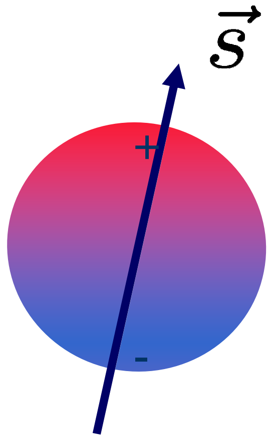


Indirect Searches for New Physics at the time of LHC
Florence, 22-24 March 2010

EDM experiments

Yannis K. Semertzidis
Brookhaven National Lab

- Mercury EDM ^{199}Hg
- Neutron EDM experiments
- Ra EDM, Electron EDM experiments
- Storage Ring EDM experiments (proton & deuteron)
- …

Electric Dipole Moments: P and T-violating when $\vec{d}$ // to spin

$$\vec{\mu} = g\left(\frac{q}{2m}\right)\vec{s},$$

$$\vec{d} = \eta\left(\frac{q}{2mc}\right)\vec{s}$$

$$\mathcal{H} = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E}$$

	$\vec{E}$	$\vec{B}$	$\vec{\mu}$ or $\vec{d}$
P	$-$	$+$	$+$
C	$-$	$-$	$-$
T	$+$	$-$	$-$

EDM physics without spins is not important (batteries are allowed!)


The great mystery in our Universe: matter dominance over anti-matter.
EDMs could point to a strong CP-violation source capable of creating the observed asymmetry.

EDM methods (they all are sensitive to different combinations of CPV sources)

- Neutrons: Ultra Cold Neutrons, apply large E-field and a small B-field. Probe frequency shift with E-field flip

- Atomic & Molecular Systems: Probe 1st order Stark effect

- Storage Ring EDM for charged particles: Utilize large E-field in rest frame-Spin precesses out of plane (Probe angular distribution changes)

Important Stages in an EDM Experiment

1. Polarize: state preparation, intensity of beams

2. Interact with an E-field: the higher the better

3. Analyze: high efficiency analyzer

4. Scientific Interpretation of Result! Easier for the simpler systems

EDM method Advances

- Neutrons: advances in stray B-field effect reduction; higher UCN intensities

- Atomic & Molecular Systems: high effective E-field

- Storage Ring EDM for D, P: High intensity polarized sources well developed; High electric fields made available; spin precession techniques in SR well understood

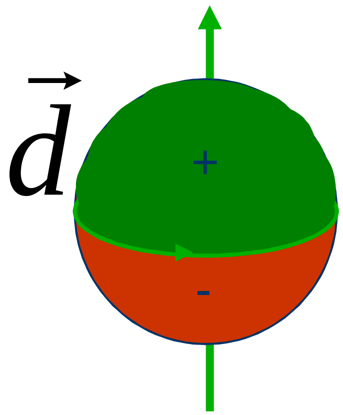
EDM method Weaknesses

- Neutrons: Intensity; High sensitivity to stray B-fields; Motional B-fields and geometrical phases

- Atomic & Molecular Systems: Low intensity of desired states; in some systems: physics interpretation

- Storage Ring EDM: sensitive to vertical E-fields or radial B-fields; some systematic errors different from g-2,…

The Electric Dipole Moment precesses in an Electric field



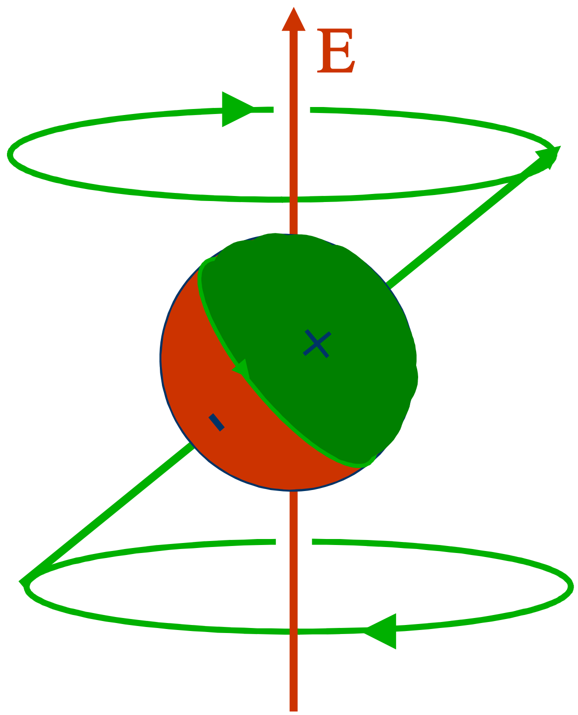
The EDM vector *d* is along the particle spin direction

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

Yannis Semertzidis, BNL

Spin precession at rest

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



Compare the Precession Frequencies with E-field Flipped:

$$\hbar\left(\omega_1 - \omega_2\right) = 4dE$$

$$\sigma_d \propto \frac{1}{EPA}\frac{1}{\sqrt{N\tau T}}$$

Main Systematic Error: particles have non-zero magnetic moments!

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

- For the nEDM experiments a co-magnetometer or SQUIDS are used to monitor the B-field

The mercury EDM experimental results published last year to the month

PRL **102,** 101601 (2009) PHYSICAL REVIEW LETTERS week ending 13 MARCH 2009

Improved Limit on the Permanent Electric Dipole Moment of ^{199}Hg

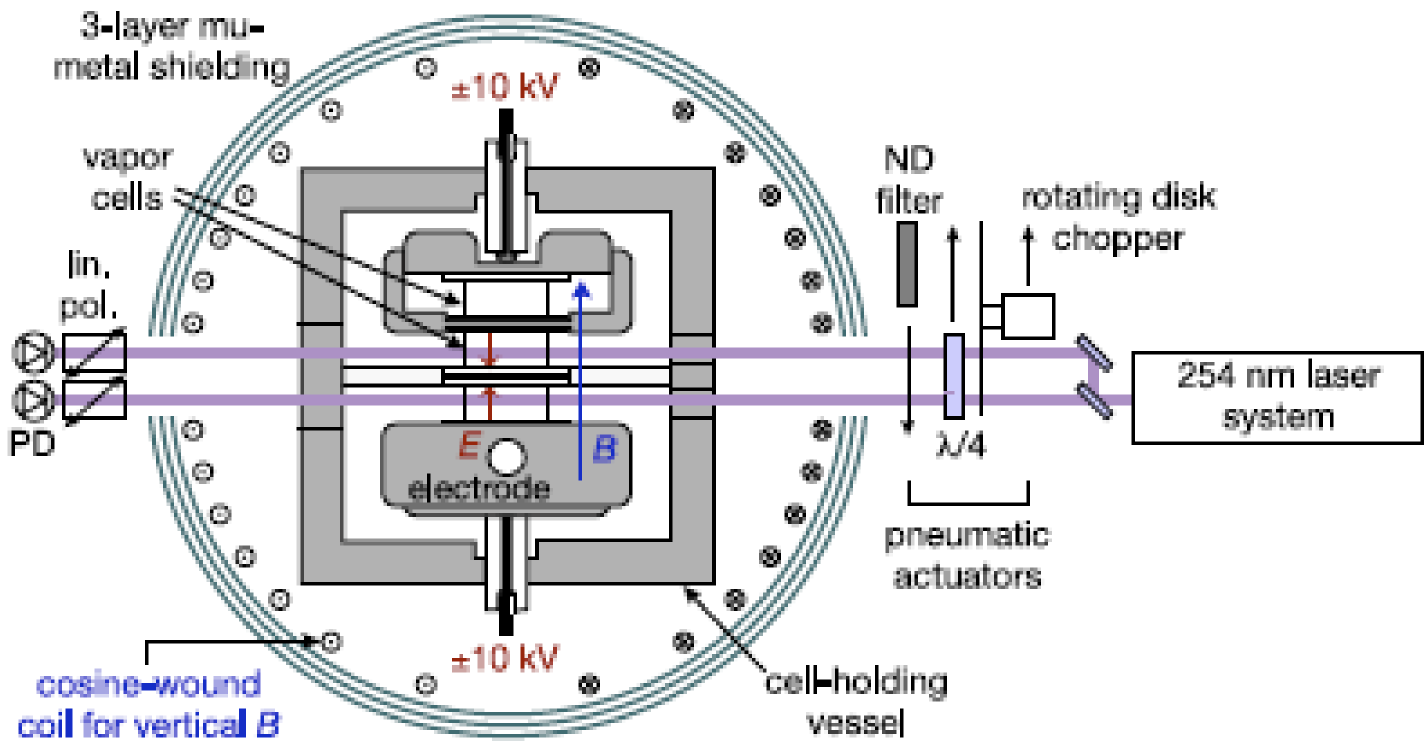
W. C. Griffith,* M. D. Swallows,† T. H. Loftus, M. V. Romalis,‡ B. R. Heckel, and E. N. Fortson§

Department of Physics, University of Washington, Seattle, Washington 98195, USA

(Received 19 January 2009; published 10 March 2009)

We report the results of a new experimental search for a permanent electric dipole moment of ^{199}Hg utilizing a stack of four vapor cells. We find $d(^{199}\mathrm{Hg}) = (0.49 \pm 1.29_{\mathrm{stat}} \pm 0.76_{\mathrm{syst}}) \times 10^{-29}$ e cm, and interpret this as a new upper bound, $|d(^{199}\mathrm{Hg})| < 3.1 \times 10^{-29}$ e cm (95% C.L.). This result improves our previous ^{199}Hg limit by a factor of 7, and can be used to set new constraints on *CP* violation in physics beyond the standard model.

The apparatus and parameter values



- B=22 mG
- V=±10 KV, E=~2 MV/m (height of cell ~1cm)
- SCT = 10^2 s

The data

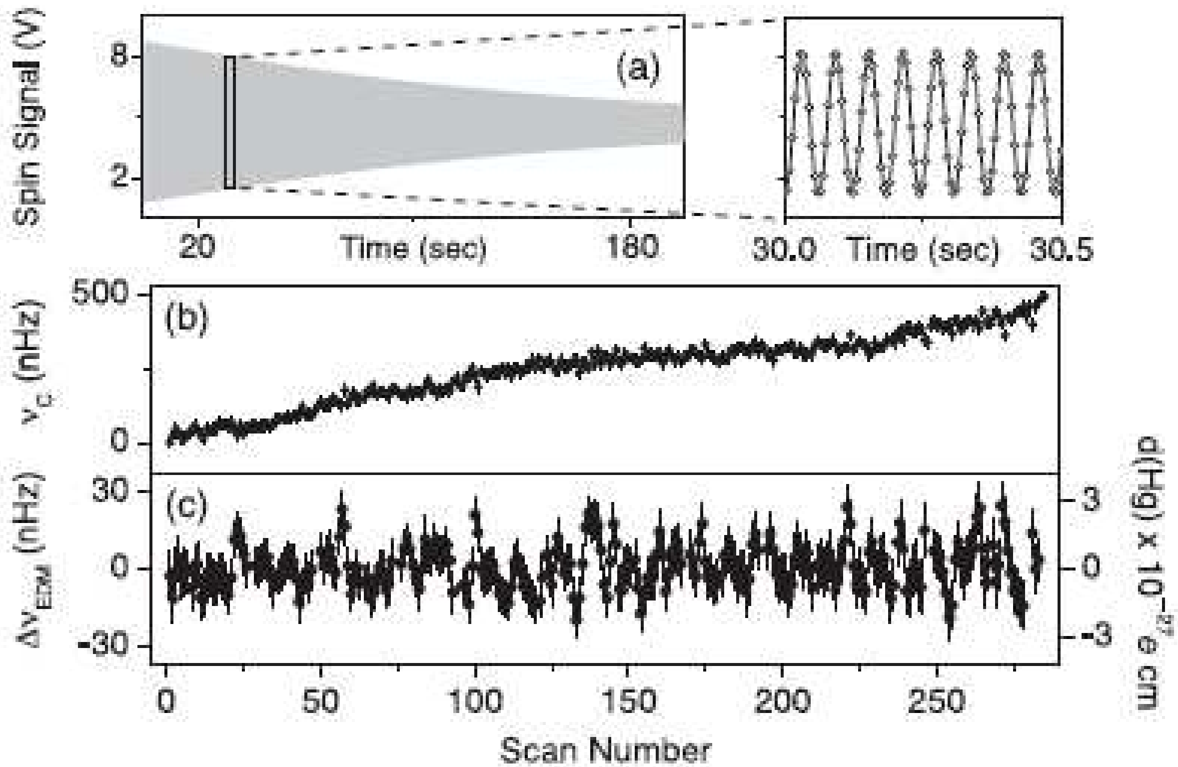


FIG. 2. (a) Typical single-cell precession signal with an expanded 0.5 sec segment. (b),(c) ν_c and $\Delta\nu_{EDM}$ for a typical run. In (c) the reduced χ^2 is 1.2 and the run-averaged statistical error is 0.85 nHz after scaling by $\sqrt{\chi^2}$.

- The drift in frequency is taken out by taking the frequency difference between the cells.
- Runs with micro-sparking are taken out.

Systematic errors

TABLE I. Systematic error budget (10^{-30} e cm).

Source	Error	Source	Error
Leakage currents	4.53	Charging currents	0.40
Parameter correlations	4.31	Convection	0.36
Spark analysis	4.16	$(\vec{v} \times \vec{E})$ B fields	0.18
Stark interference	1.09	Berry's phase	0.18
E^2 effects	0.62	*Quadrature sum*	7.63

- The systematic error is ~60% of the statistical error

The results and best limits

Parameter	^{199}Hg bound	Hg theory	Best alternate limit
$\tilde{d}_q$ (cm) [a]	6×10^{-27}	[15]	n: 3×10^{-26} [3]
d_p (e cm)	7.9×10^{-25}	[16]	TlF: 6×10^{-23} [17]
C_S	5.2×10^{-8}	[18]	Tl: 2.4×10^{-7} [19]
C_P	5.1×10^{-7}	[18]	TlF: 3×10^{-4} [1]
C_T	1.5×10^{-9}	[18]	TlF: 4.5×10^{-7} [1]
$\bar{\theta}_{QCD}$	3×10^{-10}	[20]	n: 1×10^{-10} [3]
d_n (e cm)	5.8×10^{-26}	[16]	n: 2.9×10^{-26} [3]
d_e (e cm)	3×10^{-27}	[21,22]	Tl: 1.6×10^{-27} [18]

[a]For ^{199}Hg, $\tilde{d}_q = (\tilde{d}_u - \tilde{d}_d)$, while for n, $\tilde{d}_q = (0.5\tilde{d}_u + \tilde{d}_d)$.

- It now dominates the limits on many parameters
- They expect another improvement factor ~3 - 5.

What is this?

PHYSICAL REVIEW C **81**, 038501 (2010)

Electric dipole moments (EDM) of ionic atoms

Sachiko Oshima*

Department of Physics, Faculty of Science and Technology, Nihon University, Tokyo, Japan

(Received 8 August 2009; published 17 March 2010)

Recent investigations show that the second-order perturbation calculations of electric dipole moments (EDM) from the finite nuclear size as well as the relativistic effects are all canceled out by the third-order perturbation effects and that this is due to electron screening. To derive the nucleon EDM from the nucleus, we propose to measure the EDM of an ionic system. In this case, it is shown that the nucleon EDM can survive by the reduction factor of $1/Z$ for the ionic system with one electron stripped off.

- It claims that the nuclear size and relativistic effects are cancelled when estimated to third order. If this paper is correct it changes everything. Those subjects are, however, subtle and we should not rush into conclusions yet.

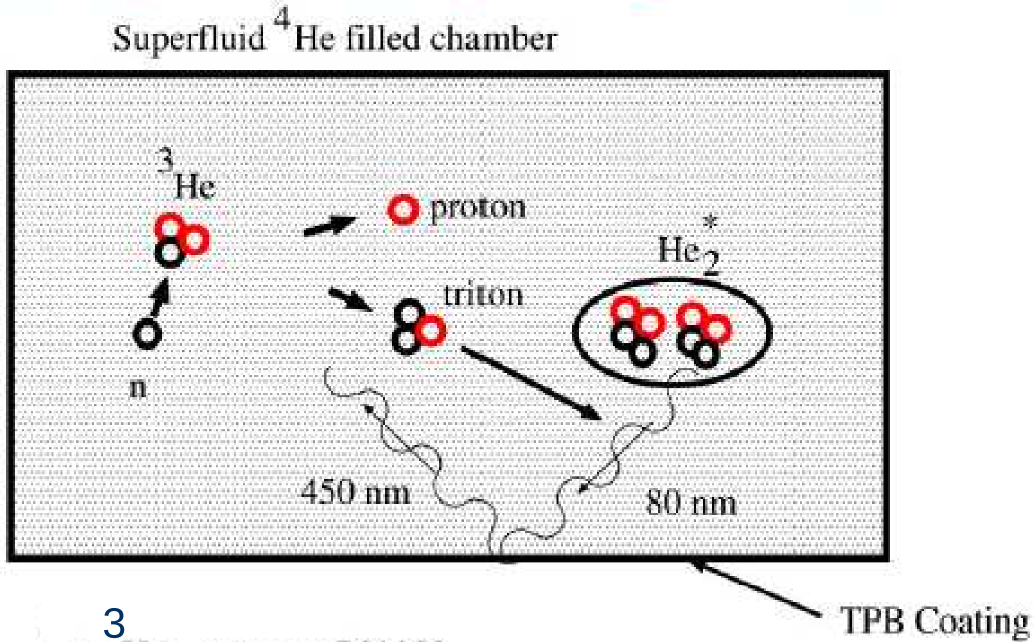
The nEDM Project

Martin Cooper

Co-spokesperson, CPM

Los Alamos National Laboratory

SUPERFLUID HELIUM AS A DETECTOR



$n + {}^3He \rightarrow p + t + 764\ kV$

The energetic charged particles produced excited state helium molecules, He_2^*

The excited state decays in a few nsec (triplet) and produces 80 nm light for which the superfluid helium is transparent.

The 80 nm light is converted to 450 nm (visible) that can be detected by a photomultiplier tube. Approximately 1 photon/keV deposited is produced.

^{3}He-DOPANT AS AN ANALYZER

$$^3\vec{He} + \vec{n} \rightarrow t + p$$

σ(parallel) $< 10^2$ b

σ(opposite) $\sim 10^4$ b

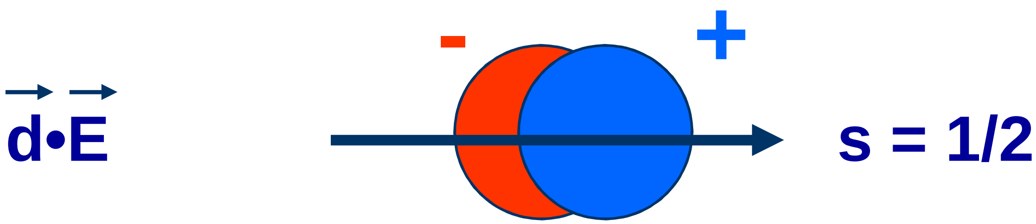
UCN loss rate ~

$$1-\vec{p}_3 \bullet \vec{p}_n = 1-p_3 p_n \cos[(\gamma_n-\gamma_3)B_0 + 2dE]t$$

Applying spin dressing techniques to equalize and further reduce the stray B-field sensitivity

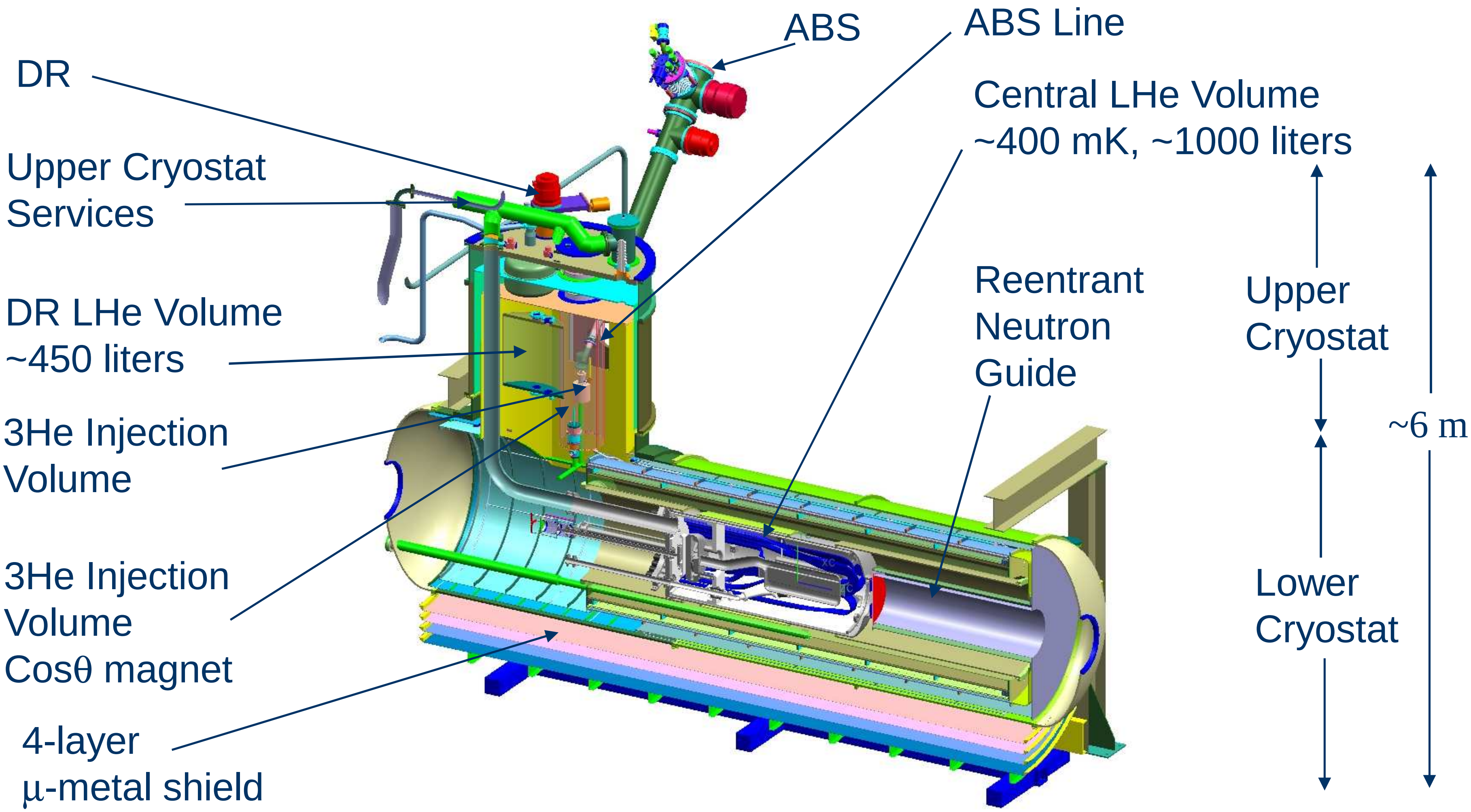
The Permanent EDM of the Neutron

- A permanent EDM $\vec{d}$

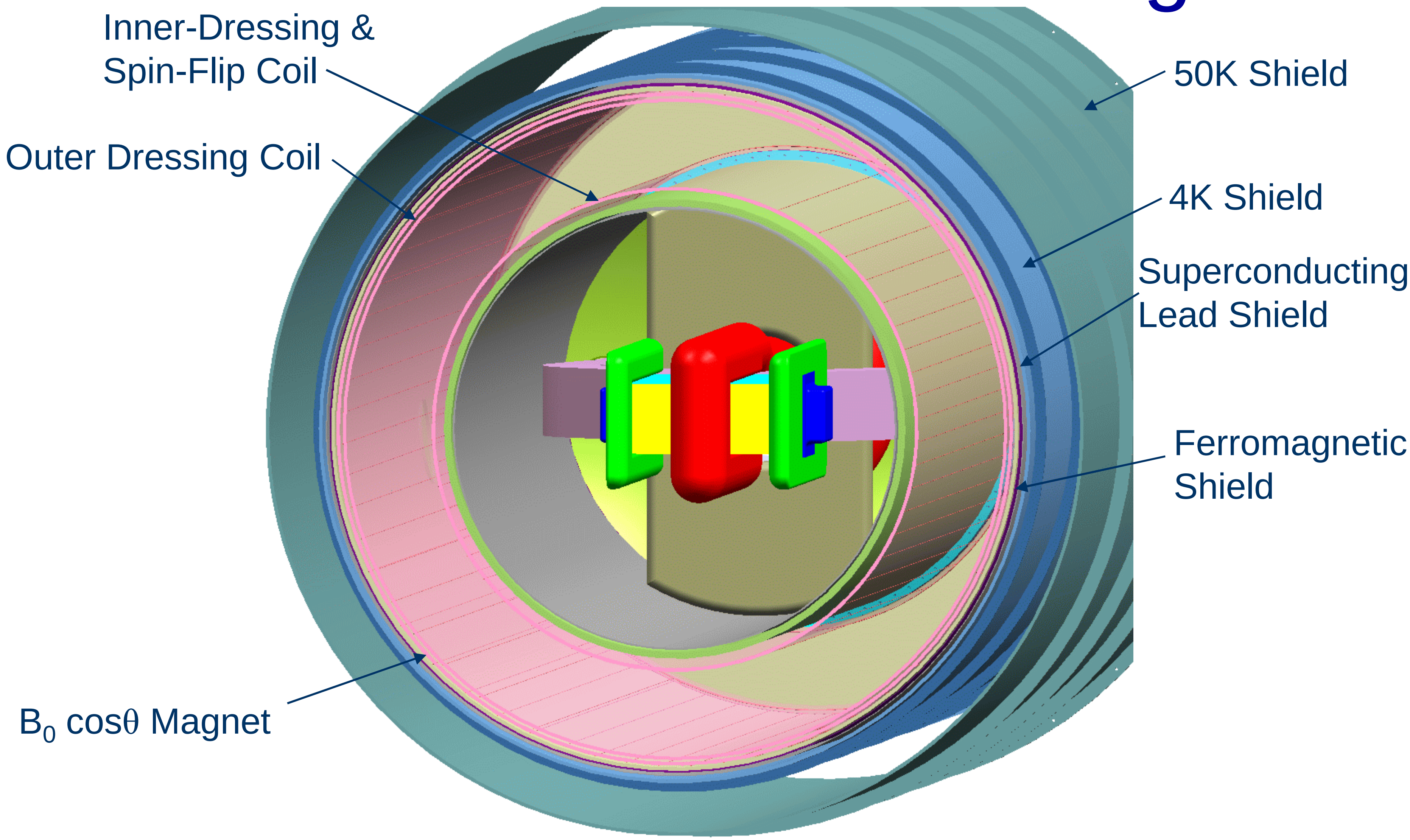


- The current value is < 3 x 10^{-26} e•cm (90% C.L.)
- Hope to obtain roughly < 2 x 10^{-28} e•cm with UCN in superfluid He

EDM Experiment - Vertical Section View



Coil and Shield Nesting



Funding

- Total DOE funding = $11,795k

- Total NSF funding = $7,450

All R&D items done or mostly done

Schedule

- Feb 2007 Conceptual Design Approved
- 2009 Technical Feasibility, Preliminary Engineering, Cost and Schedule Baseline Approved
- Aug 2010 DOE CD 2/3a Approval
- Jan 2011 Beneficial Occupancy of FnPB UCN Building
- Oct 2015 nEDM Project Completed
- 2018 First Published Results @ few ´ 10^{-27} e•cm
- 2020 nEDM Experiment Completed and Published @ few ´ 10^{-28} e•cm

Neutron EDM at PSI

Strategy

- Phase I:
  - Operate and improve OILL@ILL (-2008)
  - Move of OILL in 2008 (approved by RAL/Sussex)
  - Design of n2EDM, related R&D
- Phase II:
  - Operate OILL@PSI (2009-2010)
  - Sensitivity goal: 5×10^{-27}ecm
  - Setup of n2EDM, continued R&D
- Phase III:
  - Operate n2EDM@PSI (2011-2015)
  - Sensitivity goal: 5×10^{-28}ecm

Optimize in-vacuum, room-temperature technique

Neutron EDM Timeline

	Exp begin data taking	Exp goal
2005		
2007		
2008		
2009	UCN-PSI	$\sim 10^{-27}$ e·cm
	UCN-ILL	2×10^{-28} e·cm/yr
2011		
	UCN-LANL/SNS	$<2\times 10^{-28}$ e·cm

Deformed nuclei

- ^{225}Ra at Argonne National Lab, Roy Holt et al.

- ^{225}Ra (starting tests with Ba) at KVI (The Netherlands): K. Jungmann, L. Willmann…

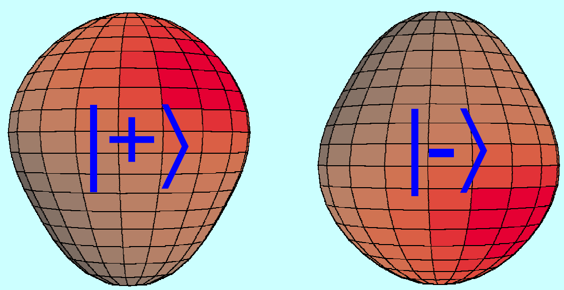
Enhanced EDM of Radium-225

Enhancement mechanisms:

- Large intrinsic Schiff moment due to octupole deformation;
- Closely spaced parity doublet;
- Relativistic atomic structure.

Haxton & Henley (1983)
Auerbach, Flambaum & Spevak (1996)
Engel, Friar & Hayes (2000)

Parity doublet



$$\Psi^- = (|+\rangle - |-\rangle)/\sqrt{2}$$

55 keV

$$\Psi^+ = (|+\rangle + |-\rangle)/\sqrt{2}$$

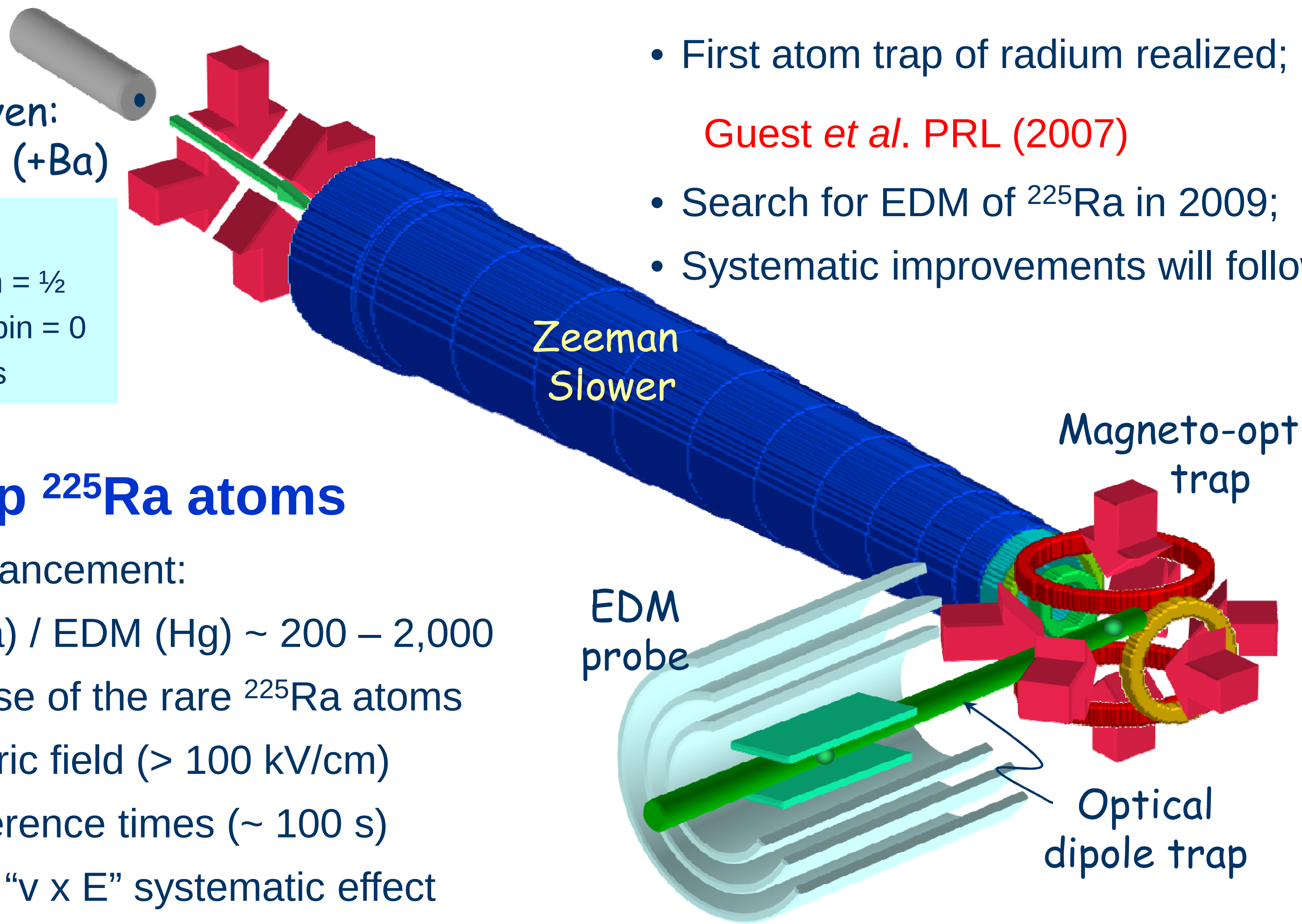
Enhancement Factor: EDM (^{225}Ra) / EDM (^{199}Hg)

Skyrme Model	Isoscalar	Isovector	Isotensor
SkM*	1500	900	1500
SkO'	450	240	600

Schiff moment of ^{199}Hg, de Jesus & Engel, PRC (2005)
Schiff moment of ^{225}Ra, Dobaczewski & Engel, PRL (2005)

From Roy Holt

An Experiment to Search for EDM of ^{225}Ra



^{225}Ra
Nuclear Spin = ½
Electronic Spin = 0
$t_{1/2}$ = 15 days

Status and Outlook

- First atom trap of radium realized;

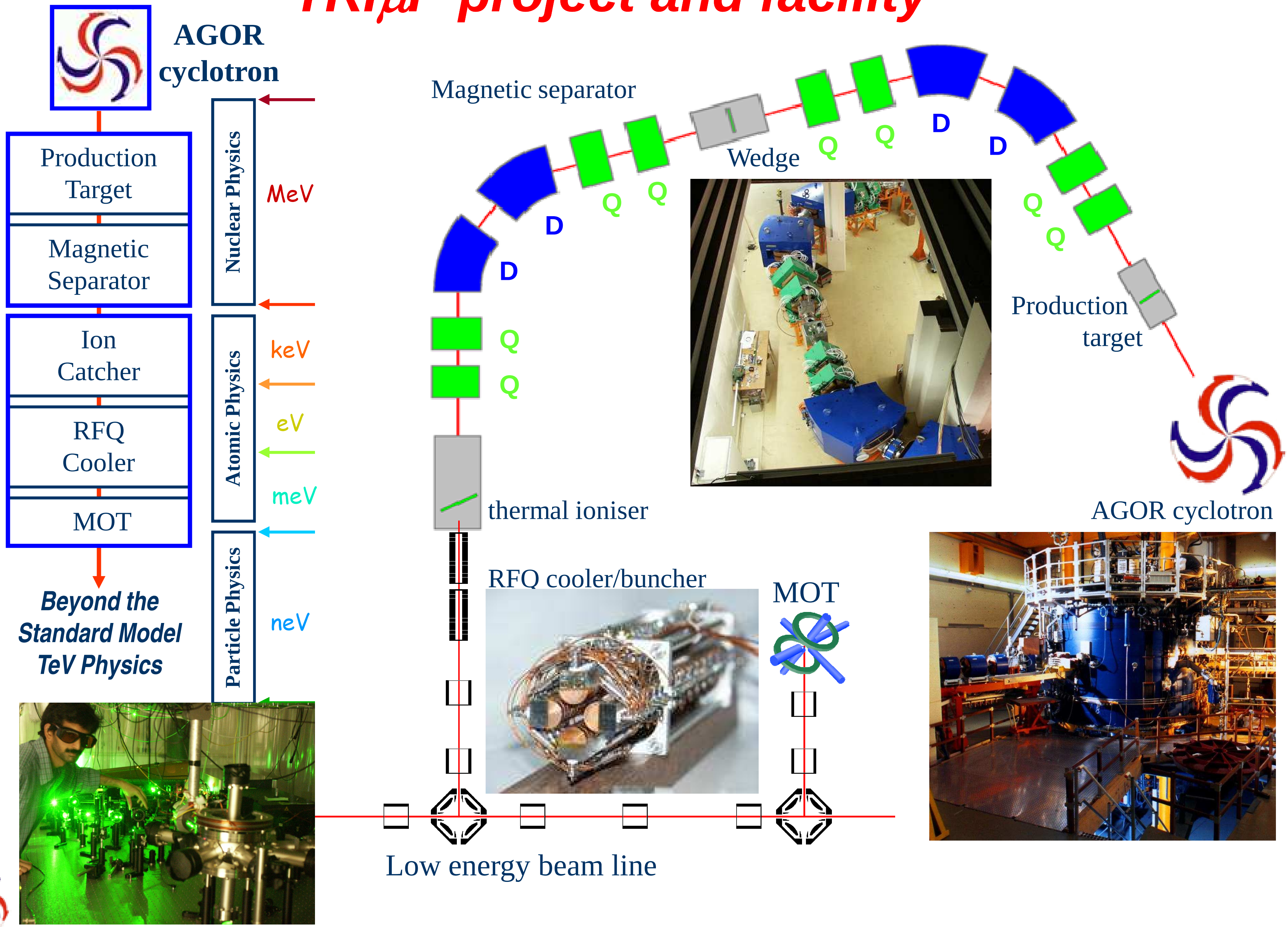
  Guest *et al*. PRL (2007)
- Search for EDM of ^{225}Ra in 2009;
- Systematic improvements will follow.

Why trap ^{225}Ra atoms

- Large enhancement:

  EDM (Ra) / EDM (Hg) ~ 200 – 2,000
- Efficient use of the rare ^{225}Ra atoms
- High electric field (> 100 kV/cm)
- Long coherence times (~ 100 s)
- Negligible "v x E" systematic effect

TRIμP project and facility

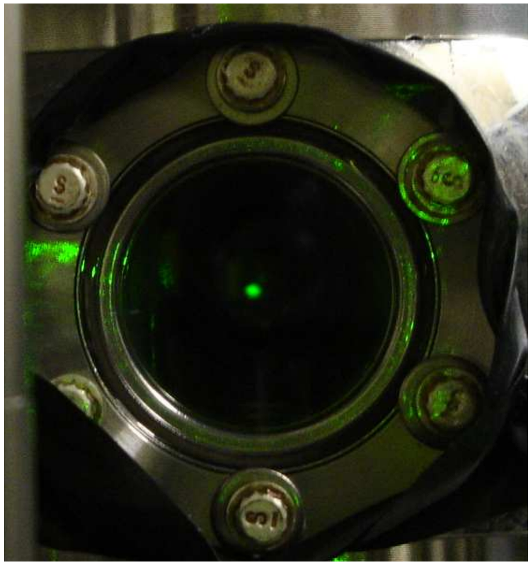


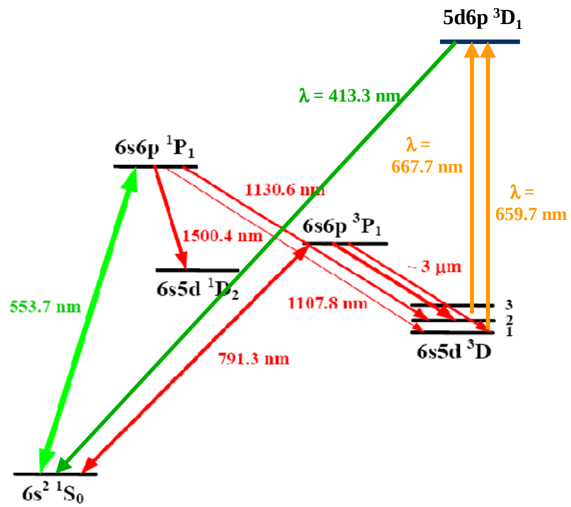
KVI

Trapped Radioactive Isotopes: μicro-laboratories for Fundamental Physics

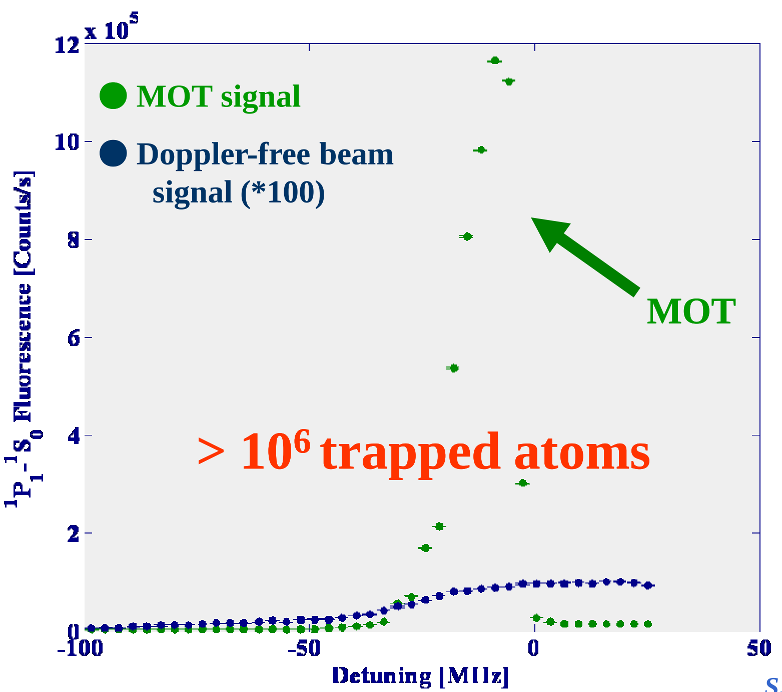
TRIμP

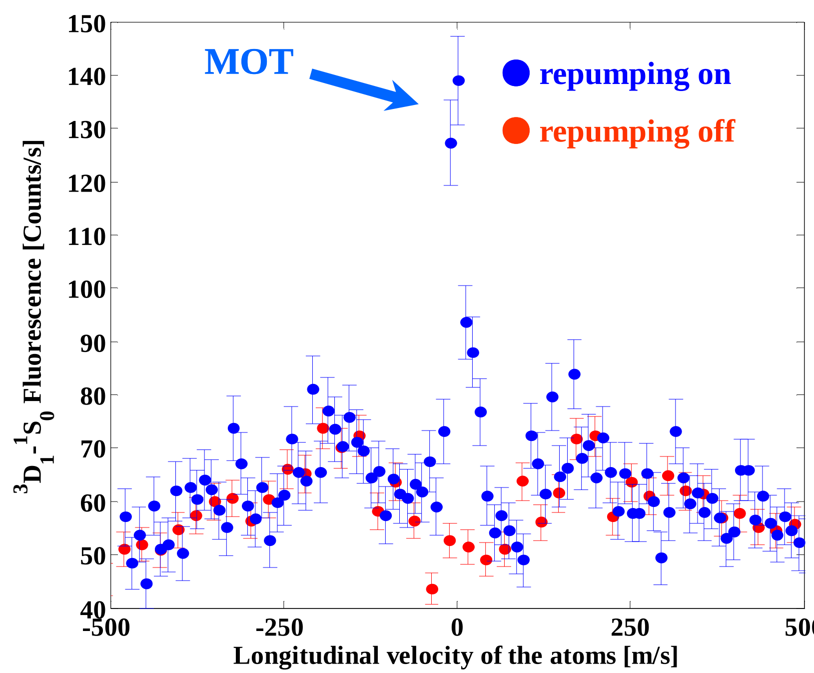
Big Step: Efficient Trapping of Barium Atoms





- Scheme avoids *dark resonances*
- 7 lasers at one time needed
- 1.5 s trap lifetime sufficient
- 10^6 atoms trapped
- improvements possible
- 10^4 higher trapping efficiency achieved than for Ra
- at TRIμP 10^5 ^{213}Ra atoms expected in trap





An untapped resource: Heavy paramagnetic molecules are approximately10,000 times more sensitive to an *e*-EDM than atoms.

Can we reach 10^{-31} *e* cm??

Active drill sites:

PbF: University of Oklahoma (Shafer-Ray)

ThO: Yale, Harvard, (DeMille, Doyle, Gabrielse)

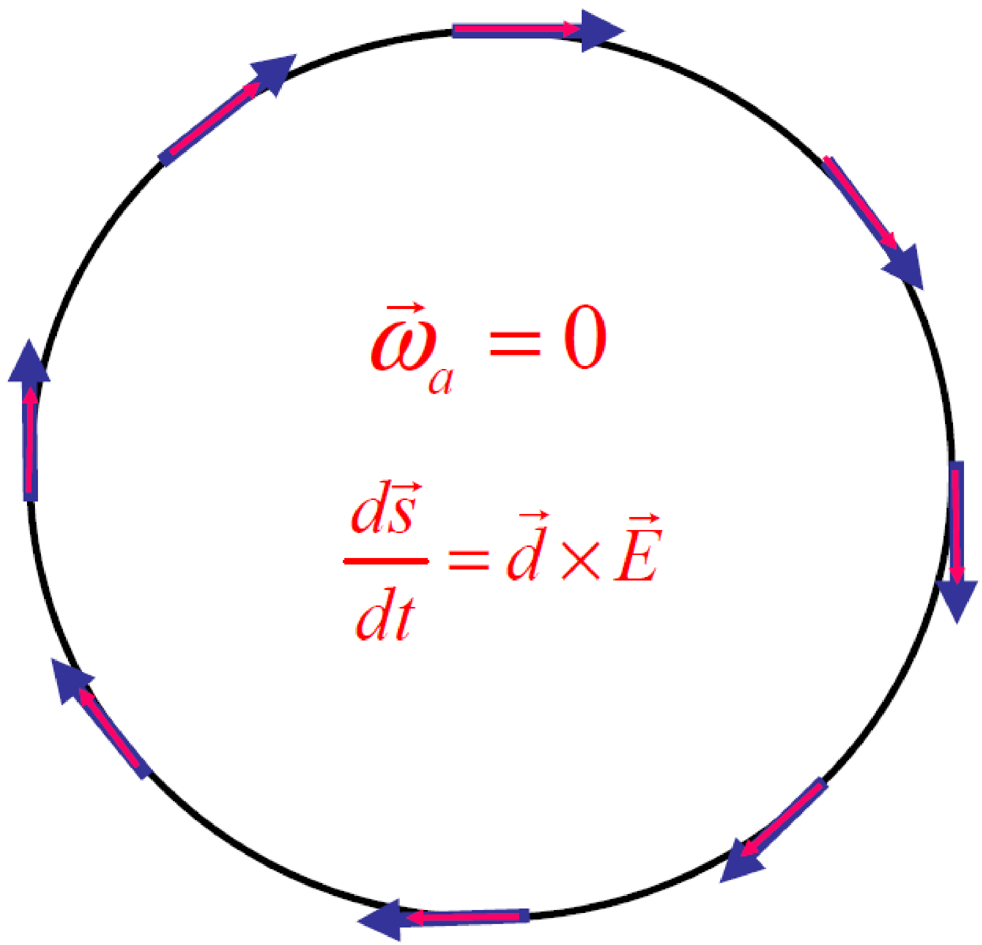
HfF^+: NIST, NRC, University of Colorado (Eric Cornell, John Bohn)

YbF: Oxford (Ed Hinds)

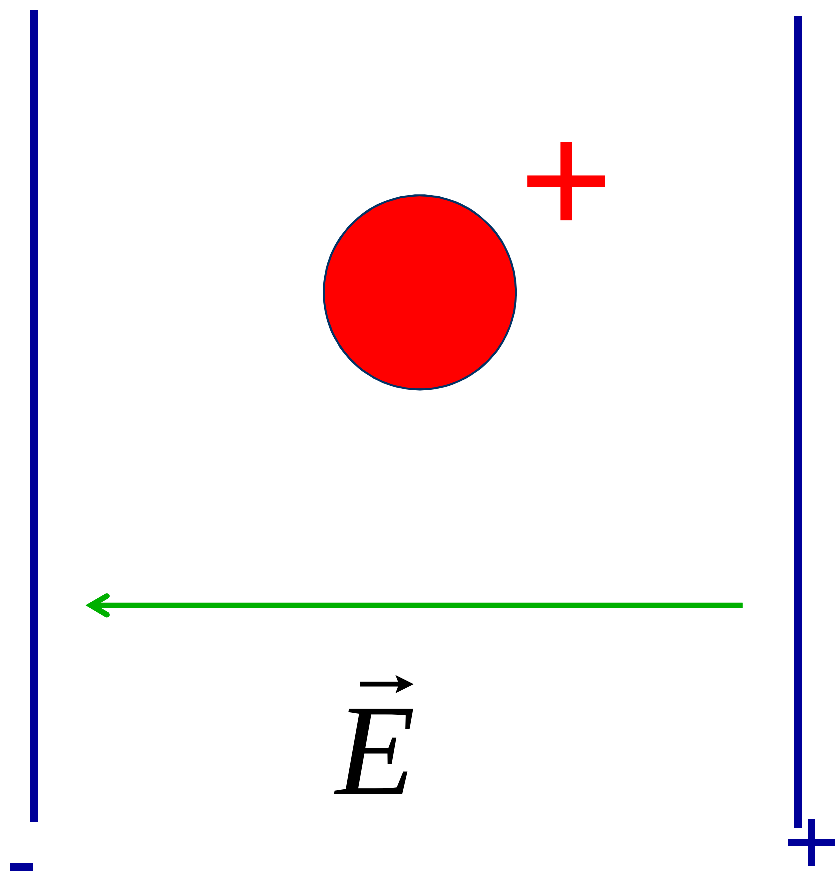
PbO: Yale (David DeMille)

WC: Michigan (Aaron Learnhardt)

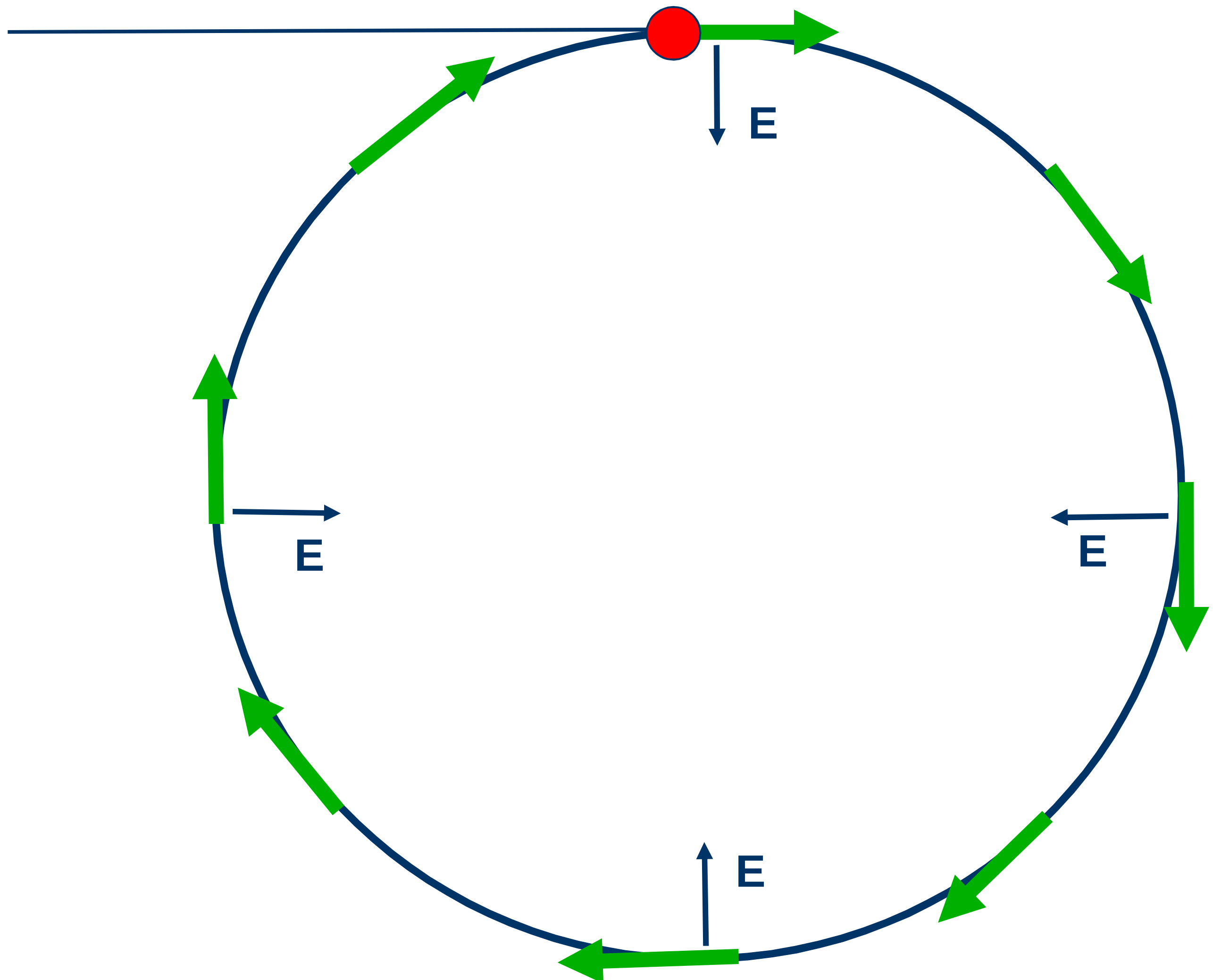
Storage Ring EDM experiments



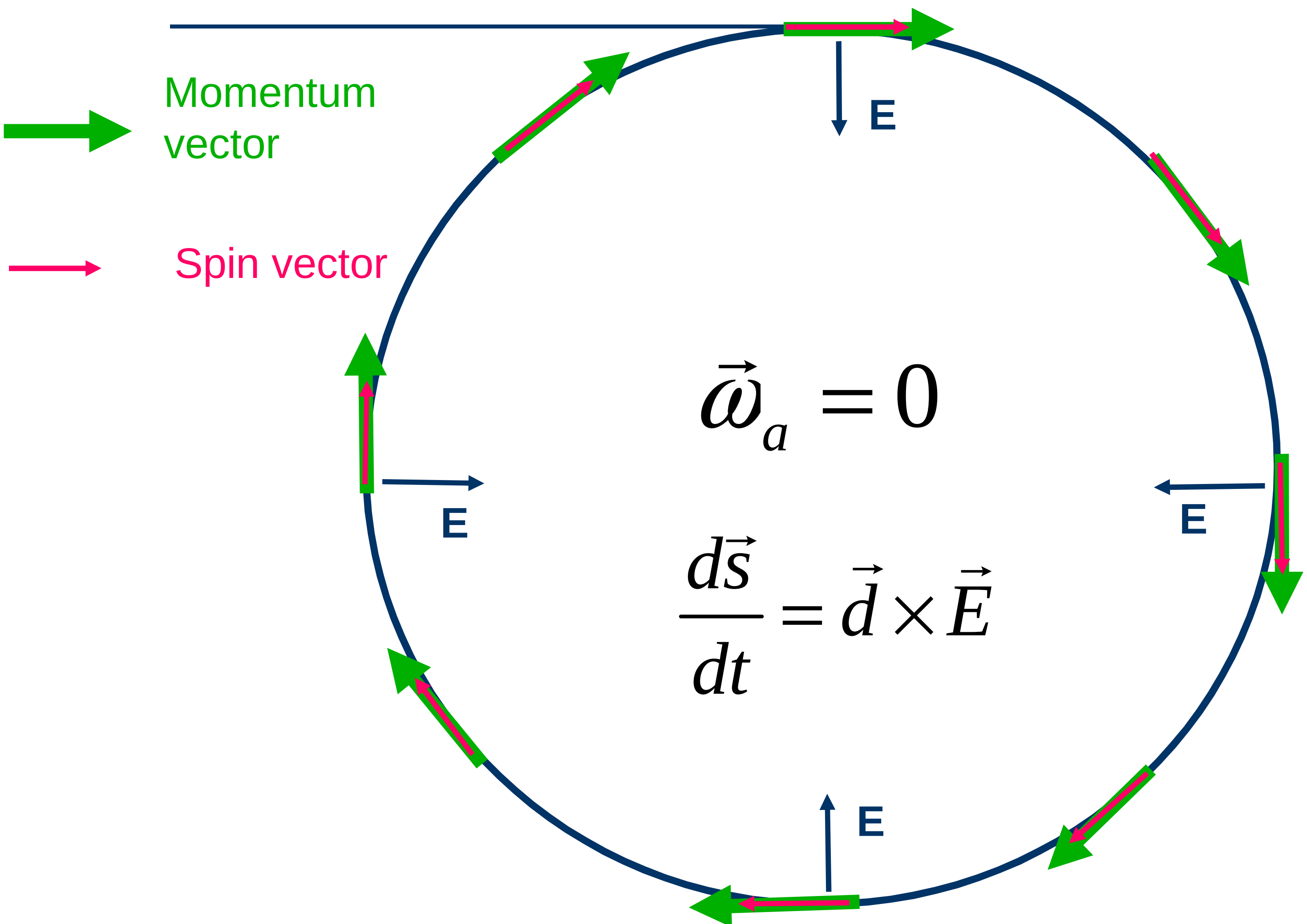
A charged particle between Electric Field plates would be lost right away…



…but can be kept in a storage ring for a long time



The sensitivity to EDM is optimum when the spin vector is kept aligned to the momentum vector

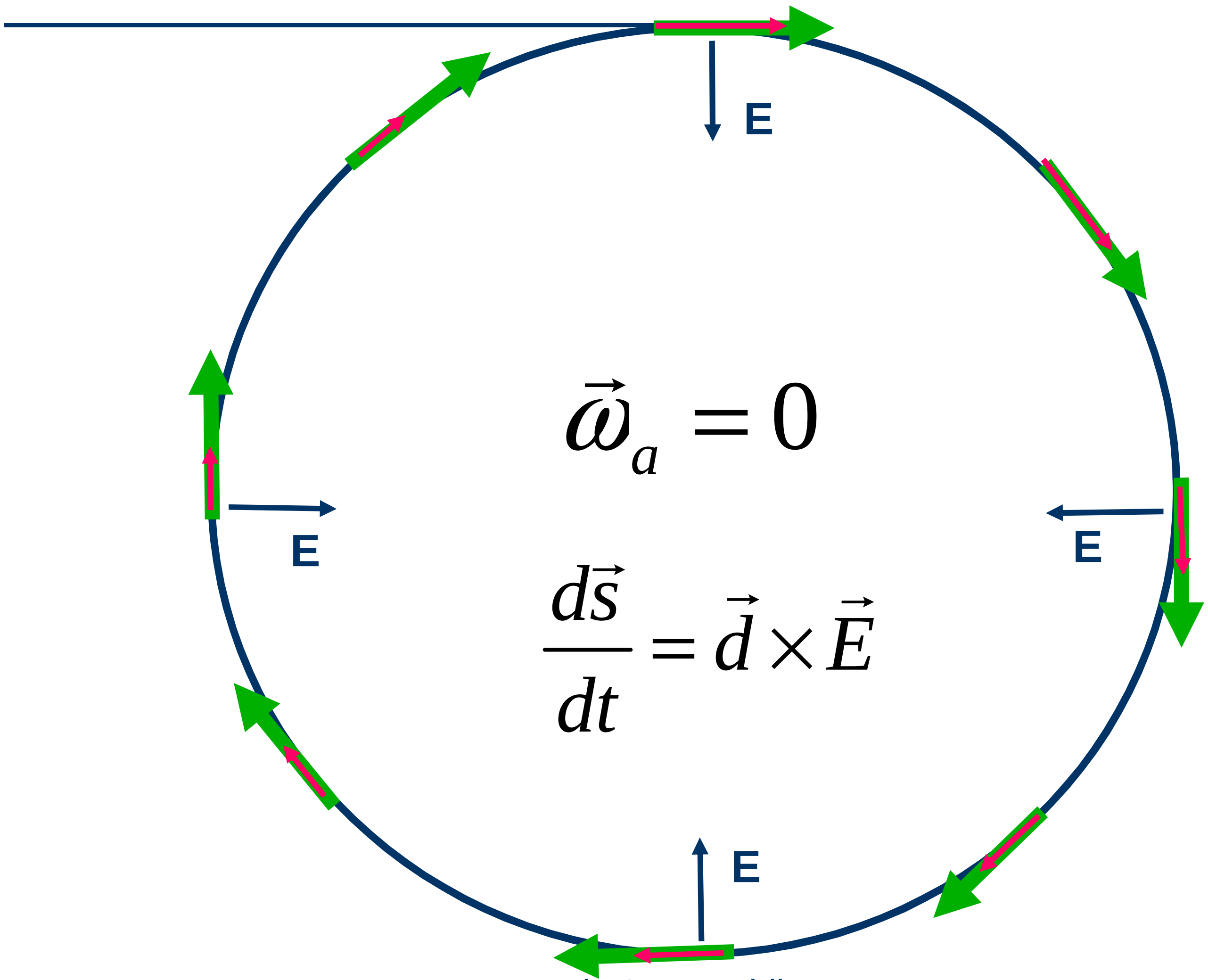


$$\vec{\omega}_a = 0$$

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

Yannis Semertzidis, BNL

The spin precession relative to momentum in the plane is kept near zero. A vert. spin precession vs. time is an indication of an EDM (*d*) signal.



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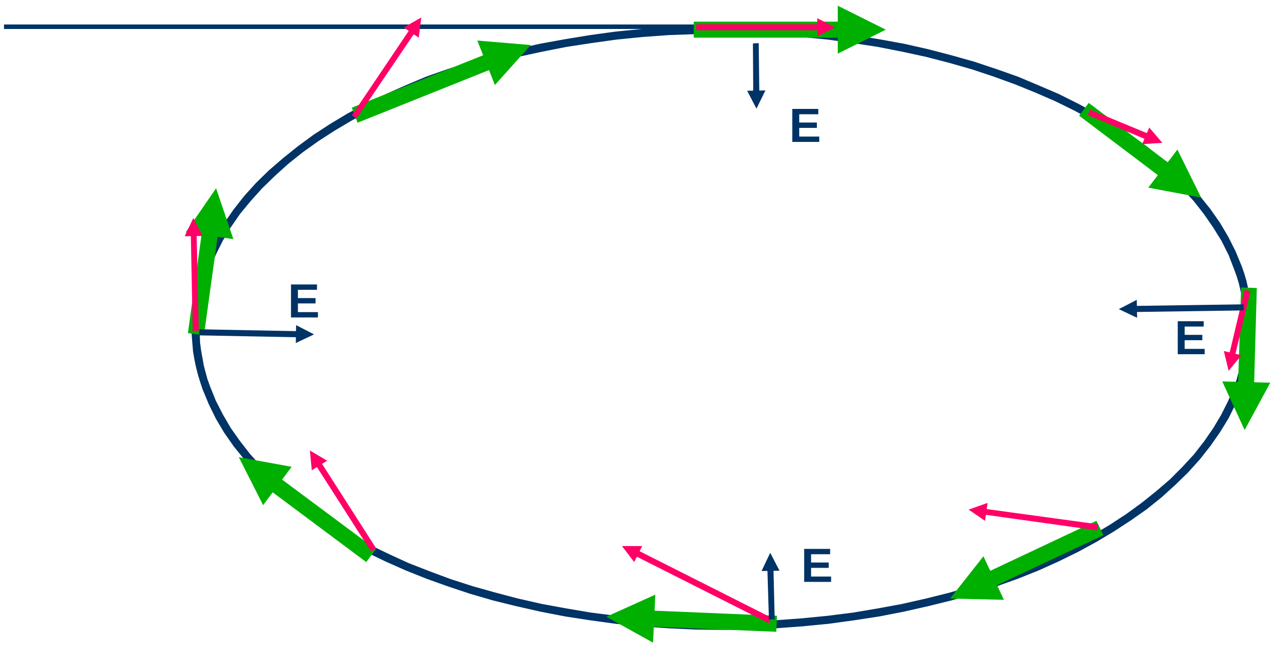


$$\vec{\omega}_a = 0 \qquad \frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$

Freezing the horizontal spin precession

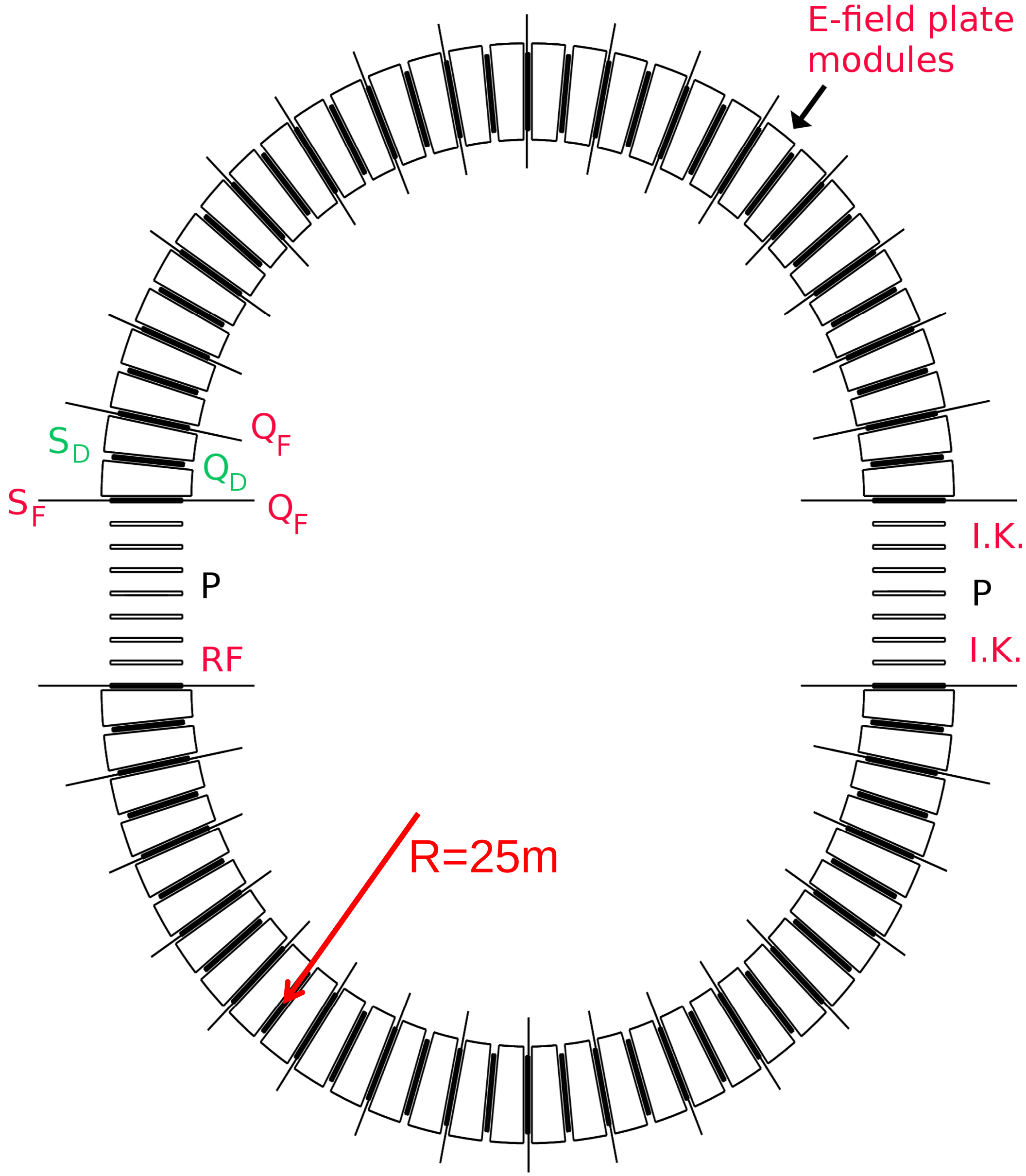
$$\vec{\omega}_a = \frac{e}{m}\left(a - \left(\frac{m}{p}\right)^2\right)\vec{\beta}\times\vec{E}$$

- The spin precession is zero at "magic" momentum (0.7 GeV/c for protons, 3.1GeV/c for muons,…)

$$p = \frac{m}{\sqrt{a}}, \text{ with } a = \frac{g-2}{2}$$

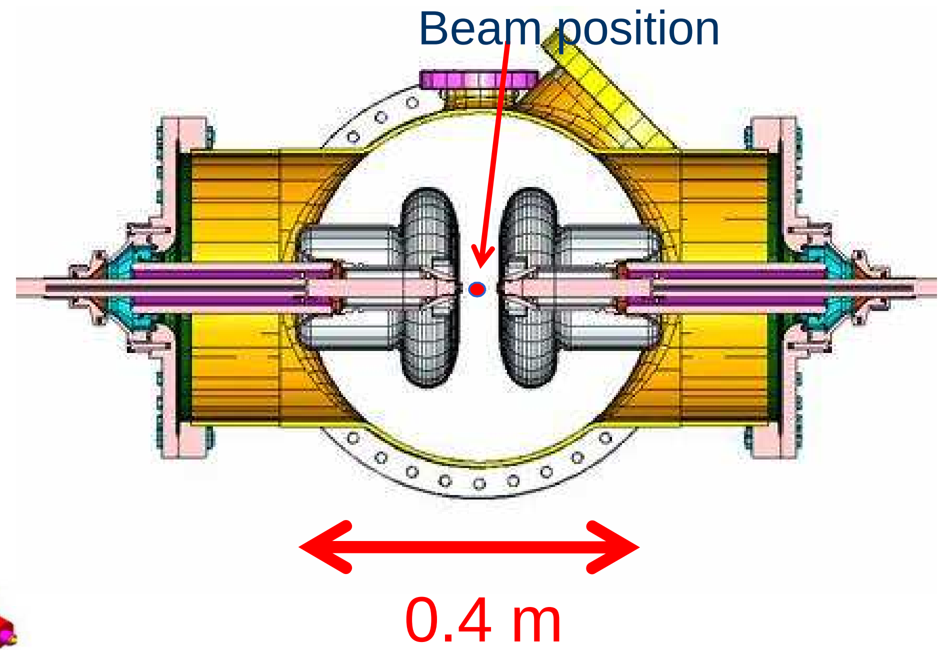
- The "magic" momentum concept was first used in the last muon g-2 experiment at CERN and BNL.

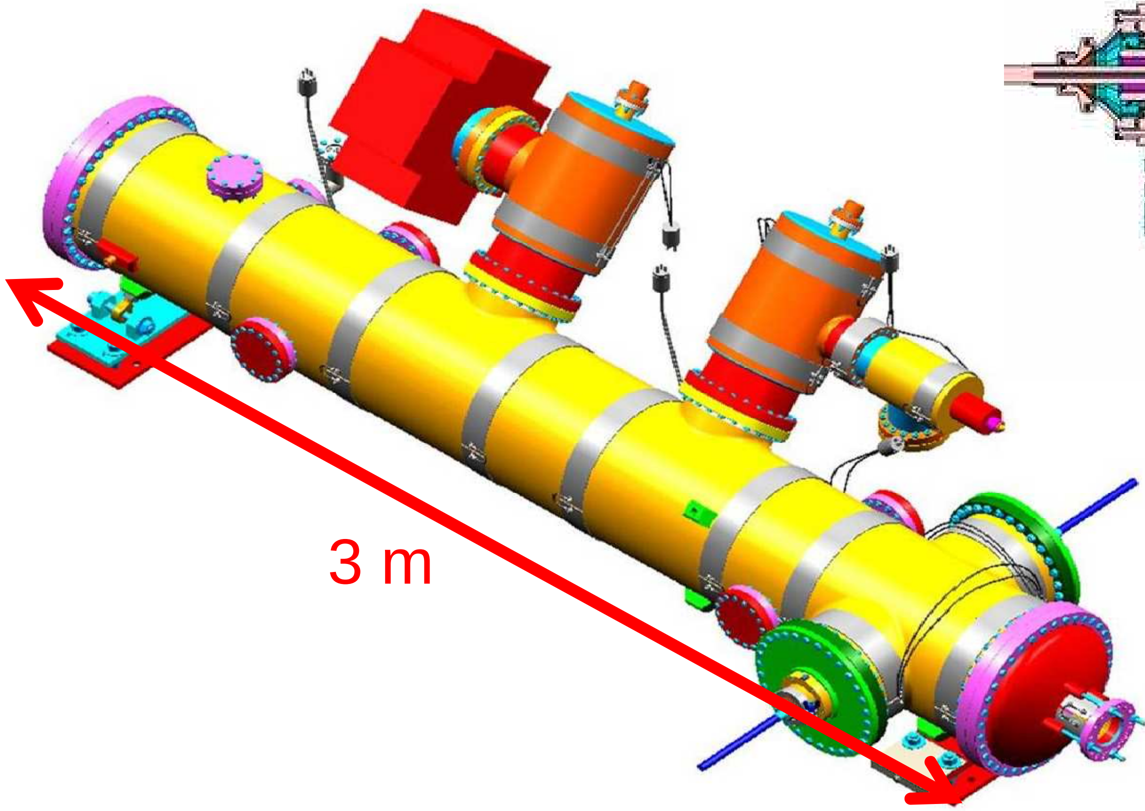
A possible "magic" proton ring lattice:
~240m circumference with ES-separators.



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

E-field plate module: The (26) FNAL Tevatron ES-separators would do





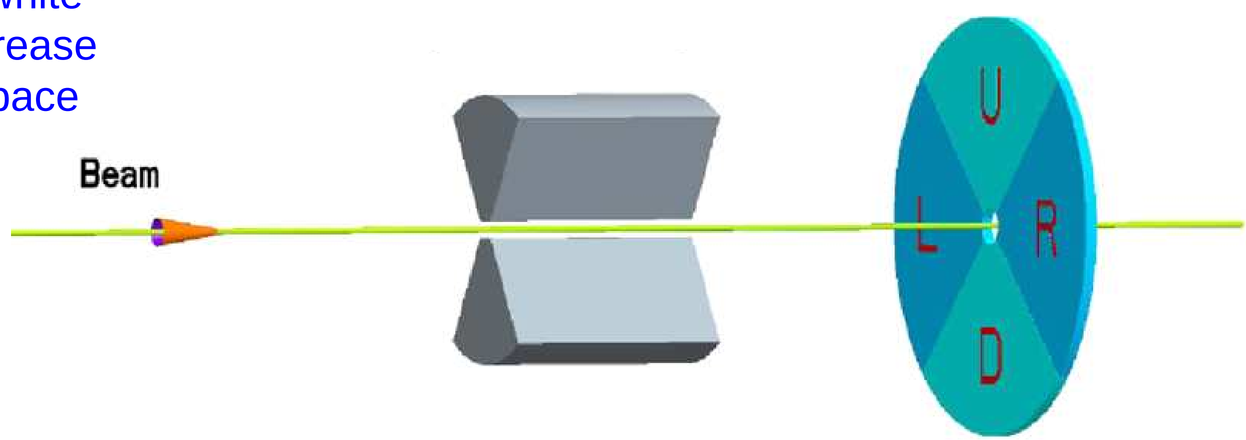
Vertical plates are placed everywhere around the ring to minimize vertical electric/radial B- fields from image charges

pEDM polarimeter principle: probing the proton spin components as a function of storage time

extraction adding white noise to slowly increase the beam phase space

“defining aperture” polarimeter target

Micro-Megas TPC detector and/or MRPC



$$\varepsilon_H = \frac{L-R}{L+R}$$

carries EDM signal
increases slowly with time

$$\varepsilon_V = \frac{D-U}{D+U}$$

carries in-plane
precession signal

Is the polarimeter analyzing power good at P_{magic}? YES!

Analyzing power can be further optimized

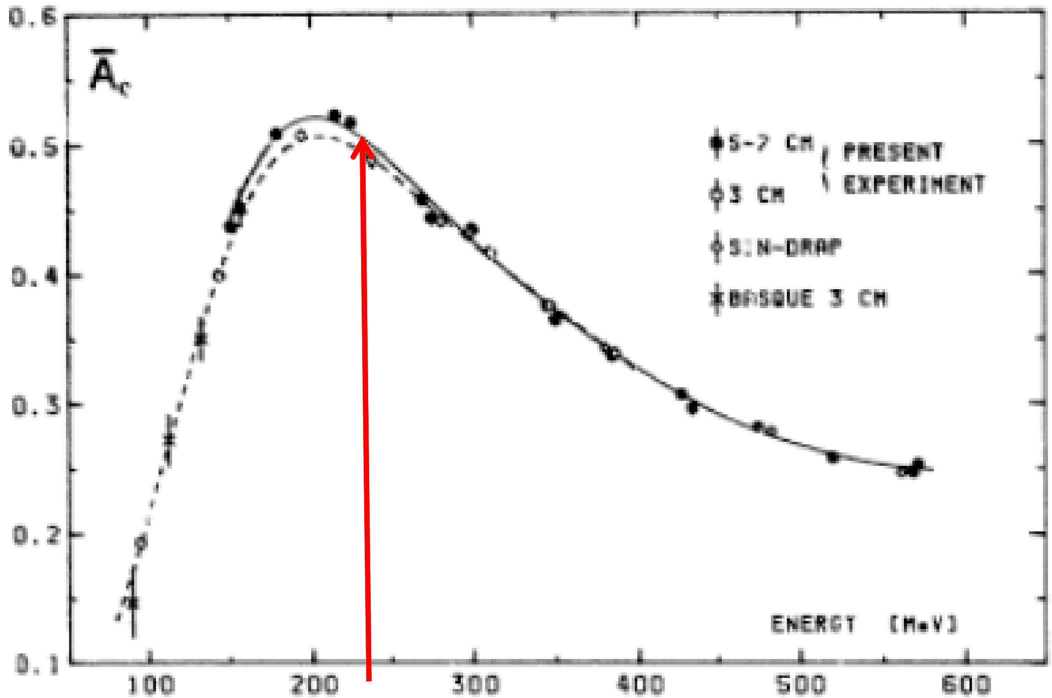


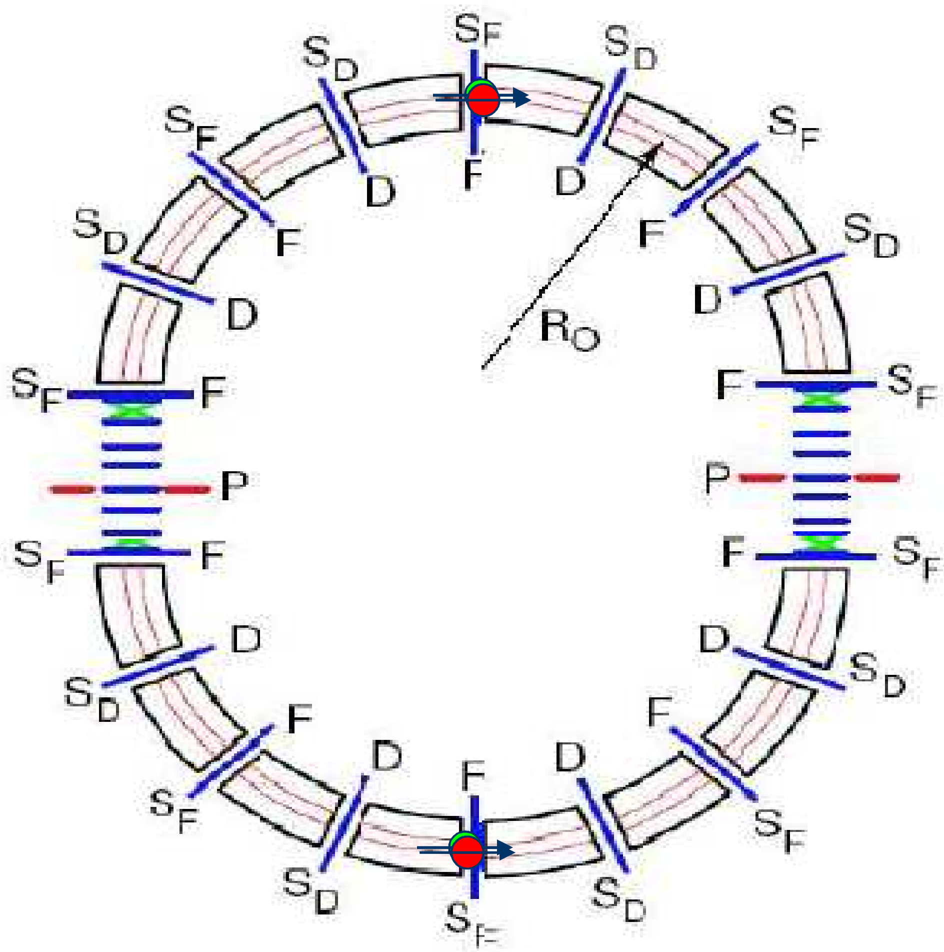
Fig. 4. Angle-averaged effective analyzing power. Curves show our fits. Points are the data included in the fits. Errors are statistical only

Fig.4. The angle averaged effective analyzing power as a function of the proton kinetic energy. The magic momentum of 0.7GeV/c corresponds to 232MeV.

Certain (main) systematic errors easier to handle if CW & CCW is done at the same time (Coincident BeamS: CBS)

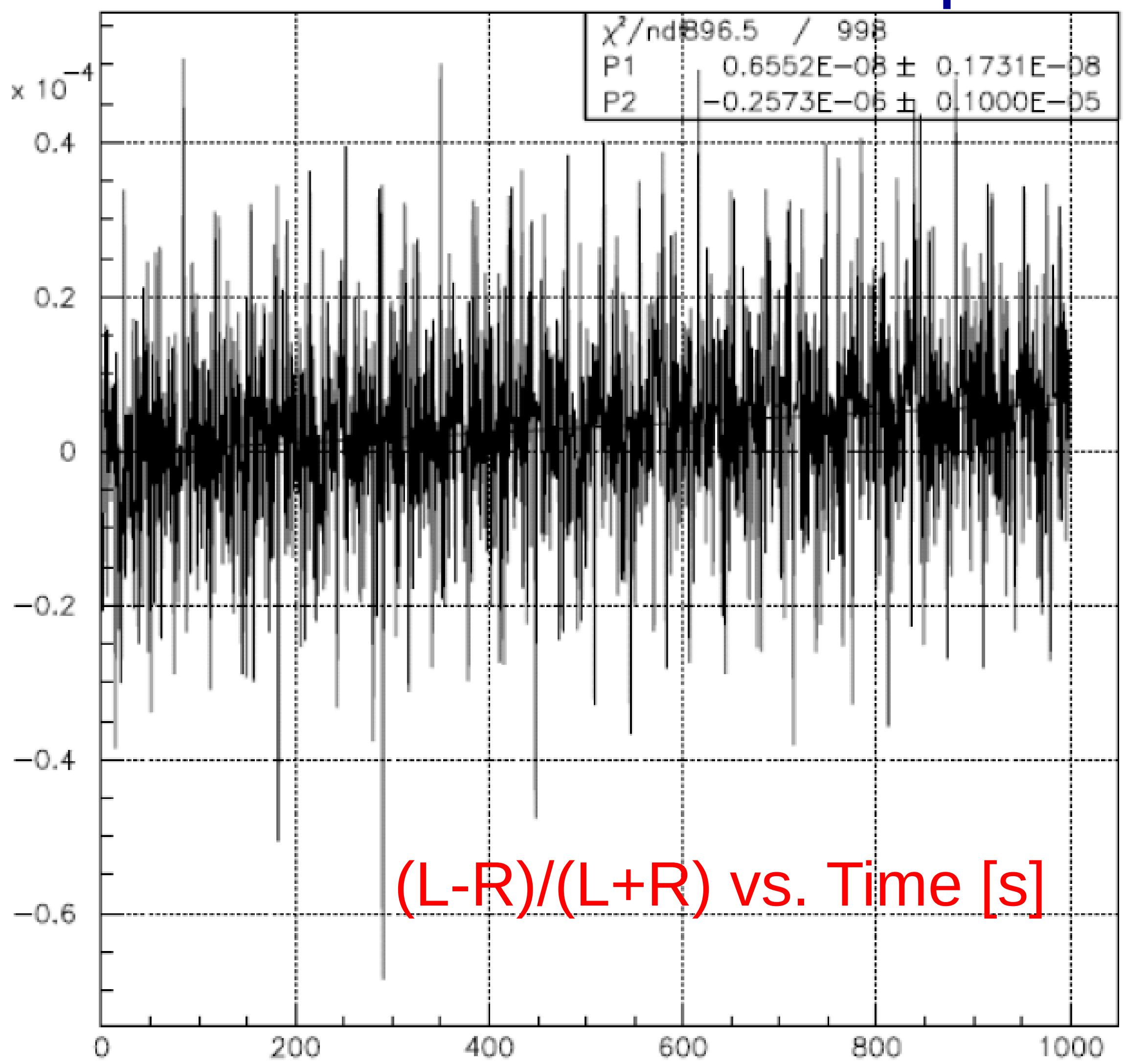
In a ring with Electric field bending it is possible to store protons CW & CCW at the same time in the same place

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



The EDM signal: early to late change

- Comparing the (left-right)/(left+right) counts vs. time we monitor the vertical component of spin



M.C. data

Proton Statistical Error (230MeV):

$$\sigma_d = \frac{2\hbar}{E_R P A \sqrt{N_c f \tau_p T_{tot}}}$$

τ_p : 10^3s Polarization Lifetime (Spin Coherence Time)
A : 0.6 Left/right asymmetry observed by the polarimeter
P : 0.8 Beam polarization
N_c : 2×10^{10}p/cycle Total number of stored particles per cycle
T_{Tot}: 10^7s Total running time per year
f : 0.5% Useful event rate fraction (efficiency for EDM)
E_R : 17 MV/m Radial electric field strength (65% azim. cov.)

$\sigma_d = 1.6\times10^{-29}\,\mathrm{e\cdot cm/year}$ for uniform counting rate and

$\sigma_d = 1.1\times10^{-29}\,\mathrm{e\cdot cm/year}$ for variable counting rate

EDMs of hadronic systems are mainly sensitive to

- Theta-QCD (part of the SM)

- CP-violation sources beyond the SM

A number of alternative simple systems could provide invaluable complementary information (e.g. neutron, proton, deuteron,…).

Two different labs to host the S.R. EDM experiments

- BNL, USA: proton "magic" ring
- COSY/IKP, Germany: deuteron ring

Storage Ring EDM Experiments

- The proton EDM at “magic” momentum (0.7 GeV/c) has been just approved at BNL after a successful conceptual technical review. We are now in the R&D period. Sensitivity goal: 10^{-29} e·cm (>10 times more sensitive than the best planned nEDM exp.).

- The lab at COSY (Juelich/Germany) is seriously considering to host the deuteron EDM experiment in a staged approach. Final sensitivity goal: 10^{-29} e·cm.

Physics reach of magic pEDM (Marciano)

- Currently: $\bar{\theta} \leq 10^{-10}$, Sensitivity with pEDM: $\bar{\theta} < 0.3\times10^{-13}$

- **Sensitivity to new contact interaction: 3000 TeV**

- **Sensitivity to SUSY-type new Physics:**

$$pEDM \approx 10^{-24}\,\mathrm{e\cdot cm} \times \sin\delta \times \left(\frac{0.1\ \mathrm{TeV}}{M_{\mathrm{SUSY}}}\right)^2$$

The proton EDM at 10^{-29}e·cm has a reach of >300TeV or, if new physics exists at the 0.1TeV scale (as indicated by the muon g-2), $\delta<10^{-7}$ rad CP-violating phase; an unprecedented sensitivity level.

The deuteron EDM sensitivity is similar.

Goals and considerations

- E-field strength: 170kV/cm, 2cm plate distance
- Polarimeter systematic errors to <1ppm (early to late times-not absolute!). The EDM signal (asymmetry) is ~3ppm early to late change in (L-R)/(L+R) counts.
- Spin Coherence Time (SCT): ~10^3s
- BPMs: 10 nm, 1Hz BW resolution, syst. < 1pm!

Duration of R&D: up to 3 years

- COSY (Juelich/Germany) is going to play a leading role in SCT with simulations support; analytical estimations; and measurements using the COSY ring to benchmark the simulations.

- COSY to continue providing beam for the polarimeter development.

Technically driven pEDM Timeline

07 08 09 10 11 12 13 14 15 16 17

- ✓ Spring 2008, Proposal to the BNL PAC
- ✓ Fall 2009 Conceptual Technical Review at BNL
- ✓ December 2009, the pEDM experiment is approved
- 2010-2013 R&D phase; ring design

- Fall 2012, Finish R&D studies:
  a) Develop BPMs, 10 nm, 1 Hz BW resolution, <1pm syst.
  b) spin/beam dynamics related systematic errors.
  c) Polarimeter detector development and prepare for testing
  d) Finalize E-field strength to use
  e) Establish Spin Coherence Time, study systematic errors, optimize lattice

- FY 2013, start ring construction (two years)

Physics strength comparison (Marciano)

System	Current limit [e·cm]	Future goal	Neutron equivalent
Neutron	$<1.6\times10^{-26}$	$\sim10^{-28}$	10^{-28}
^{199}Hg atom	$<3\times10^{-29}$		10^{-25}-10^{-26}
^{129}Xe atom	$<6\times10^{-27}$	$\sim10^{-30}$-10^{-33}	10^{-26}-10^{-29}
Deuteron nucleus		$\sim10^{-29}$	3×10^{-29}-5×10^{-31}
Proton nucleus	$<7\times10^{-25}$	$\sim10^{-29}$	10^{-29}

Summary

- The ^{199}Hg EDM sets many of the current limits
- Better sensitivity is expected within 5 years for ^{199}Hg and neutron
- The proton EDM experiment has been recently approved at BNL. We are currently in the R&D phase for the next three years. In parallel we are going to propose a staged approach for the deuteron EDM at COSY.
- At 10^{-29} e-cm the proton/deuteron EDM experiments will have the best sensitivity for beyond the SM CP-violation. If found, they will help explain the large BAU mystery.