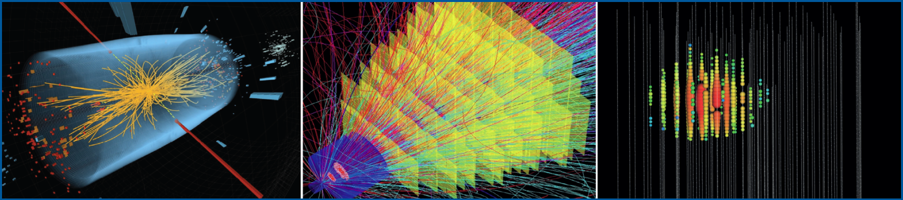
Matter and the Universe

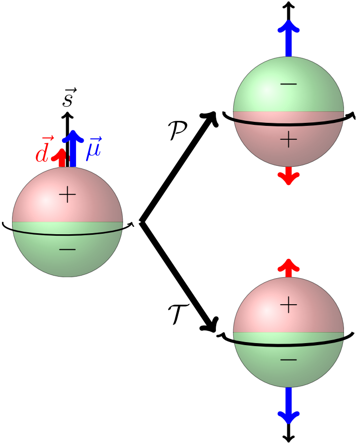
Towards Electric Dipole Moment Measurements at Storage Rings



Jörg Pretz, RWTH Aachen University & Forschungszentrum Jülich

HELMHOLTZ | ASSOCIATION

Introduction: Electric Dipole Moments

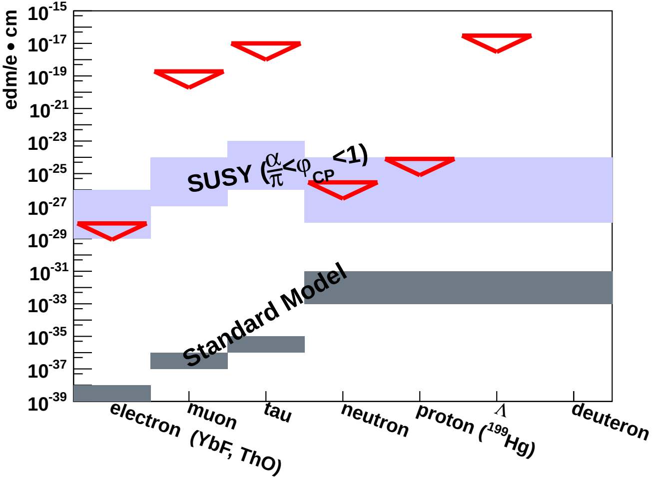


- fundamental property of particles
- violates $\mathcal{P}$ and $\mathcal{T} \overset{\mathcal{CPT}}{\equiv} \mathcal{CP}$
- search for $\mathcal{CP}$-violation beyond the Standard Model to explain matter dominance in the Universe

Motivation: Sources of $\mathcal{CP}-$Violation

Standard Model	
Weak interaction	
CKM matrix	$\rightarrow$ unobservably small EDMs
Strong interaction	
θ_{QCD}	$\rightarrow$ best limit from neutron EDM
beyond Standard Model	
e.g. SUSY	$\rightarrow$ accessible by EDM measurements

EDM: Current Upper Limits



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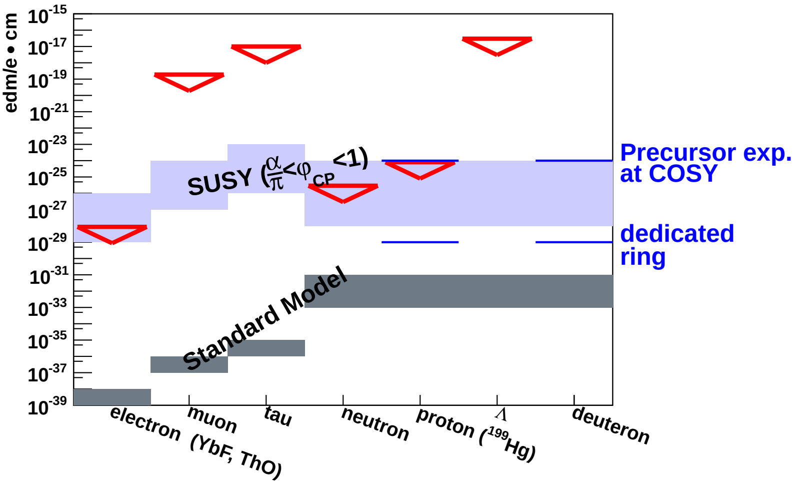


FZ Jülich: EDMs of **charged** hadrons: *p*, *d*, ^{3}He

Why Charged Particle EDMs?

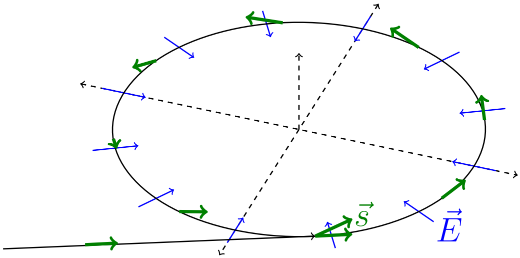
- no direct measurements for charged hadrons exist
- potentially higher sensitivity (compared to neutrons):
  - longer life time,
  - more stored protons/deuterons
- complementary to neutron EDM:
  $d_d \stackrel{?}{=} d_p + d_n \Rightarrow$ access to θ_{QCD}
- EDM of one particle alone not sufficient to identify $\mathcal{CP}-$violating source

Experimental Method: Generic Idea

For **all** EDM experiments (neutron, proton, atoms, ...):

Interaction of $\vec{d}$ with electric field $\vec{E}$

For charged particles: apply electric field in a storage ring:



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

In general:

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

build-up of vertical polarization $s_\perp \propto |d|$

Experimental Requirements

- high precision storage ring
  diagnostics: alignment, stability, field homogeneity
- high intensity beams ($N = 4 \cdot 10^{10}$ per fill)
- polarized hadron beams ($P = 0.8$)
- large electric fields ($E = 10\,\mathrm{MV/m}$)
- long spin coherence time ($\tau = 1000\,\mathrm{s}$),
- polarimetry (analyzing power $A = 0.6$, acc. $f = 0.005$)

$$\sigma_{\text{stat}} \propto \frac{1}{\sqrt{Nf}\tau PAE} \quad \Rightarrow \sigma_{\text{stat}}(1\text{year}) = 10^{-29}\; e\cdot\text{cm}$$

challenge: get σ_{sys} to the same level

Spin Precession: Thomas-BMT Equation

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \vec{\Omega} \times \vec{s} = \frac{e}{m}[G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1}\right)\vec{v} \times \vec{E} + \frac{m}{e\,s} d(\vec{E} + \vec{v} \times \vec{B})] \times \vec{s}$$

Ω: angular precession frequency

G: anomalous magnetic moment

d: electric dipole moment

γ: Lorentz factor

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Ω: angular precession frequency

G: anomalous magnetic moment

d: electric dipole moment

γ: Lorentz factor

dedicated ring: pure electric field,

freeze horizontal spin motion $\left(G - \frac{1}{\gamma^2-1}\right) = 0$

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COSY: pure magnetic ring
access to EDM via motional electric field $\vec{v} \times \vec{B}$,
requires radio-frequency E and B fields

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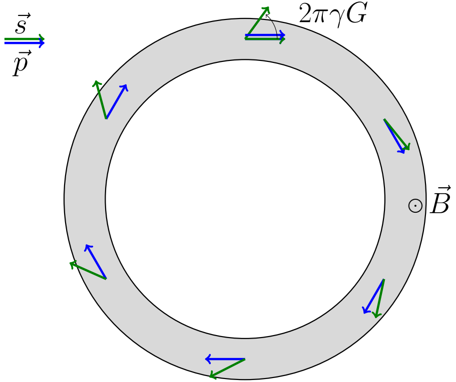
requires radio-frequency E and B fields

neglecting EDM term
spin tune: $\nu_s \approx \frac{|\vec{\Omega}|}{\omega_{\mathrm{rev}}} = \gamma G$

Spin Tune ν_s

Spin tune: $\nu_s = \gamma G = \dfrac{\text{nb. of spin rotations}}{\text{nb. of particle revolutions}}$



deuterons: $p_d = 1$ GeV/c ($\gamma = 1.13$), $G = -0.14256177(72)$

$\Rightarrow \nu_s = \gamma G \approx -0.161$

Test Measurements at COSY

unique storage ring for polarized protons and deuterons

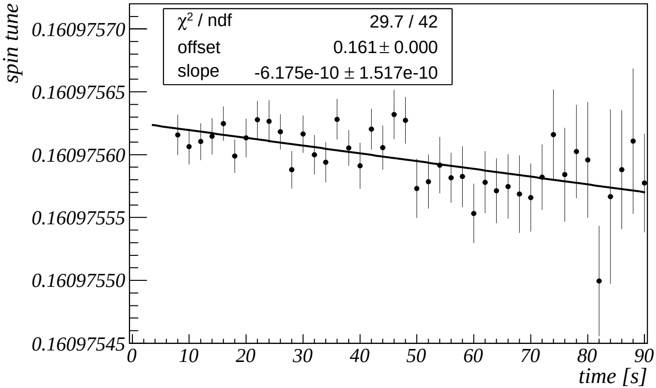
$\Rightarrow$ ideal starting point for charged hadron EDMs

Recent achievements

- **Spin tune:** $\overline{\nu_s} = -0.16097\cdots \pm 10^{-10}$ in 100 s
  (for $G = 0$, $d = 10^{-24} e{\cdot}\mathrm{cm} \Rightarrow$ spin tune = $5 \cdot 10^{-11}$)
- **Spin coherence time:** $\tau = 400$ s

Results: Spin Tune

up-down asymmetry in elastic d-carbon scattering: $A(t) \propto e^{-t/\tau} \sin(\Omega t)$

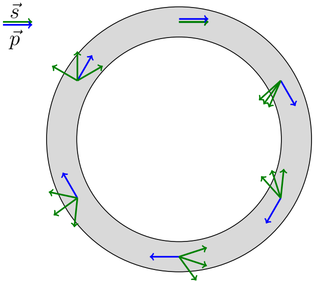


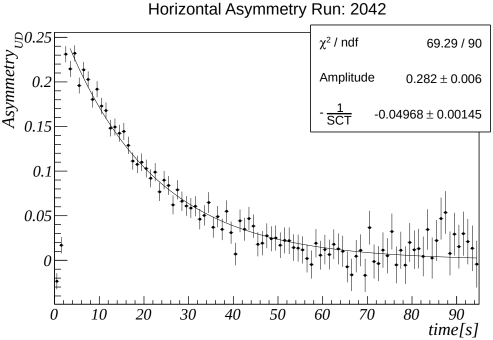
- Spin tune ν_s can be determined to $\approx 10^{-8}$ in 2 s
- Average $\overline{\nu_s}$ in cycle ($\approx$ 100 s) known to 10^{-10}

$\rightarrow$ Poster Dennis Eversmann, Fabian Hinder

Results: Spin Coherence Time (SCT)

Short Spin Coherence Time



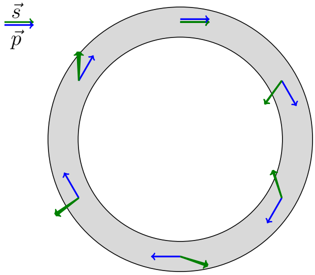


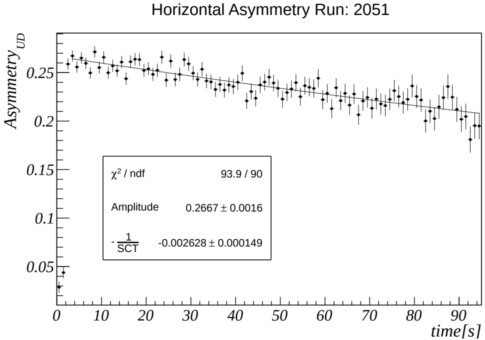
cooled bunched beam ⇒ SCT τ = 20 s

→ Poster Greta Guidoboni

Results: Spin Coherence Time (SCT)

Long Spin Coherence Time





using correction sextupole to correct for higher order effects leads to SCT of τ =400 s

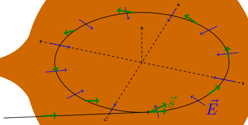
→ Poster Greta Guidoboni

International Framework

Spin physics,
Storage ring
COSY

$\vec{E}$-deflectors
FNAL,RWTH,
Jülich ZEA

Theory
Jülich IKP



Ring design,
Spin tracking
MSU, Cornell,
BNL, BINP
Jülich JSC

Polarimeter
Ferrara,
RWTH

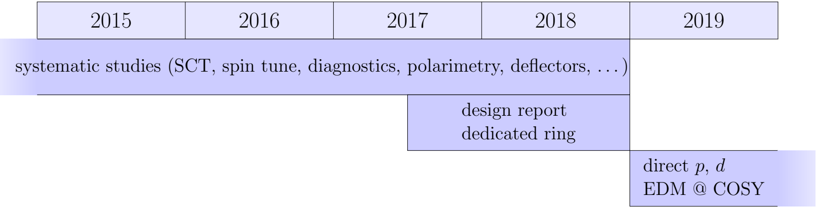
Diagnostics
Jülich PGI,
Jülich ZEA

JEDI Collaboration

- **JEDI** = **J**ülich **E**lectric **D**ipole Moment **I**nvestigations
- $\approx$ 100 members
  (Aachen, Dubna, Ferrara, Indiana, Ithaca, Jülich, Krakow, Michigan, Minsk, Novosibirsk, St. Petersburg, Stockholm, Tbilisi, . . .)
- $\approx$ 10 PhD students
- part of **JARA FAME** (**F**orces **A**nd **M**atter **E**xperiments)

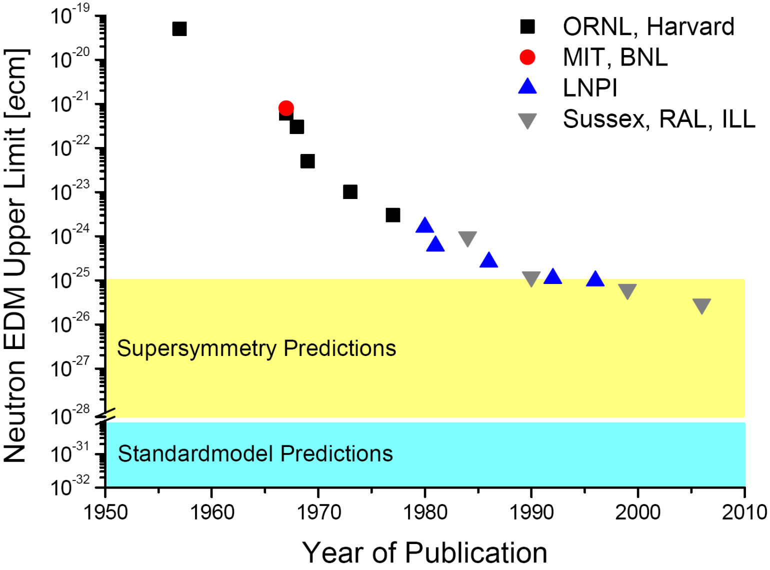
Summary & Outlook

- EDMs of **charged** particles can be measured at **storage rings**
- **COSY** at **Forschungszentrum Jülich** is ideal place to perform such measurements
- PoF 3:

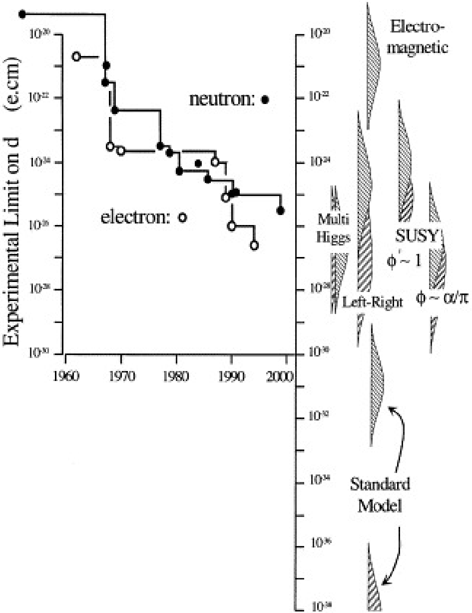


Spare

History of Neutron EDM Limits



Electron and Neutron EDM



J. M. Pendlebury & E.A. Hinds, NIMA 440(2000) 471

EDM: SUSY Limits

electron:

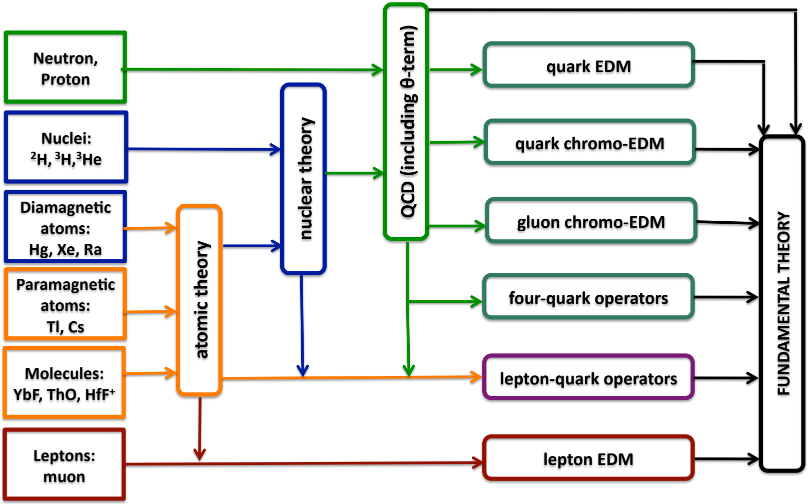
MSSM: $\varphi \approx 1 \Rightarrow d = 10^{-24} - 10^{-27} e{\cdot}\text{cm}$

$$\varphi \approx \alpha/\pi \Rightarrow d = 10^{-26} - 10^{-30} e{\cdot}\text{cm}$$

neutron:

MSSM: $d = 10^{-24} e{\cdot}\text{cm} \cdot \sin\phi_{CP} \frac{200\text{GeV}}{M_{SUSY}}$

Sources of $\mathcal{CP}$ Violation

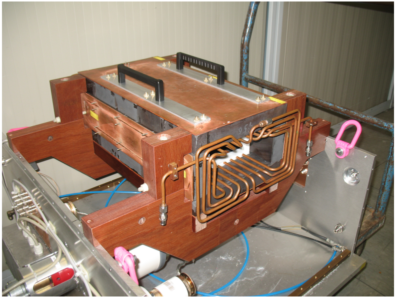


J. de Vries

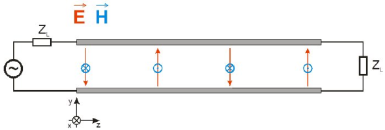
Electrostatic Deflectors

- Electrostatic deflectors from Fermilab ($\pm$125kV at 5 cm $\hat{=}$ 5MV/m)
- large-grain Nb at plate separation of a few cm yields $\approx$ 20MV/m

Wien Filter

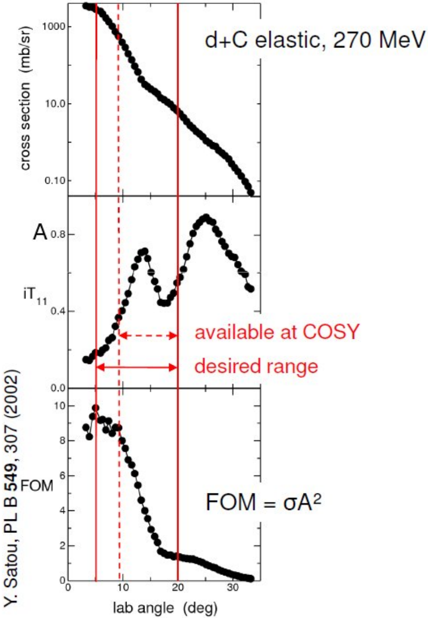


Conventional design
R. Gebel, S. Mey (FZ Jülich)



stripline design
D. Hölscher, J. Slim
(IHF RWTH Aachen)

Polarimetry



Cross Section & Analyzing Power for deuterons

$N^{up,dn} \propto$
$(1 \pm P\,A\,\sin(\gamma G f_{rev} t))$

$$A_{up,dn} = \frac{N^{up} - N^{dn}}{N^{up} + N^{dn}}$$
$$= P\,A\,\sin(\gamma G f_{rev} t)$$

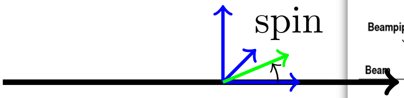
A : analyzing power
P : beam polarization

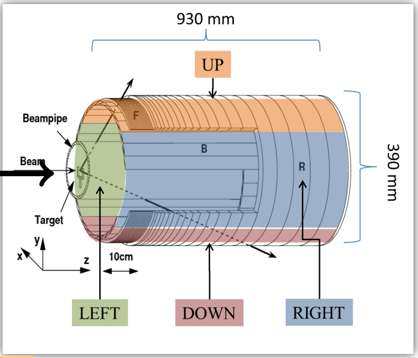
Polarimeter

elastic deuteron-carbon scattering

Left/Right asymmetry $\propto$ vertical polarization $\propto$ d

Up/Down asymmetry $\propto$ horizontal polarization $\propto$ γG





→ Poster Fabian Hinder

Paper from F. Wilczek

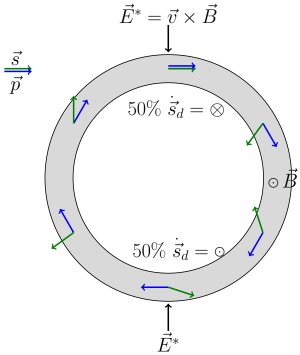
- …unique, extraordinarily sensitive way to probe … violation of microscopic time-reversal invariance.
- …put the best limits on the θ parameter, …
- …θ parameter is tied up with profound theoretical ideas, …a plausible resolution of the cosmological dark matter problem. (axions)
- …constrain many implementations of supersymmetry …
- If supersymmetry is valid, it very plausibly leads to electric dipole moments not far beyond present-day limits, and within the scope of known experimental technique.

Frank Wilczek:
"Importance and Promise of Electric Dipole Moments",Jan. 2014
http://www.usparticlephysics.org/node/901/webform-results/public)

1. Pure Magnetic Ring

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

Problem:
Due to precession caused by magnetic moment, 50% of time longitudinal polarization component is $||$ to momentum, 50% of the time it is anti-$||$.



E^* field in the particle rest frame tilts spin due to EDM up and down
$\Rightarrow$ **no net EDM effect**

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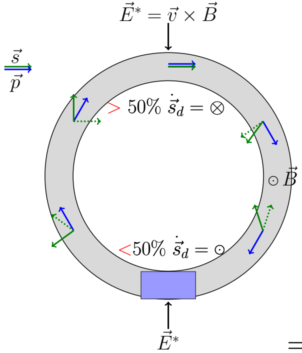

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Use resonant "magic Wien-Filter" in ring ($\vec{E} + \vec{v}\times\vec{B} = 0$):
$E^* = 0 \rightarrow$ part. trajectory is not affected but
$B^* \neq 0 \rightarrow$ mag. mom. is influenced

$\Rightarrow$ **net EDM effect can be observed!**

2. Pure Electric Ring

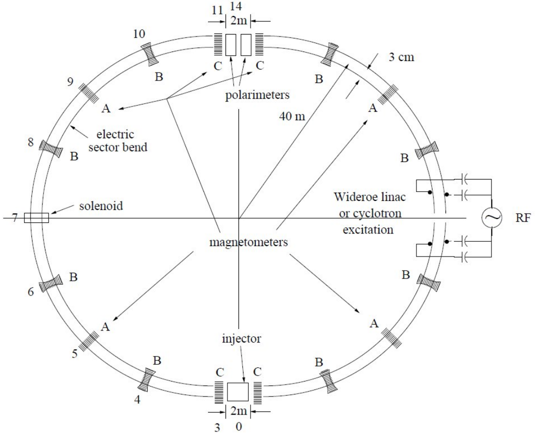


Figure 3: An all-electric storage ring lattice for measuring the electric dipole moment of the proton. Except for having longer straight sections and separated beam channels, the all-in-one lattice of Fig. 1 is patterned after this lattice. Quadrupole and sextupole families, and tunes and lattice functions of the all-in-one lattice of Fig. 1 will be quite close to those given for this lattice in reference[3]. The match will be even closer with magnetic field set to zero for proton operation.

Brookhaven National Laboratory (BNL) Proposal

3. Combined $\vec{E}/\vec{B}$ ring

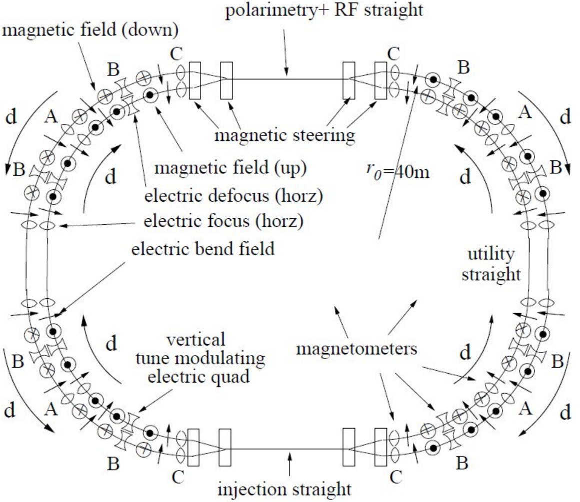


Figure 1: "All-In-One" lattice for measuring EDM's of protons, deuterons, and helions.

Under discussion at Forschungszentrum Jülich (design: R. Talman)

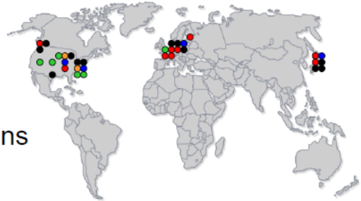
Summary of different options

	☺	☹
1.) pure magnetic ring (Jülich)	existing (upgraded) COSY ring can be used , shorter time scale	lower sensitivity
2.) pure electric ring (BNL)	no $\vec{B}$ field needed	works only for p
3.) combined ring (Jülich)	works for p, d, ^{3}He, ...	both $\vec{E}$ and $\vec{B}$ required

EDM Activities Around the World

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

K. Kirch

Investments EDM Precursor Experiment

	price per unit/ kEuro	nb. of units	total/ kEuro
Beam Diagnostics			
Beam Position Monitors	70	20	1,400
Beam Profile Monitors	150	2	300
Beam Current Monitor	300	1	300
Steerer/Power Supply	20	20	400
HF Generator	250	1	250
Power Supply RF	250	1	250
Feed Back System	50	1	50
total			2,950

according to table on page 47 in proposal

Systematics

Major source:
Radial B field mimics an EDM effect:

- Difficulty: even small radial magnetic field, B_r can mimic EDM effect if :$\mu B_r \approx dE_r$
- Suppose $d = 10^{-29} e{\cdot}\text{cm}$ in a field of $E = 10\text{MV/m}$
- This corresponds to a magnetic field:
  $B_r = \frac{dE_r}{\mu_N} = \frac{10^{-22} e\mathrm{V}}{3.1 \cdot 10^{-8} e\mathrm{V}/\mathrm{T}} \approx 3 \cdot 10^{-17}\mathrm{T}$
  (Earth Magnetic field $\approx 5 \cdot 10^{-5}$ T)

Solution: Use two beams running clockwise and counter clockwise, separation of the two beams is sensitive to B_r

Systematics

- Splitting of beams: $\delta y = \pm \frac{\beta c R_0 B_r}{E_r Q_y^2} = \pm 1 \cdot 10^{-12}\,\mathrm{nm}$
- $Q_y \approx 0.1$: vertical tune
- Modulate $Q_y = Q_y^0 (1 - m\cos(\omega_m t)),\ m \approx 0.1$
- Splitting causes B field of $\approx 0.4 \cdot 10^{-3}\,\mathrm{fT}$
- in one year: 10^4 fills of $1000\,\mathrm{s} \Rightarrow \sigma_B = 0.4 \cdot 10^{-1}\mathrm{fT}$ per fill needed
- Need sensitivity $1.25\,\mathrm{fT}/\sqrt{\mathrm{Hz}}$

D. Kawall

Systematics