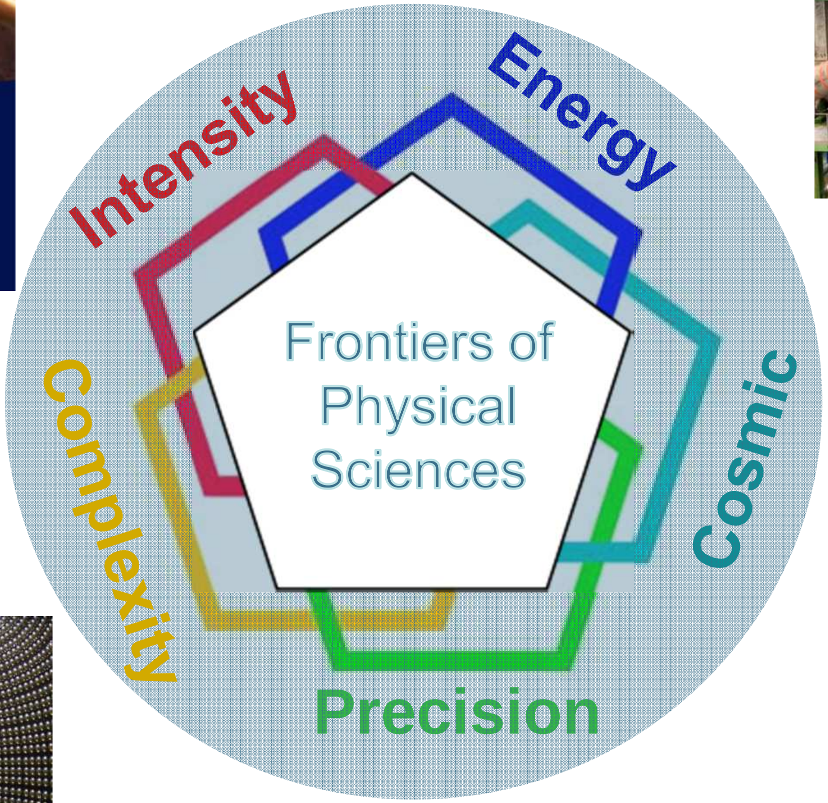
Preamble: Physics Frontiers



Secrets of neutrinos

Search for the origin of mass („Higgs"), SUSY



Intensity

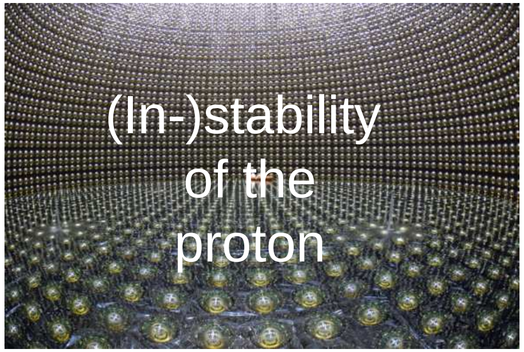
Energy

Cosmic

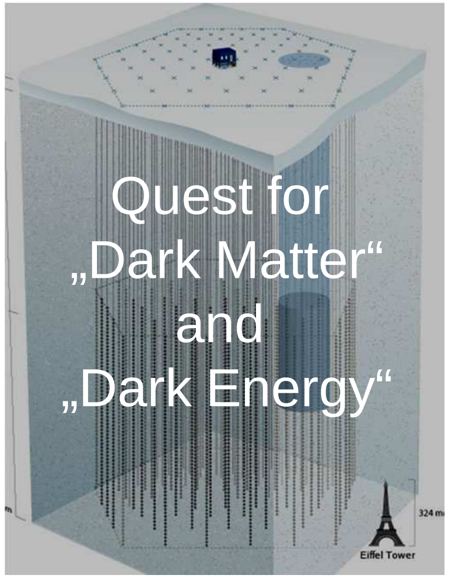
Precision

Complexity

Frontiers of Physical Sciences



(In-)stability of the proton



Quest for „Dark Matter" and „Dark Energy"

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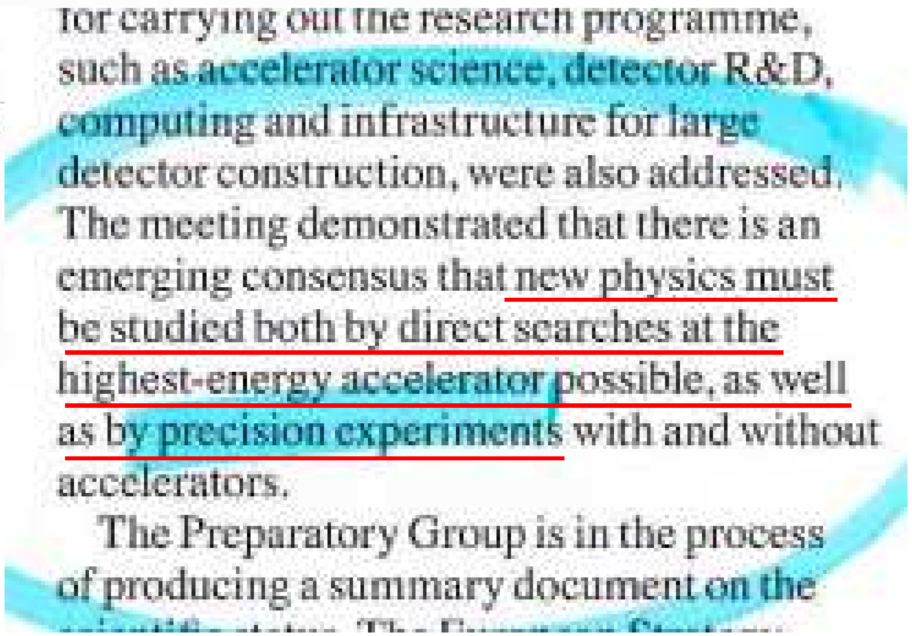
Preamble: Precision Frontier

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*

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Preamble: So, what are the burning questions?

http://particleadventure.org/beyond_start.html

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?

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Outline

- Introduction
- Electric Dipole Moments
- Physics Impact
- Charged particle EDM searches
  - Concepts for dedicated storage ring searches
  - Technological challenges
  - Precursor experiments
- Timeline
- Conclusion

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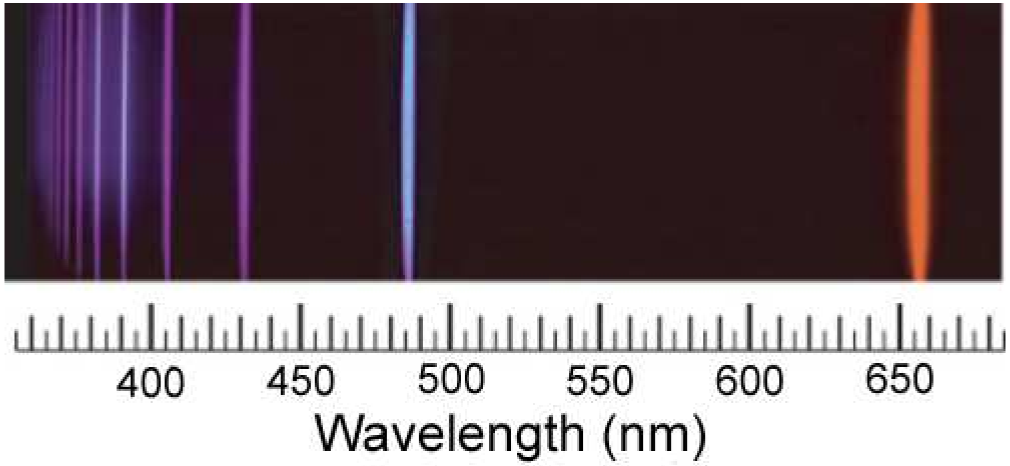
Introduction: Precision Frontier

Johann
Jakob
Balmer
(1885)

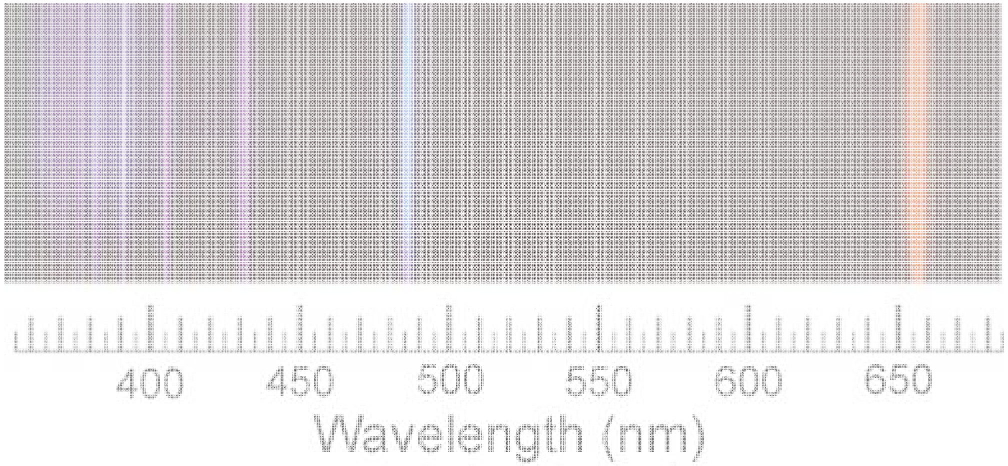


Balmer Series
→ H-atom

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

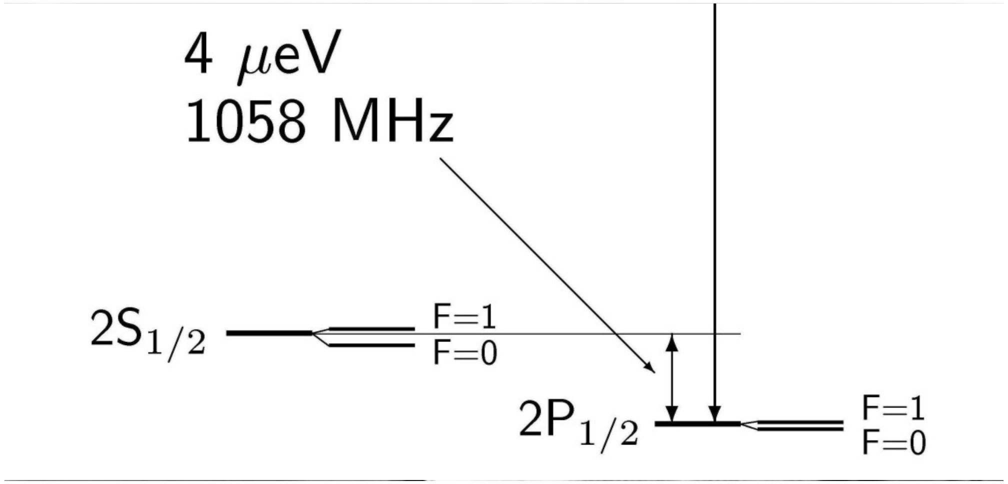
Introduction: Precision Frontier

Johann
Jakob
Balmer
(1885)



Balmer
Series
→ H-atom

Willis E.
Lamb
(1947)



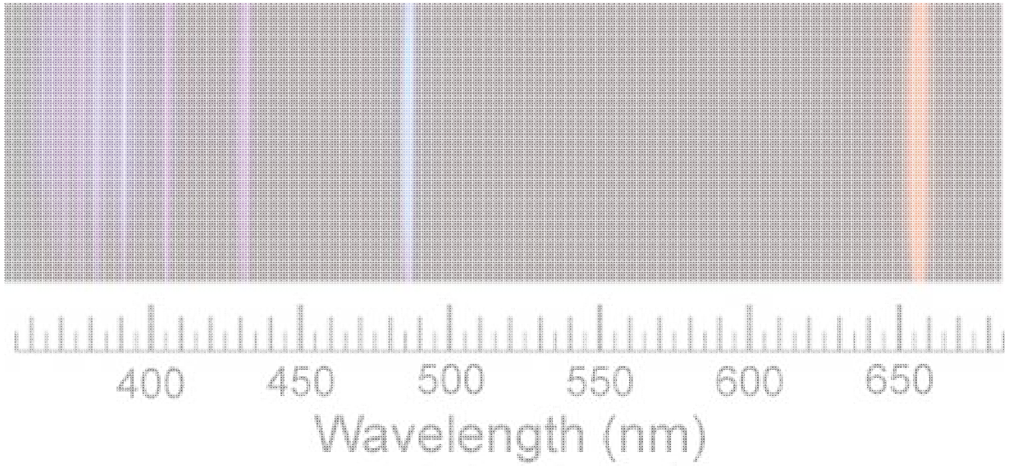
Lamb-shift
(NP 1955)
→ **QED**

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

Striving for the **ultimate precision/sensitivity**

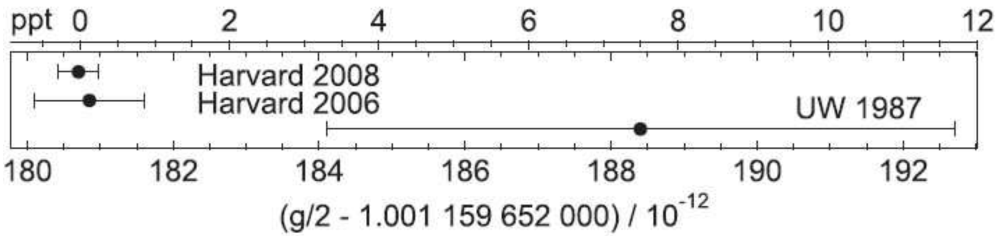
Introduction: Precision Frontier

Johann
Jakob
Balmer
(1885)



Balmer
Series
→ H-atom

Gerald
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“

Introduction: Why charged particle EDMs?

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

New approach, with potentially higher sensitivity

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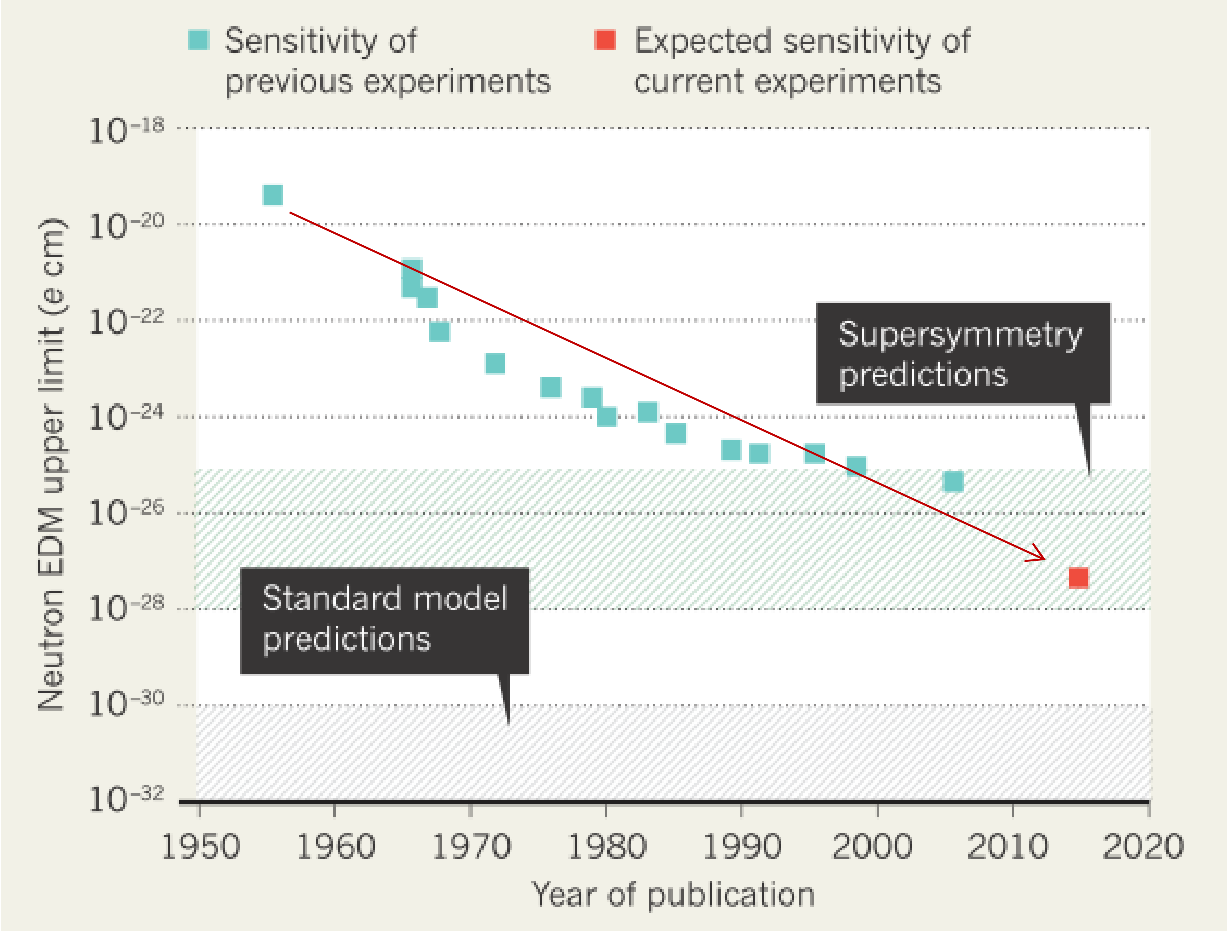
Introduction: Precision Frontier

Example: Neutron (nEDM)



Adapted from: Nature, Vol 482 (2012)

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

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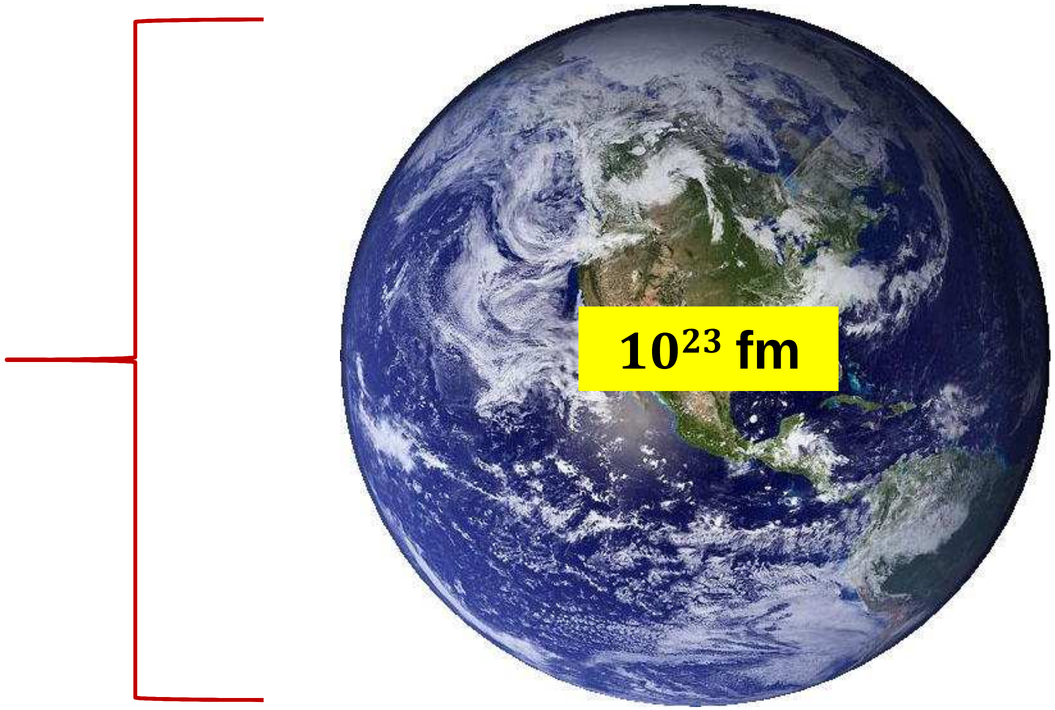
Introduction: Precision Frontier

Nucleon → Earth



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

An EDM is **VERY** small !!

Outline

- Introduction
- **Electric Dipole Moments**
- Physics Impact
- Charged particle EDM searches
  - Concepts for dedicated storage ring searches
  - Technological challenges
  - Precursor experiments
- News and new ideas
- Timeline
- Conclusion

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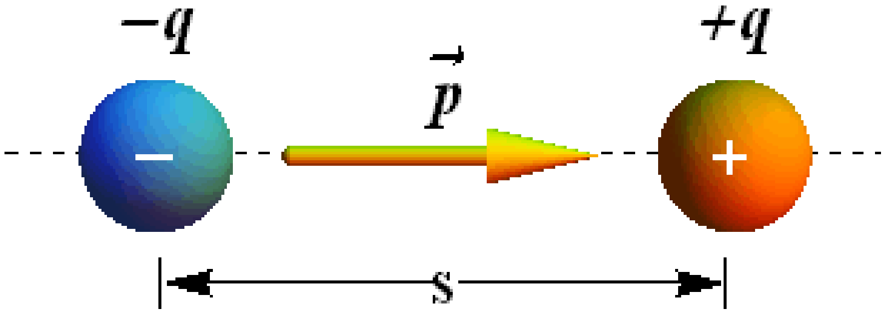
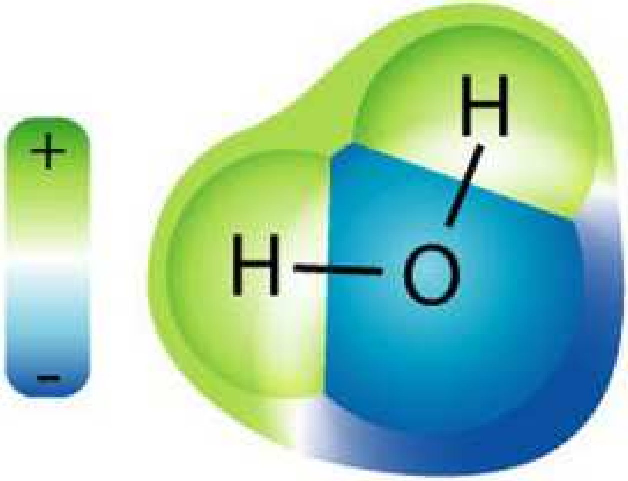
Physics: Electric Dipoles

Definition



$$\vec{p} = q \cdot \vec{s}$$

Example:
H_2O



Water molecule: permanent EDM (degenerate GS w/ different Parity)

$$p \sim 6 \times 10^{-30}\,\mathrm{C \cdot m} \sim 4 \times 10^{-9}\,\mathrm{e \cdot cm}$$

Charge separation creates an electric dipole

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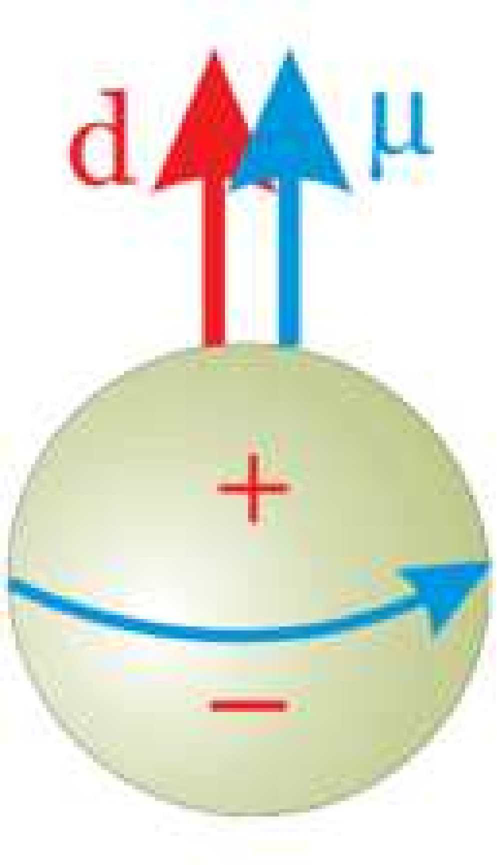
Physics: Fundamental Particles

Charge symmetric
→ No EDM ($d = 0$)



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

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

Insert: Symmetries

Physical laws are invariant under certain transformations

Parity:

$$\boldsymbol{P}: \begin{pmatrix} x \\ y \\ z \end{pmatrix} \rightarrow \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix}$$

T-Symmetry:

$$\boldsymbol{T}: \quad t \rightarrow -t$$

C-parity (or Charge parity):

Changes sign of all quantized charges

- electrical charge,
- baryon number,
- lepton number,
- flavor charges,
- Isospin (3rd-component)

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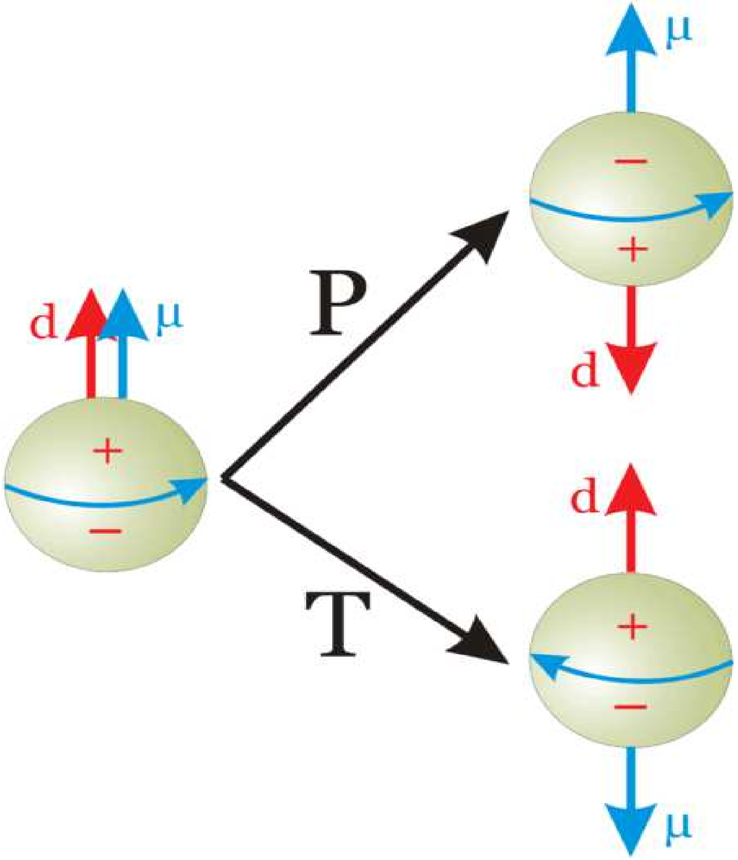
EDMs: Discrete Symmetries

Not Charge symmetric



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

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

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Outline

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Electric Dipole Moments

Physics Impact

Charged particle EDM searches

- Concepts for dedicated Storage Ring searches
- Technological challenges
- Precursor Experiments

Timelines of projects

Conclusion

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Physics: Baryogenesis

Big
Bang

↓

Early
Universe

Symmetry

Matter **Anti-matter**

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

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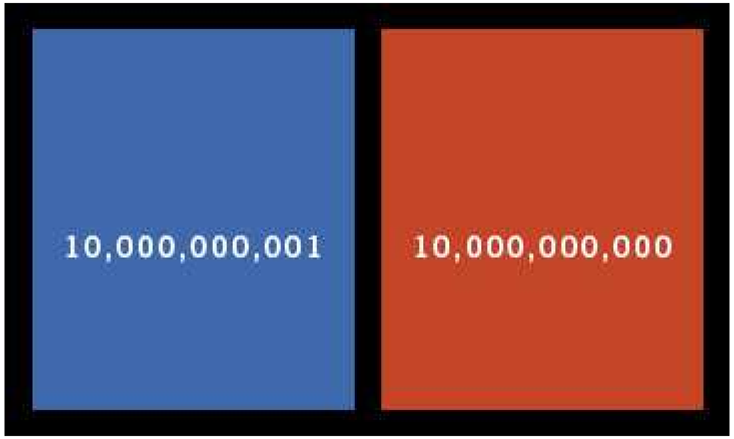
Physics: Baryogenesis

Big
Bang

Early
Universe



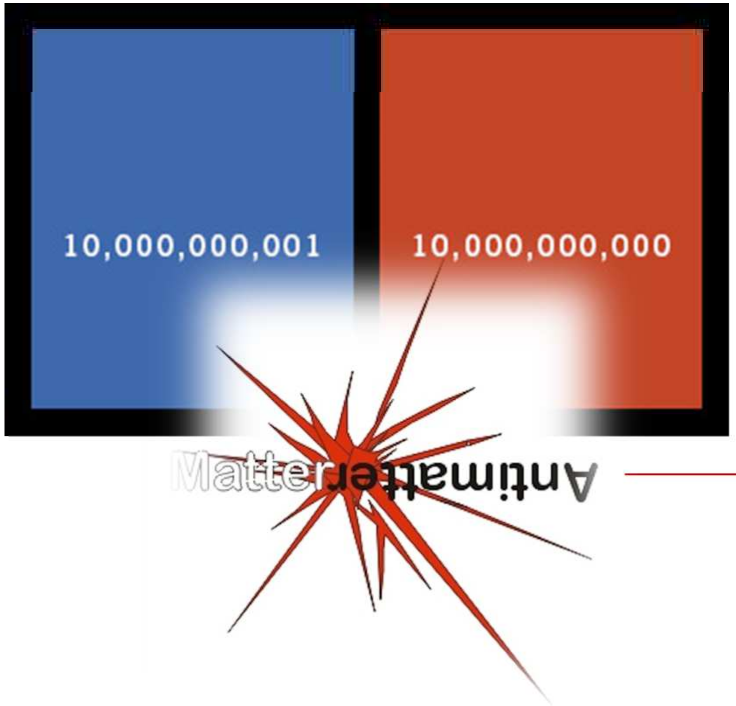
Matter **Anti-matter**

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

Physics: Baryogenesis


Big Bang

Early Universe

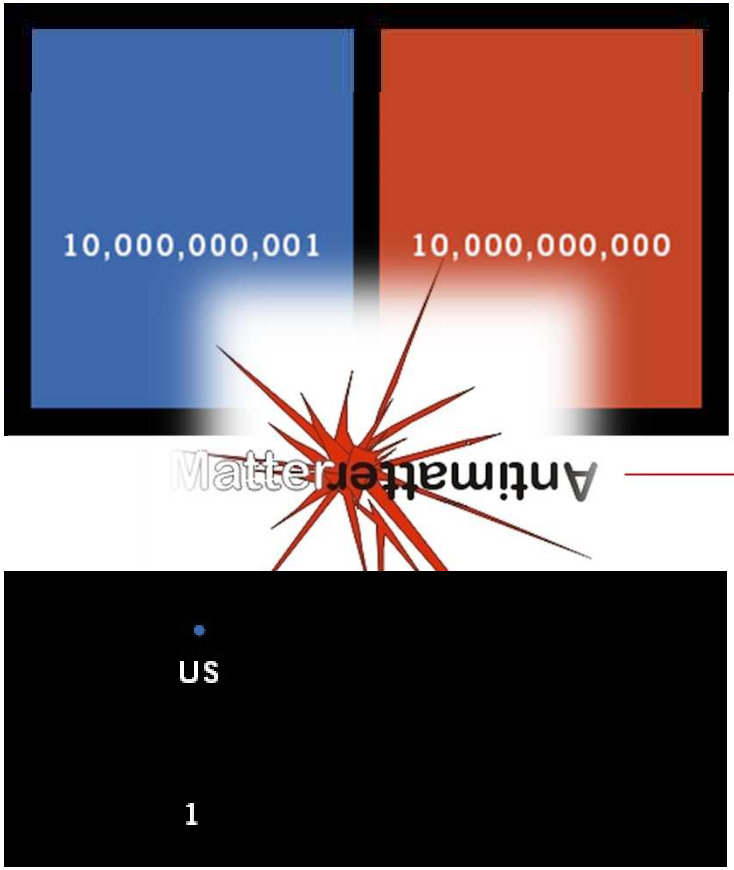


Matter anti-matter annihilation
→ photons

Matter **Anti-matter**

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

Physics: Baryogenesis



Matter **Anti-matter**

Matter
anti-matter
annihilation
→ photons

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

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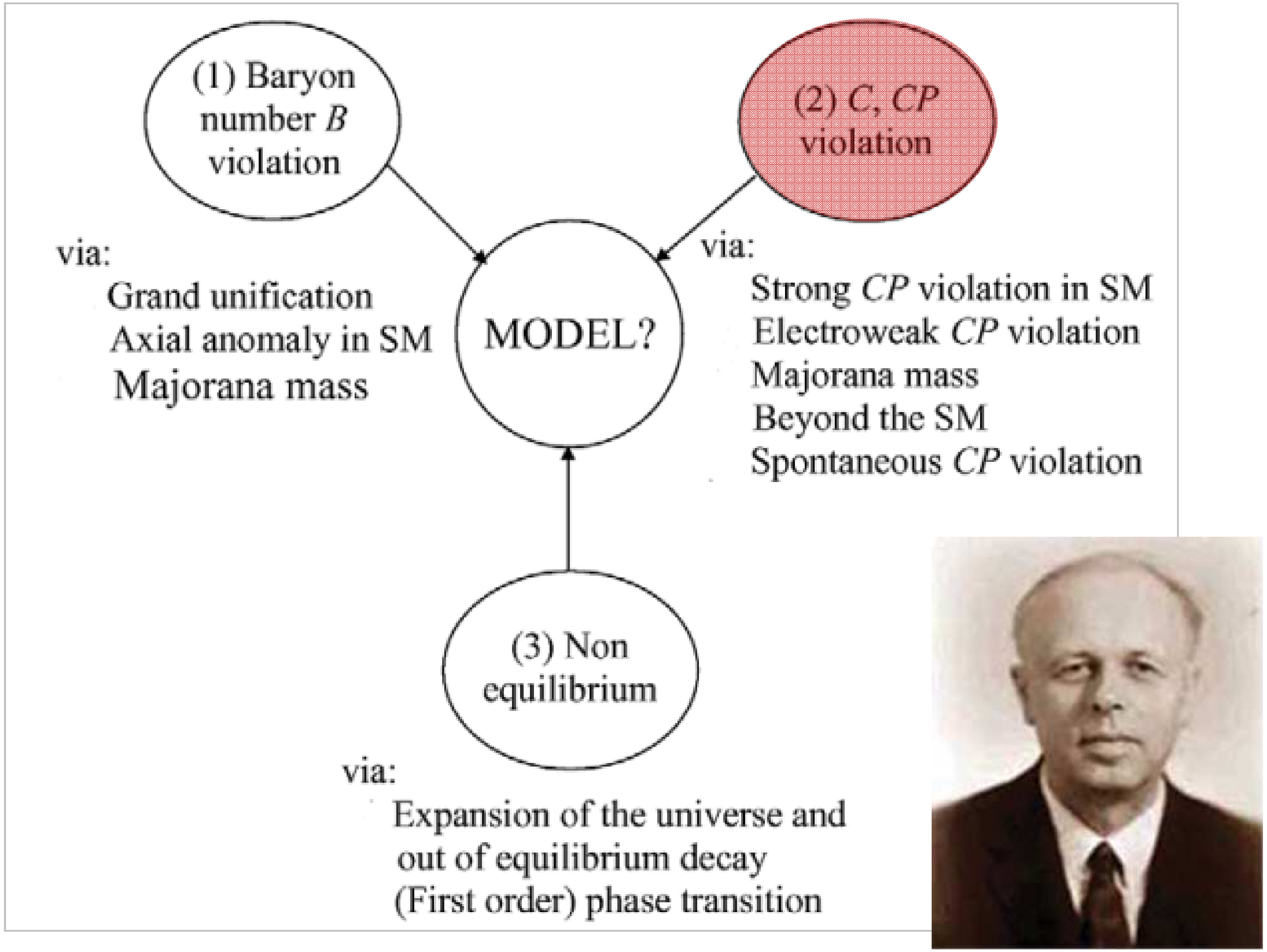
Physics: **Baryogenesis**



(1) Baryon number *B* violation

via:

Grand unification
Axial anomaly in SM
Majorana mass

(2) *C*, *CP* violation

via:

Strong *CP* violation in SM
Electroweak *CP* violation
Majorana mass
Beyond the SM
Spontaneous *CP* violation

MODEL?

(3) Non equilibrium

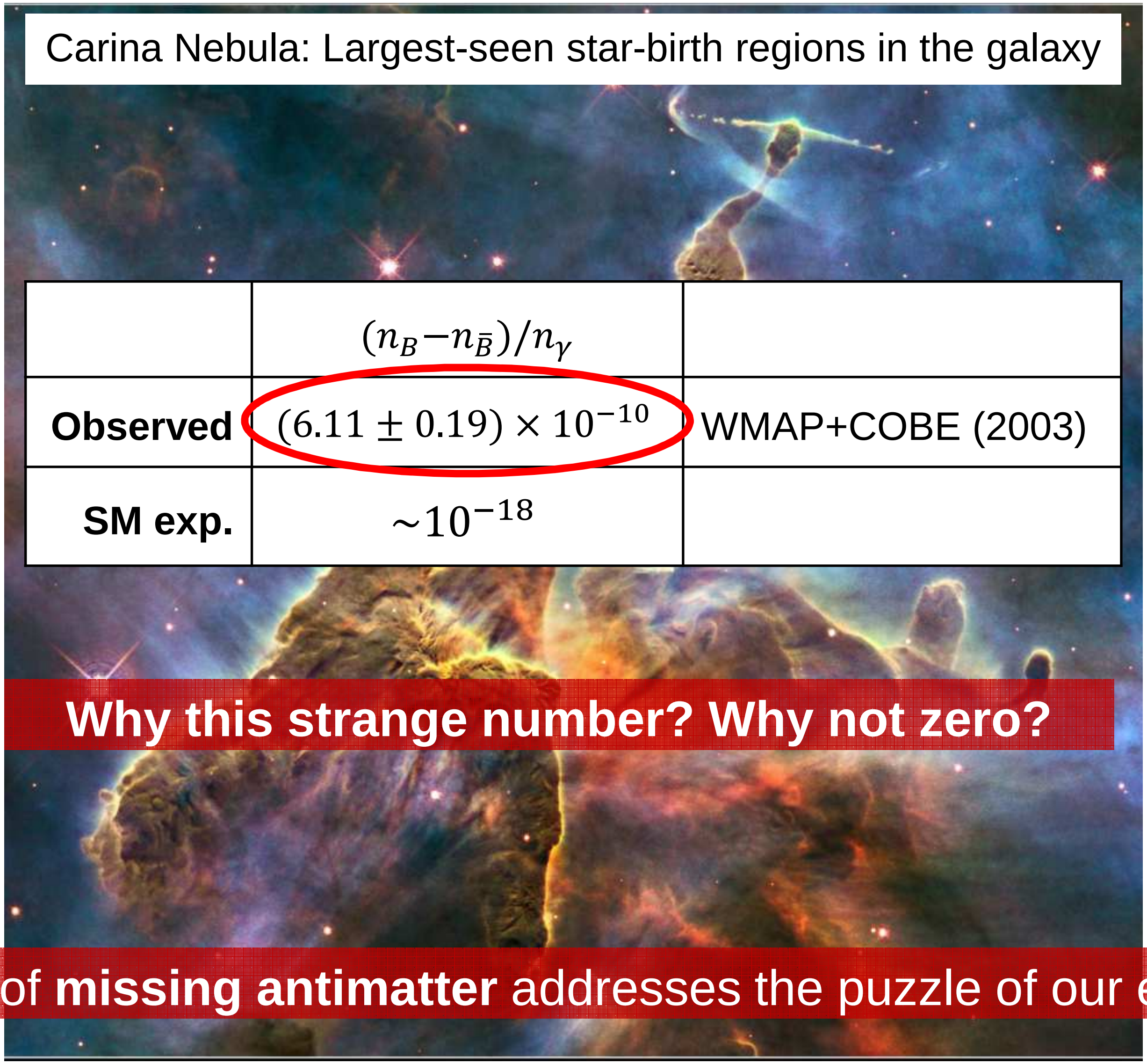
via:

Expansion of the universe and out of equilibrium decay
(First order) phase transition

(1967)

Ingredients for baryogenesis: **3 Sakharov conditions**

Physics: Observed Baryon Asymmetry



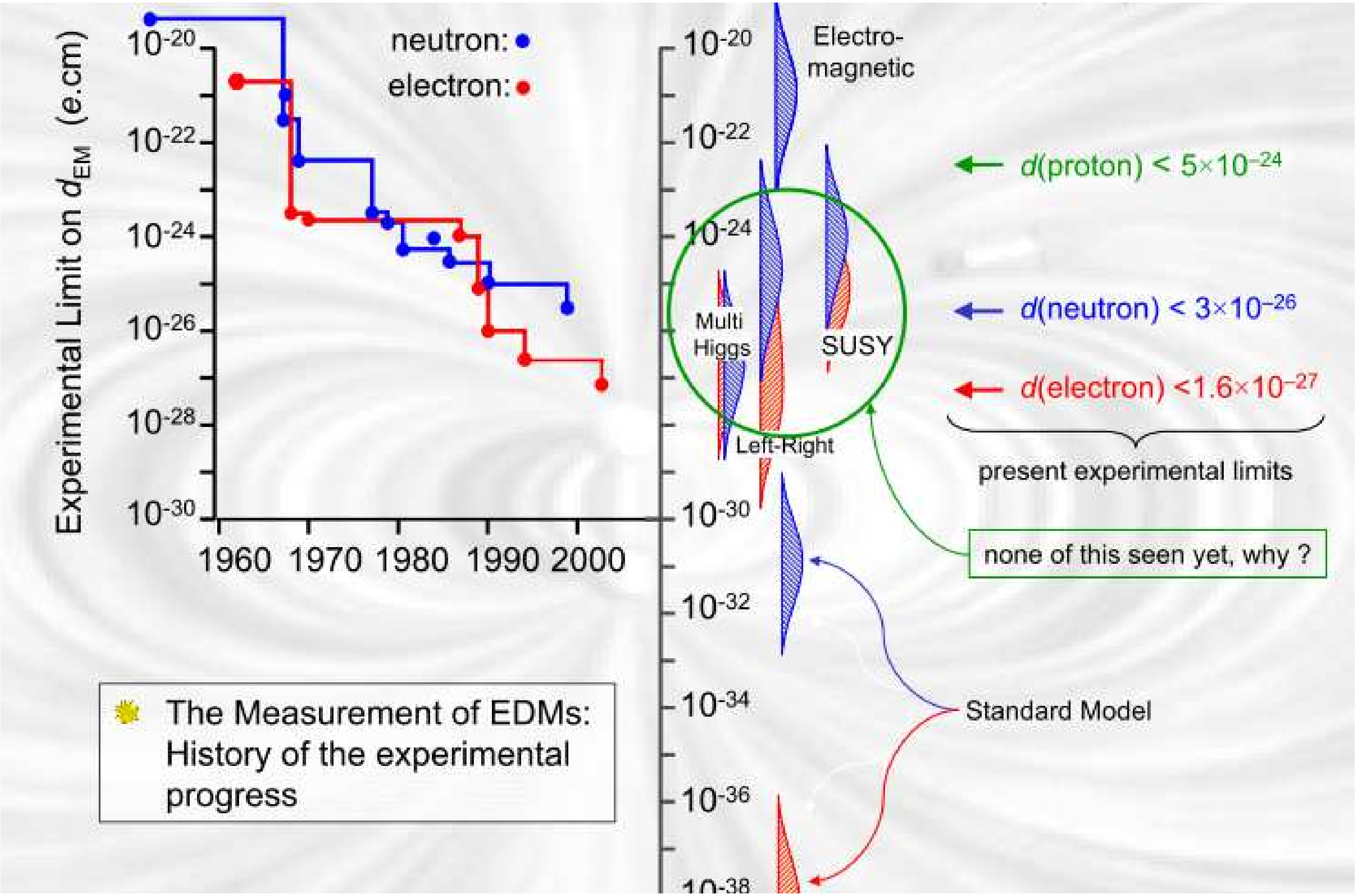
Carina Nebula: Largest-seen star-birth regions in the galaxy

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

Why this strange number? Why not zero?

Mystery of **missing antimatter** addresses the puzzle of our existence

Physics: Potential of EDMs



← d(proton) < 5×10^{-24}

← d(neutron) < 3×10^{-26}

← d(electron) < 1.6×10^{-27}

present experimental limits

none of this seen yet, why ?

The Measurement of EDMs: History of the experimental progress

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

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Physics: Limits for Electric Dipole Moments

EDM searches: only upper limits yet (in e·cm)

Particle/Atom	Current EDM Limit	Future Goal	$\sim d_n$ equivalent
Electron	$< 1.6 \times 10^{-27}$		
Neutron	$< 3 \times 10^{-26}$	$\sim 10^{-28}$	10^{-28}
^{199}Hg	$< 3.1 \times 10^{-29}$	$\sim 10^{-29}$	10^{-26}
^{129}Xe	$< 6 \times 10^{-27}$	$\sim 10^{-30} - 10^{-33}$	$\sim 10^{-26} - 10^{-29}$
Proton	$< 7.9 \times 10^{-25}$	$\sim 10^{-29}$	10^{-29}
Deuteron	?	$\sim 10^{-29}$	$3 \times 10^{-29} - 5 \times 10^{-31}$

No direct measurement of proton EDM available
No measurement at all on the deuteron

Huge efforts underway worldwide to improve limits and to find EDMs

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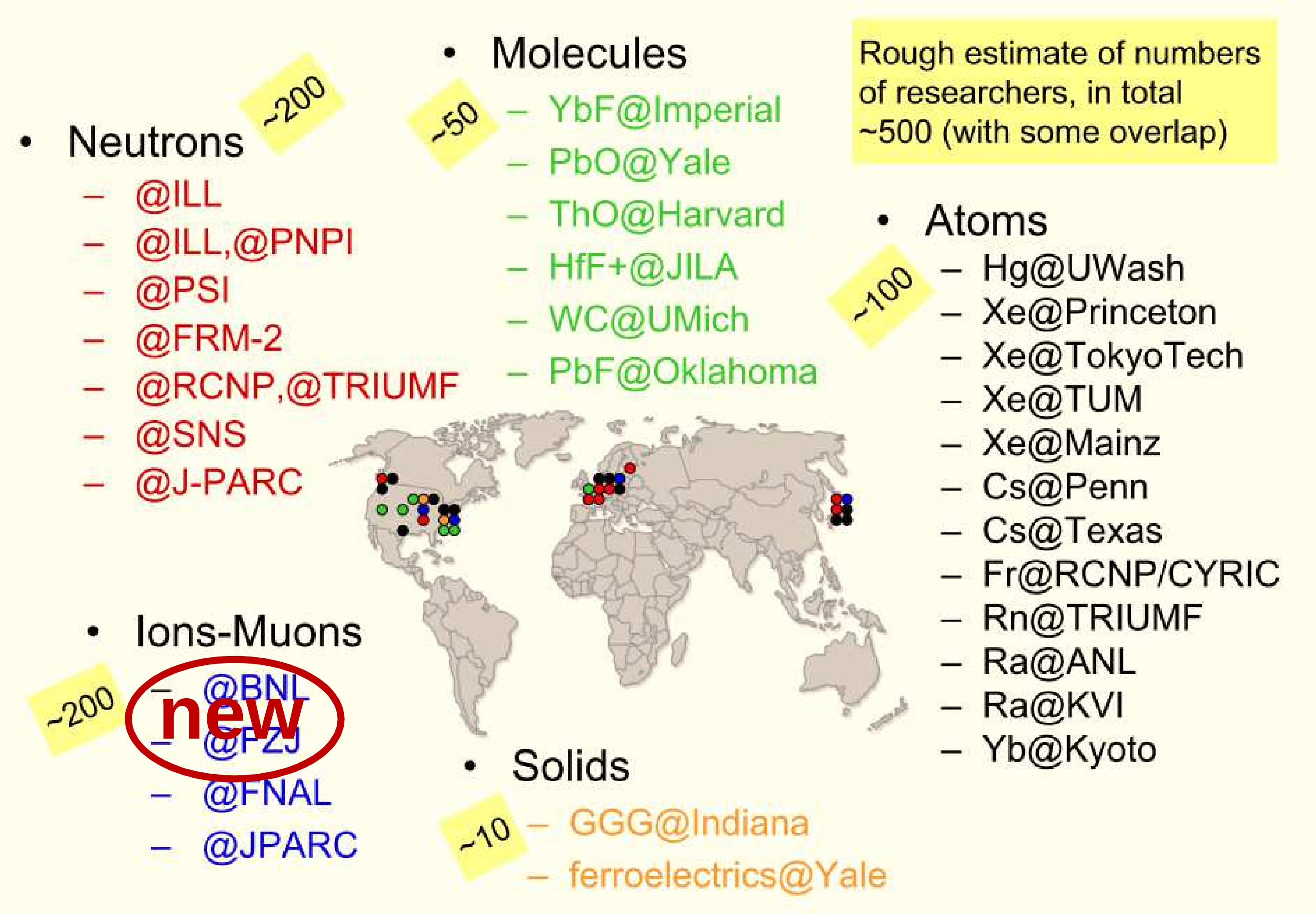
Physics: Ongoing/planned Searches



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

new

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

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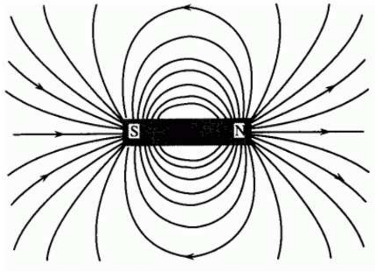
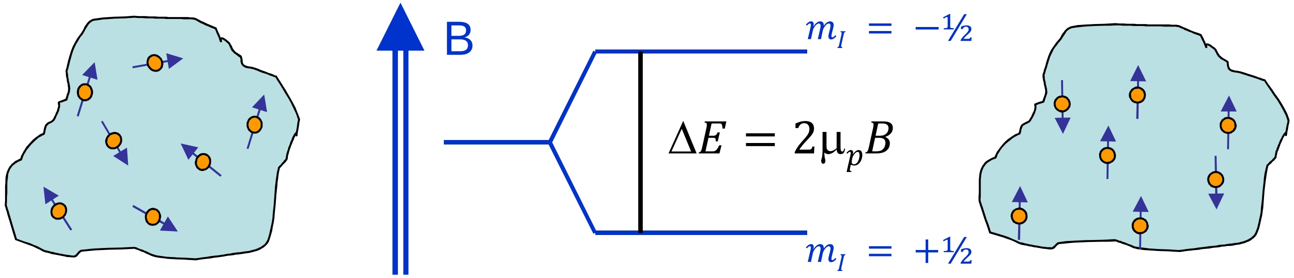
Insert: What do we mean by „polarized”?

Most particles posses a magnetic moment,
→ they behave like little magnets

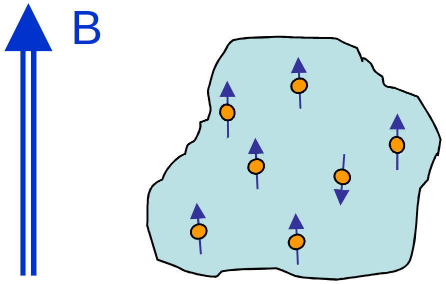


Unpolarized ensemble of particles (e.g., protons)



$$P = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} \approx \frac{\mu_p \cdot B}{k_B \cdot T} \approx 5 \cdot 10^{-6}$$

Polarized ensemble of particles



$$P = \frac{6-1}{6+1} = 0.71$$

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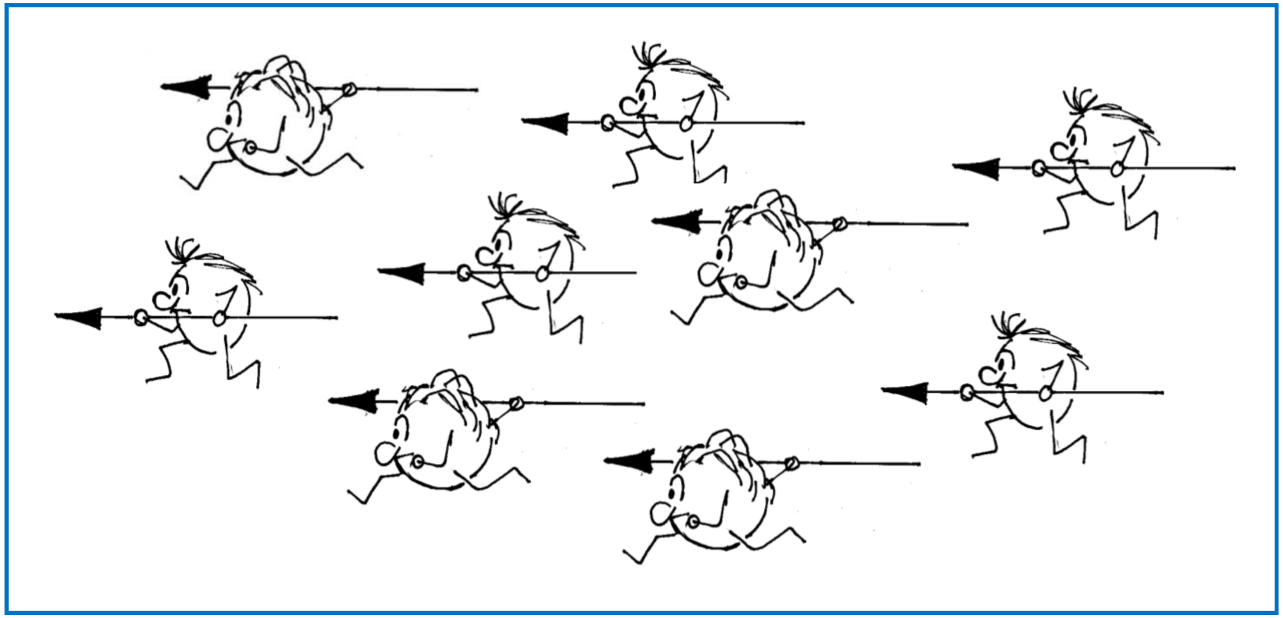
Insert: Picture polarized particles stored in a ring



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Insert: Magnetic moment, spin, g and G

Nuclear magneton $$\mu_N = \frac{e \cdot \hbar}{2 \cdot m_p} = 5.05078324\ \mathrm{JT}^{-1}$$

$$\boxed{\vec{\mu} = g \cdot \mu_N \cdot \frac{m_p}{m} \cdot Z \cdot \vec{s}}$$

particle	**spin** s	**charge** Z	**mass** m	$\frac{\mu}{\mu_N}$	g	$G = \frac{g-2}{2}$
proton	$\frac{1}{2}$	1	938.272013	2.792847356	5.586	1.793
deuteron	1	1	1875.612793	0.8574382308	1.714	-0.143
^{3}He	$\frac{1}{2}$	2	2808.391383	-2.127497718	-6.368	-4.184
electron	$\frac{1}{2}$	-1	0.510998928	-1838.28197090	2.002	0.001

e.g., NIST data base: http://www.nist.gov/pml/data

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Concept: Frozen spin Method

For transverse electric and magnetic fields in a ring $(\vec{\beta}\cdot\vec{B} = \vec{\beta}\cdot\vec{E} = 0)$, ***anomalous*** spin precession is described by Thomas-BMT equation:

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

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 $E = E_{\text{radial}}$ and $B = B_{\text{vertical}}$

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

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

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

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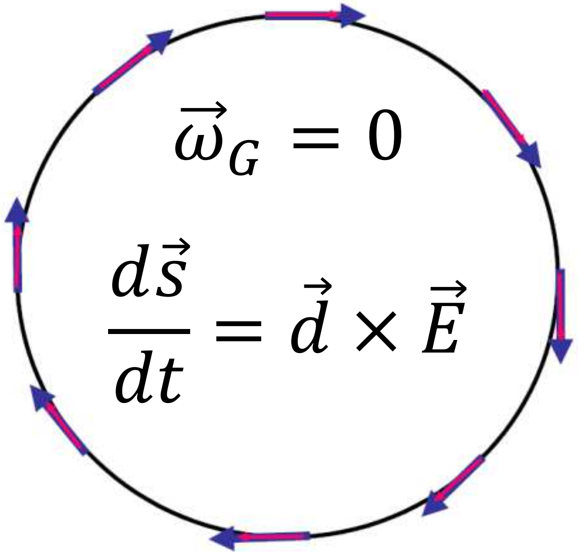
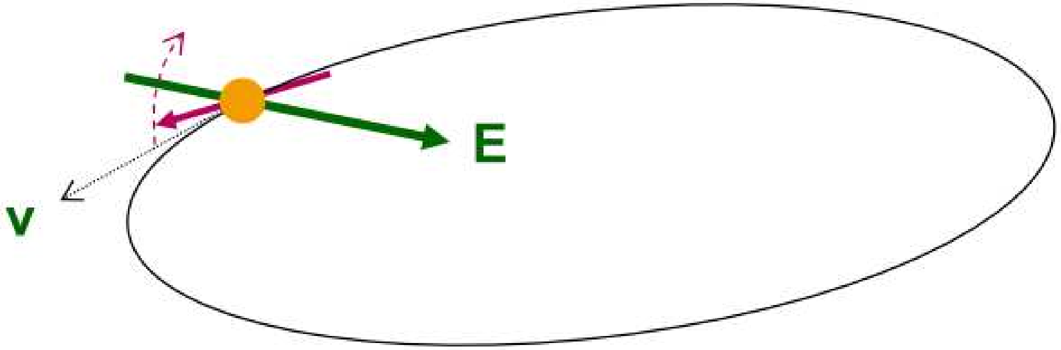
Concept: Rings for EDM searches

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



$$\vec{\omega}_G = 0$$

$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$



New Method to measure EDMs of **free** charged particles:

Magic rings with spin frozen along momentum

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 ($\tau = 1000\ \mathrm{s}$)
- 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: Systematics

Magnetic fields:

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

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

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

CW and CCW beams to tackle systematics

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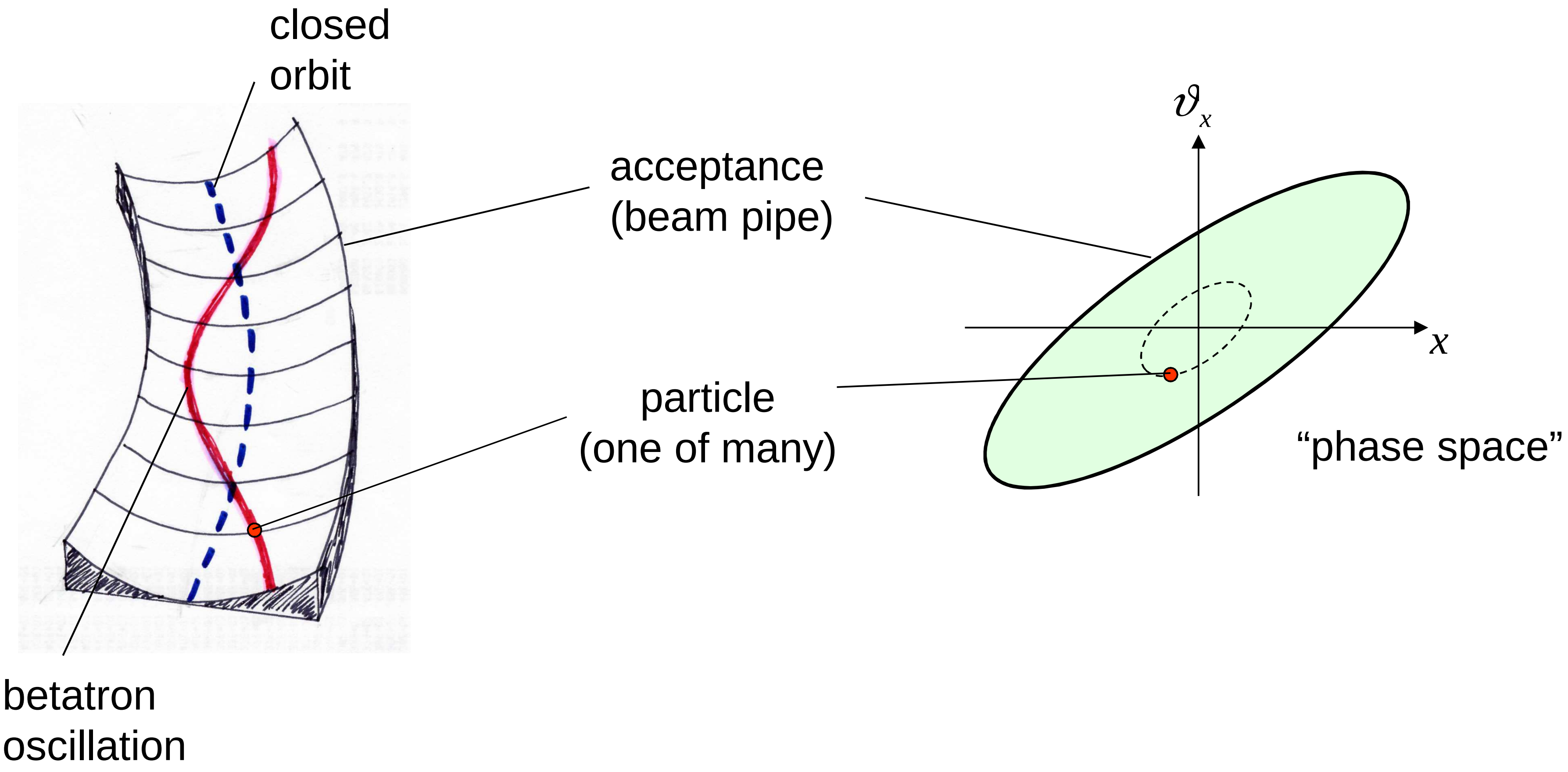
Concept: Systematics, Orbit splitting (Dave Kawall)

- 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: 10^4fills 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.

Insert: Storage ring, dynamics and acceptance



closed orbit

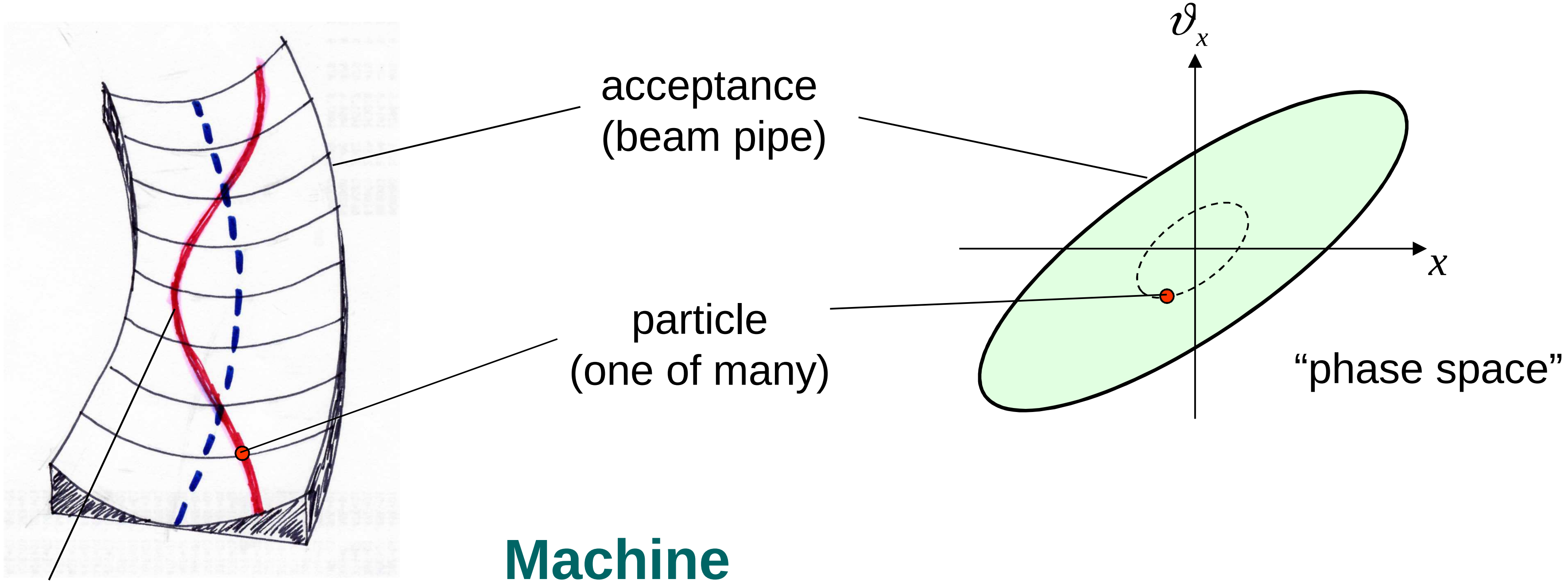
acceptance (beam pipe)

particle (one of many)

“phase space”

betatron oscillation

Insert: Storage ring, dynamics and acceptance



acceptance
(beam pipe)

particle
(one of many)

“phase space”

Betatron oscillation

Tune $Q_{x,y}$ denotes number of betatron oscillations per turn

Machine Resonances

if betatron frequency is simple fraction of periodic perturbation frequency

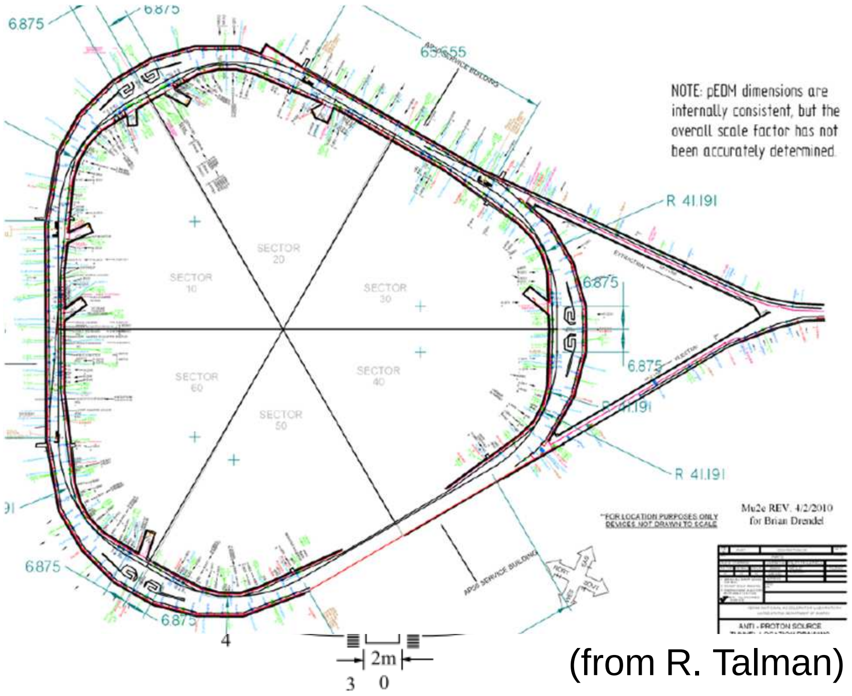
Intense beams

image charges,
intra-beam scattering

Concepts: EDMs Storage ring projects

pEDM in all electric ring at BNL

or at FNAL

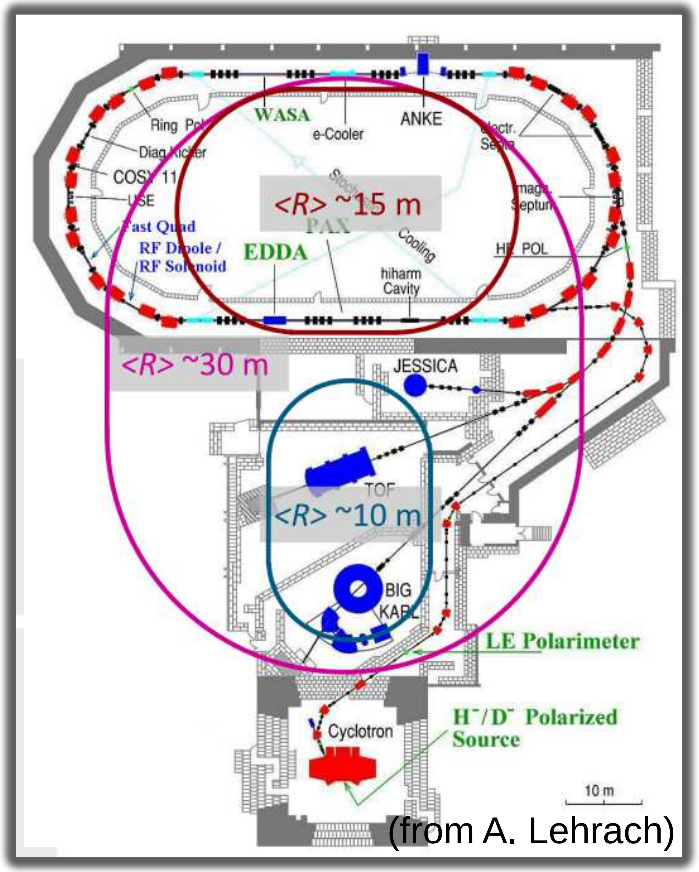


NOTE: pEDM dimensions are internally consistent, but the overall scale factor has not been accurately determined.

(from R. Talman)

CW and CCW propagating beams

Jülich, focus on deuterons,
or a combined machine



(from A. Lehrach)

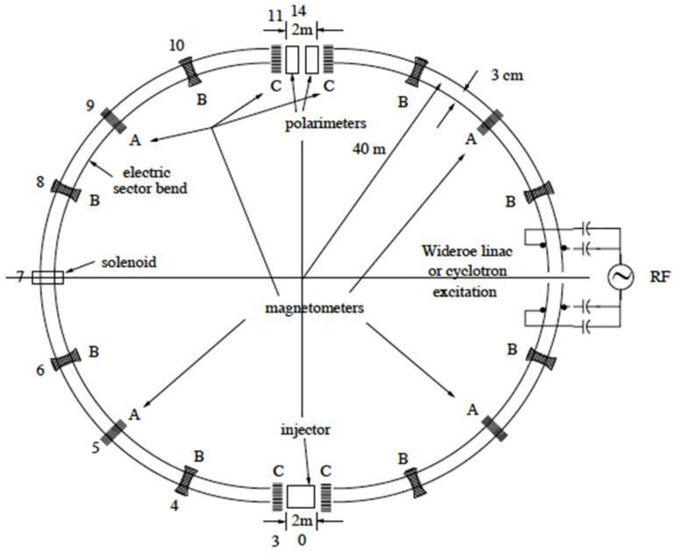
Two projects: **US** (BNL or FNAL) and **Europe** (FZJ)

Concepts: Beat the systematics

2 beams simultaneously rotating in an all electric ring (CW, CCW)

CW & CCW beams cancels systematic effects

	CW		CCW	
Polarization (P_z)	+	−	+	−
EDM $(\vec{d} \times \vec{E})$	−	+	+	−
Sokolov-Ternov	−	−	+	+
Gravitation	−	+	−	+



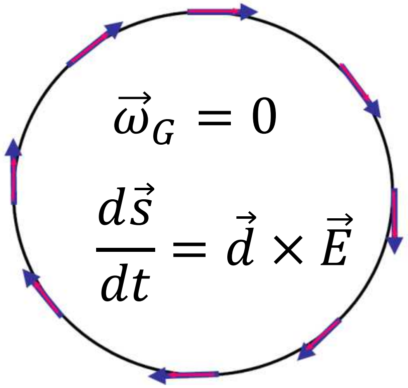
Status: Approved BNL-Proposal
Submitted to DOE
Interest FNAL!

Goal for protons $\sigma_d = 2.5 \times 10^{-29}\ \mathrm{e \cdot cm\ (one\ year)}$

Many technological challenges need to be met

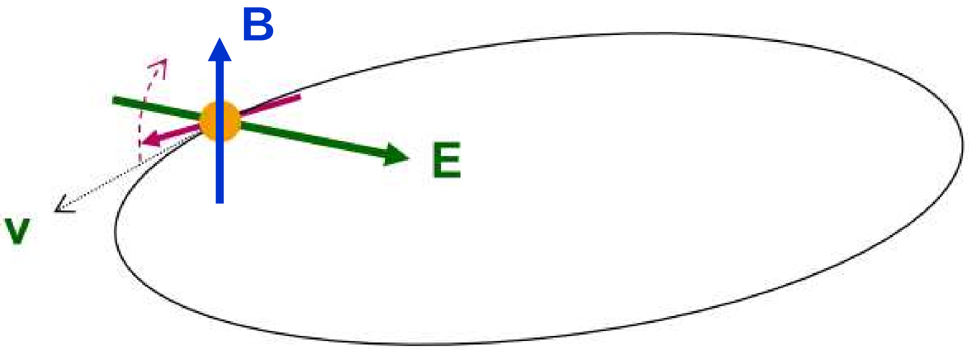
Concepts: *Magic* Storage ring

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



$$\vec{\omega}_G = 0$$

$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$



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

Possible to measure p, d, $^3\mathrm{He}$ using **one** machine with $r \sim 30$ m

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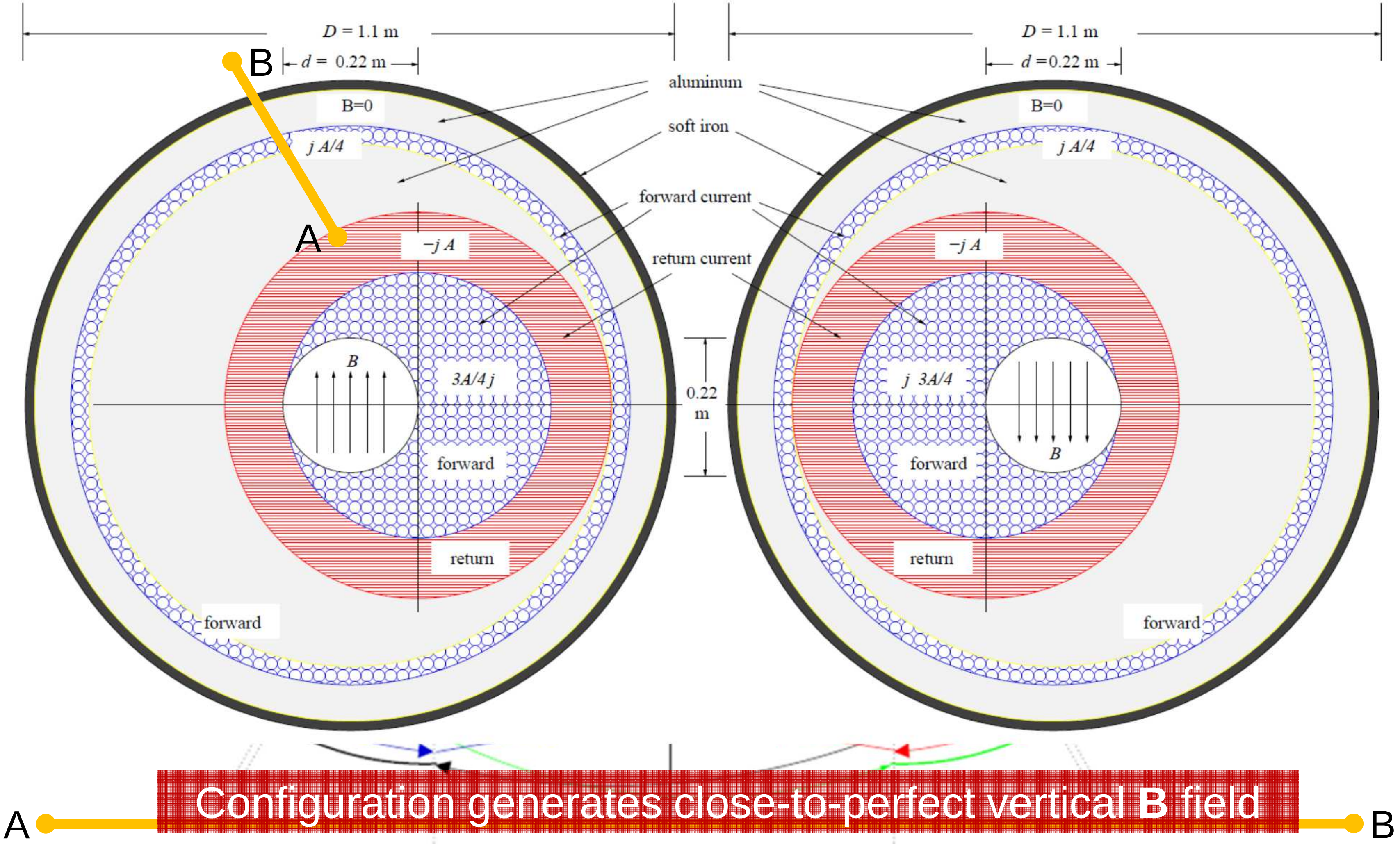
Concepts: CCW & CCW with magnetic field (all-in-one machine)

Iron-free, current-only, magnetic bending, eliminates hysteresis



Configuration generates close-to-perfect vertical **B** field

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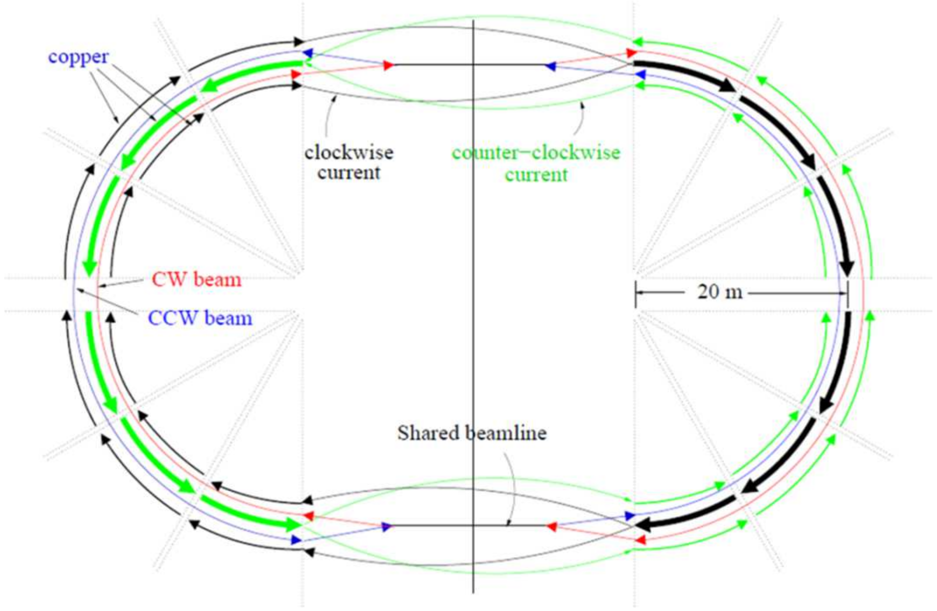
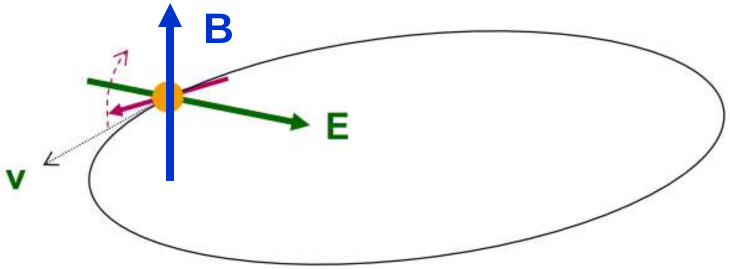
Concepts: An all-in-one machine





Maximum achievable field of copper magnets $\boldsymbol{B_\perp \sim 0.15}$ **T**.

$\boldsymbol{r = 10\ \mathrm{m}}$

particle	$\boldsymbol{p}$ (MeV/c)	$\boldsymbol{T}$ (MeV)	$\boldsymbol{E}$ (MV/m)	$\boldsymbol{B}$ (T)
proton	855.3	331.3	6.8	−0.005
deuteron	381.0	38.3	−1.3	−0.015
^{3}He	739.8	95.8	13.240	−0.050

Very compact machines possible for srEDM searches

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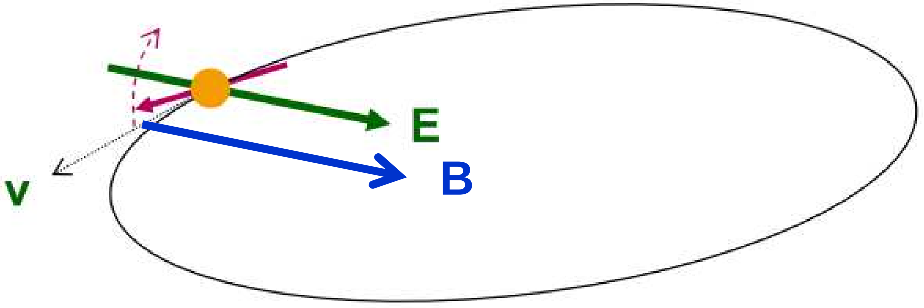
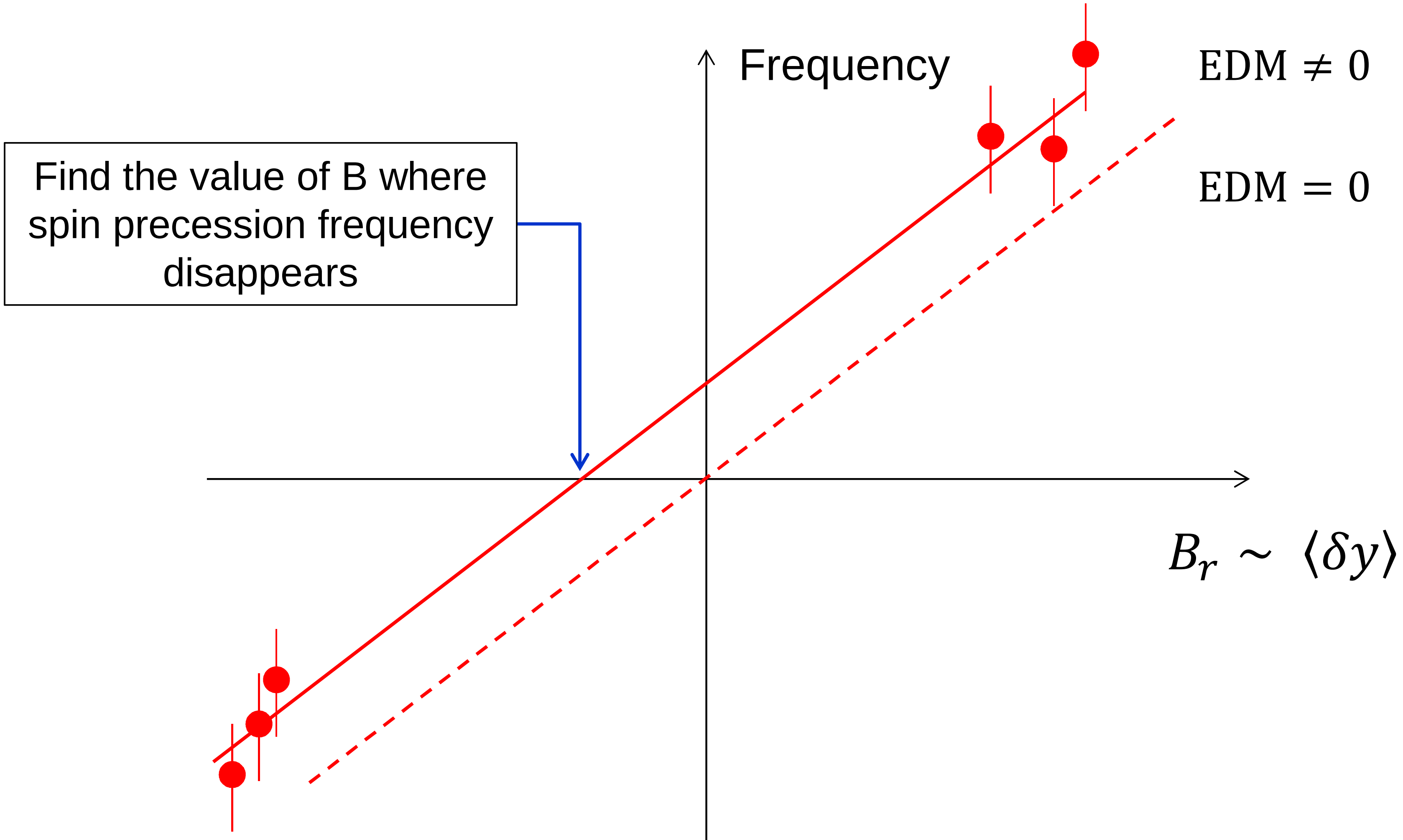
Concepts: Another Idea - Ivan Koop‘s spin wheel

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



- By appropriate choice of an additional magnetic field B_r, the spin vectors can be made to rotate fast in a plane perpendicular to the radius vector→ frequencies of the order kHz
- The measurement of the polarization buildup as function of time would be replaced by a measurement of the precession frequency.
- State-of-the-art measurements (SQUIDs) allow for $\Phi \approx 10^{-6} \times \Phi_0$, $\Phi_0 \approx 2.1 \times 10^{-15}$ Wb is the flux quantum. A bunch of 10^{10} protons 1cm from a pick-up coil generates $\Phi \approx 10^{-3} \times \Phi_0$.

Concepts: How Ivan‘s spin wheel would work?



Find the value of B where spin precession frequency disappears

This approach has to be worked out in detail.

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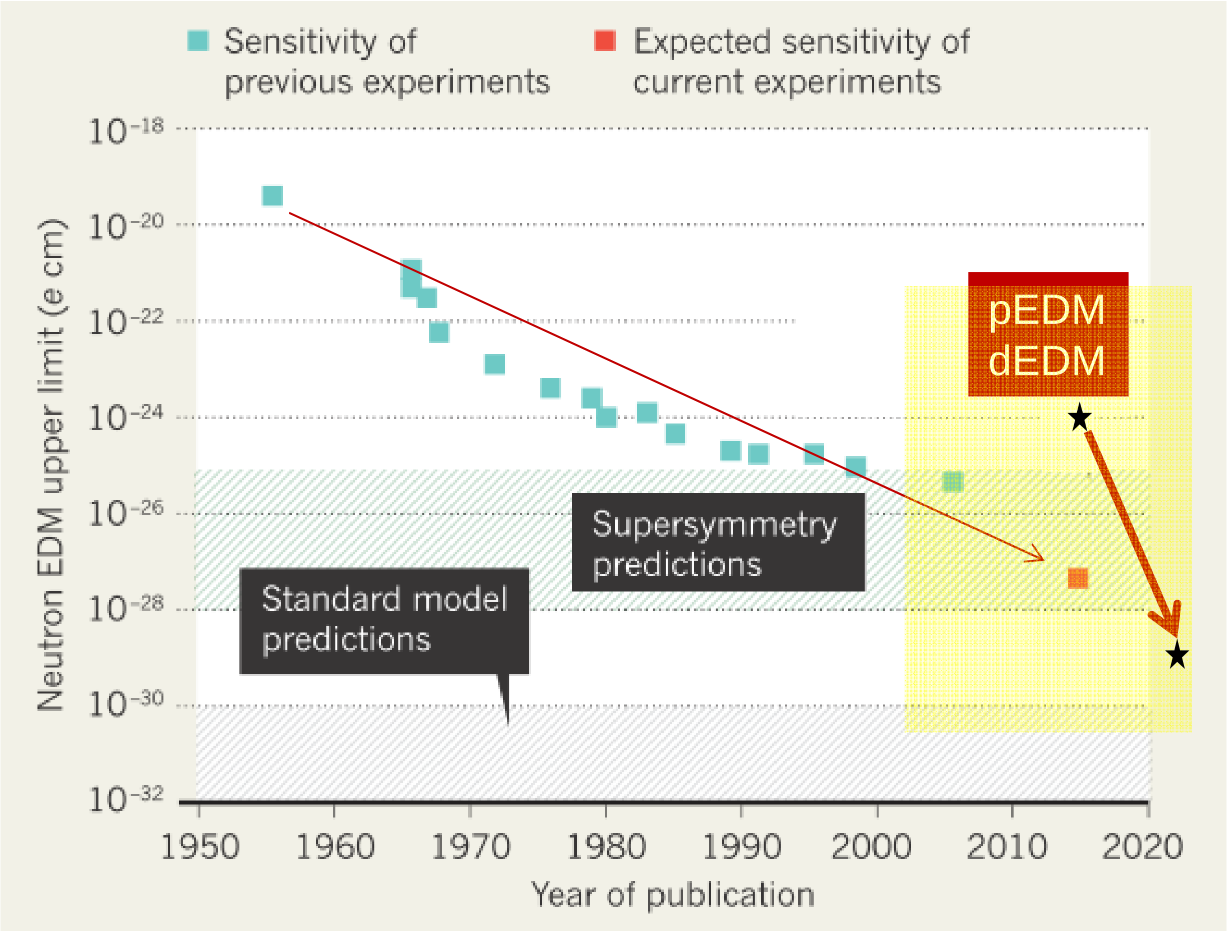
Concepts: Sensitivity Reach

JEDI goal: EDM search in charged baryon (systems)



**Adapted from:
Nature,
Vol 482 (2012)**

No direct measurements for *proton* and *deuteron* EDM yet !

Outline

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** $\left(\sim 17\,\frac{\mathrm{MV}}{\mathrm{m}}\,\mathrm{at} \sim 2\ \mathrm{cm}\right)$
- **Spin coherence time** $(\geq 1000\ \mathrm{s})$
- **Continuous polarimetry** $(< 1\ \mathrm{ppm})$
- **Beam positioning** $(10\ \mathrm{nm})$
- **Spin tracking**

These issues must be addressed *experimentally* at existing facilities

Challenges: Overview

Additional items to be adressed:

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

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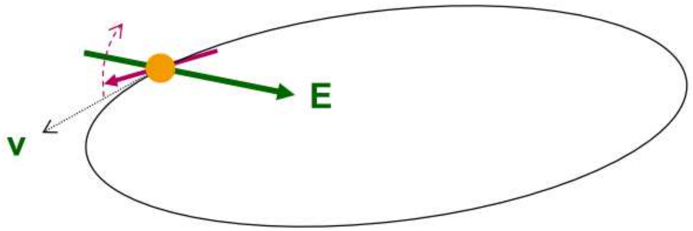
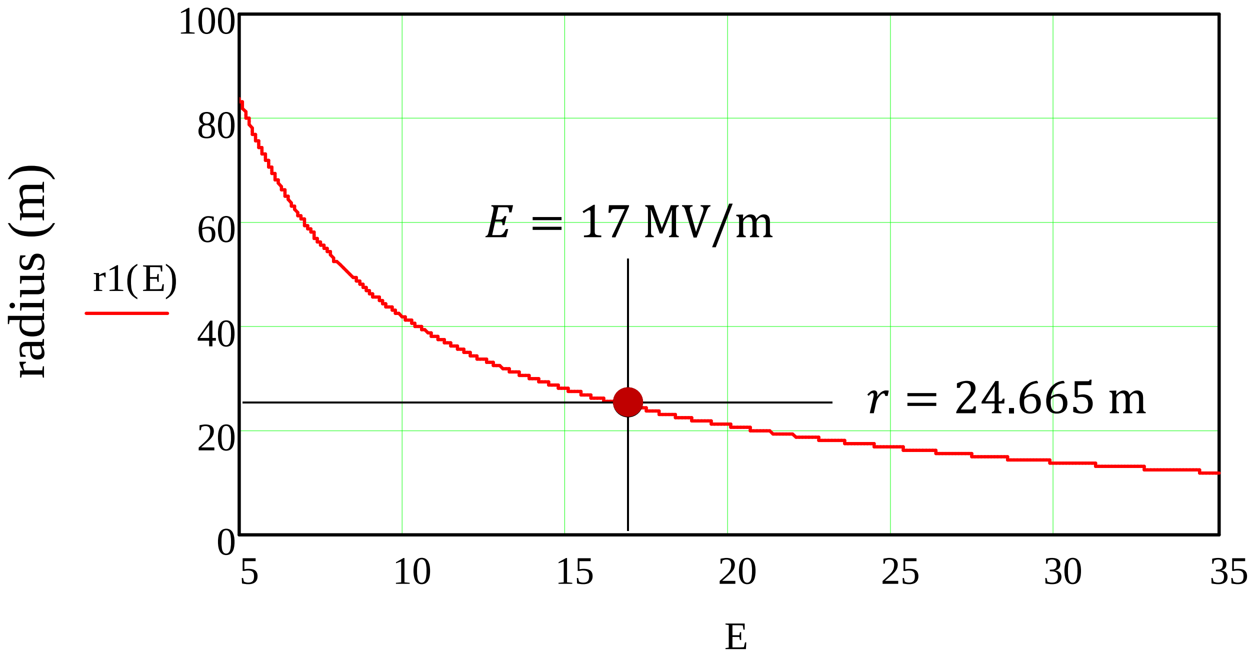
Challenges: Electric field for magic rings

Protons: Radial *E* field only



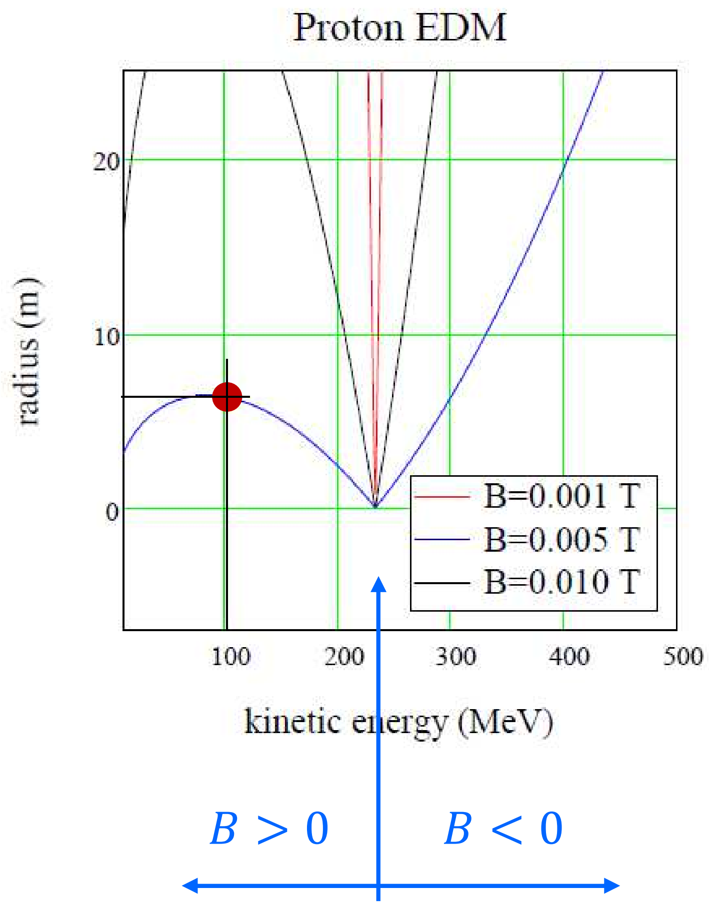


E-field (MV/m)

Challenge to produce large electric field gradients

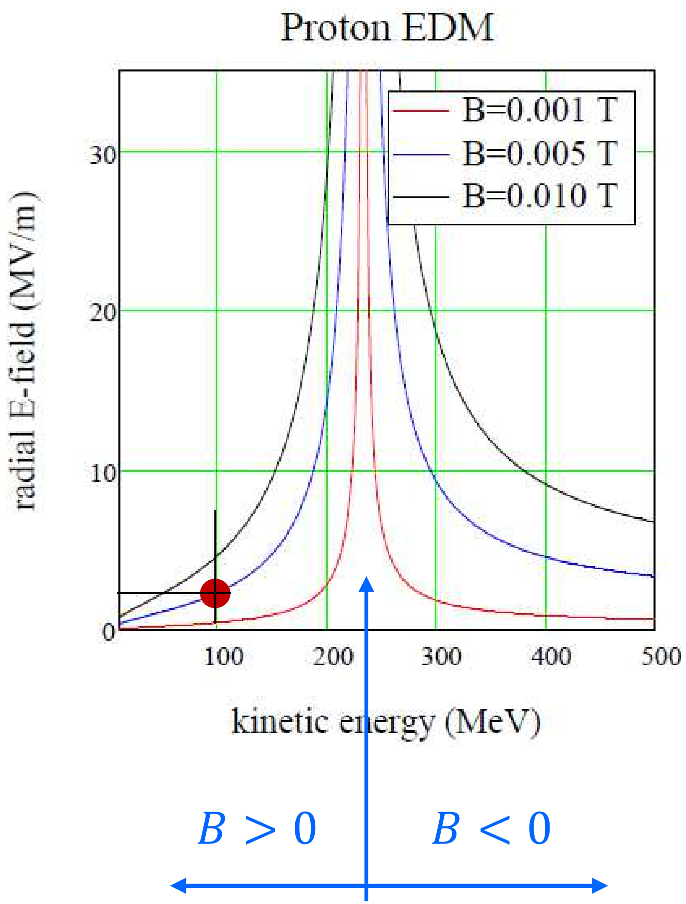
Challenges: Electric field for magic rings

Protons: Radial E and vertical B fields



$B > 0$ $B < 0$

magic energy

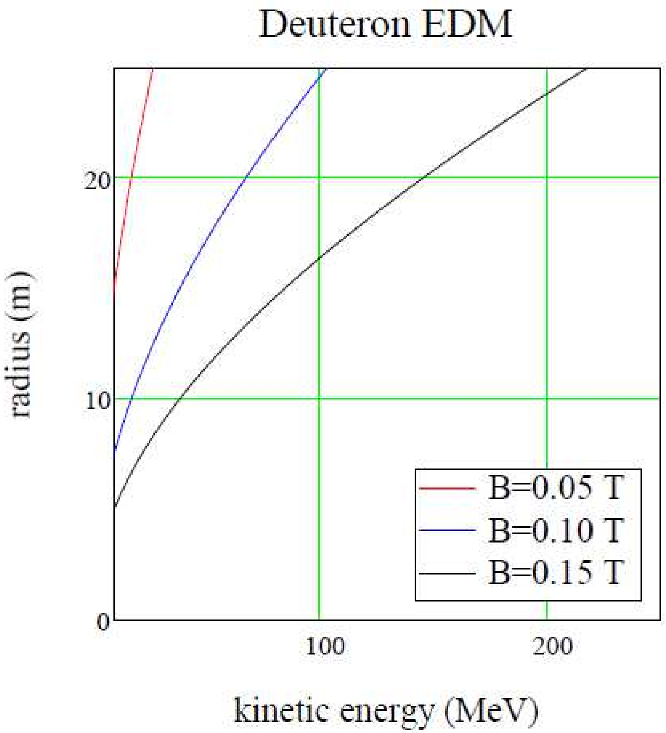


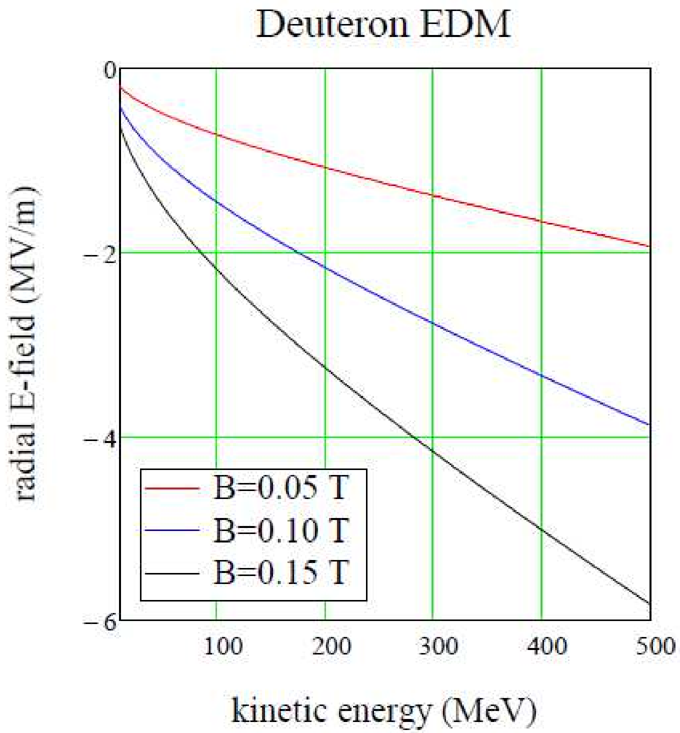
$B > 0$ $B < 0$

magic energy

Challenges: Electric field for magic rings

Deuterons: Radial E and vertical B fields





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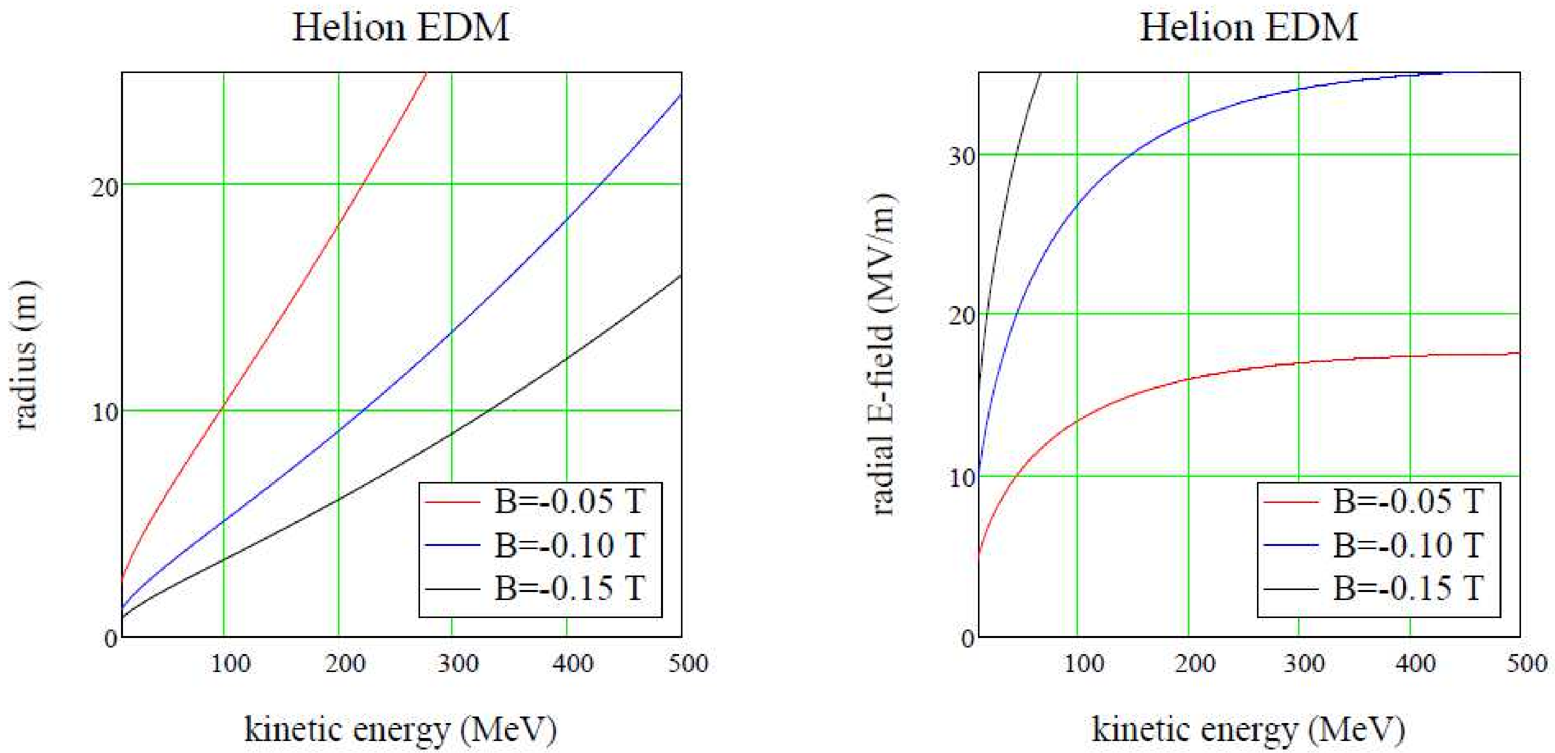
Challenges: Electric field for magic rings

Helions: Radial E and vertical B fields



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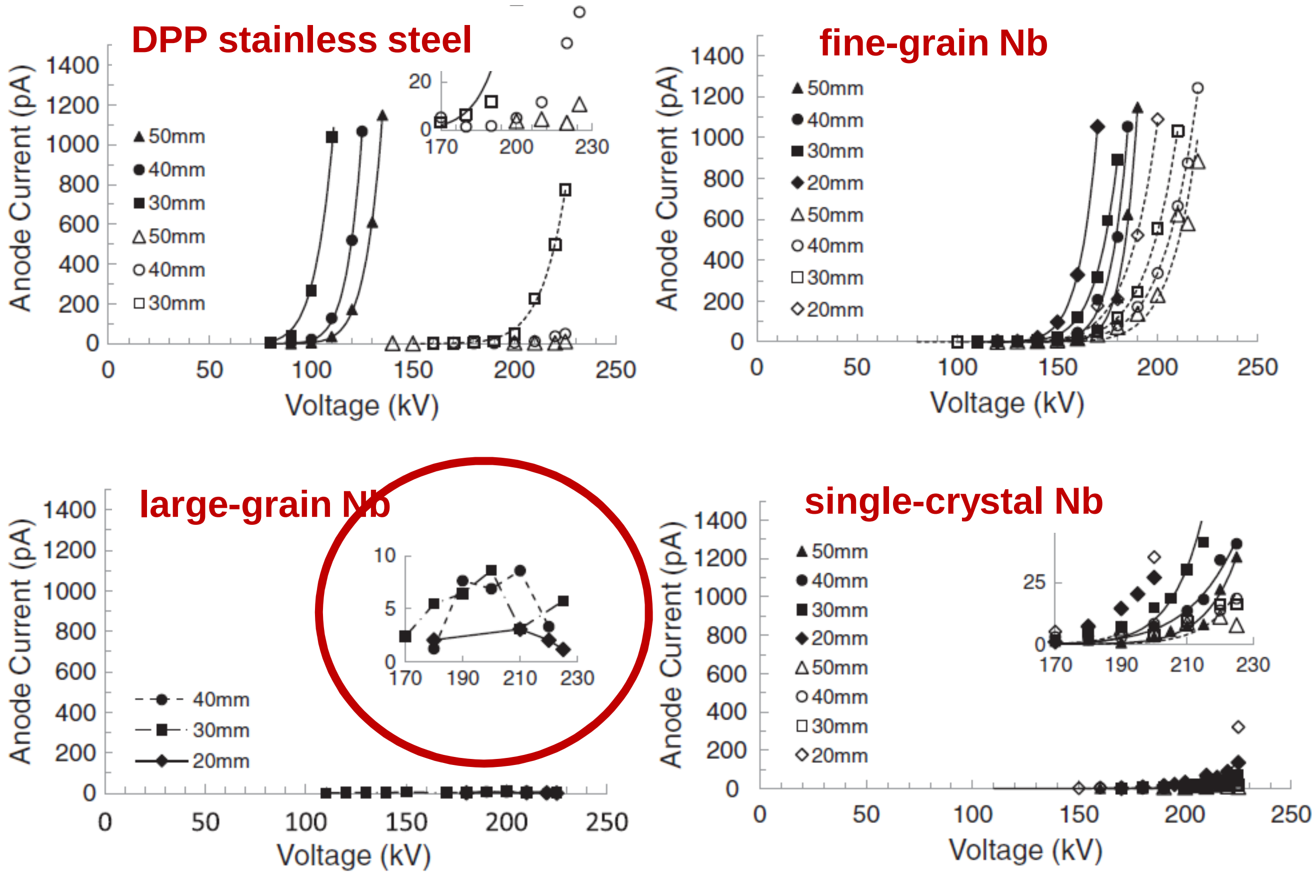
Challenges: Niobium electrodes

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

Challenges: 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

Challenges: Electric deflectors for magic rings

- Deflector development will use scaled models $\sim 1{:}\,10$
  - Electric fields will be the same, but voltages < 20 kV
  - Avoids shielding of x-rays
  - Allows tests to be done in usual lab environment
- Dedicted clean room being set up at RWTH Aachen
  - Ultrasonic bath
  - Baking system
  - Vacuum system for testing

Studies will involve

- different processing tests with steel
- steel polishing
- stainless steel as a base material

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

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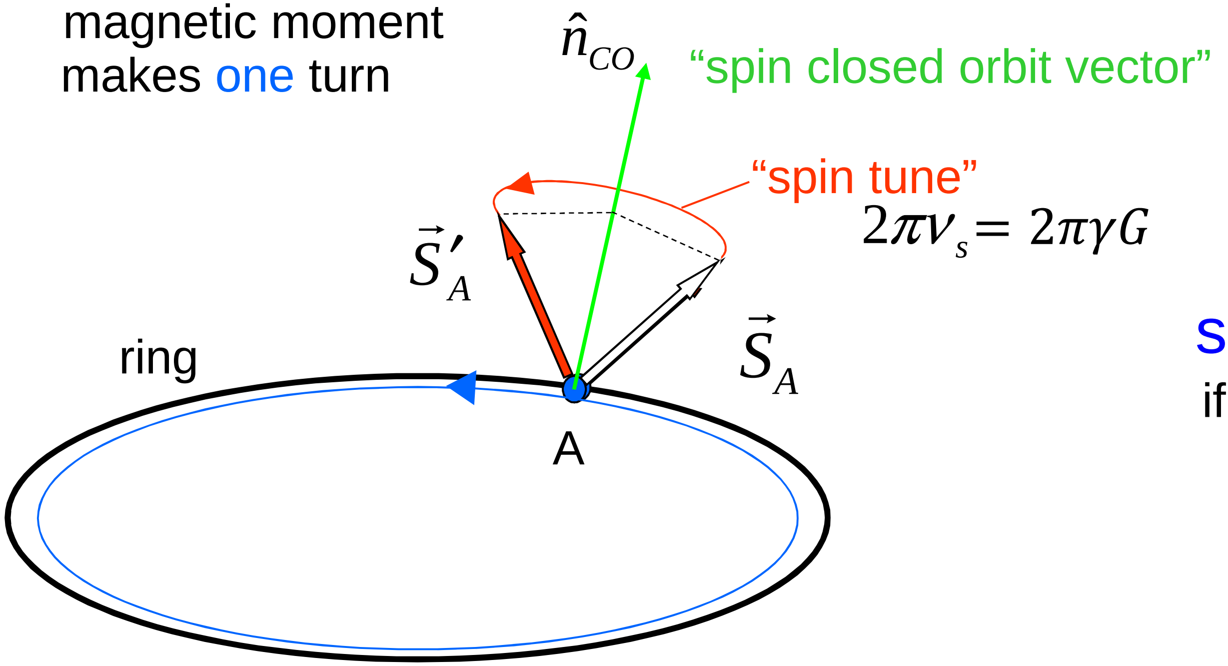
Challenges: Spin coherence time

Spin closed orbit

one particle with
magnetic moment
makes one turn



$$2\pi\nu_s = 2\pi\gamma G$$

stable polarization

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

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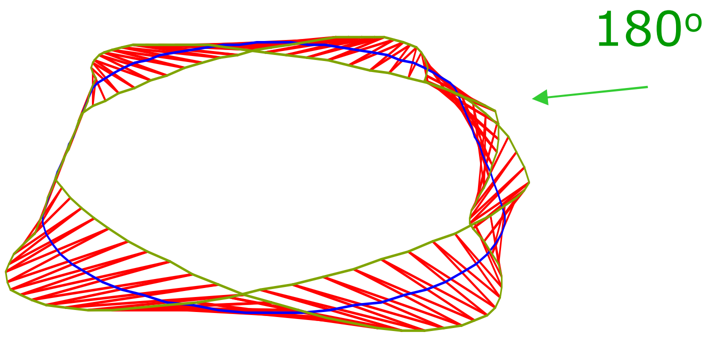
Insert: Spin manipulation

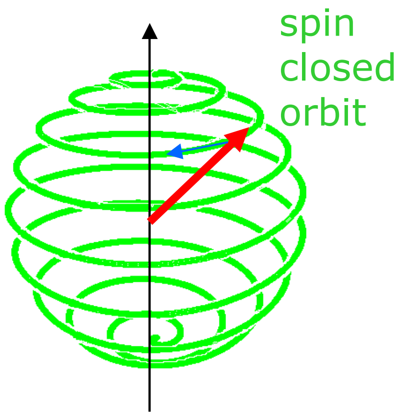


Snakes

There is an $\hat{n}_{CO}$ for every point of the orbit
Snakes (non-vertical B field) affect $\hat{n}_{CO}$

Flippers

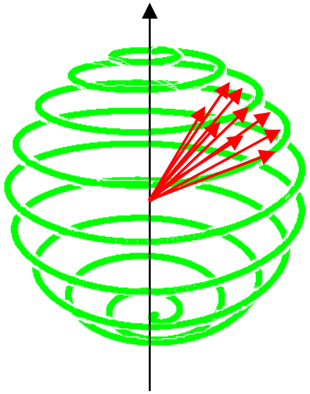
ramping through a resonance reverses $\hat{n}_{CO}$



Insert: Spin dispersion

A particle beam has **momentum spread** and **betatron amplitude spread**

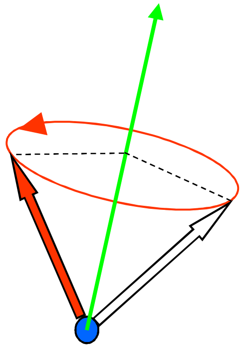
Near a resonance individual particles have different $\hat{n}_{CO}$



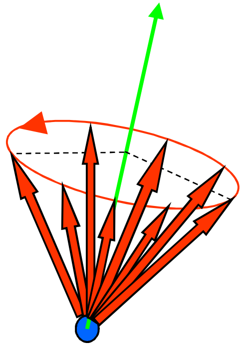
→ ensemble **decoheres and polarization is lost**

Challenge: Spin coherence time

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



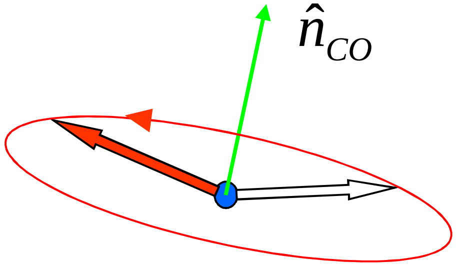
At injection all
spin vectors aligned (coherent)



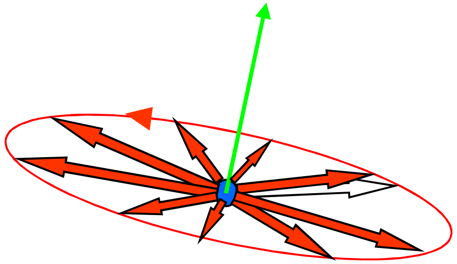
After some time, spin vectors get out of
phase and fully populate the cone

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

Spin coherence time: Estimates (N.N. Nikolaev)

One source of spin decoherence are random variations of the spin tune, due to the momentum spread in the beam

$\delta\theta = G\delta\gamma$ and $\delta\gamma$ is randomized by e.g., electron cooling,

$\cos\omega t \rightarrow \cos(\omega t + \delta\theta)$

$$\tau_{sc} \approx \frac{1}{f_{\mathrm{rev}} G^2 \langle \delta\gamma^2 \rangle} \approx \frac{1}{f_{\mathrm{rev}} G^2 \gamma^2 \beta^4} \left\langle \left(\frac{\delta p}{p} \right)^2 \right\rangle^{-1}$$

Estimate:

$T_{\mathrm{kin}} = 100\ \mathrm{MeV}$

$f_{\mathrm{rev}} = 0.5\ \mathrm{MHz}$

$G_p = 1.79$

$G_d = -0.14$

$\tau_{sc}(p) \approx 3 \cdot 10^3\ \mathrm{s}$

$\tau_{sc}(d) \approx 5 \cdot 10^5\ \mathrm{s}$

Spin coherence time for deuterons may be $\mathbf{100\times}$ larger than for protons

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Spin coherence time: Harmonic dependence

Observed oscillating P_y , driven by RF solenoid at different harmonics K

$$f_{\mathrm{RF}} = (\gamma G \pm K) f_{\mathrm{rev}}$$

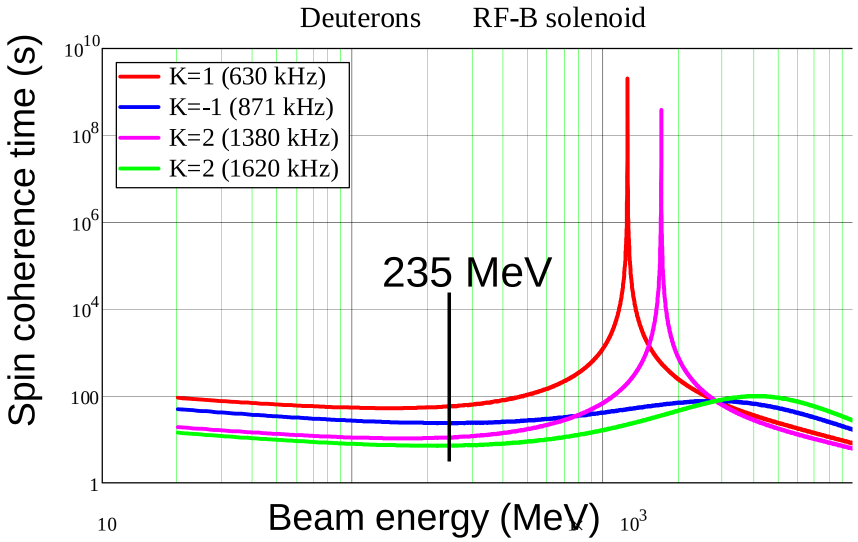
$$\tau_{\mathrm{SC}} = \frac{1}{2\pi^2 C^2 f_{\mathrm{rev}} G^2 \gamma^2 \beta^4} \left\langle \left(\frac{\Delta p}{p} \right)^2 \right\rangle^{-1}$$

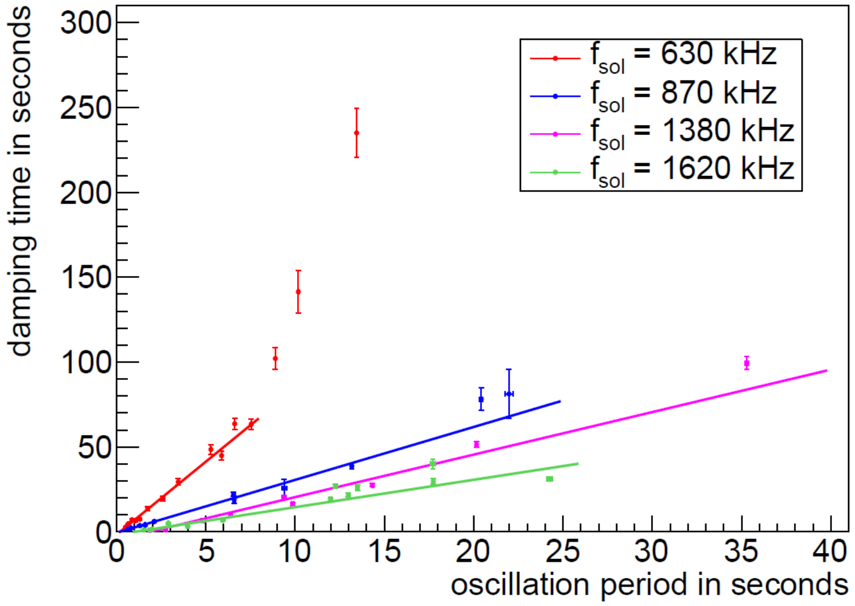
$$C = 1 - \frac{\eta}{\beta^2} \left(1 + \frac{K}{\gamma G} \right)$$

Theory: N.N.Nikolaev

At specific energies for certain K decoherence is small.

But: Observation of enhancements of τ_{SC} for p (and d) requires more flexible polarimeter



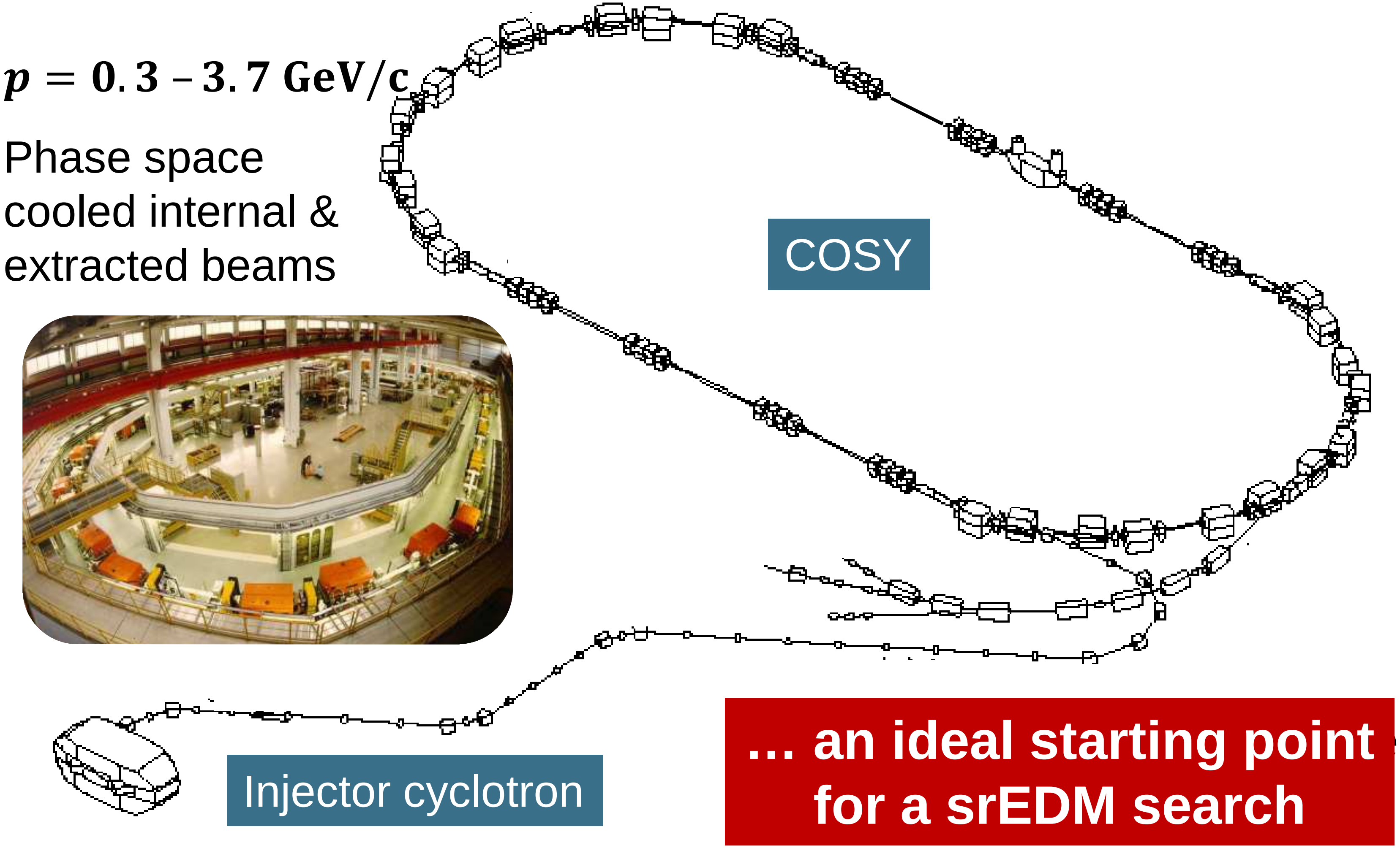


EDM at COSY: COoler SYnchrotron

Cooler and storage ring for (polarized) protons and deuterons

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

Phase space cooled internal & extracted beams

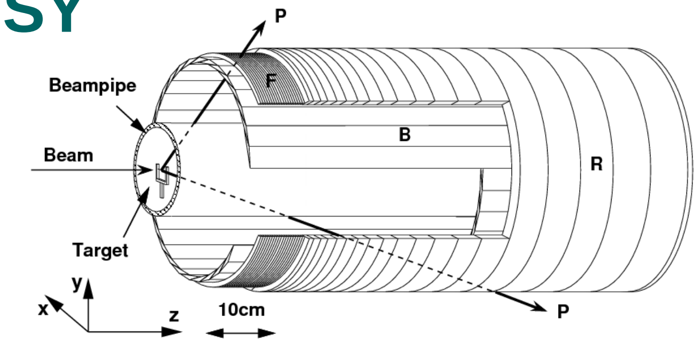


… an ideal starting point for a srEDM search

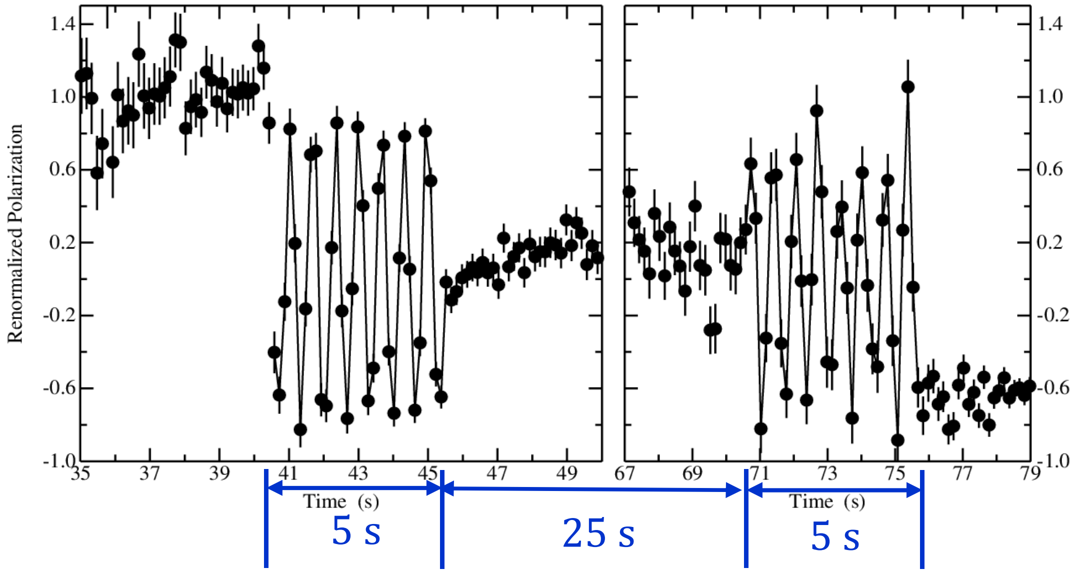
Spin coherence time: First measurement

2011 Test measurements at COSY

Polarimetry:

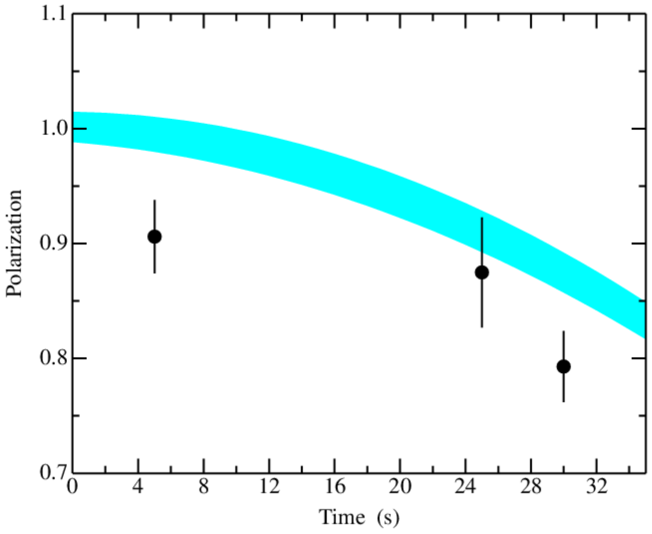


Spin coherence time:



decoherence time

oscillation capture

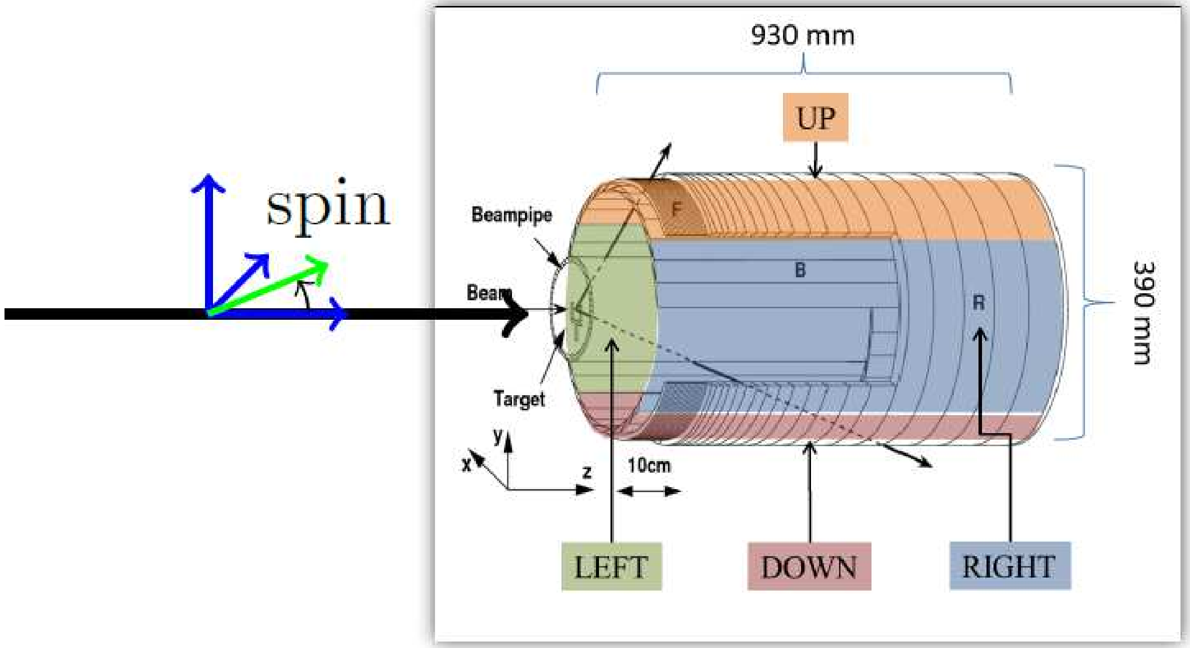


Spin coherence time: Experimental investigation

Experimental studies of spin coherence time in a storage ring are rather new. Investigations require to keep track of the event time and the revolution time in each turn during a cycle of a few hundred seconds (**time-stamping)**

- Vertically polarized deuterons are stored in COSY at $p \approx 1\,\frac{\mathrm{GeV}}{\mathrm{c}}$
- The polarization is flipped into the horizontal plane using an RF solenoid, takes about $200\ \mathrm{ms}$.
- Beam is slowly extracted onto EDDA Carbon scattering target during $\sim 100\ s$ using a ramped bump or by heating the beam.
- During this time the horizontal (in-plane) polarization is determined from Up-Do asymmetry in the detector.

Polarimeter: Experimental investigation of SCT



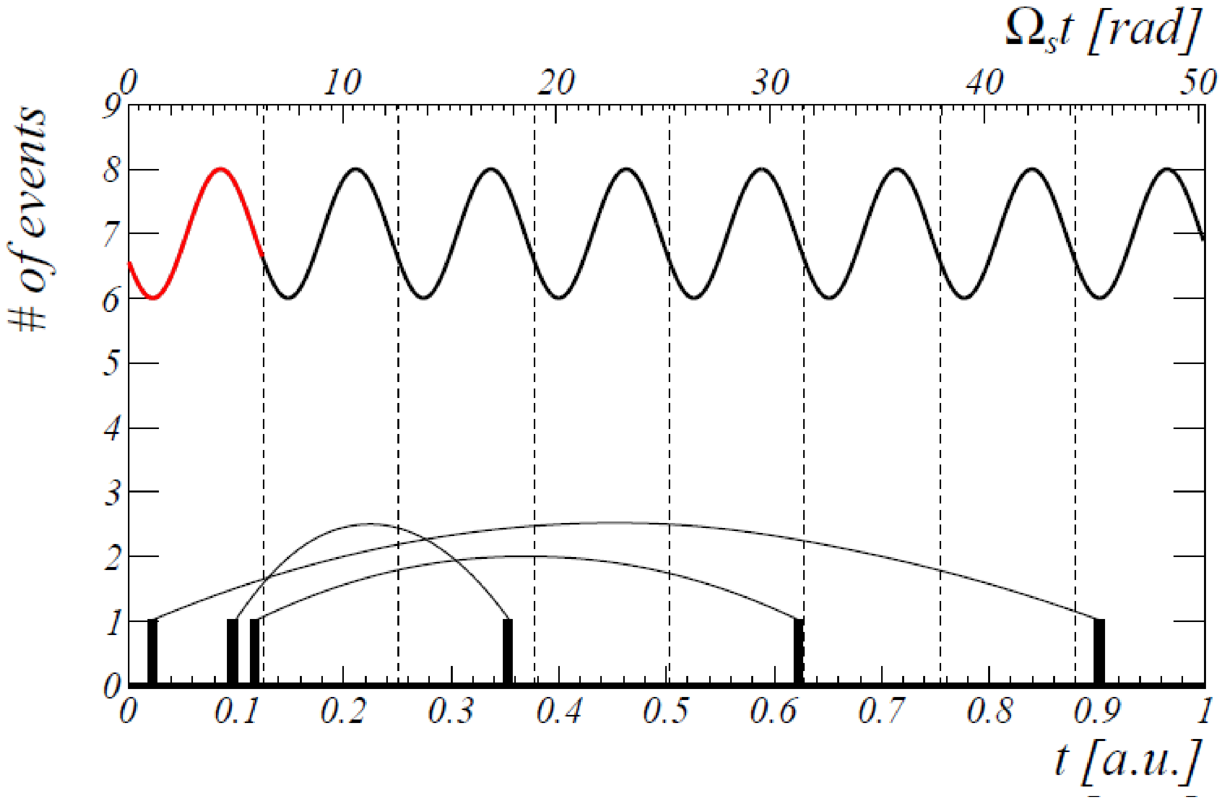
$N_{U,D} \propto 1 \pm P \cdot A \cdot \sin(\nu_s f_{\text{rev}} t)$, where $f_{\text{rev}} \approx 781\ kHz$

At $p \approx 1\ \text{GeV/c}$, $\gamma = 1.13$ and $\nu_s = \gamma \cdot G = -0.161$

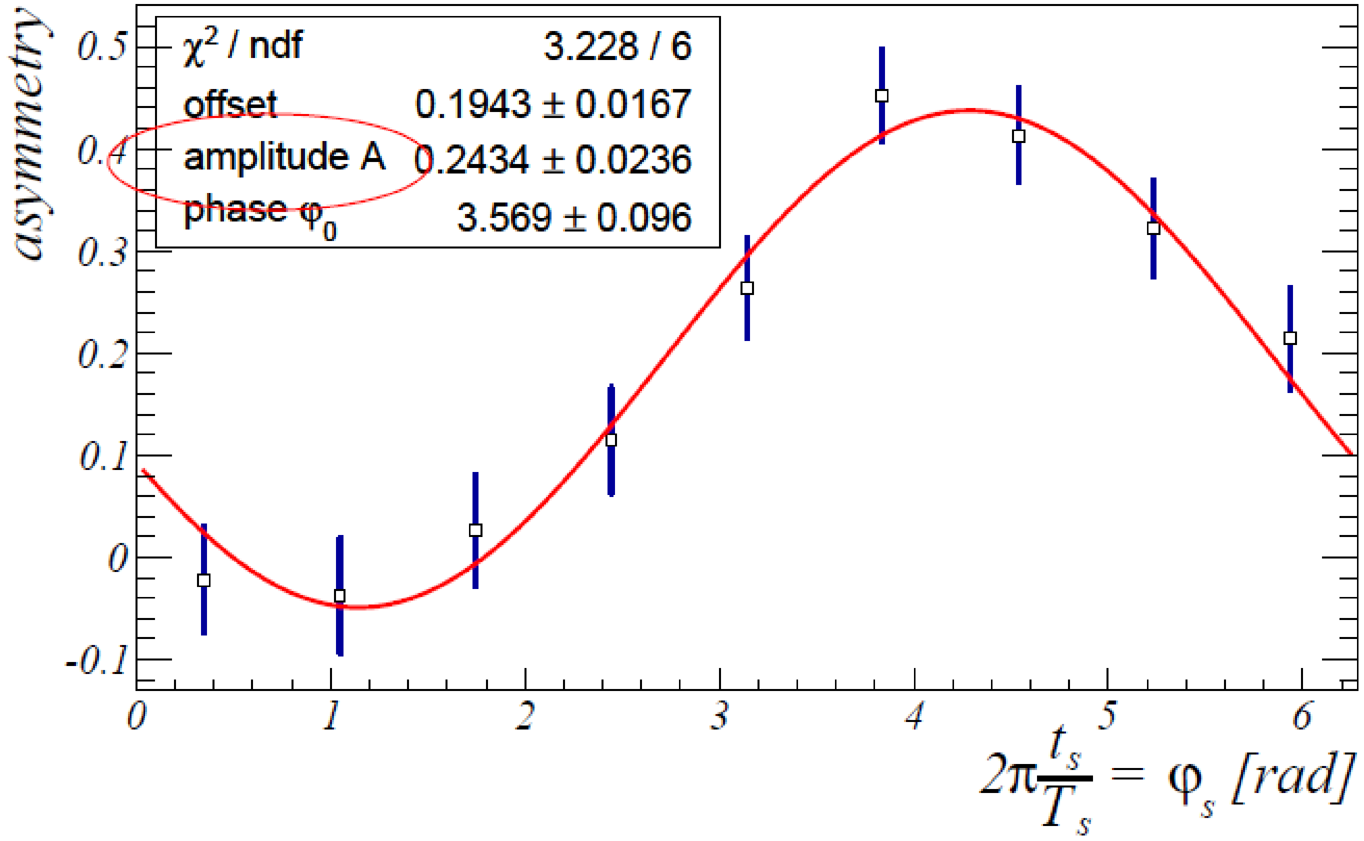
Polarimeter: How to find the correct ν_s

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

Solution: Map all events into first period.

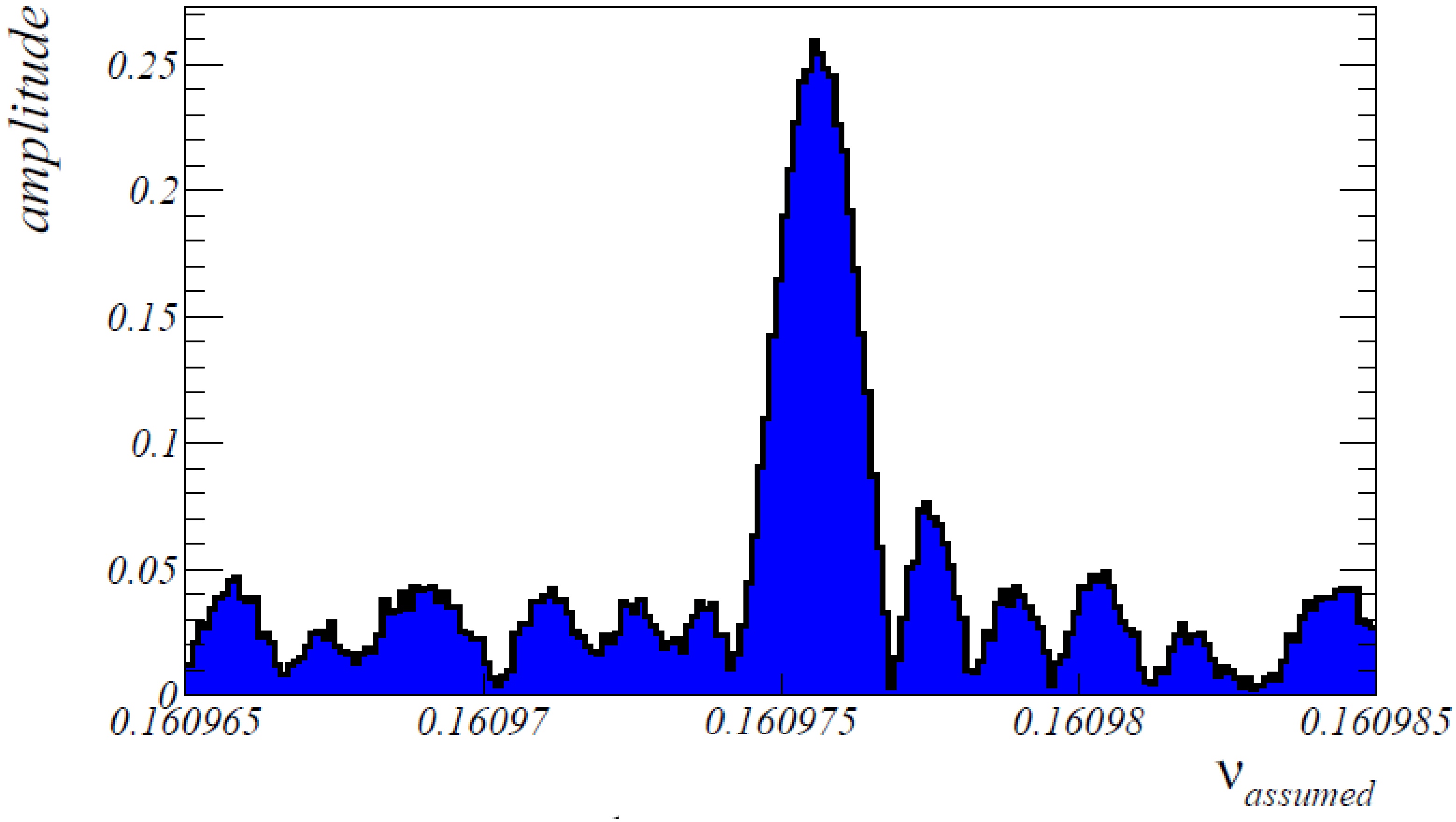


Polarimeter: How to find the correct ν_s



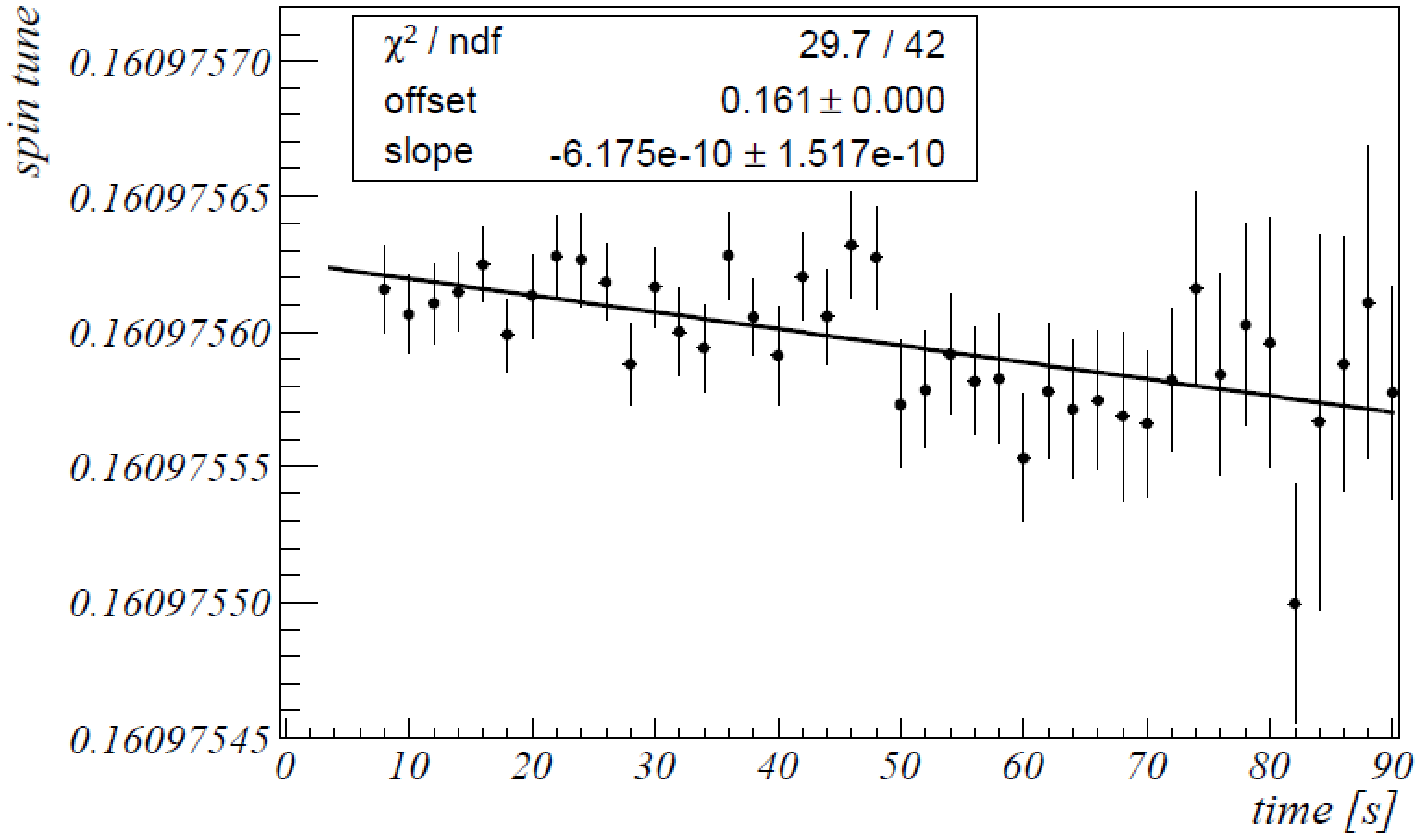
Of course, this only works when $T_s = \frac{1}{\nu_s f_{\mathrm{rev}}}$ is correct

Polarimeter: Scan of ν_s



Pick ν_s with maximum amplitude of asymmetry.

Polarimeter: Determination of ν_s

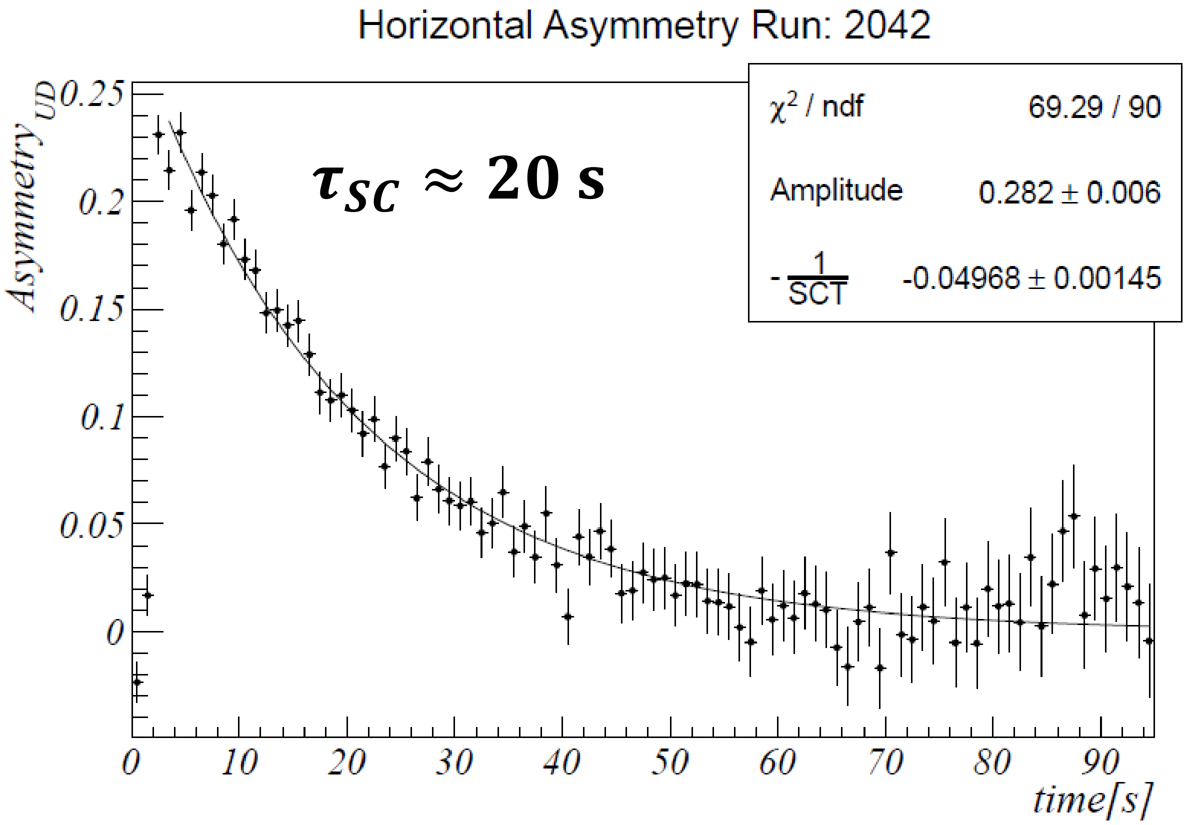


Spin tune ν_s can be determined to $\approx 10^{-8}$ in 2 s

Average $\overline{\nu_s}$ in cycle (100 s) determined to 10^{-10}

Polarimeter: Determination of SCT

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



$\boldsymbol{\tau_{SC} \approx 20\ \mathrm{s}}$

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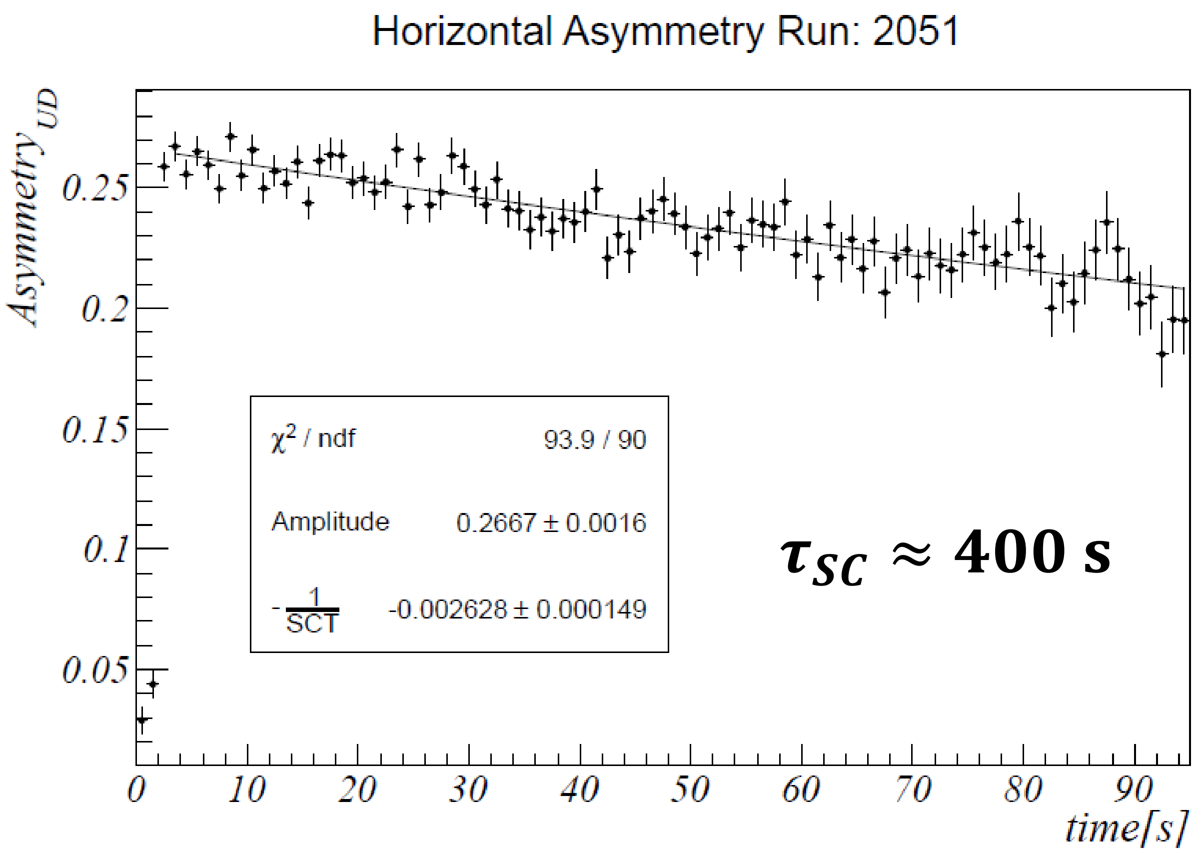
Polarimeter: Optimization of SCT

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



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

Excellent progress towards the SCT goal for pEDM: SCT~1000 s

Implications: CPT test with pol. antiprotons

Apparently, we are able to determine the spin tune ν_s to a precision of about 10^{-10}.

Suppose, we had a polarized proton beam orbiting clockwise in a magnetic storage ring, and at the same time, a polarized antiproton beam going the opposite way. Both beams on the same orbit, one Rf cavity, etc.

Measuring simultaenously the ratio of the spin tunes for the protons and the antiprotons constitutes a hadronic CPT test, capable to determine the ratio of the magnetic moments, at the level of 10^{-10}.

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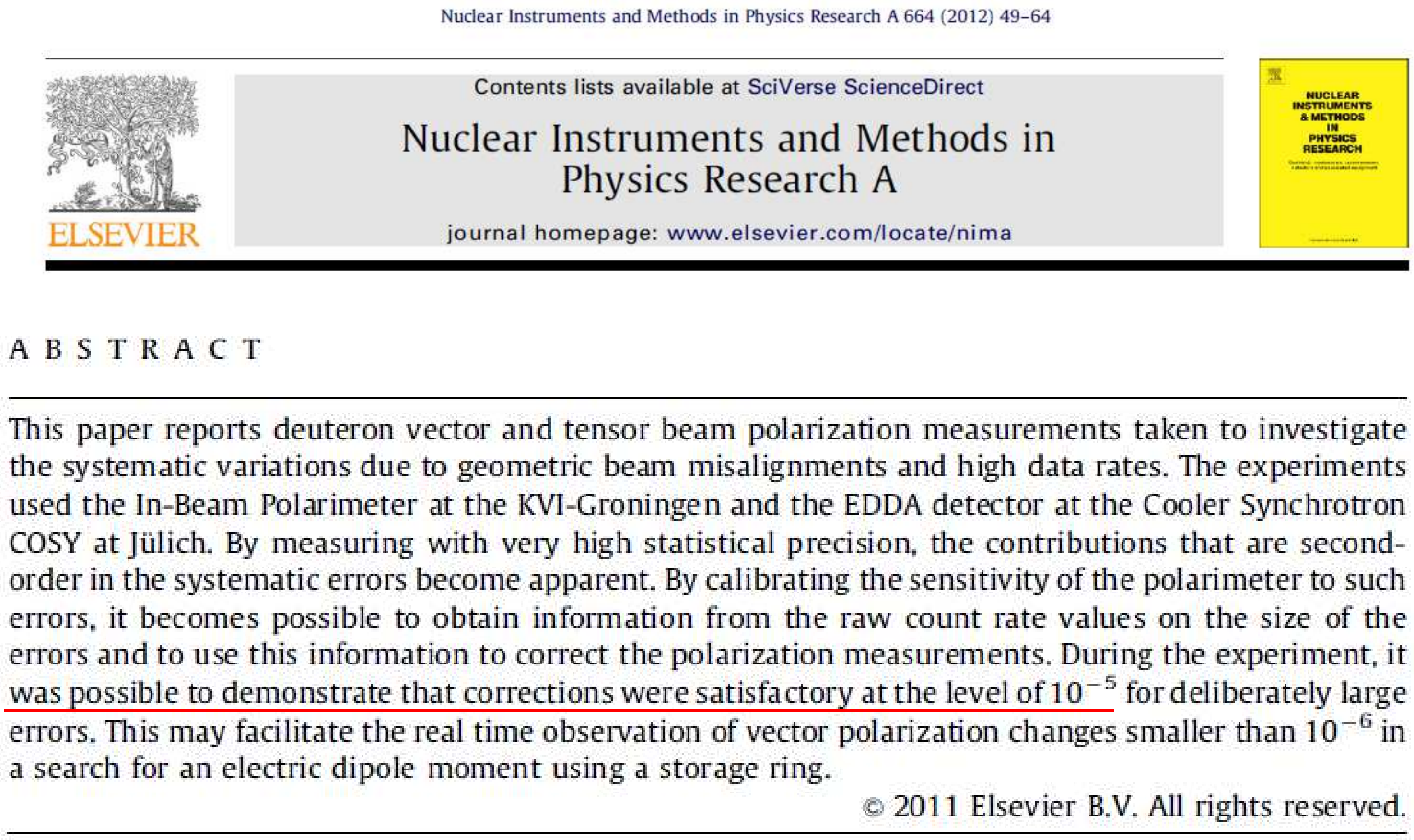
Challenge: Polarimetry



Nuclear Instruments and Methods in Physics Research A 664 (2012) 49–64

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

ABSTRACT

This paper reports deuteron vector and tensor beam polarization measurements taken to investigate the systematic variations due to geometric beam misalignments and high data rates. The experiments used the In-Beam Polarimeter at the KVI-Groningen and the EDDA detector at the Cooler Synchrotron COSY at Jülich. By measuring with very high statistical precision, the contributions that are second-order in the systematic errors become apparent. By calibrating the sensitivity of the polarimeter to such errors, it becomes possible to obtain information from the raw count rate values on the size of the errors and to use this information to correct the polarization measurements. During the experiment, it was possible to demonstrate that corrections were satisfactory at the level of 10^{-5} for deliberately large errors. This may facilitate the real time observation of vector polarization changes smaller than 10^{-6} in a search for an electric dipole moment using a storage ring.

Beam polarimetry at **ppm level** achieved for deuteron beams

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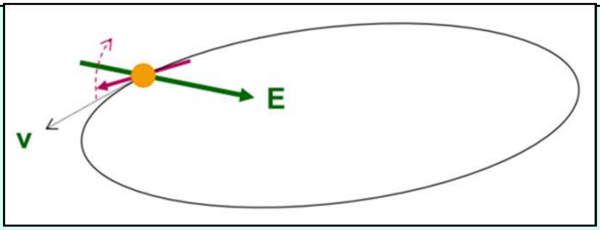
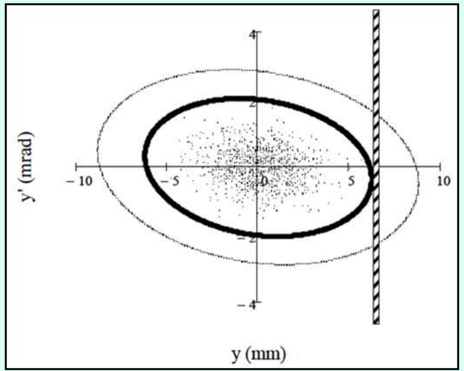
Polarimetry: **Some issues**

pC and dC polarimetry is the currently favored approach for the pEDM experiments



srEDM experiments in frozen spin mode have beam mostly polarized along direction of motion,

Most promising ring options use cw & ccw beams.

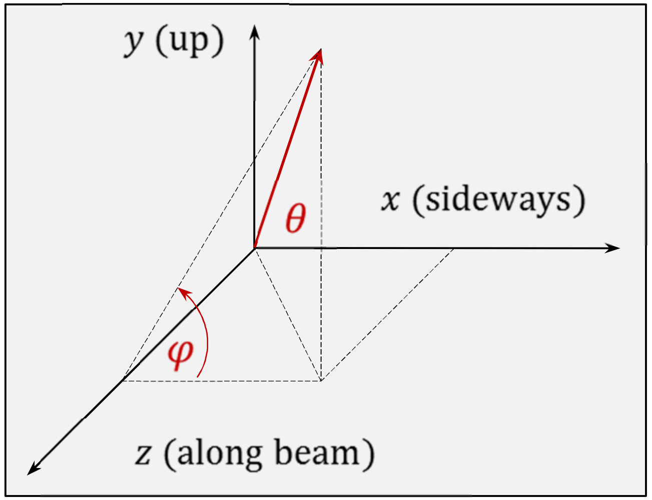


- scattering on C destructive on beam and phase-space,
- scattering on C determines polarization of mainly particles with large betatron amplitudes,
- is not capable to determine $\vec{P} = \begin{pmatrix} P_x \\ P_y \\ P_z \end{pmatrix}$, and
- is not capable to provide info on phase-space distribution of the beam.
- For elastic scattering longitudinal analyzing powers are tiny (A_z violates parity).

Ideally, use method that determines $\vec{P}(t)$, (x,x‘), and (y,y‘) phase-spaces

Polarimetry: Exploit observables that depend on beam and target polarization

$$\text{beam 1 } \vec{P} = \begin{pmatrix} P_x \\ P_y \\ P_z \end{pmatrix} \quad \text{target (or beam 2) } \vec{Q} = \begin{pmatrix} Q_x \\ Q_y \\ Q_z \end{pmatrix}$$



Spin-dependent differential cross section for

$$\overrightarrow{\left(\tfrac{1}{2}\right)} + \overrightarrow{\left(\tfrac{1}{2}\right)} \to \frac{1}{2} + \frac{1}{2}$$

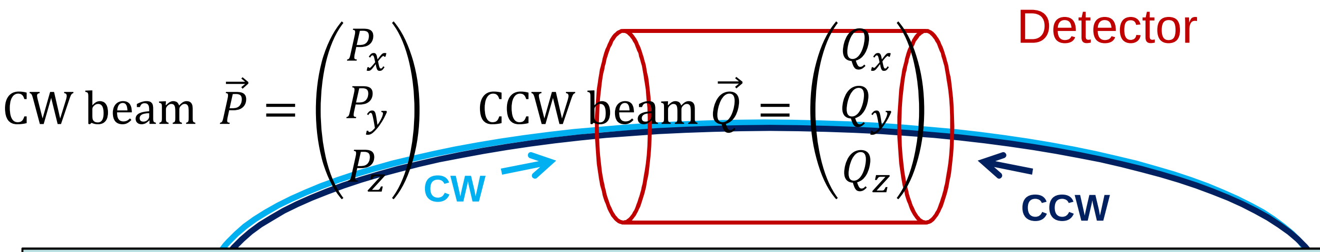
$$\begin{aligned}
\frac{\sigma}{\sigma_0} = 1 &+ A_y\left[\left(P_y + Q_y\right)\cos\varphi - \left(P_x + Q_x\right)\sin\varphi\right] \\
&+ A_{xx}\left[P_x Q_x \cos^2\varphi + P_y Q_y \sin^2\varphi + \left(P_x Q_y + P_y Q_x\right)\sin\varphi\cos\varphi\right] \\
&+ A_{yy}\left[P_x Q_x \sin^2\varphi + P_y Q_y \cos^2\varphi - \left(P_x Q_y + P_y Q_x\right)\sin\varphi\cos\varphi\right] \\
&+ A_{xz}\left[\left(P_x Q_z + P_z Q_x\right)\cos\varphi + \left(P_y Q_z + P_z Q_y\right)\sin\varphi\right] \\
&+ A_{zz} P_z Q_z
\end{aligned}$$

Analyzing power $A_y = A_y(\theta)$
Spin correlations $A_{ij} = A_{ij}(\theta)$

In $\vec{p}\vec{p}$ scattering, necessary observables are very well-known in the range 50 – 2000 MeV (not so for $\vec{p}\vec{d}$ or $\vec{d}\vec{d}$).

Polarimetry: Determine $\vec{P}$?

Exploit reactions from colliding beams



$$
\begin{aligned}
\frac{\sigma}{\sigma_0} = 1 &+ A_y\left[\left(P_y + Q_y\right)\cos\varphi - \left(P_x + Q_x\right)\sin\varphi\right] \\
&+ A_{xx}\left[P_x Q_x \cos^2\varphi + P_y Q_y \sin^2\varphi + \left(P_x Q_y + P_y Q_x\right)\sin\varphi\cos\varphi\right] \\
&+ A_{yy}\left[P_x Q_x \sin^2\varphi + P_y Q_y \cos^2\varphi - \left(P_x Q_y + P_y Q_x\right)\sin\varphi\cos\varphi\right] \\
&+ A_{xz}\left[\left(\boldsymbol{P_x Q_z} + \boldsymbol{P_z Q_x}\right)\cos\varphi + \left(\boldsymbol{P_y Q_z} + \boldsymbol{P_z Q_y}\right)\sin\varphi\right] \\
&+ A_{zz}\boldsymbol{P_z Q_z}
\end{aligned}
$$

Requires luminosity, β-functions at IP should be rather small.

- Sensitivity comes mainly from terms with A_{xz} and A_{zz}.
- Detailed estimates necessary.

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Polarimetry: Luminosity estimate

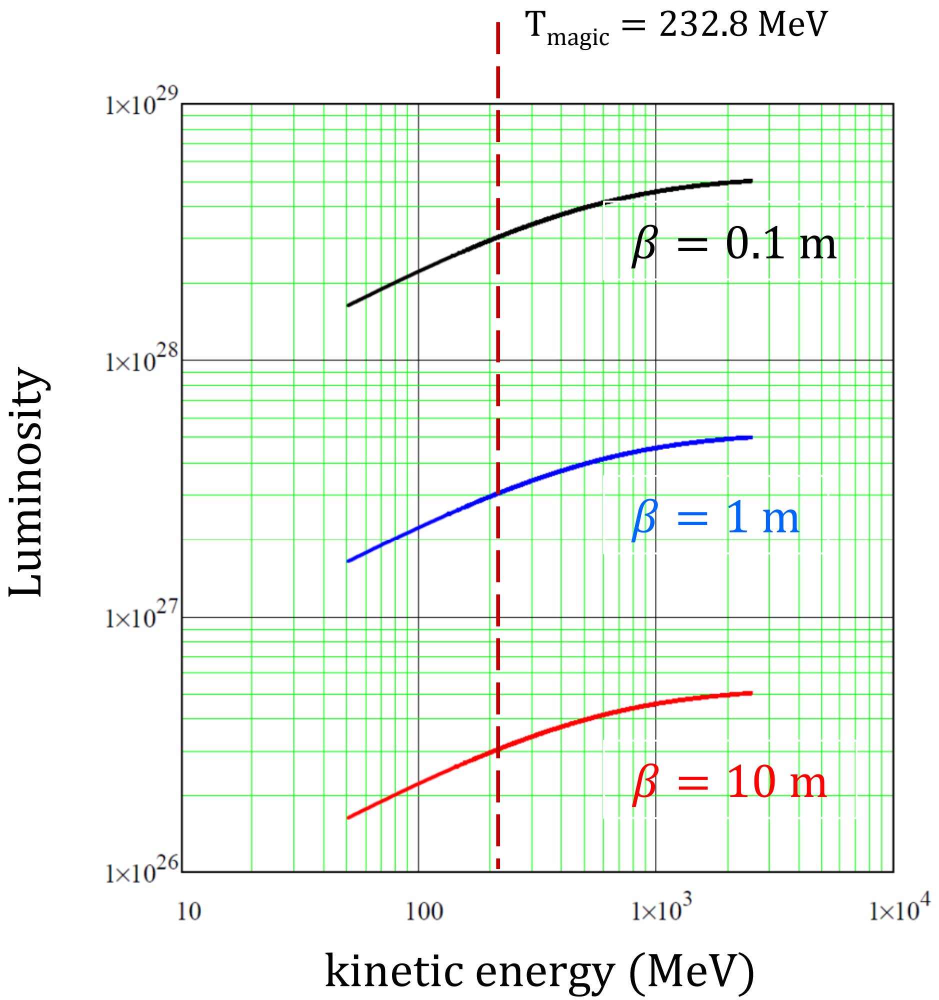
$$\sigma(\beta) = \sqrt{\epsilon \cdot \beta}$$

$$L(T, \beta) = \frac{N_1 N_2 f_{\mathrm{rev}}(T) n_b}{4\pi\sigma(\beta)^2}$$

Conditions:

$\varepsilon = 1\ \mu\mathrm{m}$
$N_1 = N_2 = 10^{11}$
$n_b = 4$

β (m)	σ (mm)
10	3.2
1	1
0.1	0.32



Under these optimistic assumptions, event rate would be rather low.
$\mathbf{Rate} = \boldsymbol{L} \times \sigma_{pp} = 3.1 \cdot 10^{28}[\mathrm{cm}^{-2}\mathrm{s}^{-1}] \times 10^{-27}[\mathrm{cm}^2\mathrm{mb}^{-1}] \times 15[\mathrm{mb}] \approx \mathbf{466\ s^{-1}}$

Polarimetry: Alternatives?

Alternatives to scattering polarimeter presently under discussion:

- SQUID based detection, which would move the precision requirements from polarization to frequency
- Compton Laser back scattering of protons or deuterons
    - Recently, new ideas being discussed for RHIC
    - Advantages: Non-destructive + phase-space detection

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Outline

- Introduction
- Electric Dipole Moments
- Physics Impact
- Charged particle EDM searches
  - Concepts for dedicated Storage Ring Searches
  - Technological challenges
  - **Precursor Experiments**
- Timeline
- Conclusion

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Precursor: Three options

Goal: Use COSY to determine first upper limit of the EDMs of deuteron and proton

All methods are based on making spin precession in machine resonant with the motion around the orbit

Two ways:

- Use an RF device that operates on some harmonics of the spin precession frequency
- Operate ring on an imperfection resonance

1. Use RF Wien filter to accumulate EDM signal during the spin coherence time
2. Use a static Wien filter on the $\gamma G = 2$ imperfection resonance (for protons only) at $T = 108.4\ \mathrm{MeV}$
3. Use combination of RF solenoid and RF Wien filter

Use existing magnetic machine for first direct EDM measurement.

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Precursor: 1. Resonance Method with „magic“ RF Wien filter

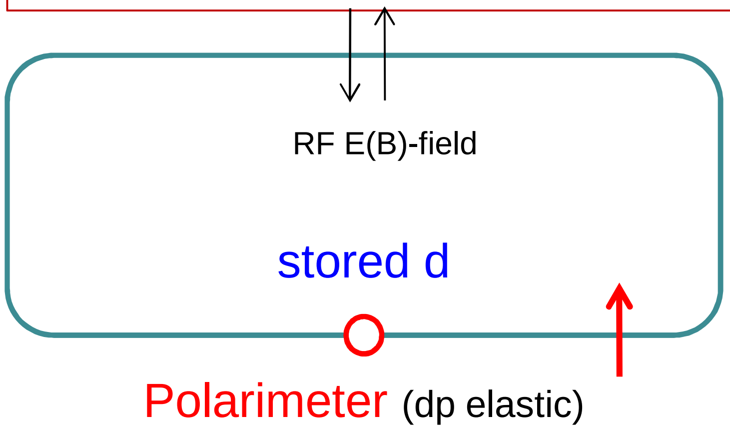
Avoids coherent betatron oscillations of beam.

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

Approach pursued for a first direct measurement at COSY.

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

→ **Indirect** EDM effect



In-plane polarization

Observable:
Accumulation of vertical polarization during spin coherence time

Statistical sensitivity for d_d in the range 10^{-23} to 10^{-24} $\mathrm{e{\cdot}cm}$ range possible.

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

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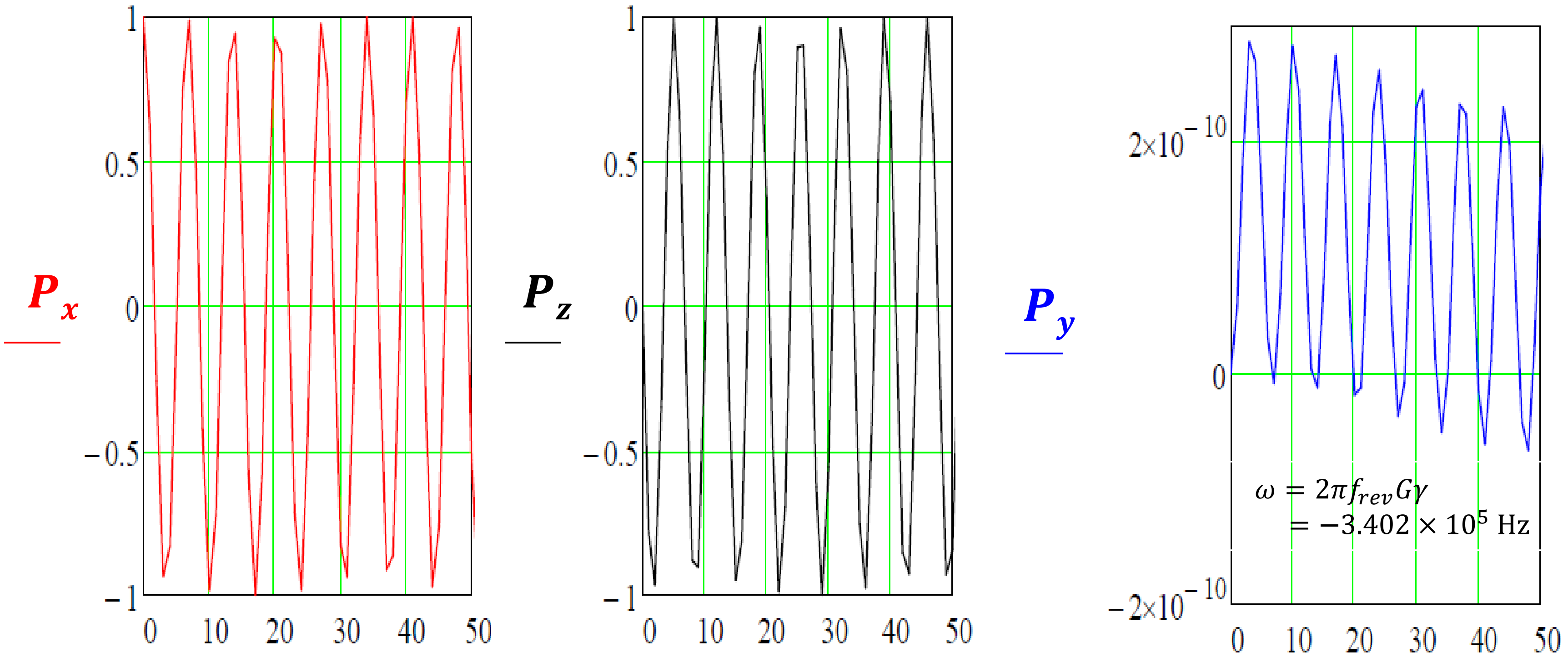
Precursor: 1. Resonance Method for deuterons

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



$$\omega = 2\pi f_{rev} G\gamma = -3.402 \times 10^5\ \mathrm{Hz}$$

turn number

EDM effect accumulates in P_y

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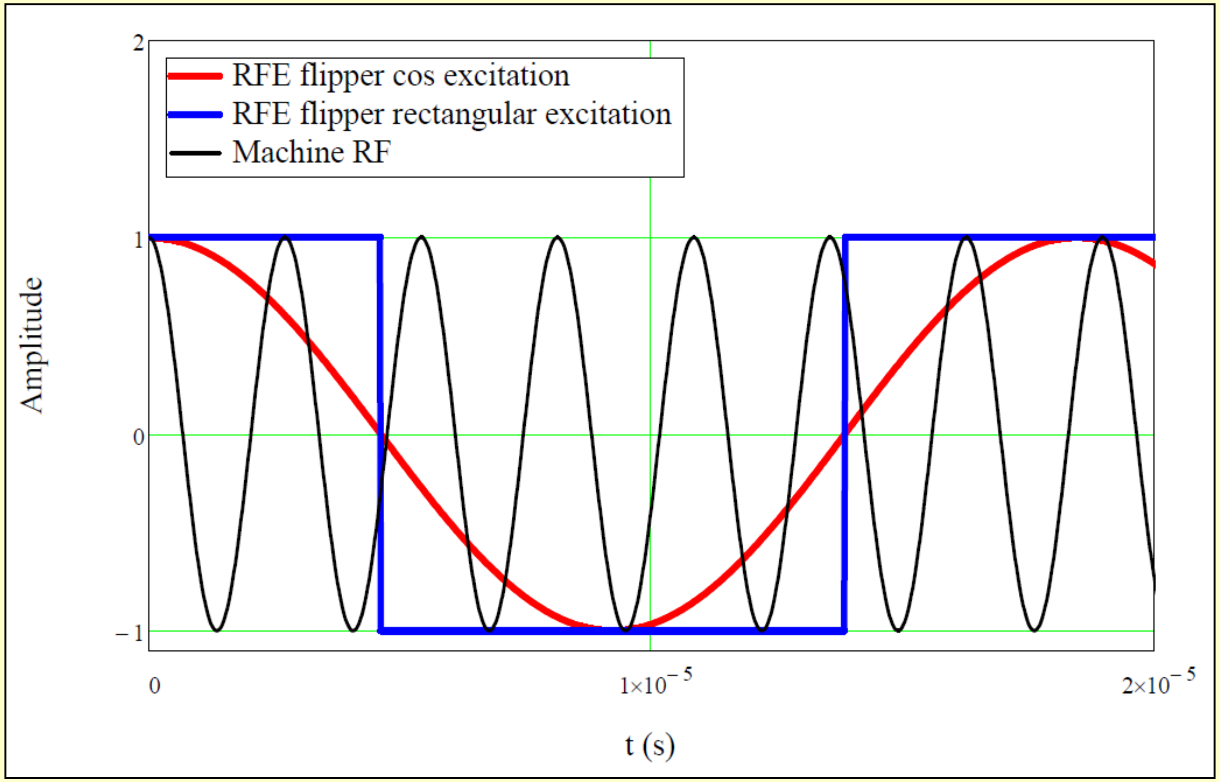
Precursor: 1. Resonance Method for deuterons

Radial E and vertical B fields oscillate, e.g., with
$f_{HV} = (K + G\gamma) \cdot f_{\text{rev}} = -54.151 \times 10^3\ \text{Hz}$ (here $K = 0$).

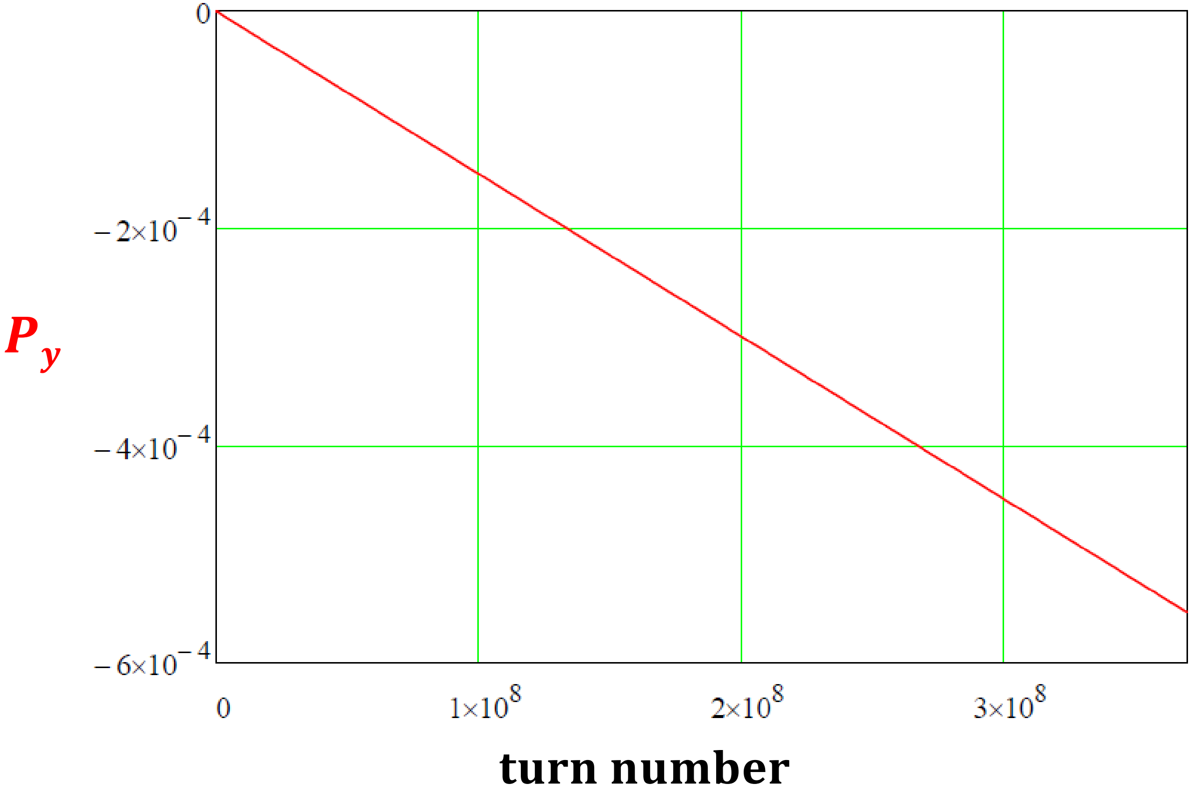
beam energy
$T_d = 50\ \text{MeV}$



Spin coherence time depends on excitation and on harmonics K.

Precursor: 1. 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 ($= 3.7\cdot10^8$ turns) yields a sizeable $P_y \sim 10^{-3}$.

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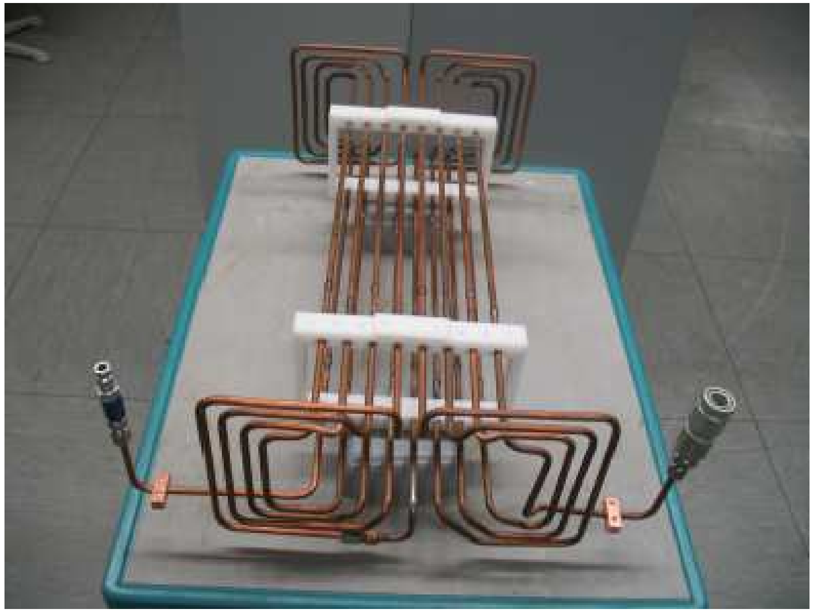
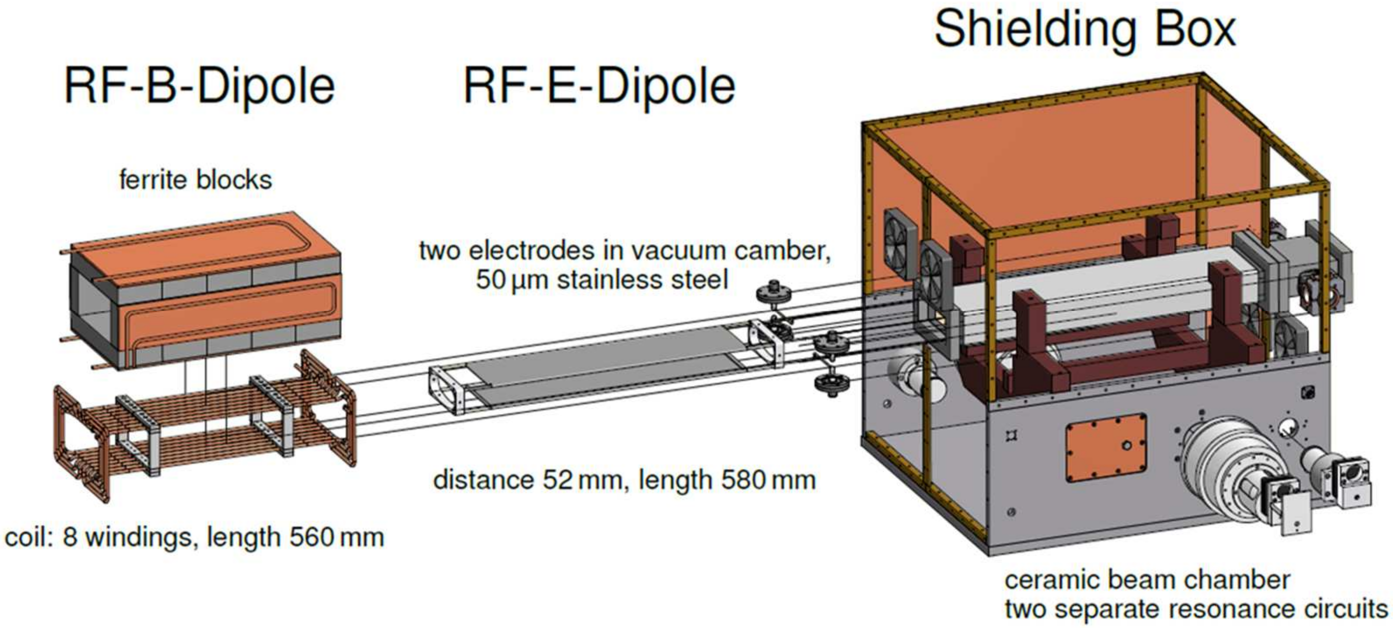
Precursor: RF Wien Filter

1. Upgrade test flipper with electrostatic field plates ready end of year.
2. Build lower power version using a stripline system
3. Build high-power version of stripline system ($E > 100\ \mathrm{kV/m}$)



Work by S. Mey, R. Gebel (Jülich)
J. Slim, D. Hölscher (IHF RWTH Aachen)

Precursor: RF Wien Filter ($E \times B$ prototype)



Shielding Box

RF-B-Dipole

RF-E-Dipole

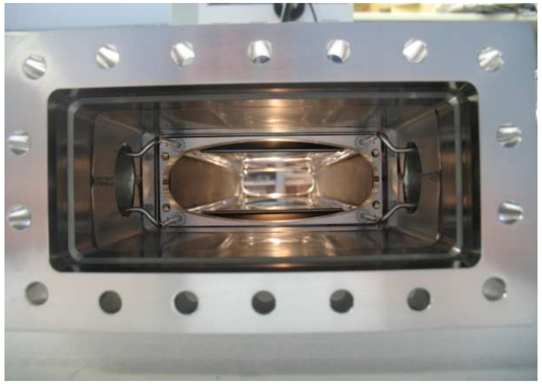
ferrite blocks

two electrodes in vacuum camber,
50 µm stainless steel

distance 52 mm, length 580 mm

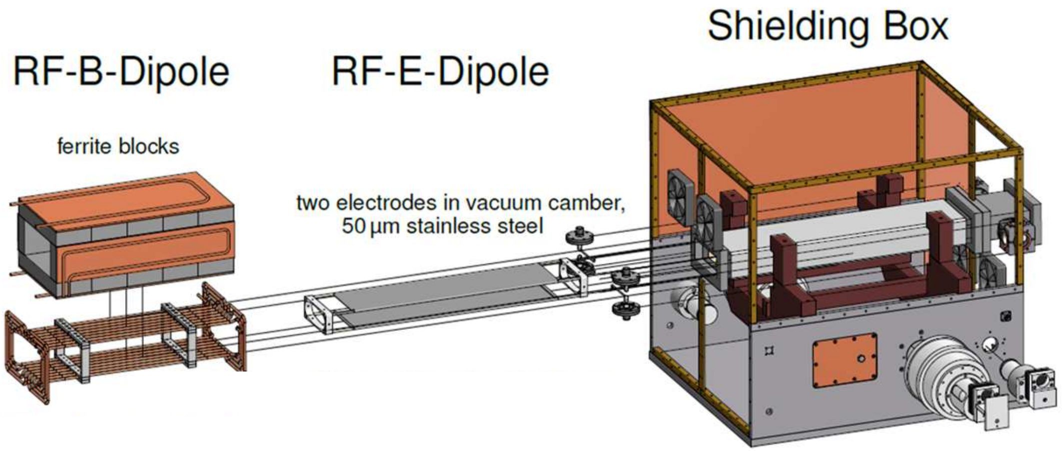
coil: 8 windings, length 560 mm

ceramic beam chamber
two separate resonance circuits



Prototype already installed and ready for beam.

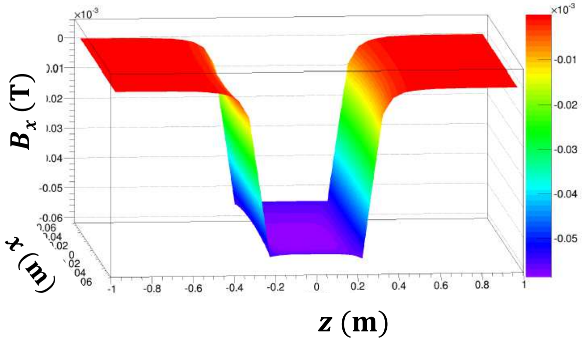
Precursor: RF Wien Filter (field calculations)

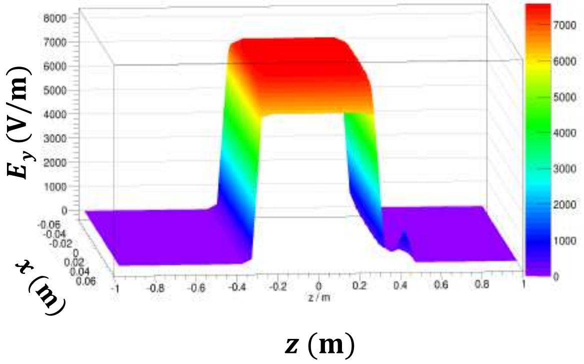


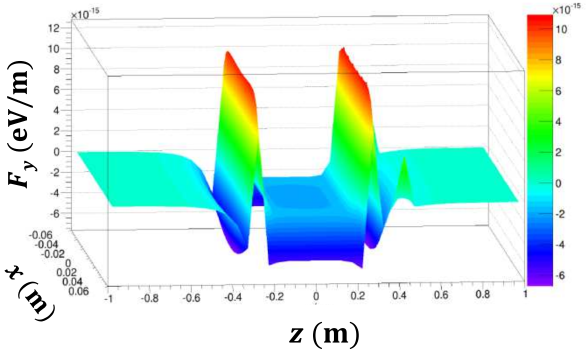
Main field component
$\hat{B}_x = 0.058\ \text{mT}$ at $y = 0,\ \ I = 1\ \text{A},$
$\int \boldsymbol{\hat{B}_x dz = 0.035\ \text{Tmm}}$

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

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



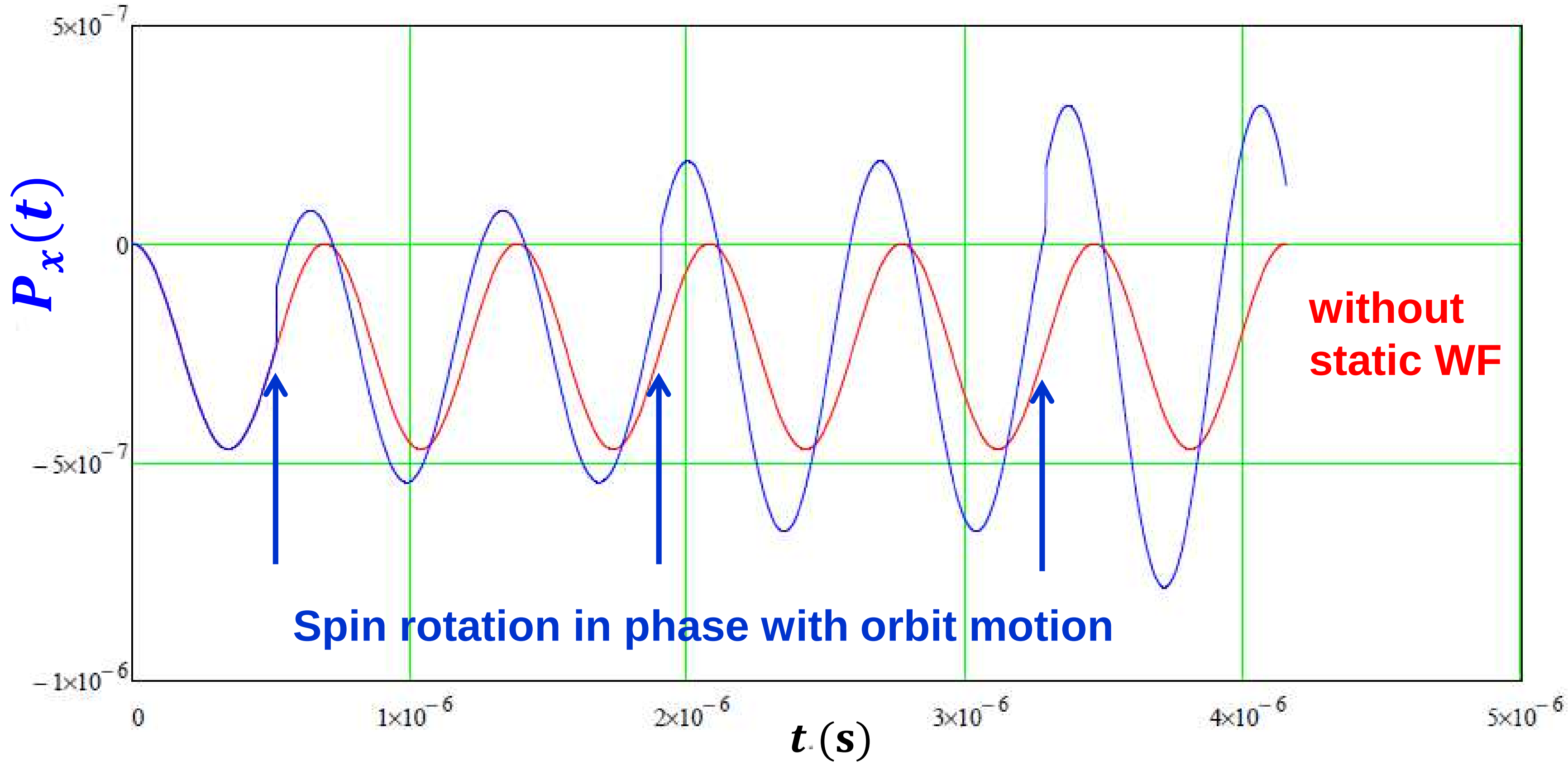




RF $\boldsymbol{E}\times\boldsymbol{B}$ Wien filter will operate like RF solenoid

Precursor:
2. Resonant EDM measurement with static Wien Filter

Machine operated on imperfection spin resonance at $\gamma G = 2$



Spin rotation in phase with orbit motion

Similar accumulation of EDM signal, systematics more difficult, strength of imperfection resonance must be suppressed by closed-orbit corrections.

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Timeline: Stepwise approach towards all-in-one machine

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

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

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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 of $\boldsymbol{p}$ and $\boldsymbol{d}$ at COSY $(10^{-24}\ \mathrm{e}\cdot\mathrm{cm})$
- Development of dedicated EDM storage rings $(10^{-29}\ \mathrm{e}\cdot\mathrm{cm})$
  - All-electric machine (BNL, FNAL)
  - All-in-one machine (Jülich)
- Development of high precision spin tracking tools, incl. RF structures
- Electrostatic deflector development based on FNAL equipment

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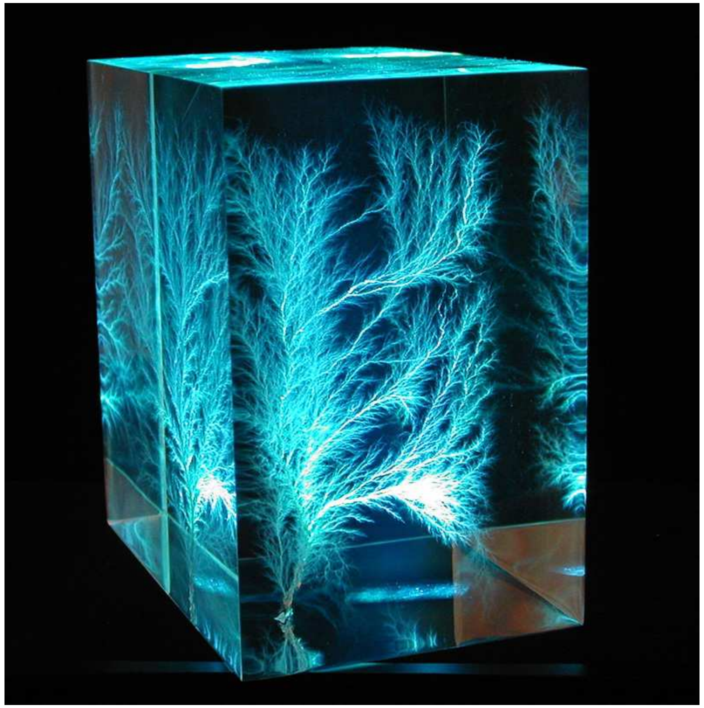
Georg Christoph Lichtenberg (1742-1799)



“Man muß etwas Neues machen, um etwas Neues zu sehen.”

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

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