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PROJECT OVERVIEW AND COMPUTATIONAL NEEDS

TO MEASURE EDMs AT STORAGE RINGS

August 20, 2012 | Andreas Lehrach

on behalf of the JEDI collaboration
(Jülich Electric Dipole Moment Investigations)

Outline

Introduction

- Motivation and History of EDM Measurements

EDM Measurements in Storage Rings

- Principle and Methods
- Dedicated Storage Rings
- First Direct Measurement at COSY

Simulation Programs

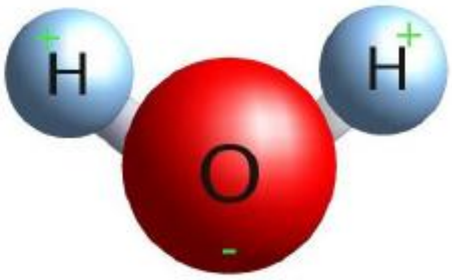
- Computational Needs
- Utilized Simulation Programs
- Performance and Benchmarking

Summary/Outlook

Electric Dipole Moments: What is it?

EDM: Permanent spatial separation of positive an negative charges

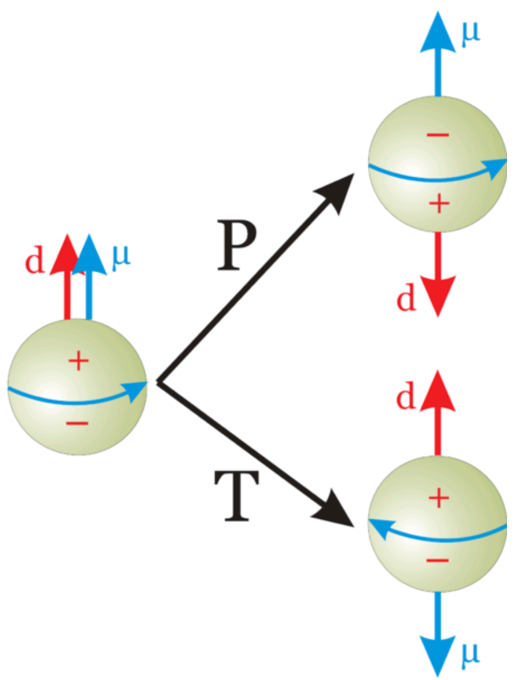
- Water molecule: $d = 2{\cdot}10^{-9}\ e{\cdot}\mathrm{cm}$



- Water molecule can have large electric dipole moment because ground state has two degenerate states of different parity

- This is not the case for proton.
- Here the existence of a permanent EDM requires both T and P violation, i.e. assuming CPT invariance this implies CP violation.

Electric Dipole Moments



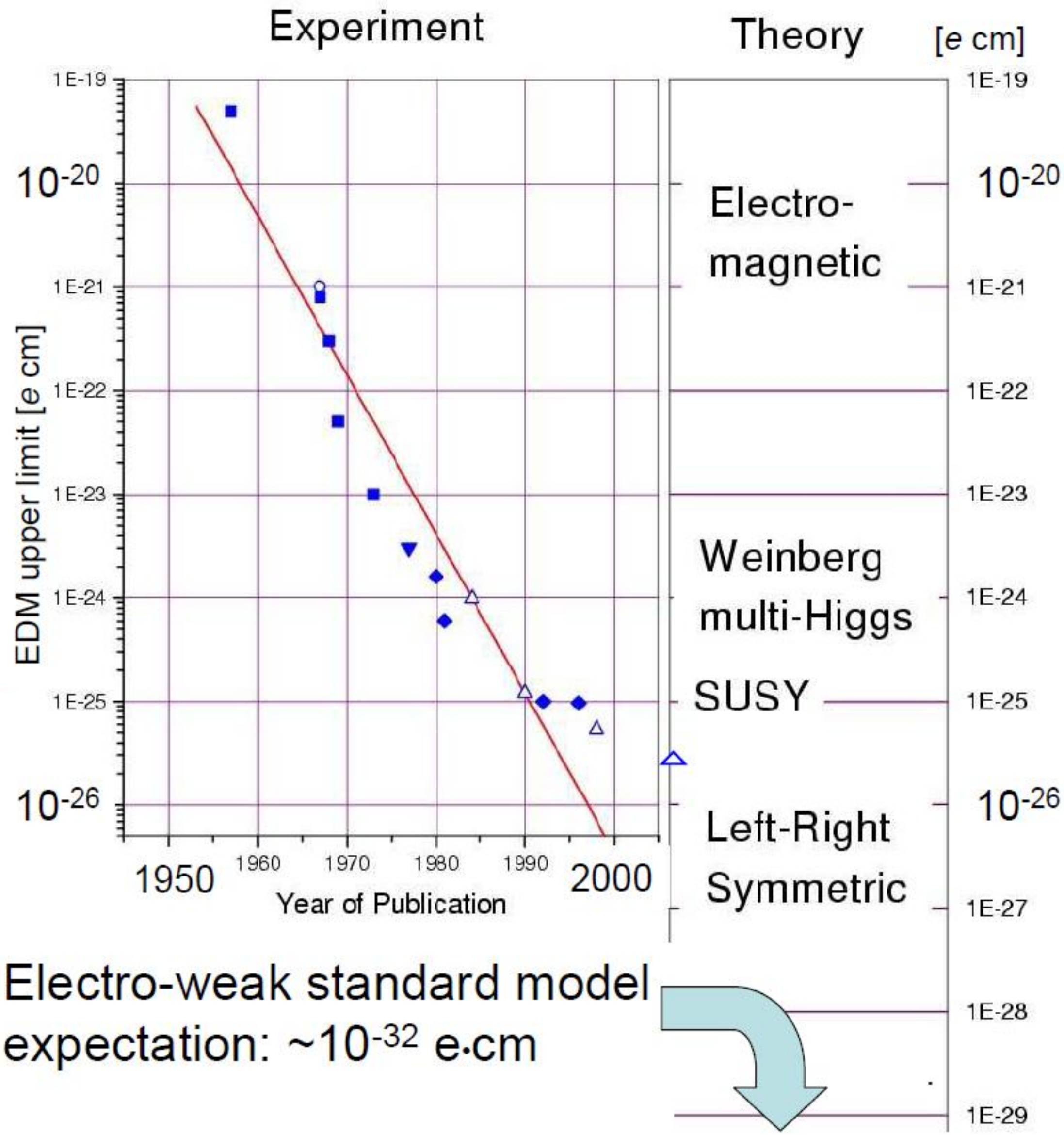
CP can have different sources:

- Weak Interaction (unobservable small)
- QCD θ term (limit set by neutron EDM measurement)
  ——— Part of Standard Model ———
- Sources beyond SM

It is important to measure neutron **and proton and deuteron**, light nuclei EDMs in order to disentangle various sources of CP violation.

EDMs are candidates to solve mystery of matter-antimatter asymmetry

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)

More than
50 years of effort

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
Neutron	$< 3 \times 10^{-26}$	$\sim 10^{-28}$
^{199}Hg	$< 3.1 \times 10^{-29}$	$\sim 10^{-29}$
^{129}Xe	$< 6 \times 10^{-27}$	$\sim 10^{-30} - 10^{-33}$
Proton	$< 7.9 \times 10^{-25}$	$\sim 10^{-29}$
Deuteron	?	$\sim 10^{-29}$

Huge efforts underway to improve limits / find EDMs

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

EDM workshop at ECT* Trento, Italy
October 1 - 5, 2012
„EDM Searches at Storage Rings“
http://www.ectstar.eu/

Spin Precession

Spin precession for particles at rest in electric and magnetic fields:

$$\frac{\mathrm{d}\vec{S}^*}{\mathrm{d}t^*} = \vec{d} \times \vec{E}^* + \vec{\mu} \times \vec{B}^*$$

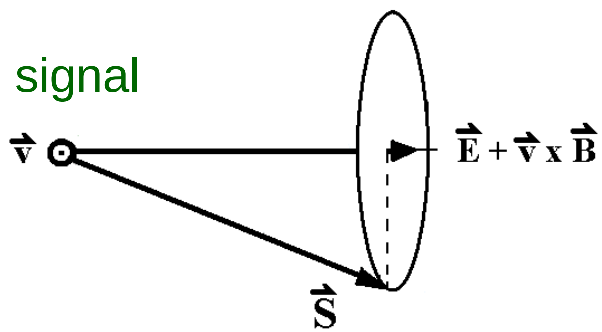
(* rest frame)

In a real neutral particle EDM experiment for non-relativistic particles, the spin precession is given by:

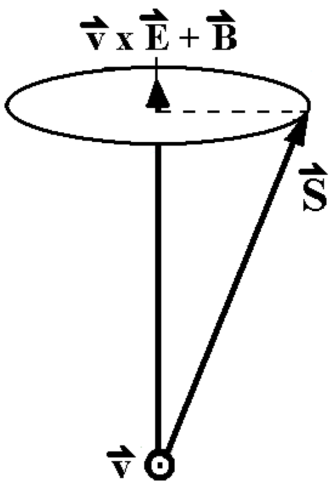
$$\frac{\mathrm{d}\vec{S}^*}{\mathrm{d}t^*} = \vec{d} \times (\vec{E} + \vec{v} \times \vec{B}) + \vec{\mu} \times (\vec{B} - \vec{v} \times \vec{E})$$

Ideal vertical B-Fields and horizontal E-Fields:

EDM signal



Systematic error



Equation for spin motion of relativistic particles in storage rings more complicated

Thomas-BMT Equation

Equation for spin motion of relativistic particles in storage rings for $\vec{\beta}\cdot\vec{B} = \vec{\beta}\cdot\vec{E} = 0$.

The spin precession relative to the momentum direction is given by:

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

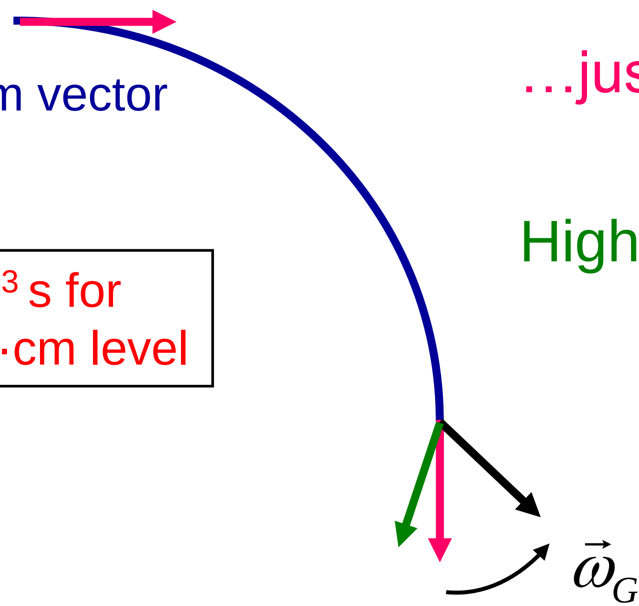
$$\vec{\Omega} = \frac{e\hbar}{mc}\left\{G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1}\right)\left(\vec{v}\times\vec{E}\right) + \frac{\eta}{2}\left(\vec{E} + \vec{v}\times\vec{B}\right)\right\}.$$

Magnetic Moment

Electric Dipole Moment

$$G = \frac{g-2}{2},\ \vec{\mu} = 2(G+1)\frac{e\hbar}{2mc}\vec{S},\ \text{and}\ \vec{d} = \eta\frac{e\hbar}{2mc}\vec{S}.$$

Frozen Spin Method (FSM)



Lower energy particle

…just right

Higher energy particle

Spin coherence time: 10^3 s for measurement on 10^{-29} e·cm level

For $\vec{\beta}\cdot\vec{B}=\vec{\beta}\cdot\vec{E}=0$, the spin precession (magnetic moment) relative to the momentum direction is given by

$$\vec{\omega}_G=\frac{e}{m}\left[G\cdot\vec{B}+\left(\frac{1}{\gamma^2-1}-G\right)\frac{\vec{\beta}\times\vec{E}}{c}\right],\qquad G=\frac{g-2}{2}$$

Freezing Spin Precession with E-Fields

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

→ $G > 0$, if only electric fields are applied

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

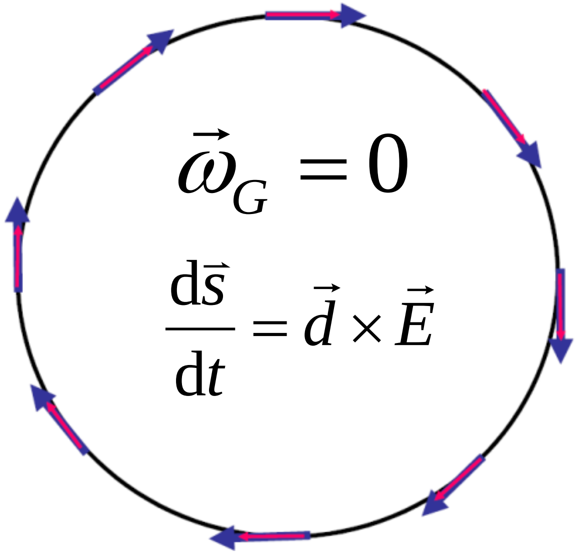
μ_p / μ_N = **2.792 847 356 (23)** → G_p = 1.7928473565
μ_d / μ_N = **0.857 438 2308 (72)** → G_d = -0.14298727202
$\mu_{He\text{-}3} / \mu_N$ = **-2.127 497 718 (25)** → G_{3He} = -4.1839627399

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

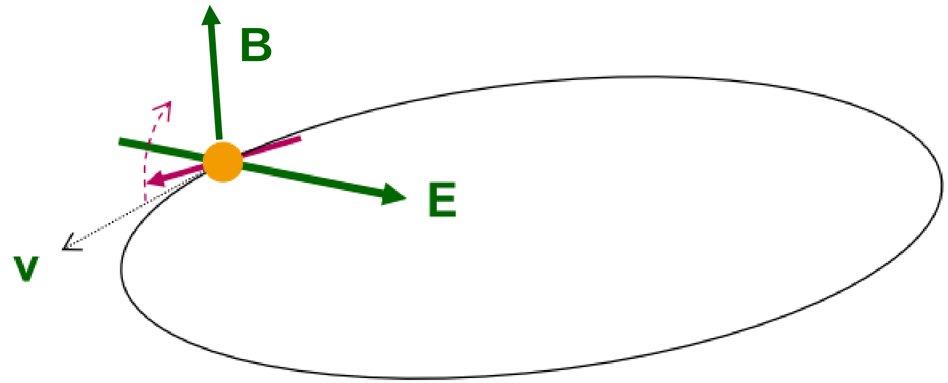
Search for Electric Dipole Moments

NEW approach: 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

Statistical Sensitivity of an EDM Experiment

$$\sigma_{d\,p} \approx \frac{3\hbar}{PAE_R\sqrt{N_{Beam}\,fT_{Tot}\tau_{Spin}}}$$

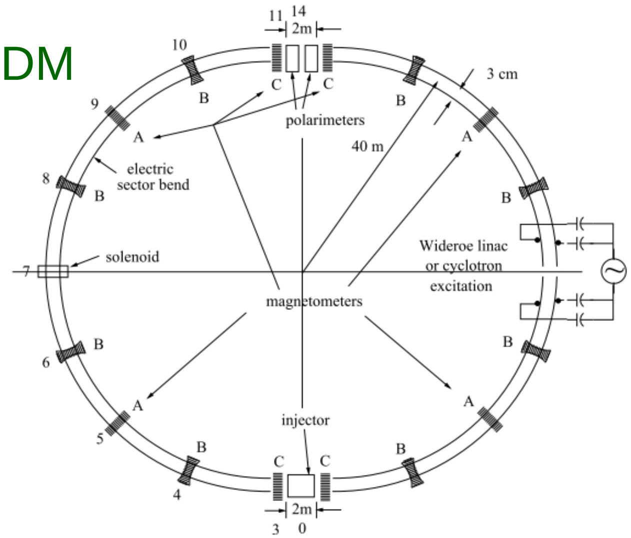
$P = 0.8$	Beam polarization
$A = 0.6$	Analyzing power of polarimeter
$E_R = 17$ MV/m	Radial electric field strength
$N_{Beam} = 2\cdot 10^{10}$ p/fill	Total number of stored particles per fill
$f = 0.55\%$	Useful event rate fraction (polarimeter efficiency)
$T_{Tot} = 10^7$ s	Total running time per year
$\tau_{Spin} = 10^3$ s	Polarization lifetime (Spin Coherence Time)

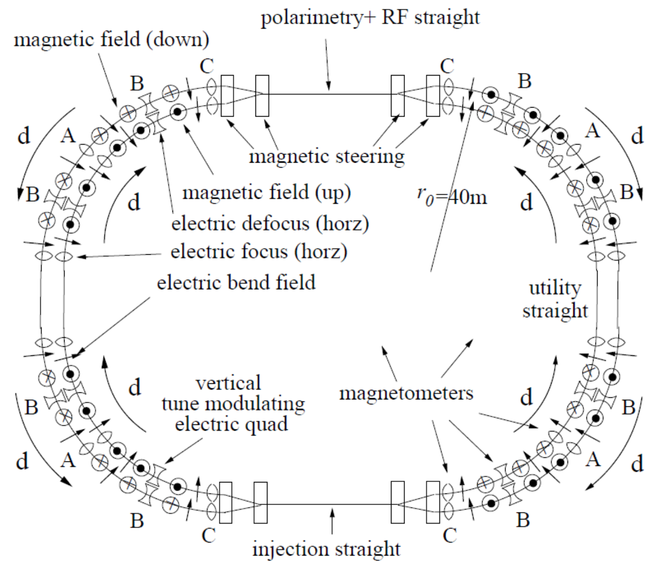
$$\sigma \approx 2.5\cdot 10^{-29}\,e\cdot\mathrm{cm}$$ for one year measurement

Systematic error due to vertical electric fields and horizontal magnetic fields

EDM Projects

Proton EDM
BNL



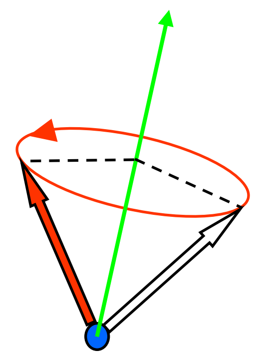


Light-Ion EDM
Jülich

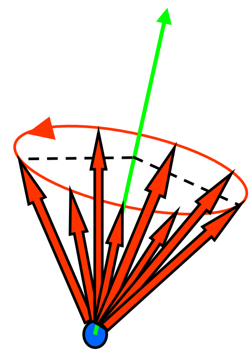
R&D Activity	Goal	Test
Internal Polarimeter	spin as a function of time Systematic errors < 1 ppm	EDM at COSY
	Full-scale polarimeter	EDM at COSY
Spin Coherence Time	$>10^3$ s	EDM at COSY
Beam Position Monitor	resolution 10 nm,1 Hz BW 64 BPMs, 10^7 s measurement time → 1 pm (stat.) relative position (CW-CCW)	BNL RHIC IP
E/B-field Deflector	17 MV/m 2 cm plate separation, 0.15-0.5T	Jülich

Spin coherence

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



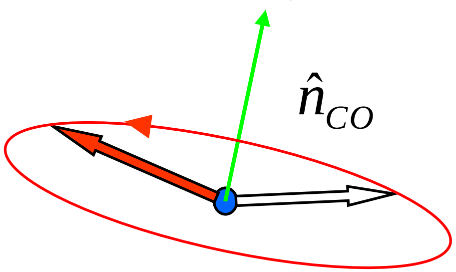
At injection all
spin vectors aligned (coherent)



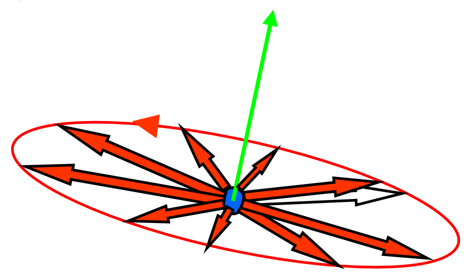
After some time, spin vectors get out of
phase and fully populate the cone

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.

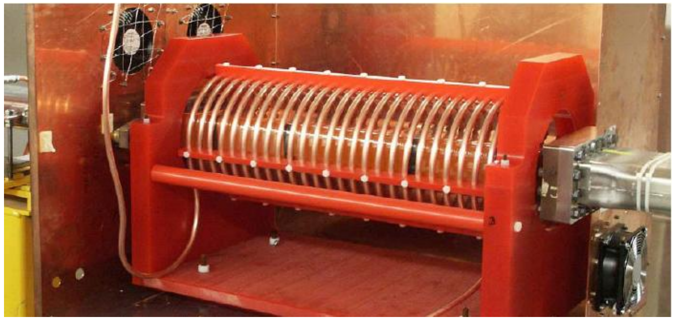
Spin coherence time: 10^3 s for measurement on 10^{-29} $e\cdot$cm level

Spin Coherence EDM@COSY

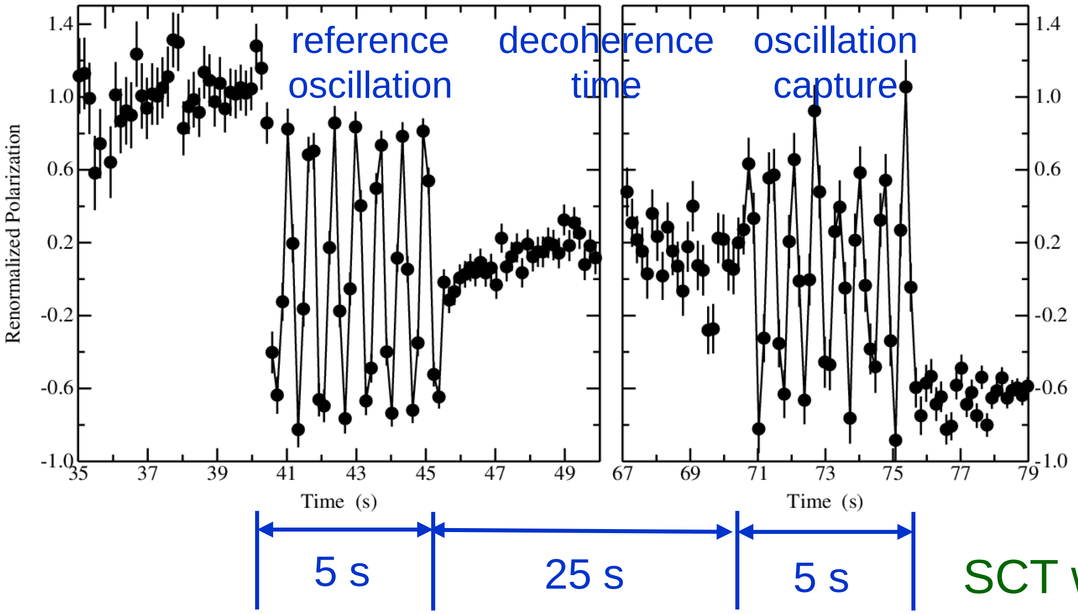
RF Solenoid:

water-cooled copper coil in a ferrite box

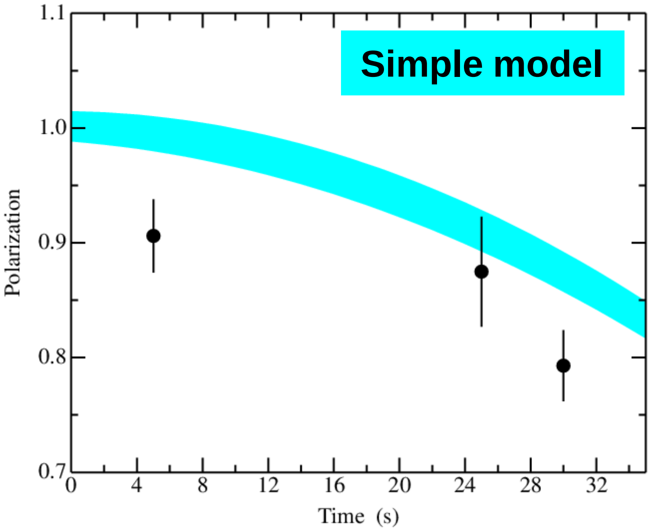
- Length 0.6 m
- Frequency range 0.6 to 1.2 MHz
- Integrated field $\int B_{rms}\, dl \sim 1$ T·mm



$$f_r = f_c(k \pm \gamma G)$$



RF solenoid: on off on



SCT with sextupole correction > 100s

Spokesperson: E. Stephenson (IUCF)

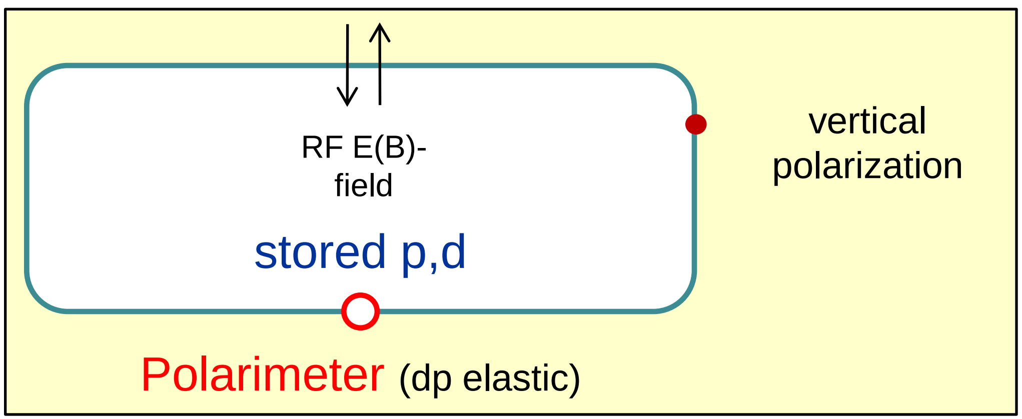
Resonance Method with RF E/B Fields

First direct measurement in COSY developed by the Jülich study group

RF-E/B spin flipper to observe a spin rotation by the EDM

Two possibilities:

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 Wienfilter" No-Lorenz Force, „Indirect" EDM effect



Tilt of the precession plane due to EDM

Observable:
Accumulation of spin rotations within spin coherence time

- EDM signal is **increased** during the cycle
- Statistical sensitivity for d_d in the 10^{-23} to 10^{-24} $e\cdot$cm range possible
- Alignment and field stability of ring magnets
- Imperfection of RF E(B) spin flipper?

R&D Program JEDI

(Jülich Electric Dipole Moment Investigations)

1. Studies of the spin coherence time (SCT) with horizontal/vertical RF-B/E spin flipper
- Different wave forms at different spin harmonics and beam energies
- Goal is to get optimum setting of the RF-B field for maximum spin coherence time

2. Investigation of systematic effect with vertical/horizontal RF-B/E spin flipper
- Alignment and field quality RF-B flipper
- Opening angle of spin ensemble (beam cooling and heating)
- Alignment of the ring magnets

3. Development and benchmark precision simulation programs for spin dynamics in storage ring
- COSY-Infinity, integrating code, simple code

4. Polarimetry

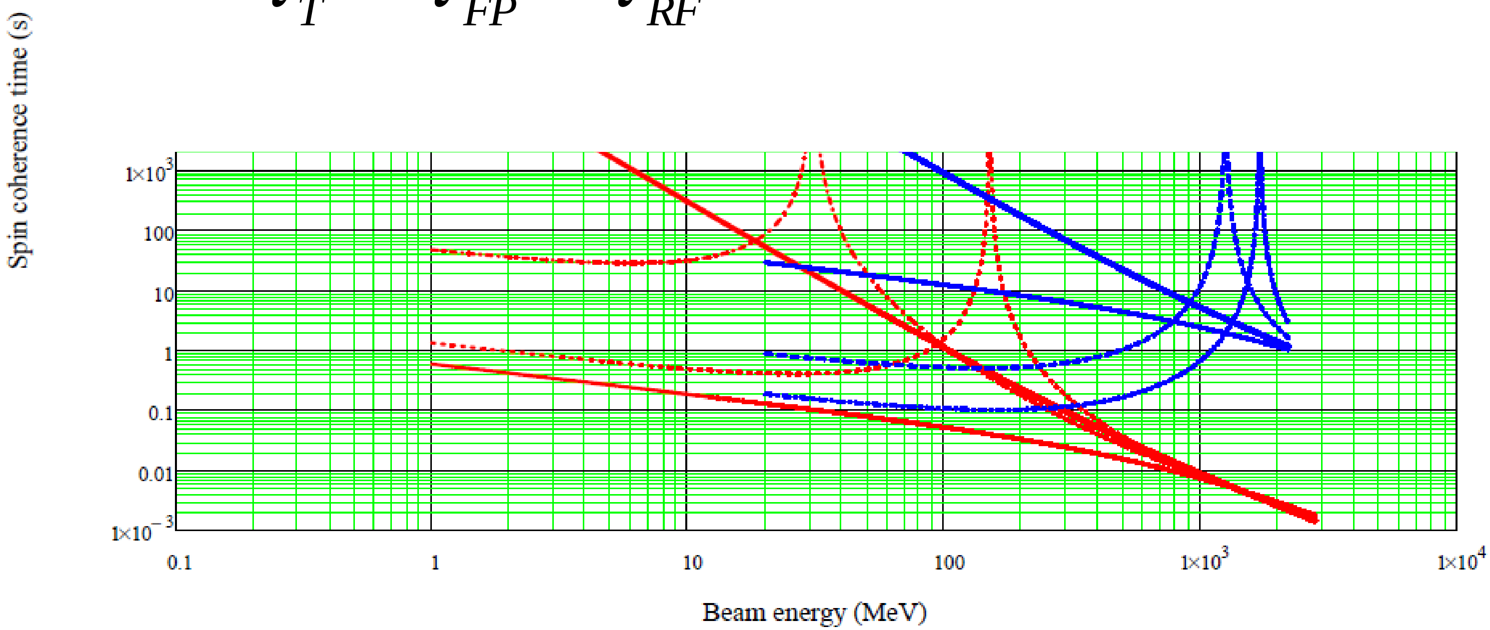
5. Development of a high-power RF-E(B) spin flipper

Spin Coherence Time with RF Flipper

Exciting result of the Jülich Study Group

$$f_r = f_c(k \pm \gamma G)$$

$$\frac{1}{\tau_T} = \frac{1}{\tau_{FP}} + \frac{1}{\tau_{RF}} - A_{FP,RF} \cdot f(\tau_{FP}, \tau_{RF})$$



- Possibility to increase spin coherence time by 3 to 5 orders of magnitude in the ideal case

Computational Needs

- Particle revolutions: >>10^6 turns (1 seconds)
  → efficient simulation program
- Number of particle: 10^6
  → MPI version on a supercomputer
- Precision:
  COSY measurement: 10^{-13}–10^{-12} radians per turn
  Dedicated ring: EDM rotation with by of 10^{-15} radians per turn → roughly 10^{-18} radians per element
  → double precision (64 Bit) provides16 significant decimal digits precision
- EDM spin kick is required
- RF E/B spin flipper element is needed

Utilized Simulation Programs

COSY Infinity:

- based on map generation using differential algebra and the subsequent calculation of the spin-orbital motion for an arbitrary particle
- including higher-order nonlinearities, normal form analysis, and symplectic tracking
- the upgrade of COSY Infinity is supervised by M. Berz

- an MPI version of COSY Infinity is already running on the computer cluster at Michigan State University
- a project for the Jülich supercomputer is starting end of this year

Code Performance

Sc

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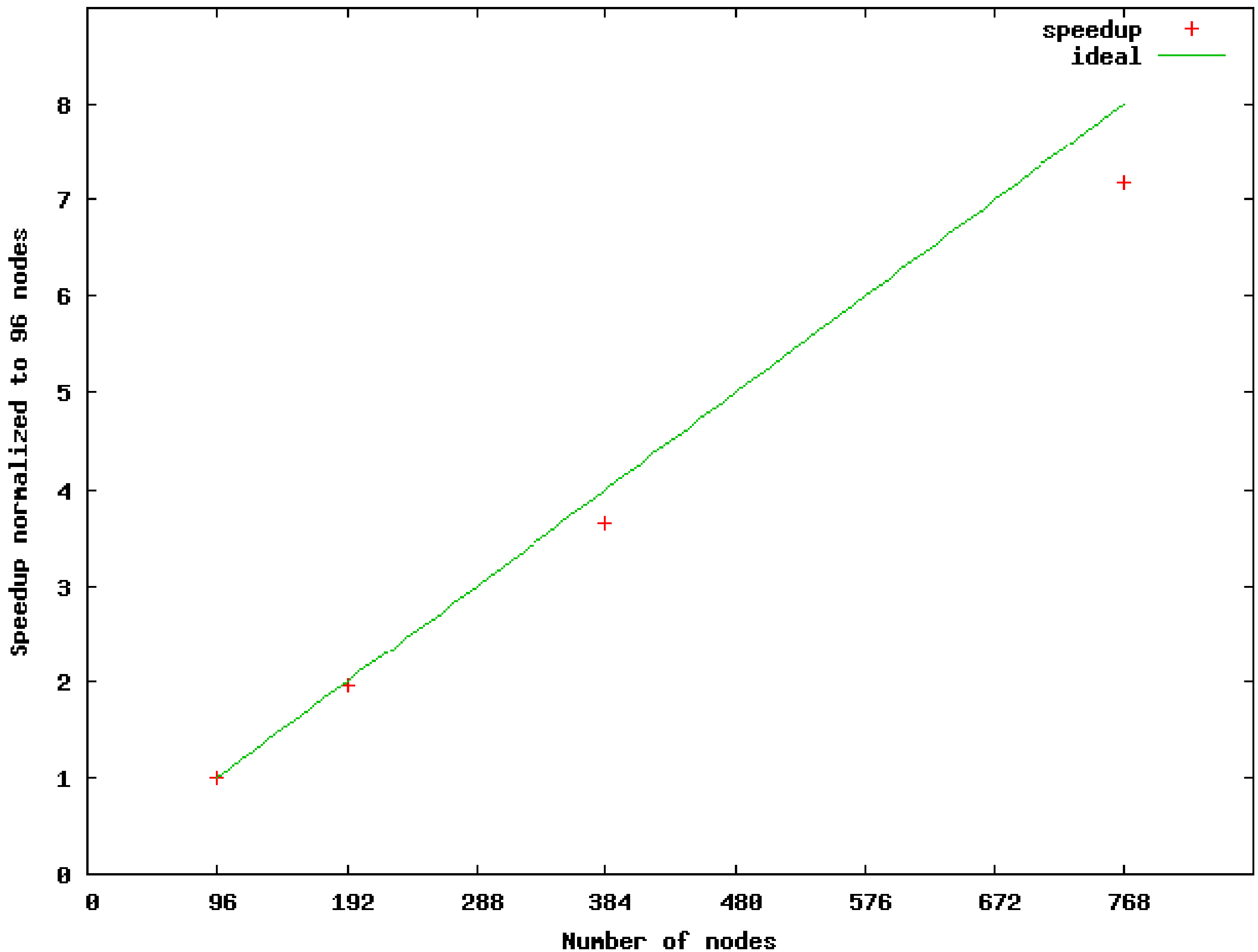

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Courtesy: Denis Zyuzin(FZJ)

Code Performance

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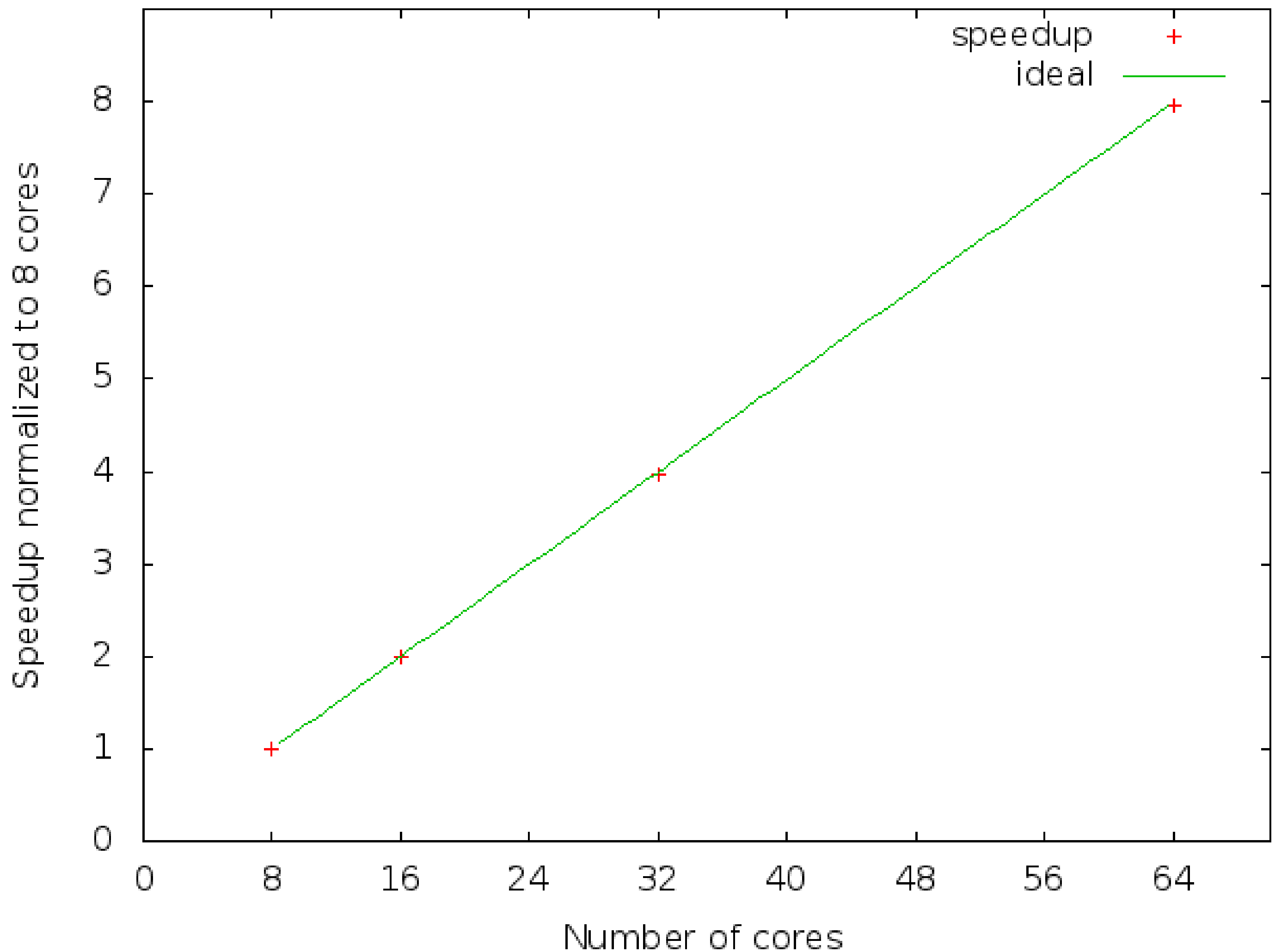

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Courtesy: Denis Zyuzin(FZJ)

Utilized Simulation Programs

Integrating program:

- differential equations of particle and spin motion in electric and magnetic fields are solved using Runge-Kutta integration
- accurate to sub-part per billion levels in describing the muon (g-2) spin precession frequency
- integration step size is 0.5 ps, making it rather slow with a possible maximum tracking time of about 10 ms for a particle in the ring
- suitable to study effects that do not require a long numerical time
- for benchmarking the results of the much more efficient COSY Infinity

→ Talk by Y. Senichev tomorrow

Utilized Simulation Programs

For benchmarking

Numerical integration:

- numerical integration of the Thomas-BMT differential equations for a spin motion with smoothly approximated parameters of orbital motion

Rotation matrices:

- matrices for dipoles and RF Spin flipper including synchrotron oscillation

Experiments:

- “analog computer” Cooler Synchotron COSY

Conclusion / Outlook

EDM Measurement: Stepwise approach of the JEDI Project

- R&D work together with BNL
- First direct measurement at COSY
- Build a dedicated storage ring

Computational Needs

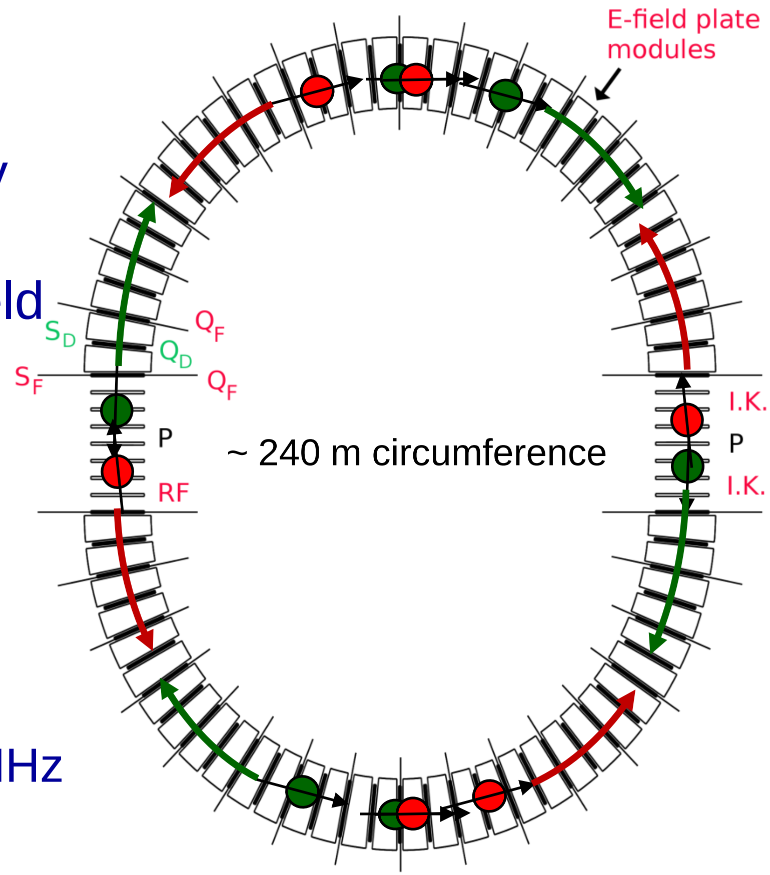
- Efficient simulation program on a super computer
- High precision spin simulation
- EDM spin kick and RF E/B spin flipper to be implemented
- Benchmarking with other simulation programs and COSY experiments

Brookhaven Proposal
A Magic Proton Ring for 10^{-29} e·cm

2 beams simultaneously rotating in a radial electric field

E_R = 17 MV/m

Beams are bunched with h = 120, f = 90 MHz



I.K.: Injection Kickers
P: Polarimeters
RF: RF-system
S: Sextupoles
Q: Quadrupoles
BPMs: ~70

Clock-wise (CW) & Counter-clock-wise (CCW) storage

2012 proposal send to US-DoE

Courtesy: Storage Ring EDM Collaboration
21 Institutions, 80 Collaborators
http://www.bnl.gov/edm

Deuteron EDM Proposal

Deuteron momentum: p = 1 GeV/c,

Ring parameter: R_B = 8.4 m, $\langle R \rangle$ ~ 10 m, C = 85m

Deflectors: E_R = -12 MV/m (radial), B_V = 0.48 T (vertical)

- 2004 BNL proposal: single ring

  CW and CCW consecutive beam injections

  Limiting error: time-dependent part of the average vertical electric field over the entire ring

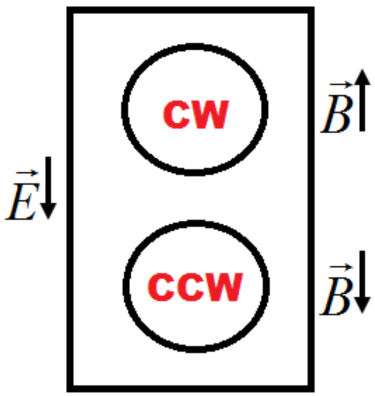
  → sensitivity ~ 10^{-27} e · cm for one year measurement

- 2008 BNL proposal: double ring

  CW and CCW simultaneously

  2-in-1 magnet design with common E-field plates

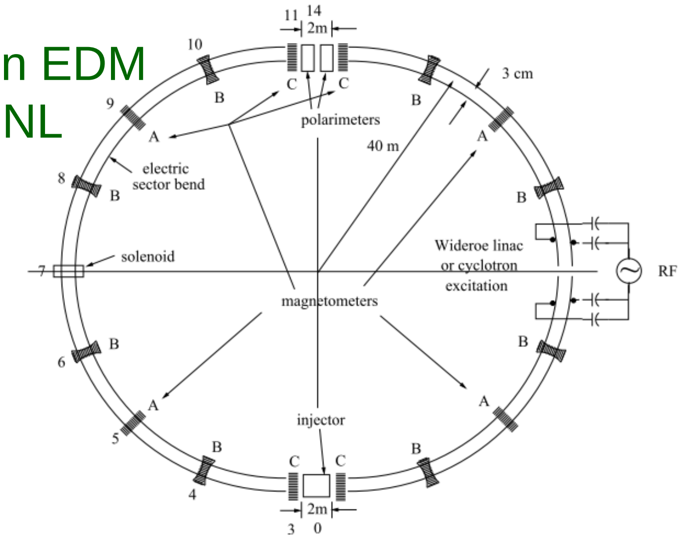
  → sensitivity ~ 10^{-29} e · cm for one year measurement

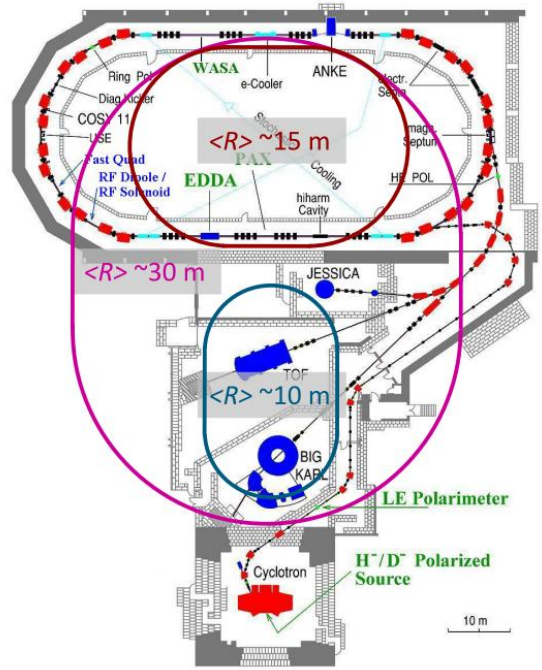


See http://www.bnl.gov/edm

EDM Projects

Proton EDM
BNL





Light-Ion EDM
Jülich

R&D Activity	Goal	Test
Internal Polarimeter	spin as a function of time Systematic errors < 1 ppm	EDM at COSY
	Full-scale polarimeter	EDM at COSY
Spin Coherence Time	$>10^3$ s	EDM at COSY
Beam Position Monitor	resolution 10 nm,1 Hz BW 64 BPMs, 10^7 s measurement time → 1 pm (stat.) relative position (CW-CCW)	BNL RHIC IP
E/B-field Deflector	17 MV/m 2 cm plate separation, 0.15-0.5T	Jülich

Jülich All-In-One Ring Lattice

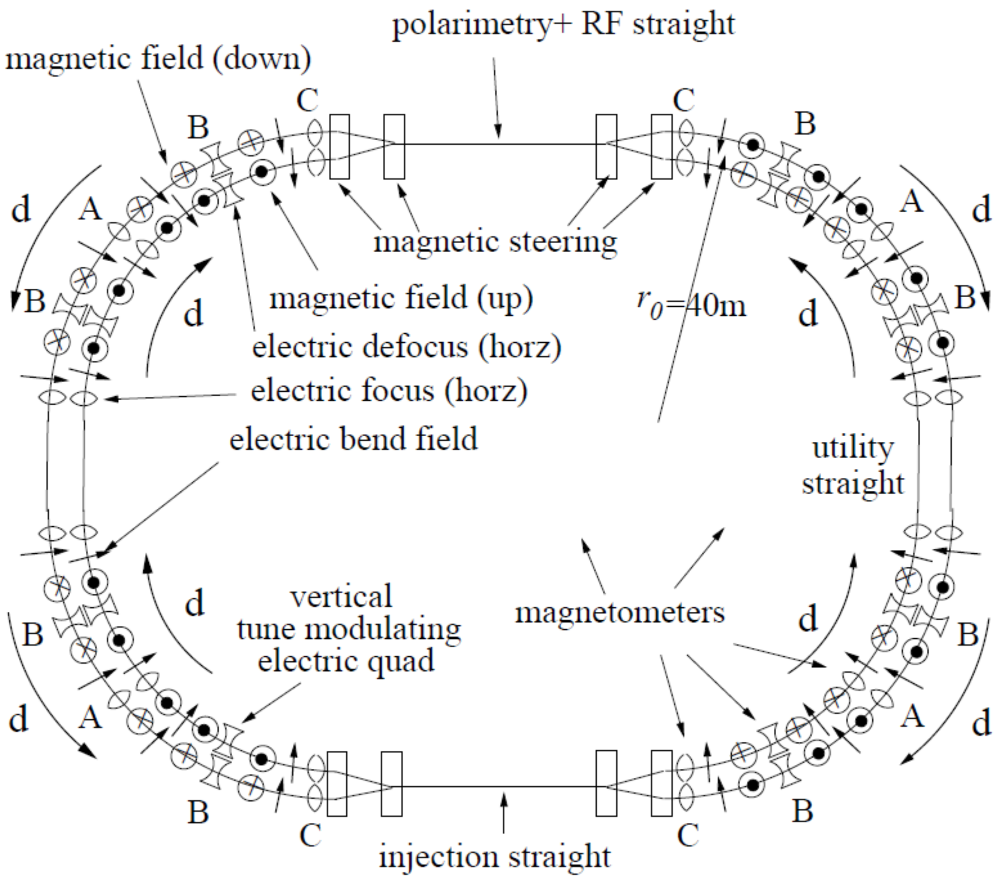


Figure 1: "All-In-One" lattice for measuring EDM's of protons, deuterons, and helions.

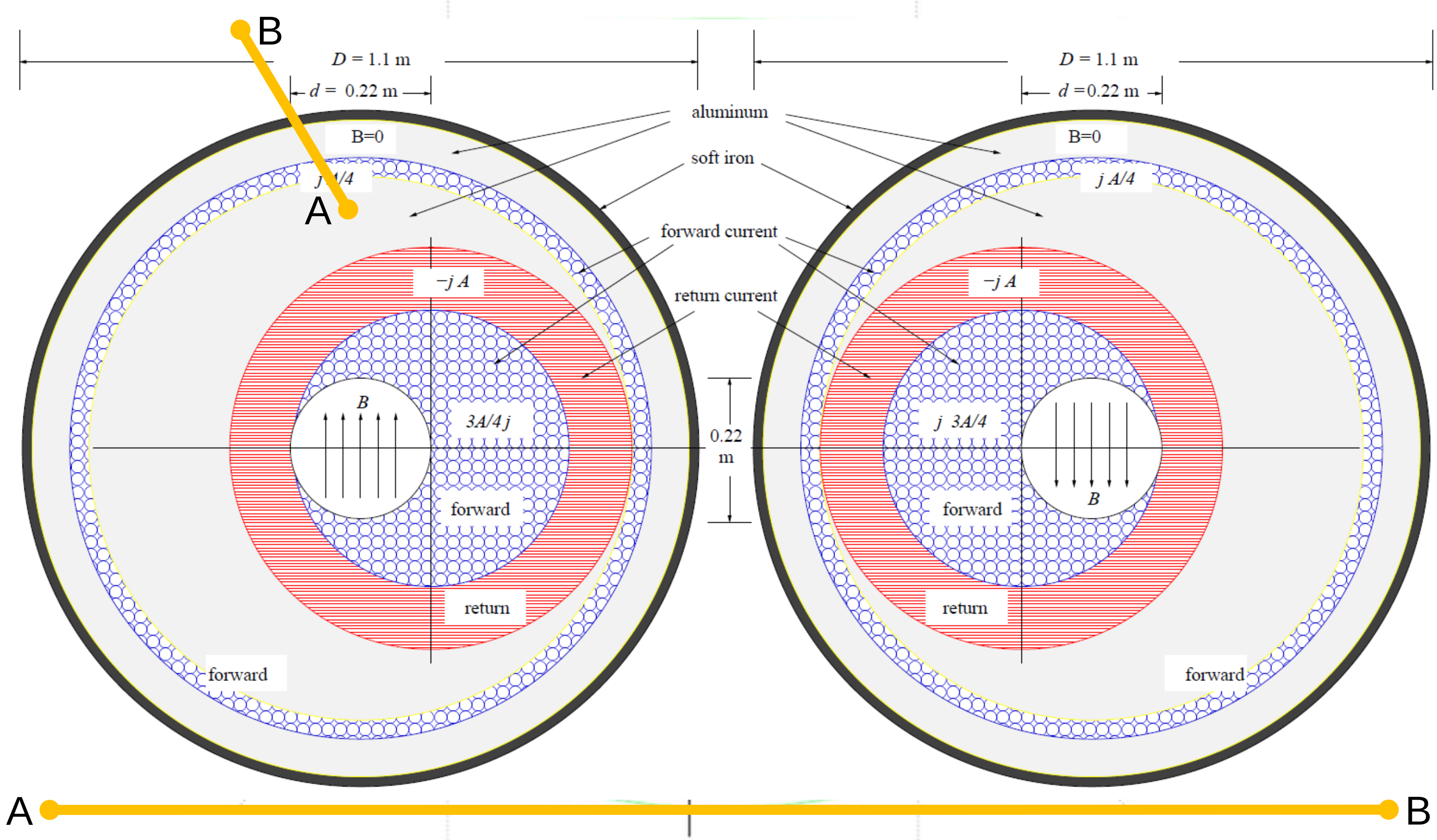
All-In-One Storage Ring Lattice for Baryon EDM Measurements
February, 2012

Richard Talman, Cornell University, Ithaca, N.Y.

February 13, 2012

Jülich All-In-One Ring Lattice

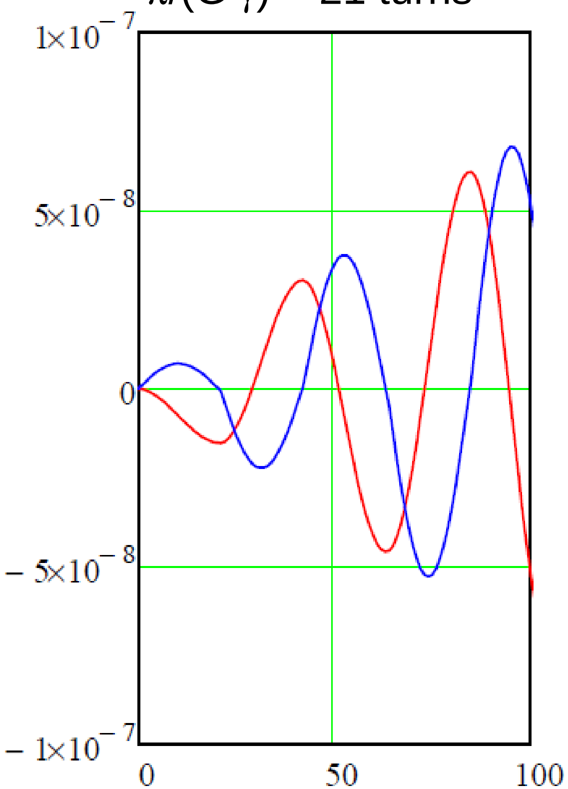
Iron-free, current-only, magnetic bending, eliminates hysteresis
→ achievable field of copper magnets of ~ 0.15 T.



Simulation of Spin Rotations

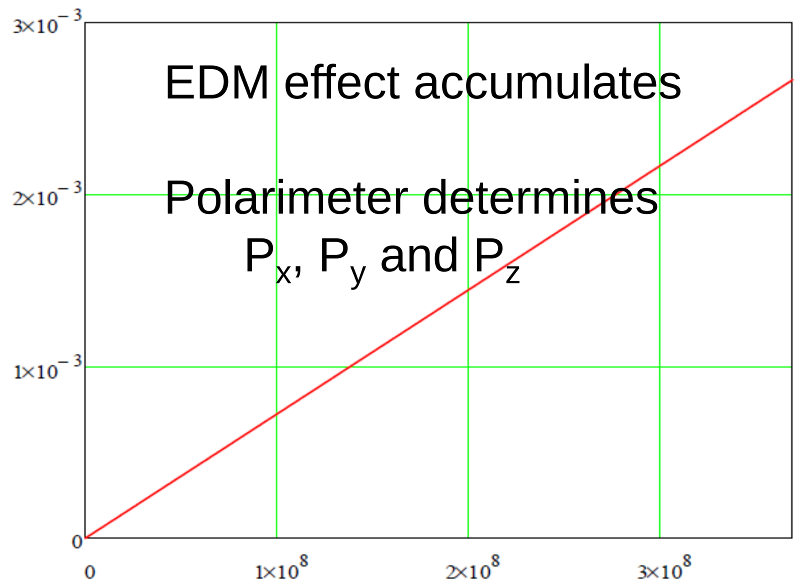
Parameters:	beam energy	T_d=50 MeV
	assumed EDM	$d_d=10^{-20}$ e·cm
	E-field	10 kV/cm

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



Number of turns

Linear extrapolation of $P=\sqrt{P_x^2+P_z^2}$ for a time period of τ_{sc}=1000 s (=$3.7\cdot10^8$ turns)



Number of turns

Courtesy: F. Rathmann

Overall Schedule

Stepwise Approach of the JEDI Project

Step	Aim / scientific goal	Device / Tools	Storage ring
1	Spin coherence time studies	Horizontal/vertical RF-B/E spin flipper	COSY
	Systematic error studies	Vertical/horizontal RF-B/E spin flipper	COSY
2	COSY upgrade	Orbit control, magnets, …	COSY
	First direct EDM measurement **at 10^{-24} e·cm**	High-power RF-E/B spin flipper	Modified COSY
3	Built a dedicated all-in-one ring for p, d, ^{3}He	Common magnetic-electrostatic deflectors R&D funded by ARD (Accelerator Research and Development) of HGF	Dedicated ring
4	EDM measurement for p, d, ^{3}He **at 10^{-29} e·cm**		Dedicated ring

Time scale

Step 1-2: > five years
Step 3-4: > five years