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EDM (Theory and) Experiment: Search for new Physics beyond the Standard Model

December 5, 2012

Frank Rathmann
(on behalf of the **BNL-EDM** and **JEDI collaborations**)

DISCRETE 2012, JINR, Lisboa, Portugal

Outline

Introduction

Electric Dipole Moments

Physics Impact

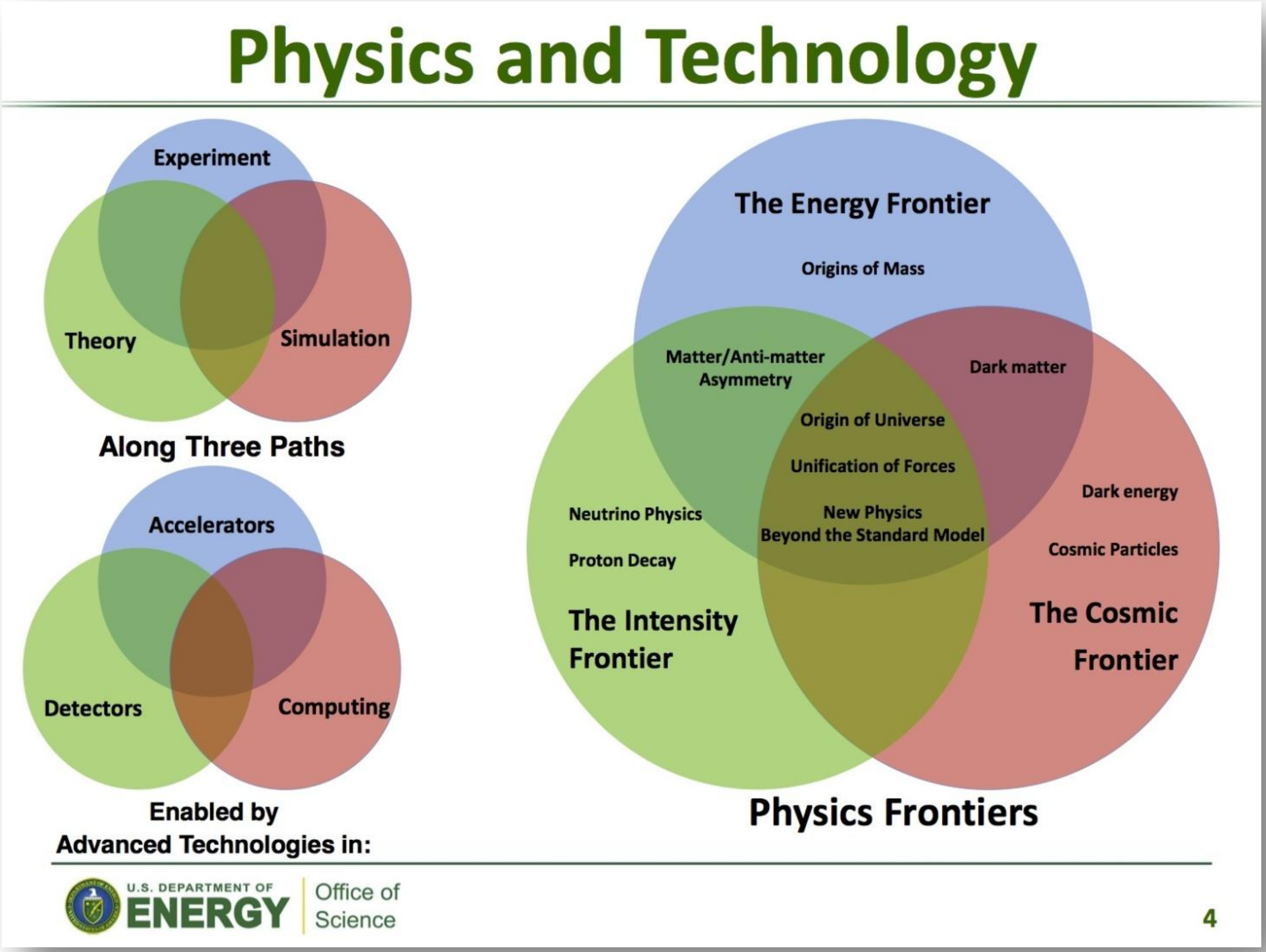
Charged particle EDM searches

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

Timelines of projects

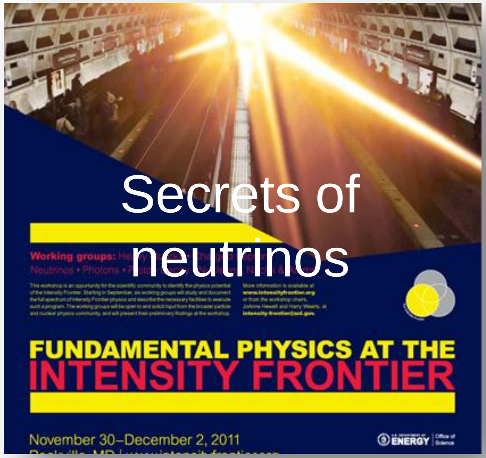
Conclusion

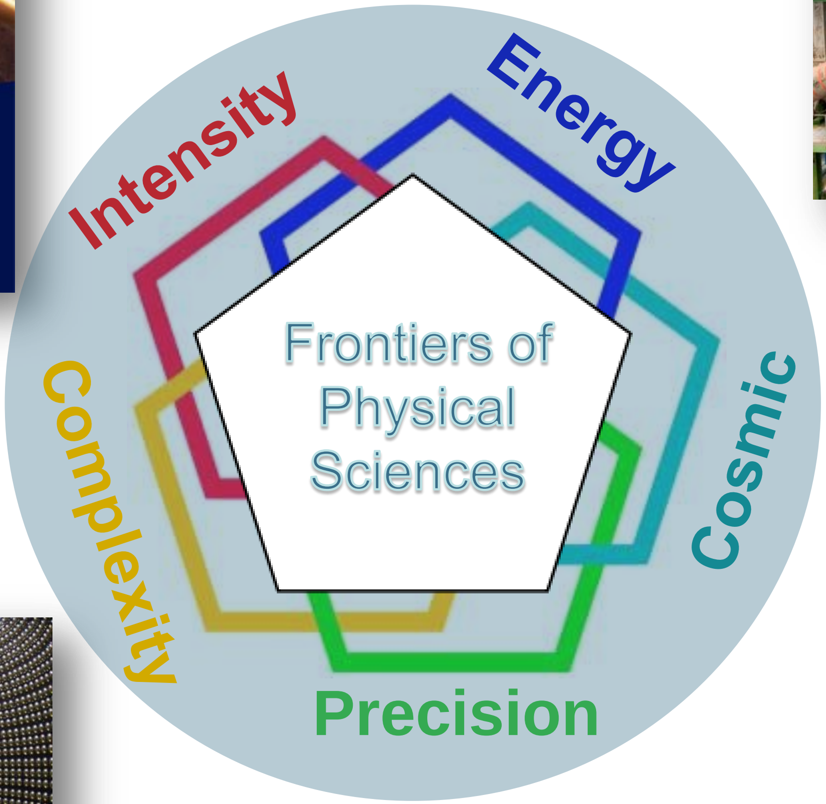
Introduction: The big challenges

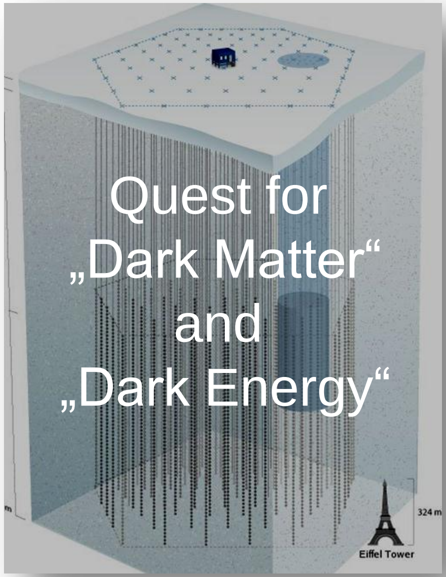


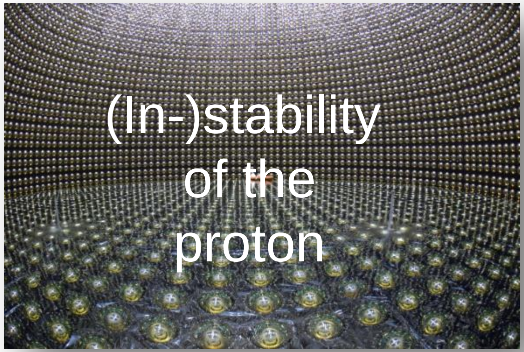
Conventional HEP wisdom, but there is more than that …

Introduction: Physics Frontiers









Introduction: 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.

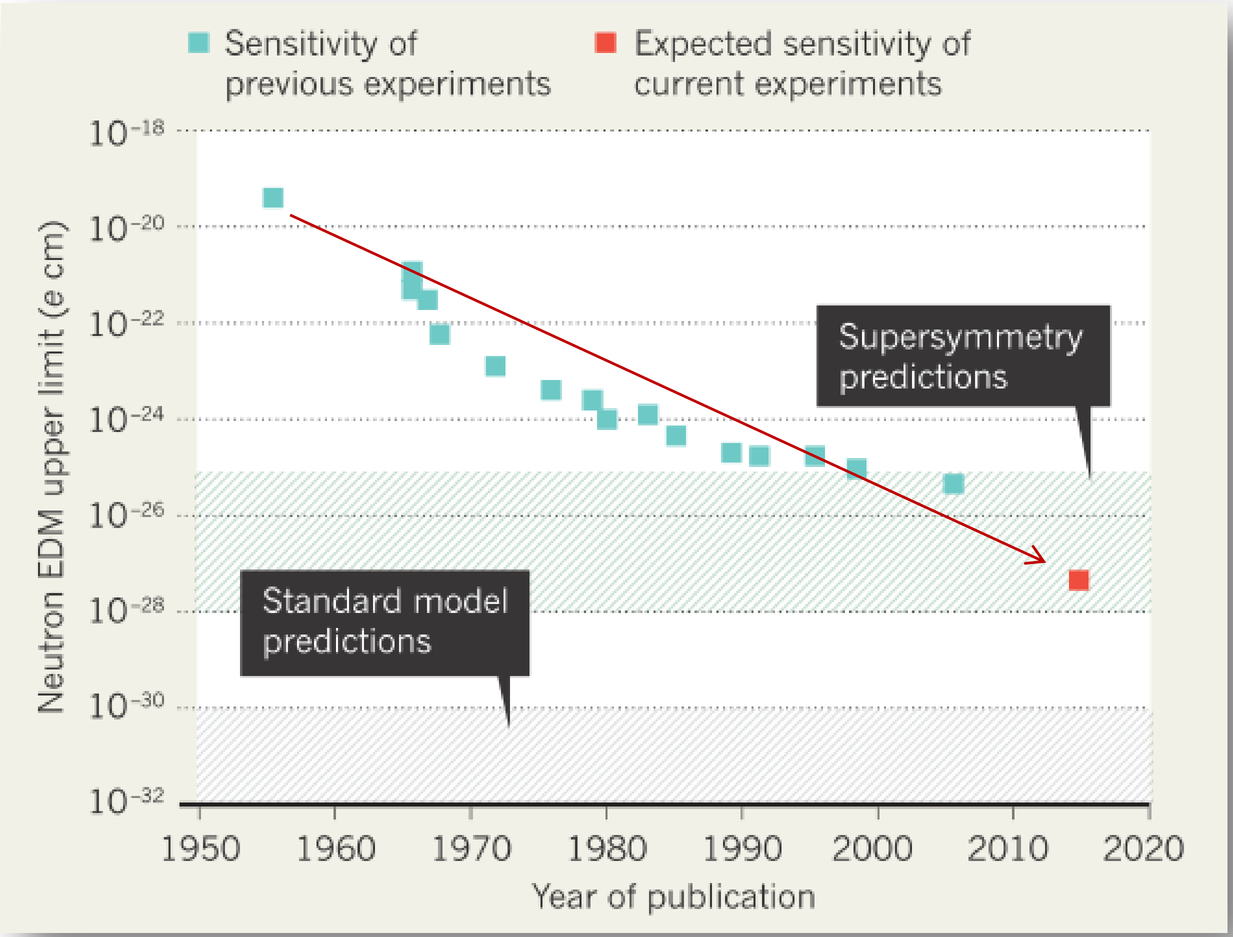
The Preparatory Group is in the process of producing a summary document on the

ESPP, Cracow, September 2012

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

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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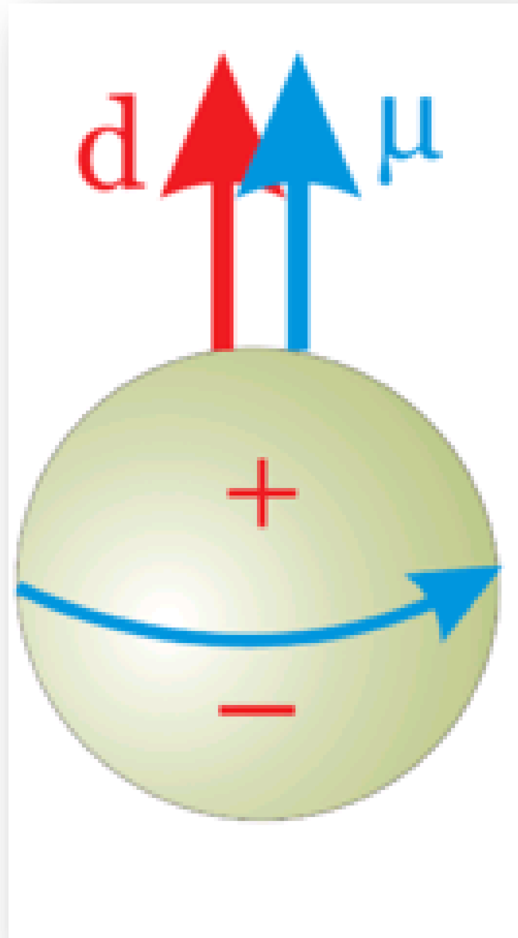
Physics: Fundamental Particles

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

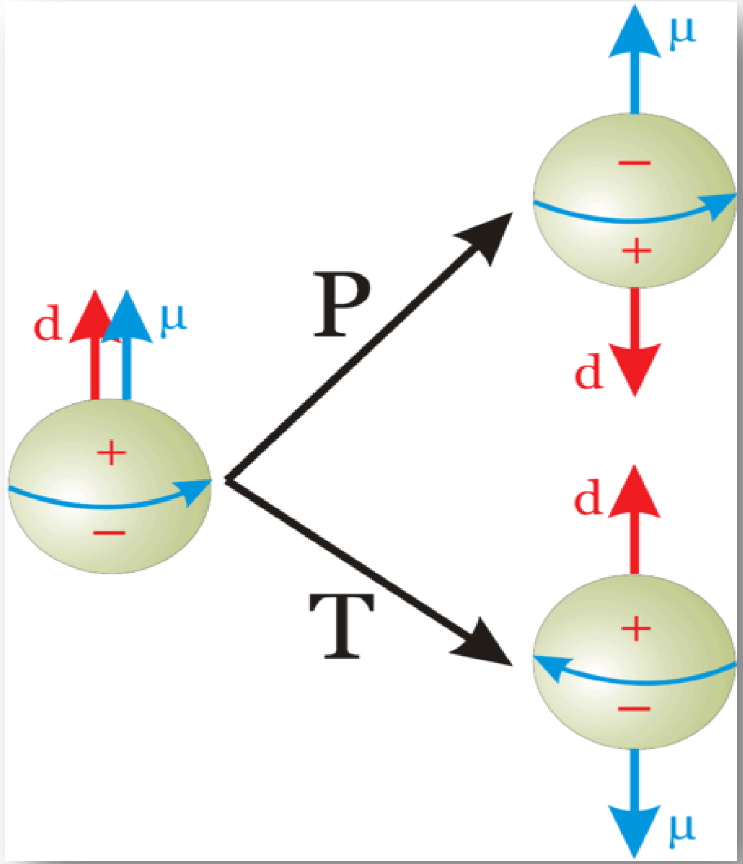


$\vec{\mu}$: **MDM**
$\vec{d}$: **EDM**

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

EDMs: Discrete Symmetries

Not Charge symmetric

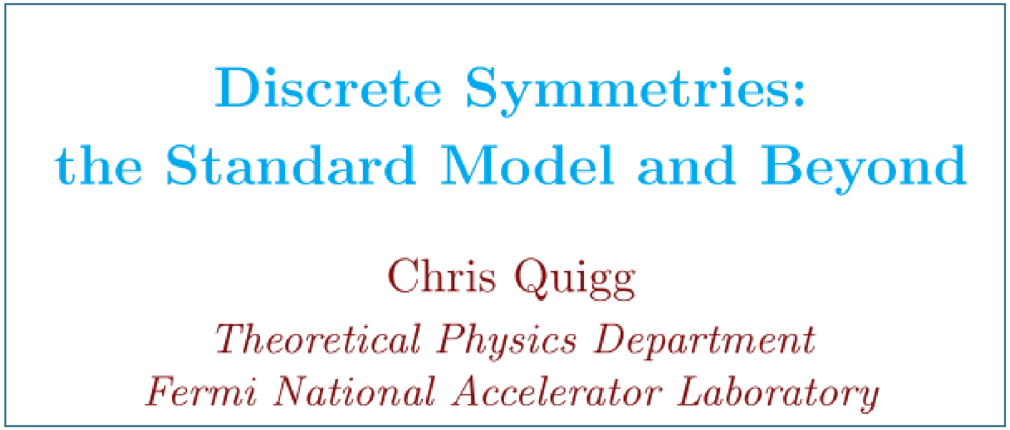


$\vec{d}$ (aligned w/ spin)

Permanent EDMs violate **P** and **T.**

Assuming **CPT** to hold, **CP** violated also.

EDMs: Why is CPV so interesting?

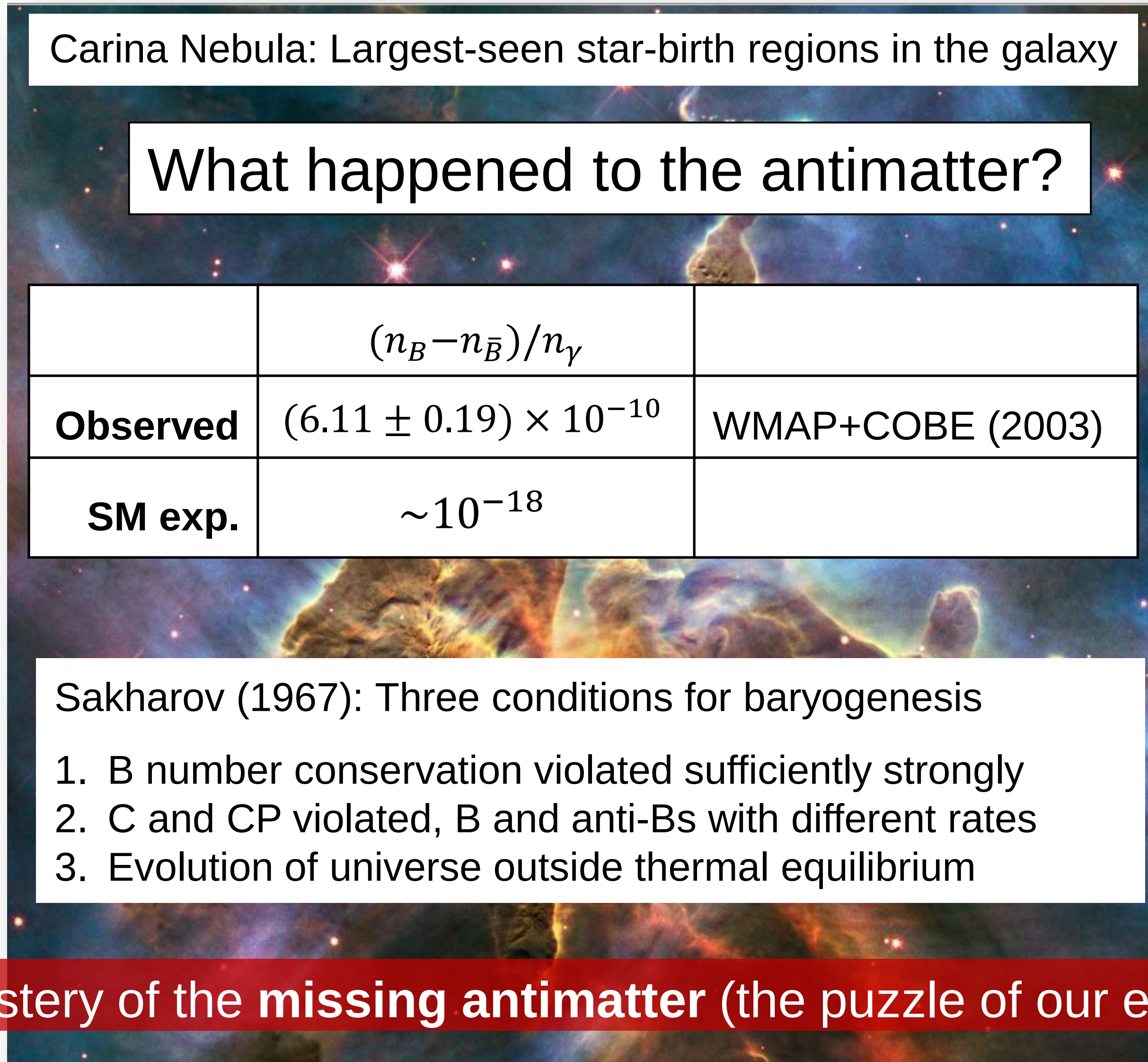


- CPV in the SM points to physics we do not understand
- CPV is highly sensitive to physics beyond the SM (New Physics)
- CPV is accessible to a wide range of experiments
- New source of CPV beyond the SM required for baryogenesis

Physics beyond the Standard Model (**BSM**)

Outline

Physics: What caused the Baryon asymmetry?



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

What happened to the antimatter?

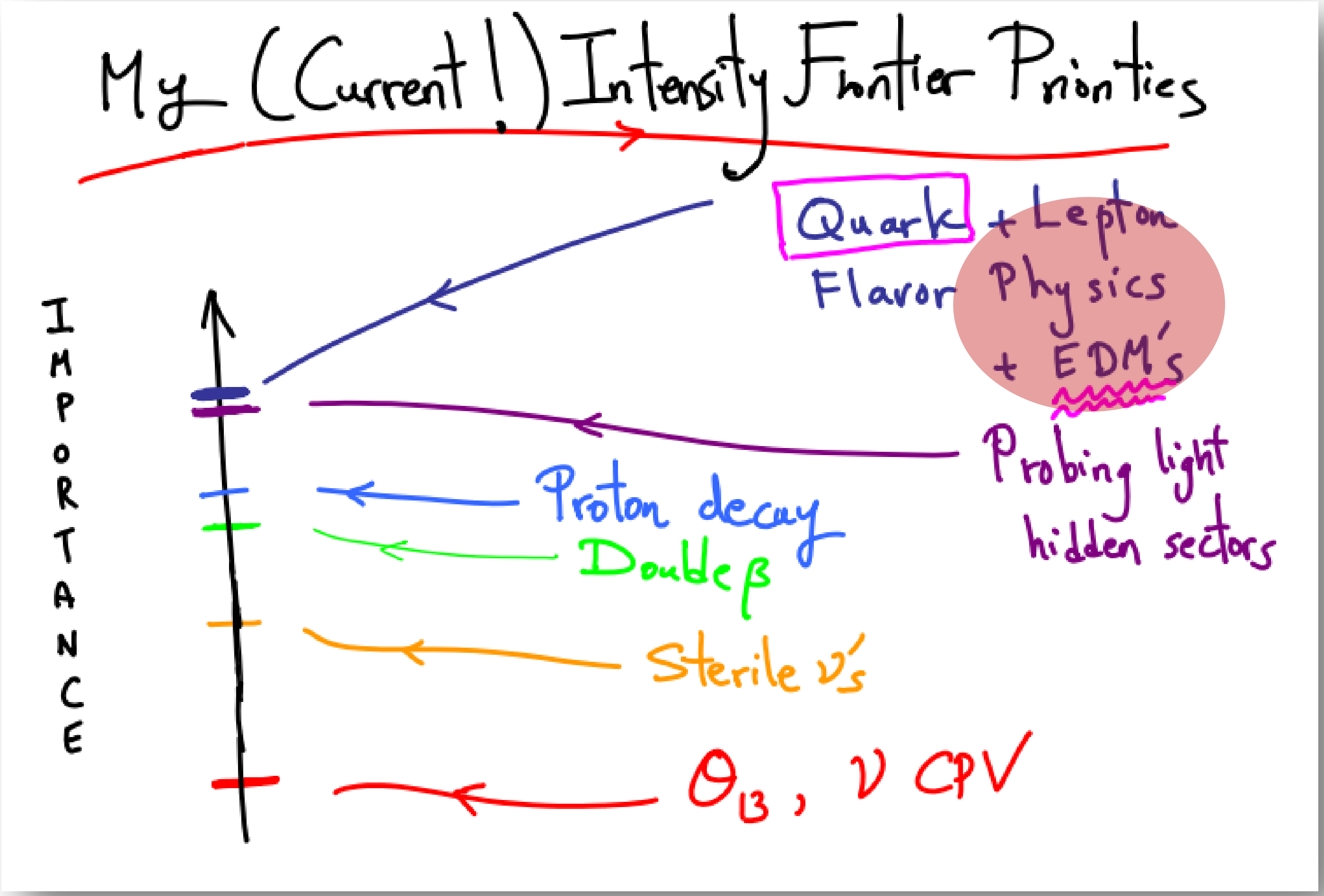
	$(n_B - n_{\bar{B}})/n_\gamma$	
Observed	$(6.11 \pm 0.19) \times 10^{-10}$	WMAP+COBE (2003)
SM exp.	$\sim 10^{-18}$	

Sakharov (1967): Three conditions for baryogenesis

1. B number conservation violated sufficiently strongly
2. C and CP violated, B and anti-Bs with different rates
3. Evolution of universe outside thermal equilibrium

The mystery of the **missing antimatter** (the puzzle of our existence)

Physics: Potential of EDMs



N. Arkani-Hamed (IAS, Princeton) at Intensity Frontier WS, USA (2011)

Physics: Potential of EDMs

G. Isidori – Symmetry Physics Implications — *ESPP Open Symposium* [Cracow, 10-12 Sep. 2011]

★ *The key role of LFV and EDMs*

The search for Electric Dipole Moments of fundamental particles (n, e, μ, … *and, more generally, atoms or heavy nuclei*), share the three main virtues of LFV searches:

- We know CP is not an exact symmetry of nature => non-vanishing EDMs
- Virtually no problems of SM backgrounds
- EDMs close to the present bounds in several realistic models

Observable	Exp. Current
$\lvert d_{Tl}\rvert$ [e cm]	$< 9.0 \times 10^{-25}$
$\lvert d_{Hg}\rvert$ [e cm]	$< 3.1 \times 10^{-29}$
$\lvert d_{n}\rvert$ [e cm]	$< 2.9 \times 10^{-26}$

- 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

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

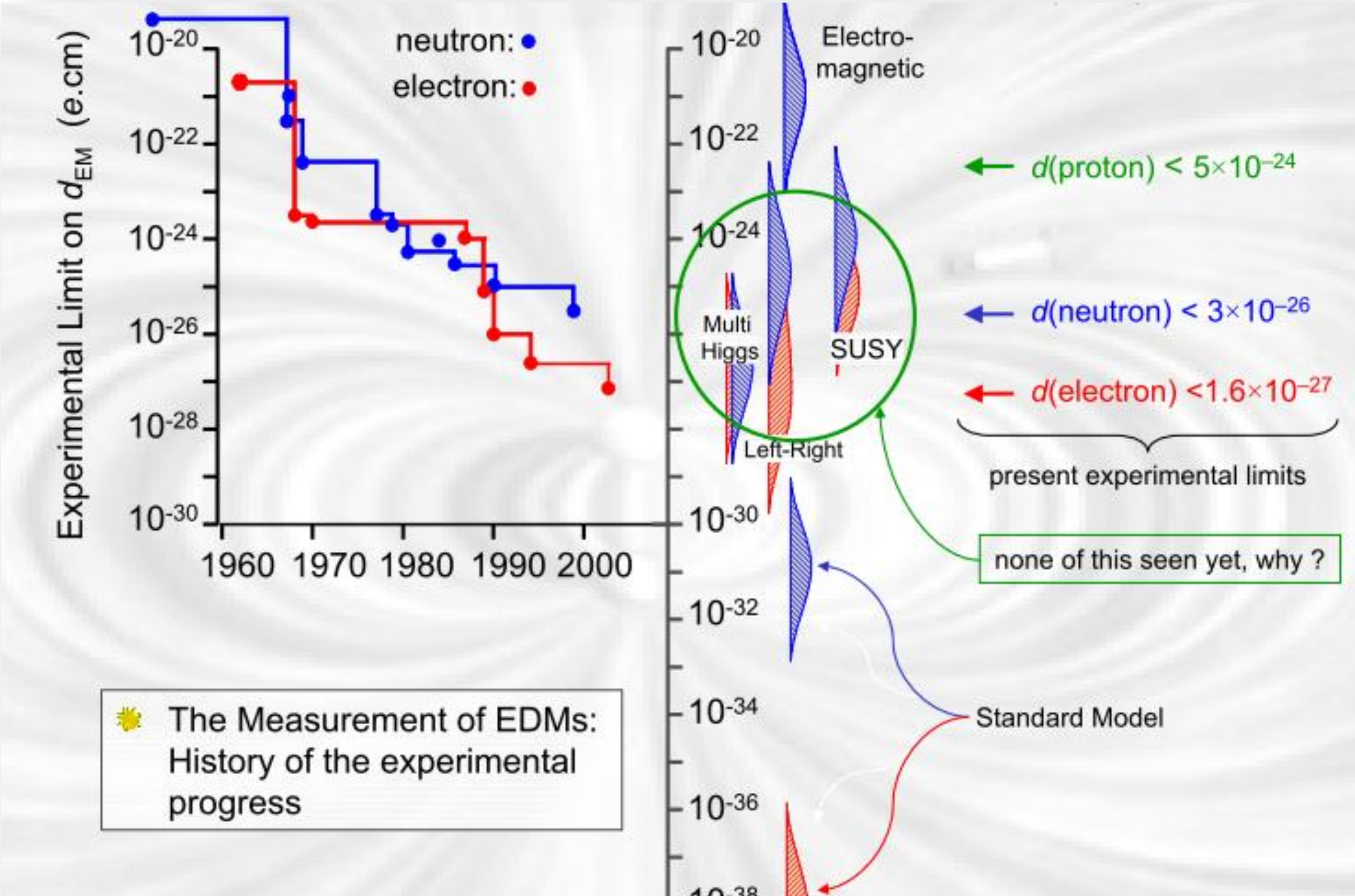
- Atoms ~100
  - Hg@UWash
  - Xe@Princeton
  - Xe@TokyoTech
  - Xe@TUM
  - Xe@Mainz
  - Cs@Penn
  - Cs@Texas
  - Fr@RCNP/CYRIC
  - Rn@TRIUMF
  - Ra@ANL
  - Ra@KVI
  - Yb@Kyoto

- Ions-Muons ~200
  - @BNL
  - @FZJ
  - @FNAL
  - @JPARC
- Solids ~10
  - GGG@Indiana
  - ferroelectrics@Yale

world-wide effort in trying to improve the limits by ~ 1 order of magnitude

G. Isidori at ESPP Open Symposium, Cracow (Sept. 2012)

Physics: Potential of EDMs



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

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	?	$\sim 10^{-29}$	$3 \times 10^{-29} - 5 \times 10^{-31}$

Huge efforts underway worldwide to improve limits / find EDMs

Physics: Ongoing/planned Searches

- Neutrons ~200
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  - @ILL,@PNPI
  - @PSI
  - @FRM-2
  - @RCNP,@TRIUMF
  - @SNS
  - @J-PARC

- Molecules ~50
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  - ThO@Harvard
  - HfF+@JILA
  - WC@UMich
  - PbF@Oklahoma

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  - Xe@Mainz
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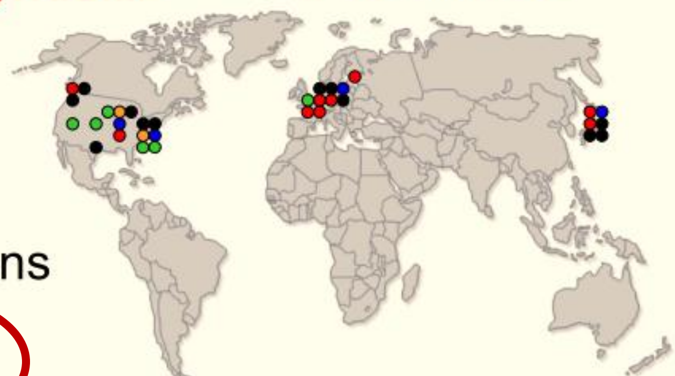
  - Cs@Texas
  - Fr@RCNP/CYRIC
  - Rn@TRIUMF
  - Ra@ANL
  - Ra@KVI
  - Yb@Kyoto



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

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

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

Outline

Principle: 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:

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

Magic condition: Spin along momentum vector

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

$$E = \frac{GBc\beta\gamma^2}{1-G\beta^2\gamma^2} \approx GBc\beta\gamma^2 \qquad \begin{aligned} E &= E_{\text{radial}} \\ B &= B_{\text{vertical}} \end{aligned}$$

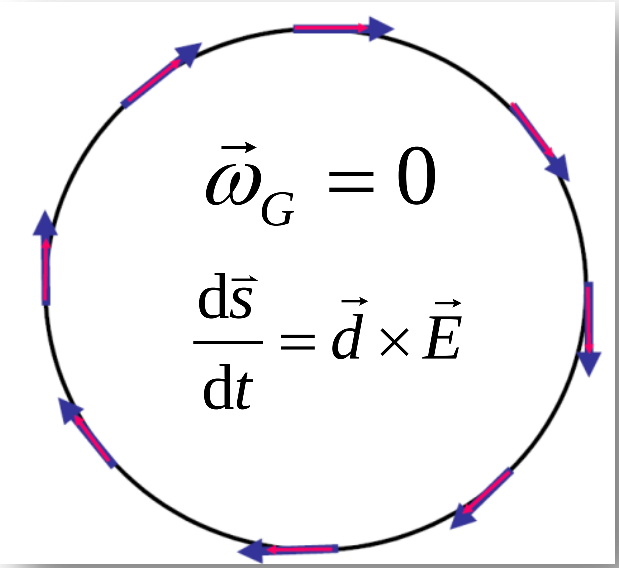
2. For $G > 0$ (protons) in an all electric ring

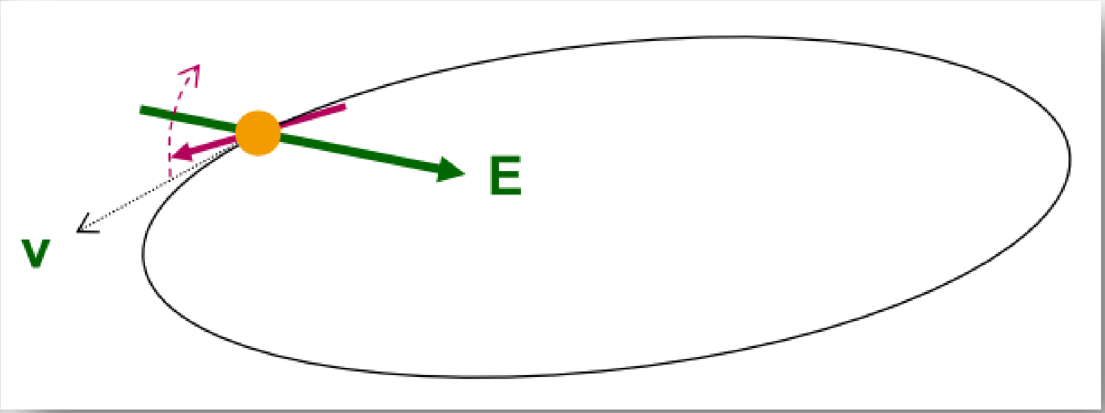
$$G - \left(\frac{m}{p}\right)^2 = 0 \rightarrow p = \frac{m}{\sqrt{G}} = 700.74\,\frac{\text{MeV}}{\text{c}} \qquad \text{(magic)}$$

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

Principle: Rings for srEDM searches

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

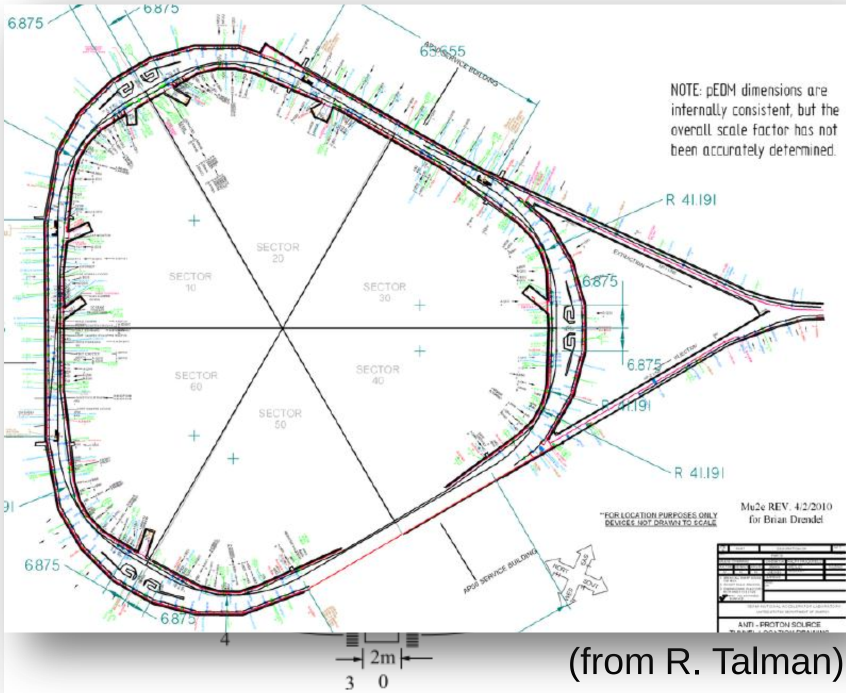




New Method to measure EDMs of **free** charge particles:
Magic rings with spin frozen along momentum

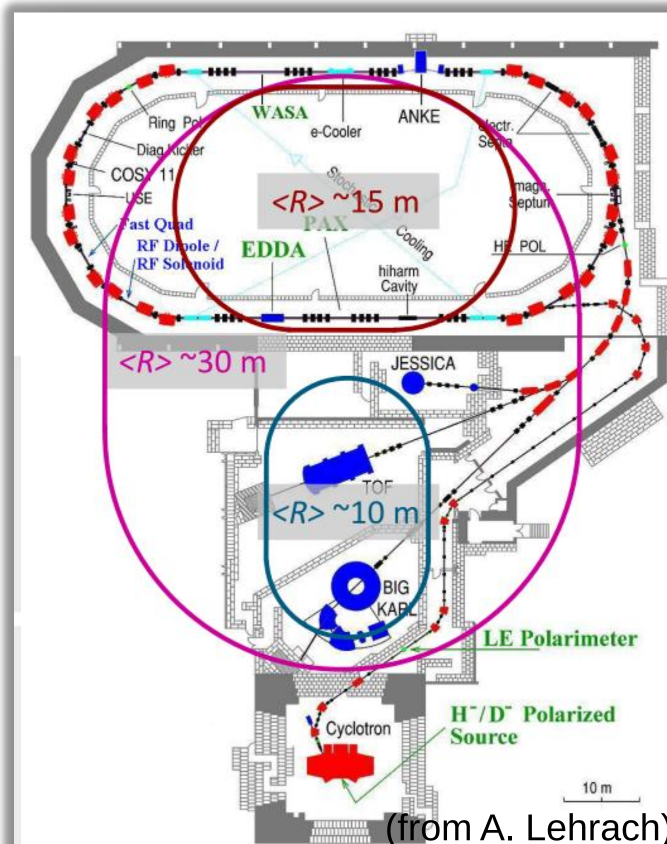
EDMs: Storage ring projects

pEDM in all electric ring at BNL
or at FNAL



CW and CCW propagating beams

Jülich, focus on deuterons,
or a combined machine



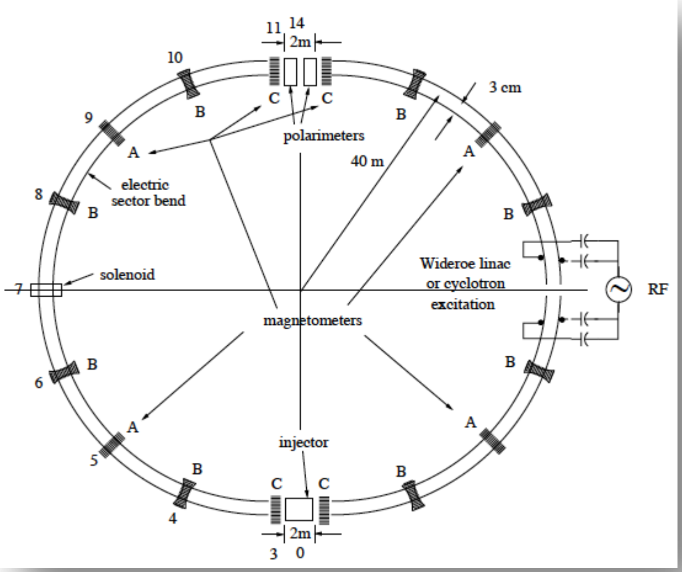
Two projects: **US** (BNL or FNAL) and **Europe** (FZJ)

Beat systematics: BNL Proposal

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

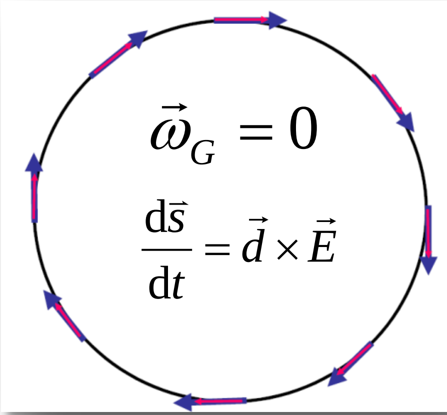
Goal for protons

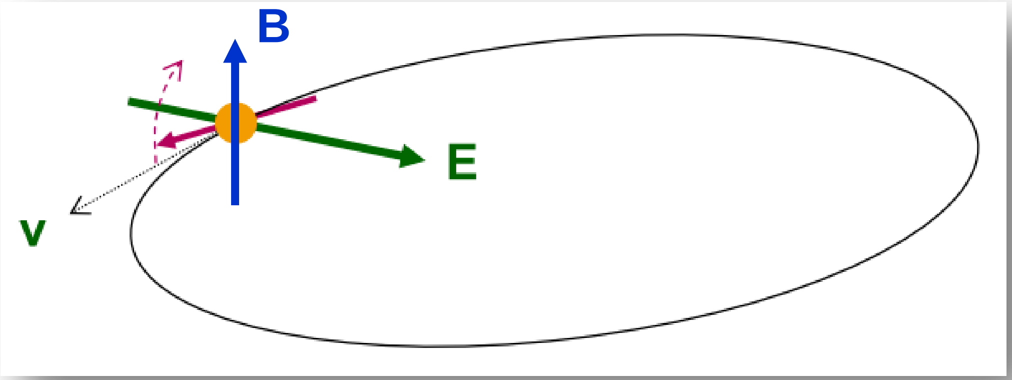
$$\boxed{\sigma_{d_p} \approx 2.5\times 10^{-29}\ \mathrm{e\cdot cm\ (one\ year)}}$$

Many technological challenges need to be met

Principle: *Magic* Storage ring

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



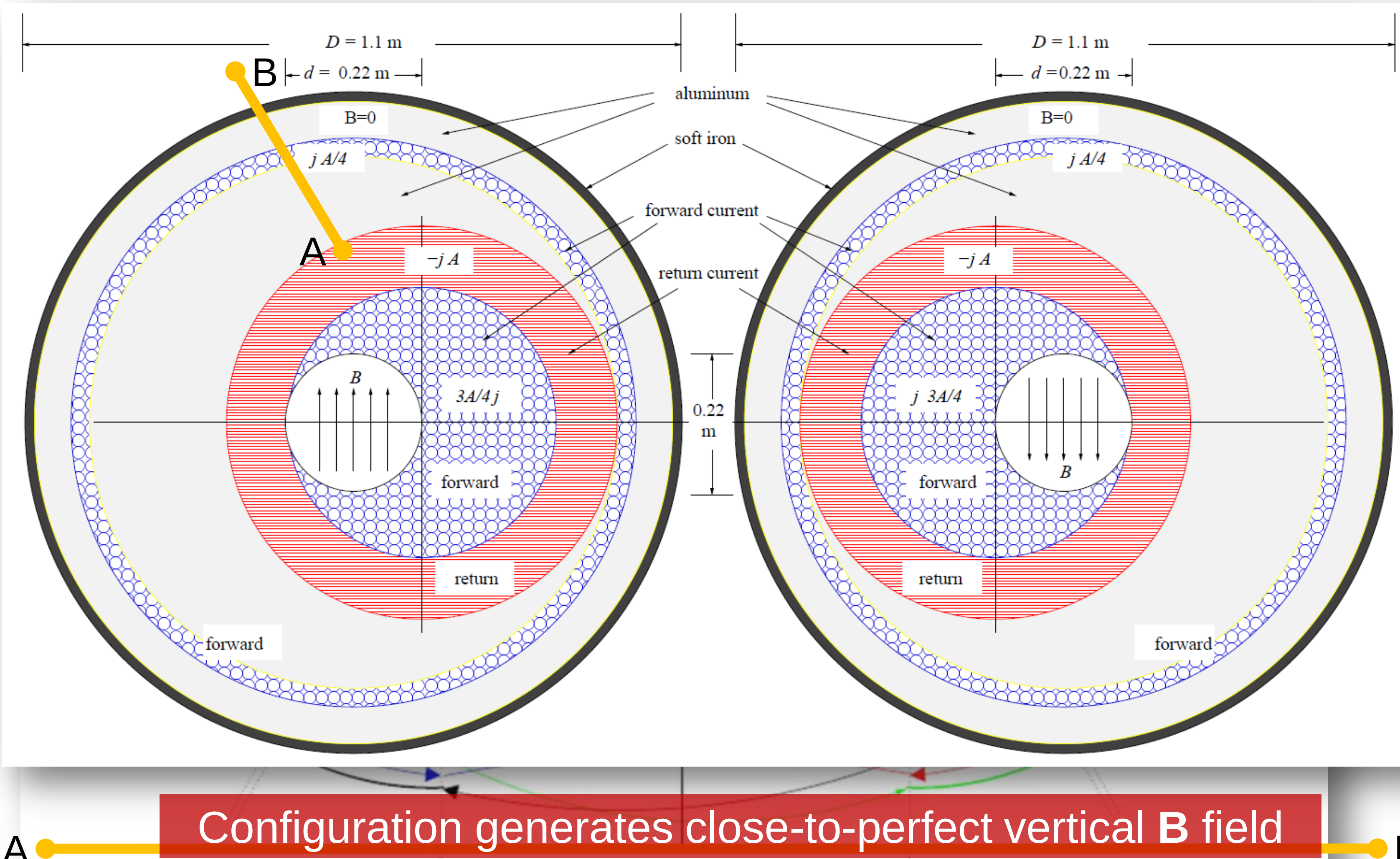


particle	p (GeV/c)	E (MV/m)	B (T)
proton	0.701	16.789	0.000
deuteron	1.000	−3.983	0.160
^{3}He	1.285	17.158	−0.051

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

CCW & CCW with magnetic field:
Richard Talmans concept for a Jülich all-in-one machine

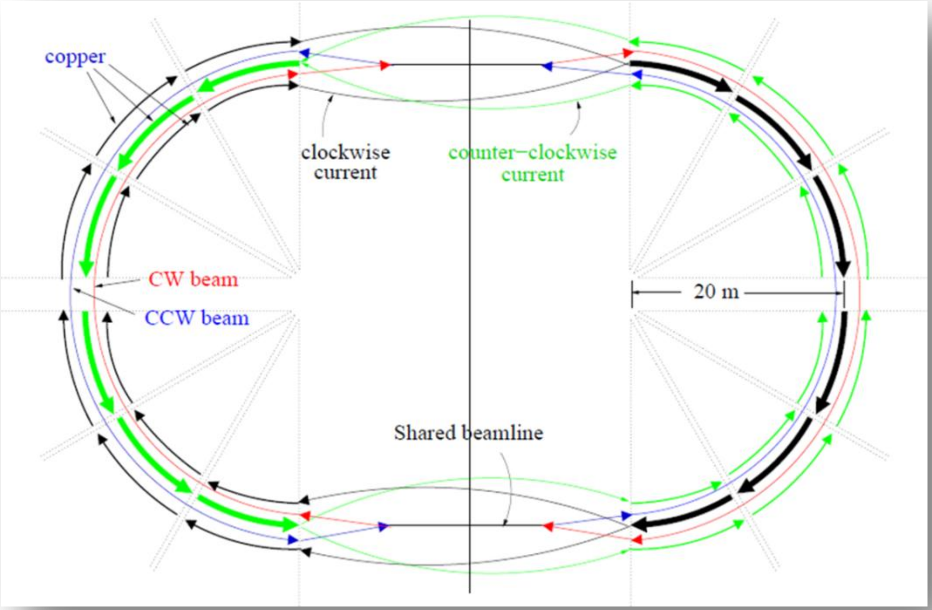
Iron-free, current-only, magnetic bending, eliminates hysteresis

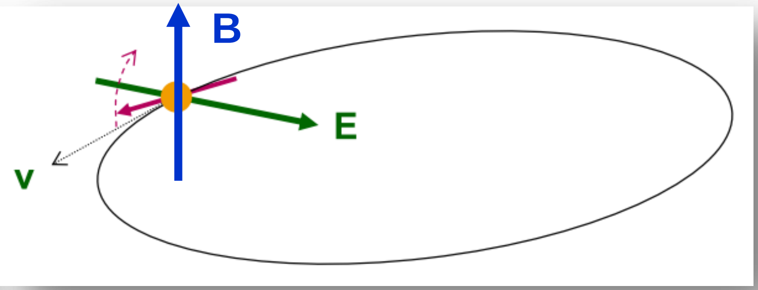


Configuration generates close-to-perfect vertical **B** field

A B

Magic ring: Jülich all-in-one machine (R. Talmans concept)





Maximum achievable field of copper magnets ~0.15 T.

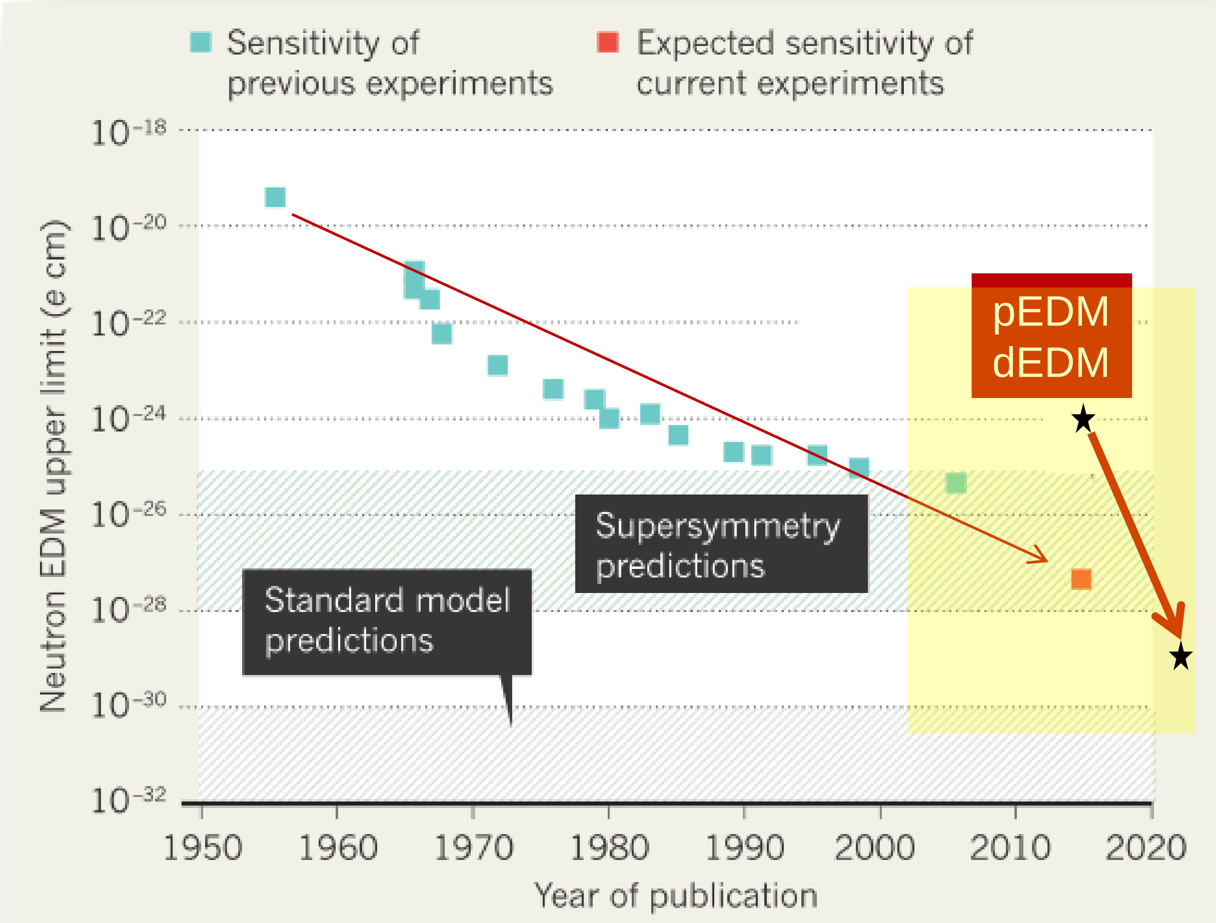
$r = 10$ m

particle	p (GeV/c)	T (GeV)	E (MV/m)	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

EDMs – Sensitivity Reach

EDM search in charged baryon (systems)



Adapted from: Nature, Vol 482 (2012)

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

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srEDM searches: Technogical challenges

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

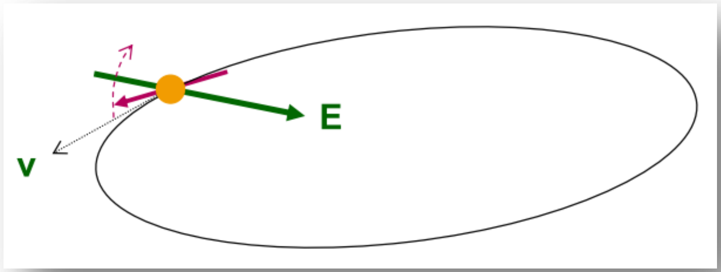
Other topics:

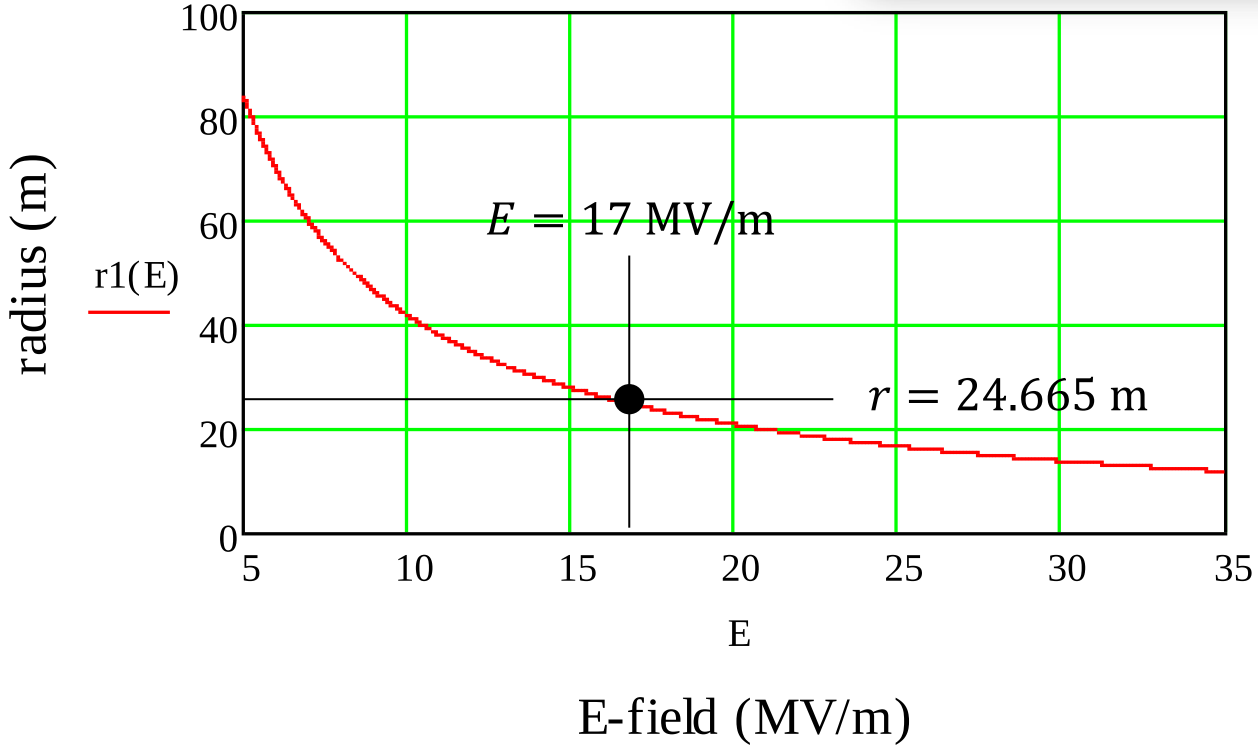
- **Electric field gradients** $(\sim 17\ \mathrm{MV/m\ at\ 2\ cm})$
- **Spin coherence time** $(\geq 1000\ s)$
- **Continuous polarimetry** $(< 1\ \mathrm{ppm})$
- Beam positioning $(10\ nm)$
- Spin tracking

These issues must be addressed experimentally at existing facilities

Challenge: Electric field for magic rings

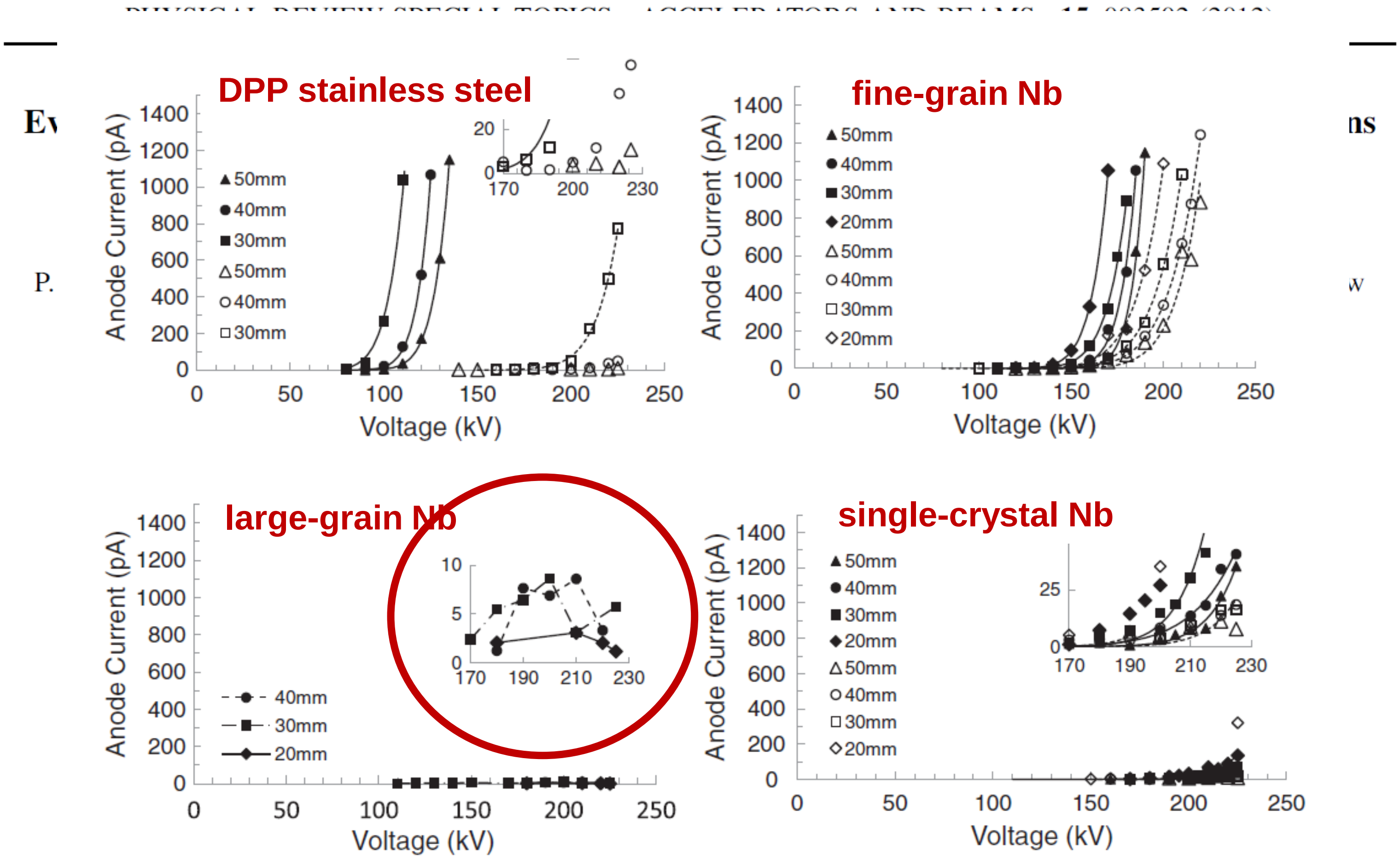
Radial *E* field only





Challenge to produce large electric field gradients

Challenge: Niobium electrodes

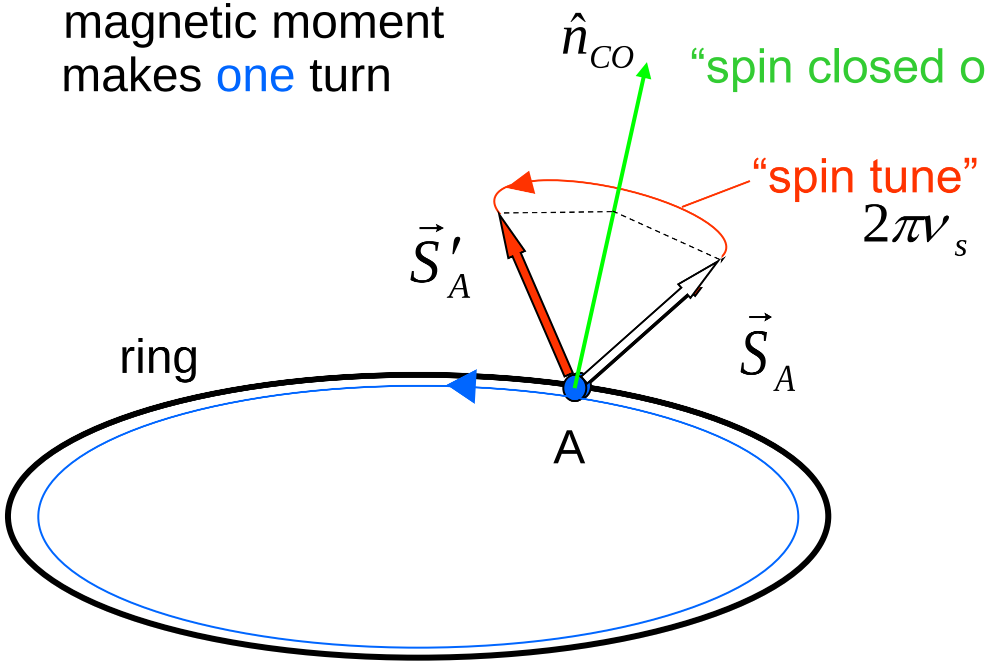


Large-grain Nb at plate separation of a few cm yields ~20 MV/m

Challenge: Spin coherence time

Spin closed orbit

one particle with magnetic moment makes one turn

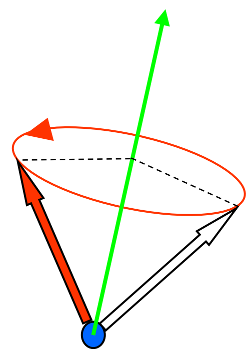


stable polarization

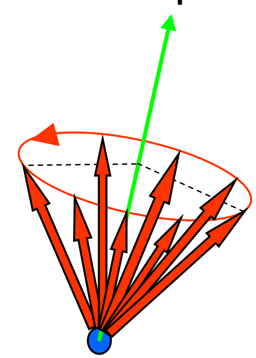
if $\vec{S} \parallel \hat{n}_{CO}$

Challenge: Spin coherence time

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



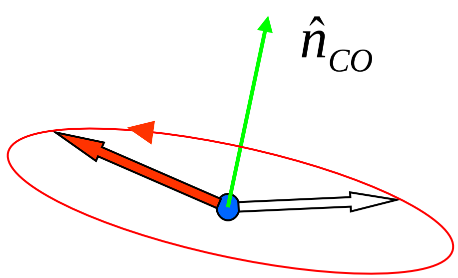
At injection all
spin vectors aligned (coherent)



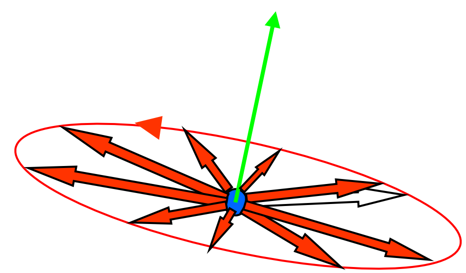
After some time, spin vectors get out of
phase and fully populate the cone

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.

Challenge: SCT stimates (N.N. Nikolaev)

One source of spin coherence 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

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

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

Estimate: $T_{\mathrm{kin}} = 100\ \mathrm{MeV}$ $f_{\mathrm{rev}} = 0.5\ \mathrm{MHz}$

$G_p = 1.79$ $G_d = -0.14$

$\tau_{sc}(p) \approx 3 \cdot 10^3\ \mathrm{s}$ $\tau_{sc}(d) \approx 5 \cdot 10^5\ \mathrm{s}$

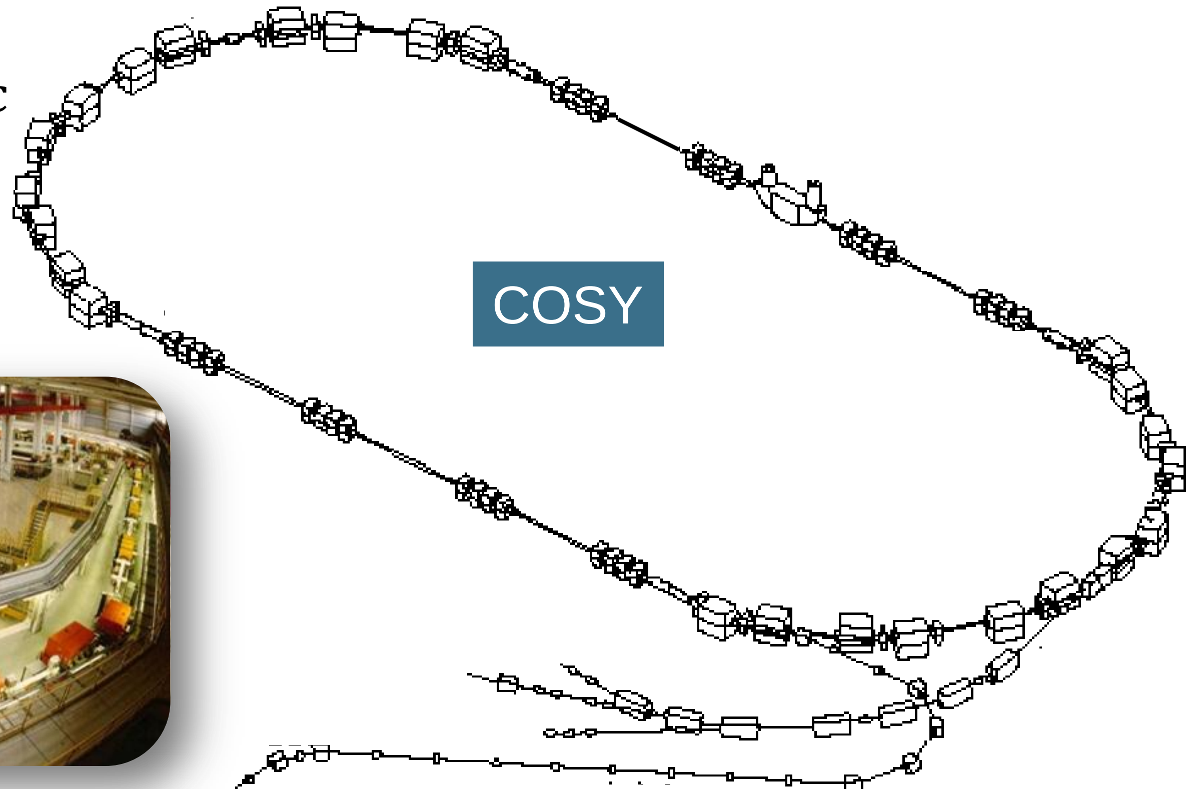
Spin coherence time for deuterons may be $\mathbf{100\times}$ larger than for protons

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

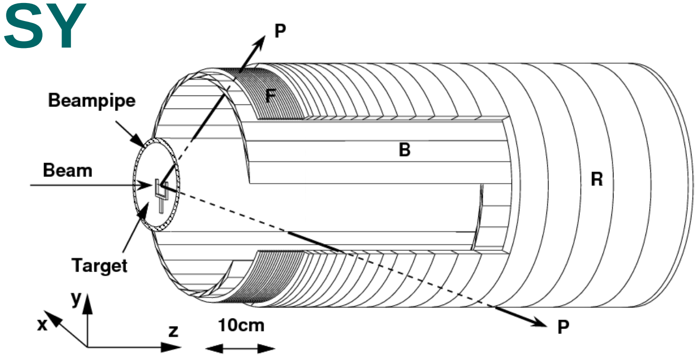


… an ideal starting point for a srEDM search

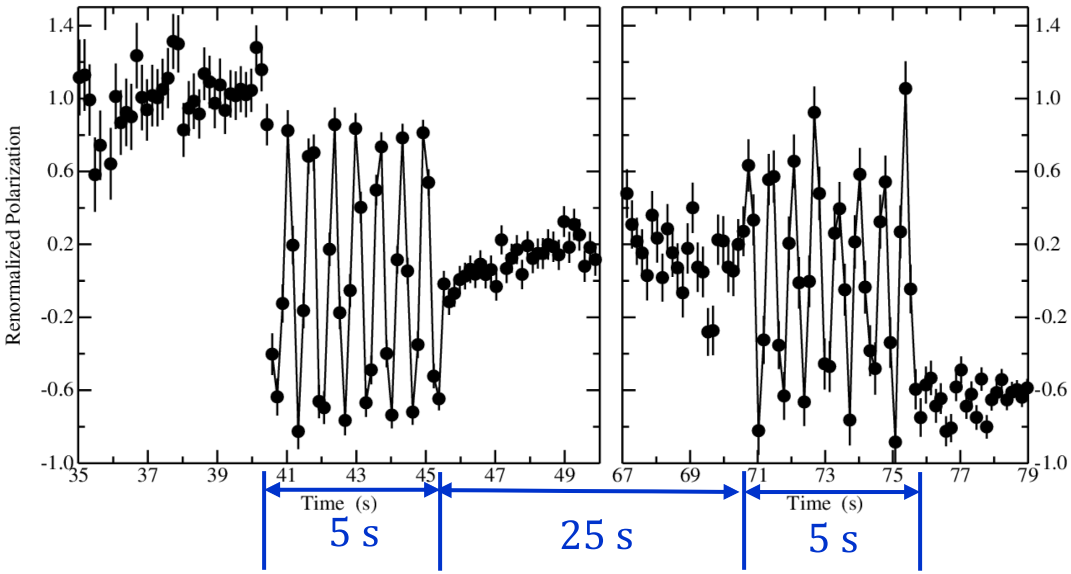
Challenge: First measurement of SCT

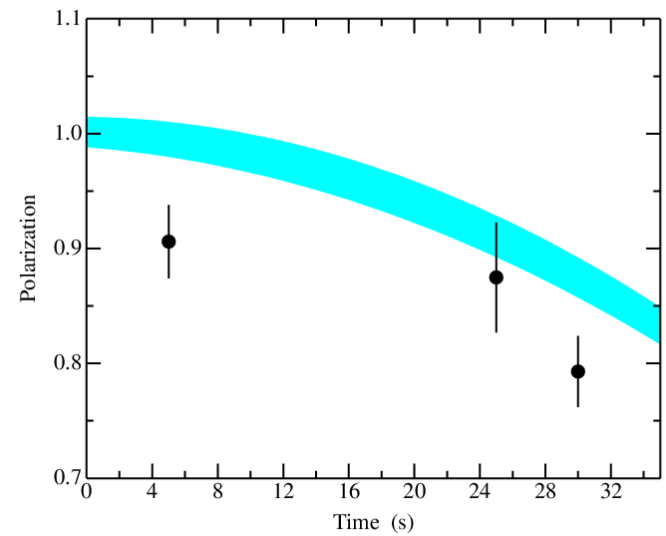
2011 Test measurements at COSY

Polarimetry:



Spin coherence time:





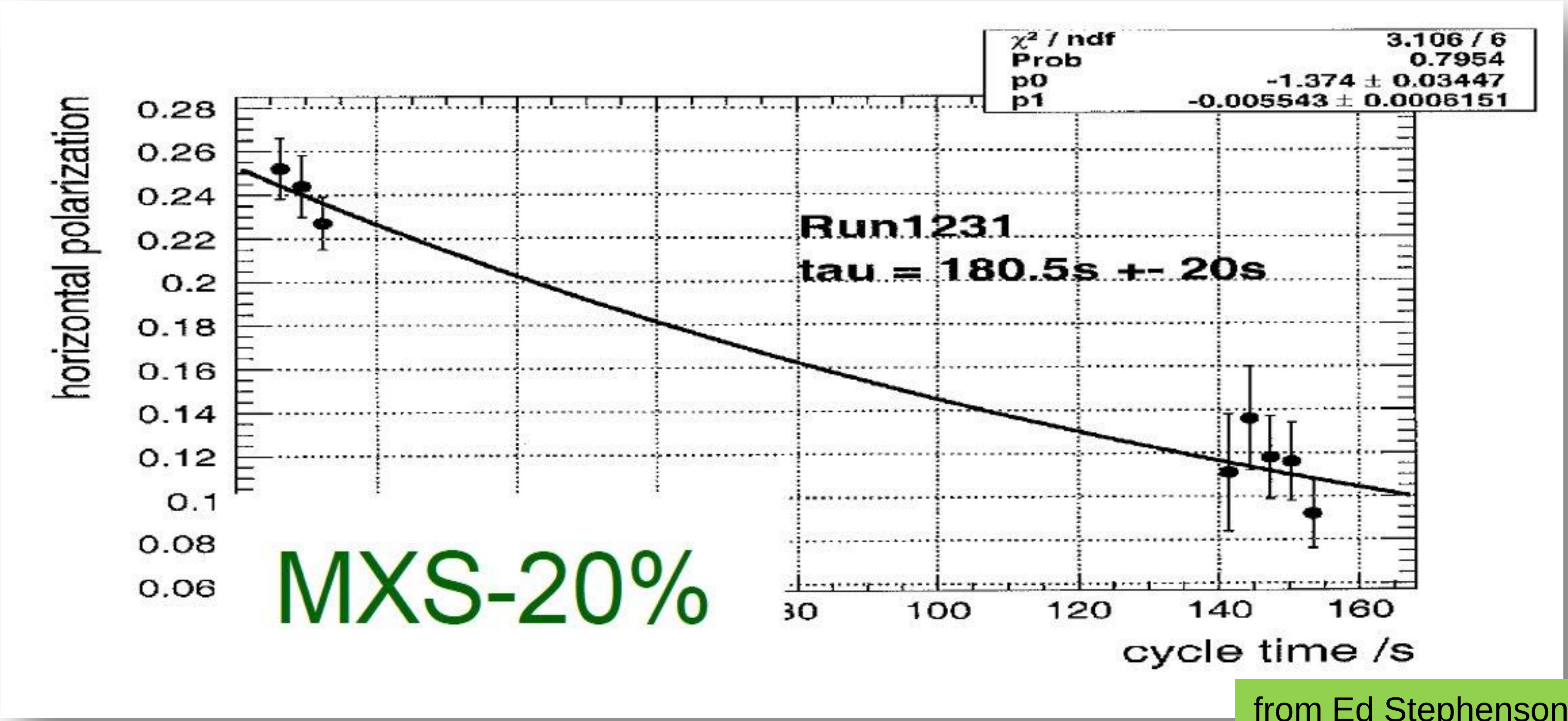
decoherence time

oscillation capture

from Ed Stephenson and Greta Guidoboni

Challenge: SCT recent achievements

Result from 2012 run



from Ed Stephenson and Greta Guidoboni

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

Challenge: Polarimetry

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A B S T R A C T

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 the ppm level achieved for deuteron beams

Outline

Precursor experiments: RF methods

Methods based on making the spin precession in the machine resonant with the orbit motion

Two ways:

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

Use existing magnetic machines for first direct EDM measurements

Precursor experiments:
Resonance Method with „magic“ RF Wien filter

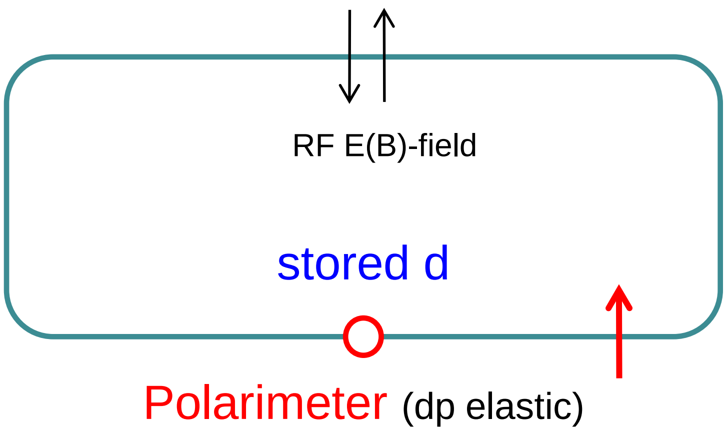
Avoids coherent betatron oscillations of beam.

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



In-plane polarization

Tilt of precession plane due to EDM

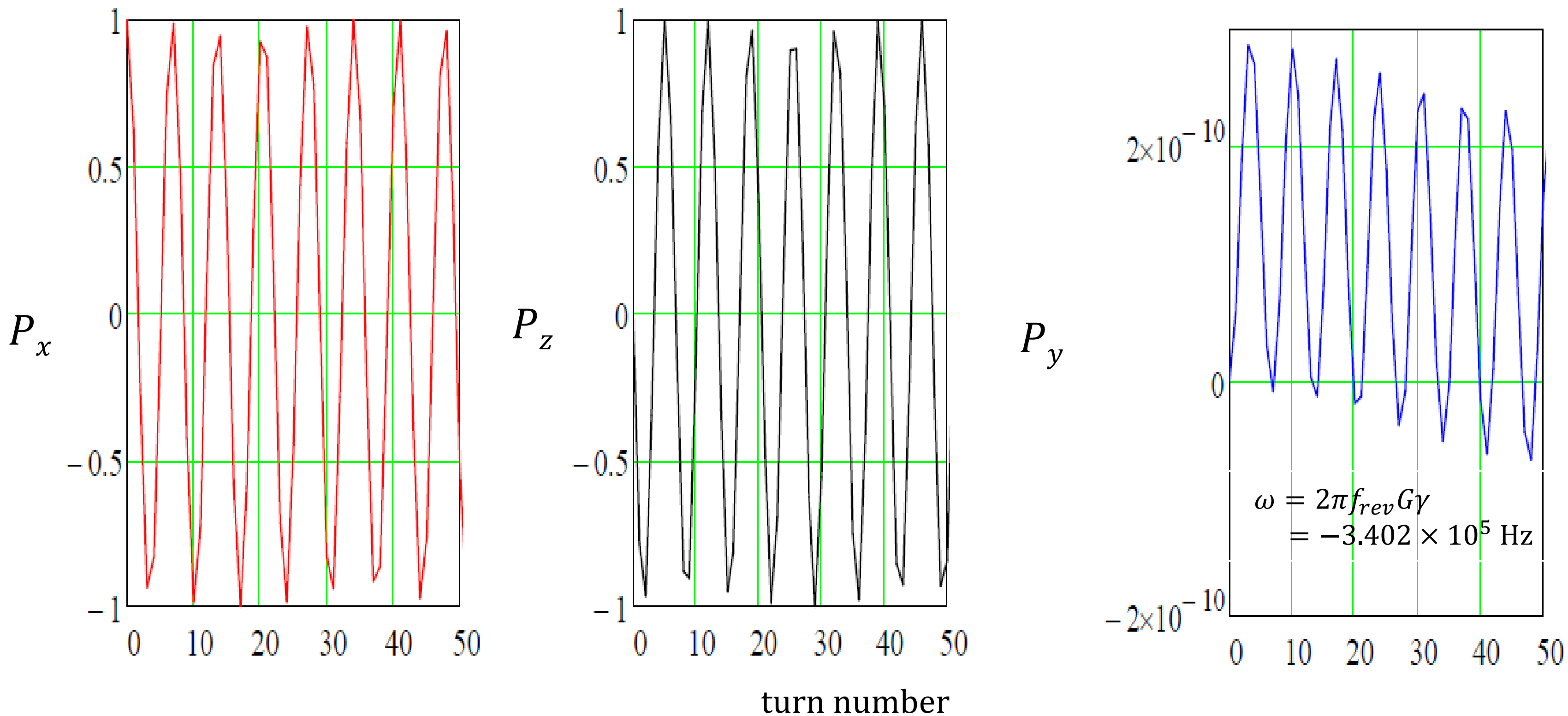
Observable:
Accumulation of vertical polarization during spin coherence time

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

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

Precursor experiments:
Resonance Method for deuterons at COSY

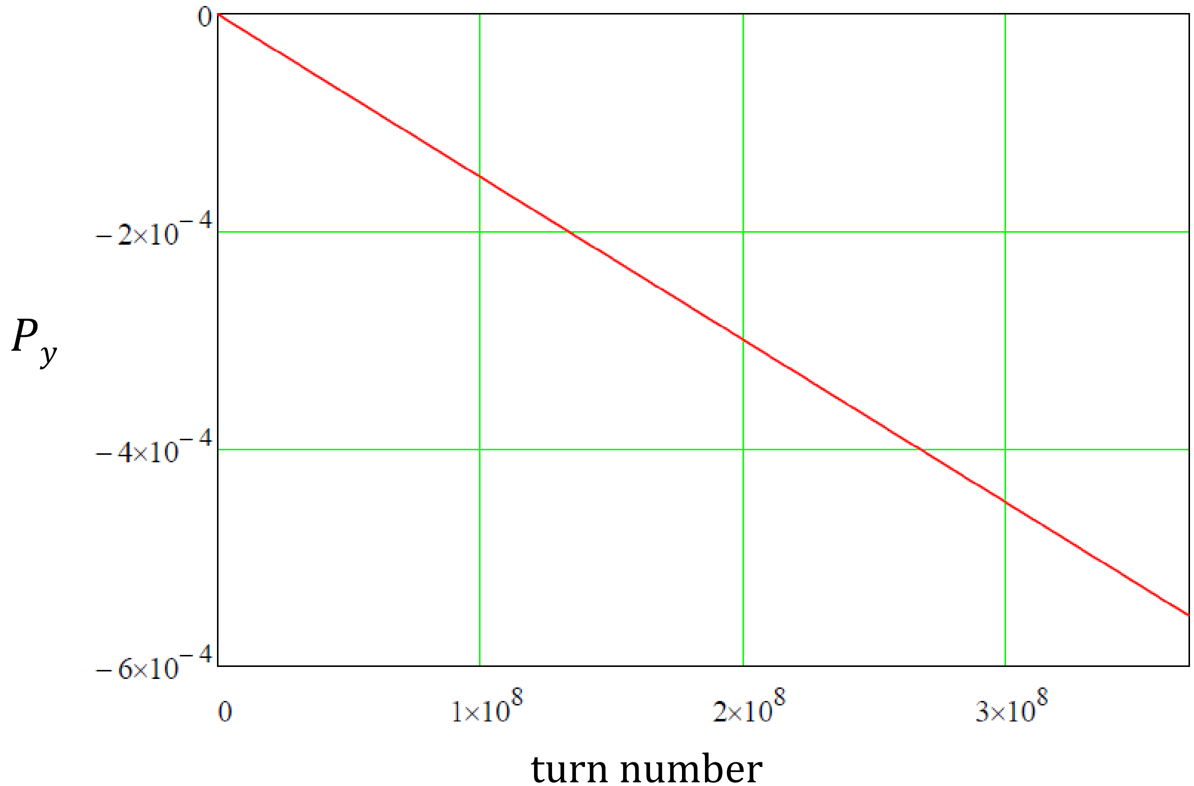
Parameters:	beam energy	$T_d = 50$ MeV	$L_{\mathrm{RF}} = 1$ m
	assumed EDM	$d_d = 10^{-24}$ e·cm	
	E-field	30 kV/cm	



EDM effect accumulates in P_y

Precursor experiments: Resonance Method for deuterons at COSY

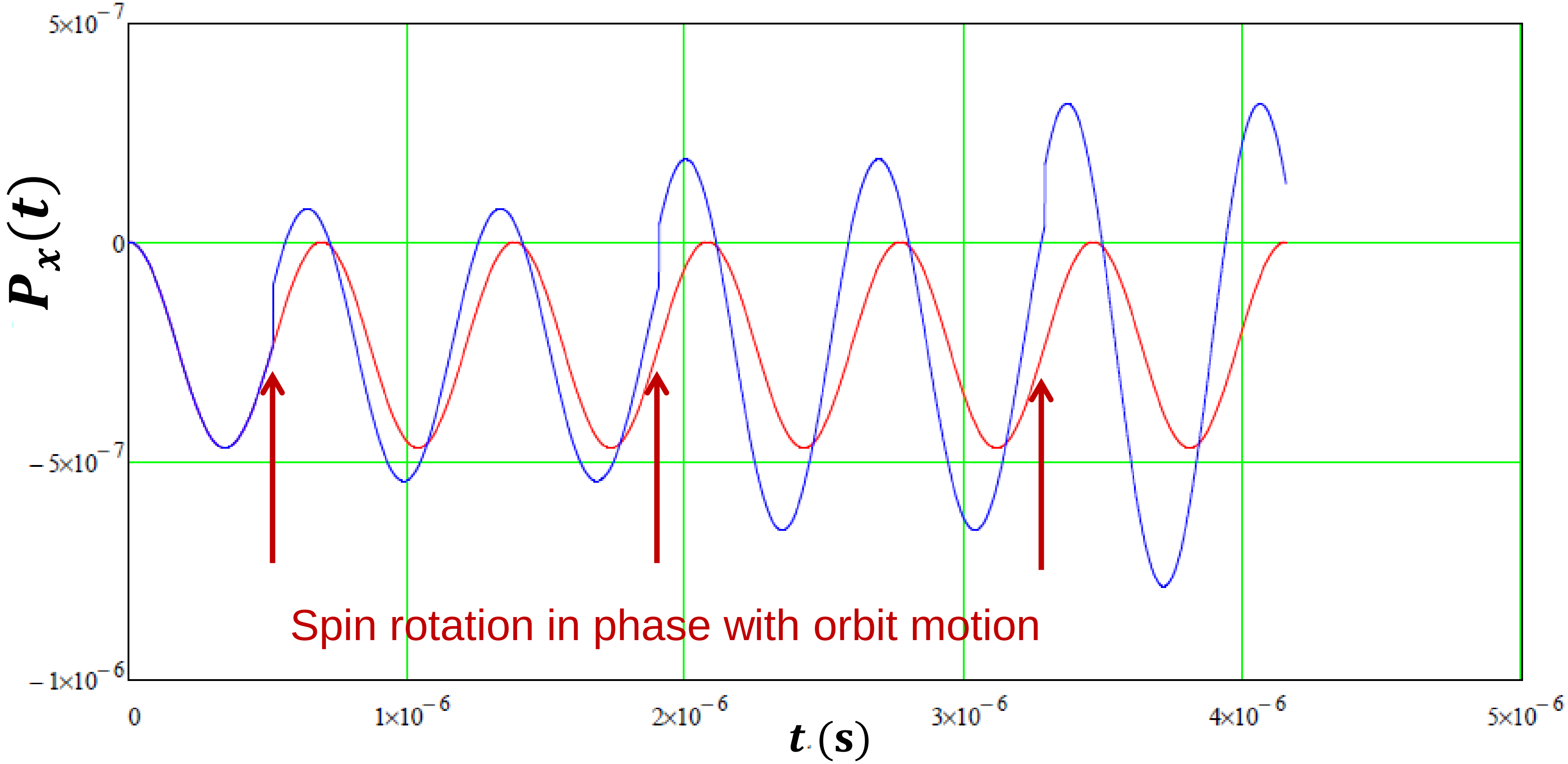
Parameters:	beam energy	$T_d = 50$ MeV	$L_{\mathrm{RF}} = 1$ m
	assumed EDM	$d_d = 10^{-24}$ e·cm	
	E-field	30 kV/cm	



Linear extrapolation of P_y for a time period of $\tau_{sc} = 1000$ s ($= 3.7\cdot10^8$ turns) yields a sizebale $P_y \sim 10^{-3}$.

Precursor experiments:
Resonance EDM measurement with a static Wien filter

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

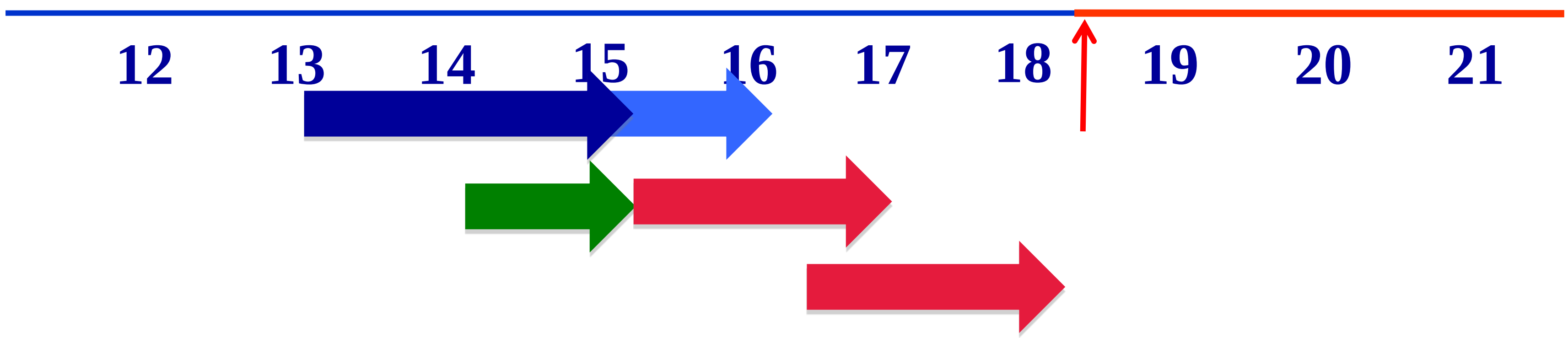


Similar accumulation of EDM signal, systematics more difficult, strength of imperfection resonance must be suppressed by closed-orbit corrections.

Outline

Timeline: BNL EDM

Technically driven for all-electric pEDM



Two years R&D/preparation

One year final ring design

Two years ring/beam-line construction

Two years installation

One year “string test”

Timeline:
Stepwise approach all-in-one machine for JEDI

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**
Steps 3 and 4: > 5 years

Conclusion

- Measurements of EDMs are extremely difficult,
  but fantastic BSM physics reach
- Two storage ring projects, at BNL and Jülich
  - Jülich goes for all-in-one machine with copper-only magnets
- Pursue SCT investigations at COSY
- Very good prospects for first direct EDM measurements of p and d at COSY using resonance methods based on RF E(B) -fields
- New JEDI collaboration established
- Both Collaborations work on technological challenges: Polarimetry, SCT, E-fields, BPMs

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"

Spares

srEDM cooperations

International srEDM Network

Institutional (MoU) and Personal (Spokespersons …) Cooperation, Coordination

srEDM Collaboration (BNL)
(spokesperson Yannis Semertzidis)

JEDI Collaboration (FZJ)
(spokespersons: A. Lehrach, J. Pretz, F.R.)

Common R&D

RHIC
Beam Position Monitors
(…)

EDM-at-COSY
Polarimetry
Spin Coherence Time
Cooling
Spin Tracking (…)

DOE-Proposal (submitted)

CD0, 1, …

pEDM Ring at BNL

Study Group

First direct measurement
Ring Design

HGF Application(s)

JEDI

Magnetic moment, spin, g and G

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

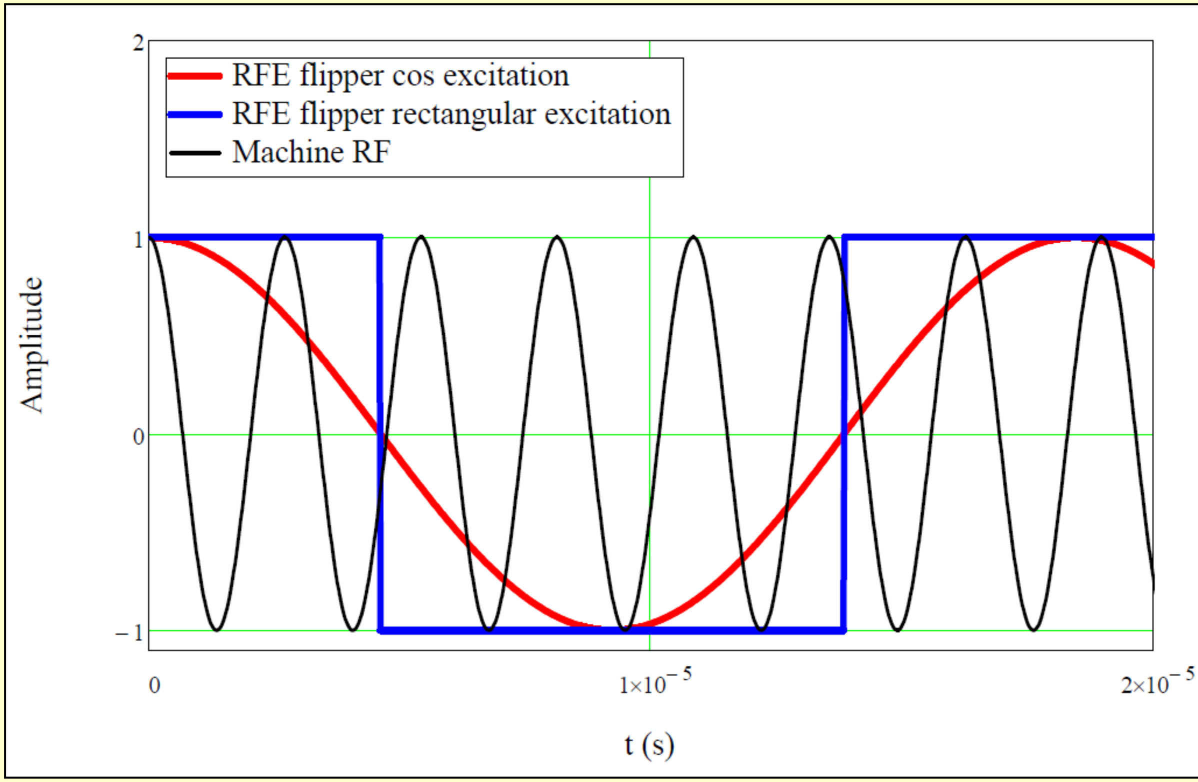
$$\vec{\mu} = g \cdot \mu_N \cdot \frac{m_p}{m} \cdot Z \cdot \vec{s}$$

particle	**spin s**	**charge Z**	g	$G = \frac{g-2}{2}$
proton	$\frac{1}{2}$	1	5.586	1.793
deuteron	1	1	1.714	-0.143
^{3}He	$\frac{1}{2}$	2	-6.368	-4.184

Operation of „magic“ RF Wien filter

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
$T_d = 50\ \text{MeV}$

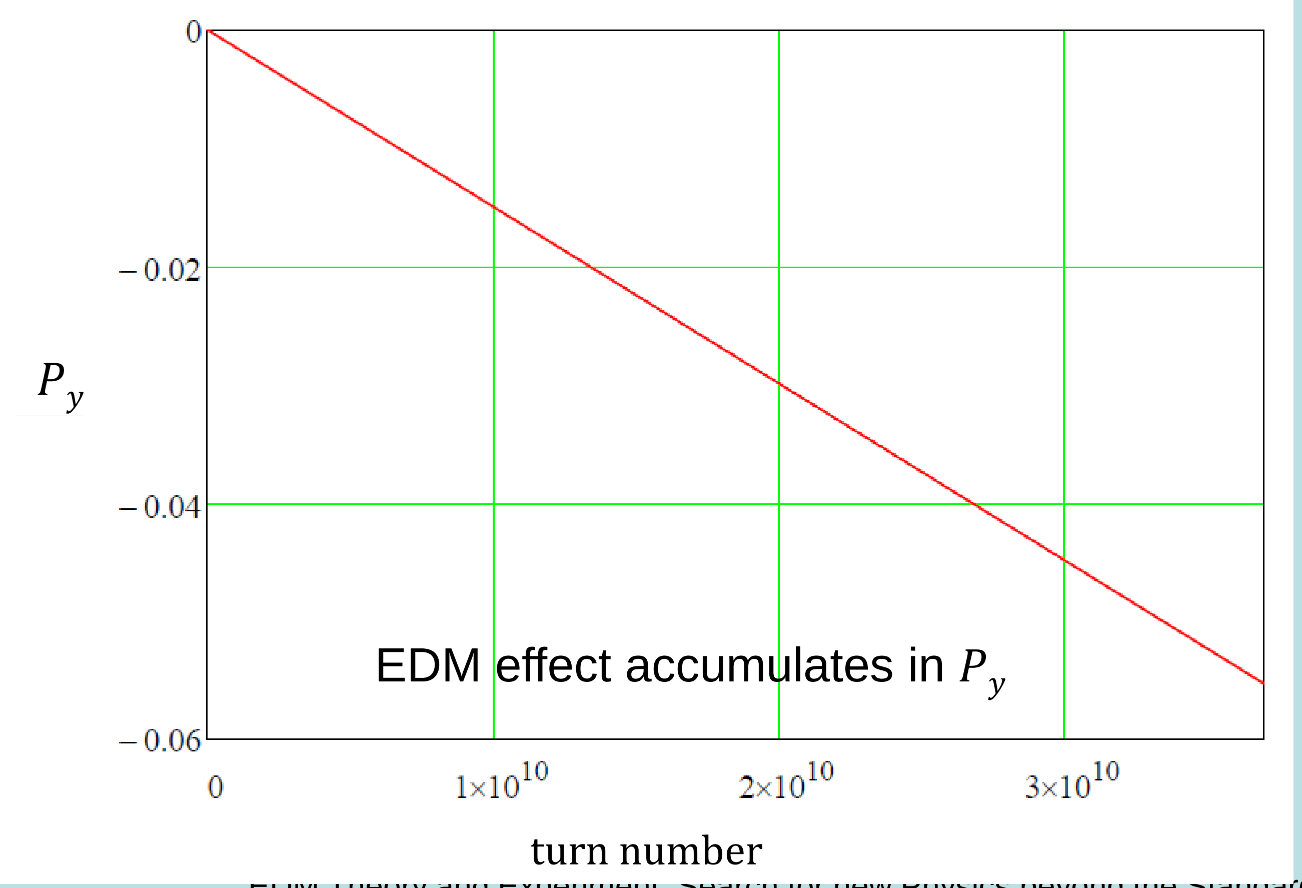


Spin coherence time may depend on excitation and on chosen harmonics K.

Simulation of resonance Method with Magic Wien filter for deuterons at COSY

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

Linear extrapolation of P_y for a time period of $\tau_{sc} = 100000$ s $(= 3.7 \cdot 10^{10}$ turns).



Why also EDMs of protons and deuterons?

Proton and deuteron EDM experiments may provide one order higher sensitivity.

In particular the deuteron may provide a much higher sensitivity than protons.

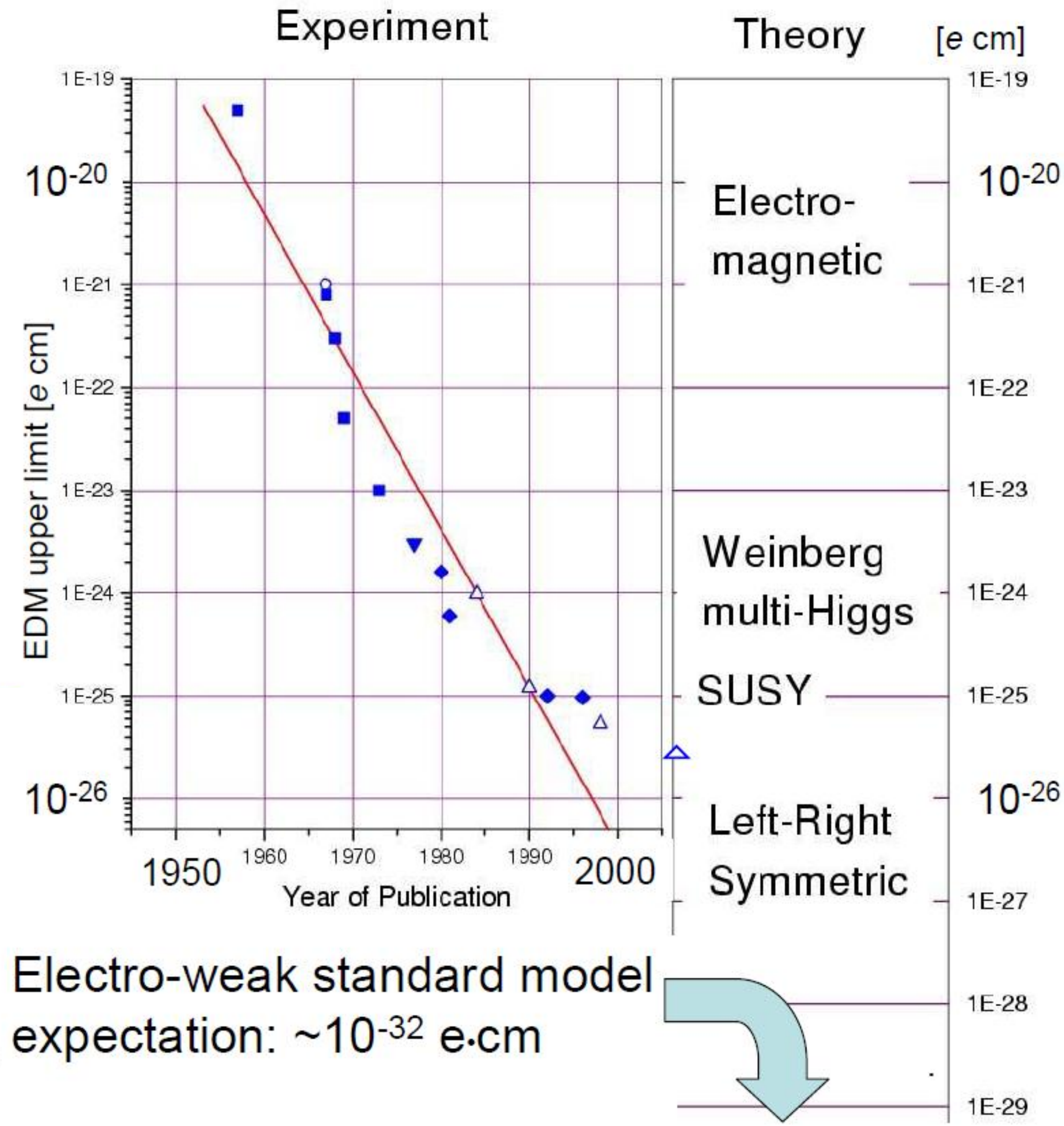
Nuclear EDM:
T,P-odd NN interaction gives 50 times larger contribution than nucleon EDM
Sushkov, Flambaum, Khriplovich 1984

Consensus in the theoretical community:
Essential to perform EDM measurements on different targets $(p, d, 3\mathrm{He})$ with similar sensitivity:

- unfold the underlying physics,
- explain the baryogenesis.

History of neutron EDM limits

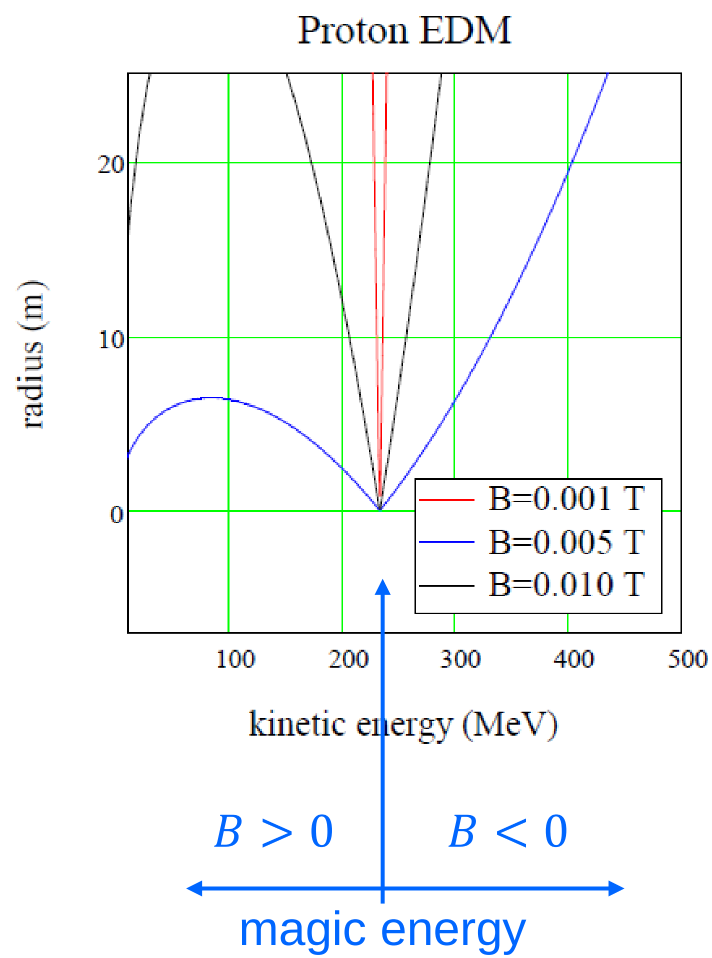
- **Smith, Purcell, Ramsey**
  PR 108, 120 (1957)
- **RAL-Sussex-ILL**
  ($d_n < 2.9 \times 10^{-26}$ e·cm)
  PRL 97,131801 (2006)

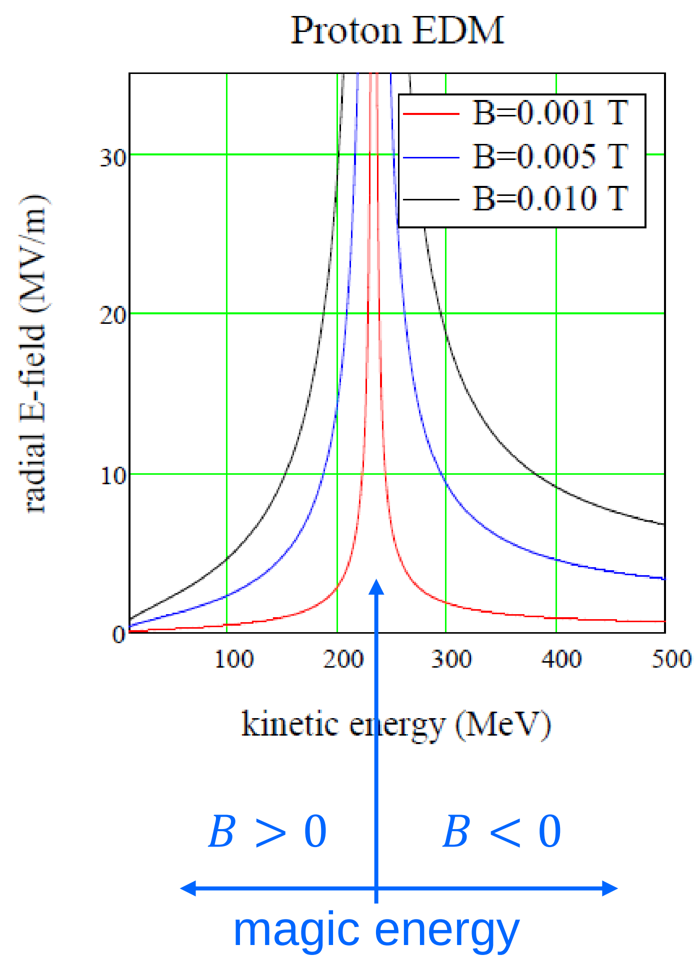


Adopted from K. Kirch

Magic condition: Protons

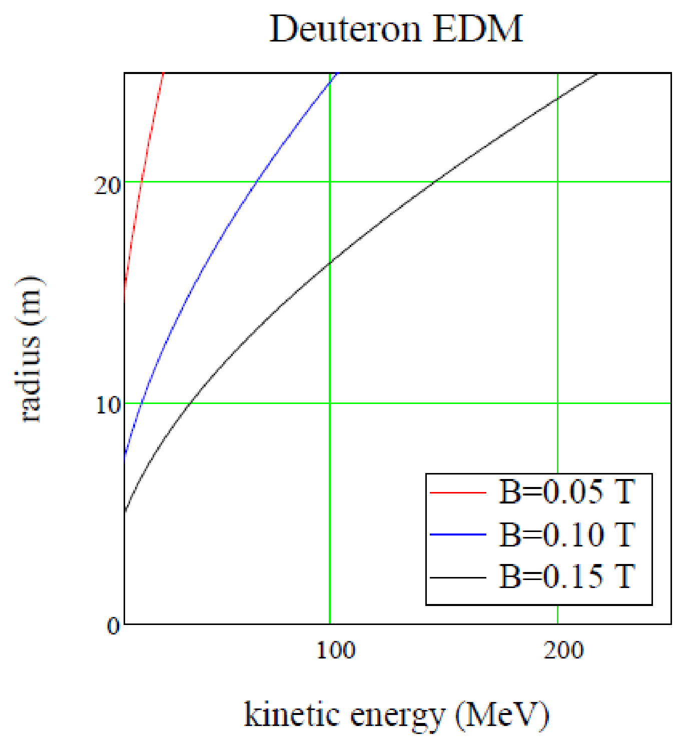
Case 2: radial E and vertical B fields

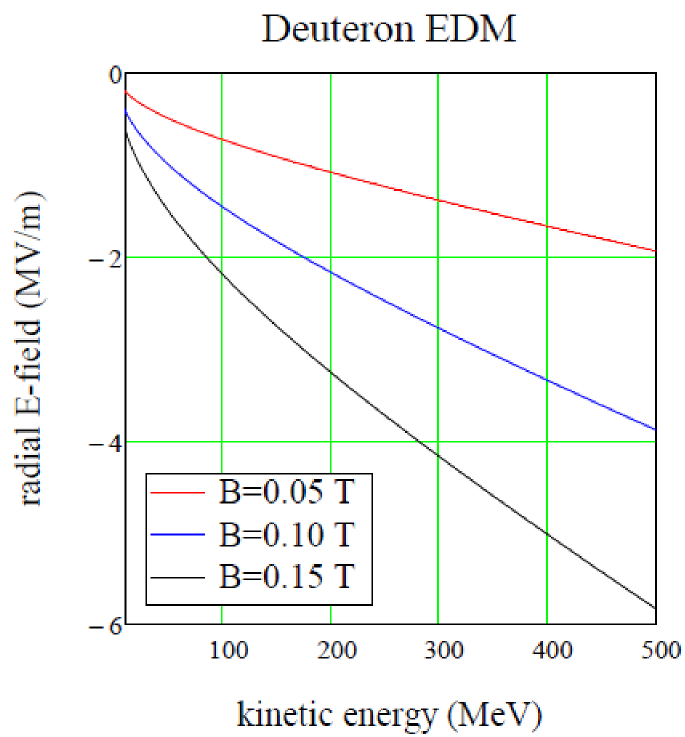




Magic condition: Deuterons

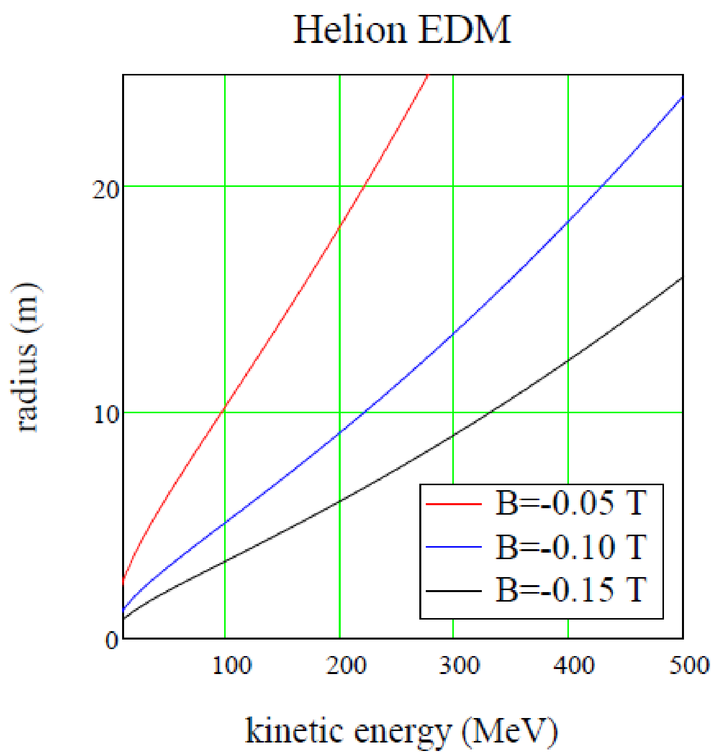
radial *E* and vertical *B* fields

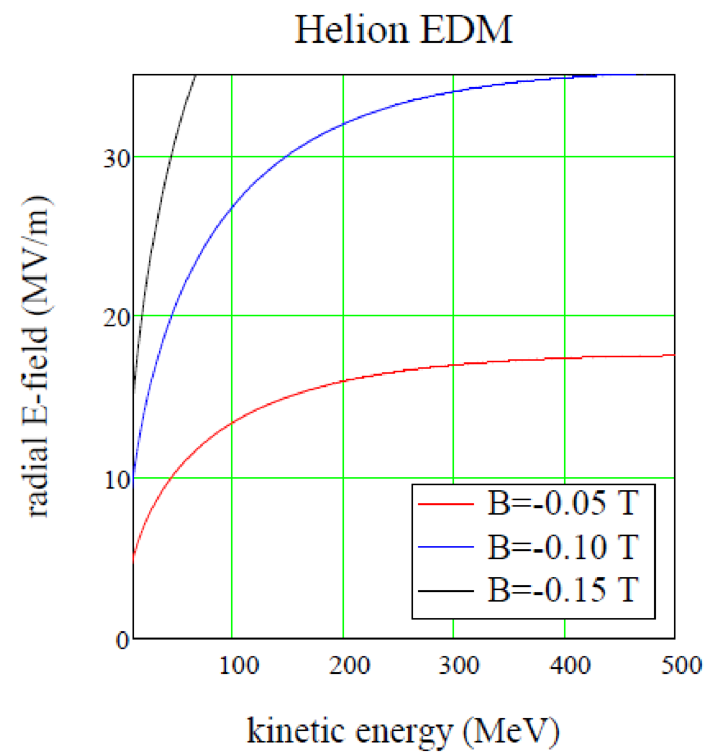




Magic condition: Helions

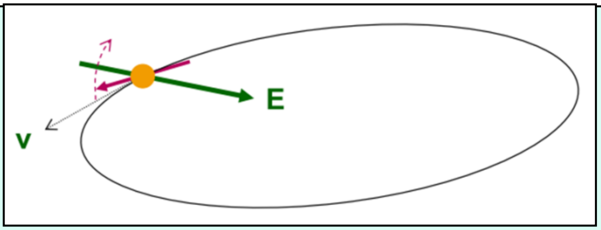
radial *E* and vertical *B* fields





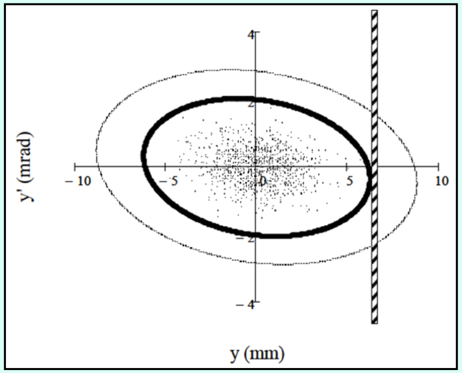
Some polarimetry issues

pC and dC polarimetry is the currently favored approach for the pEDM experiment at BNL



srEDM experiments use frozen spin mode, i.e., beam mostly polarized along direction of motion,

most promising ring options use cw & ccw beams.

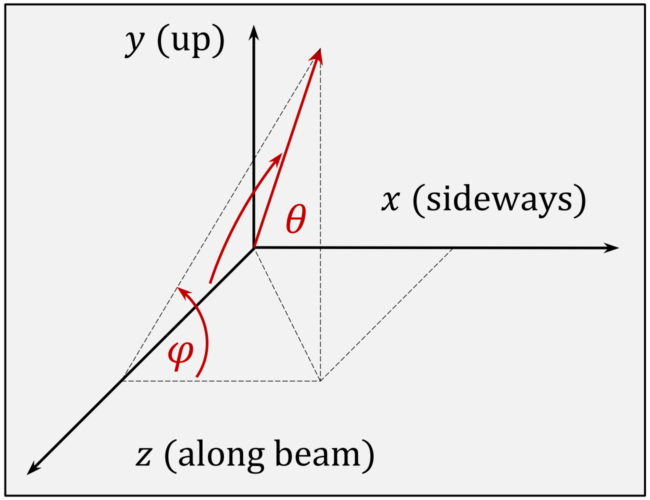


- scattering on C destructive on beam and phase-space,
- scattering on C determines polarization of mainly particles with large betatron amplitudes, and
- is not capable to determine $\vec{P} = \begin{pmatrix} P_x \\ P_y \\ P_z \end{pmatrix}$.
- For elastic scattering longitudinal analyzing powers are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

Ideally, use a method that would determine $\vec{P}(t)$.

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

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

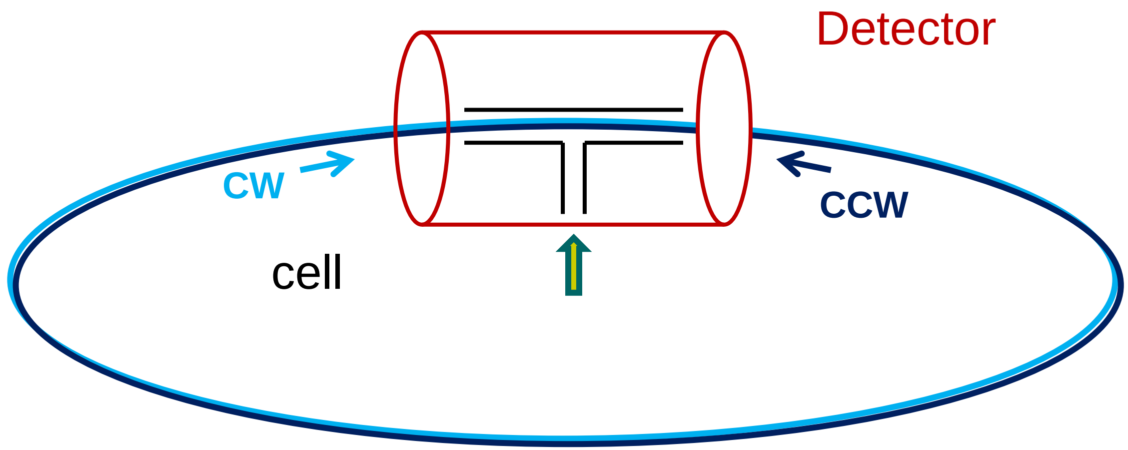
$$\begin{aligned}\frac{\sigma}{\sigma_0} = 1 &+ A_y\left[\left(P_y + Q_y\right)\cos\varphi - (P_x + Q_x)\sin\varphi\right] \\ &+ A_{xx}\left[P_x Q_x \cos^2\varphi + P_y Q_y \sin^2\varphi + \left(P_x Q_y + P_y Q_x\right)\sin\varphi\cos\varphi\right] \\ &+ A_{yy}\left[P_x Q_x \sin^2\varphi + P_y Q_y \cos^2\varphi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

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

In pp scattering, necessary observables are well-known in the range $50 - 2000$ MeV (not so for pd or dd).

How could one do that, determine $\vec{P}$?

Suggestion 1: Use a polarized $\vec{\mathrm{H}}$ storage cell target

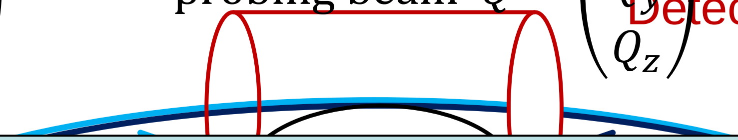


- Detector determines $\vec{P}$ of cw & ccw beams separately, based on kinematics.
- Alignment of target polarization $\vec{Q}$ along x, y, z axes by *magnetic* fields. Leads to unwanted MDM rotations $\rightarrow$ absolute no-go in EDM experiments.

How could one do that, determine $\vec{P}$?

Suggestion 2: Use colliding beam from external source

$$\text{cw beam } \vec{P} = \begin{pmatrix} P_x \\ P_y \\ P_z \end{pmatrix} \qquad \text{probing beam } \vec{Q} = \begin{pmatrix} Q_x \\ Q_y \\ Q_z \end{pmatrix} = \begin{pmatrix} Q_x \\ 0 \\ 0 \end{pmatrix}, \begin{pmatrix} 0 \\ Q_y \\ 0 \end{pmatrix}, \text{or} \begin{pmatrix} 0 \\ 0 \\ Q_z \end{pmatrix}$$



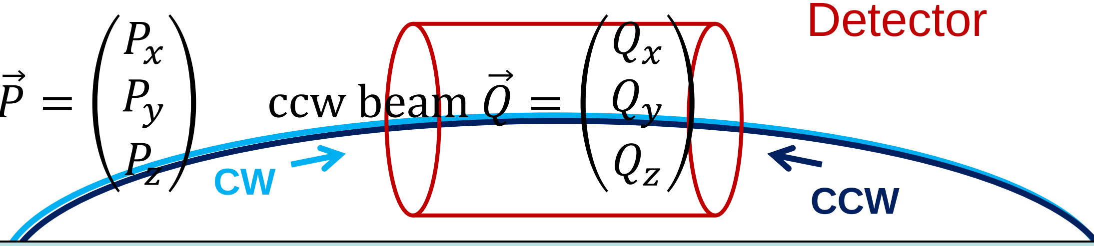
$$\begin{aligned}\frac{\sigma}{\sigma_0} = 1 &+ A_y\left[\left(P_y + \boldsymbol{Q_y}\right)\cos\varphi - \left(P_x + \boldsymbol{Q_x}\right)\sin\varphi\right] \\ &+ A_{xx}\left[P_x\boldsymbol{Q_x}\cos^2\varphi + P_y\boldsymbol{Q_y}\sin^2\varphi + \left(P_x\boldsymbol{Q_y} + P_y\boldsymbol{Q_x}\right)\sin\varphi\cos\varphi\right]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

- Collide two external beams with cw and ccw stored beams.
- Energy could be tuned to match detector acceptance.
- Polarization components of probing low-energy beam can be made **large**, would be selected by spin rotators in the transmission lines.
- Luminosity estimates necessary

How could one do that, determine $\vec{P}$?

Suggestion 3: Use directly reactions from colliding beams

cw beam $\vec{P} = \begin{pmatrix} P_x \\ P_y \\ P_z \end{pmatrix}$ ccw beam $\vec{Q} = \begin{pmatrix} Q_x \\ Q_y \\ Q_z \end{pmatrix}$



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

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

- Advantage over suggestion 2. is that f_{rev} supports luminosity.
- Disadvantage is that sensitivity comes mainly from terms with A_{xz} and A_{zz}.
- Detailed estimates necessary.

Luminosity estimate for the collider option

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

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

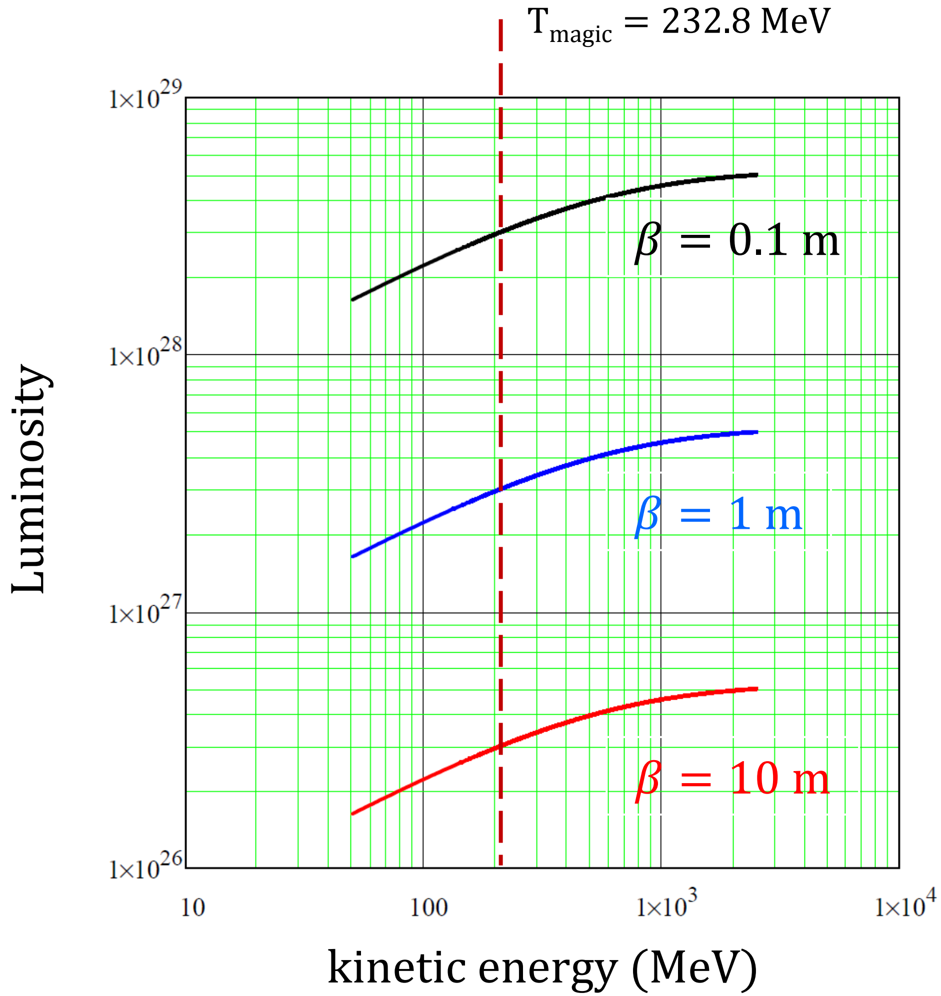
Conditions:

$\varepsilon = 1\ \mu\mathrm{m}$

$N_1 = N_2 = 10^{11}$

$n_b = 4$

β (m)	**σ (mm)**
10	3.2
1	1
0.1	0.32



Even under these very optimistic assumptions, event rate will be rather low.

Rate $= \boldsymbol{L} \times \sigma_{pp}$

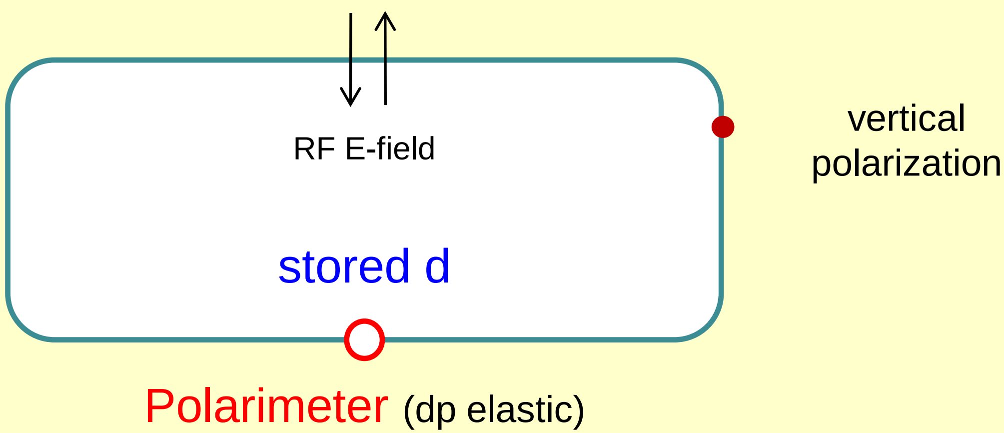
$$= 3.1 \cdot 10^{28}[\mathrm{cm}^{-2}\mathrm{s}^{-1}] \times 10^{-27}[\mathrm{cm}^2\mathrm{mb}^{-1}] \times 15[\mathrm{mb}] \approx \mathbf{466\ s^{-1}}$$

Resonance Method with RF E-fields

spin precession governed by: $$\frac{d\vec{S}}{dt^*} = \vec{d} \times \vec{E}^* + \vec{\mu} \times \vec{B}^*$$ (* rest frame)

Two situations:

1. $B^* = 0 \Rightarrow B_y = \beta \times E_R$ ($= 70$ G for $E_R = 30$ kV/cm) EDM effect
2. $E^* = 0 \Rightarrow E_R = -\beta \times B_y$ no EDM effect



P_y *drops*

$\sqrt{P_x^2 + P_z^2}$ *grows*

This way, the EDM signal is **accumulated** during the cycle.

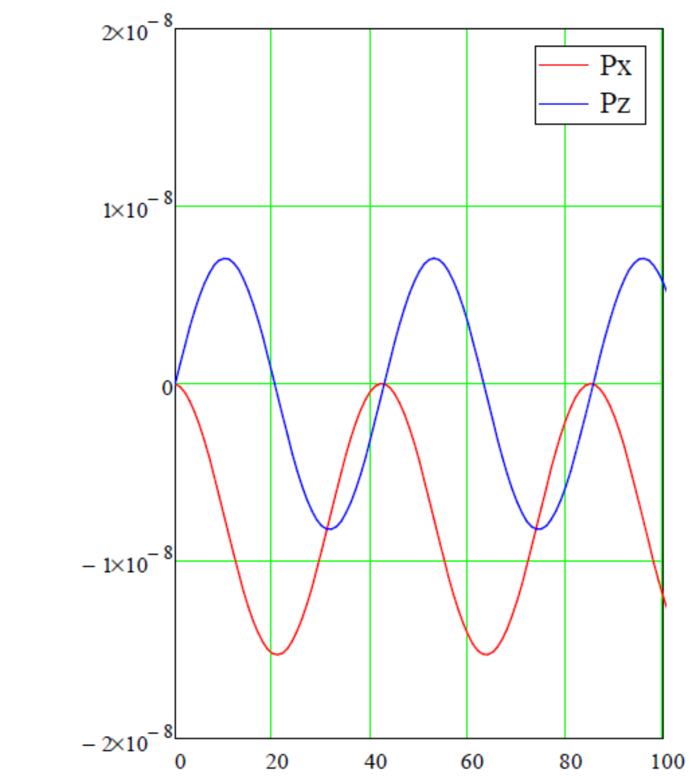
- Statistical improvement over single turn effect is about: $\sqrt{1000s/1\mu s} \approx 10^5$.
- Brings us in the 10^{-24} e·cm range for d_d.

- But: Flipping fields will lead to coherent betatron oscillations, with hard to handle systematics.

Simulation of resonance Method with RF E-fields for deuterons at COSY

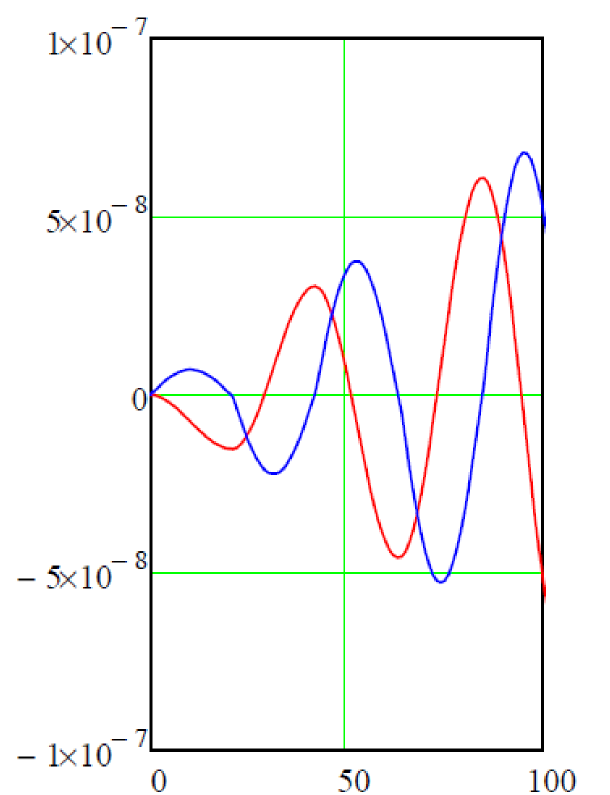
Parameters:	beam energy	$T_d = 50$ MeV	$L_{\mathrm{RF}} = 1$ m
	assumed EDM	$d_d = 10^{-20}$ e·cm	
	E-field	10 kV/cm	

Constant E-field



Number of turns

E-field reversed every $-\pi/(G\cdot\gamma) \approx 21$ turns

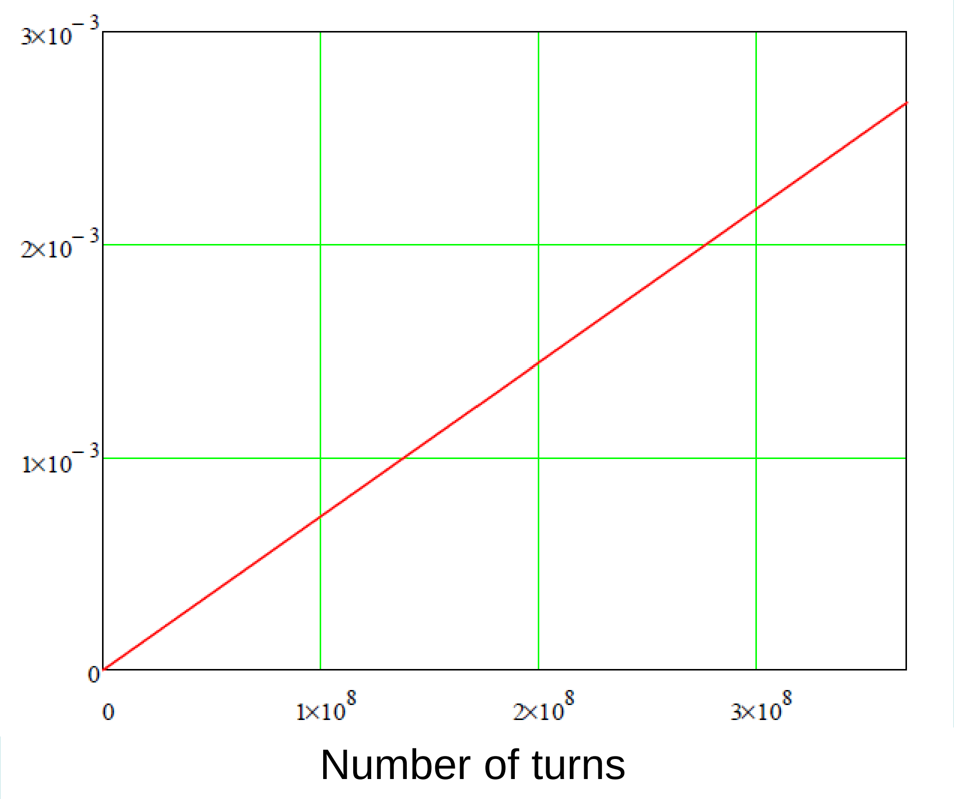


Number of turns

Simulation of resonance Method with RF E-fields for deuterons at COSY

Parameters:	beam energy	$T_d = 50\ \mathrm{MeV}$
	assumed EDM	$d_d = 10^{-20}\ \mathrm{e\cdot cm}$
	E-field	$10\ \mathrm{kV/cm}$

Linear extrapolation of $P = \sqrt{P_x^2 + P_z^2}$ for a time period of $\tau_{sc} = 1000\ \mathrm{s}\ (= 3.7\cdot 10^8\ \mathrm{turns})$



EDM effect accumulates

Polarimeter determines
P_x, P_y and P_z

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):

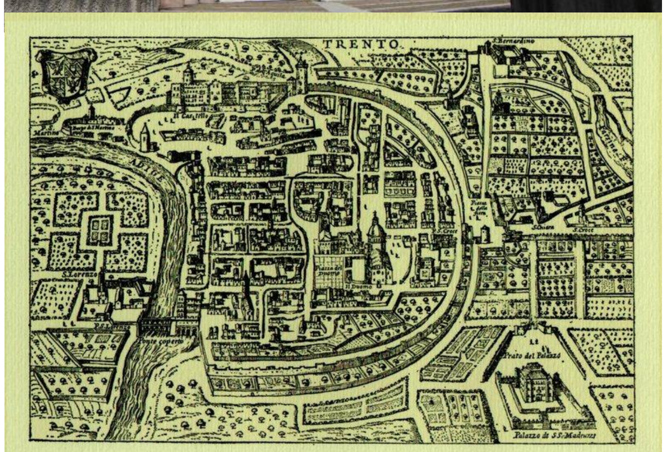
Changes sign of all quantized charges

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

EDM Workshop at ECT* (Trento)

October 1-5, 2012

http://www.ectstar.eu/



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