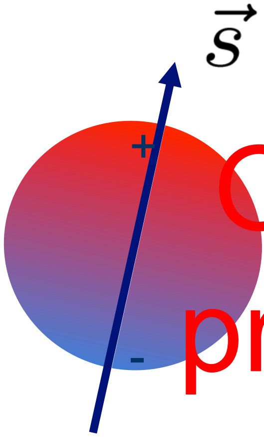
Proton EDM Review
BNL, 14&15 March 2011



Overview of the proton EDM proposal at the 10^{-29}e·cm level

Yannis K. Semertzidis, BNL

- Motivation (W. Marciano, tomorrow morning)
- Since last review
- A working proton EDM lattice, SCT (R. Talman)
- Beam parameters at BNL (A. Fedotov)
- E&B-fields; injection (B. Morse)
- BPM plans (D. Kawall)
- SCT runs at COSY; polarimeter plans (E. Stephenson)
- COSY S.R. EDM plan (H. Stroeher)
- Software development (Talman, Luccio, Haciomeroglu)

Why this review?

- The collaboration is putting a proposal together to be submitted to DOE for CD0
- Evaluate the proposal:

1. Motivation (still current?)
2. EDM-ring lattice (presented well enough?)
3. Beam parameters feasibility?
4. SCT and BPM plans?
5. E-field and B-field (shielding) plans?
6. Cost estimate good enough?

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,…).

- At $10^{-29}e\cdot cm$ is at least an order of magnitude more sensitive than the current nEDM plans

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:**

$$pEDM \approx 10^{-24}\mathrm{e\cdot\ cm}\ \times \sin\delta \times \left(\frac{1\mathrm{TeV}}{M_{\mathrm{SUSY}}}\right)^2$$

The proton EDM at 10^{-29}e·cm has a reach of >300TeV or, if new physics exists at the LHC scale, $\delta<10^{-7}$-10^{-5} rad CP-violating phase; an unprecedented sensitivity level.

The deuteron EDM sensitivity is similar.

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

- BNL, USA:
  proton “magic” ring

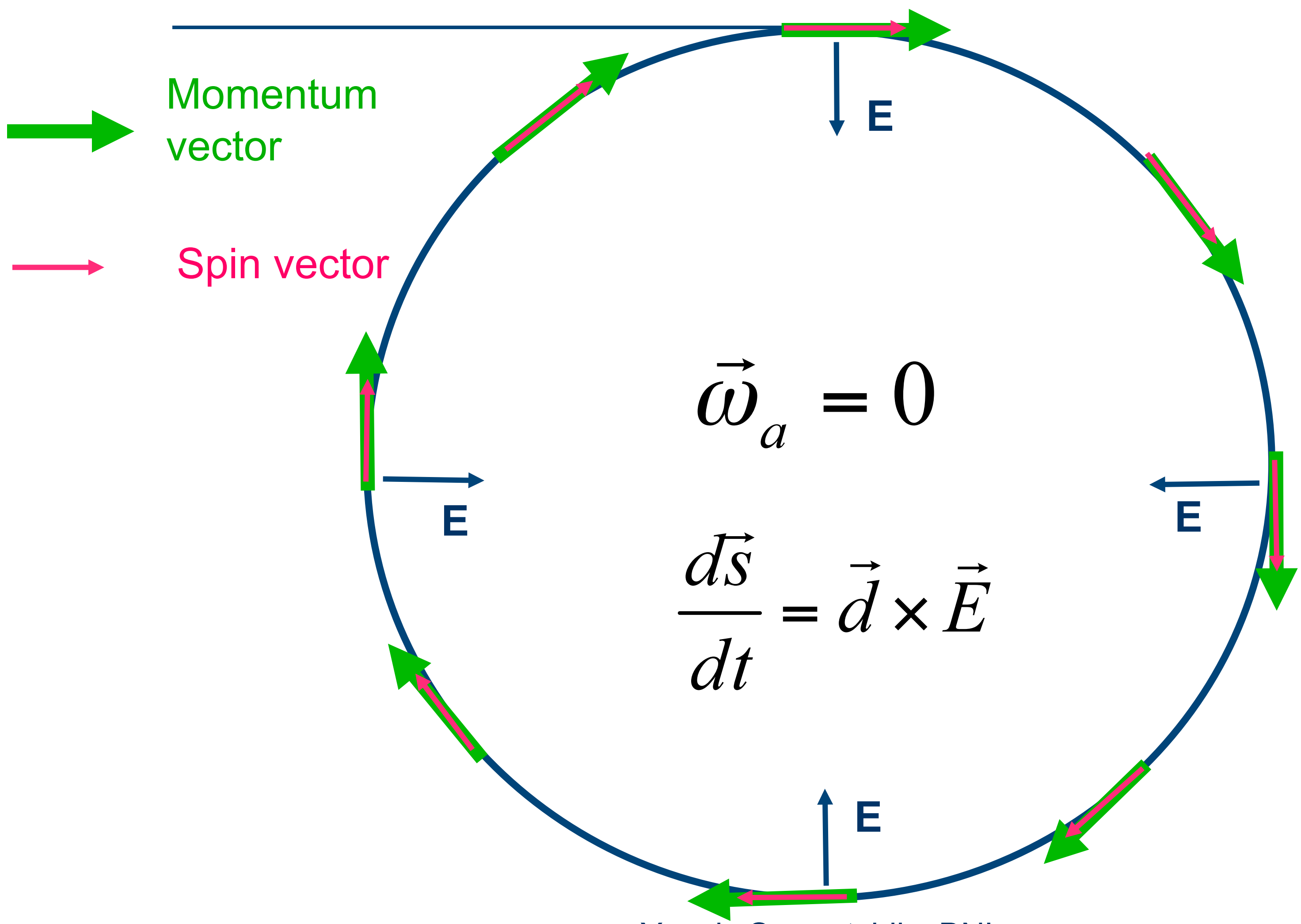
- COSY/IKP, Germany:
  deuteron ring (H. Ströher)

Proton EDM experiment at BNL with COSY as a partner Institute

Storage Ring EDM Collaboration

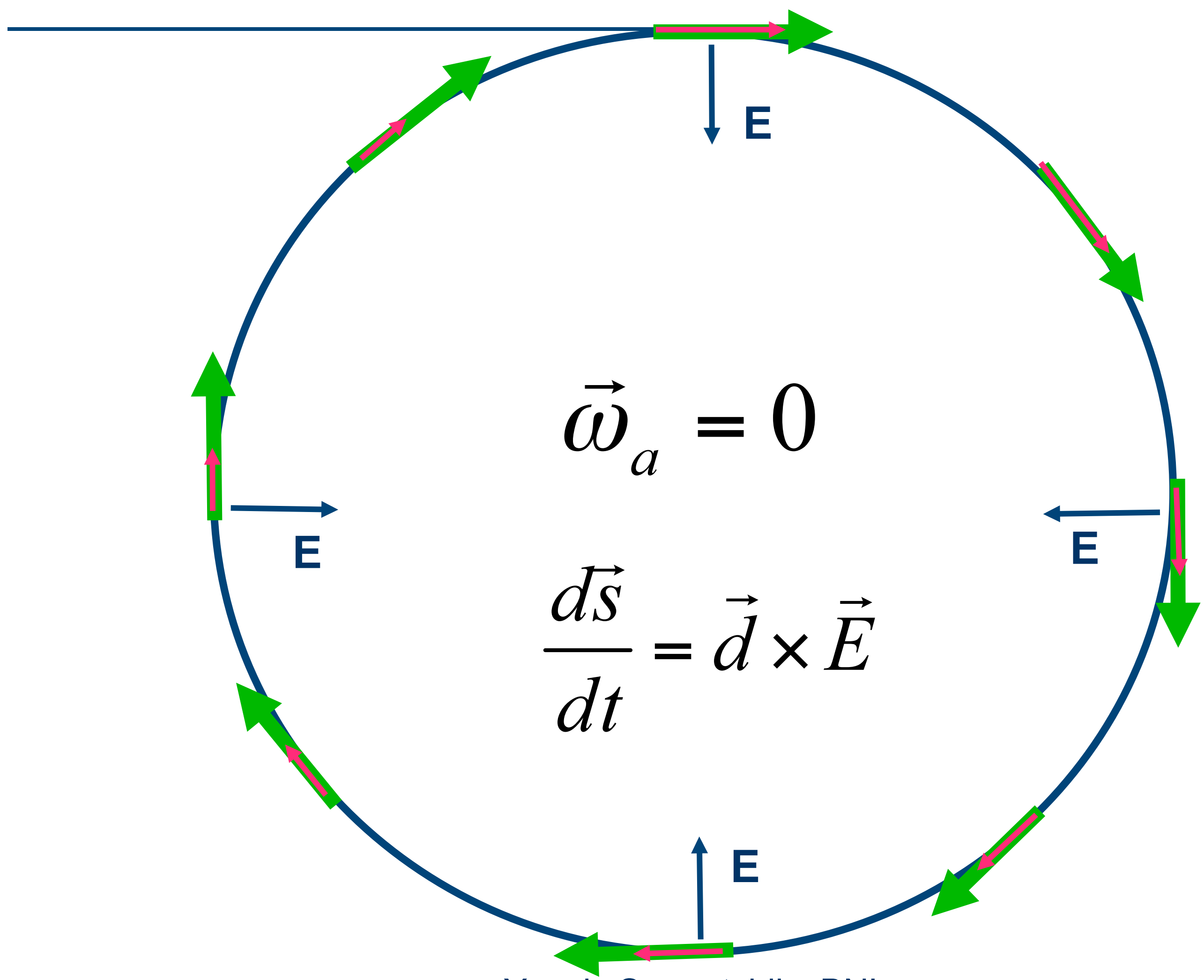
V. Anastassopoulos[18], D. Babusci[10], M. Bai[3], S. Baessler[23], M. Berz[17], M. Blaskiewicz[3], K. Brown[3], P. Cameron[3], G. Daskalakis[6], M.E. Emirhan[13], F. Esser[24], G. Fanourakis[6], A. Fedotov[3], A. Ferrari[25], W. Fischer[3], T. Geralis[6], Y. Giomataris[21], F. Gonnella[20], M. Gross Perdekamp[11], R. Gupta[3], G. Guidoboni[8], S. Haciomeroglu[13,3], Y. Haritantis[18], G. Hoffstaetter[5], H. Huang[3], M. Incagli[19], D. Kawall[16], B. Khazin[4], I.B. Khriplovich[4], I.A. Koop[4], T. Laopoulos[1], R. Larsen[3], D.M. Lazarus[3], A. Lehrach[9], P. Lenisa[8], P. Levi Sandri[10], F. Lin[3], A. Luccio[3], A. Lyapin[15], W.W. MacKay[3], R. Maier[9], K. Makino[17], N. Malitsky[3], W. Marciano[3], S. Martin[26], W. Meng[3], R. Messi[20], D. Moricciani[20], W.M. Morse[3], S.K. Nayak[3], Y.F. Orlov[5], C.S. Ozben[13], A. Pesce[8], V. Ptitsyn[3], B. Parker[3], P. Pile[3], V. Polychronakos[3], B. Podobedov[3], D. Raparia[3], F. Rathmann[9], S. Redin[4], S. Rescia[3], G. Ruoso[14], T. Russo[3], N. Saito[22], Y.K. Semertzidis[3,*], Yu. Shatunov[4], V. Shemelin[5], A. Sidorin[7], A. Silenko[2], N. Simos[3], S. Siskos[1], E.J. Stephenson[12], H. Stroeher[9], J. Talman[3], R.M. Talman[5], P. Thieberger[3], N. Tsoupas[3], Y. Valdau[9], G. Venanzoni[10], K. Vetter[3], S. Vlassis[18], G. Zavattini[8], A. Zelenski[3], K. Zioutas[18]

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



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.

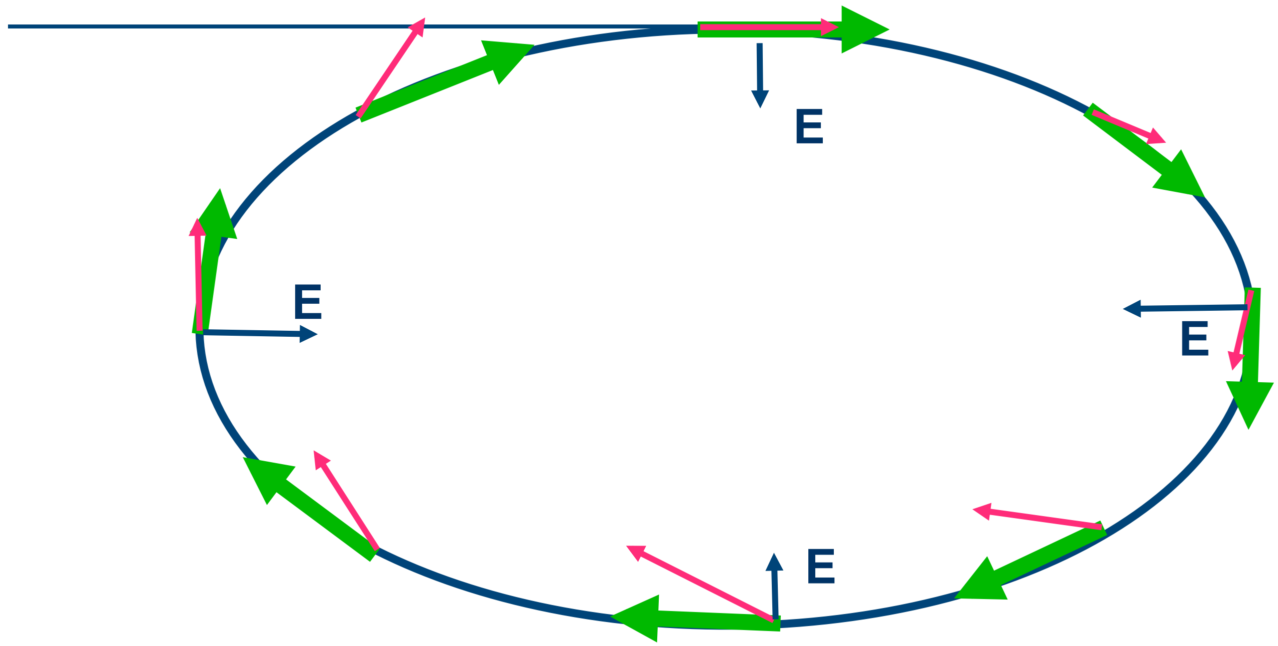


$$\vec{\omega}_a = 0$$

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

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.



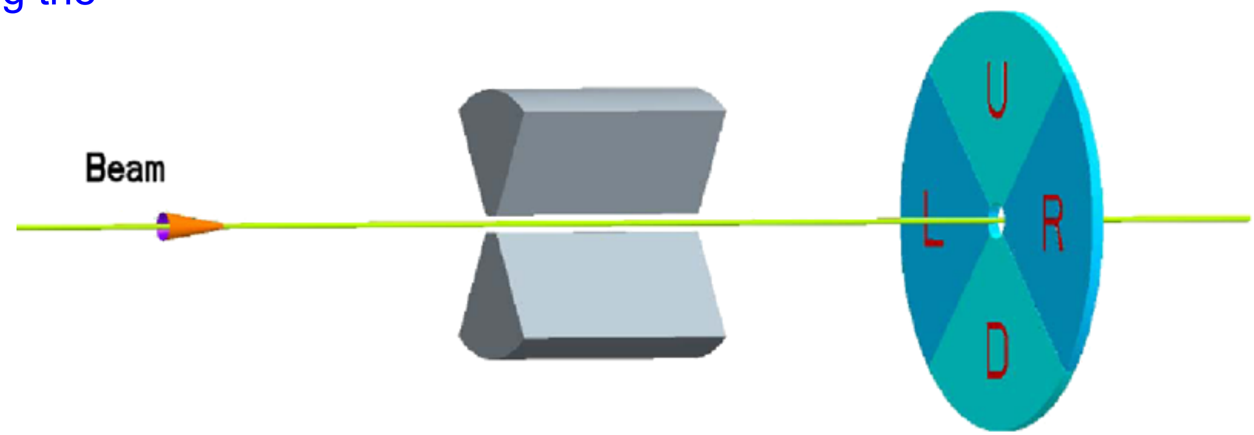
$$\vec{\omega}_a = 0 \qquad \frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$

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

“defining aperture” polarimeter target

Micro-Megas TPC detector and/or MRPC

Extraction: lowering the vertical focusing



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

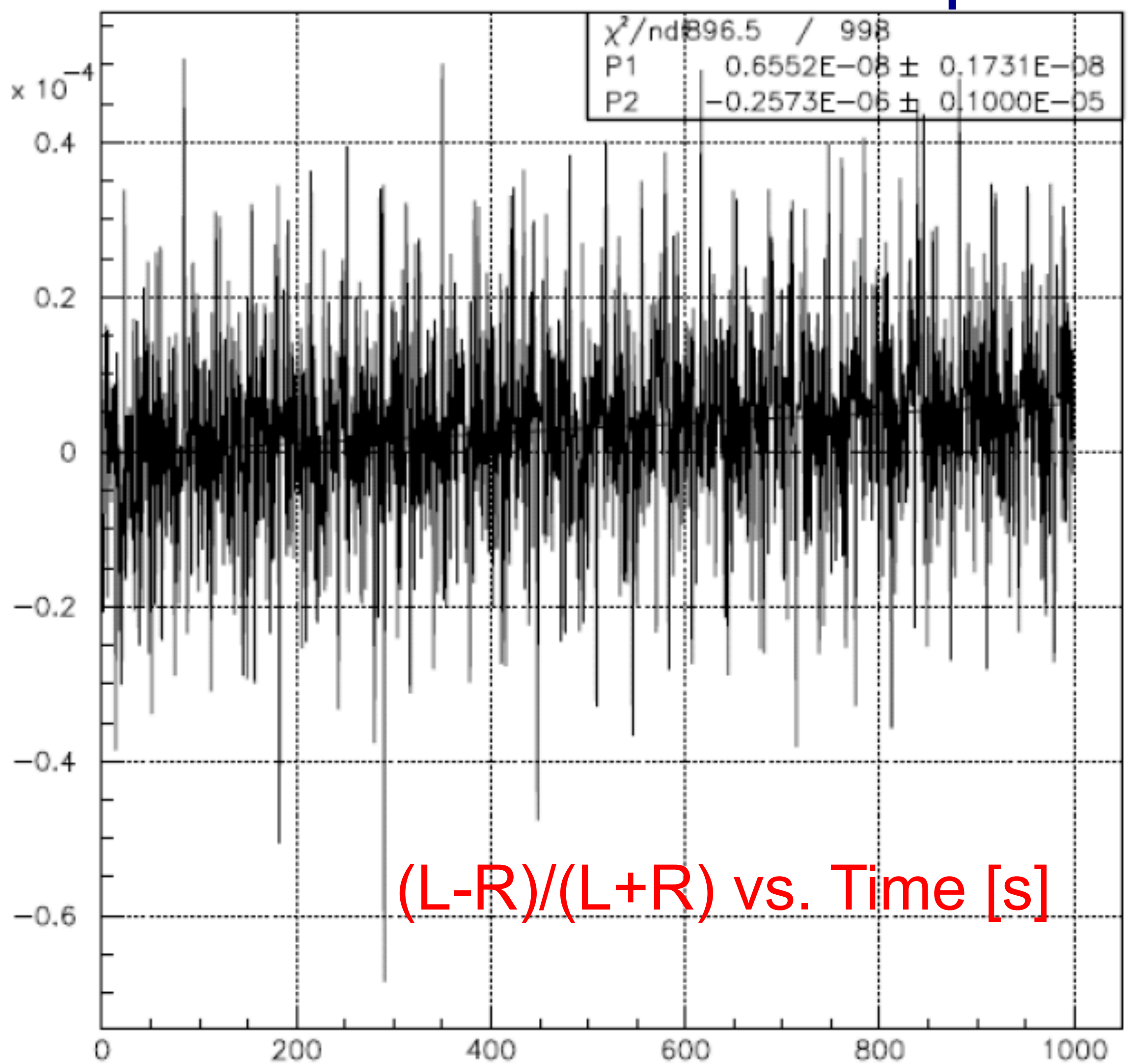
carries EDM signal
increases slowly with time

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

carries in-plane (g-2)
precession signal

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

Figure 2. (L-R)/(L+R) vs. time [s] is shown here as well as the fit results to two parameters (slope and dc offset). More details on the parameters used are given in table 1

After the review committee suggestion (T. Roser) : Take more beam very early and late

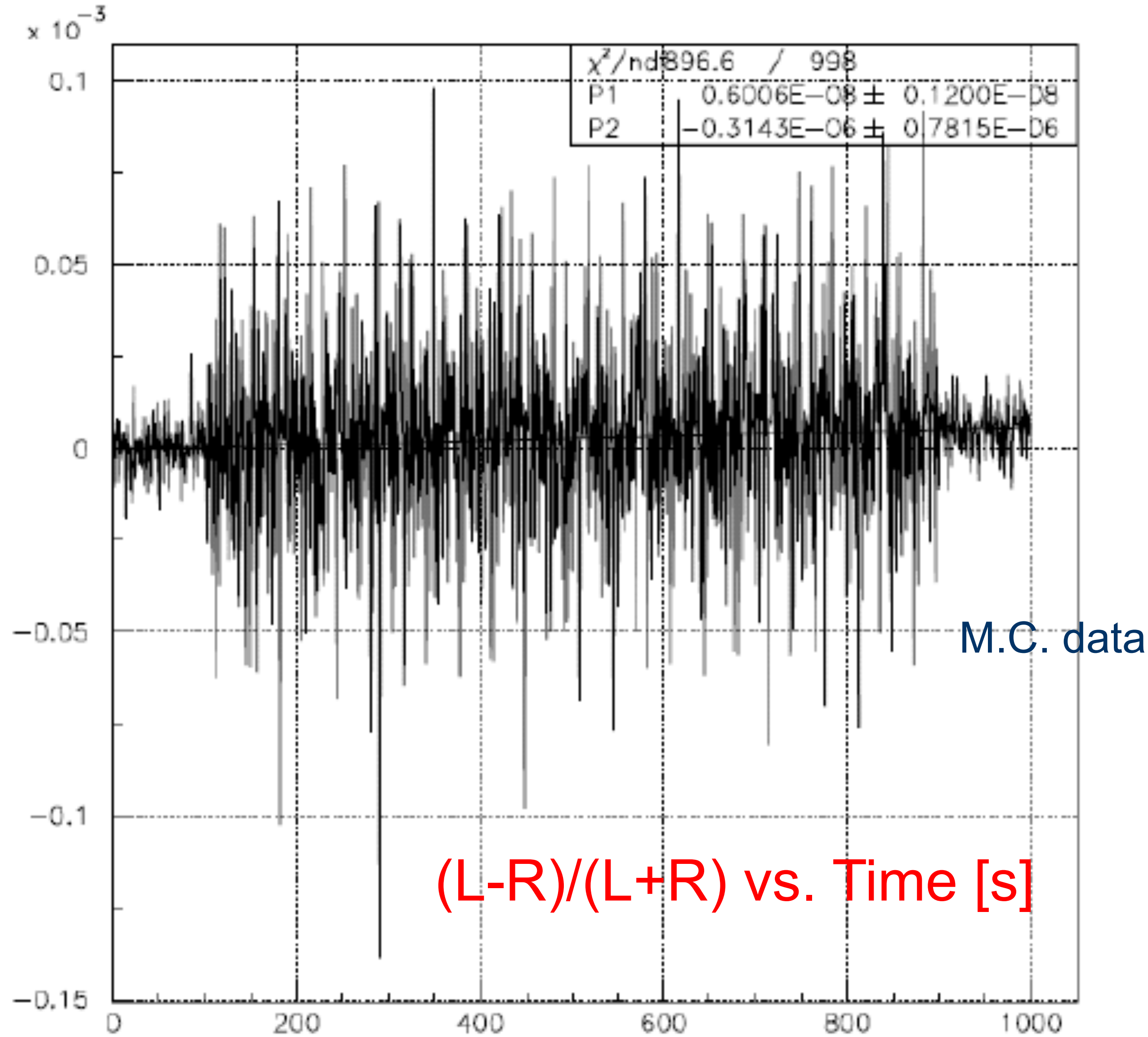


Figure 5. The two parameters fit for the 1000s data taking time case and acquisition rate as described in the text is shown here. The total counts are 4×10^{12}, the same as in the previous figure. The fit result on the slope is $0.6\times10^{-8}\pm0.12\times10^{-8}$/s i.e. a five sigma effect. The error is reduced from 0.17×10^{-8}/s to 0.12×10^{-8}/s, i.e. by ~30%, which is significant.

Freezing the horizontal spin precession

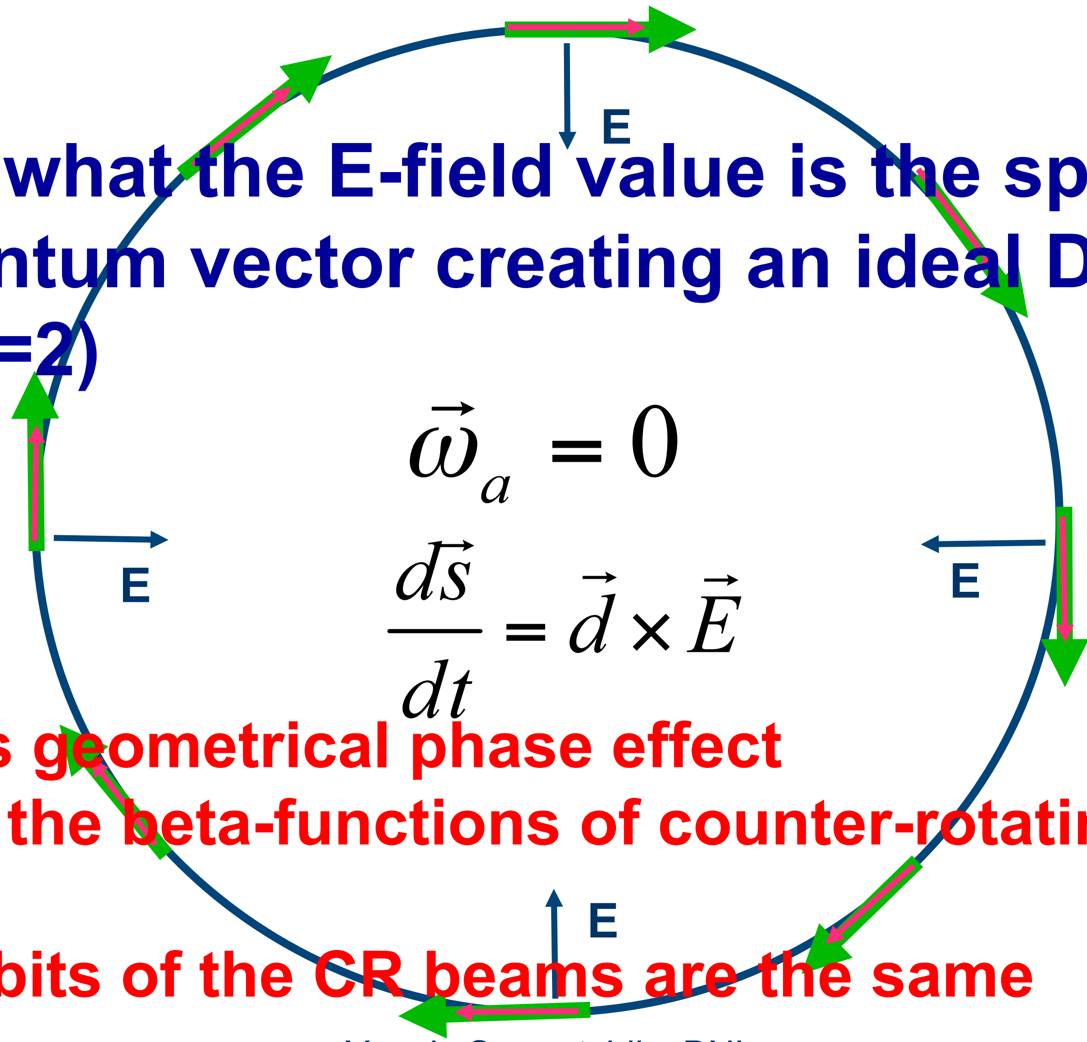
$$\vec{\omega}_a = \frac{e}{m}\left(a - \left(\frac{m}{p}\right)^2\right)\vec{\beta} \times \vec{E}$$

- 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.

When $P=P_{magic}$ the spin follows the momentum



No matter what the E-field value is the spin follows the momentum vector creating an ideal Dirac-like particle (g=2)

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

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

1. **Eliminates geometrical phase effect**
2. **Equalizes the beta-functions of counter-rotating (CR) beams**
3. **Closed orbits of the CR beams are the same**

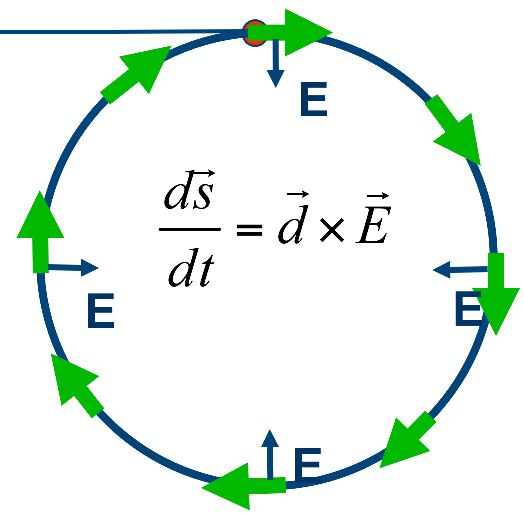
High intensity charged particle beams can be stored for a long time

Statistics:

- **High intensity (4×10^{10}), highly polarized beams (>80%)**
- **Keep spin along the momentum, radial E-field (10MV/m) acts on proton EDM**
- **Long (10^3s) spin coherence time (SCT) is possible**
- **High efficiency (0.5%), with large analyzing power (50%)**

Systematics:

- **Magnetic field shielding + feedback to keep vertical spin <0.3mrad/storage**
- **Store counter-rotating beams + BPMs to probe $\langle B_r \rangle$**
- **Longitudinal impedance: <10KΩ**
- **Forward/backward bunch polarizations (polarimeter)**



Software development:

- **Benchmarking at COSY with stored beams**
- **At least two different approaches, speed, accuracy**

Last review (Dec 2009)

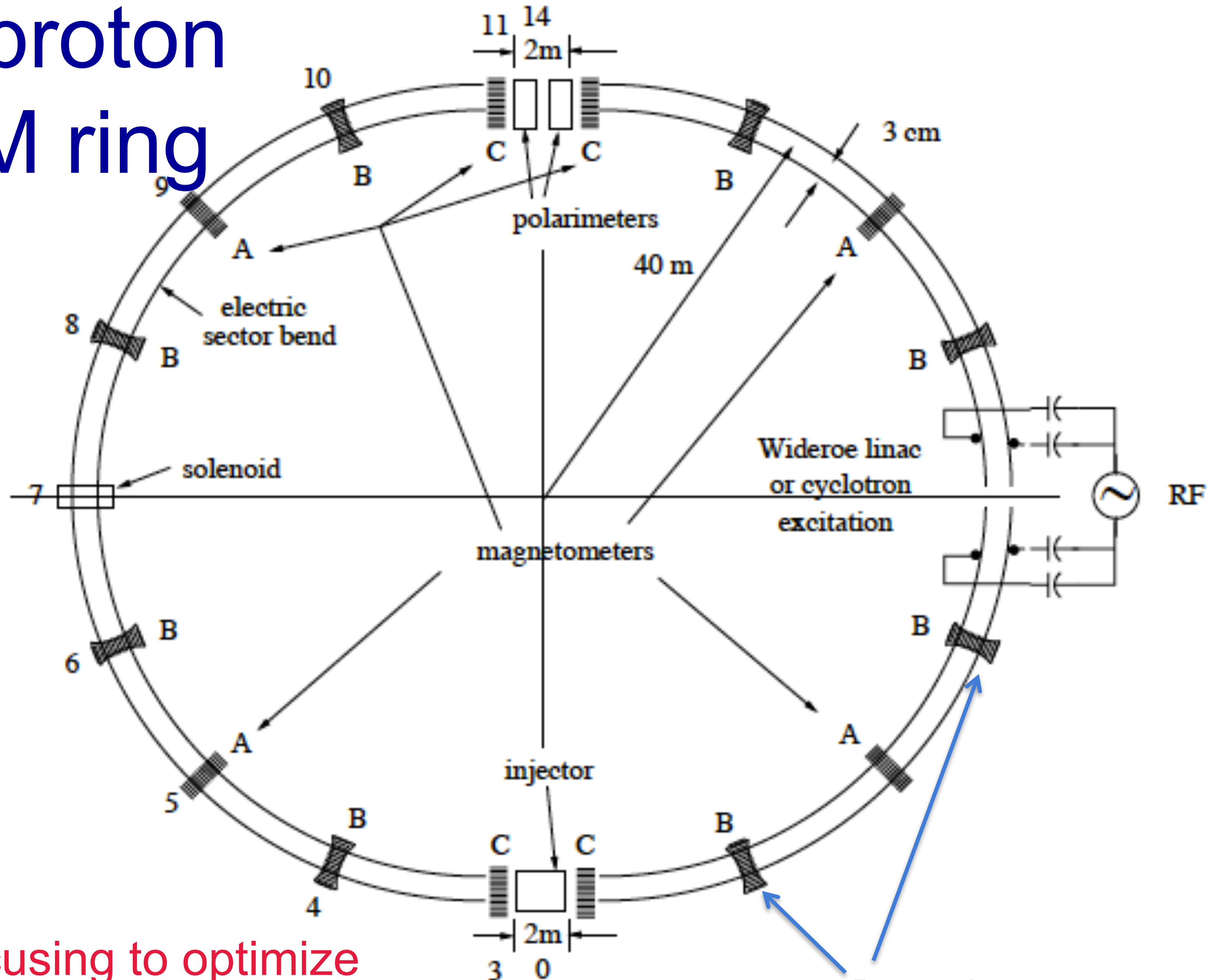
- Great Physics, complementary to LHC
- Use all E-field focusing (all-electric ring)

- Critical items:
- 1) SCT (benchmark software with polarized beams at COSY)
- 2) BPMs (test with beams at RHIC)

Since last review

1. Adopted the E-field focusing option in spring 2010 after studying issues
2. Started a test program at COSY on SCT, software benchmarking
3. Developed a ring lattice with long SCT and large acceptance.
4. Developed significant understanding of the E-field issues for beam dynamics tracking
5. Prepared and installed a BPM for testing at RHIC, while studying systematics

The proton EDM ring



Weak focusing to optimize SCT and BPM

Some ring parameters

Table 2. The table of parameters for the proton EDM ring is shown here. The lattice has been estimated using the exact electric field and not an effective dipole magnetic field.

Parameter	**Value**	**Comment**
Proton Momentum	0.7007405 GeV/c	Kinetic energy: 232.8 MeV, $\beta = 0.59838$, $\gamma = 1.2481$
Ring bending radius	40 m	
Total length of straight sections	11.6 m	If more straight section length is needed the ring bending radius has to increase proportionally.
Radial E-field strength	10.5 MV/m	For plate separation of 3 cm the voltage on the plates is about ±160 KV.
Number of sections	16	The E-field plates within a section are ~16m long each. They can be segmented into 5 pieces, 3.14 m long each.
Radial E-field dependence at y=0	$R^{0.2}$	The E-field is slightly increased at larger radius.
Total length of orbit	263 m	
Horizontal tune	1.3	
Vertical tune	0.2-0.1	To be modulated by ~10% around 0.1
$\beta_{x,max}$	28 m	Horizontal aperture: 3 cm
$\beta_{y,max}$	240 m	Vertical aperture: 8 cm
Cyclotron frequency	0.6839 MHz	
$f_{rf} = 135 \times 0.6839$ MHz	90 MHz	Total RF voltage: 5 KV for synchrotron tune of 0.01
Slip factor	0.45	Sign is – (TBC)

Experimental needs

C.R. proton beams	0.7 GeV/c	≥80% polariz.;	~4×10^{10} protons/store
<10^2 m base length	Repetition period: 10^3s	Beam energy: ~1J	Average beam power: ~1mW
Beam emittance: 95%, norm.	Horizontal: 2 mm-mrad	Vertical: 6 mm-mrad	$(dp/p)_{rms}$~ 2×10^{-4}

- CW & CCW injections: Average emittance parameters: same to ~10%

Spin Coherence Time

- Not all particles have same deviation from magic momentum, or same horizontal and vertical divergence (second order effects)

- They Cause a spread in the g-2 frequencies:

$$d\omega_a = a\vartheta_x^2 + b\vartheta_y^2 + c\left(\frac{dP}{P}\right)^2$$

- Correct by tuning plate shape/straight section length plus fine tuning with sextupoles (current plan) or cooling (mixing) during storage (under evaluation).

Software development

- Two competing requirements: accuracy, speed
- Total storage ~10^9 revolutions, ~1.5μs/rev.
- E-field complication: Kinetic energy changes with radial oscillations → horizontal focusing

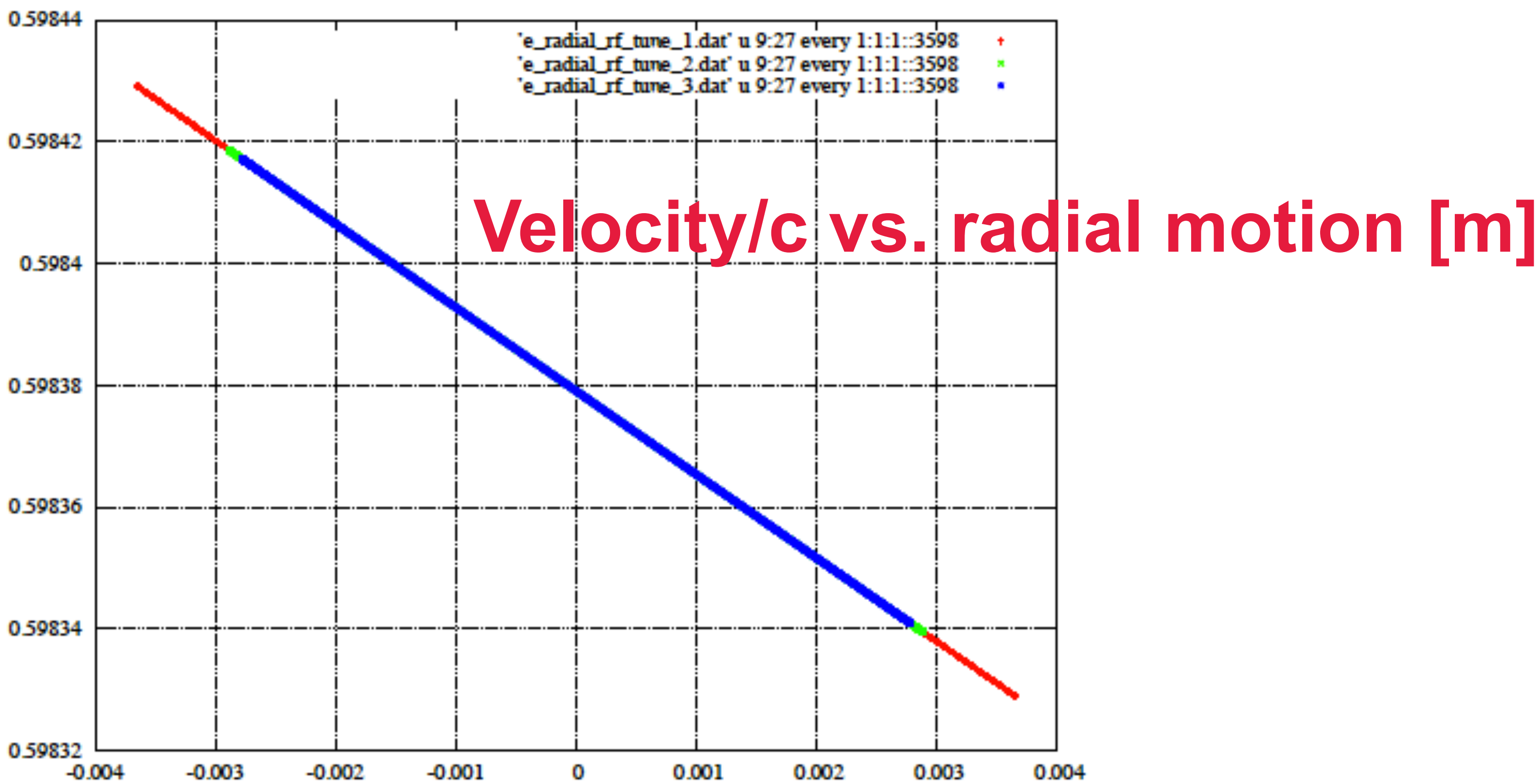
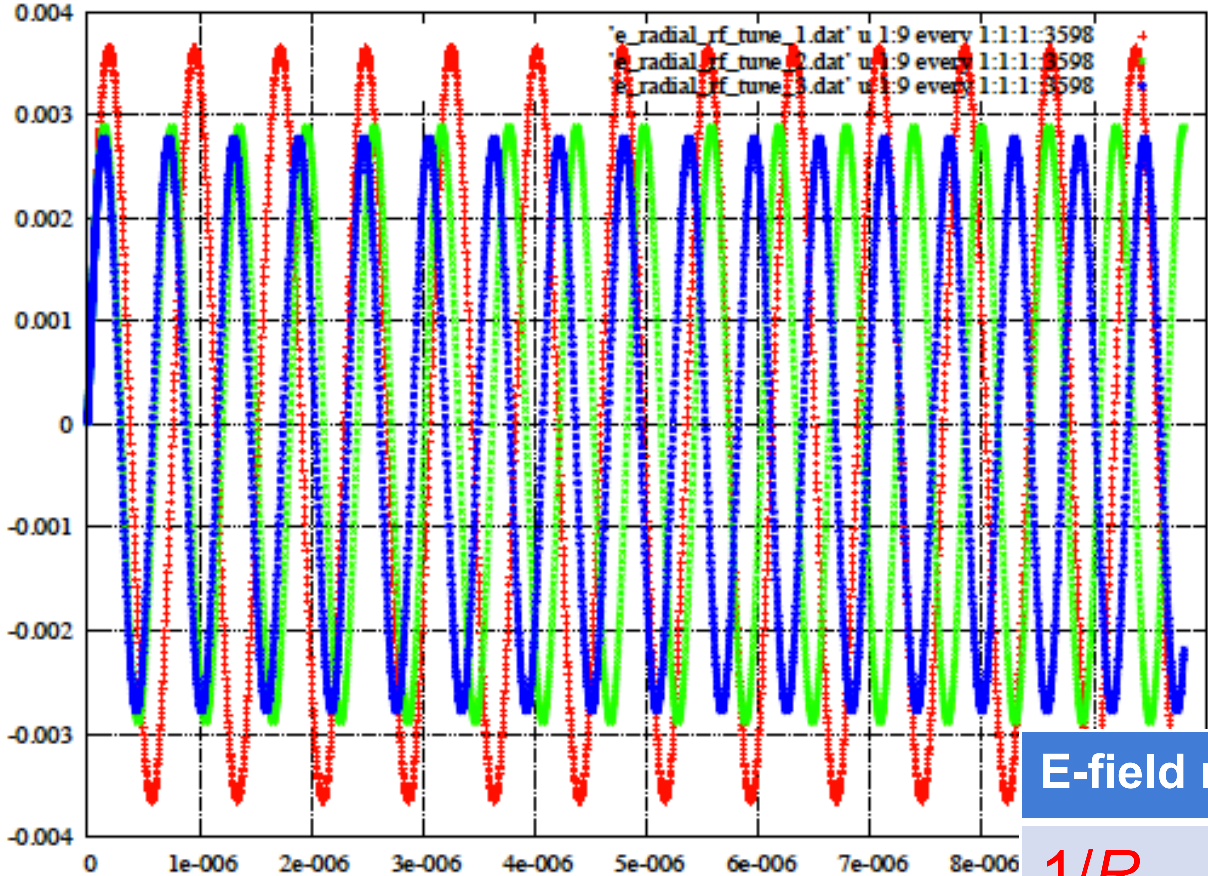


Figure 6. the particle velocity divided by the speed of light (vertical) vs. the (local) radial deviation [m]. Red corresponds to eq. (1), green to eq. (2) and blue to eq. (3).

Software development

- 4th order R.K. integrator (accurate but slow)



Radial motion [m] vs. time [s]

Three different E-field dependences:
$1/R$
Constant
$R^{0.2}$

Consistent with analytical estimations:

E-field radial dep.	Horizontal tune
$1/R$	1.275
Constant	1.625
$R^{0.2}$	1.680

Software development

- 4^{th} order R.K. integrator (accurate but slow, 10^4 revolutions in ~10 hours CPU)

- Analytic integration with UAL+ ETEAPOT; UAL + SPINK: Fast enough,…

BPMs

- A radial B-field would cause an EDM-like spin precession AND would split the vertical position of the counter-rotating beams

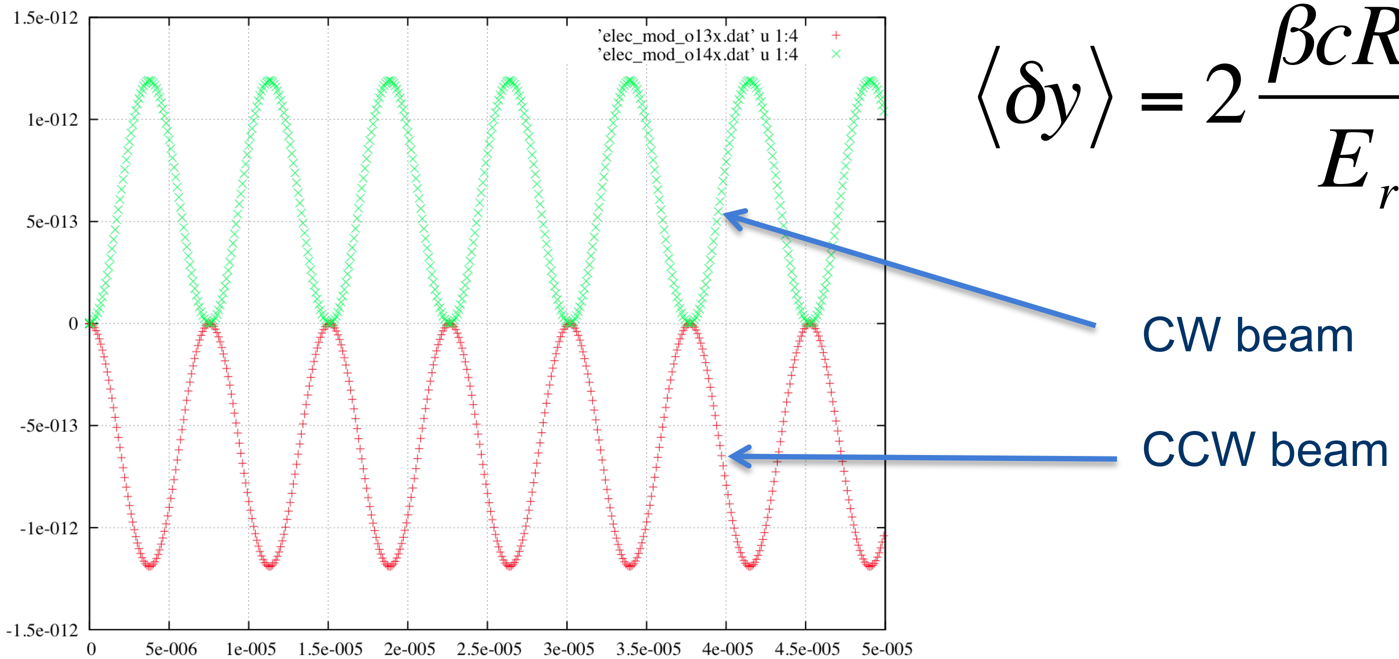
- The splitting depends on the vertical tune Q_y

$$\langle \delta y \rangle = 2 \frac{\beta c R_0 B_{r0}}{E_r Q_y^2} \sim 2\,pm$$

BPMs

- The splitting depends on the vertical tune Q_y
- Modulating Q_y would create a frequency dependent separation and a B-field at the same frequency.

Vertical position vs. time



$$\langle \delta y \rangle = 2\frac{\beta c R_0 B_{r0}}{E_r Q_y^2} \sim 2\,pm$$

BPMs

- Developed and installed a resonant BPM in IP10 of RHIC; resonance ~100MHz
- Statistics adequate for S/N=1 per day
- Estimated systematics large (BPM alignment, bunch parameters,…). Will still take data for diagnostics…

- We took a conservative approach instead: use near-DC effect → B-field generated by the beam itself (position modulated only when $\langle B_{r0} \rangle \neq 0$).

Low T_c SQUIDS as BPMs

- Place them behind a shield (protect from the high frequency beam noise)
- Look at the vertical tune modulation frequency
- Minimize B-field noise from shields (important)
- Direction sensitive

- Commercially available SQUIDS have enough sensitivity. Expect S/N>6, for 10^{-29}e•cm
- Plan to develop it and install it in RHIC ($0.6M)

So what are the BPM issues?

- B-field noise: addressed by shielding + feedback

- Vibrations: Commercial SQUID system with vibration damping has noise figure plenty good enough

What are NOT BPM issues?

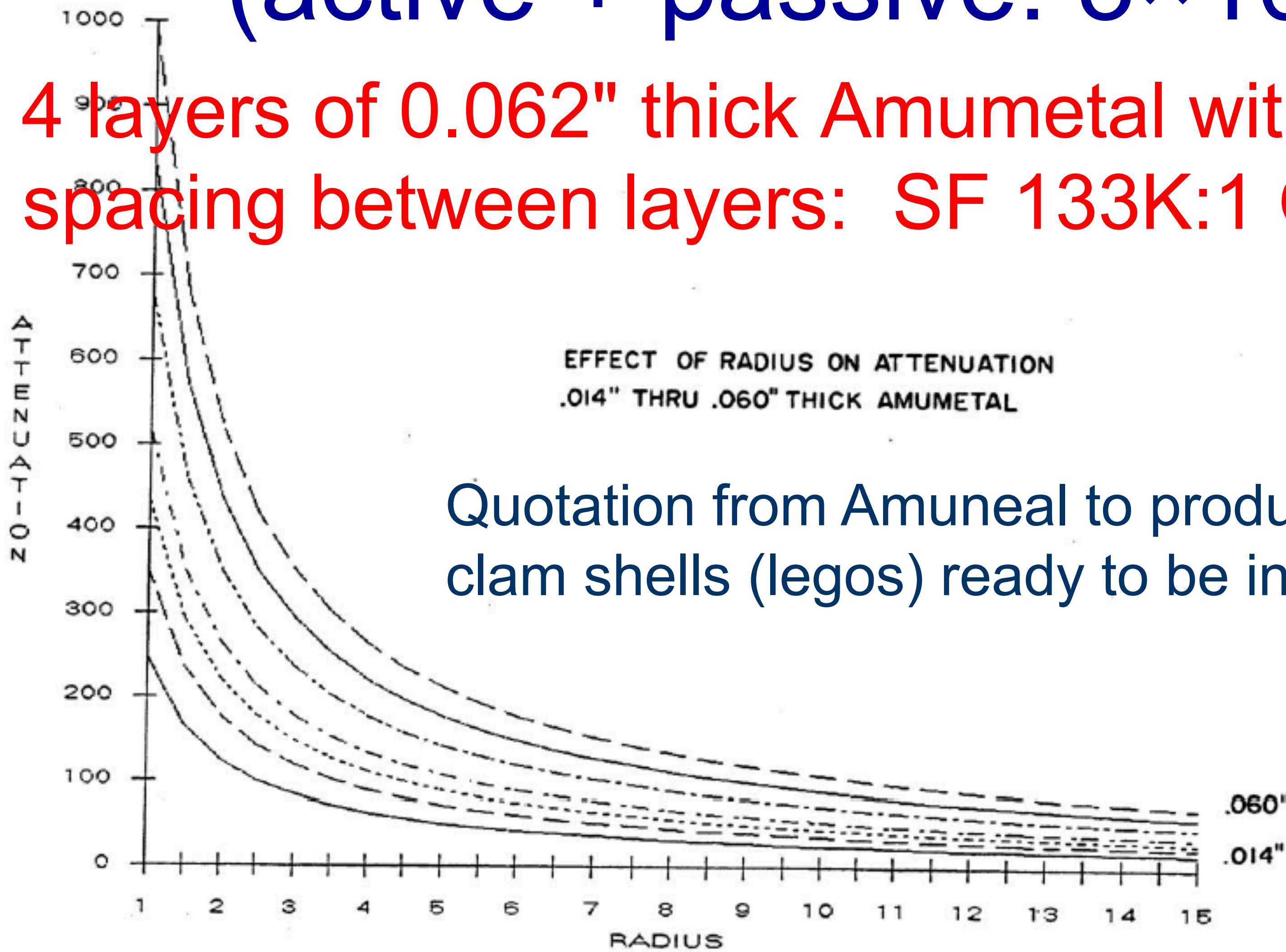
- Electronics rack temperature stability. NSLS II: two BPMs sense the absolute position of beam. They require 0.1C stability for 200nm resolution

- EDM ring: One BPM senses the difference between two C.R. beams at the modulation frequency. (Kurt Vettel responsible for NSLS II BPMs just joined the collaboration.)

- Ring temperature stability: just as any other accelerator

Magnetic shielding (active + passive: 3×10^8)

4 layers of 0.062" thick Amumetal with 3" spacing between layers: SF 133K:1 OD 35”



Quotation from Amuneal to produce 4 layers of clam shells (legos) ready to be installed.

amuneal

Magnetic shielding options (active + passive: 3×10^8)

4 layers of 0.062" thick Amumetal with 3" spacing between layers: SF 133K:1 OD 35”

Item	Part	Rev	Description	Lead Time
3	17014-03	A	SREDM Magnetic Shielding - 4 Layers of .062" Thick Amumetal	

1. This is a budgetary quote for a three layer clamshell magnetic shield to shield an approx 277 foot diameter ring.

2. Shield to be fabricated using .062" thick Amumetal, which conforms to MIL-N-14411C, Comp. 1 and ASTM A753-02, Alloy Type 4.

3. 3.00" spacing between shield layers.

4. Shields will be supplied as half cylinders with a 2.00" overlap in 60.00 long segments (two 30" segments assembled with joiner band).

5. Quoting spacers between layers to be fabricated from High Density Polyethylene (HDPE) plastic.

6. Price includes a one time engineering/programming charge, plus commercial truck freight to Brookhaven National Laboratory, Upton, NY 11973.

Quantity	Unit Price	Extended Price
1.00	$5,560,858.00 EA	$5,560,858.00

In conclusion

BPMs:

- A combination of passive and active magnetic shielding
- Took conservative approach to use near-DC effects eliminating a whole class of systematic errors.
- Using proven techniques (Romalis et al.)
- Risk factor: high (it needs to be proven in accelerator environment)

cont'd

SCT:

- Lattice: to 1st order SCT very long. Use sextupoles to tune out construction & placements errors
- Tracking studies underway to fine tune the specs
- Risk factor: medium

- SCT at COSY a great success. Mixing w/ cooling eliminates the issue. Studying st. cooling

cont'd

Software development:

- Accurate beam and spin dynamics tracking based on 4th order RK integration.
- It's slow: 10 h CPU for 10 ms tracking
- It confirmed estimation of tunes, radial B-field effect, tune modulation, etc.
- Studying SCT dependence on straight section length, E-field plate shape, etc.
- Fast UAL+SPINK is used for SCT @ COSY
- Plus UAL+ETEAPOT for all-electric; more…

cont'd

E-field strength:

- ~10MV/m for 3 cm plate separation. Stainless steel and high pressure water rinsing (HPWR) is below expected E-field limit
- Challenge: QA is critical for large area plates
- Risk factor: low

cont'd

Polarimeter:

- Polarimeter data have been analyzed, long paper to be submitted
- Expected systematic error <<1ppm

- Risk factor: low

Risk factors

System	Risk factor at prev. rev.	Current Risk factor
Spin coherence time	High	Medium (to become low after software studies)
Beam position monitors	High	High (test in accelerator environment is required)
Polarimeter	Low	Low
E-field strength	Low	Low
E-field plates shape	Low	Low
Software development	Medium	Low

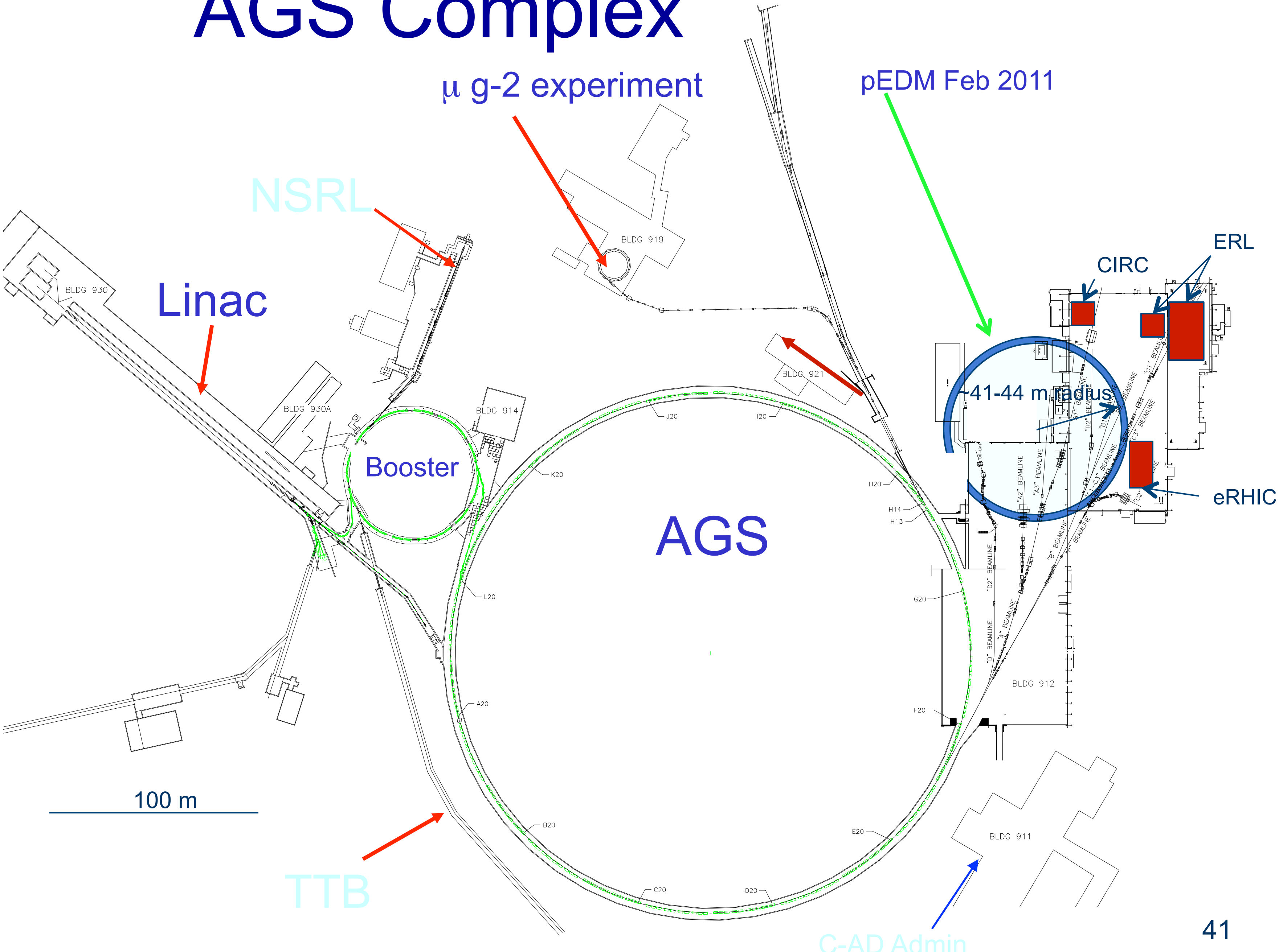
Proton EDM R&D cost

- BPM development & testing over two years: $0.6M
- E-field prototype development & testing: 1.5 years: $0.4M
- SCT tests at COSY: travel support & 1 post doc
- Polarimeter prototype: $0.6M

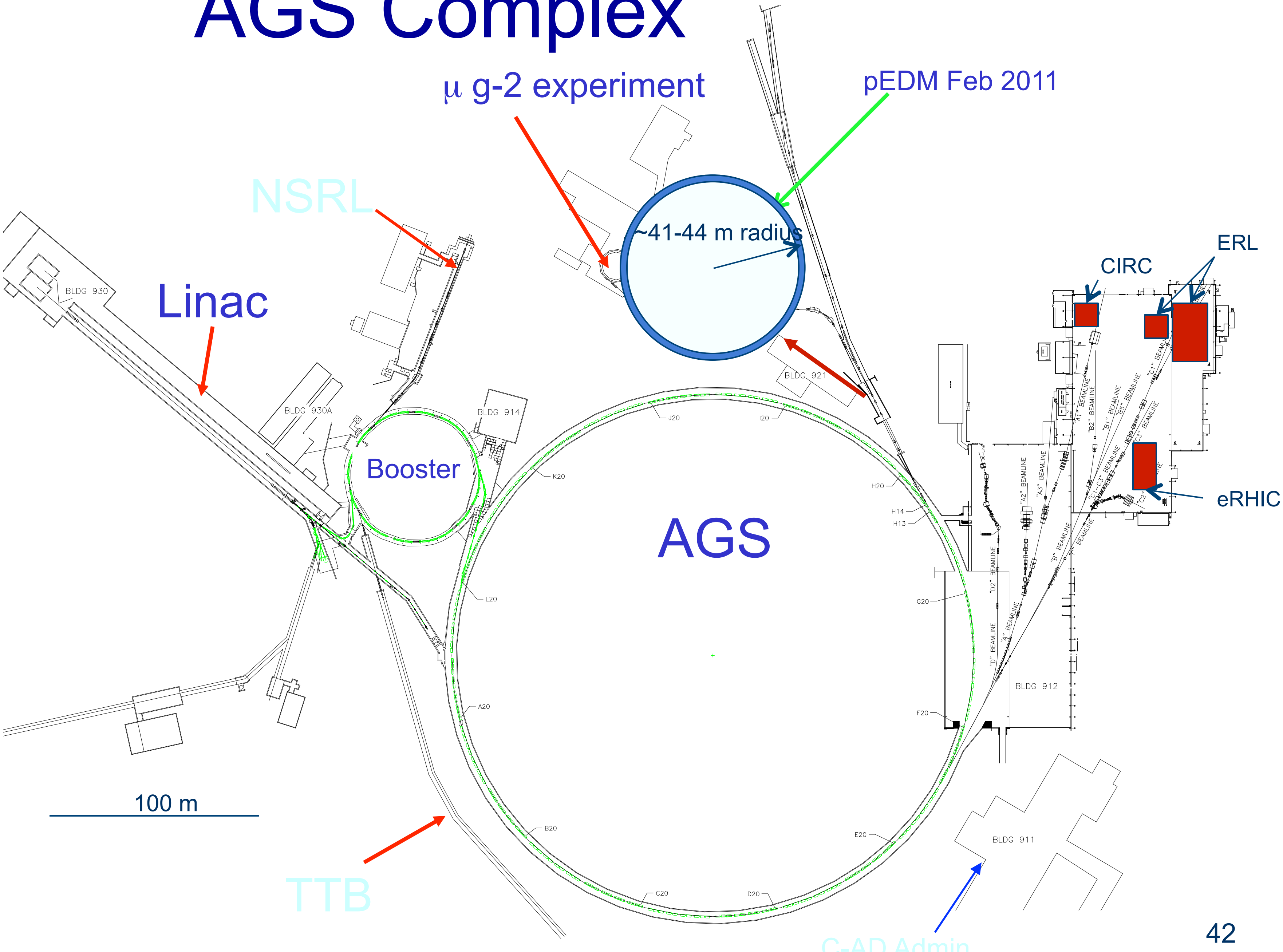
Proton EDM ring candidate locations at BNL

- We considered a couple of places, have made first cost estimate for one.
- We will go ahead and cost estimate one more place (AGS experimental floor)

AGS Complex


μ g-2 experiment
pEDM Feb 2011
NSRL
Linac
BLDG 930
BLDG 919
BLDG 921
BLDG 930A
BLDG 914
Booster
AGS
~41-44 m radius
CIRC
ERL
eRHIC
BLDG 912
BLDG 911
100 m
TTB
C-AD Admin

AGS Complex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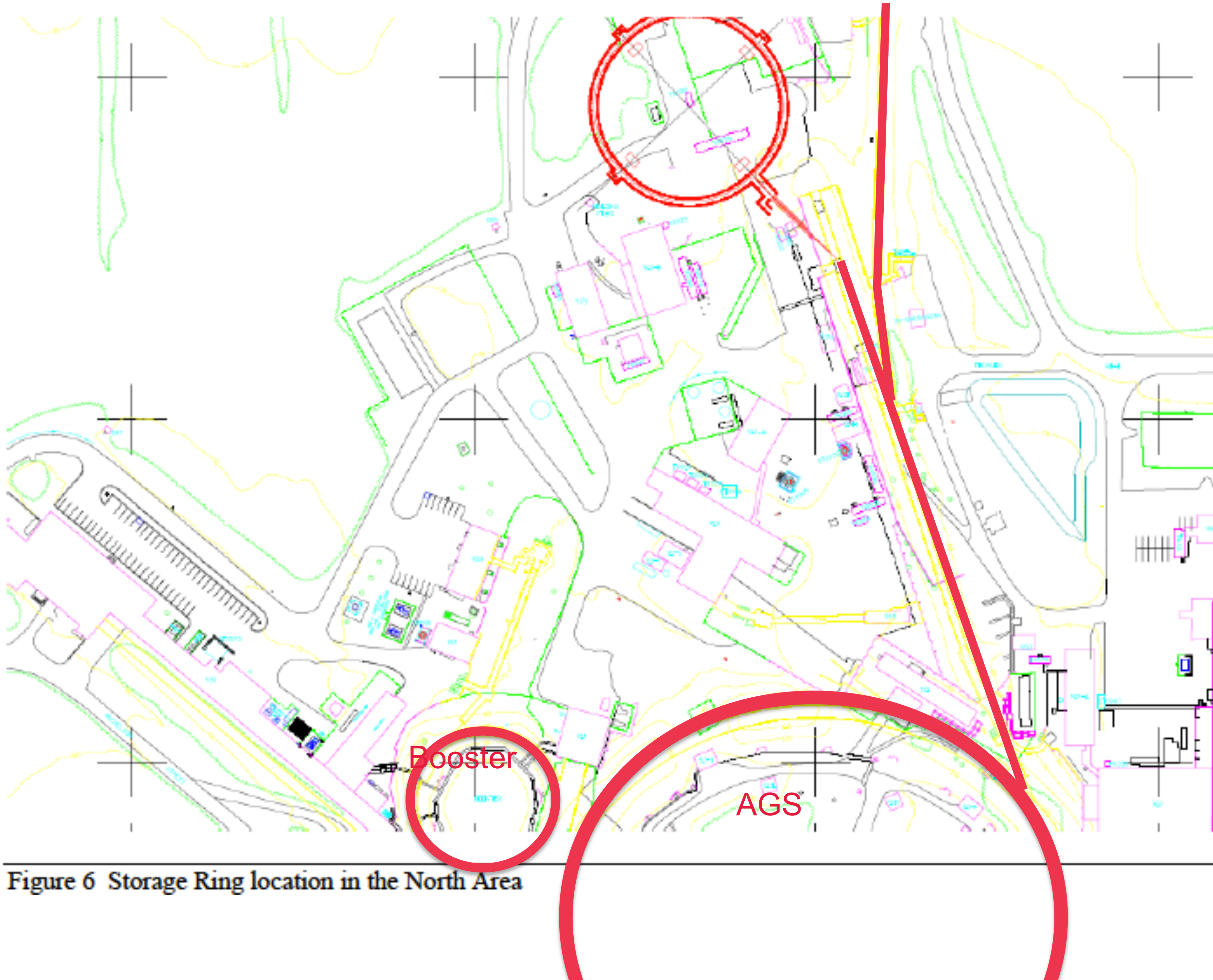


Figure 6 Storage Ring location in the North Area

Proton EDM experiment at BNL cost estimate

- There is still substantial double counting and excessive counting.
- Some items are still missing
- Overhead rate for small project of 39% used. We expect to get the large project rate of 14%.

- Large contingency, 50%-100% was used. Cost estimation will become more realistic with value engineering.

Filling-in the blanks

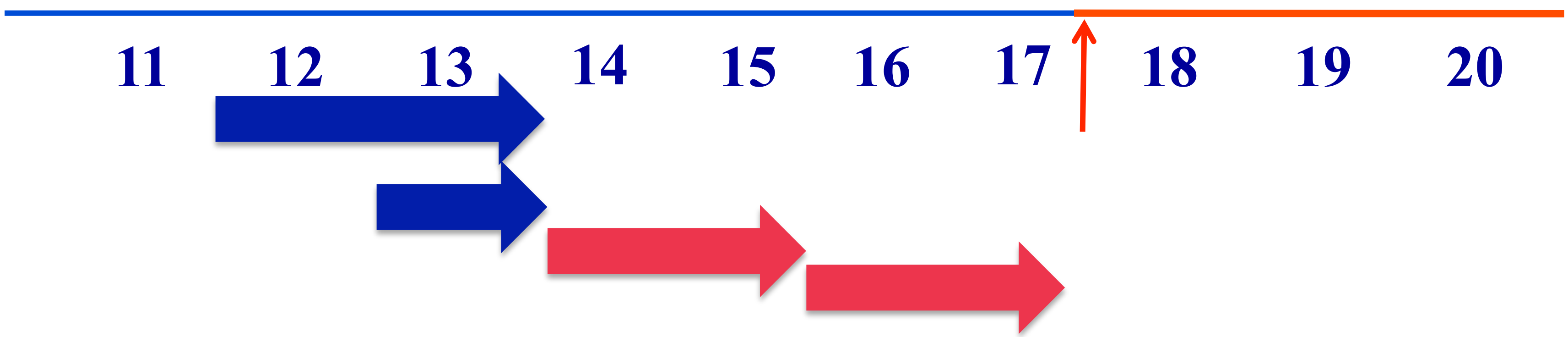
System	Cost	Cost including overhead and contingency	Comments
Electrical		$10.5M	C-AD
V.C. + plates + Vacuum system		$15M	C-AD
Magnetic shielding	$5.6M		From Amuneal company
SQUID-BPM system	$2.5M		pEDM
Polarimeter	$0.6M		pEDM
Active magn. feedback	$1M		
Controls		$1.6M	C-AD
Control room		$0.5M	C-AD
Installation		$15M	C-AD

Filling-in the blanks

System	Cost	Cost including overhead and contingency	Comments
Beamline		$12M	C-AD
Conventional: Ring tunnel, power, water, …		$18.3M	C-AD

- 25% less by using the 14% overhead
- Eliminate several doubles
- Add missing items
- The final estimates for the proposal will be ready in ~2 weeks

Technically driven pEDM timeline



- Two years R&D
- One year final ring design
- Two years ring/beamline construction
- Two years installation

We'll also estimate the schedule for another ring location

Summary

- ✓ Physics is a must do
- ✓ E-field issues understood well
- ✓ Working EDM lattice with long SCT and large enough acceptance (1.3×10^{-29} e•cm/year)
- ✓ Critical to demonstrate feasibility of BPM assumptions including tests at RHIC
- ✓ We need R&D support

- ✓ We are ready to submit the proposal to DOE

Extra slides

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 : 4×10^{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 : 10.5 MV/m Radial electric field strength (95% azim. cov.)

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

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

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	$<3\times10^{-29}$	$<10^{-29}$	10^{-25}-10^{-26}
^{129}Xe atom	$<6\times10^{-27}$	$\sim10^{-29}$-10^{-31}	10^{-25}-10^{-27}
Deuteron nucleus		$\sim10^{-29}$	3×10^{-29}-5×10^{-31}
Proton nucleus	$<7\times10^{-25}$	$\sim10^{-29}$	10^{-29}

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

Analyzing power can be further optimized

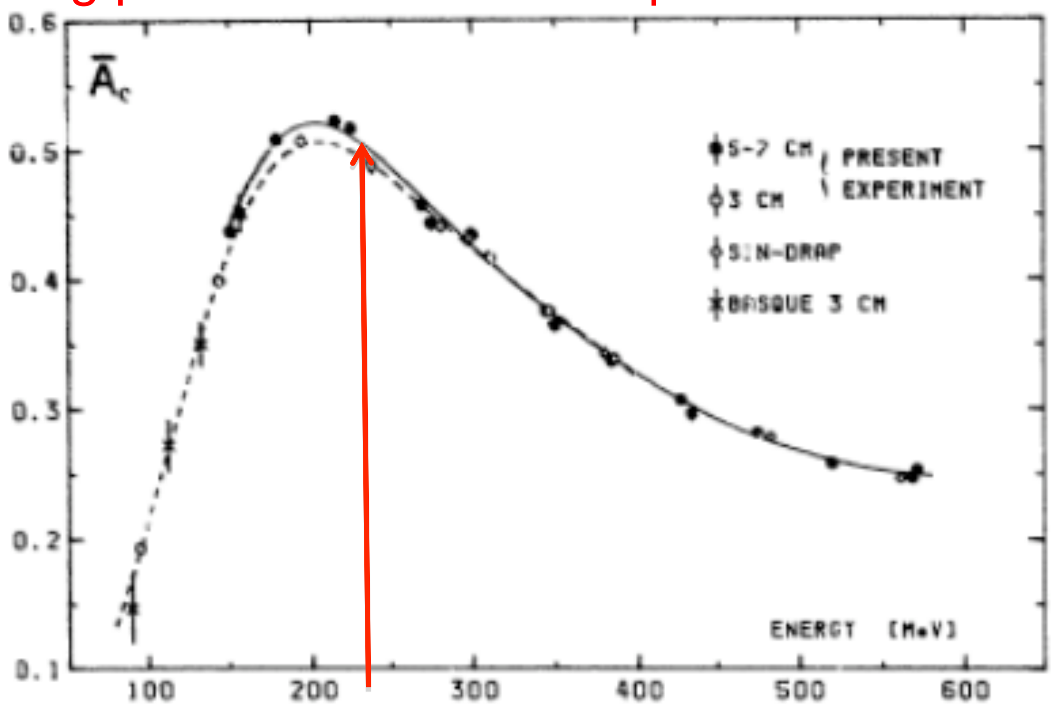


Fig. 4. Angle-averaged effective analyzing power. Curves show our fits. Points are the data included in the fits. Errors are statistical only

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.

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: cancellation level needed for 10^{-28}e-cm is of order 3pG. (See Josh Long's talk for application of ^{199}Hg co-magnetometer in the nEDM.)

EDMs of different systems

Theta_QCD: $$d_n \simeq -d_p \simeq 3\times 10^{-16}\bar{\theta}\ \mathrm{e\cdot cm}$$

$$d_D\left(\bar{\theta}\right)/d_N\left(\bar{\theta}\right) \approx 1/3$$

Super-Symmetry (SUSY) model predictions:

$$d_n \simeq 1.4\left(d_d - 0.25 d_u\right) + 0.83e\left(d_u^c + d_d^c\right) - 0.27e\left(d_u^c - d_d^c\right)$$

$$d_p \simeq 1.4\left(d_d - 0.25 d_u\right) + 0.83e\left(d_u^c + d_d^c\right) + 0.27e\left(d_u^c - d_d^c\right)$$

$$d_D \simeq \left(d_u + d_d\right) - 0.2e\left(d_u^c + d_d^c\right) - 6e\left(d_u^c - d_d^c\right)$$

$$d_N^{I=1} \simeq 0.87\left(d_u - d_d\right) + 0.27e\left(d_u^c - d_d^c\right)$$

$$d_N^{I=0} \simeq 0.5\left(d_u + d_d\right) + 0.83e\left(d_u^c + d_d^c\right)$$

$$d_N^{I=1} = \left(d_p - d_n\right)/2$$

$$d_N^{I=0} = \left(d_p + d_n\right)/2$$

^{3}He Co-magnetometer

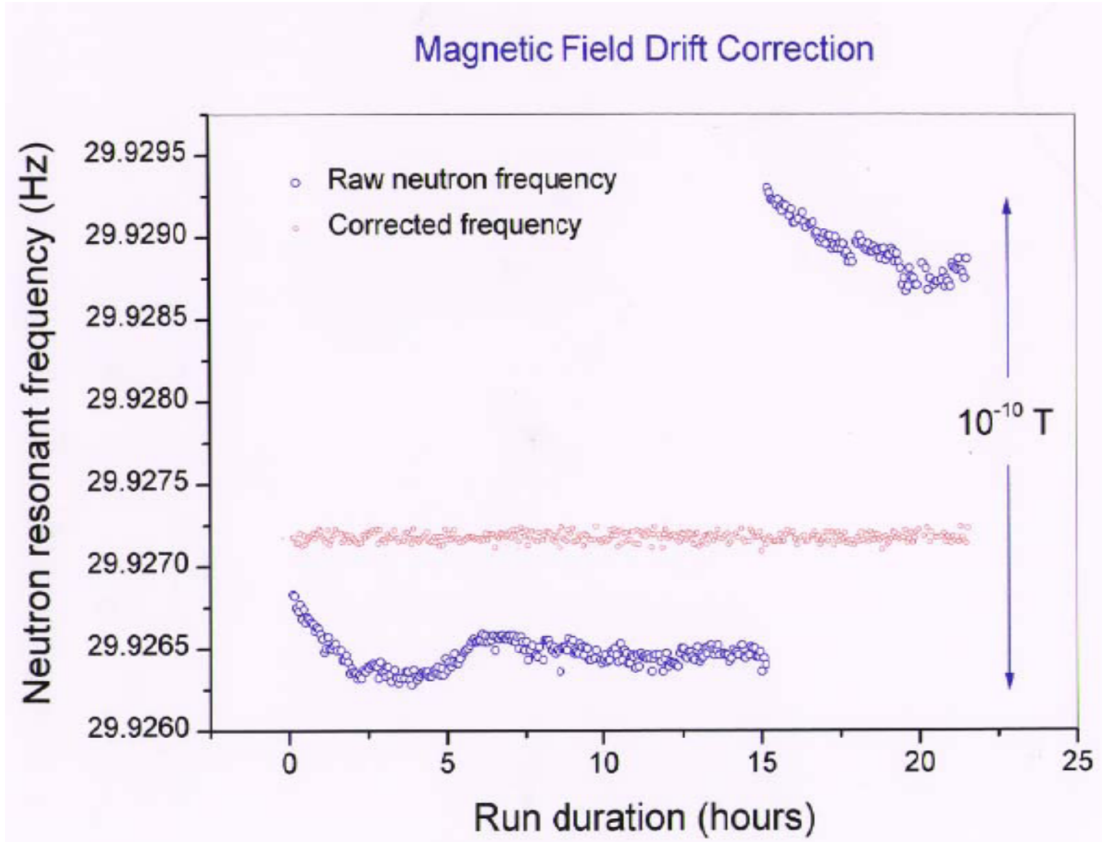
If nEDM = 10^{-26} e·cm,

10 kV/cm → 0.1 μHz shift

≅ B field of 2×10^{-15} T.

Co-magnetometer :

Uniformly samples the B Field faster than the relaxation time.

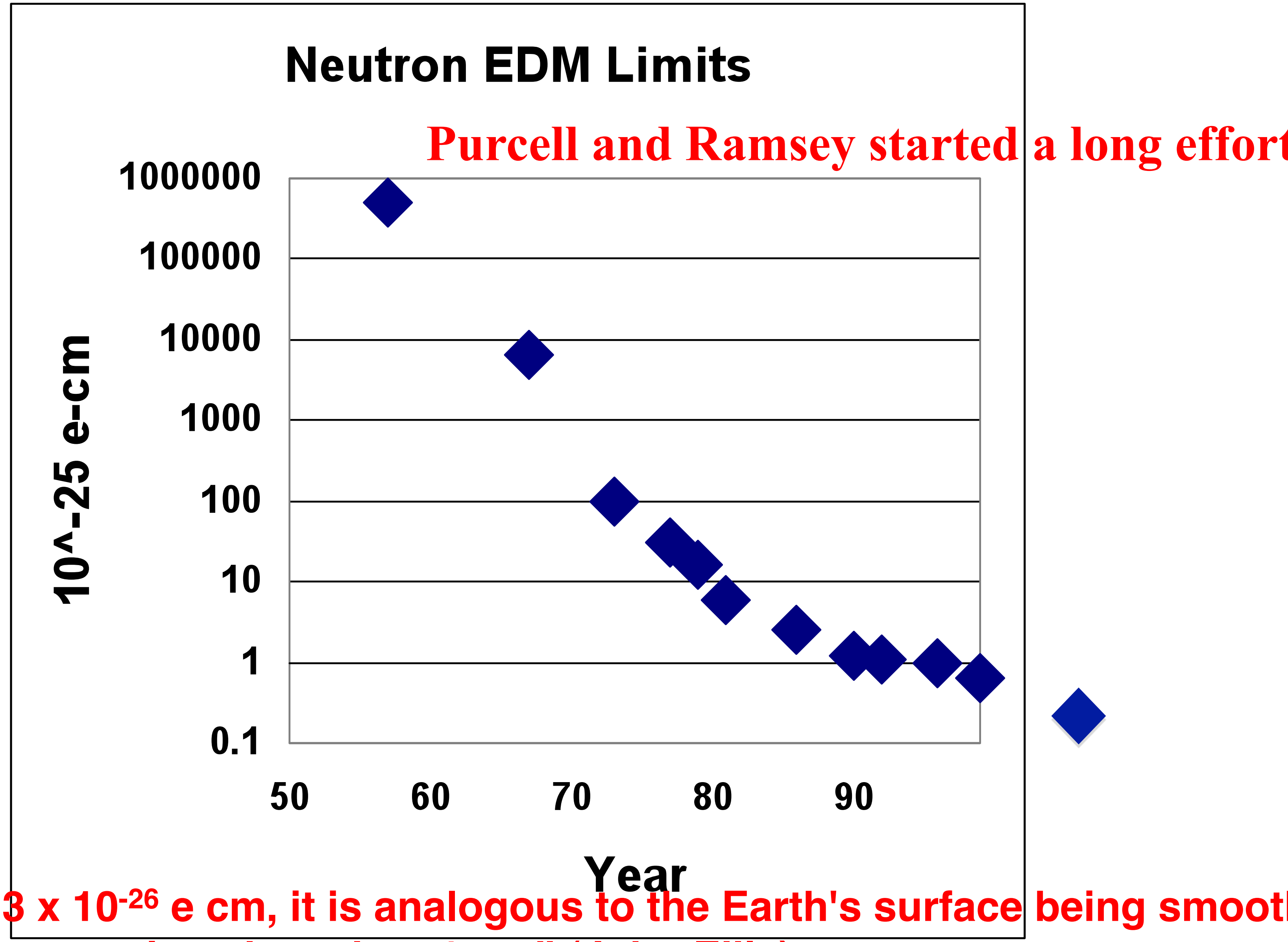


Data: ILL nEDM experiment with ^{199}Hg co-magnetometer

EDM of ^{199}Hg < 10^{-28} e-cm (measured); atomic EDM ~ Z^2 → ^{3}He EDM << 10^{-30} e-cm

Under gravity, the center of mass of He-3 is higher than UCN by $\Delta h \approx 0.13$ cm, sets ΔB = 30 pGauss (1 nA of leakage current). $\Delta B/B = 10^{-3}$.

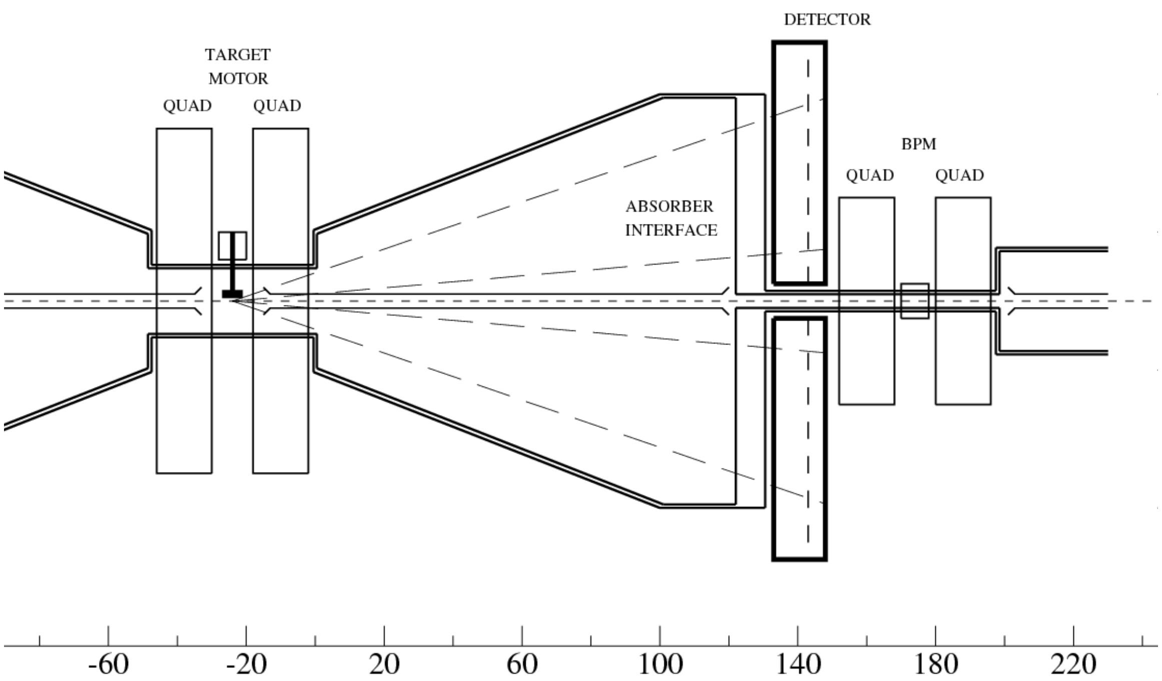
Neutron EDM Vs Year

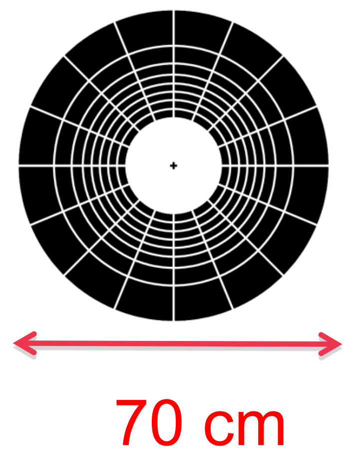


"…at 3 x 10^{-26} e cm, it is analogous to the Earth's surface being smooth and symmetric to less than 1 μm" (John Ellis).

Polarimeter rates:

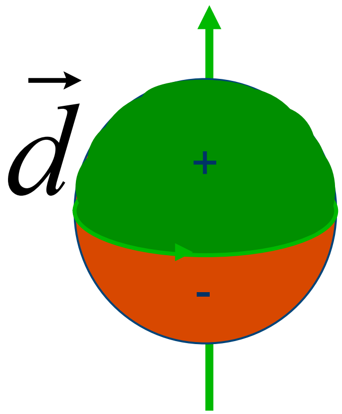
- Beam intensity with 2×10^{10} pol. protons/ $\sim 10^3$s and a detection efficiency of 1% → 200KHz for $\sim 3000 cm^2$ area, or $\sim 100 Hz/cm^2$ on average but much higher at small radius. Design: ~1KHz/pad.





The Electric Dipole Moment precesses in an Electric field

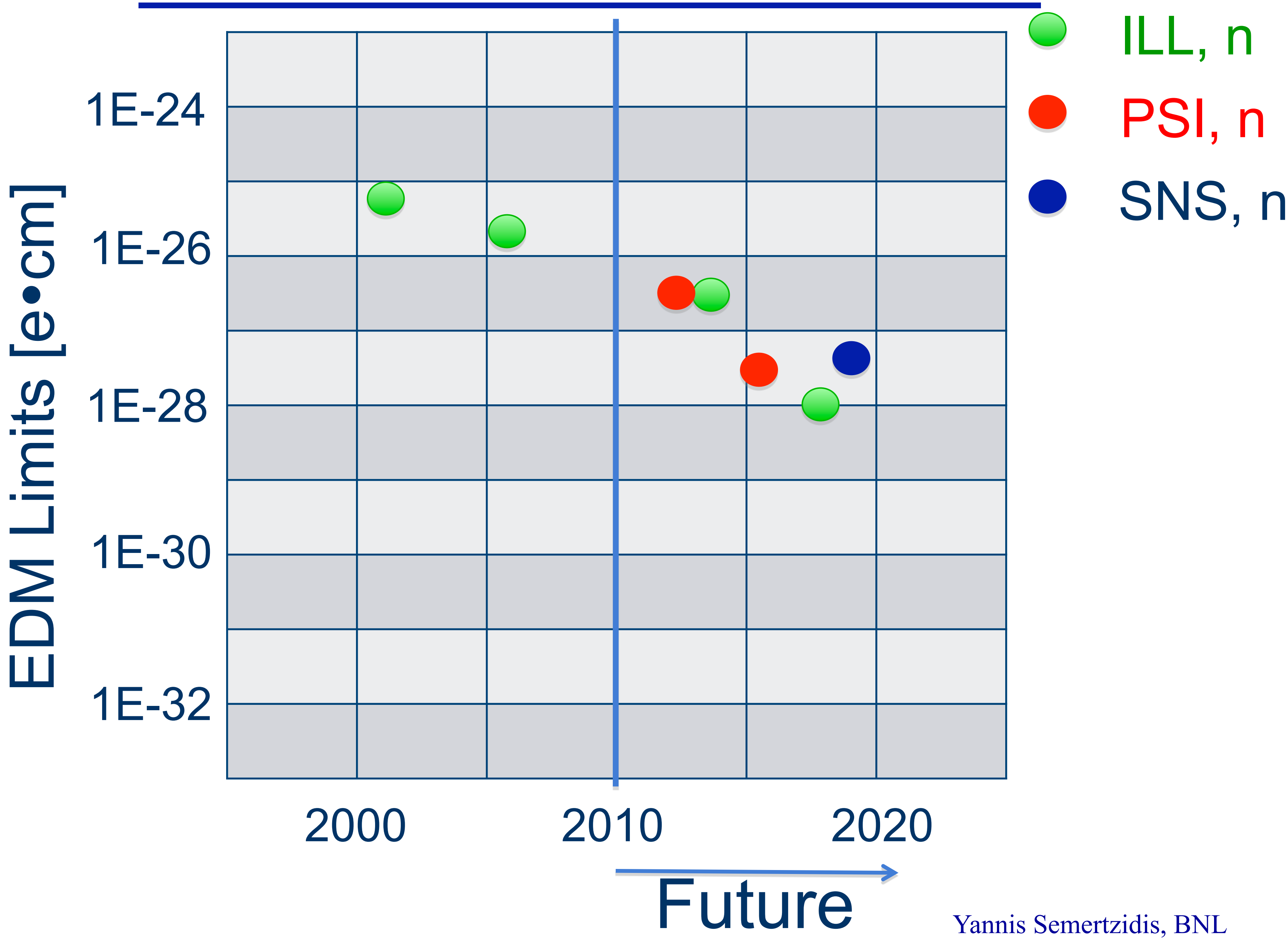
The EDM vector *d* is along the particle spin direction



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

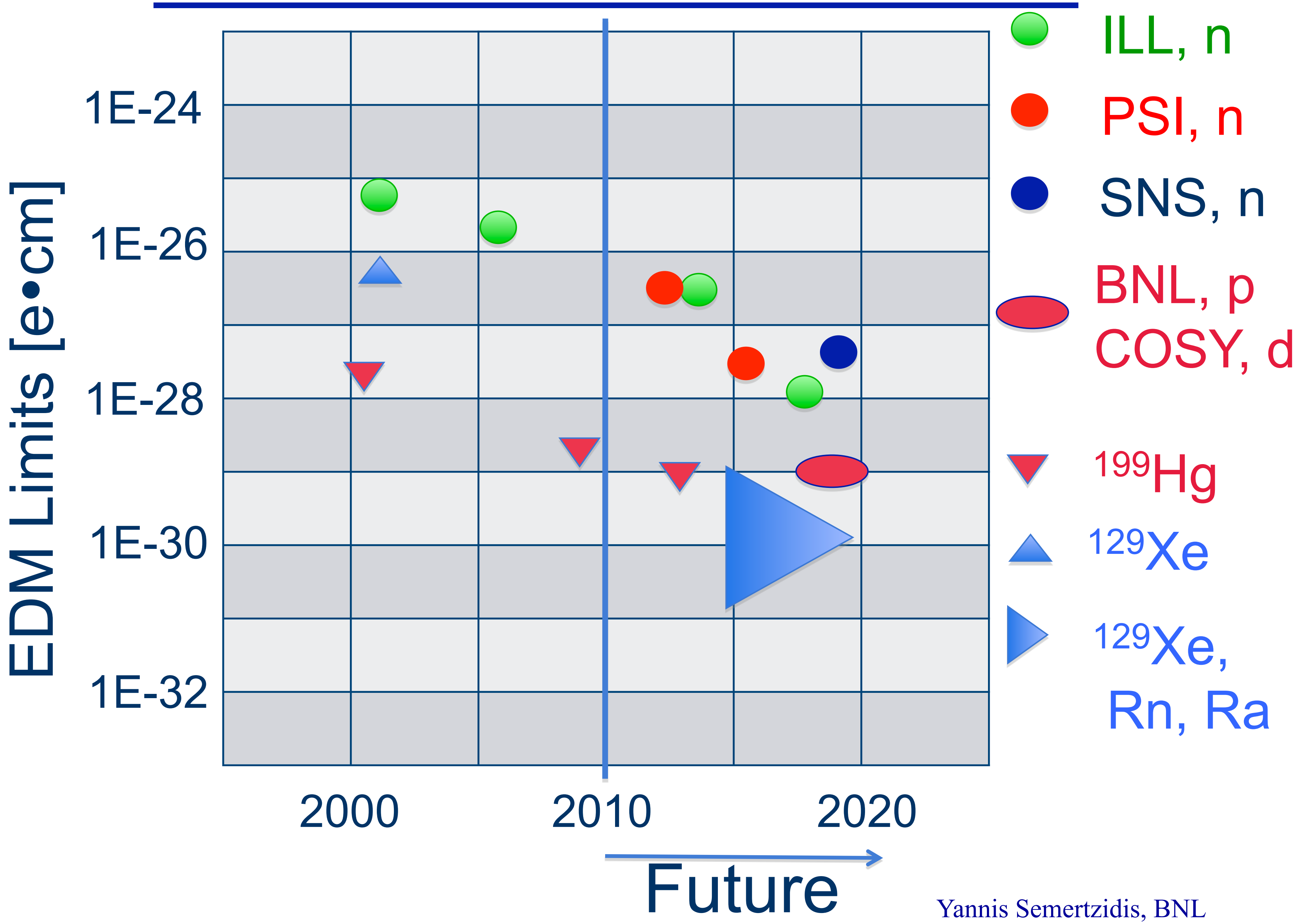
Yannis Semertzidis, BNL

Neutron EDM Timeline



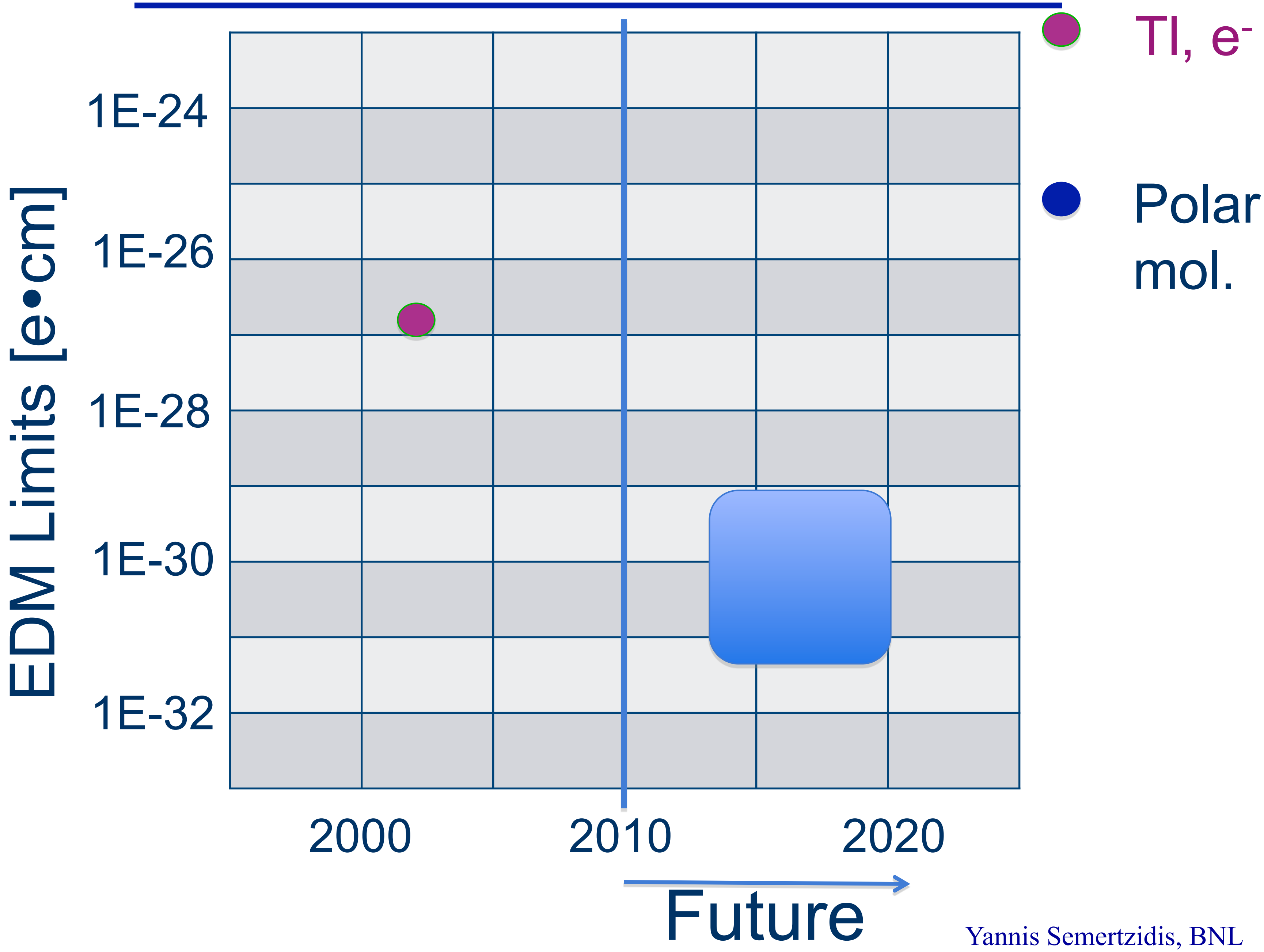
Yannis Semertzidis, BNL

Hadronic EDM Timeline



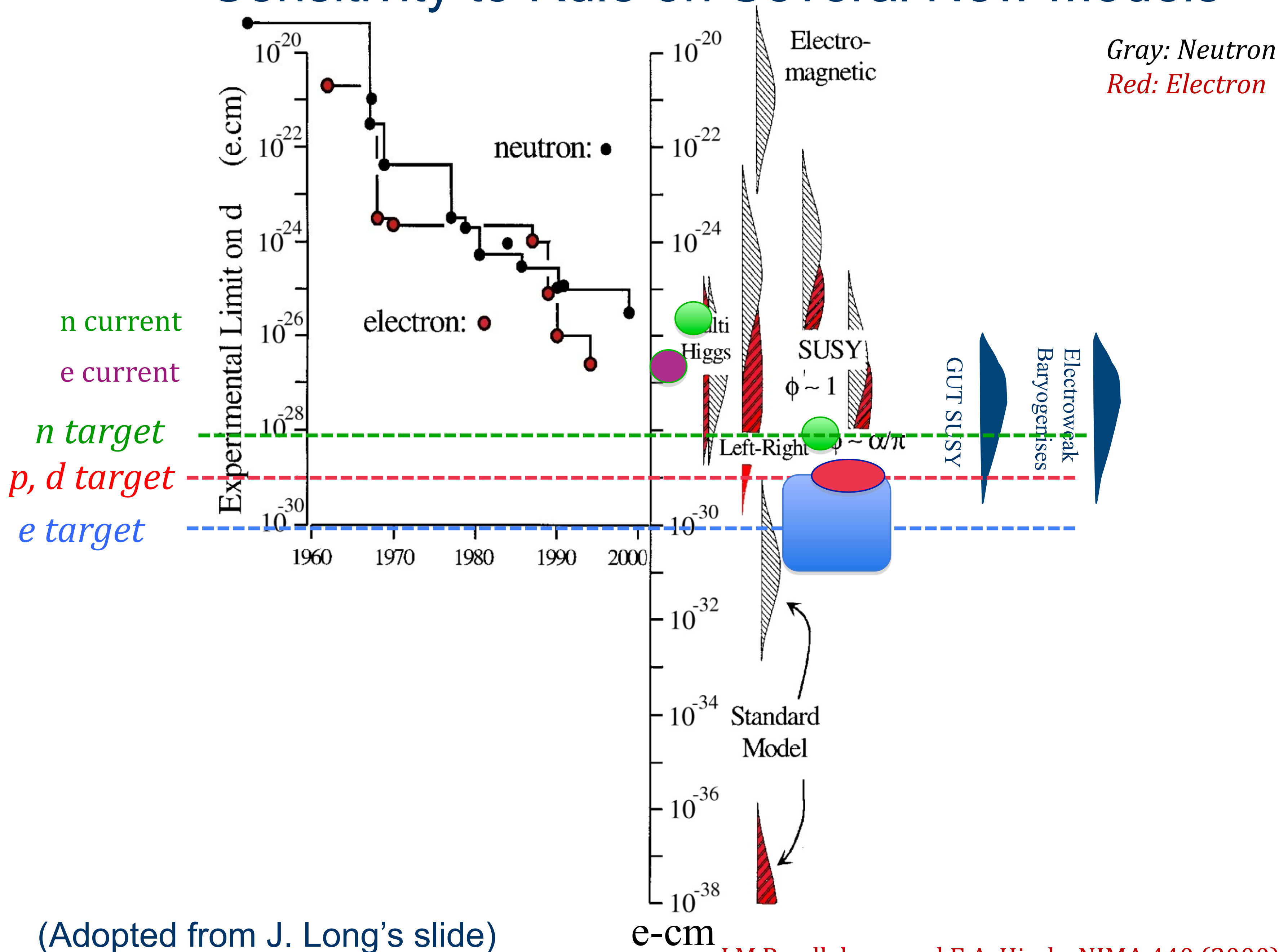
Yannis Semertzidis, BNL

Electron EDM Timeline



Yannis Semertzidis, BNL

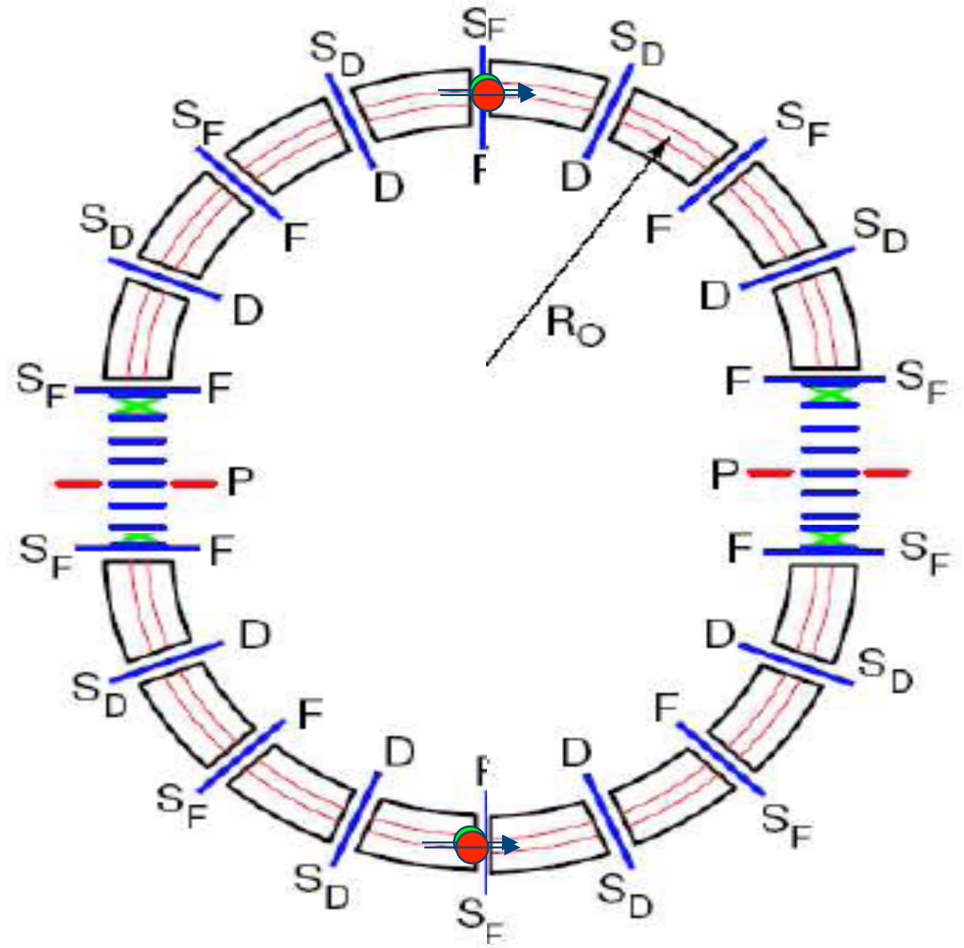
Sensitivity to Rule on Several New Models



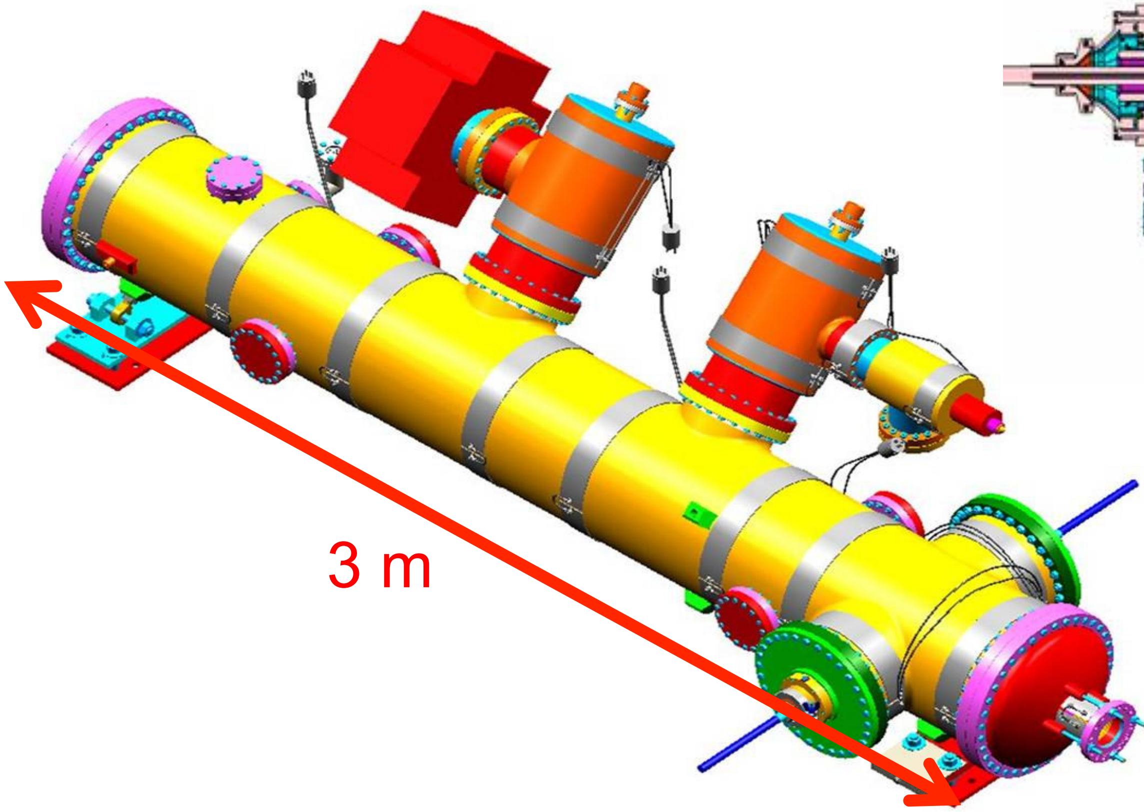
(Adopted from J. Long's slide)

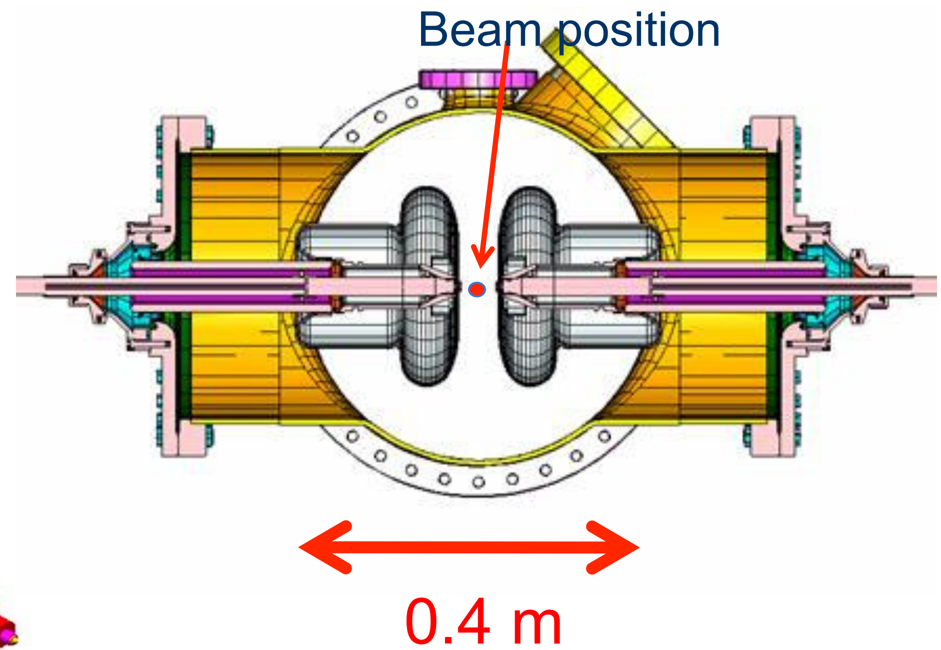
J.M.Pendlebury and E.A. Hinds, NIMA 440 (2000) 471

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



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



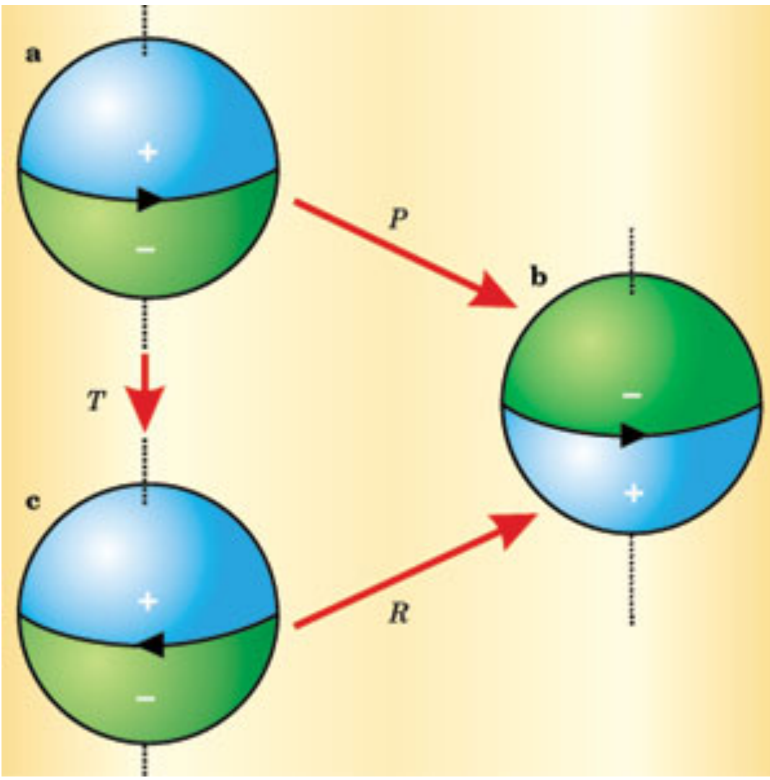


Vertical plates are placed everywhere around the ring to minimize vertical electric/ radial B- fields from image charges

Test of Discrete Spacetime Symmetries

$$H = -\left(\mu\vec{B} + d_n\vec{E}\right)\cdot\frac{\vec{S}}{|S|}$$

EDM: violates P and T



CPT theorem → also CP

Figure: E. N. Fortson,
Physics Today 56 6 (2003) 33

$Y_B = n_B/\gamma \sim 10^{-10}$

WMAP, PDB (2010)

Sakharov's criteria

- Baryon number violation

  $\phi \rightarrow B;\ \phi \rightarrow \bar{B}$ $\Delta B \neq 0$

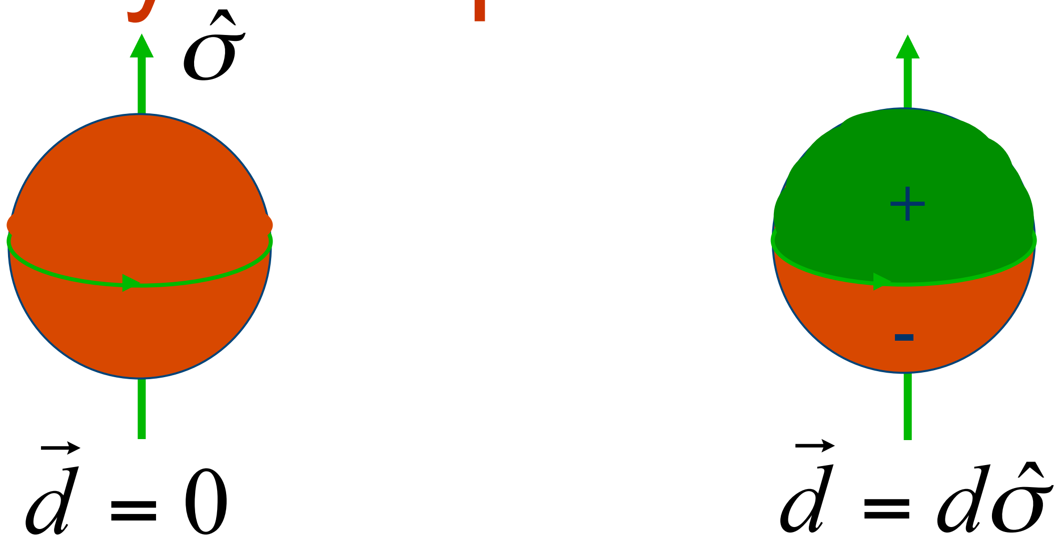
- CP violation and C violation

  $R(\phi \rightarrow B) > R(\phi \rightarrow \bar{B})$

- Departure from thermal equilibrium

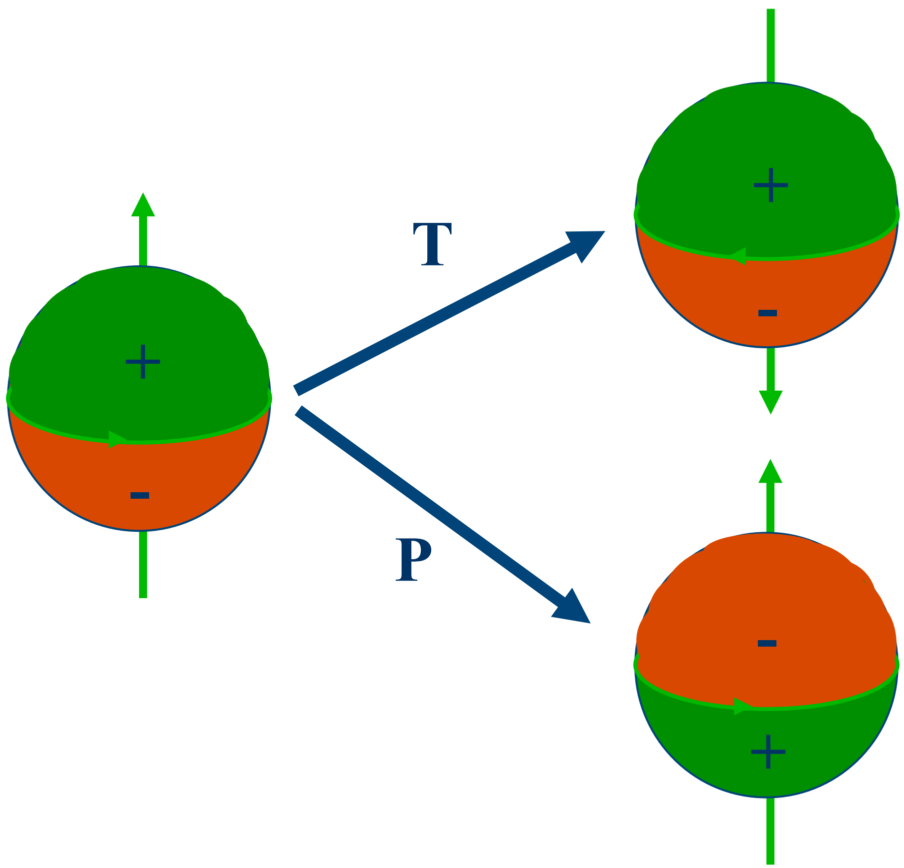
  $R(\phi \rightarrow B) > R(B \rightarrow \phi)$

In Quantum Mechanics: a non-degenerate system with Spin is defined by the spin vector

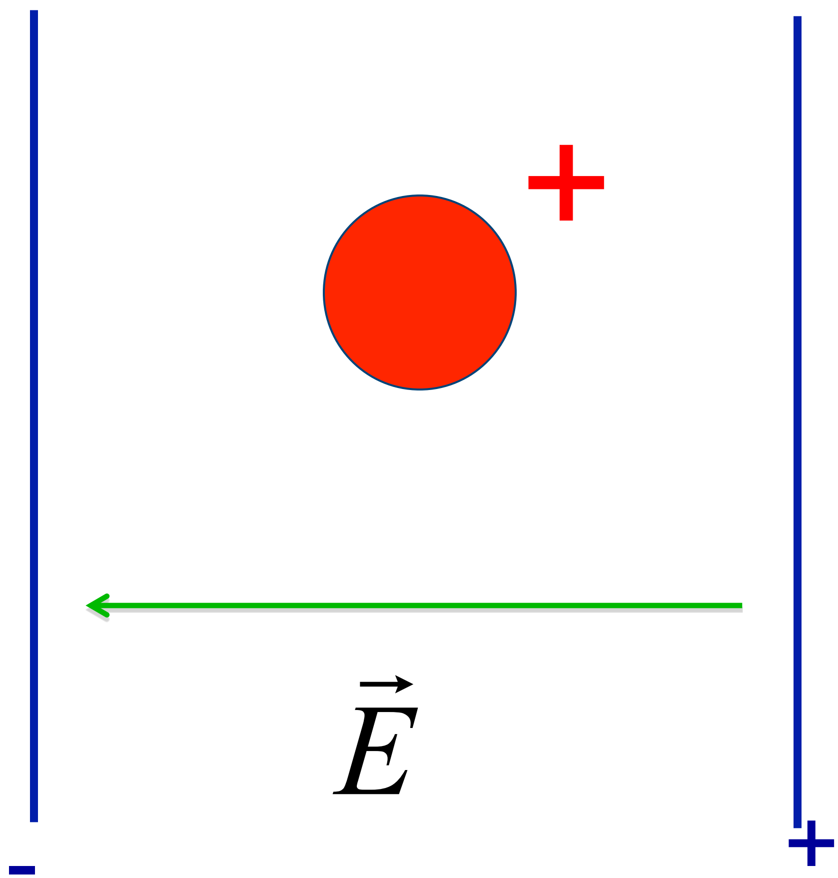


If the particle has an EDM, its vector needs to be aligned with the spin vector, locked to its direction, i.e. it needs to choose either along or opposite but not both (non-degenerate). “CP-Violation Without Strangeness”, Khriplovich/Lamoreaux.

A Permanent EDM Violates both T & P Symmetries:

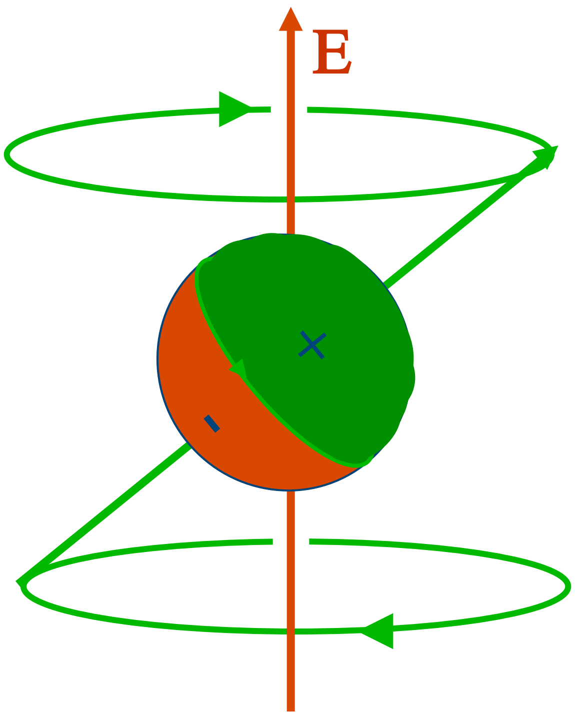


A charged particle between Electric Field plates would be lost right away.



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:

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

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

Caution is needed applying this equation to obtain the statistical accuracy…

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

The data

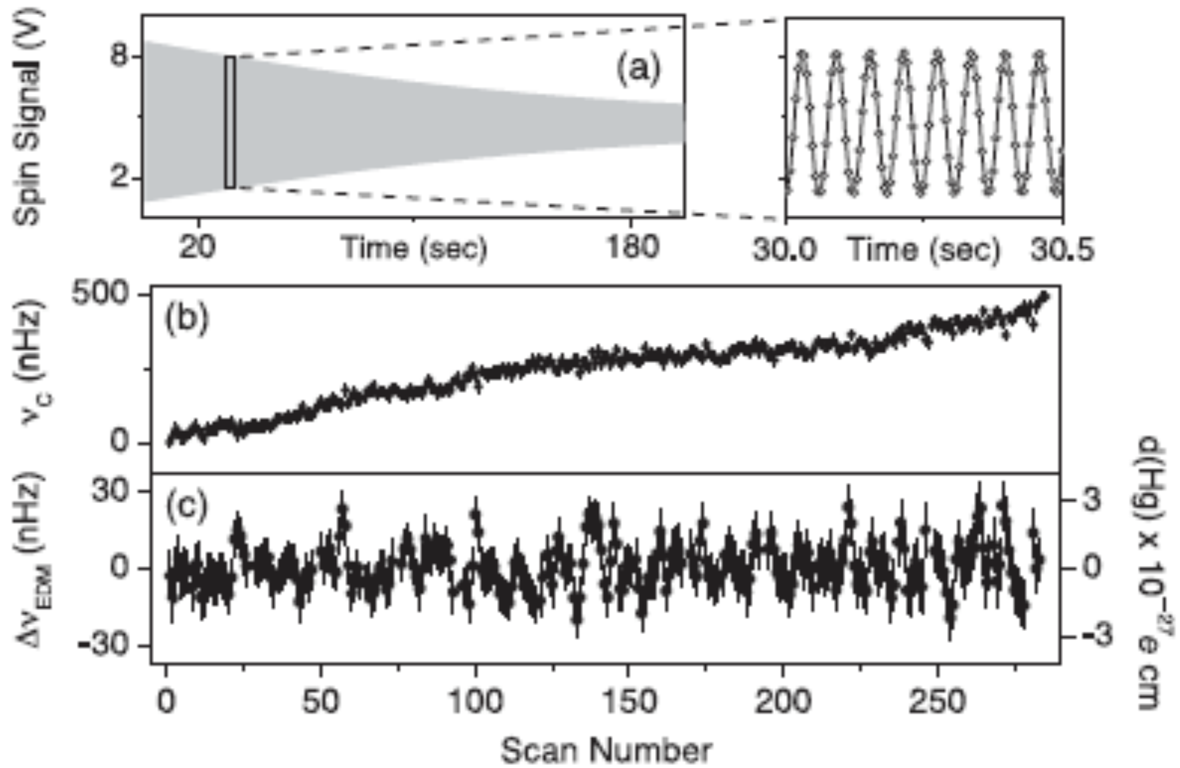


FIG. 2. (a) Typical single-cell precession signal with an expanded 0.5 sec segment. (b),(c) ν_c and $\Delta\nu_{\mathrm{EDM}}$ for a typical run. In (c) the reduced χ^2 is 1.2 and the run-averaged statistical error is 0.85 nHz after scaling by $\sqrt{\chi^2}$.

- 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

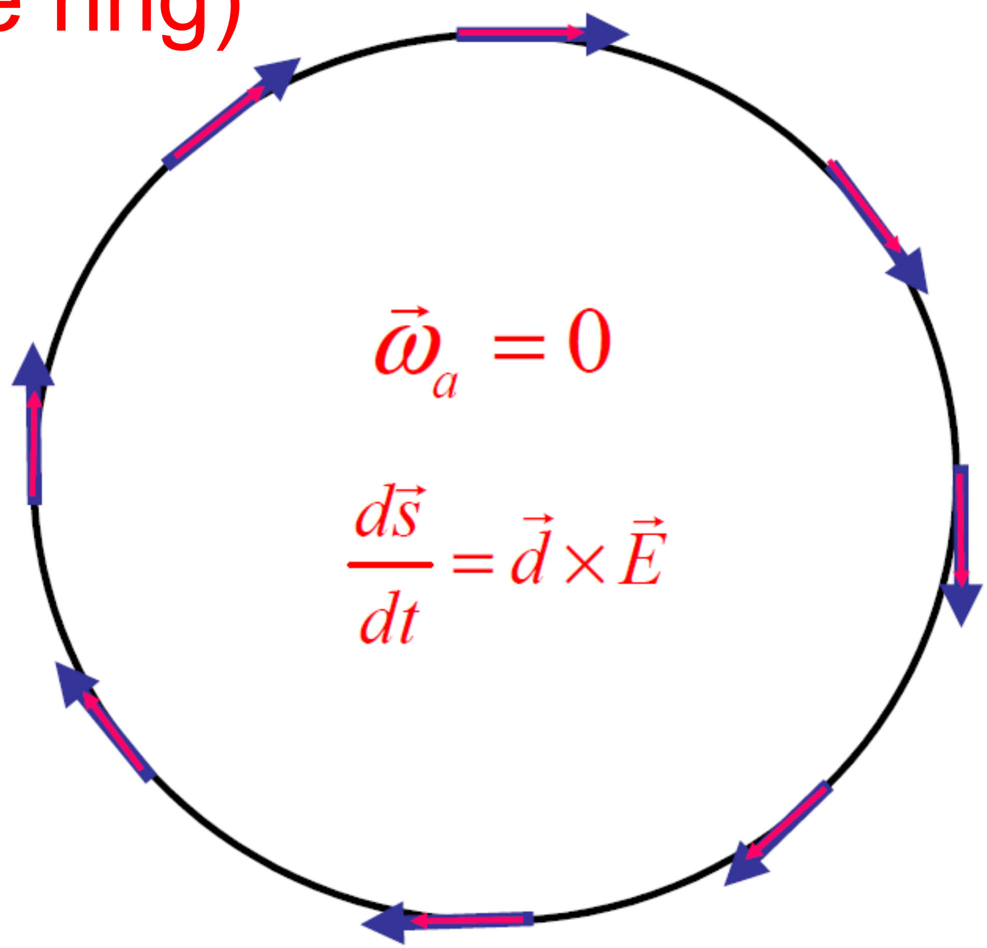
Parameter	^{199}Hg bound	Hg theory	Best alternate limit
$\tilde{d}_q$ (cm) [a]	6×10^{-27}	[15]	n: 3×10^{-26} [3]
d_p (e cm)	7.9×10^{-25}	[16]	TlF: 6×10^{-23} [17]
C_S	5.2×10^{-8}	[18]	Tl: 2.4×10^{-7} [19]
C_P	5.1×10^{-7}	[18]	TlF: 3×10^{-4} [1]
C_T	1.5×10^{-9}	[18]	TlF: 4.5×10^{-7} [1]
$\bar{\theta}_{QCD}$	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, $\tilde{d}_q = (0.5\tilde{d}_u + \tilde{d}_d)$.

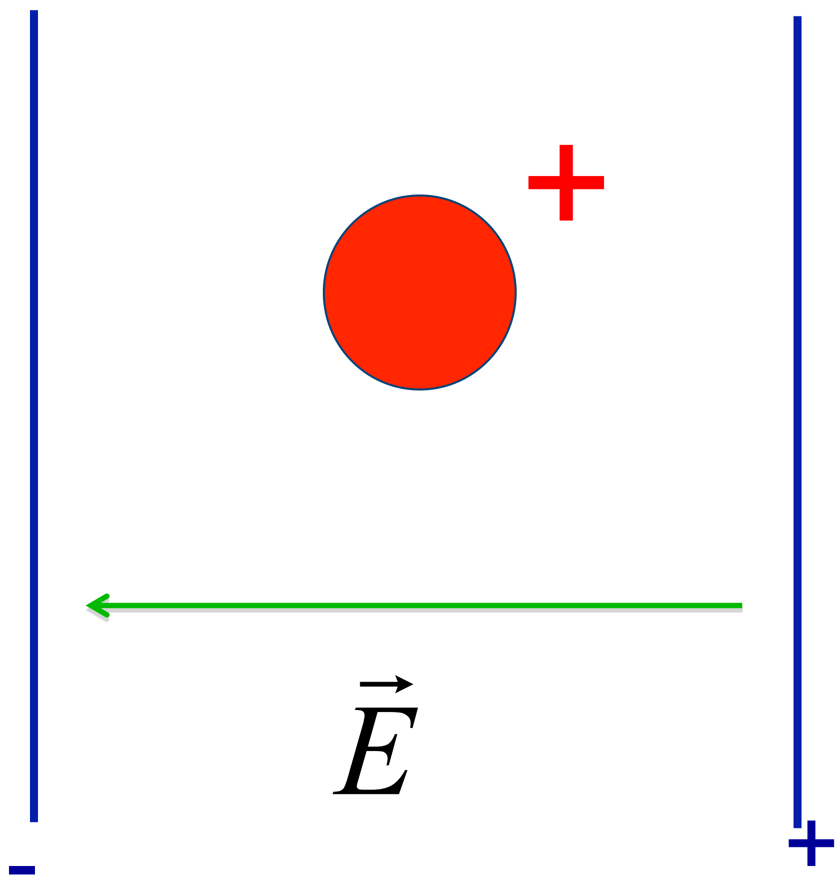
- It now dominates the limits on many parameters
- They expect another improvement factor ~3 - 5.

Storage Ring EDM experiments

(or how to create a Dirac-like particle in a storage ring)



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



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