Mitglied der Helmholtz-Gemeinschaft

ICFP 2012

JÜLICH FORSCHUNGSZENTRUM

Search for permanent Electric Dipole Moments of light ions (p, d, 3He) in storage rings

June 14, 2012

Frank Rathmann

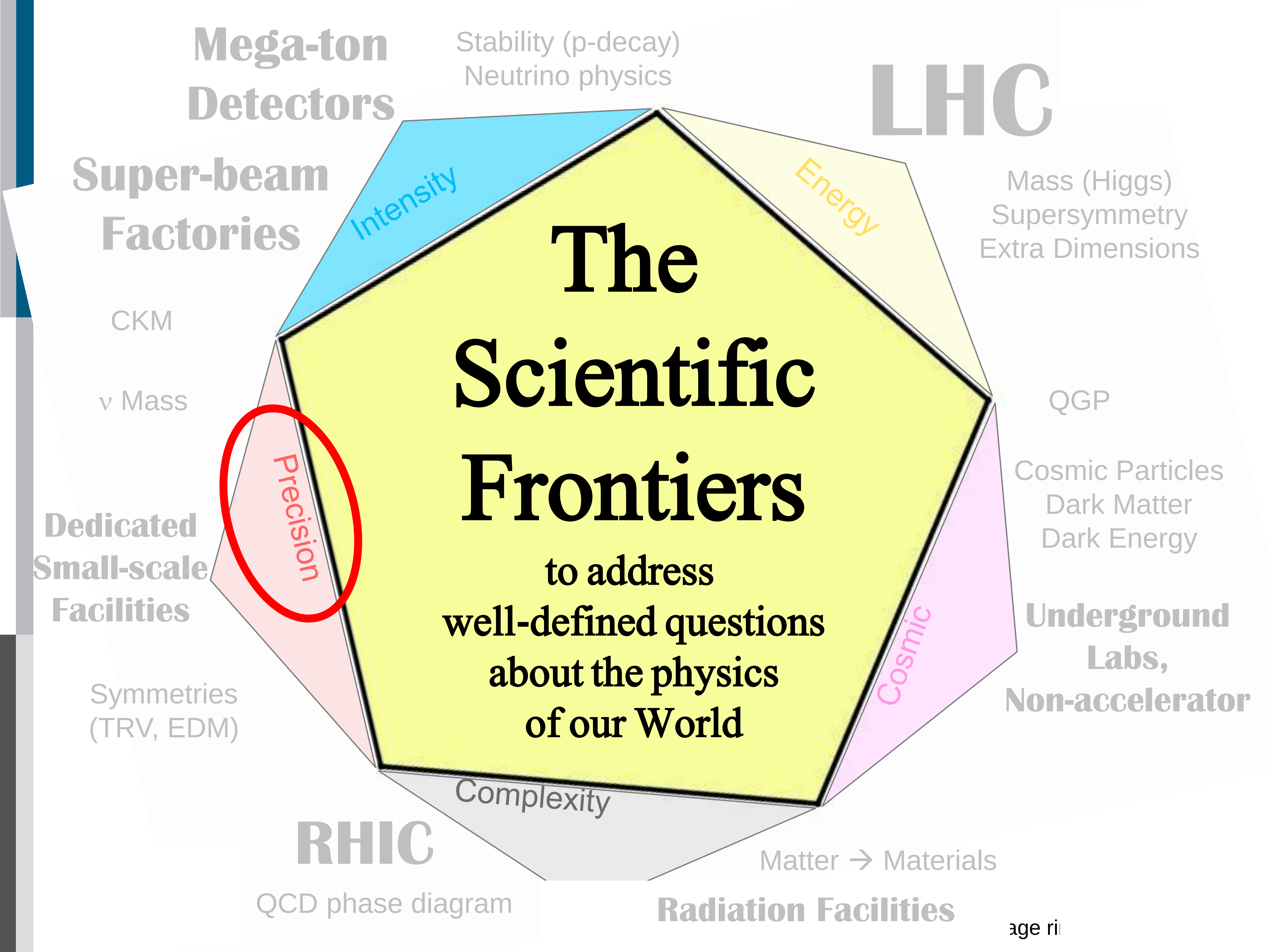
On behalf of the JEDI collaboration

International Conference on New Frontiers in Physics
10-16 June 2012

Topics

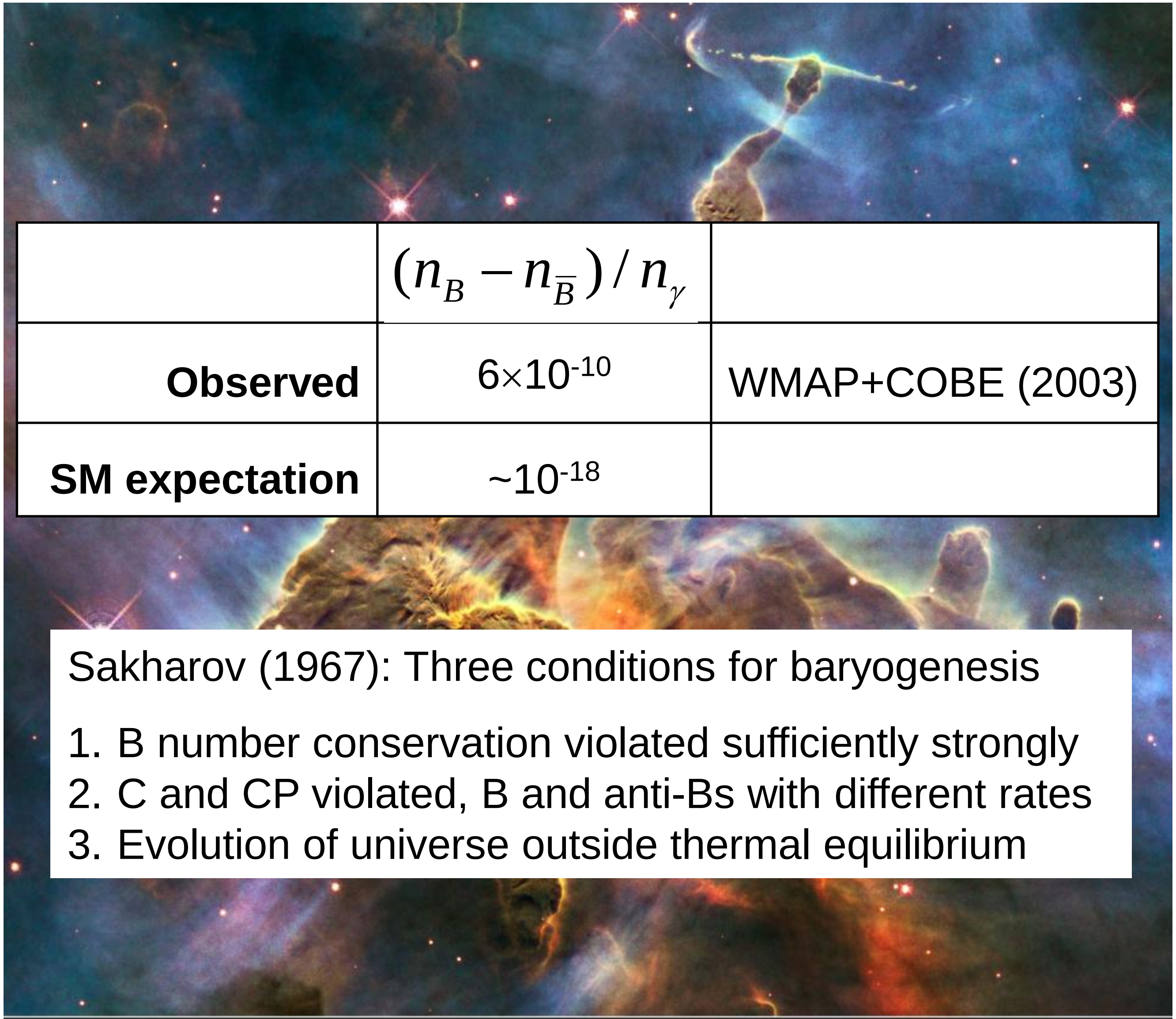
- Why EDMs?
- Search for EDMs using storage rings
- Two projects, at BNL and Jülich
- Spin coherence time
- First direct measurement

  Resonance Method with RF E(B) -fields
- Summary


Mega-ton Detectors
Stability (p-decay)
Neutrino physics
LHC
Super-beam Factories
Intensity
Energy
Mass (Higgs)
Supersymmetry
Extra Dimensions
The Scientific Frontiers
to address
well-defined questions
about the physics
of our World
CKM
ν Mass
QGP
Precision
Cosmic Particles
Dark Matter
Dark Energy
Dedicated Small-scale Facilities
Underground Labs, Non-accelerator
Cosmic
Symmetries
(TRV, EDM)
Complexity
RHIC
QCD phase diagram
Matter → Materials
Radiation Facilities

What caused the Baryon asymmetry?

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

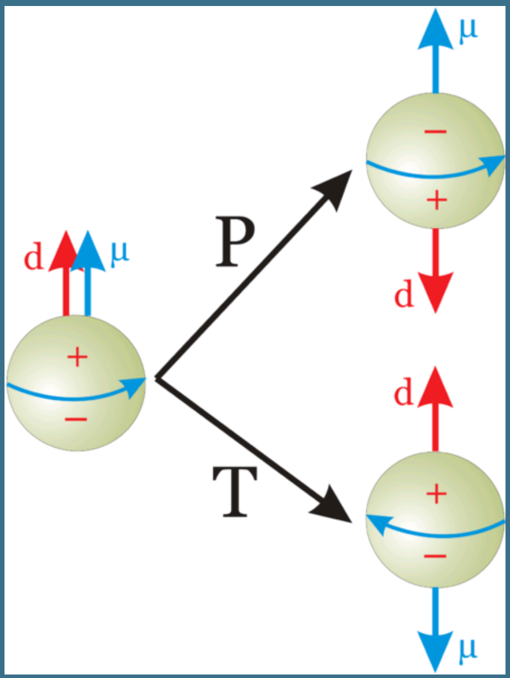


	$(n_B - n_{\overline{B}})/n_\gamma$	
Observed	6×10^{-10}	WMAP+COBE (2003)
SM expectation	$\sim10^{-18}$	

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

Electric Dipole Moments (EDMs)



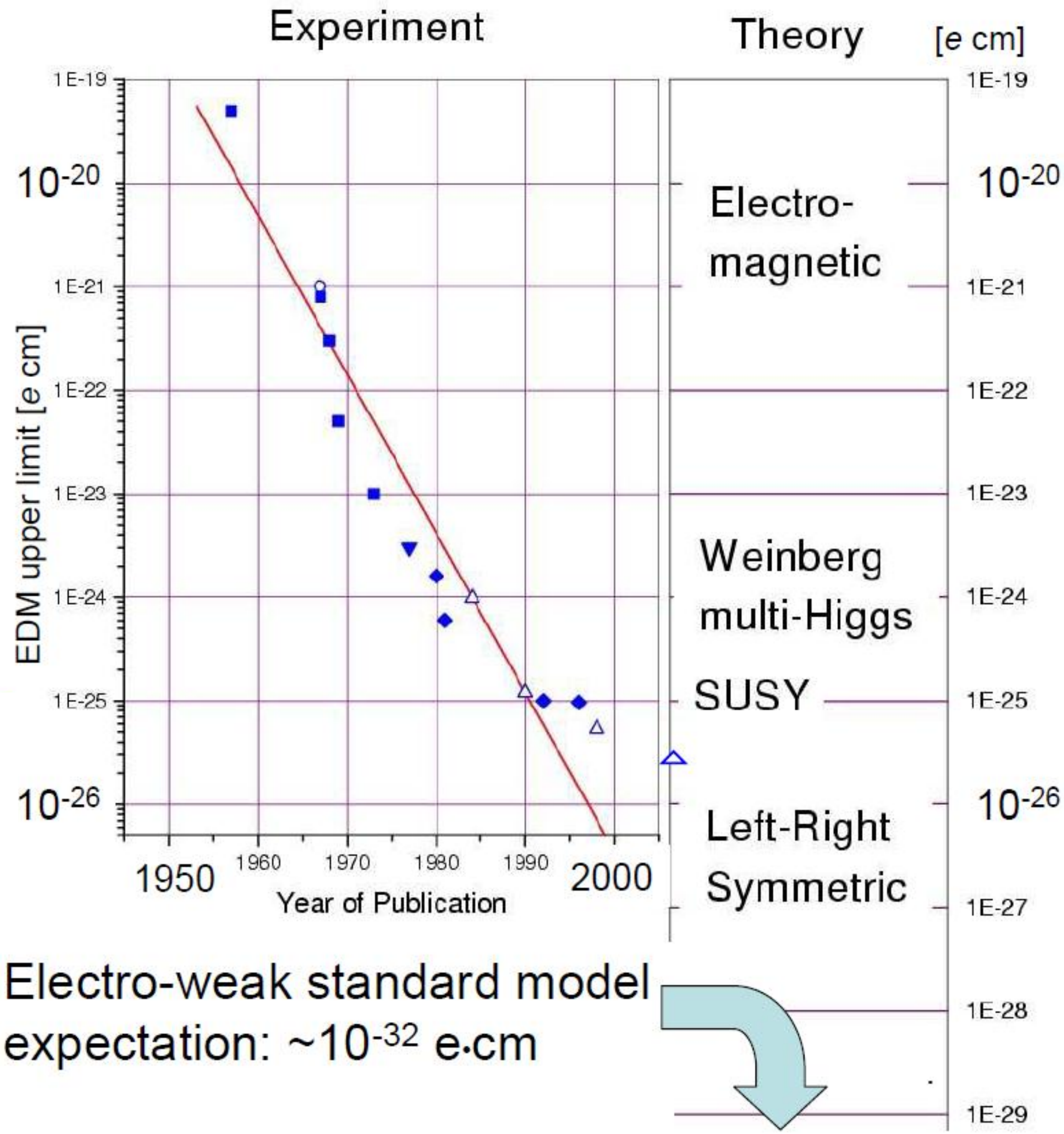
Permanent EDMs violate parity **P** and time reversal symmetry **T**

Assuming **CPT** to hold, combined symmetry **CP violated** as well.

EDMs are candidates to solve mystery of matter-antimatter asymmetry
→ may explain why we are here!

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)



Electro-weak standard model expectation: ~10^{-32} e·cm

Adopted from K. Kirch

Limits for Electric Dipole Moments

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

Particle/Atom	Current EDM Limit	Future Goal	~ d_n equivalent
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	?	$\sim 10^{-29}$	$3 \times 10^{-29} - 5 \times 10^{-33}$

Huge efforts underway to improve limits / find EDMs

Sensitivity to **NEW PHYSICS** beyond the Standard Model

485. WE-Heraeus-Seminar (July 04–06, 2011)
Search for Electric Dipole Moments (EDMs) at Storage Rings
http://www2.fz-juelich.de/ikp/edm/en/

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.

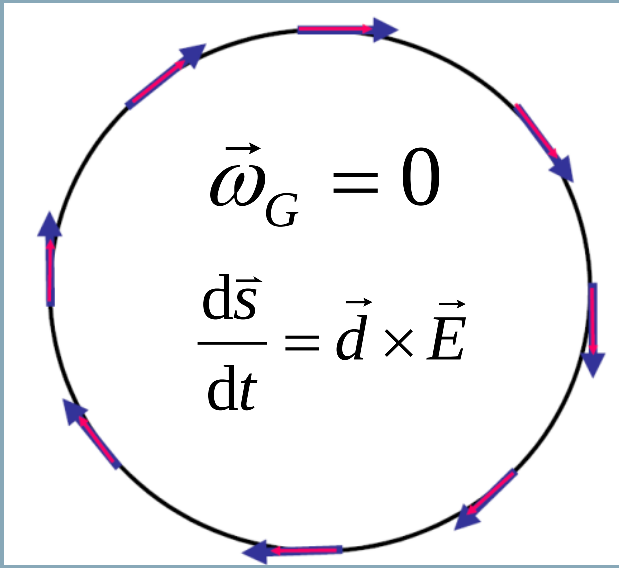
Nuclear EDM:
T,P-odd NN interaction gives 50 times larger contribution than nucleon EDM
Sushkov, Flambaum, Khriplovich
1984

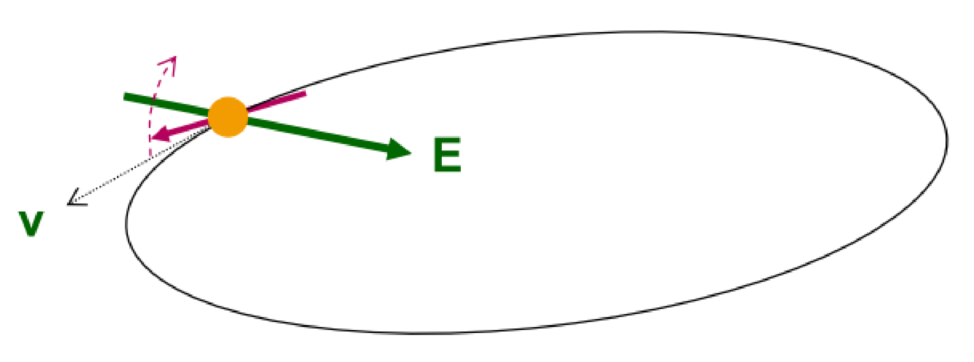
Consensus in the theoretical community:
Essential to perform EDM measurements on different targets (p, d, ^{3}He) with similar sensitivity:

- unfold the underlying physics,
- explain the baryogenesis.

Search for Electric Dipole Moments

NEW: **EDM search in time development of spin in a storage ring:**





"Freeze" horizontal spin precession; watch for development of a vertical component !

The 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

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

Magic condition: Spin along momentum vector

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

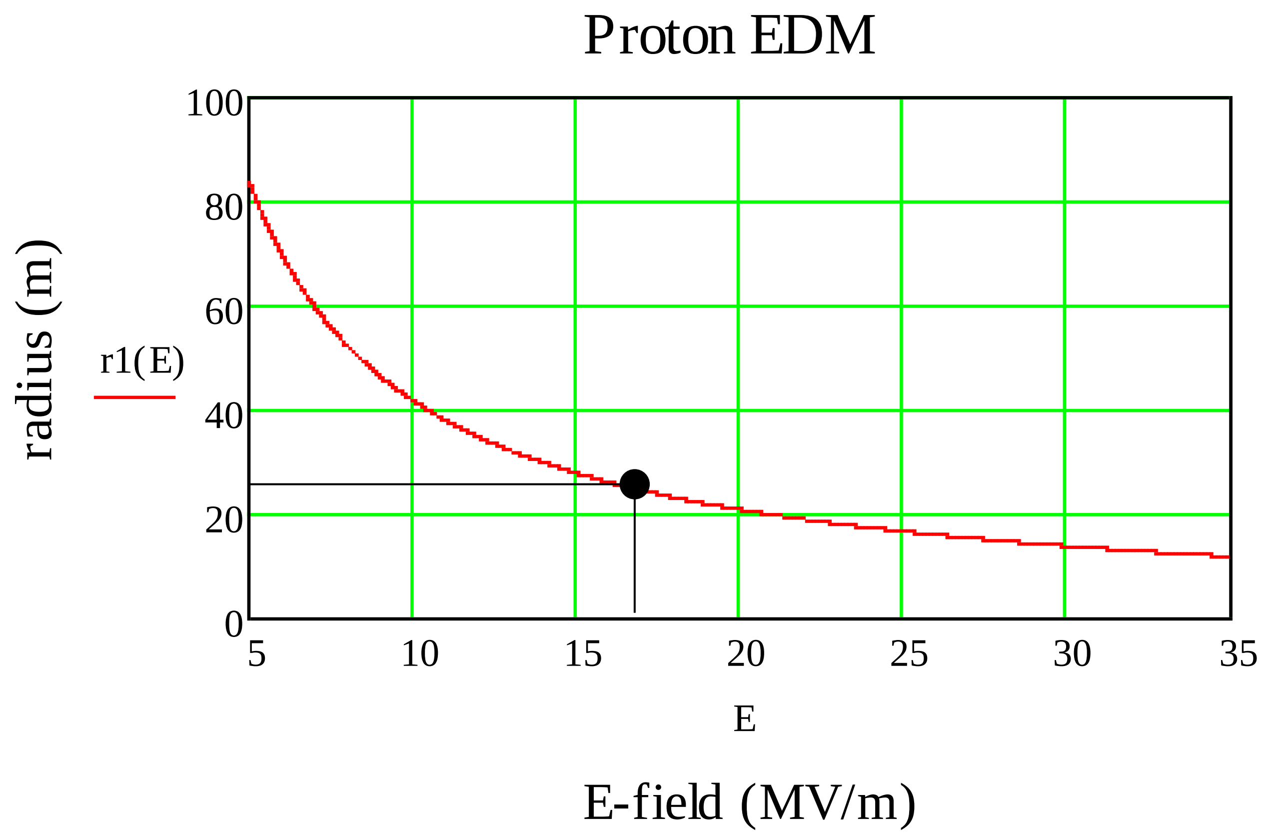
$$E = \frac{GBc\beta\gamma^2}{1 - G\beta^2\gamma^2} \approx GBc\beta\gamma^2$$

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

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

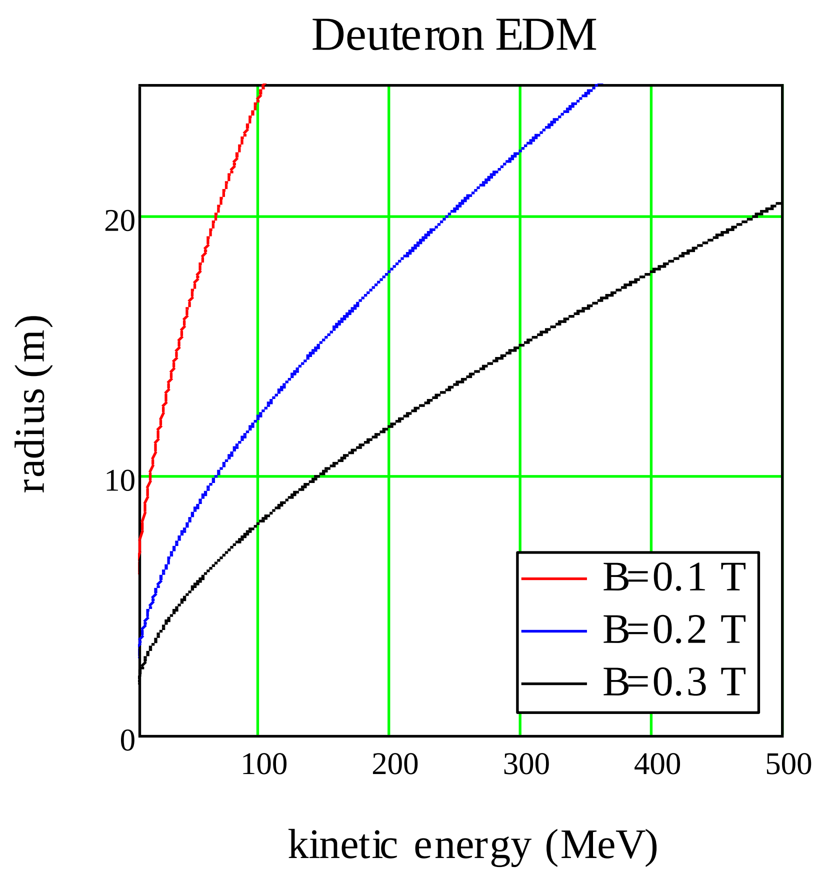
Magic condition: Protons

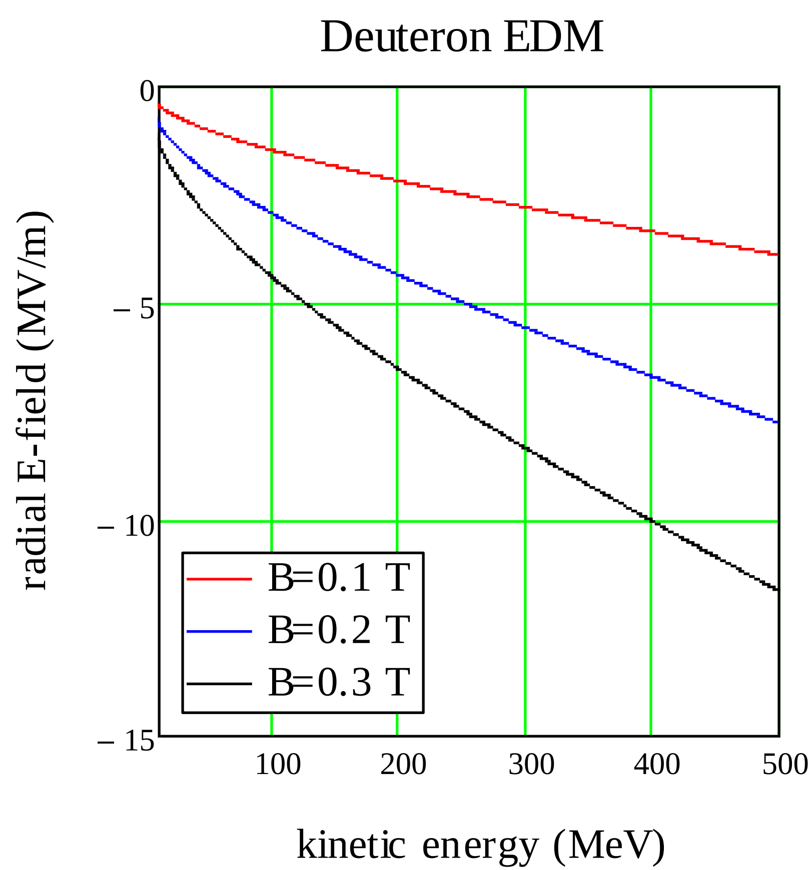
E-field only



Magic condition: Deuterons

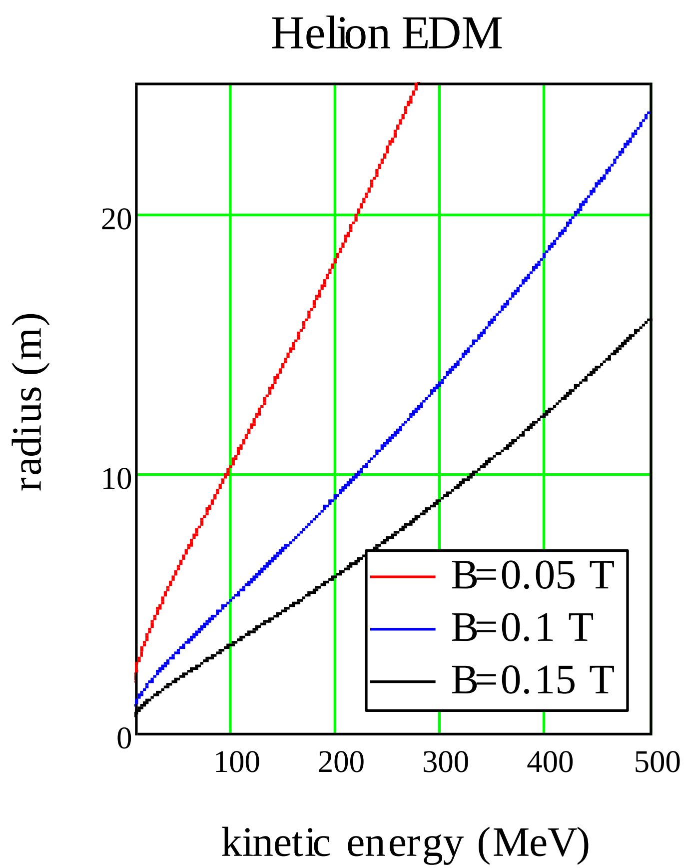
E and B fields

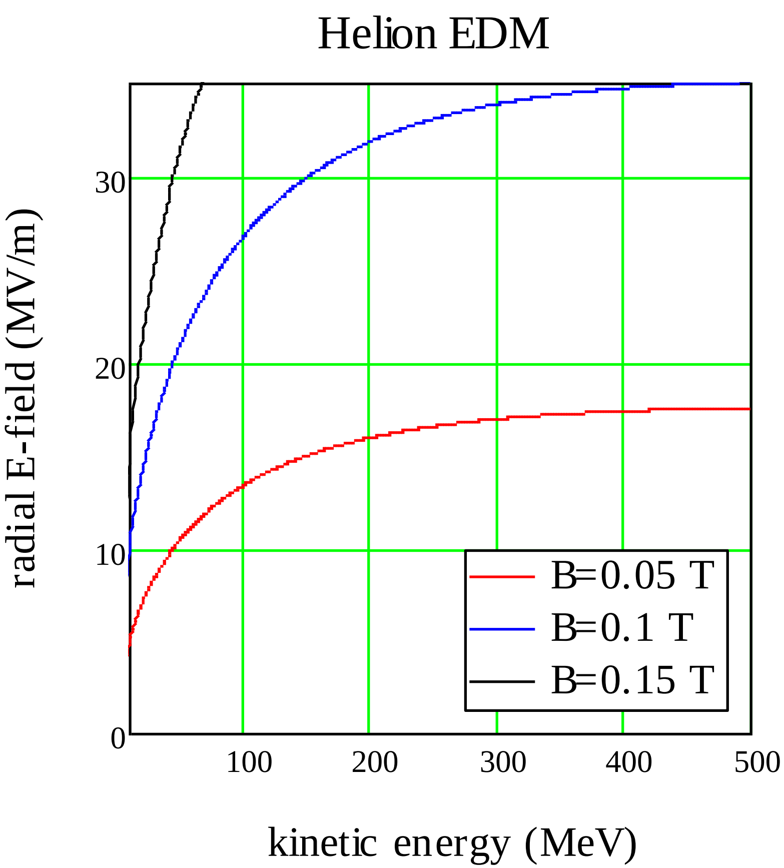




Magic condition: Helions

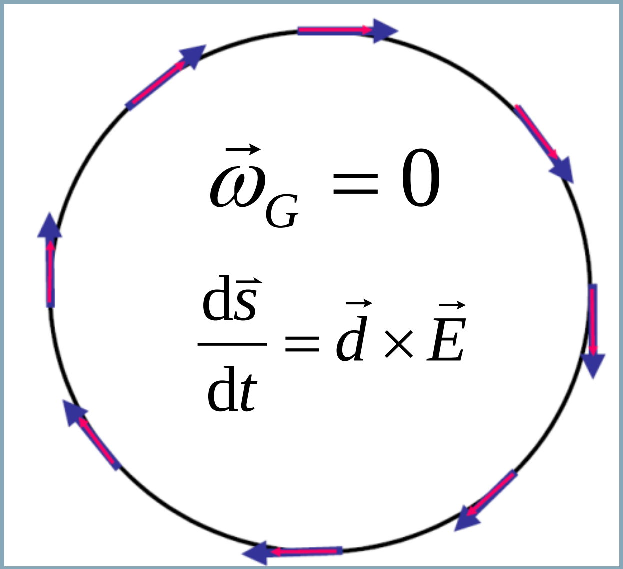
E and B fields





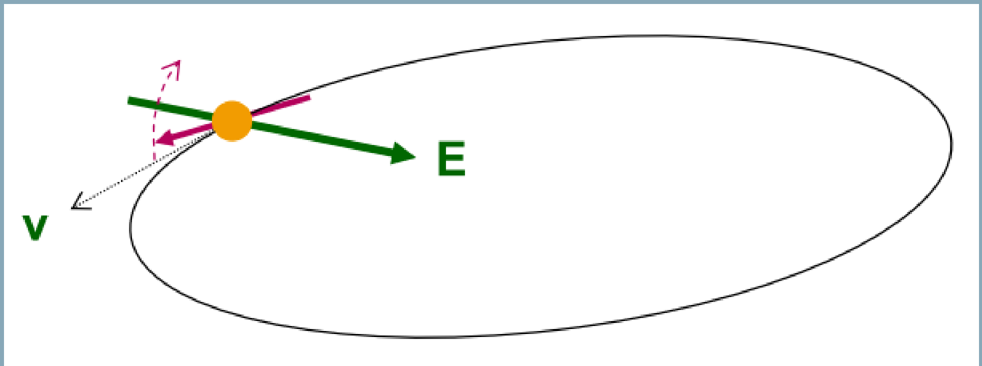
Search for Electric Dipole Moments

NEW: EDM search in time development of spin in a storage ring:



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

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \vec{d} \times \vec{E}$$



"Freeze" horizontal spin precession; watch for development of a vertical component !

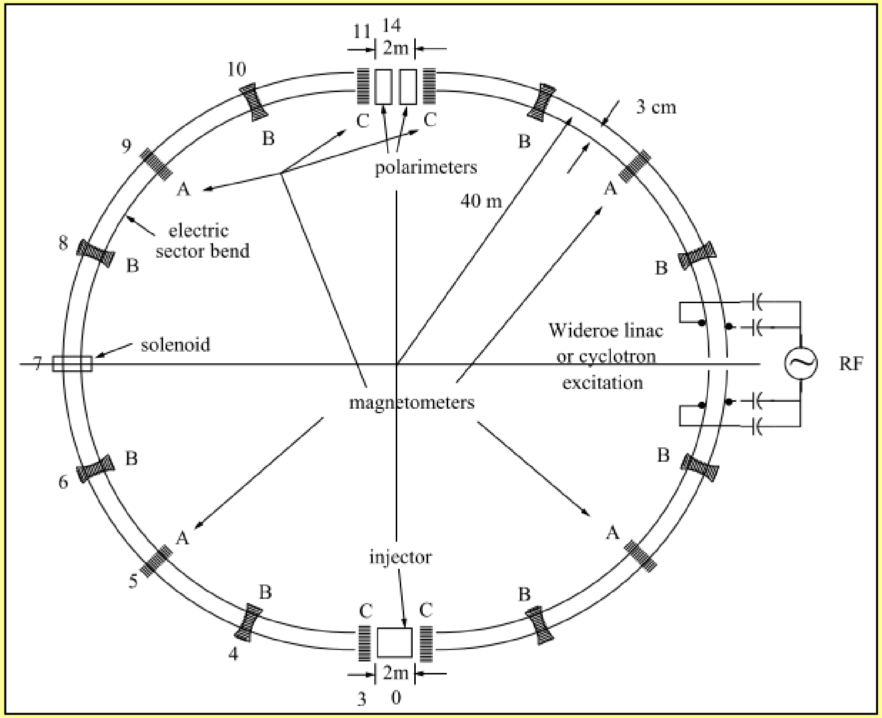
A *magic* storage ring for protons (electrostatic), deuterons, …

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

One machine with r ~ 30 m

Two storage ring projects being pursued

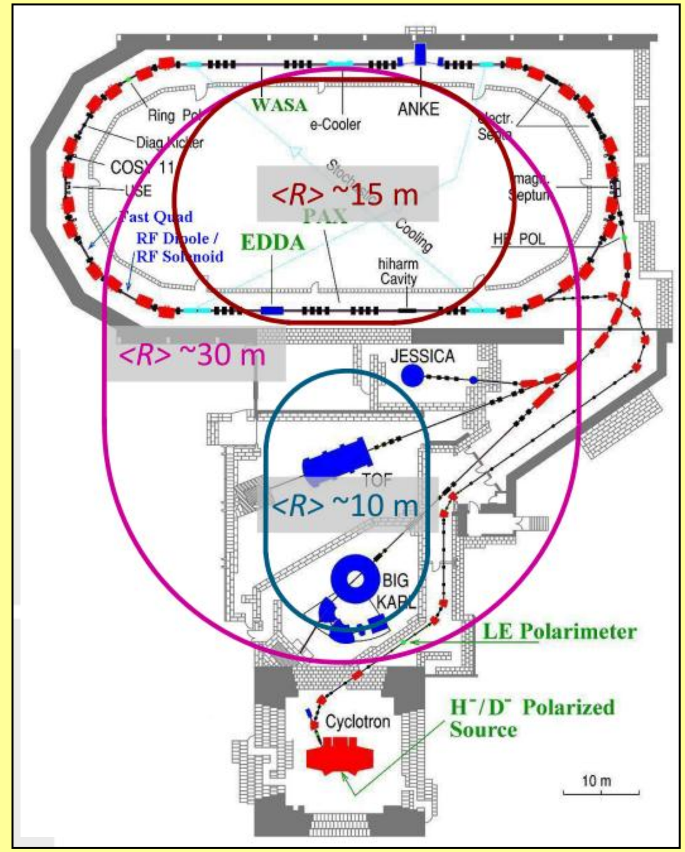
BNL for protons all electric machine



CW and CCW propagating beams

(from R. Talman)

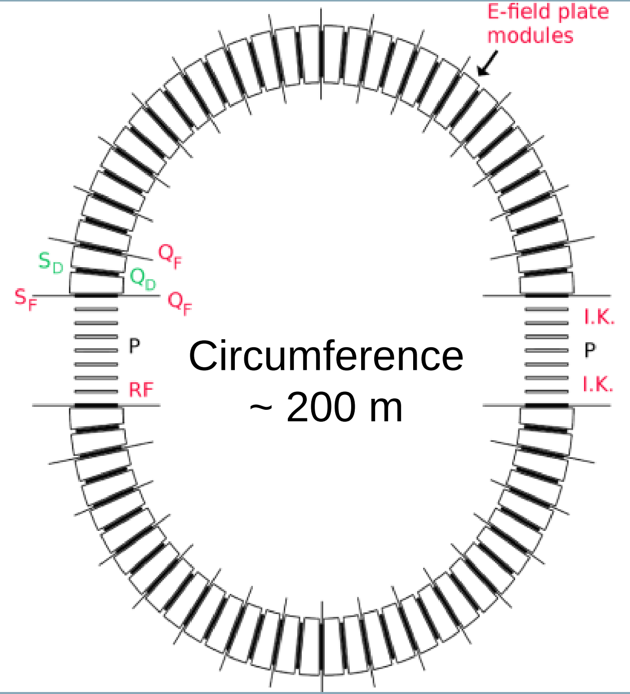
Jülich, focus on deuterons, or a combined machine



(from A. Lehrach)

BNL Proposal

2 beams simultaneously rotating in a ring (CW, CCW)



Approved BNL-Proposal
Submitted to DOE
Goal for protons

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

Technological challenges !

- **Spin coherence time (1000 s)**
- **Beam positioning (10 nm)**
- **Continuous polarimetry (< 1ppm)**
- **E - field gradients (~ 17MV/m at 2 cm)**

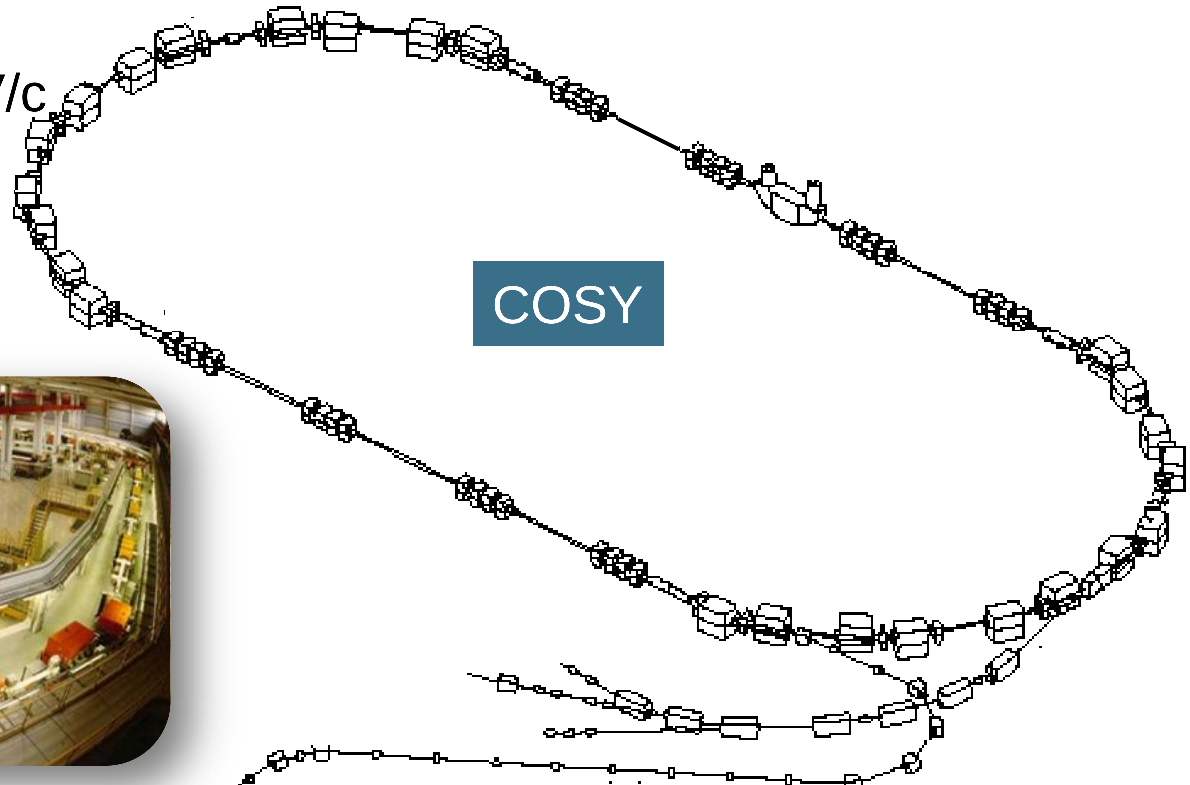
Carry out proof of principle experiments (demonstrators) at COSY

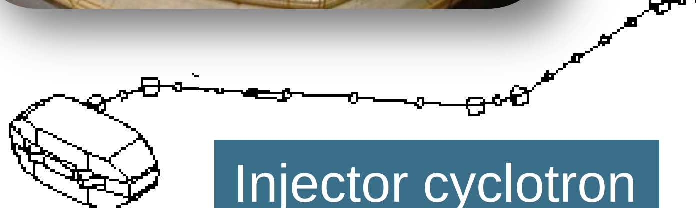
EDM at COSY – COoler SYnchrotron

Cooler and storage ring for (polarized) protons and deuterons

p = 0.3 – 3.7 GeV/c

Phase space cooled internal & extracted beams





… *the* spin-physics machine for hadron physics

EDM at COSY – COoler SYnchrotron

Cooler and storage ring for (polarized) protons and deuterons

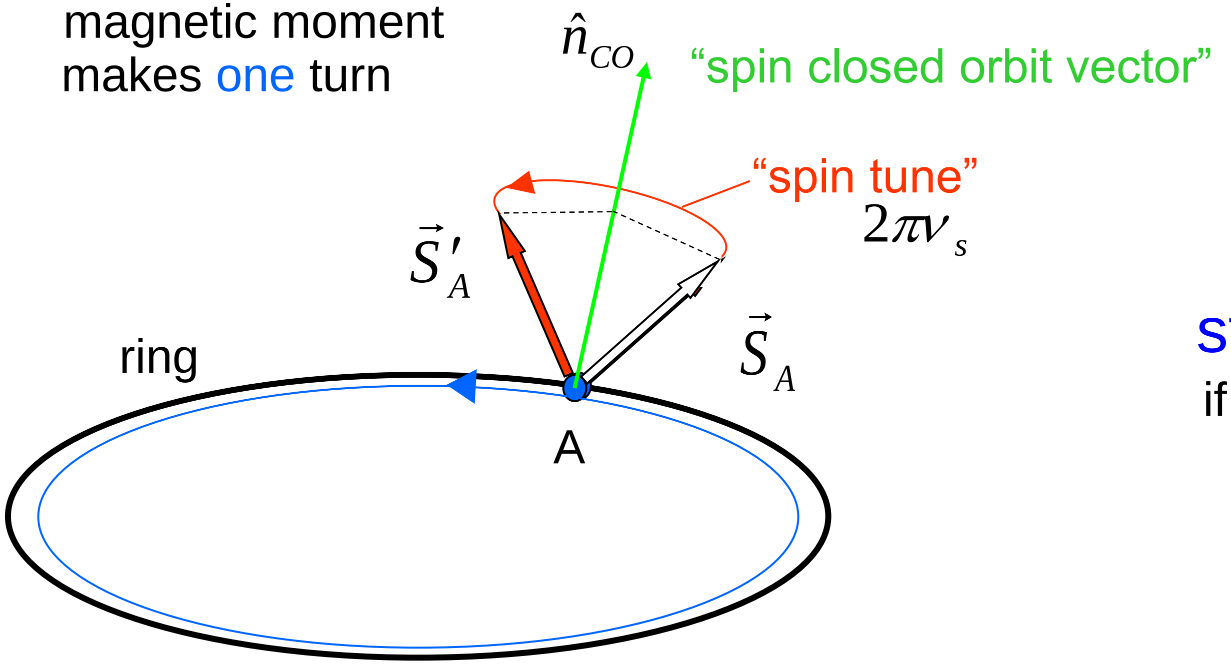
p = 0.3 – 3.7 GeV/c

Phase space cooled internal & extracted beams

… an ideal starting point for a srEDM search

Spin closed orbit

one particle with magnetic moment makes one turn



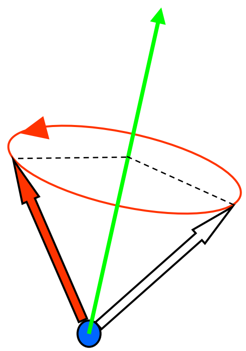
stable polarization

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

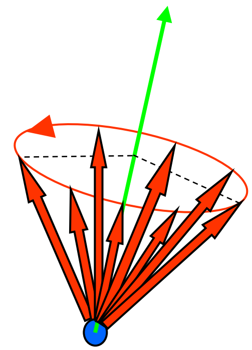
Adopted from H.O. Meyer

Spin coherence

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



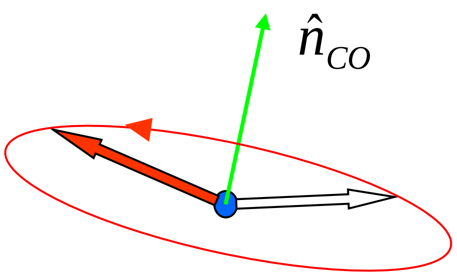
At injection all
spin vectors aligned (coherent)



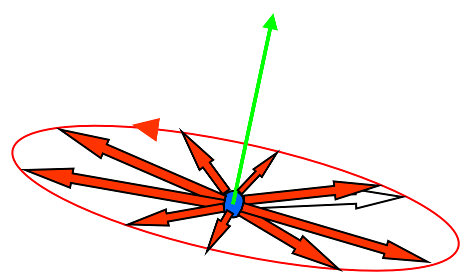
After some time, spin vectors get out of
phase and fully populate the cone

Polarization not affected!

Situation very different, when you deal with $\vec{S} \perp \hat{n}_{CO}$



At injection all spin vectors aligned



After some time, the spin
vectors are all out of phase
and in the horizontal plane

Longitudinal polarization vanishes!

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

Estimate of spin coherence times (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

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

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

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

$G_p = 1.79$ $\quad G_d = -0.14$

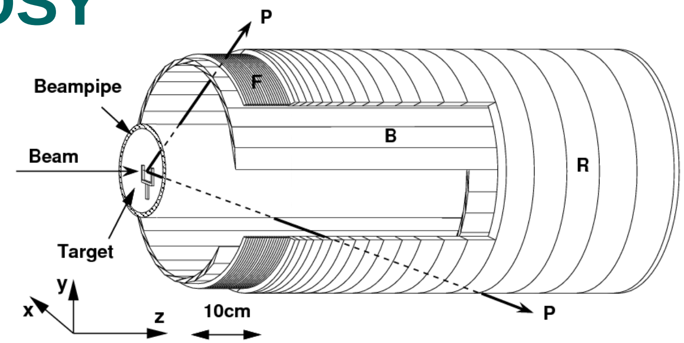
$\tau_{sc}(p) \approx 3 \times 10^3\ \text{s}$ $\quad \tau_{sc}(d) \approx 5 \times 10^5\ \text{s}$

Spin coherence time for deuterons may be ~100 larger than for protons

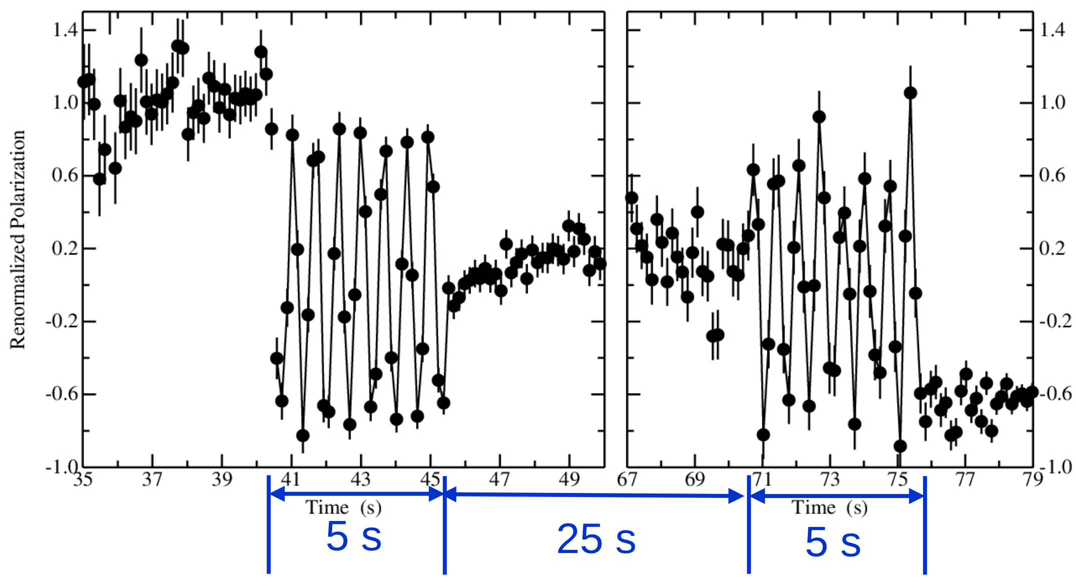
First measurement of spin coherence time

2011 Test measurements at COSY

Polarimetry:

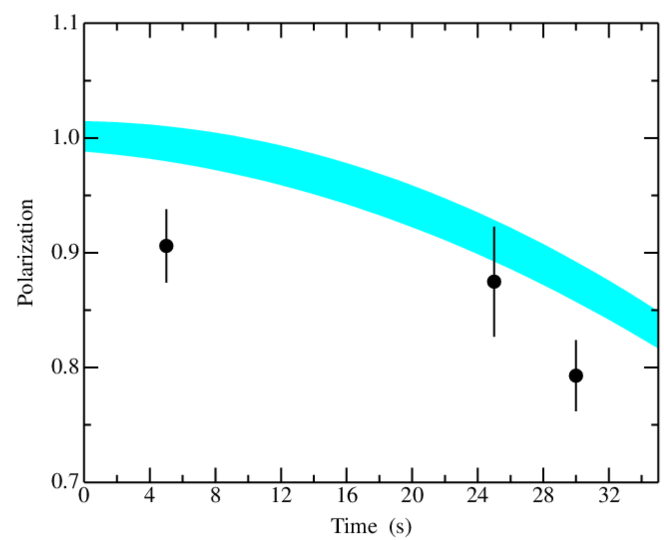


Spin coherence time:



decoherence time

oscillation capture



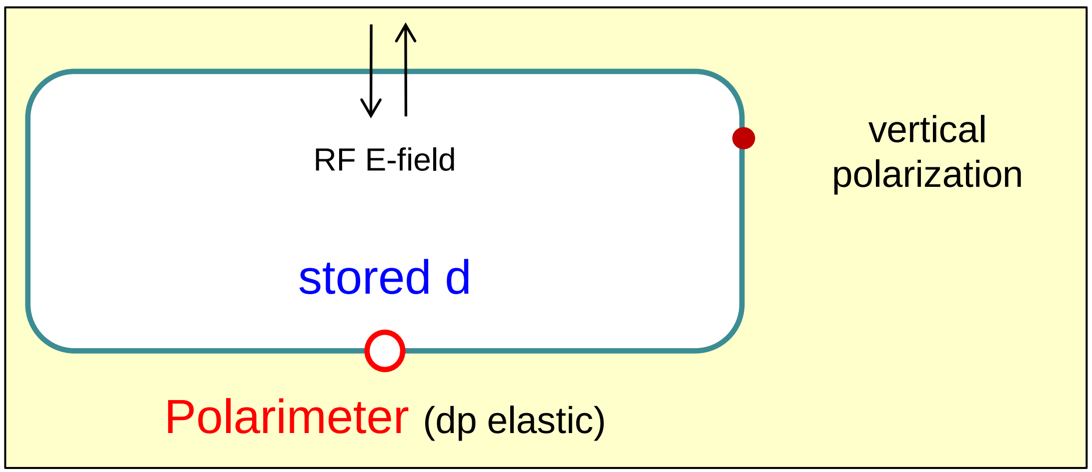
from E. Stephenson

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*

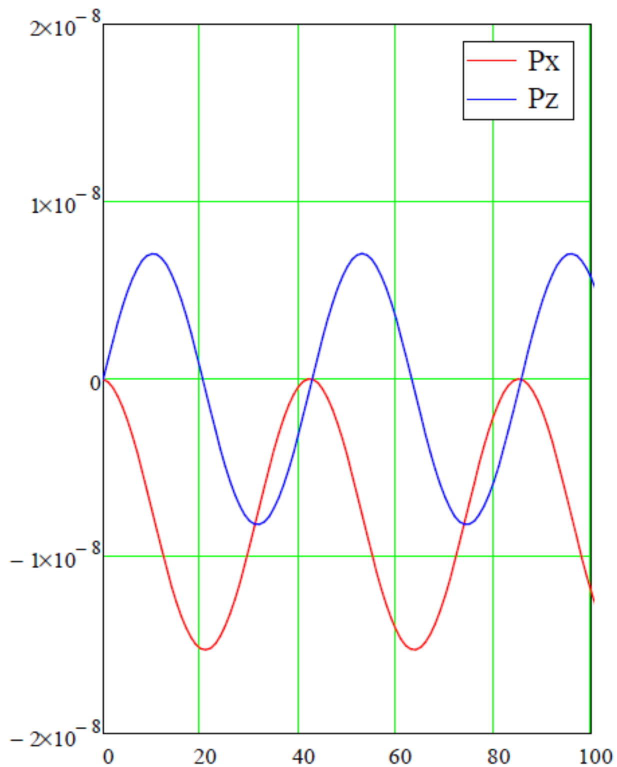
$\sqrt{P_x^2 + P_z^2}$ *grows*

This way, the Edm signal gets **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

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

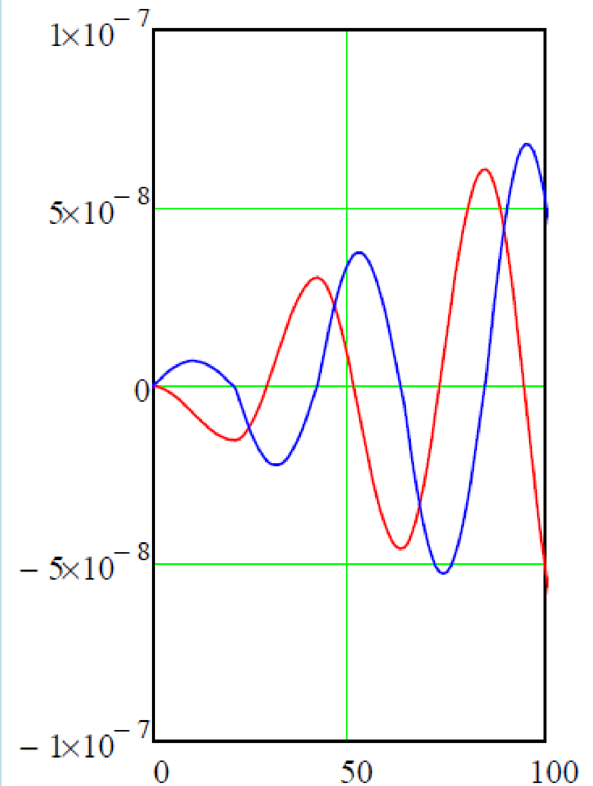
Parameters:	beam energy	T_d=50 MeV
	assumed EDM	$d_d=10^{-20}$ e·cm
	E-field	10 kV/cm

Constant E-field



Number of turns

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

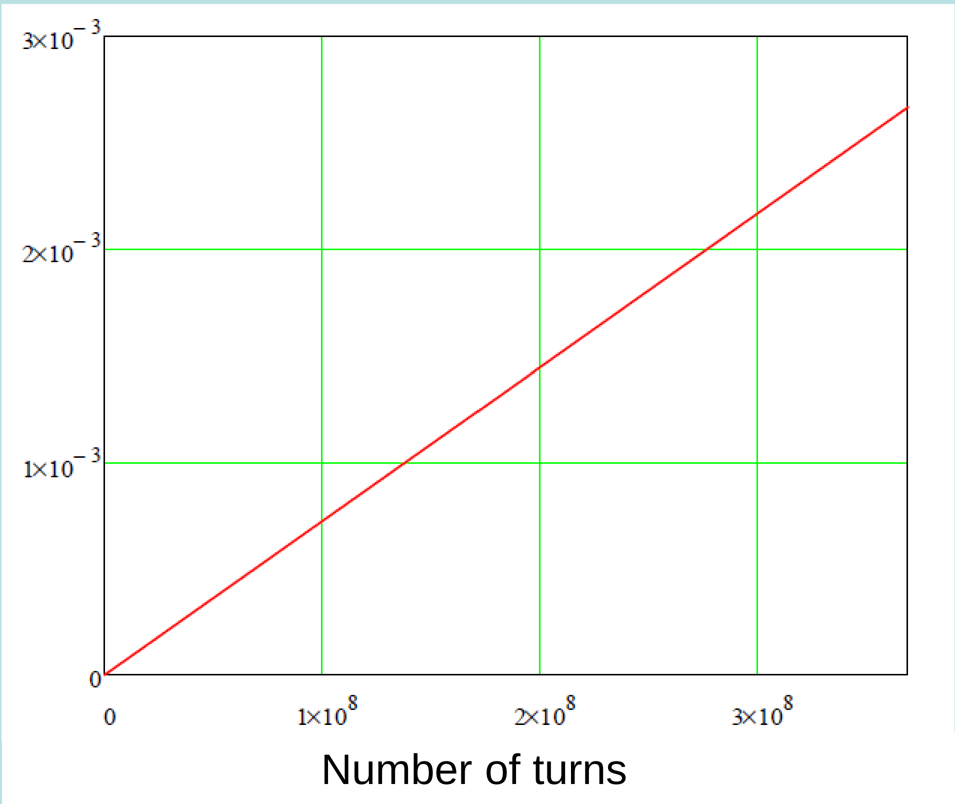


Number of turns

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

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

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



EDM effect accumulates

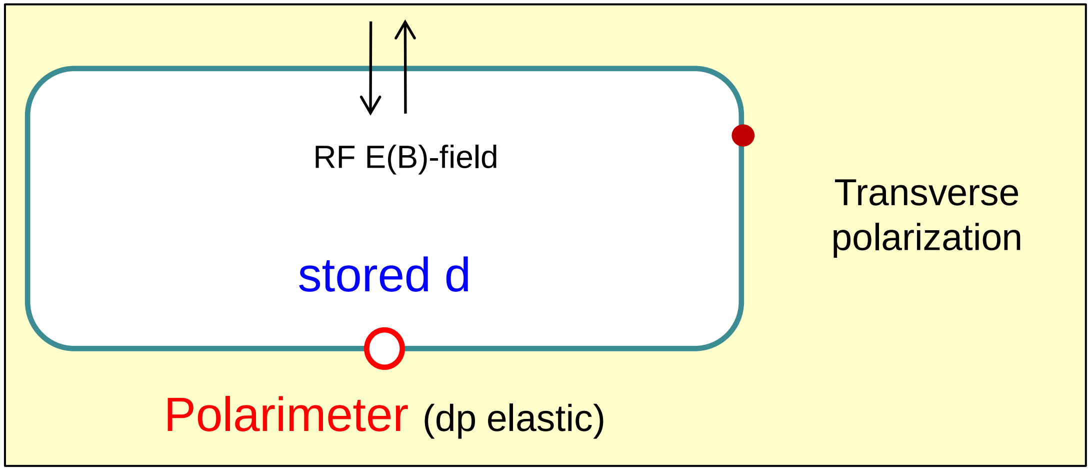
Polarimeter determines P_x, P_y and P_z

Resonance Method with RF E(B)-fields

Approach pursued for a first direct measurement at COSY
Radial RF-E and vertical RF-B fields to observe spin rotation due to EDM

Two situations:

1. $B^*=0 \Rightarrow B_y = \beta \times E_R$ (= 70 G for E_R=30 kV/cm) „Direct“ EDM effect
2. $E^*=0 \Rightarrow E_R = -\beta \times B_y$ **„Magic RF Wien Filter“** no Lorentz force „Indirect“ EDM effect

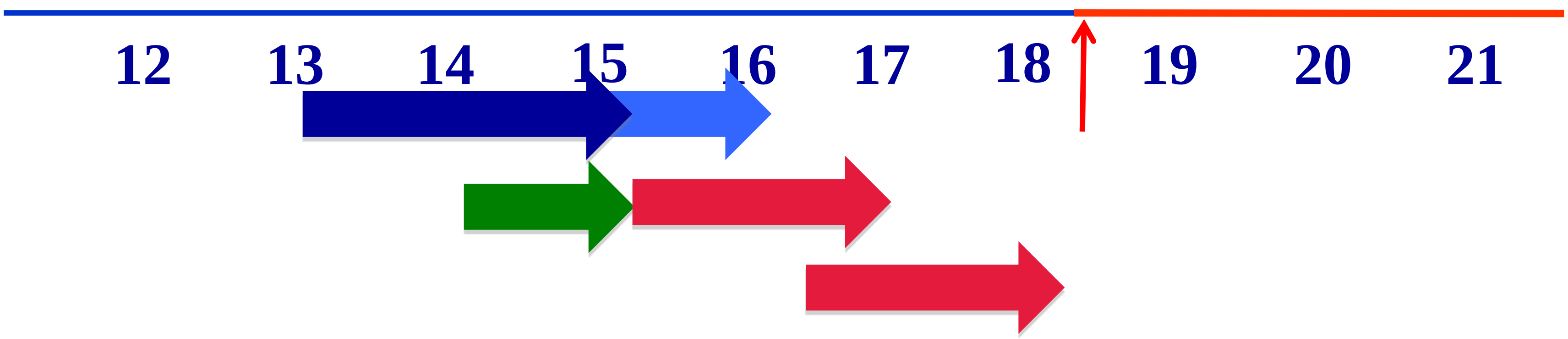


Tilt of precession plane due to EDM

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

Technically driven timeline for pEDM at BNL



Two years R&D/preparation

One year final ring design

Two years ring/beam-line construction

Two years installation

One year “string test”

Stepwise approach in the JEDI project

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 10^{-24} e·cm**	RF-E(B) spin flipper	Modified COSY
3	Built dedicated all-in-one ring for p, d, ^{3}He	Common magnetic-electrostatic deflectors	Dedicated ring
4	EDM measurement of p, d, ^{3}He at **at 10^{-24} e·cm**		Dedicated ring

Time scale:	Steps 1 and 2: < 5 years Steps 3 and 4: > 5 years

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

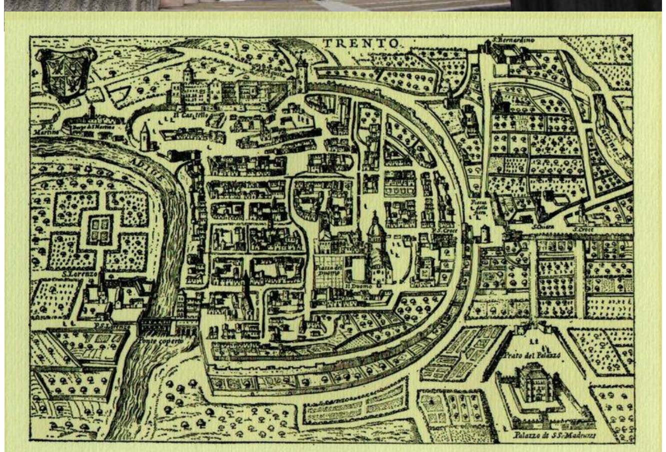
HGF Application(s)

JEDI

EDM Workshop at ECT* (Trento)

October 1-5, 2012

http://www.ectstar.eu/



Organizing committee

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Yannis Semertzidis yannis@bnl.gov

Summary

- Measurement of EDMs extremely difficult,
  but the physics is fantastic!
- Two storage ring projects, at BNL and Jülich
- Pursue spin coherence time measurements at COSY
- First direct measurement at COSY
  Resonance Method with RF E(B) -fields
- New JEDI collaboration established

Georg Christoph Lichtenberg (1742-1799)

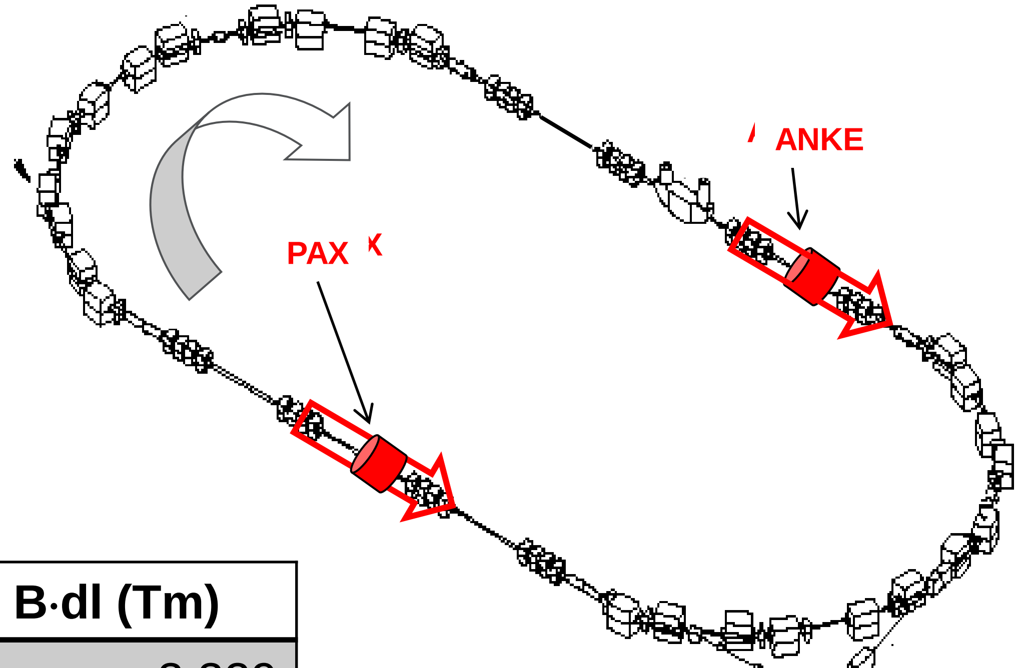
"Man muß etwas Neues machen, um etwas Neues zu sehen."

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

Spare transparencies

COSY: Concept for Snake

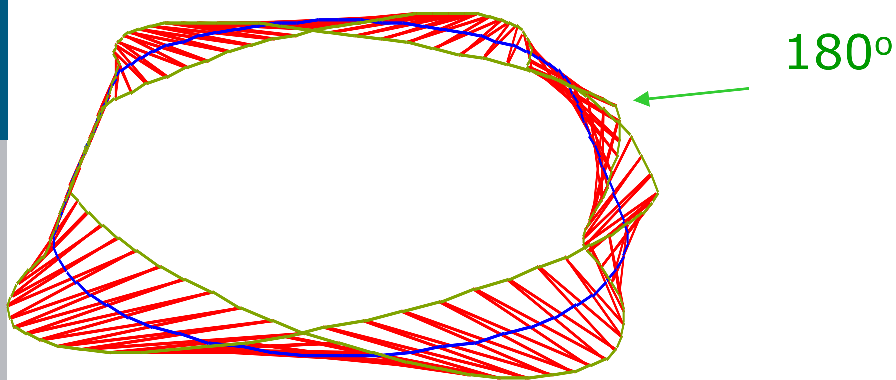
- Should allow for flexible use at two locations
- Fast ramping (< 30s), with injection of P_y
- Cryogen-free system
- Should be available in 2012



	B·dl (Tm)
pn→$\{pp\}_s\pi^-$ at 353 MeV	3.329
PAX at COSY 140 MeV	1.994
PAX at AD 500 MeV	4.090
T_{max} at COSY 2.88 GeV	13.887

One backup slide for olrov

spin manipulation



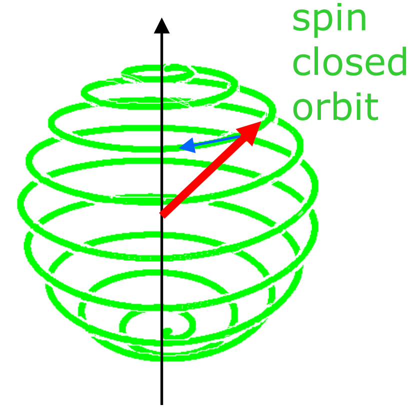
snakes

there is an $\hat{n}_{CO}$ for every point of the orbit

Snakes (non-vertical B field) affect $\hat{n}_{CO}$

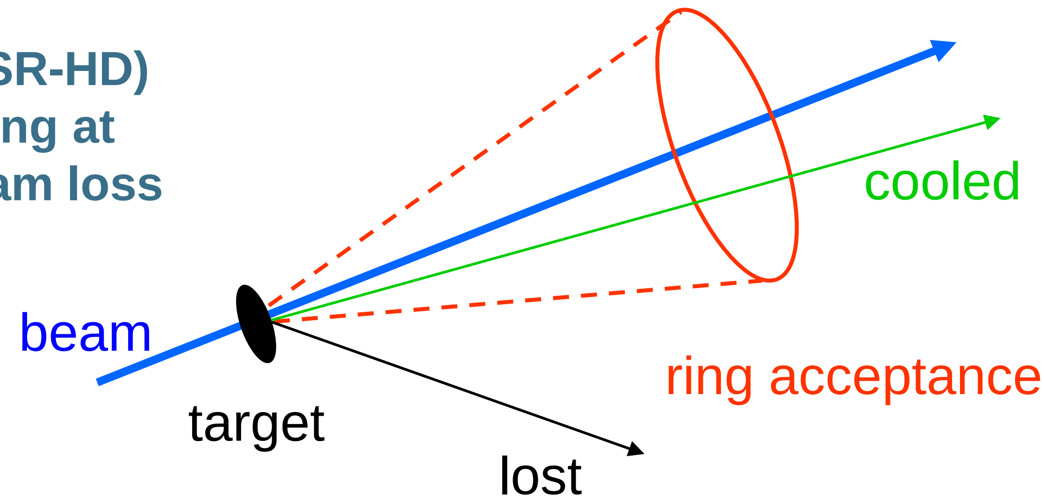
flippers

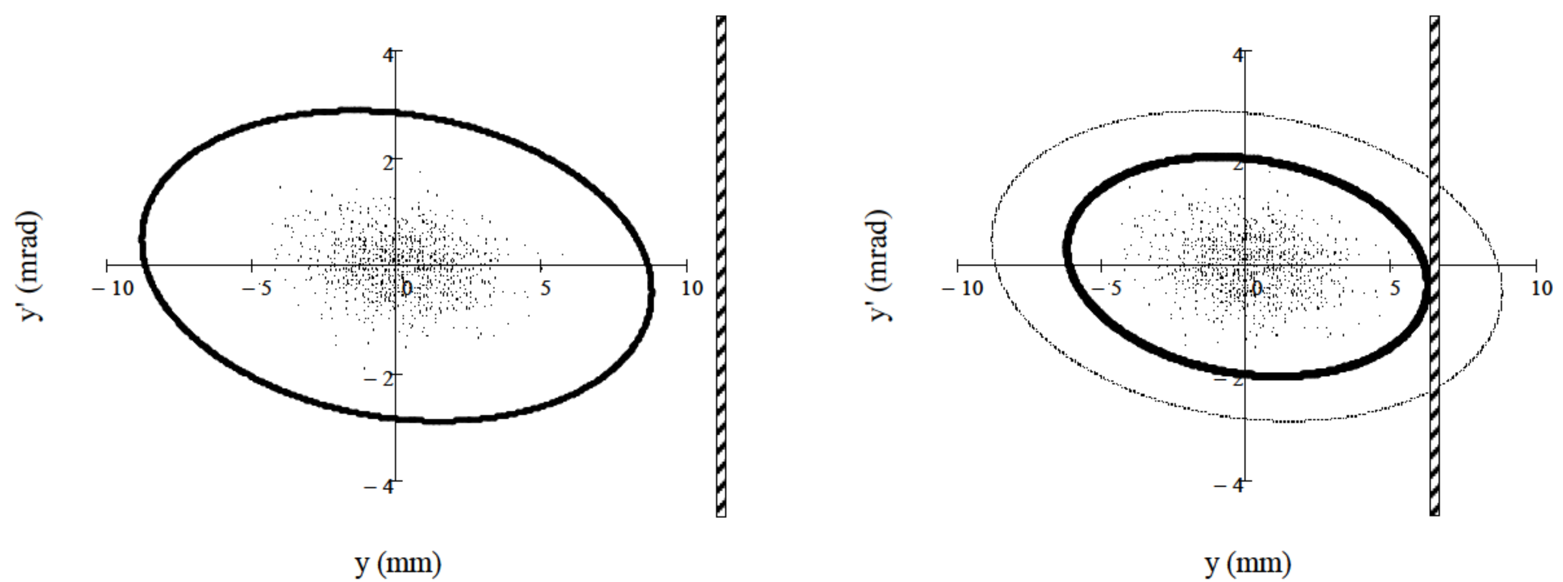
ramping through a resonance reverses $\hat{n}_{CO}$



Machine acceptance

In an ideal machine (like TSR-HD)
→ Single-Coulomb scattering at the target dominates beam loss

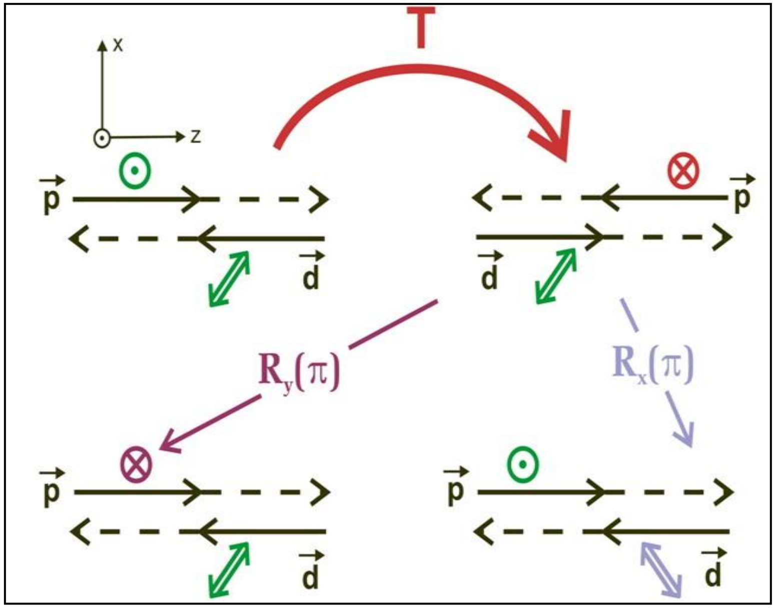


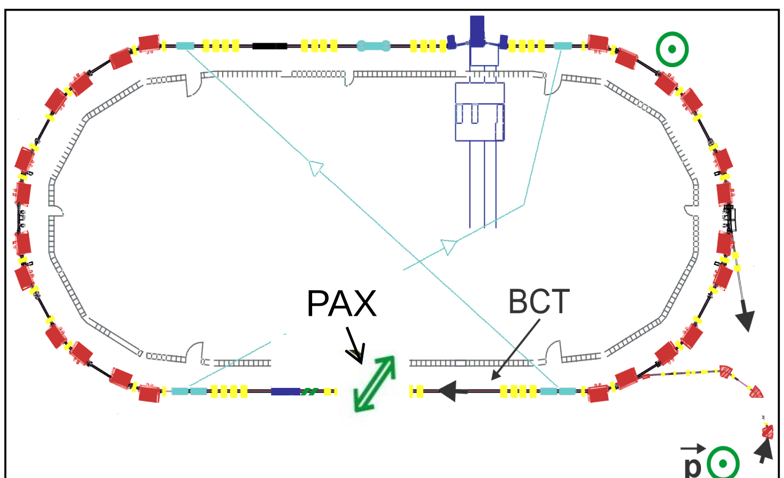


K. Grigoriev et al., NIMA 599,130 (2009)

Future: Time Reversal Invariance Test

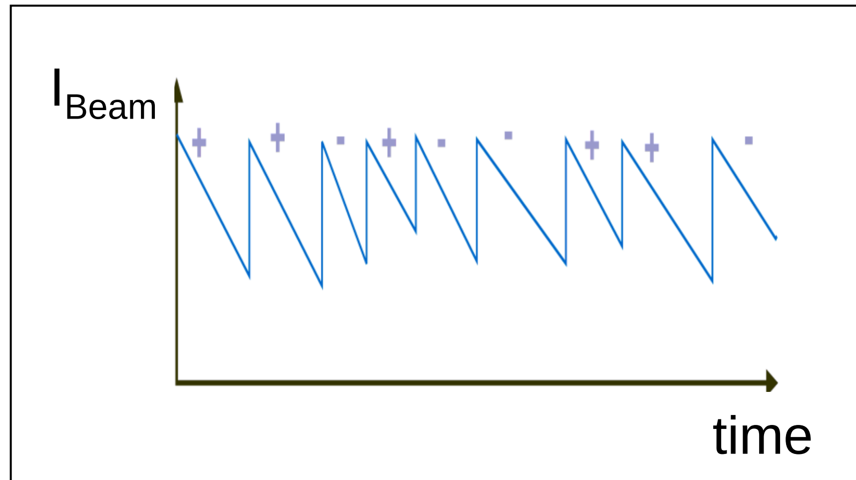
COSY-TRIC: P-even, T-odd





COSY used as accelerator and detector:

Total polarization correlation coefficient $A_{y,xz}$ leads to relative difference of current slopes

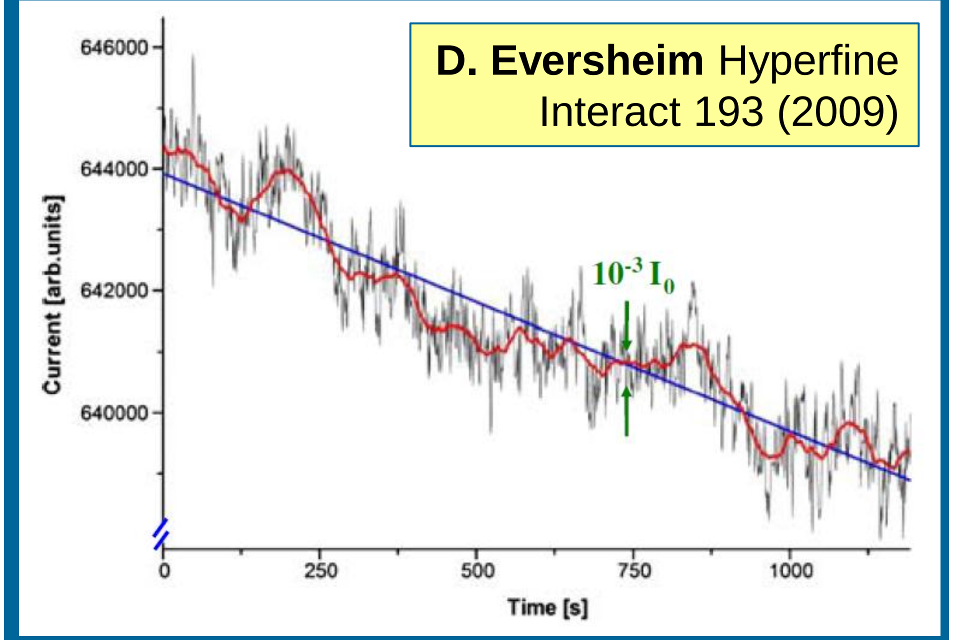


Milestone: Operation of Precision BCT with $\Delta I/I<10^{-4}$

Need for a high precision BCT

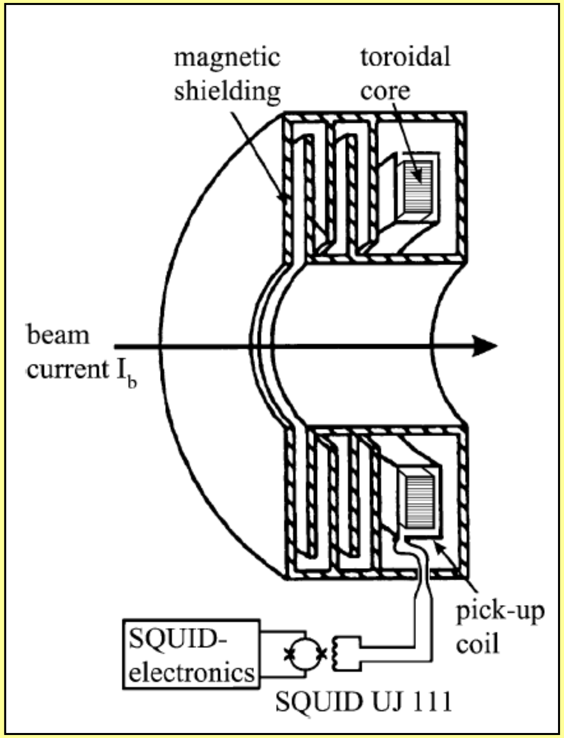
Status TRI Test at COSY

- Slow fluctuations in the measured BCT signal exceed the noise band at higher frequencies



Possible solution:

Cryogenic Current Comparator, read out by low-temperature super-conducting quantum interference device



A. Steppke, IEEE Trans. Appl. Superc. (2009)

Highest resolution achieved: 250 pA/√Hz

Freezing Spin Precession with E-Fields

$$\frac{1}{\gamma^2 - 1} - G = 0 \rightarrow \gamma = \sqrt{\frac{1}{G} + 1}$$

→ $G > 0$ for $\gamma > 1$, if only electric fields are applied

$$\gamma = \sqrt{\frac{1}{G} + 1} \Leftrightarrow p = \frac{m}{\sqrt{G}}$$

μ_p / μ_N = **2.792 847 356 (23)** → G_p = 1.7928473565
μ_d / μ_N = **0.857 438 2308 (72)** → G_d = -0.14298727202
$\mu_{He\text{-}3} / \mu_N$ = **-2.127 497 718 (25)** → G_{3He} = -4.1839627399

Nuclear magneton: $\mu_N = e\hbar / (2m_p c)$ = **5.050 783 24 (13) · 10^{-27} J T^{-1}**

→ Magic momentum for protons: p = 700.74 MeV/c