SACLAY

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Muon g-2 and Electric Dipole Moments in Storage Rings: Powerful Probes of Physics Beyond the SM

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- Muon g-2, Principle, Status, Future
- dEDM: "Frozen" Spin Method

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

Definition of g-Factor

$$g \equiv \frac{\dfrac{\text{magnetic moment}}{e\hbar/2mc}}{\dfrac{\text{angular momentum}}{\hbar}}$$

g-2 measures the difference between the charge and mass distributions. g-2=0 when they are the same all the time…

From Dirac equation g-2=0 for point-like, spin ½ particles.

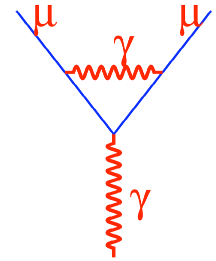
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

g-factors:

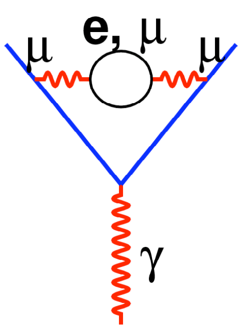
- Proton (g_p=+5.586) and the neutron (g_n=-3.826) are composite particles.
- The ratio g_p/g_n=-1.46 close to the predicted –3/2 was the first success of the constituent quark model.
- The g_e-2 (of the electron) is non-zero mainly due to quantum field fluctuations involving QED.
- The g_μ-2 is more sensitive to a class of particles than the g_e-2 by $(m_\mu/m_e)^2$~40,000.

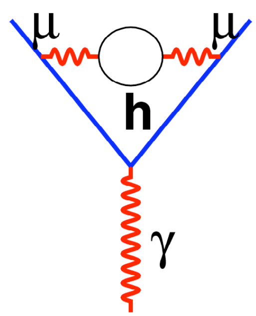
g - 2 for the muon

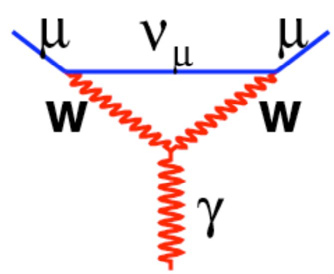
Largest contribution : $a_\mu = \frac{\alpha}{2\pi} \approx \frac{1}{800}$

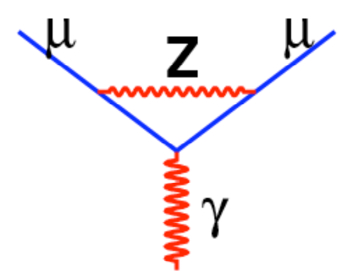


Other standard model contributions :







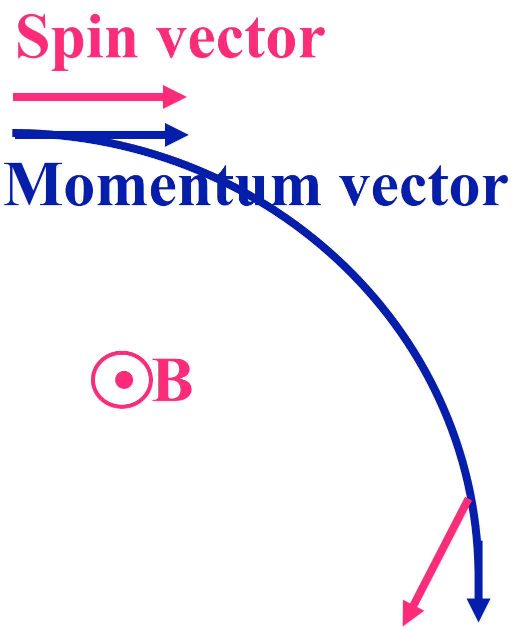


QED hadronic weak

Experimental Principle:

- Polarize: Parity Violating Decay $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
- Interact: Precess in a Uniform B-Field
- Analyze: Parity Violating Decay $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

The Principle of g-2



Non-relativistic case

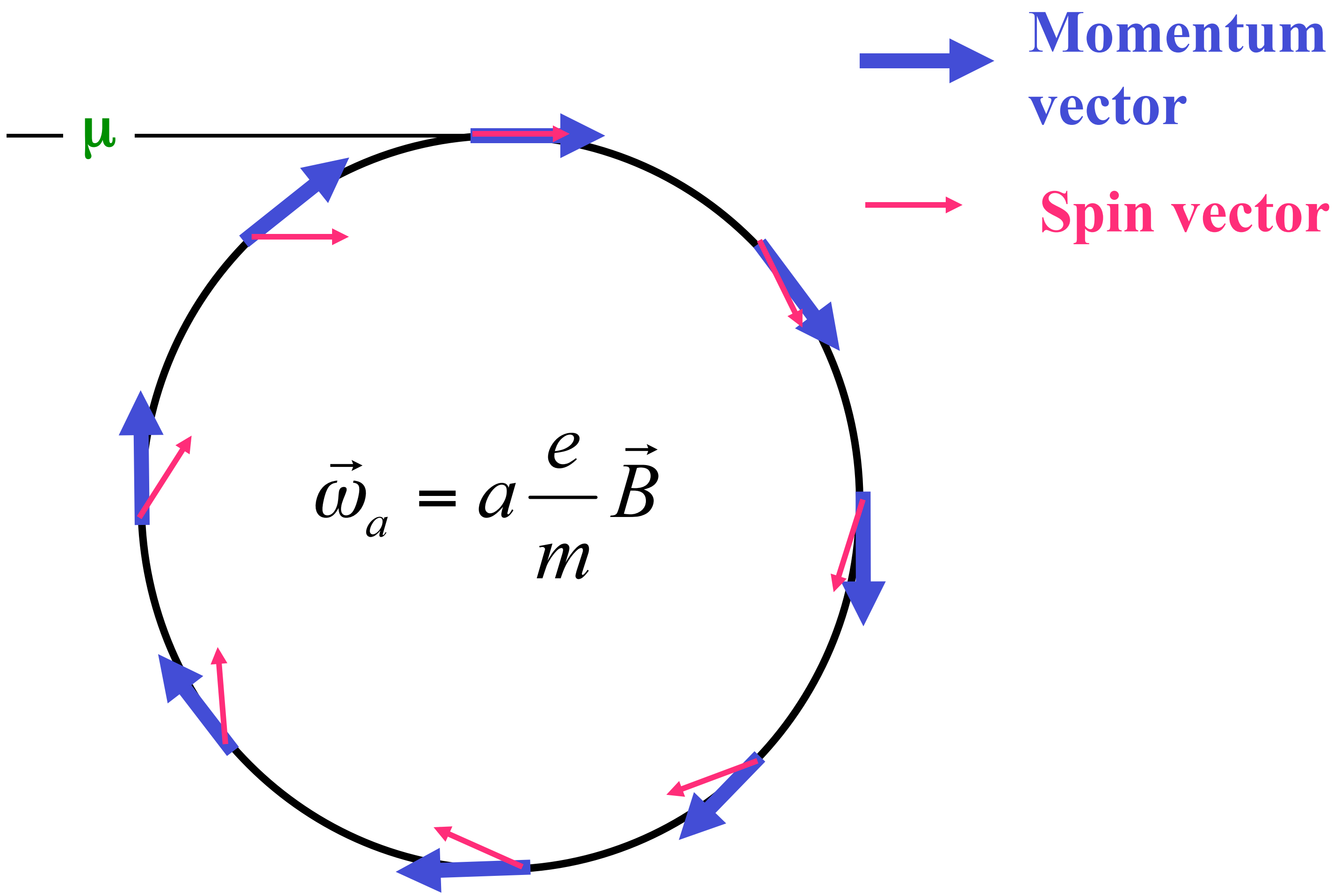
$$\omega_c = \frac{eB}{m}$$

$$\omega_s = \frac{g}{2}\frac{eB}{m}$$

$$\omega_a = \omega_s - \omega_c = \frac{g}{2}\frac{eB}{m} - \frac{eB}{m} = \left(\frac{g-2}{2}\right)\frac{eB}{m} \Rightarrow \boxed{\omega_a = a\frac{eB}{m}}$$

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

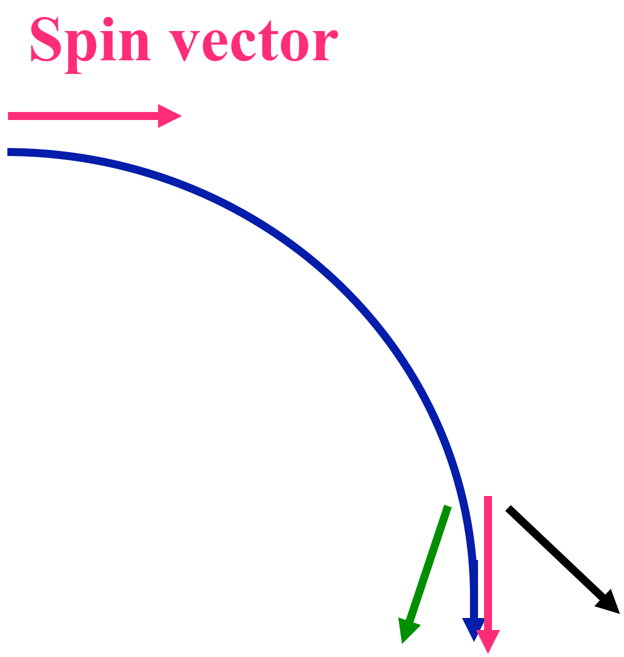
Spin Precession in g-2 Ring (Top View)



$$\vec{\omega}_a = a \frac{e}{m} \vec{B}$$

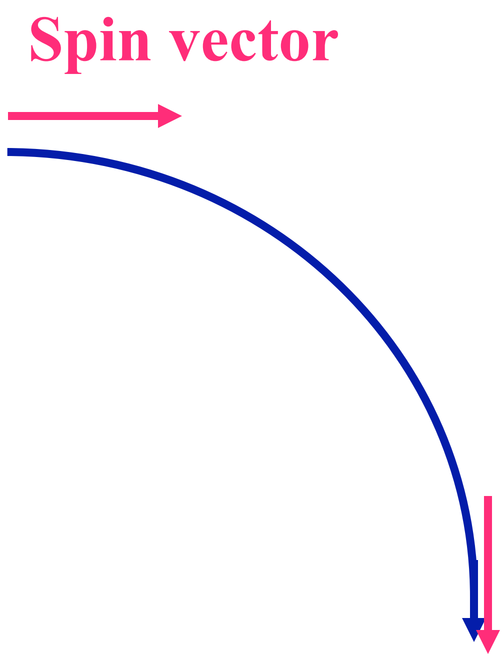
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

Effect of Radial Electric Field (used for focusing the muons)



- Low energy particle
- …just right
- High energy particle

Effect of Radial Electric Field

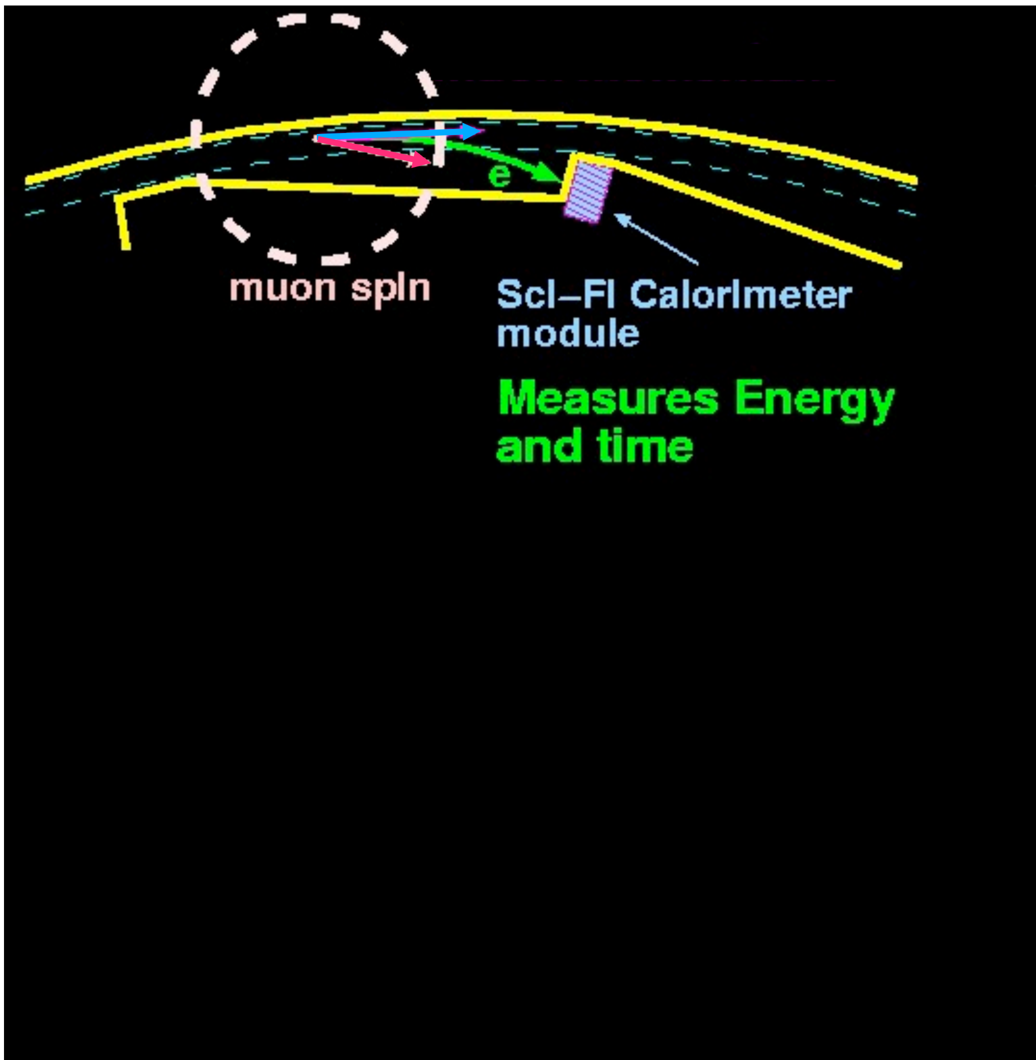


- …just right, $\gamma \approx 29.3$
  for muons
  (~3GeV/c)

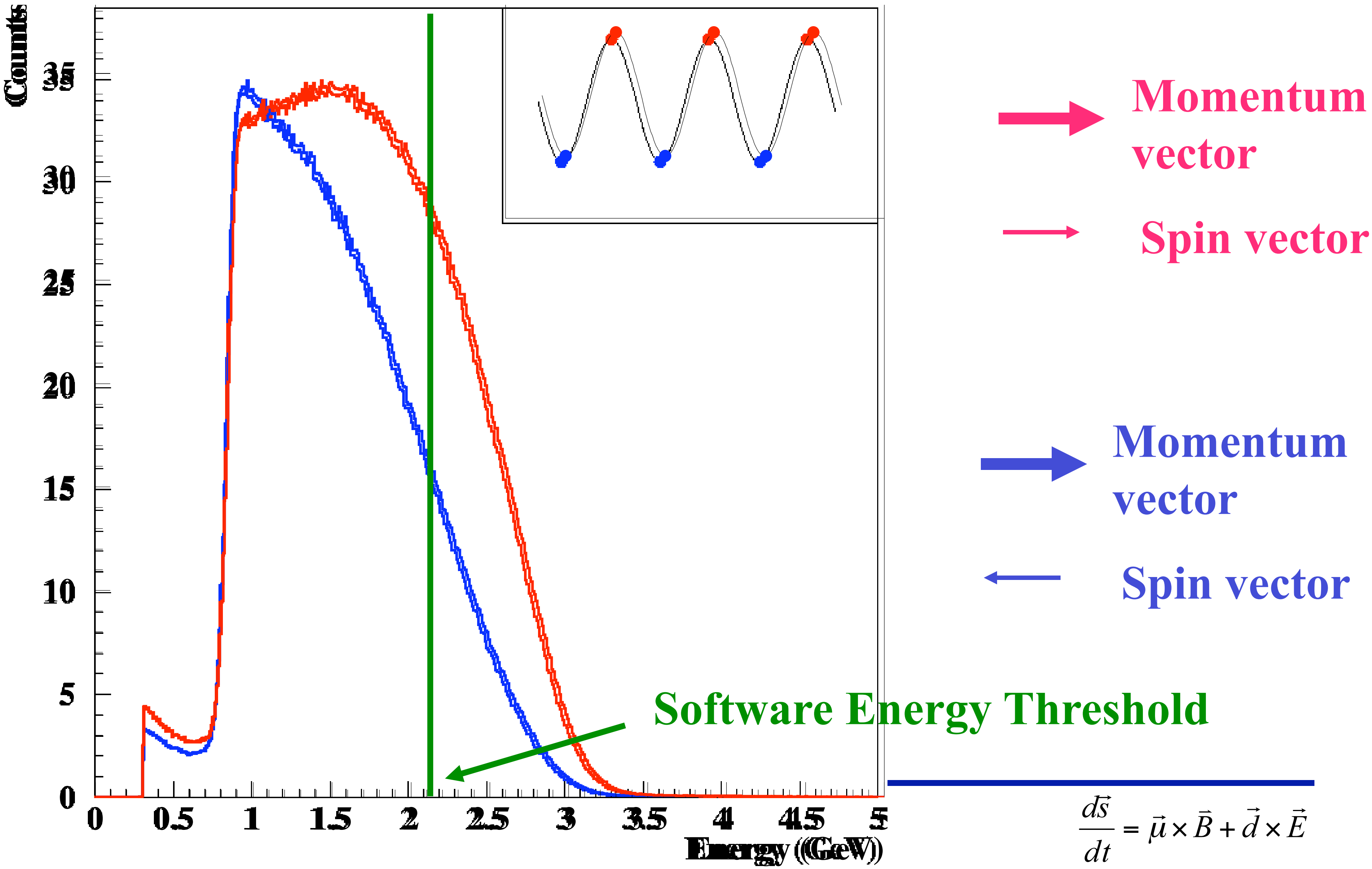
• The Muon Storage Ring:
$B \approx 1.45T, P_{\mu} \approx 3$ GeV/c

• High Proton Intensity from AGS

Detectors and vacuum chamber



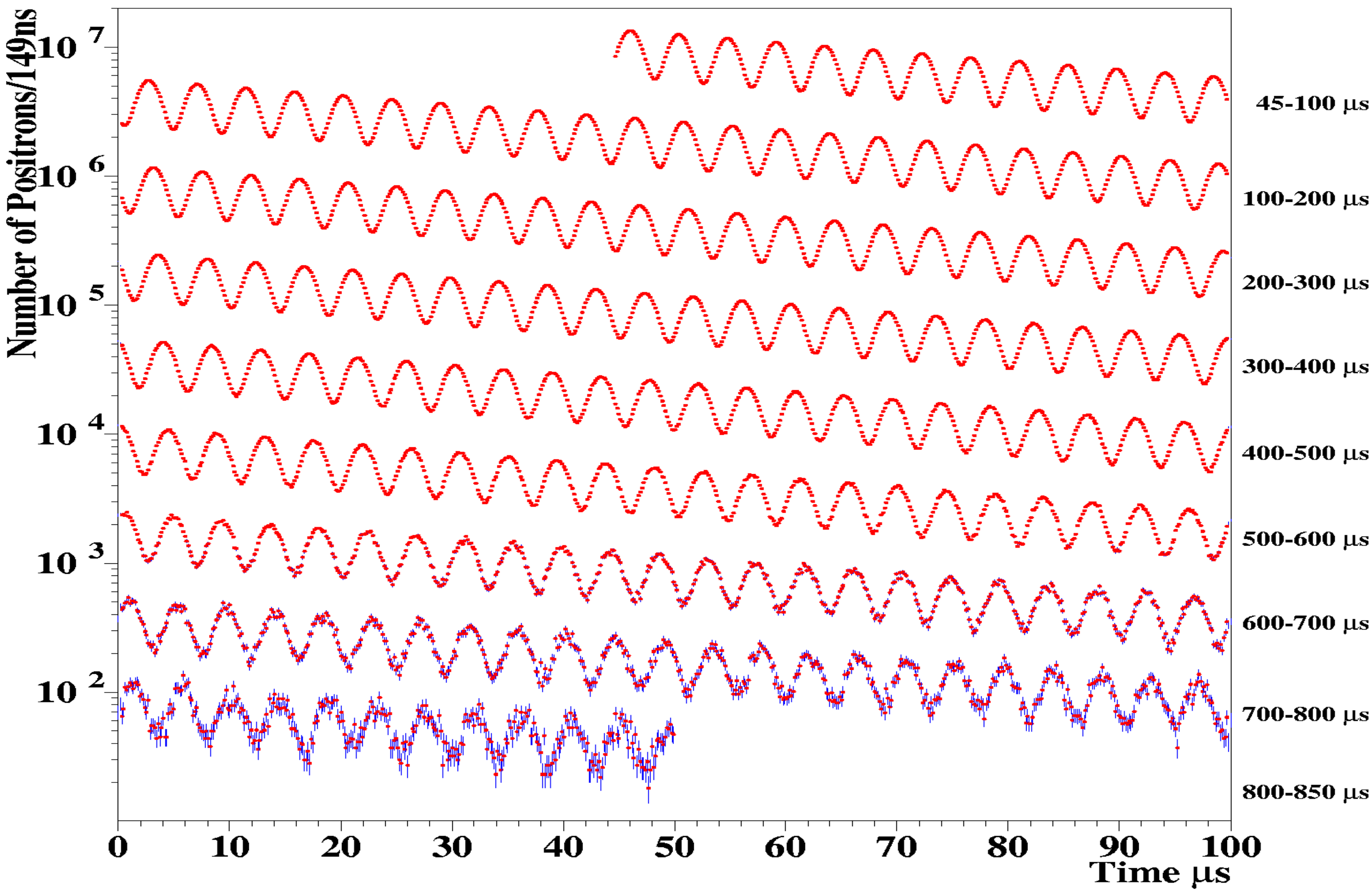
Energy Spectrum of Detected Positrons



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

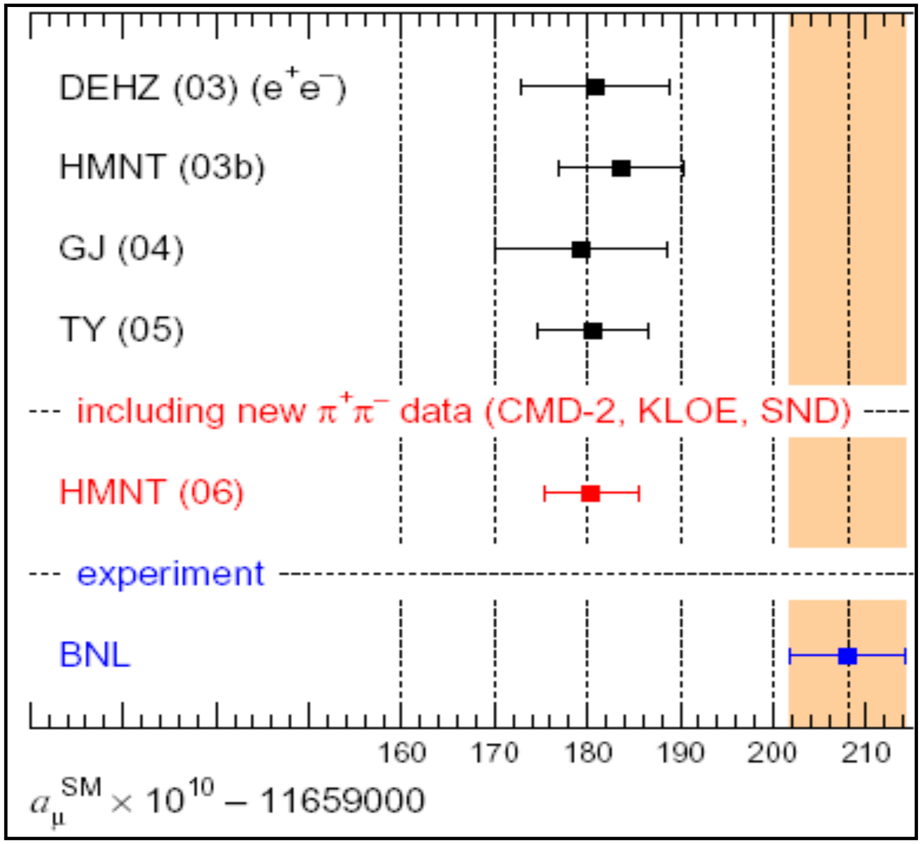
4 Billion e^+ with E>2GeV

$$dN/dt = N_0 e^{-\frac{t}{\tau}}\left[1 + A\cos(\omega_a t + \phi_a)\right]$$



Theory and experiment

Date

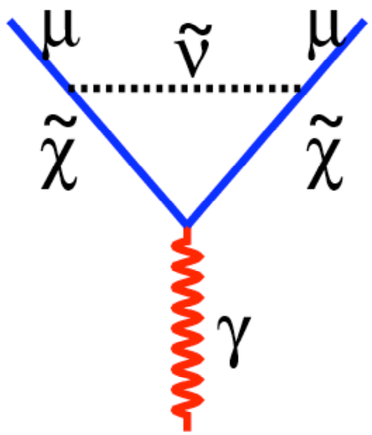


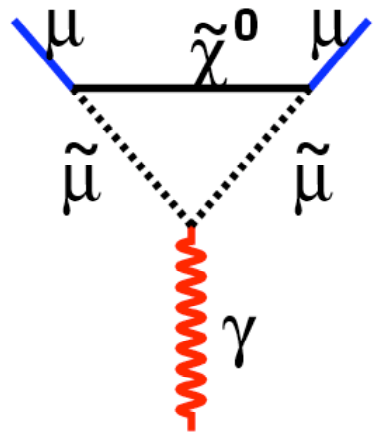
Δa_μ(expt-thy) = (29.5±8.8) x 10^{-10} (3.4 σ)

Based on de Rafael's theory summary (2007), using inputs from Davier (2006) and HMNT (2006). **Rep.Prog.Phys. 70, 795 (2007).**

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

Beyond standard model, e.g. SUSY





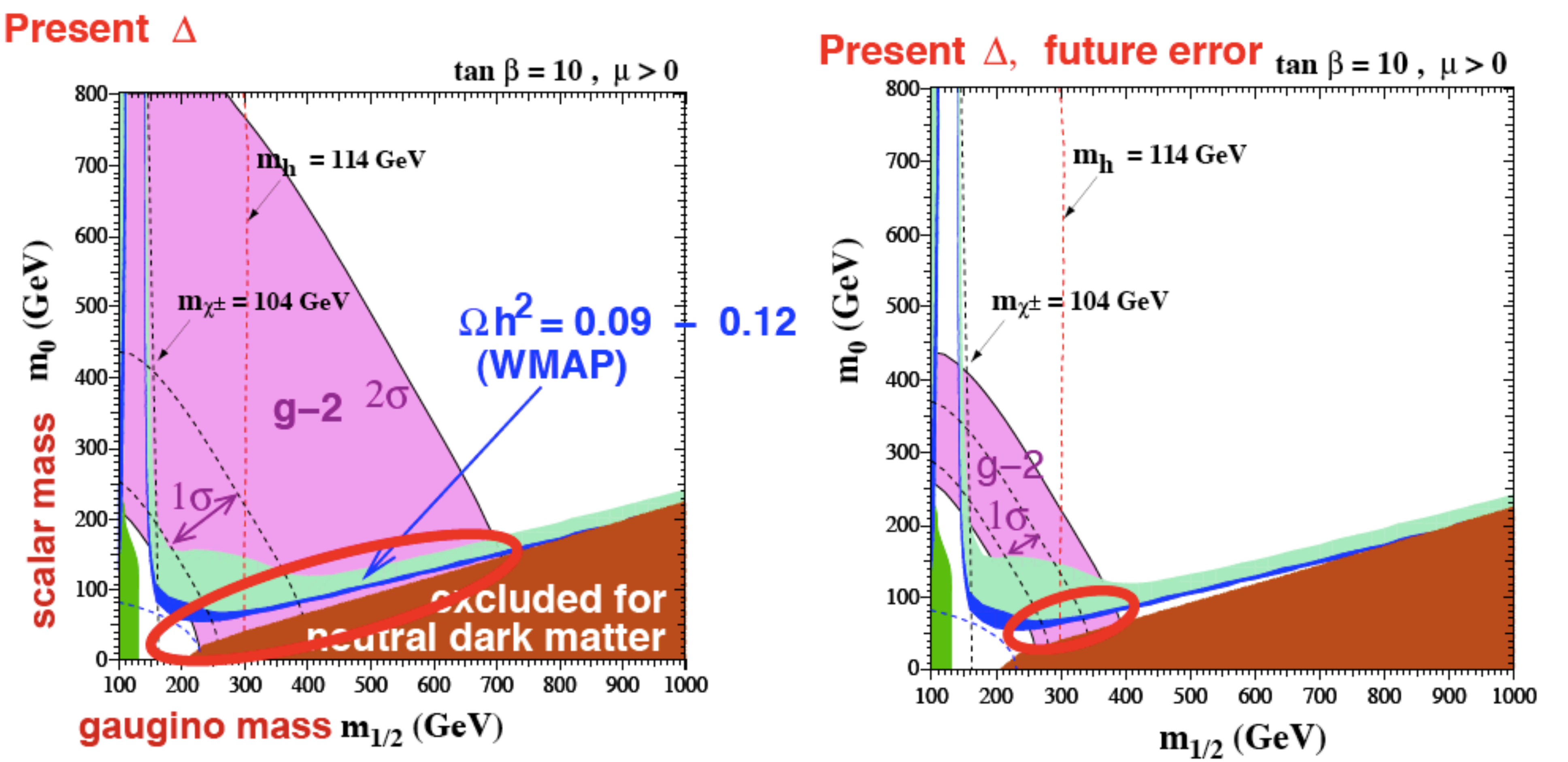
$$a_\mu^{\text{susy}} \cong \text{sgn}(\mu) \times 13 \times 10^{-10} \left(\frac{100\text{GeV}}{m_{\text{susy}}} \right)^2 \tan\beta$$

W. Marciano, J. Phys. G29 (2003) 225

New g-2 Proposal at BNL

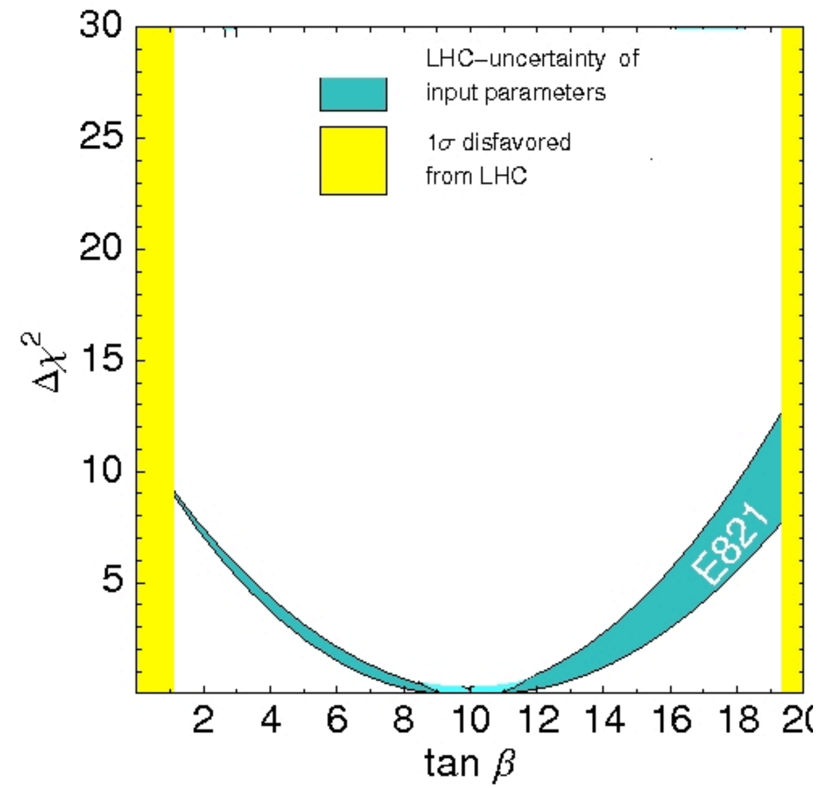
- Increase Beam-line acceptance (×4)
- Open up the two Inflector ends (×1.7)
- Use Backward Muons (i.e. π @ 5.3GeV/c, μ @ 3.1GeV/c). Provides great π-Rejection.
- An additional Muon Accumulation Ring can allow an overall reduction factor of five in error
- Possible other places: JPARC and FNAL

Constraining new physics with present (left) and possible reduction of the error by ×2 (right)



a_μ will help constrain the interpretation of LHC data, e.g. $\tan\beta$ and $\text{sgn}\,\mu$ parameter

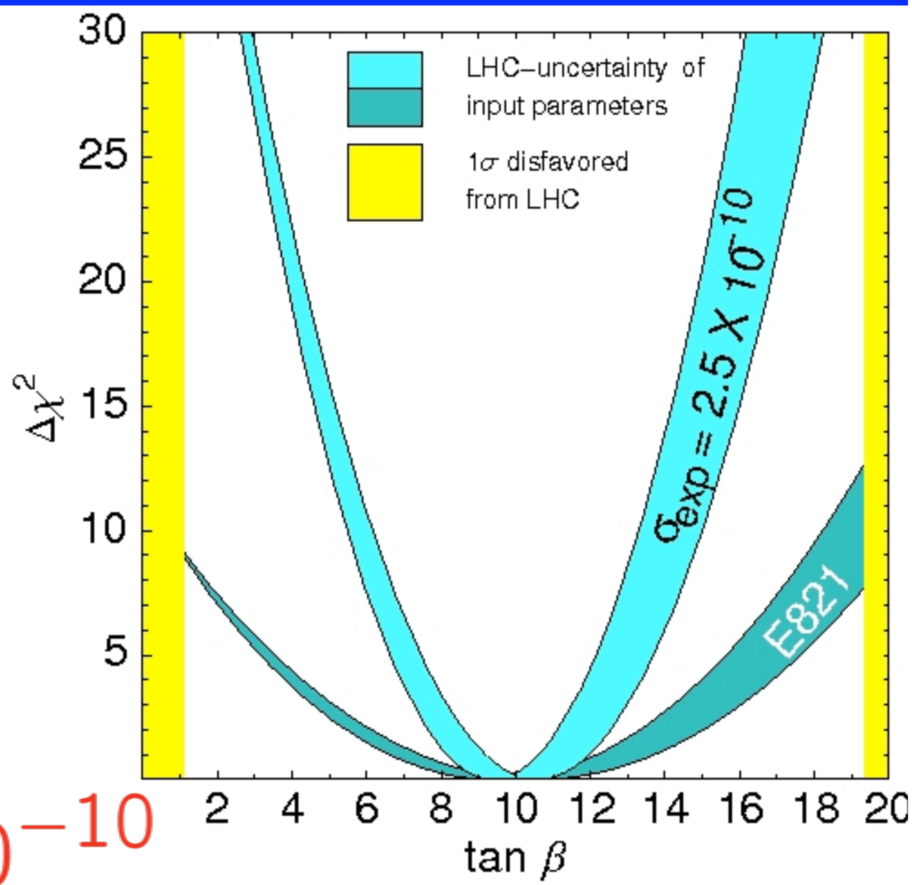
Even with no improvement, a_μ will provide the best value for $\tan\beta$, and show $\mu > 0$ to $> 3\,\sigma$



$$\Delta a_\mu^{(\text{today})} = (29.5 \pm 8.8) \times 10^{-10}$$

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

Improved experiment and theory for a_μ is important



$\mu > 0$ by $> 6\,\sigma$
$\tan\beta$ to < 20%

$$\sigma^{E821} \quad (6.3 \rightarrow 2.5) \times 10^{-10}$$

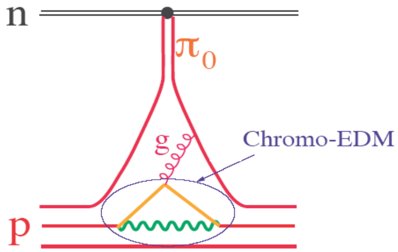
$$\sigma^{SM} \quad (6.1 \rightarrow 3.0) \times 10^{-10}$$

$$\Delta a_\mu^{(\text{future})} = (29.5 \pm 3.9) \times 10^{-10}$$

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

Prospects and Summary

- Total experimental error: 0.5ppm; probing physics beyond the S.M.
- More data from the theory front are/will be analyzed: Novosibirsk, KLOE, BaBar, Belle.
- The g-2 collaboration is working towards reducing the experimental error to 0.2ppm - 0.1ppm (with even more muons). Possible places: BNL, FNAL, JPARC



Deuteron EDM case:

Storage ring EDM experiment with 10^{-29} e·cm sensitivity

- Utilizing the strong E-field present in the rest frame of a relativistic particle in a storage ring.

- Its physics reach is much beyond the LHC scale and complementary to it.

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

Deuteron EDM

- High sensitivity to non-SM CP-violation
- Negligible SM background
- Physics beyond the SM (e.g. SUSY) expect CP -violation within reach
- Great sensitivity to T-odd Nuclear Forces
- Complementary and better than nEDM
- If observed it will provide a new, large source of CP-violation that could explain the Baryon Asymmetry of our Universe (BAU)

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

Physics Motivation of dEDM

- $\text{Currently}: \ \bar{\theta} \leq 10^{-10}, \text{ Sensitivity with dEDM}: \ \bar{\theta} \leq 10^{-13}$

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

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

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

The Deuteron EDM at 10^{-29}e·cm has a reach of ~300 TeV or, if new physics exists at the LHC scale, 10^{-5} rad CP-violating phase. Both are much beyond the design sensitivity of LHC.

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

Physics strength comparison

System	Current limit [e·cm]	Future goal	Neutron equivalent
Neutron	$<1.6\times10^{-26}$	$\sim10^{-28}$	10^{-28}
^{199}Hg atom	$<2\times10^{-28}$	$\sim2\times10^{-29}$	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}
			$\frac{d\vec{s}}{dt} = \vec{\mu}\times\vec{B} + \vec{d}\times\vec{E}$

If nEDM is discovered at 10^{-28} e•cm level?

- If $\bar{\theta}$ is the source of the EDM, then

$$d_D(\bar{\theta})/d_n(\bar{\theta}) \approx 1/3 \Rightarrow d_D \approx 3 \times 10^{-29} \mathrm{e} \cdot \mathrm{cm}$$

- If SUSY is the source of the EDM (isovector part of T - odd N - forces), then

$$d_D(\bar{\theta})/d_n(\bar{\theta}) \approx 20 \Rightarrow d_D \approx 2 \times 10^{-27} \mathrm{e} \cdot \mathrm{cm}$$

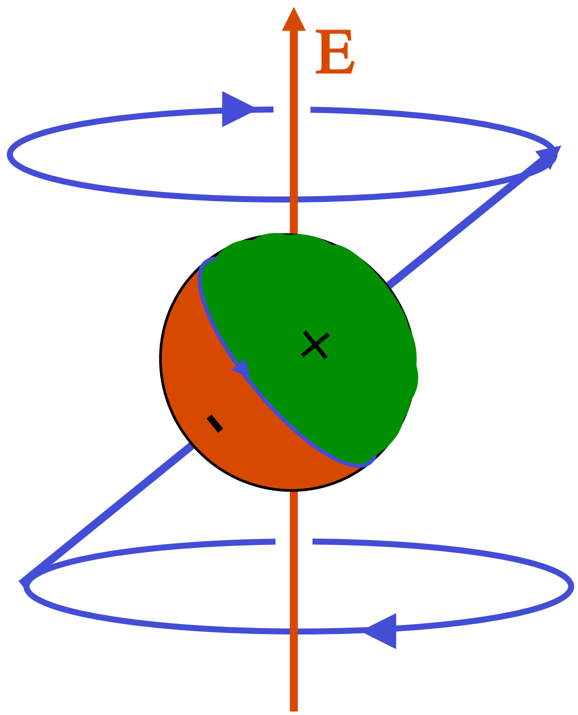
The deuteron EDM is complementary to neutron and in fact has better sensitivity.

Usual Experimental Method

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

Carrier Signal

Small Signal



Compare the Zeeman Frequencies When E-field is Flipped:

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

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

The Electric Dipole Moment precesses in an Electric field

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

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

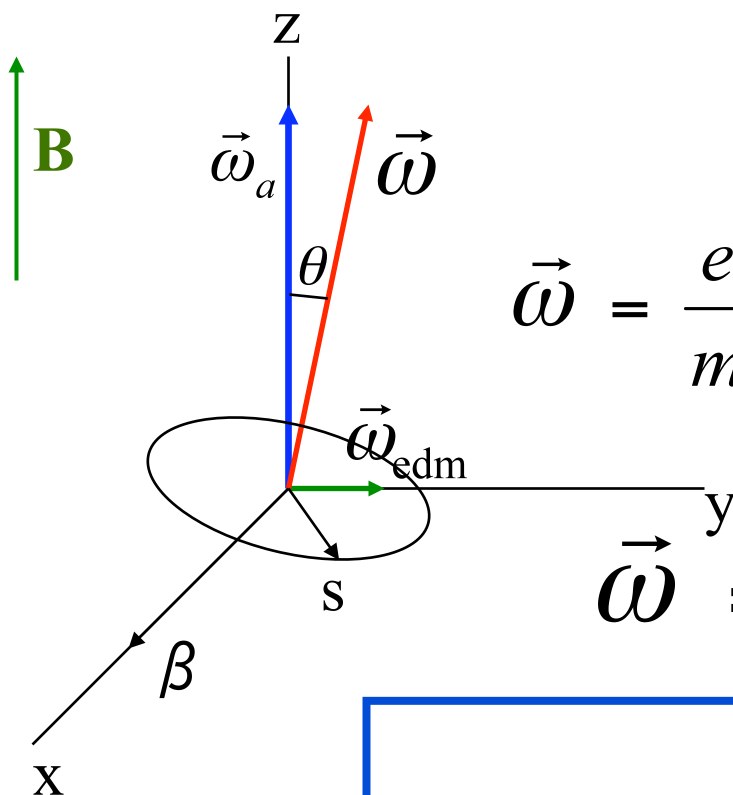
Electric Dipole Moments in Magnetic Storage Rings

$$\frac{d\vec{s}}{dt} = \vec{d} \times \left(\vec{v} \times \vec{B}\right)$$

e.g. 1 T corresponds to 300 MV/m for relativistic particles

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

Indirect Muon EDM limit from the g-2 Experiment



$$\vec{\omega} = \frac{e}{m}\left\{a\vec{B} + \frac{\eta}{2c}\left(\vec{u}\times\vec{B}\right)\right\}$$

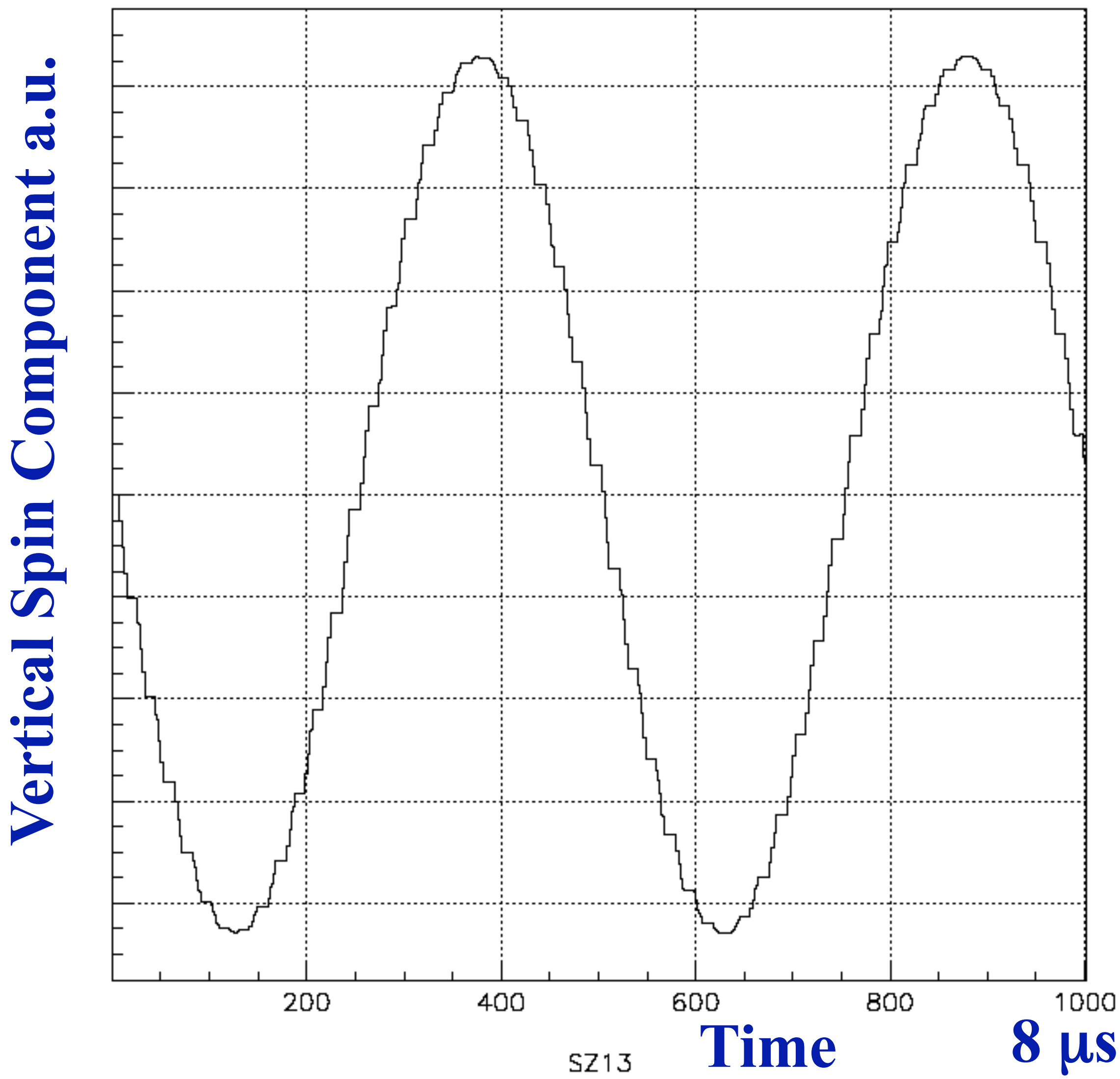
$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_{\mathrm{edm}}$$

$$\tan\theta = \frac{\omega_{edm}}{\omega_a}$$

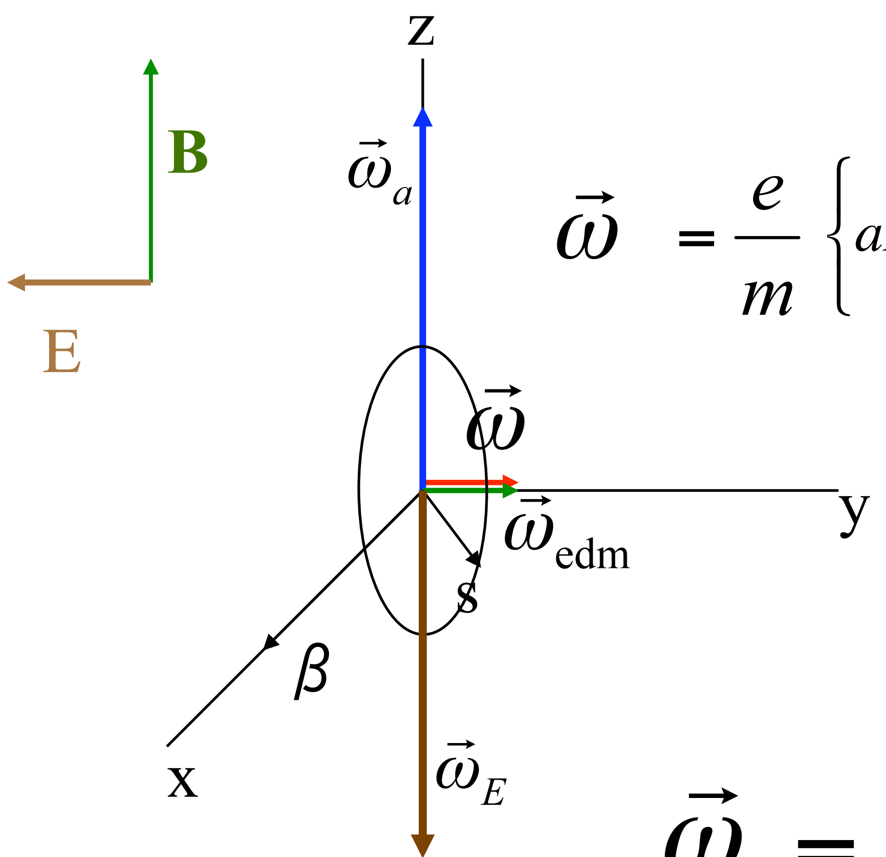
Ron McNabb's Thesis 2003: $< 2.7\times10^{-19}\,\mathrm{e}\cdot\mathrm{cm}$ 95% C.L.

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

The Vertical Spin Component Oscillates



Frozen Spin Method: Canceling g-2 with a Radial E-field

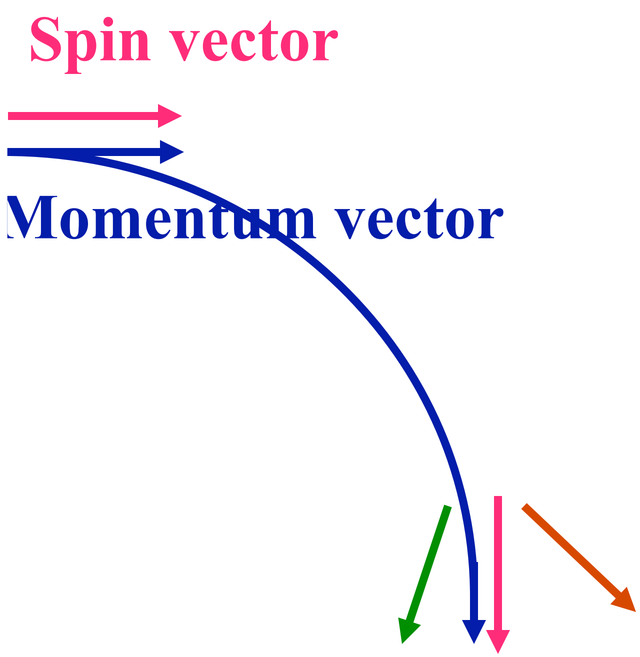


$$\vec{\omega} = \frac{e}{m}\left\{a\vec{B} + \overbrace{\left(\frac{1}{\gamma^2-1} - a\right)\frac{\vec{\beta}\times\vec{E}}{c}}^{\vec{\omega}_E} + \frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\right\}$$

$$\vec{\omega} = \vec{\omega}_{\text{edm}} = \frac{e}{m}\frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)$$

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

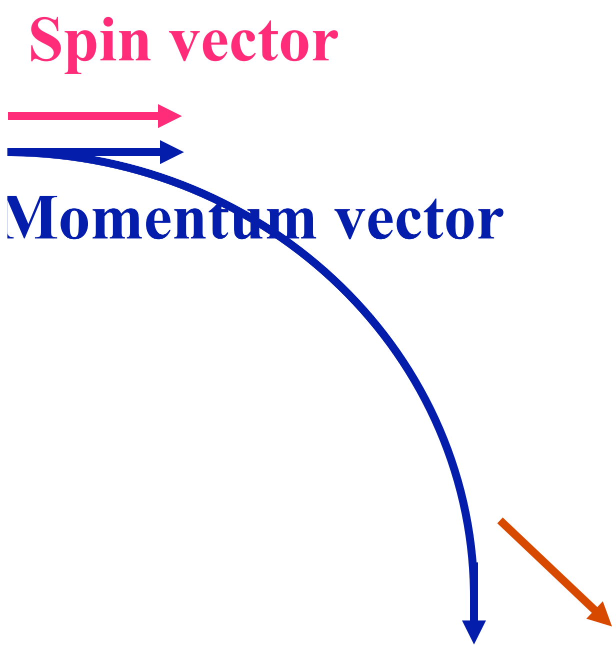
Effect of Radial Electric Field



- Low energy particle
- …just right
- High energy particle

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

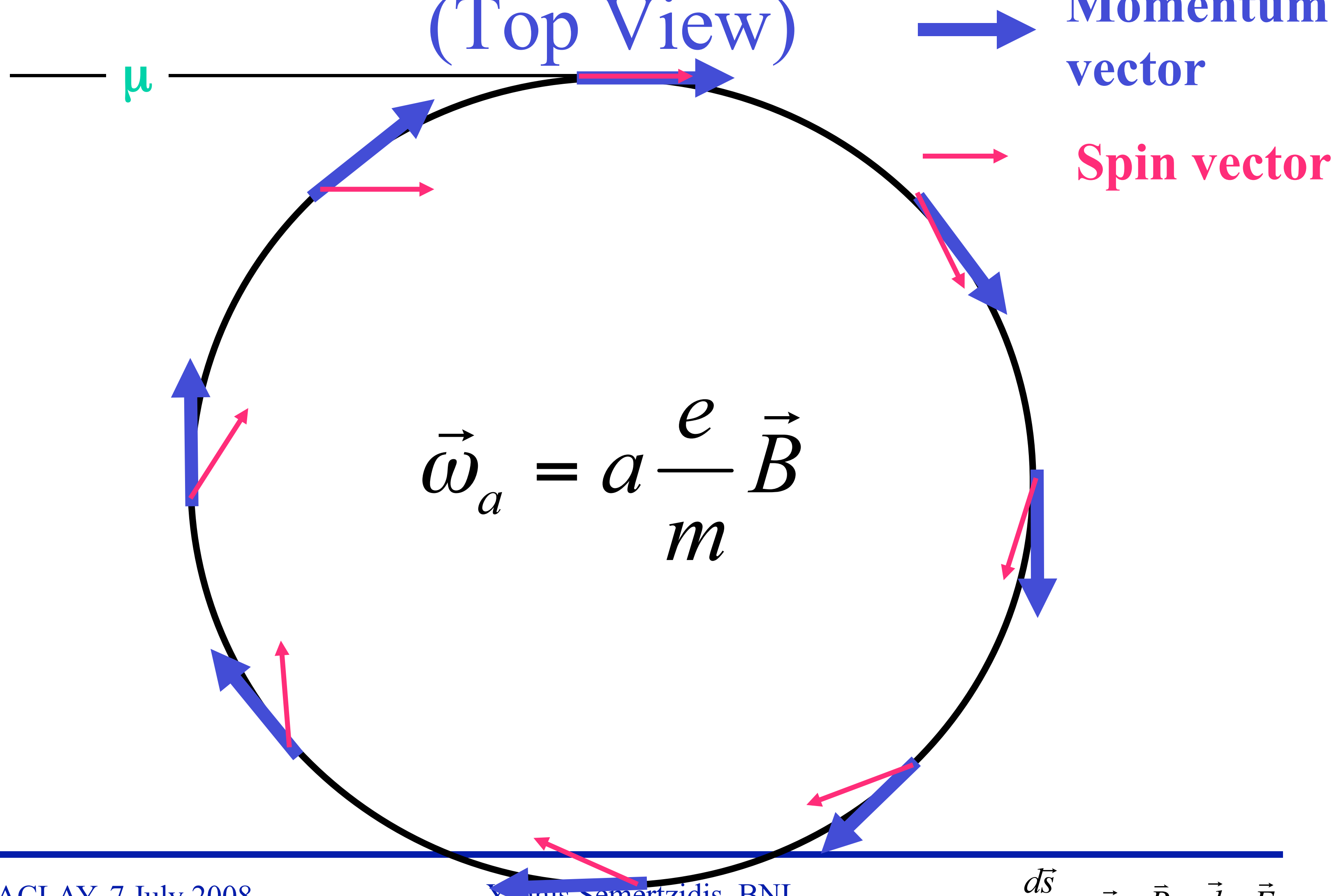
Use a Radial Electric Field and a



- Low energy particle

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

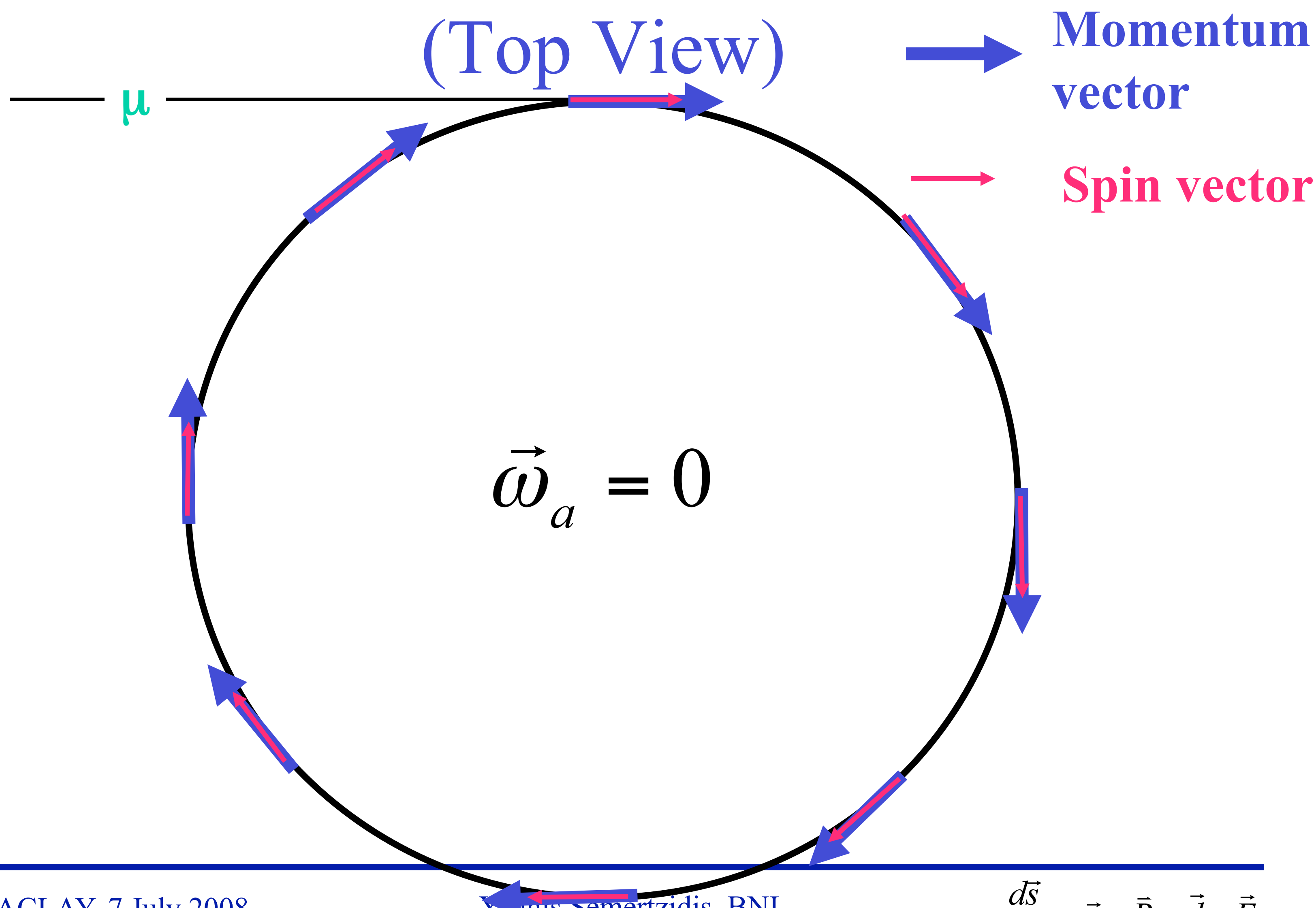
Spin Precession in g-2 Ring (Top View)



$$\vec{\omega}_a = a\frac{e}{m}\vec{B}$$

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

Spin Precession in EDM Ring (Top View)



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

(U-D)/(U+D) vs. Time, muon case

(U-D)/(U+D)

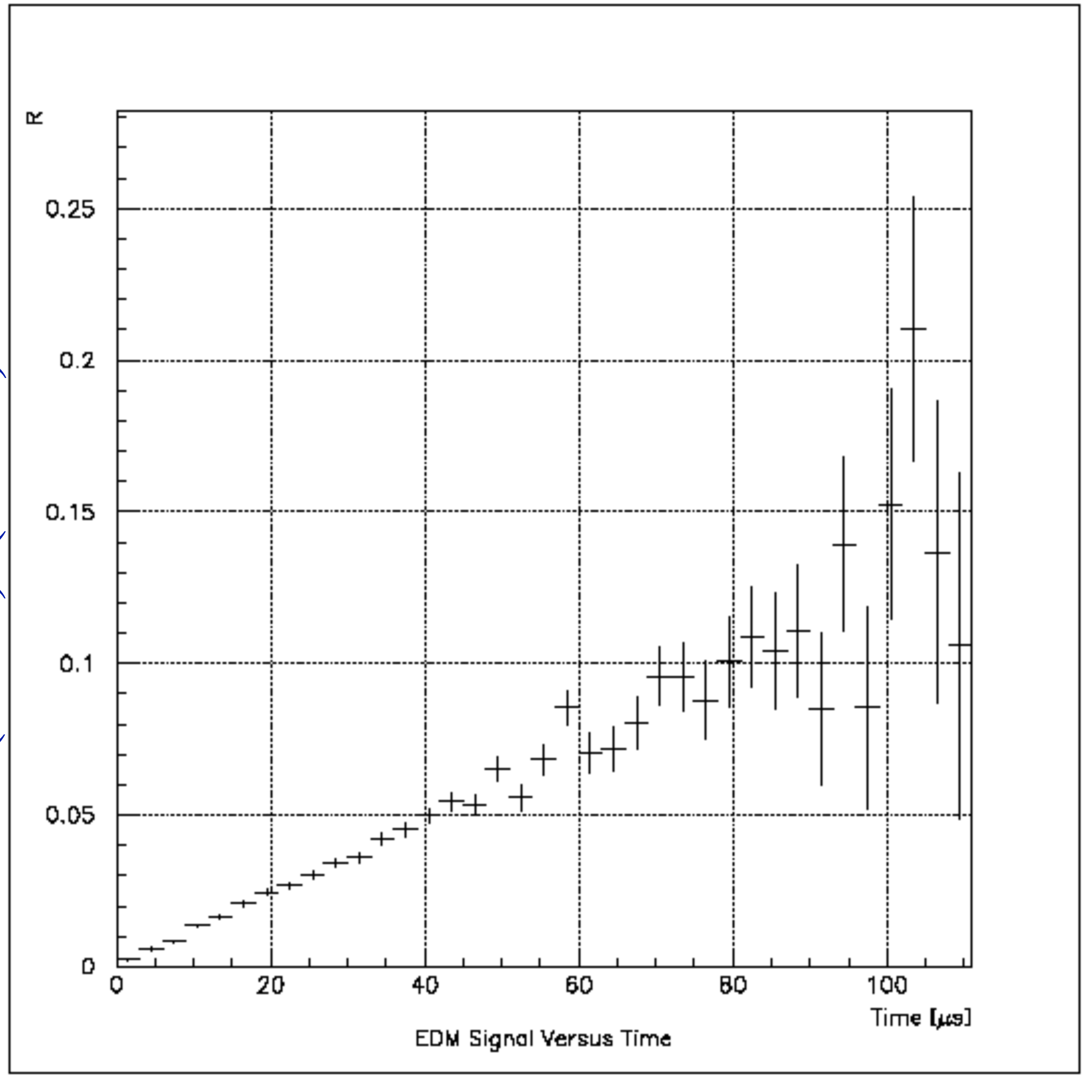
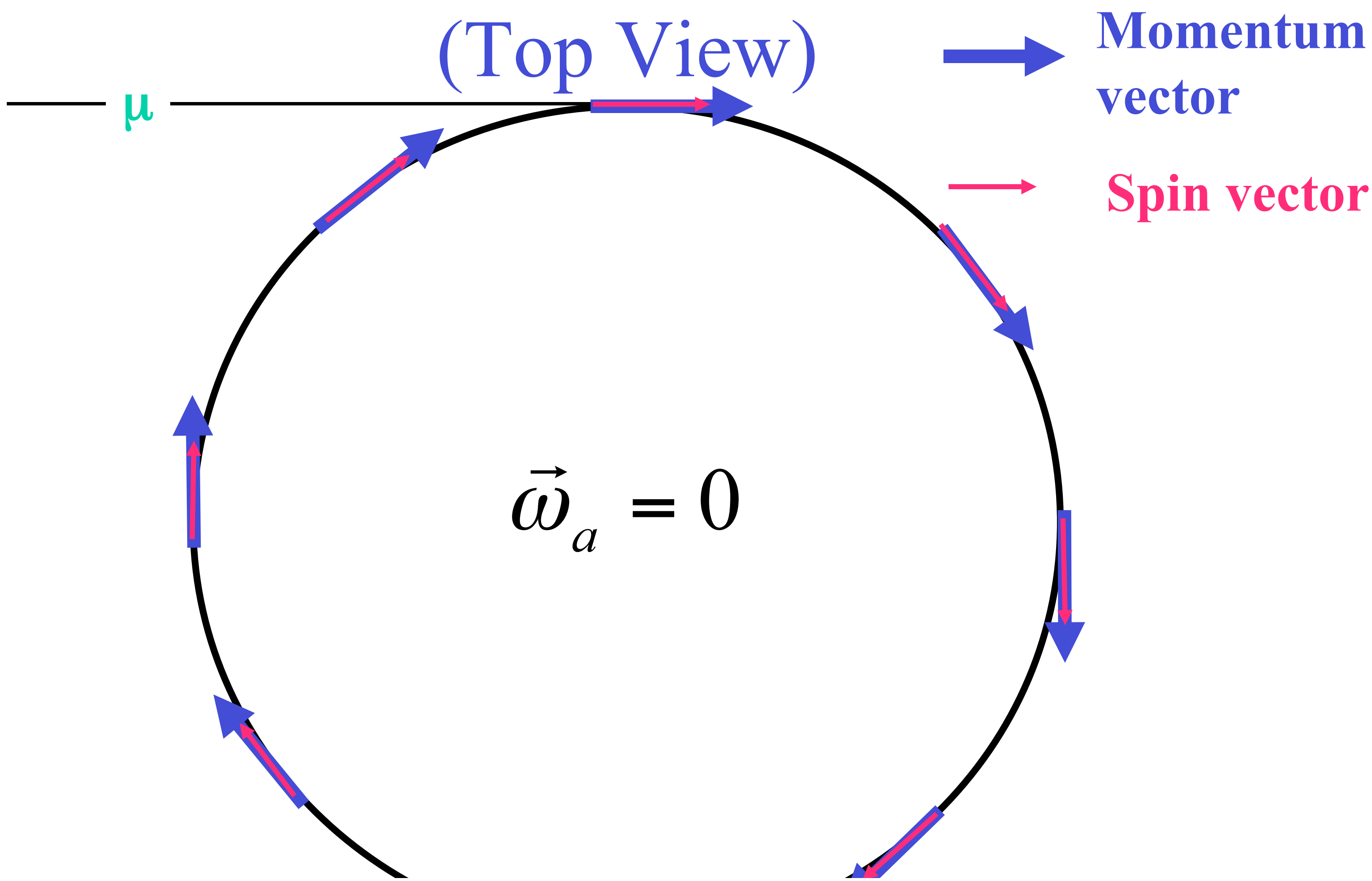


Figure 3: MC simulation of the muon EDM signal, $R = \frac{N_{up} - N_{down}}{N_{up} + N_{down}}$, versus time.

$\vec{d} \times \vec{E}$

Spin Precession in EDM Ring (Top View)



$$\Delta P_V = P\,\frac{\omega_{edm}}{\Omega}\,\sin(\Omega t + \theta_0), \qquad \Omega = \sqrt{\omega_{edm}^2 + \omega_a^2},$$

Experimental Principle of dEDM

- Polarize
- Interact with an E-field
- Analyze as a function of time

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

Deuteron Statistical Error (250MeV):

$$\sigma_d \approx 8 \frac{\hbar a \gamma^2}{\sqrt{\tau_p} E_R (1+a) A P \sqrt{N_c f T_{Tot}}}$$

τ_p : 10^3s **Polarization Lifetime (Coherence Time)**
A : 0.3 **The left/right asymmetry observed by the polarimeter**
P : 0.8 **The beam polarization**
N_c : 4×10^{11}d/cycle **The total number of stored particles per cycle**
T_{Tot}: 10^7s **Total running time per year**
f : 0.01 **Useful event rate fraction**
E_R : 12 MV/m **Radial electric field**

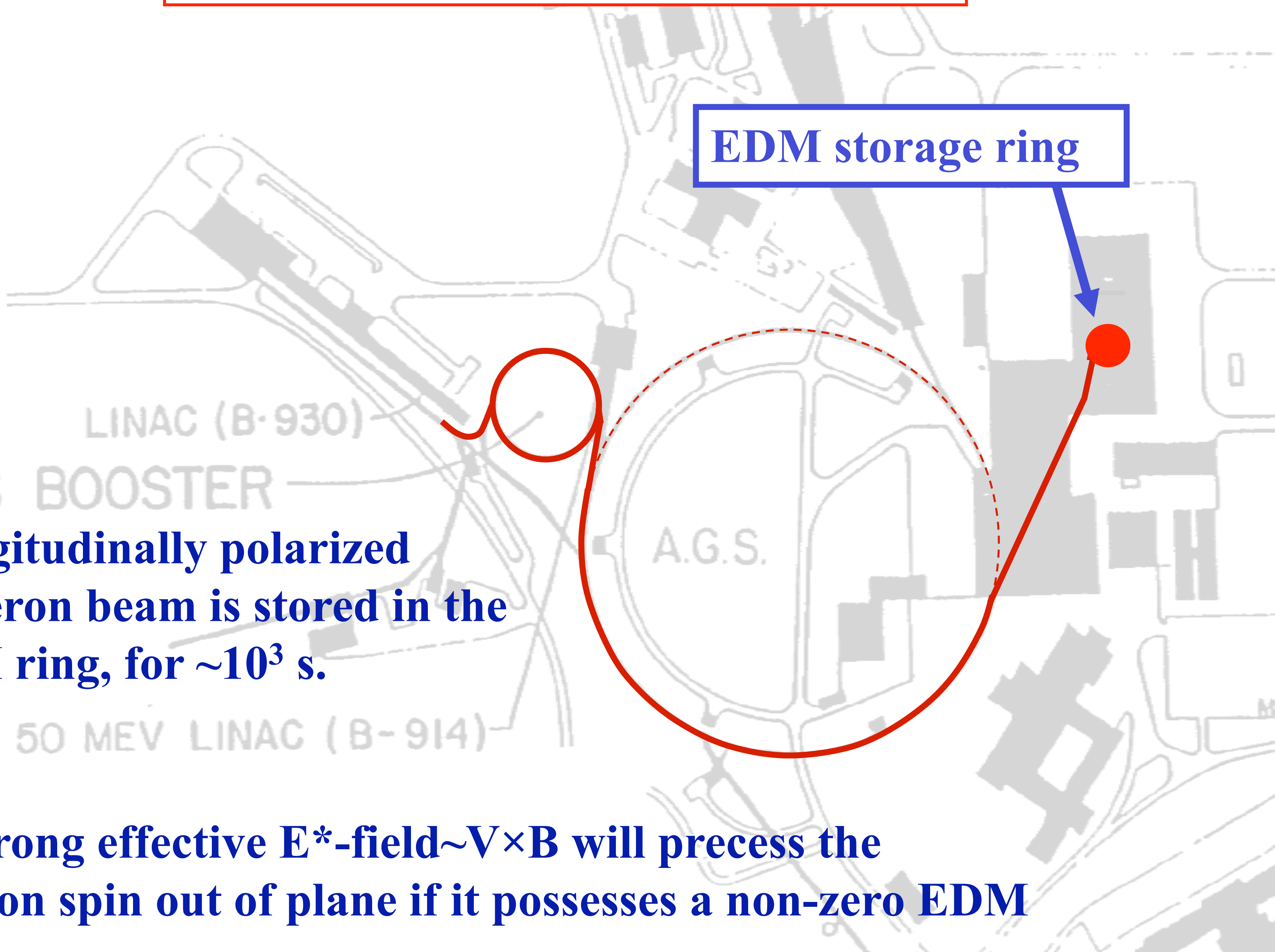
$$\sigma_d \approx 10^{-29} \mathrm{e} \cdot \mathrm{cm} \quad \text{per year}$$

Storage ring EDM: The deuteron case

- High intensity sources ($\sim 10^{11}$/fill)
- High vector polarization (~80%)
- High analyzing power for ~1 GeV/c (250MeV)
- Long spin coherence time possible ($\sim 10^{3}$s)
- Large effective E^{*}-field

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

deuteron EDM search at BNL

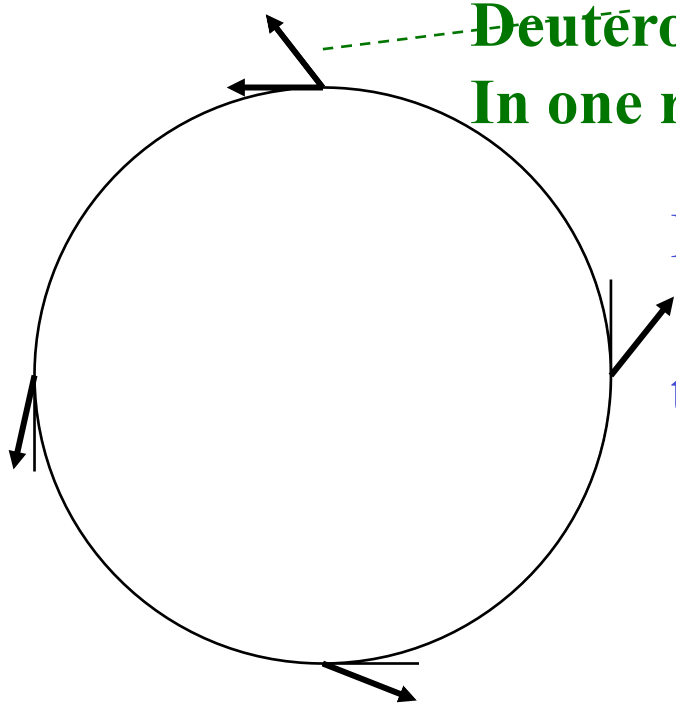


A longitudinally polarized deuteron beam is stored in the EDM ring, for ~10^3 s.

The strong effective E*-field~V×B will precess the deuteron spin out of plane if it possesses a non-zero EDM

Top view of deuteron spin precession in ring. Optimizing the dEDM search…

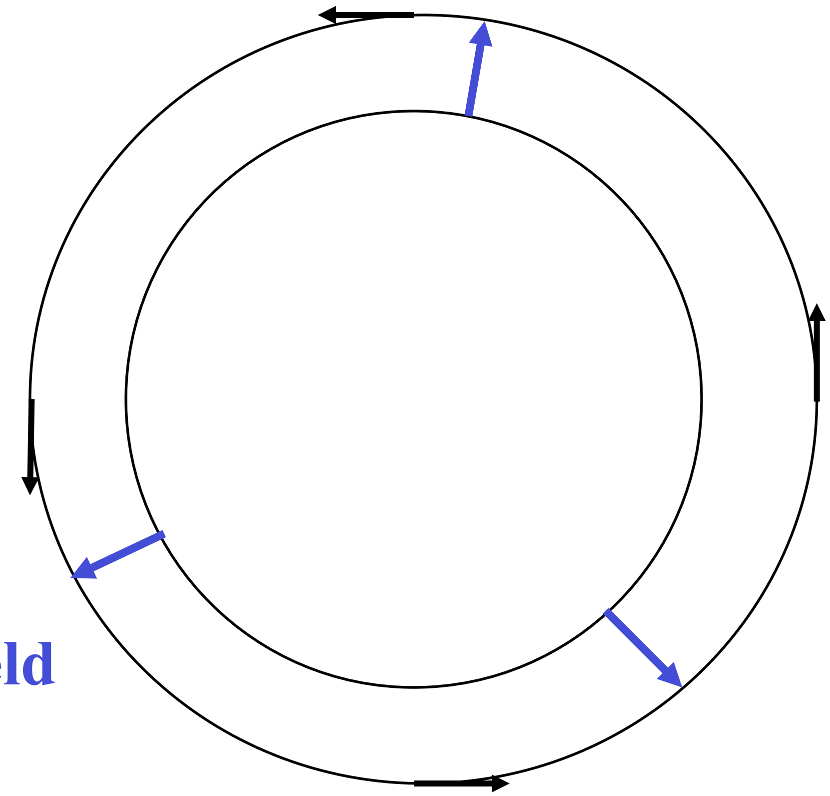
Deuteron anomalous moment = – 0.14.
In one revolution, spin lags momentum.



Idea: Use radial electric field to enlarge orbit and revolution time while keeping B constant.

$$\Delta P_V = P\,\frac{\omega_{edm}}{\Omega}\,\sin(\Omega t + \theta_0), \qquad \Omega = \sqrt{\omega_{edm}^2 + \omega_a^2},$$

Top view of deuteron spin precession in ring. Optimizing the dEDM search…

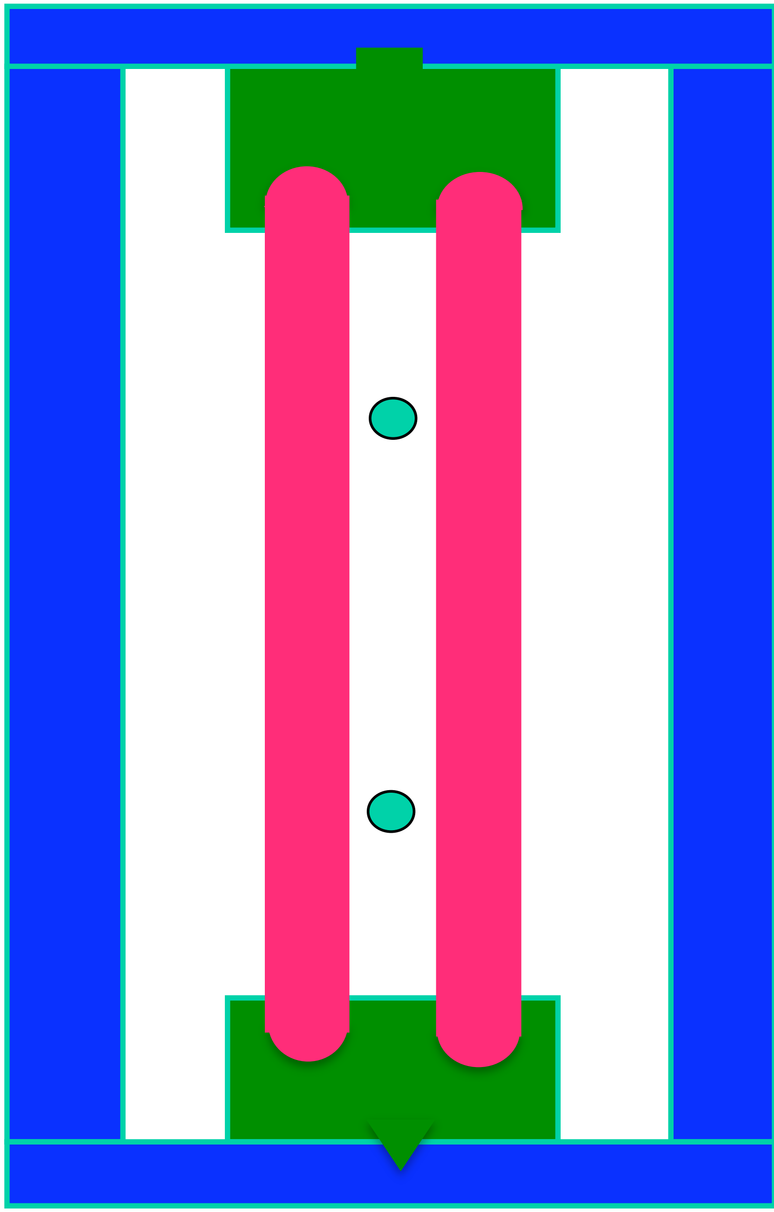


For some ratio of E and B, the lengthened path will be just right for the spin to track the velocity.

(Small precessions will be used for systematic checks.)

$$\Delta P_V = P\,\frac{\omega_{edm}}{\Omega}\,\sin(\Omega t + \theta_0), \qquad \Omega = \sqrt{\omega_{edm}^2 + \omega_a^2},$$

Concept picture



E-field: using well established scaling rules & extrapolating from the FNAL ES separators and CERN ES septum we should be able to get 120KV/cm.

The B-field presence is not a concern…

E-field design: 120 KV/cm

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

Clock Wise (CW) and Counter Clock Wise (CCW) injections

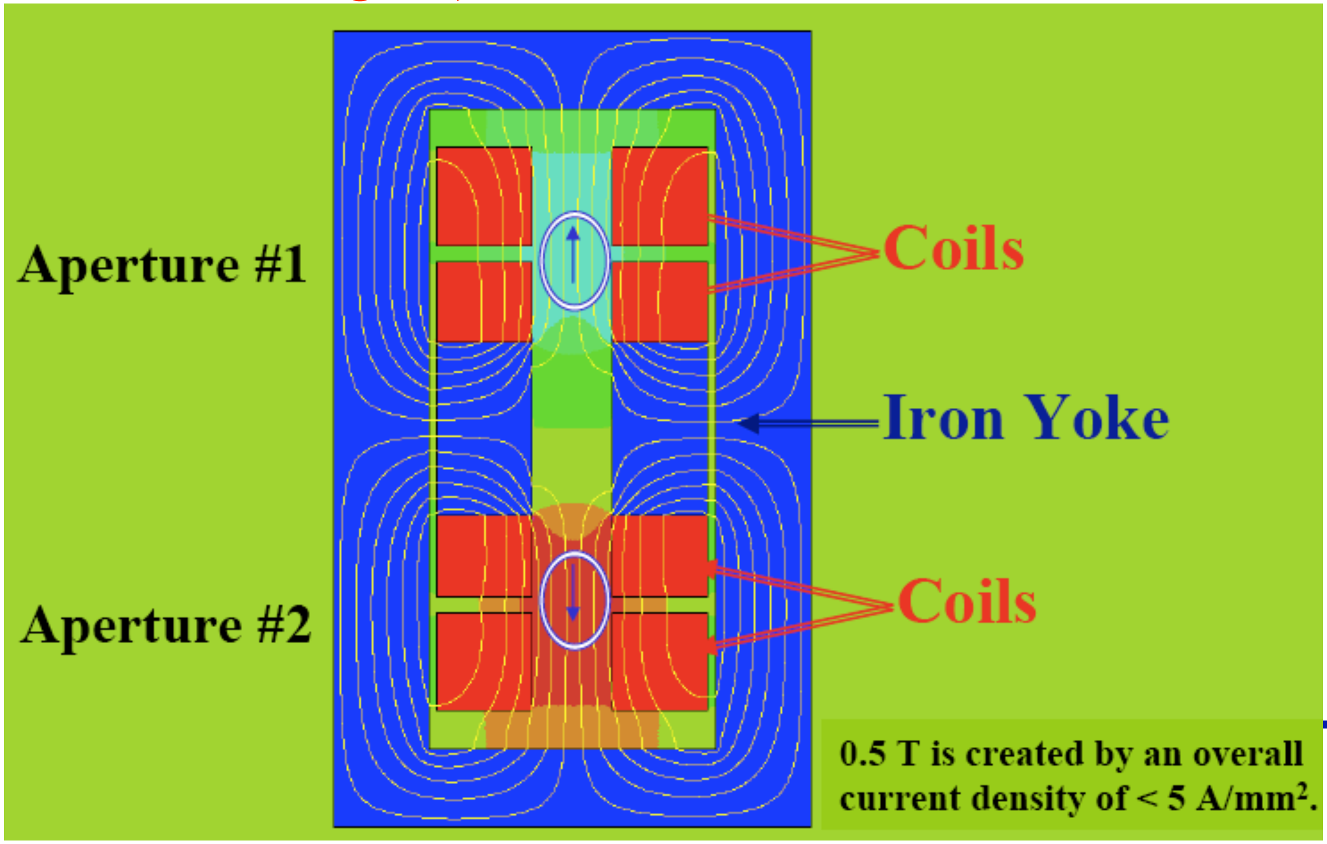
- CW and CCW injections to cancel all T -reversal preserving effects. EDM is T -violating and behaves differently.

- Issue: Stability as a function of time

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

Clock Wise (CW) and Counter Clock Wise (CCW) injections

- Solution: Use the 2-in-1 magnet design for simultaneous CW and CCW storage. R. Gupta considered two options: Normal conducting magnet (design shown here) and high temperature superconducting magnet (in progress) operating at LN_2 (uses much less power than normal magnet).

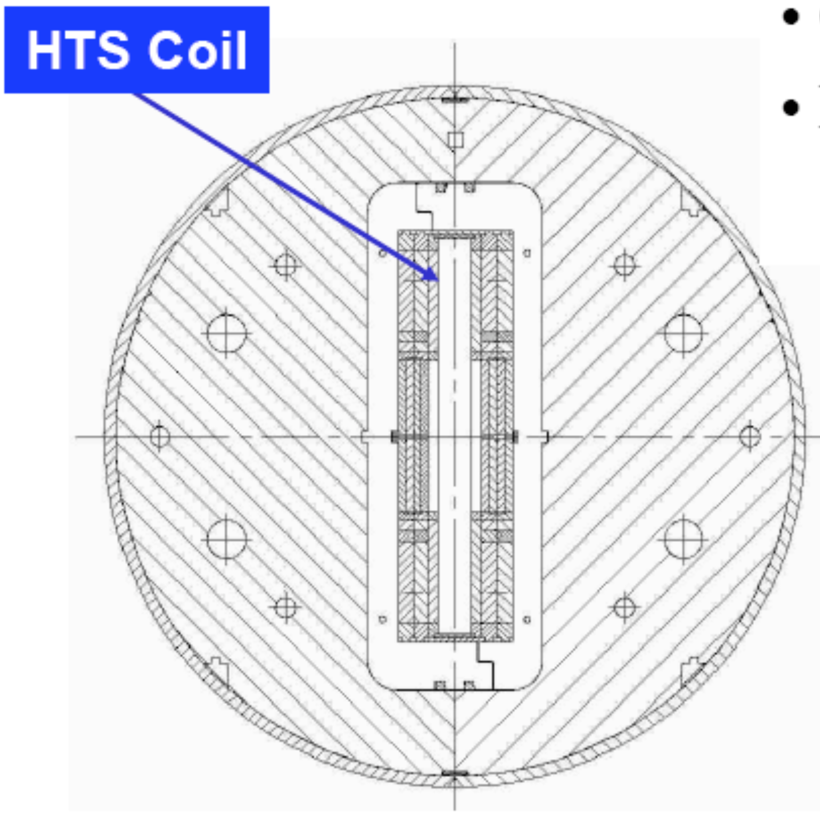


$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

A Unique Feature of BNL Common Coil Design

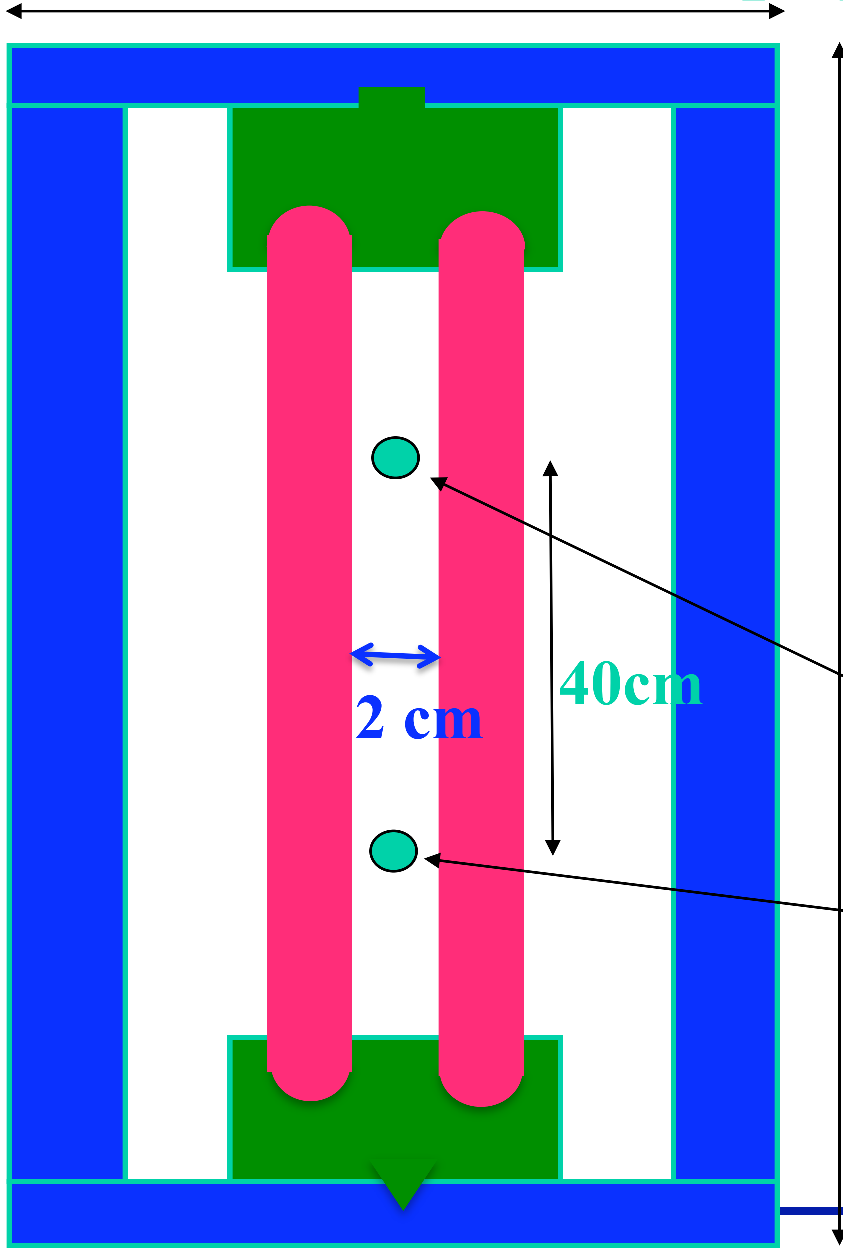
A unique feature of BNL design is a large vertical open space between the two coils.

- Can be used for insert HTS coil testing.
- For EDM proposal, it is ideally suited for electric plates inside the coils!



HTS insert coil test configuration
(HTS/Nb_3Sn Hybrid magnet)

Concept picture



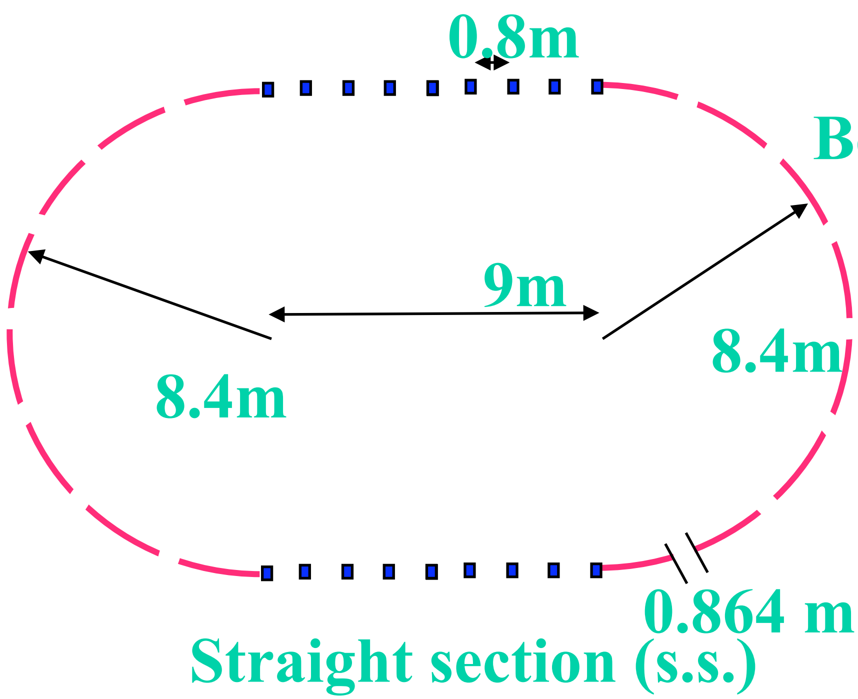
Electrostatic plates,
Vacuum chamber,
Insulators

CW or CCW rotating beam

CCW or CW rotating beam

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

The dEDM ring lattice



Ring circumference: 85m

Horizontal beam radius (95%): 6mm

16 free spaces (80cm) in the s.s. per ring

4 places in s.s. reserved for the kicker

1 free space for the RF cavity (normal)

1 free space for the AC-solenoid

2 polarimeters

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

Development Plan

a) Develop the tools for spin tracking: F. Lin (Physics), N. Malitsky (NSLS 2), A. Luccio (CAD), Y. Orlov (Cornell), …

b) Determine spin coherence time (SCT) using tracking.

c) Simulate systematic errors in the presence of several backgrounds.

d) Optimize polarimetry using beams at KVI and COSY: A. Imig, M. da Silva e Silva (KVI), G. Onderwater (KVI), E. Stephenson (IUCF), Groups from Italy, Greece, BNL,…

Development Plan (cont'ed)

e) Electric field testing in the presence of B-field: V. Dzhordzhadze (Physics), R. Larsen (Physics), …

f) Electrostatic plate initial alignment: 10μrad locally, <1μrad on average per plate (VD, RL,…).

g) Design magnets: predict, and measure vertical & horizontal fields: R. Gupta (Magnet D.), B. Parker (NSLS-2),…

h) Using Fabry-Perot interferometers establish that B-field reversals do not affect E-field plate alignment (VD, RL, RG, BP, G. Zavattini (Ferrara/Italy), …)

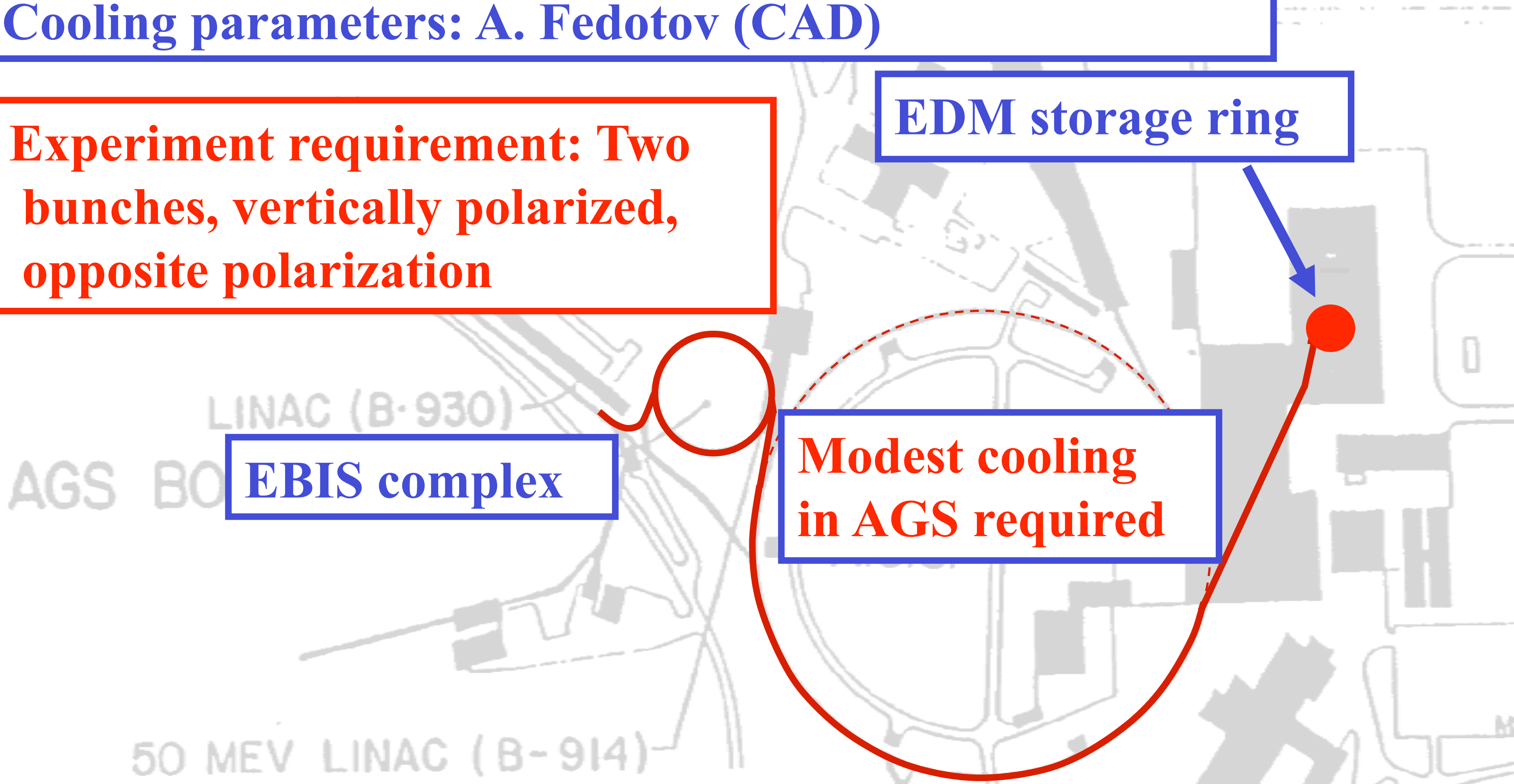
i) Develop dEDM ring base and enclosure, measure vibration resonances in presence of concrete shielding (floor loading) and temperature monitoring: N. Simos (EST D.),…

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

Source parameters: A. Zelenski (CAD)
Emittance numbers: D. Raparia (CAD)
Cooling parameters: A. Fedotov (CAD)

Experiment requirement: Two bunches, vertically polarized, opposite polarization

EDM storage ring

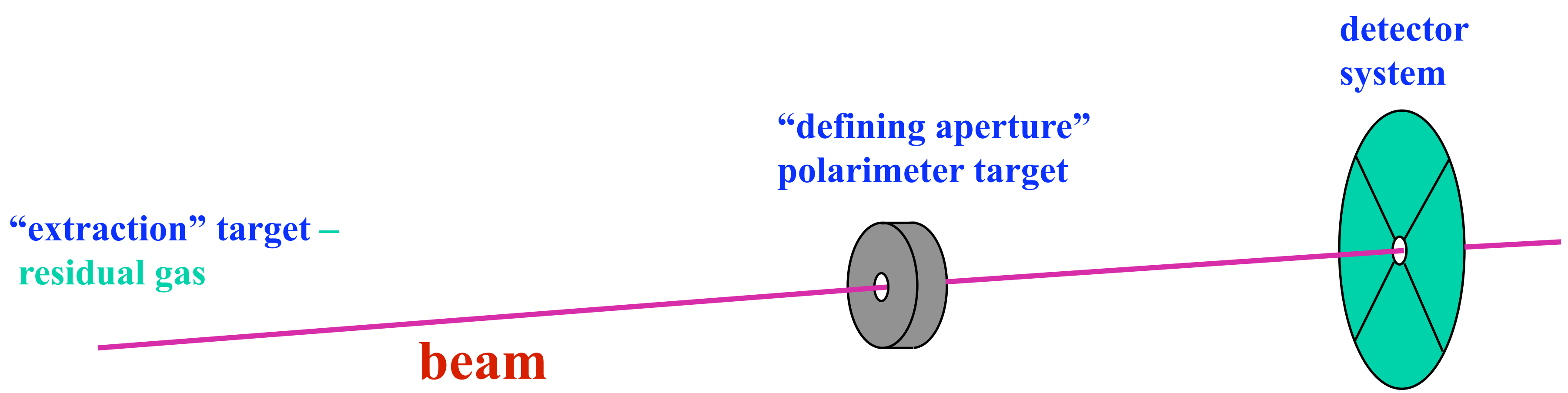


EBIS complex

Modest cooling in AGS required

Beam-line, dEDM ring shielding cost: A. Pendzick (CAD)
Beam-line design: F. Lin, K. Brown, A. Luccio
dEDM ring lattice: F. Lin, A. Luccio, Y. Orlov

dEDM polarimeter principle



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

carries EDM signal
small
increases slowly with time

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

carries in-plane precession signal

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

Cross section and analyzing power

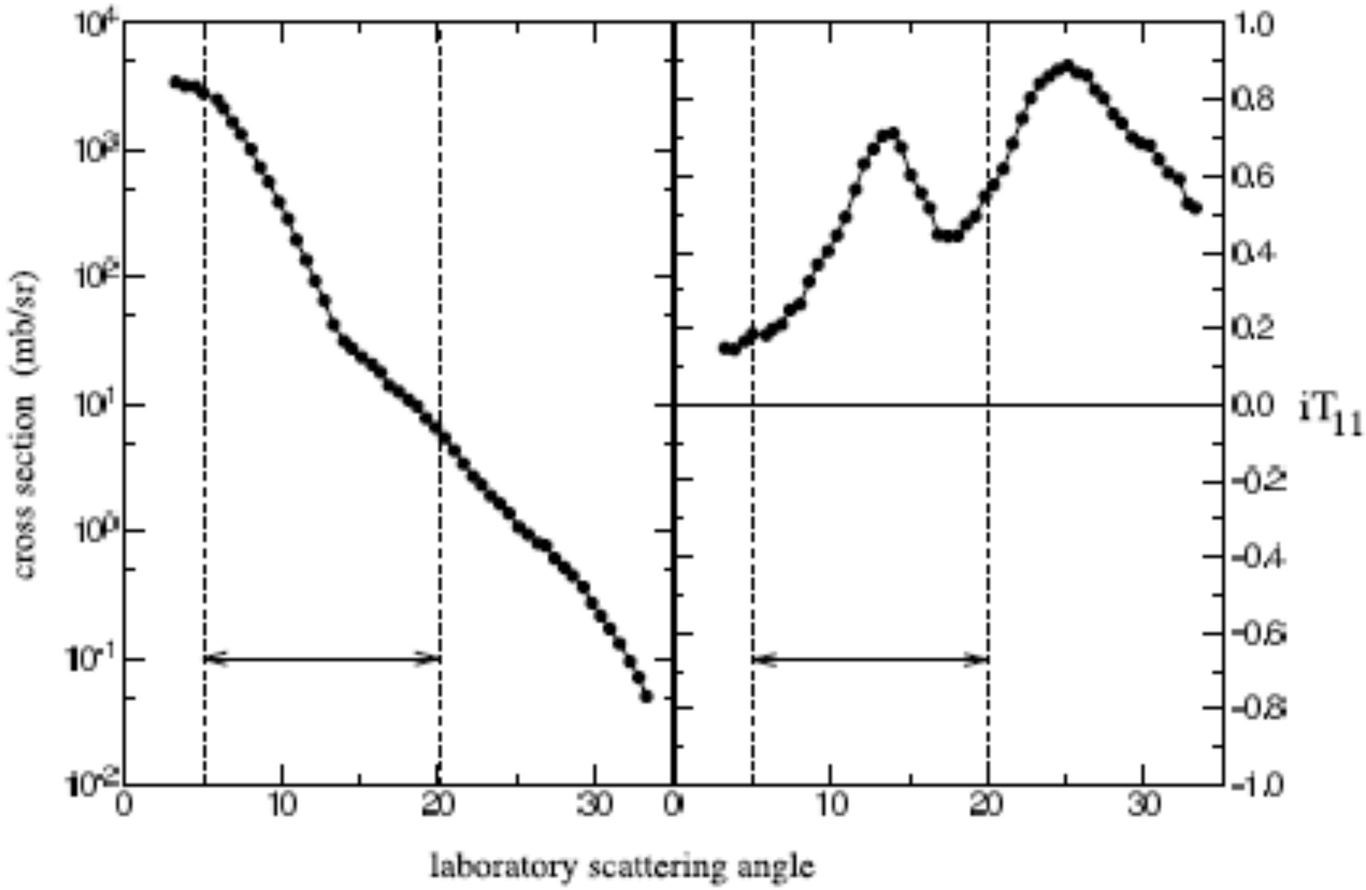


Figure 2: Deuteron elastic cross section and analyzing power at 270 MeV from carbon [29]. The dashed lines indicate the preferred acceptance limits for an EDM polarimeter.

$$\sigma_{pol} = \sigma_{unpol} \ (1 + 2\ it_{11}\ iT_{11} + t_{20}\ T_{20} + 2\ t_{21}\ T_{21} + 2\ t_{22}\ T_{22})\ ,$$

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

From the June 2008 run at COSY

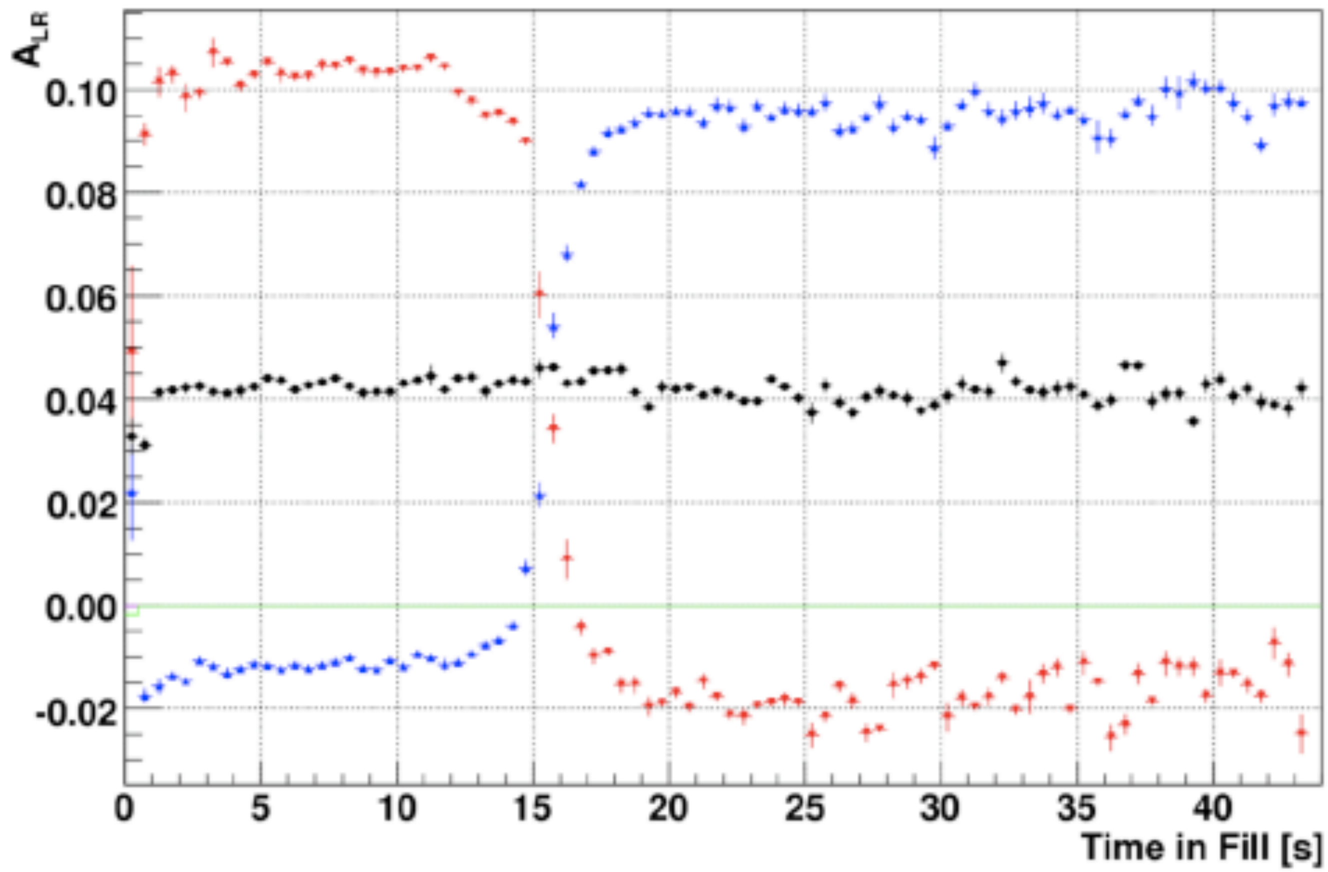


Figure 3. Asymmetry measurements made continuously during a beam store for spin up (red), spin down (blue), and unpolarized states. At the same time the frequency of the RF solenoid is ramping through the 1 – Gγ resonance at 1030.048 kHz.

Systematic Error Strategy

1. Use of Symmetries

2. Determine the specs for systems where symmetries don't cancel systematic errors, e.g., leakage currents, E-field power supply stability, …

1. Symmetries

Table 4: **This table lists a number of causes of an asymmetry and testable characteristics for each cause. A plus indicates that this cause appears to be the same as an EDM and a minus indicates where there is a distinguishable difference (see text for description of the asymmetries and characteristics).**

ERROR	term	spin-flip	sign ω_a	mag. ω_a	locat.	CW/ CCW	sens. (e·cm)
(1) source p_y	−	+	−	−	+	−	$< 10^{-29}$
(2) source t_{21}	−	*	+	−	+	−	$< 10^{-29}$
(3) det. rotation	+	+	−	−	*	+	$< 10^{-29}$
(4) off axis/angle	−	−	−	−	*	−	see text
(5) non-linear det.	+	+	−	−	*	+	$< 10^{-29}$
(6) self-polarization	−	−	+	+	+	−	$< 10^{-29}$

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

Polarimeter Systematic errors (off axis/angle)

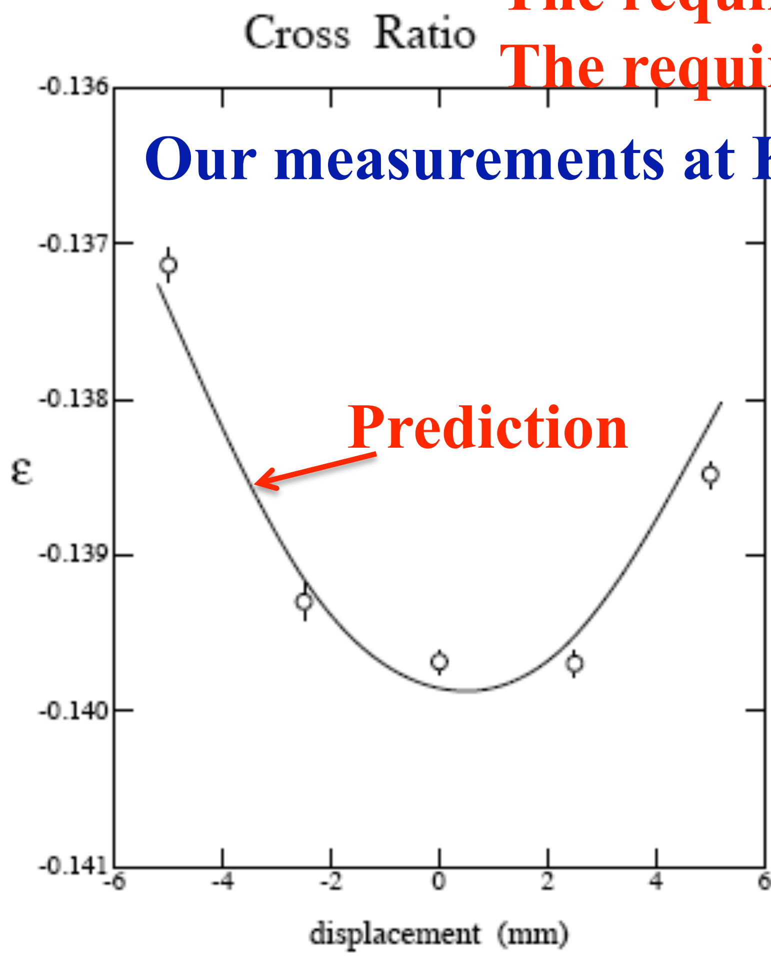
Observable: L-R asymmetry as a function of time:

a) Target position changes from early (~1s) to late times (10^3s).

b) The beam axis changes from early to late times

Off axis/angle systematic error

The required position stability: ~100µm
The required beam axis stability: ~100µrad



Pickup electrodes monitor the beam axis direction to better than 10µrad.
The polarimeter detector will be designed to have ~500µm /event pointing accuracy, or better than 10µm on the average position early to late.

Figure 3: Measurements of the change in left-right asymmetry as the target position is moved horizontally. The solid line is an *a priori* prediction based on the older scattering measurements at 113 MeV. The curve has been offset vertically to match the average asymmetry. The errors shown are statistical only and do not include effects due to the setup of the beam position shifts and other systematic considerations.

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

Main polarimeter systematic errors

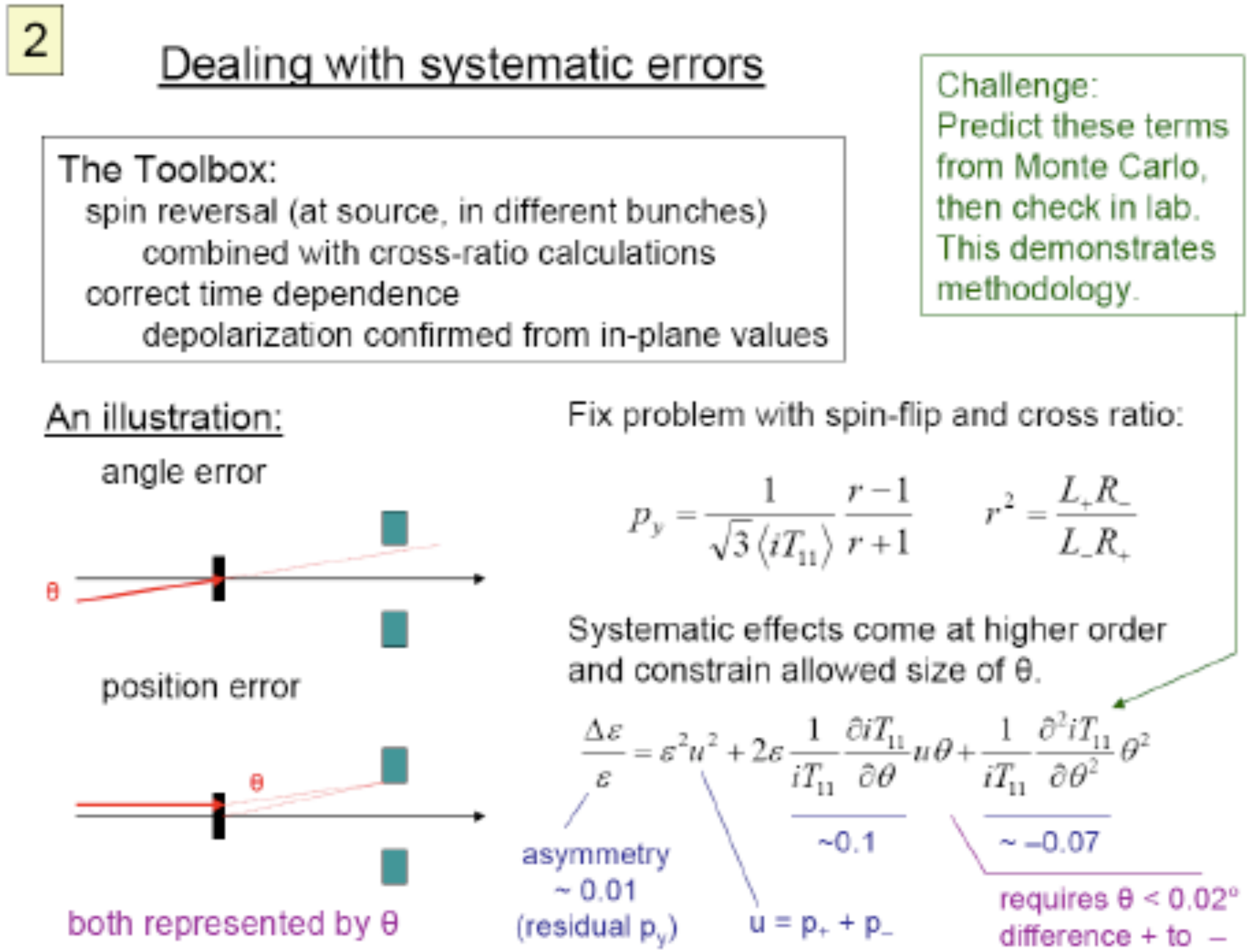
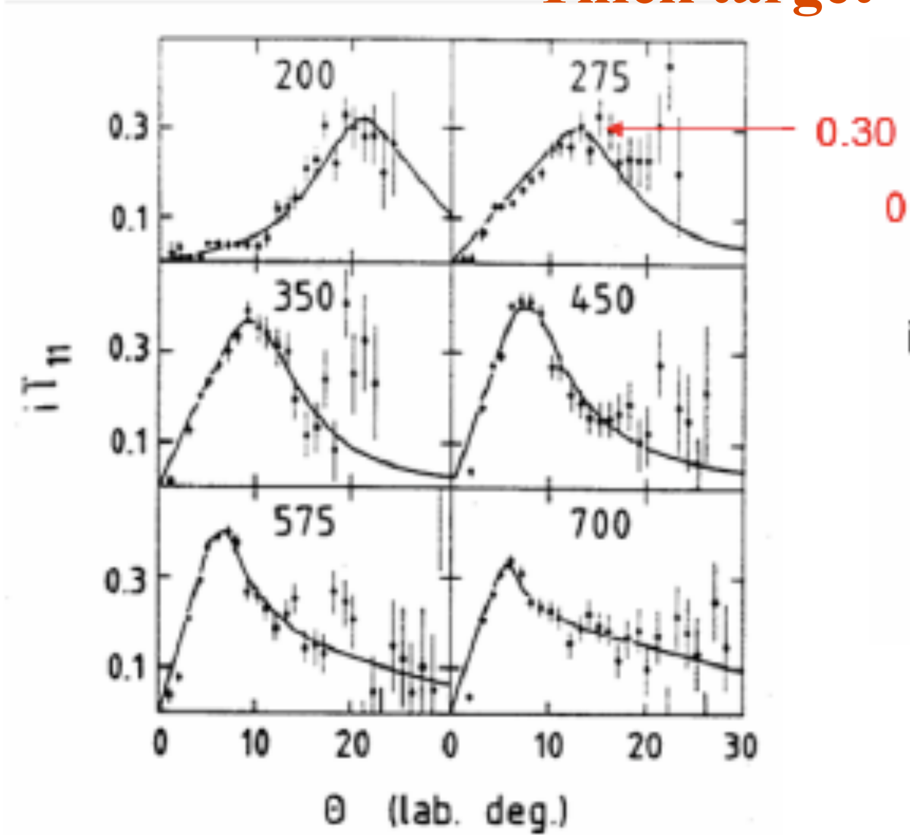


Figure 9, from reference [8]. The systematic errors in both beam direction angle and position change can be both represented by a requirement on the angle stability. 0.02° corresponding to 0.35 mrad is the required limit on the corresponding position stability.

Break-up protons lower the asymmetry

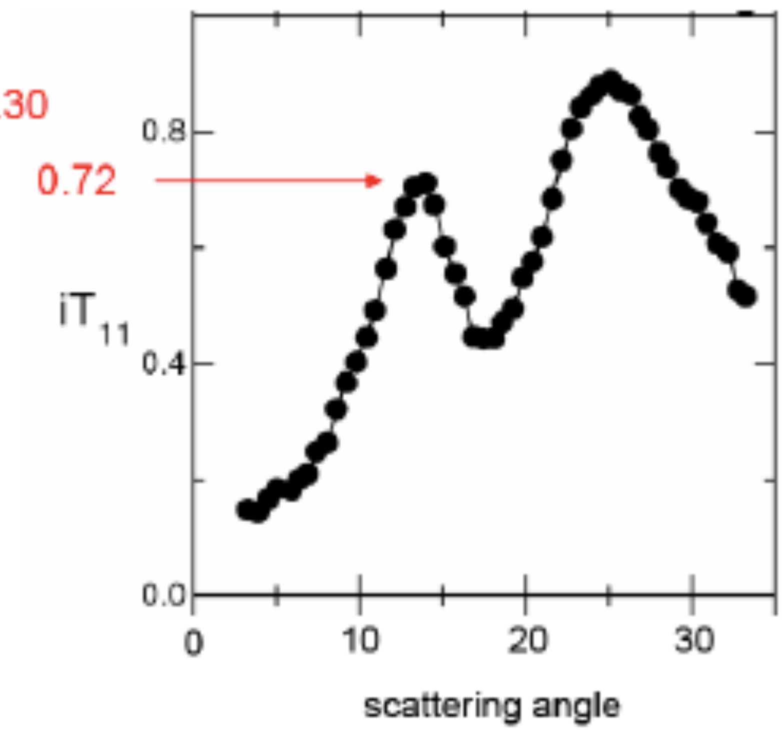
An example at 275 MeV

Thick target



Bonin *et al.*, NIM **A288**, 389 ('90)

Thin target

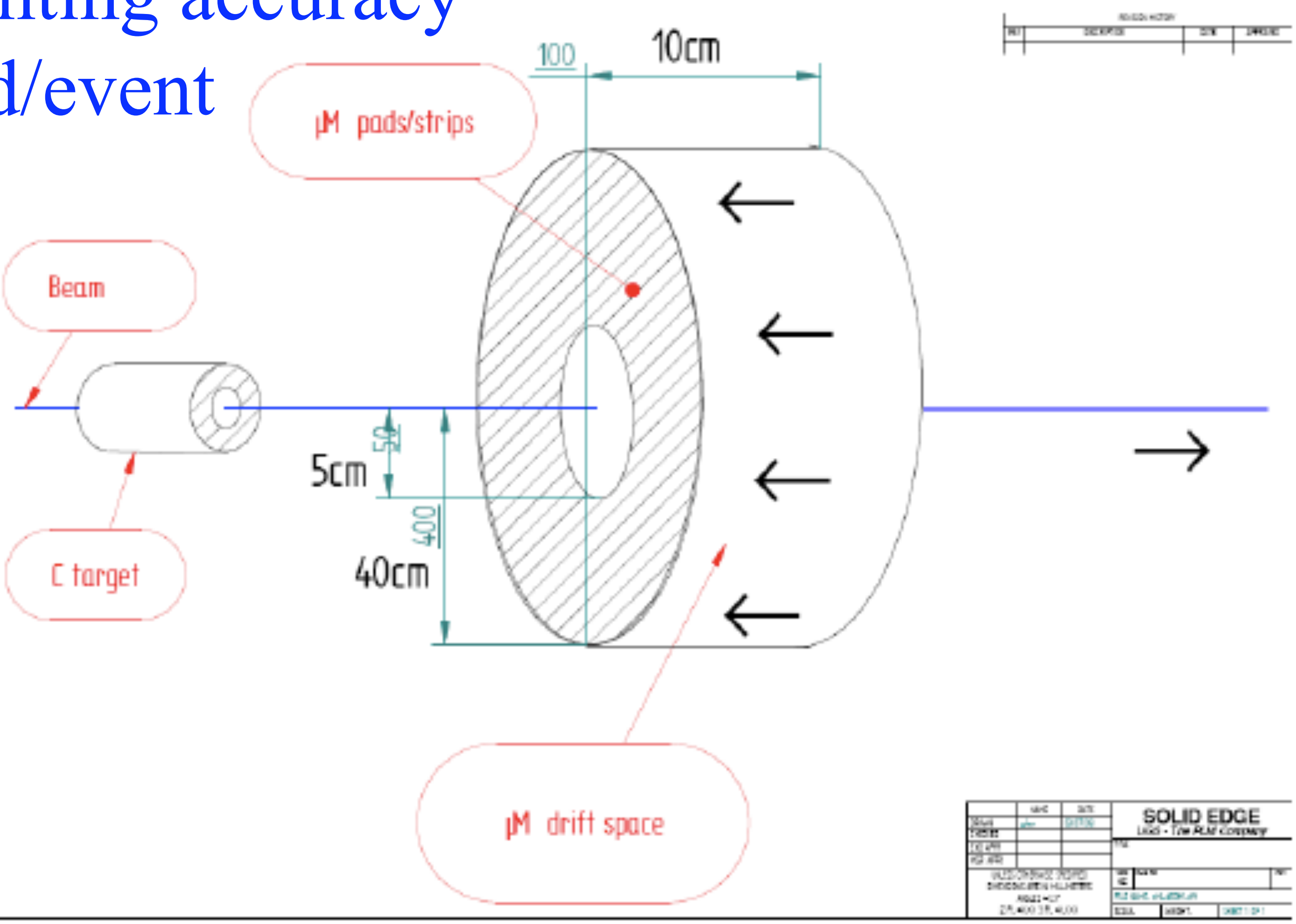


Y. Satou, private communication

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

Applying Micro-Megas TPC

- Differentiate between protons and deuterons
- Have a pointing accuracy of 0.5mrad/event



Expected rates

- 10^6/s (minimum) – 10^7/s (maximum)

- $10^3/cm^2$ - $10^4/cm^2$

- Maximum rates are very challenging. Potential to gain ~2 in statistical error (a factor of ~4 in running time)

- It can potentially eliminate the main polarimeter systematic error

2. Specs

a) Leakage currents: <1μA

b) Power Supply stability (on average): $<10^{-4}$

c) Net heat source in enclosed ring: <(±20 kwatt)

d) Average field uniformity over 2cm diameter: ~1ppm

Run Plan

a) Run 1 to shim the ring and study the systematic errors. Collect data for 10^{-28}e•cm

b) Run 2 for statistical error $\leq 10^{-29}$e•cm and total systematic error $<10^{-29}$e•cm.

1^{st} Run Plan

a) Commissioning of the ring with low intensity beam (kickers, AC solenoid, Pick-up electrodes,…)

b) Commissioning of the polarimeter with deuteron beams of various polarization states & values

c) Establish spin coherence time of $\geq 10^3$s

d) Collect data for 10^{-28}e•cm

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

Next, Run for 10^7s

Collect data for 10^{-29}e•cm

Storage
Ring
EDM
Collaboration

A strong collaboration
With strong motivation

AGS Proposal: Search for a permanent electric dipole moment of the deuteron nucleus at the 10^{-29} $e \cdot cm$ level.

D. Anastassopoulos,[21] V. Anastassopoulos,[21] D. Babusci,[8] M. Bai,[4] G. Bennett,[4] J. Bengtsson,[4] I. Ben-Zvi,[4] M. Blaskiewicz,[4] K. Brown,[4] G. Cantatore,[17] M. Dabaghyan,[20] V. Dzhordzhadze,[4] P.D. Eversheim,[2] M.E. Emirhan,[11] G. Fanourakis,[22] A. Facco,[13] A. Fedotov,[4] A. Ferrari,[8] T. Geralis,[22] Y. Giomataris,[23] F. Gonnella,[16] F. Gray,[18] R. Gupta,[4] S. Haciomeroglu,[11] G. Hoffstaetter,[6] H. Huang,[4] M. Incagli,[19] K. Jungmann,[9] M. Karuza,[17] D. Kawall,[14] B. Khazin,[5] I.B. Khriplovich,[5] I.A. Koop,[5] Y. Kuno,[15] D.M. Lazarus,[4] R. Larsen,[4] P. Levi Sandri,[8] F. Lin,[4] A. Luccio,[4] N. Malitsky,[4] W.W. MacKay,[4] W. Marciano,[4] A. Masaharu,[15] W. Meng,[4] R. Messi,[16] L. Miceli,[4] J.P. Miller,[3] D. Moricciani,[16] W.M. Morse,[4,a] C.J.G. Onderwater,[9,b] Y.F. Orlov,[6,c] C.S. Ozben,[11] T. Papaevangelou,[23] V. Ptitsyn,[4] B. Parker,[4] D. Raparia,[4] S. Redin,[5] S. Rescia,[4] G. Ruoso,[13] T. Russo,[4] A. Sato,[15] Y.K. Semertzidis,[4,*] Yu. Shatunov,[5] V. Shemelin,[6] A. Sidorin,[12] A. Silenko,[1] M. da Silva e Silva,[9] N. Simos,[4] E.J. Stephenson,[10,d] G. Venanzoni,[8] A. Vradis,[21] G. Zavattini,[7] A. Zelenski,[4] K. Zioutas[21]

[1]Research Inst. for Nucl. Probl. of Belarusian State University, Minsk, Belarus; [2]University of Bonn, Bonn, D-53115, Germany; [3]Boston University, Boston, MA 02215; [4]Brookhaven National Laboratory, Upton, NY 11973; [5]Budker Institute of Nuclear Physics, Novosibirsk, Russia; [6]Cornell University, Ithaca, NY 14853; [7]University and INFN, Ferrara, Italy; [8]Laboratori Nazionali di Frascati dell'INFN, Frascati, Italy; [9]University of Groningen, NL-9747AA Groningen, the Netherlands; [10]Indiana University Cyclotron Facility, Bloomington, IN 47408; [11]Istanbul Technical University, Istanbul 34469, Turkey; [12]Joint Institute for Nuclear Research, Dubna, Moscow region, Russia; [13]Legnaro National Laboratories of INFN, Legnaro, Italy; [14]University of Massachusetts, Amherst, MA 01003; [15]Osaka University, Osaka, Japan; [16]Dipartimento di Fisica, Universita' "Tor Vergata" and Sezione INFN, Rome, Italy; [17]University and INFN Trieste, Italy; [18]Physics Dept., Regis University, Denver, CO 80221; [19]University and INFN Pisa, Italy; [20]Brigham and Women's Hospital, Harvard Medical School, Boston, MA 02115; [21]University of Patras, Patras, Greece; [22]Institute of Nuclear Physics Dimokritos, Athens, Greece; [23]Saclay/Paris, France

Possible dEDM Timeline

07 08 09 10 11 12 13 14 15 16 17

- ✓ Spring 2008, Proposal to the BNL PAC
- 2008-2012 R&D phase; ring design
- Fall 2011, Finish systematic error studies:
  a) spin/beam dynamics related systematic errors.
  b) Polarimeter systematic errors studies with polarized deuteron beams
  c) Finalize E-field strength to use

- Start of 2012, finish dEDM detailed ring design

- Fall 2012, start ring construction

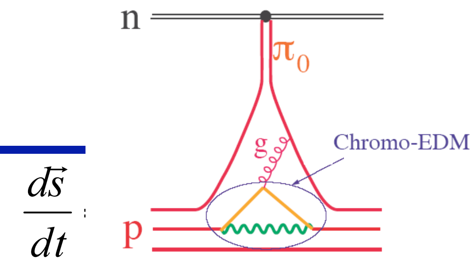
- Fall 2014, dEDM engineering run starts
- Fall 2015, dEDM physics run for three (calendar) years

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

Summary

- There is a very Strong Physics motivation: Complementary to nEDM and LHC and many times much better. It is designed to be the best experiment to study non-SM CP-violation when compared to present and presently planned experiments.

- The main ideas are well developed. No indication of show stoppers.
- The experimental cost is ~$30M, beam-line ~$7M.
- The Micro-Megas TPC is essential to control both the statistical and systematic errors in the dEDM experiment



Extra sides

Symmetries for syst. error cancellation

Table 4: This table lists a number of causes of an asymmetry and testable characteristics for each cause. A plus indicates that this cause appears to be the same as an EDM and a minus indicates where there is a distinguishable difference (see text for description of the asymmetries and characteristics).

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(2) source t_{21}	−	*	+	−	+	−	$< 10^{-29}$
(3) det. rotation	+	+	−	−	*	+	$< 10^{-29}$
(4) off axis/angle	−	−	−	−	*	−	see text
(5) non-linear det.	+	+	−	−	*	+	$< 10^{-29}$
(6) self-polarization	−	−	+	+	+	−	$< 10^{-29}$

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

CERN Septum (conditioned to ~15MV/m)

Proceedings of the 2001 Particle Accelerator Conference, Chicago

CONSOLIDATION PROJECT OF THE ELECTROSTATIC SEPTA IN THE CERN PS RING

J. Borburgh, M. Hourican, M. Thivent, CERN, Geneva, Switzerland

Abstract

After almost two decades of reliable service, the electrostatic septa of the CERN PS complex need to be upgraded. This is to fulfil the increased requirements on vacuum performance and the need to reduce the time spent on maintenance interventions. Two electrostatic septa are used in the PS ring: septum 23 is used for a resonant slow extraction, while septum 31 is used for the so-called 'continuous transfer' (CT) 5-turn extraction. This paper describes the experience gained with these septa over the years. We report the main characteristics and technological advantages of the new septum 23, together with its present performance.

1 INTRODUCTION

Electrostatic septa have been used in the CERN PS

Figure 1: The new septum 23

Statistics with 2×10^{11} d/ring

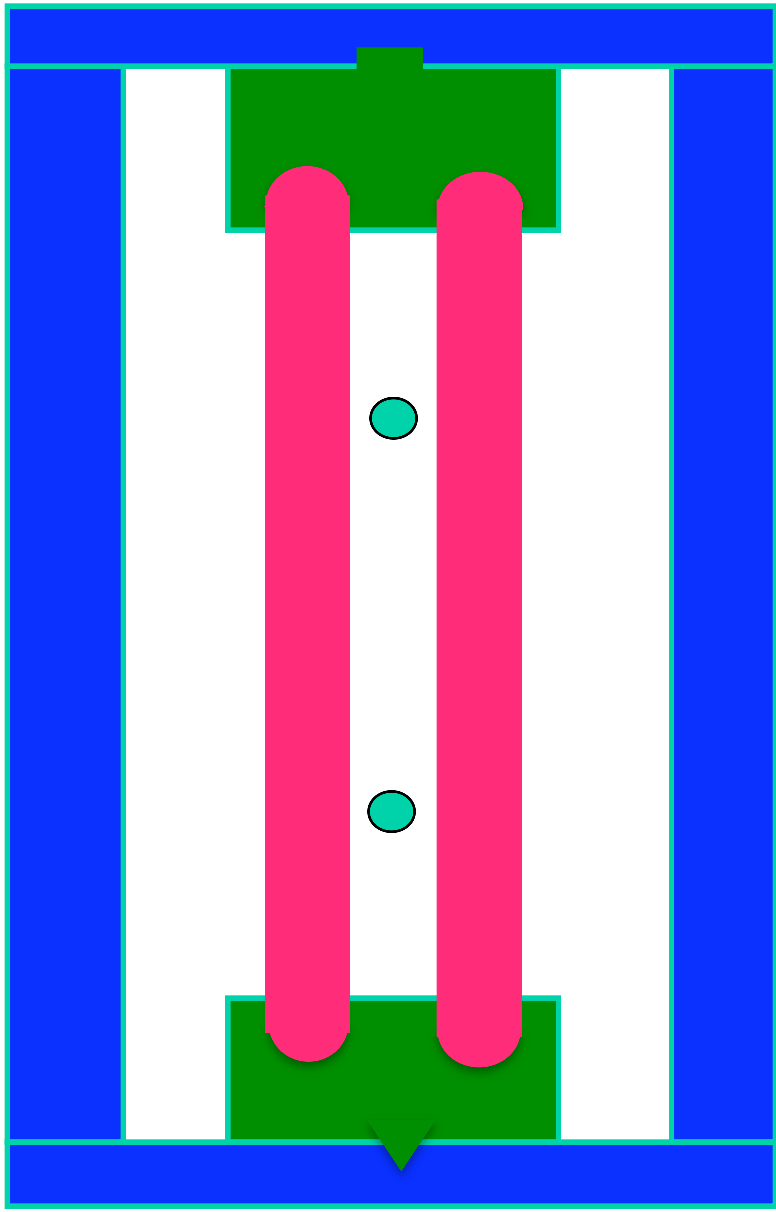
- Polarization: 80%
- SCT ≈ 10^3s; Asymmetry≈0.3; Efficiency≈0.01

<10^7s are needed for 10^{-29}e•cm. The maximum expected asymmetry change in L/R counting from early (~1s) to late times (10^3s) is 3×10^{-6}.

With 10^3s/storage means 10^4 CW and CCW injections, i.e. the statistical power is ≈10^{-27}e•cm/single store or ≈10^{-28}e•cm/day

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

Canceling higher order E-field backgrounds



We will run moving the horizontal beam position in steps of 1mm. Same with vertical position.
The DC E-field multipoles will be shimmed using E-field trim plates.

The AC E-field multipoles are small by design. CW and CCW average beam location needs to repeat to 0.1mm.

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

1. Symmetries

a) CW → CCW → CW →… injections into the same ring to cancel the DC component of $\langle E_v \rangle$.

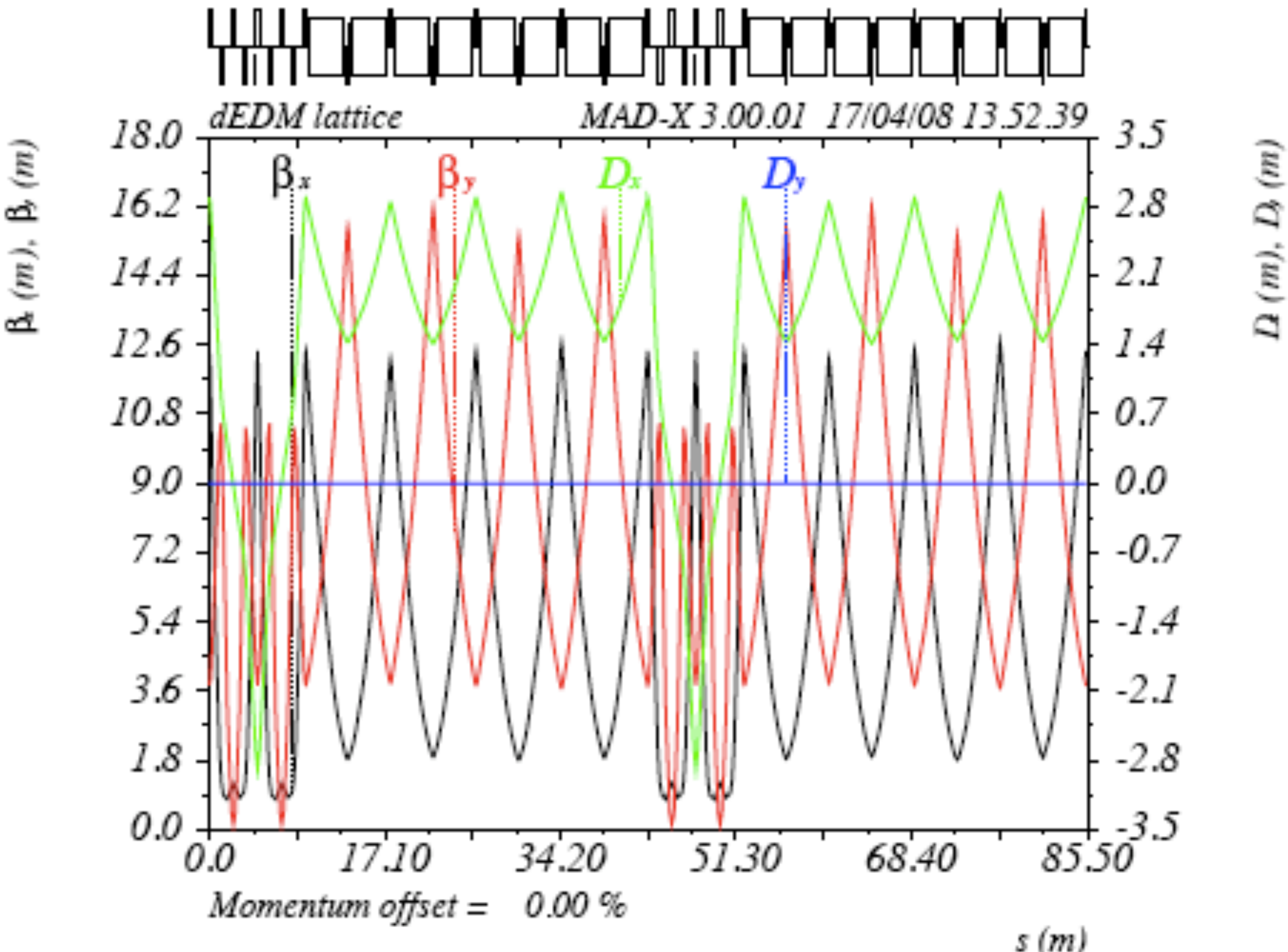
b) Ring 1: CW & ring 2: CCW → ring 1: CCW & ring 2: CW →… injections into two strongly coupled rings to cancel the AC component of $\langle E_v \rangle$.

c) Store simultaneously two bunches in the same ring with opposite polarization to cancel polarimeter related systematic errors, tensor component development, etc.

d) Change speed and phase of ω_a to control geometrical phases.

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

The dEDM Ring Lattice

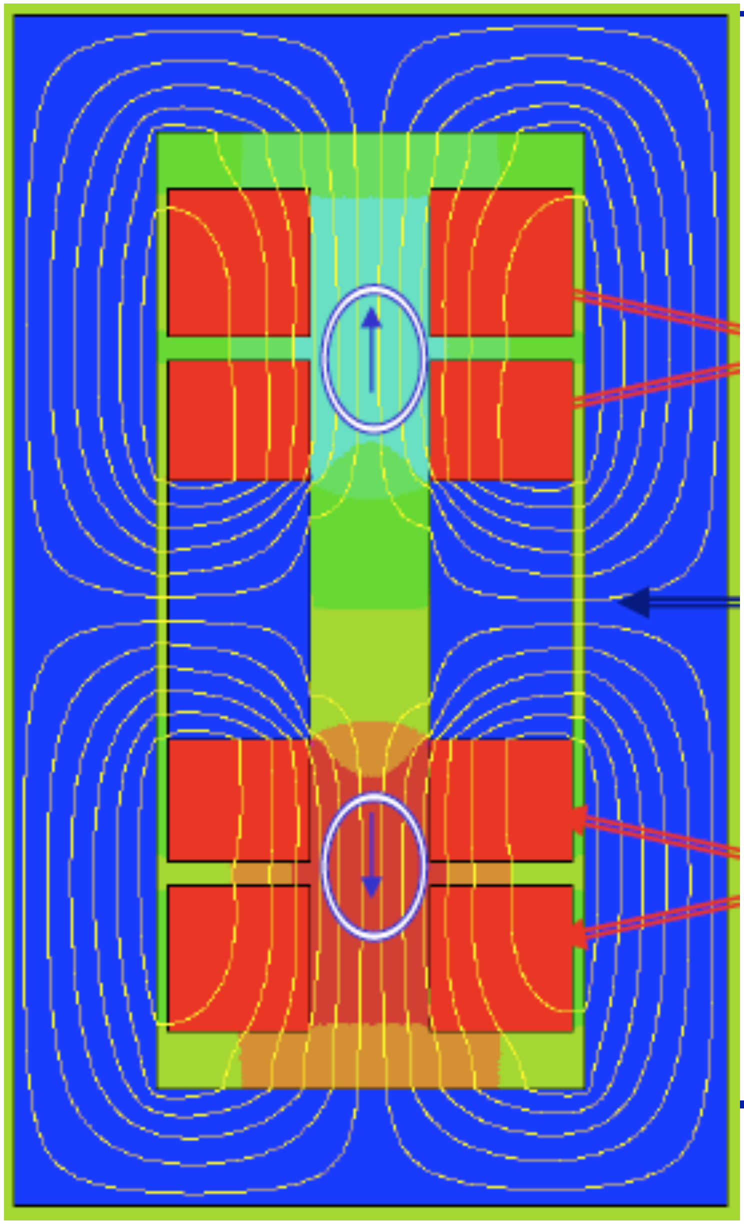


Ring Circumference: 85m

Yannis Semertzidis, BNL

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

Operating Electric Fields in the Presence of Magnetic Fields



Trapped electrons may cause trouble. They undergo three motions:

1) cyclotron, 2) Axial (up/down), 3) Magnetron (drift in the E×B direction)

Fortunately our dipole magnets are essentially skew quads in the middle of the plates and the electron trapping is quenched before it has a chance to form…

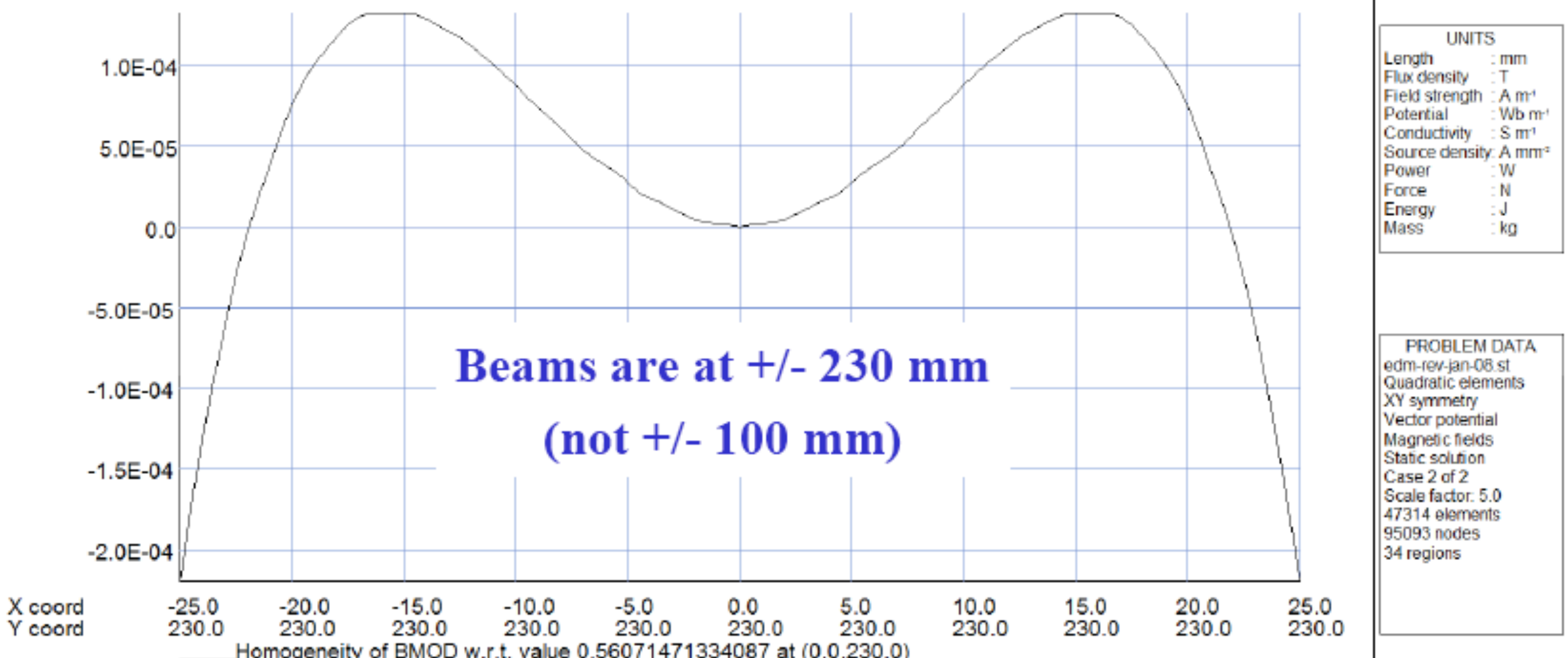
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

Relative Field Errors on the Horizontal Axis in One Aperture

Proof that a good field quality can be obtained.



This preliminary design was presented in the last meeting.

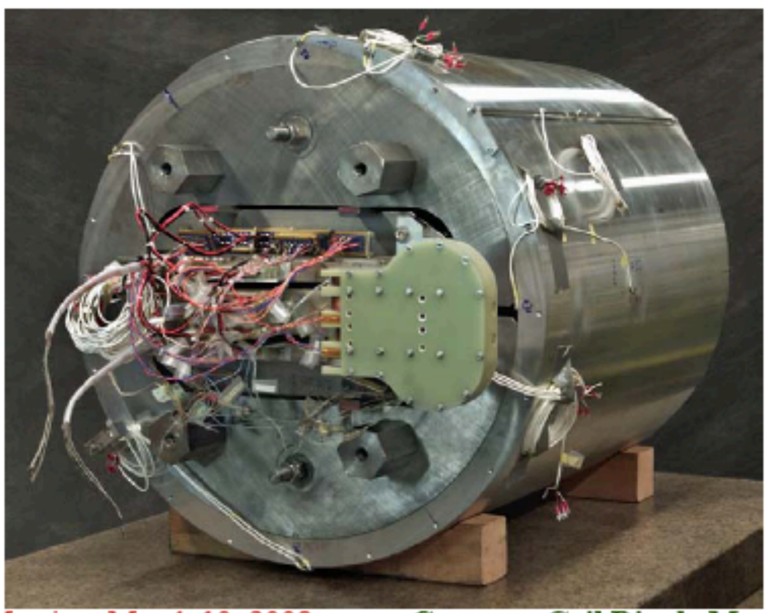
Field errors are displayed for +/- 25 mm. Actual beam size is much smaller.

Also, this is an easy way to evaluate overall field quality, but in a more detailed design and analysis, field errors in terms of harmonics are examined.

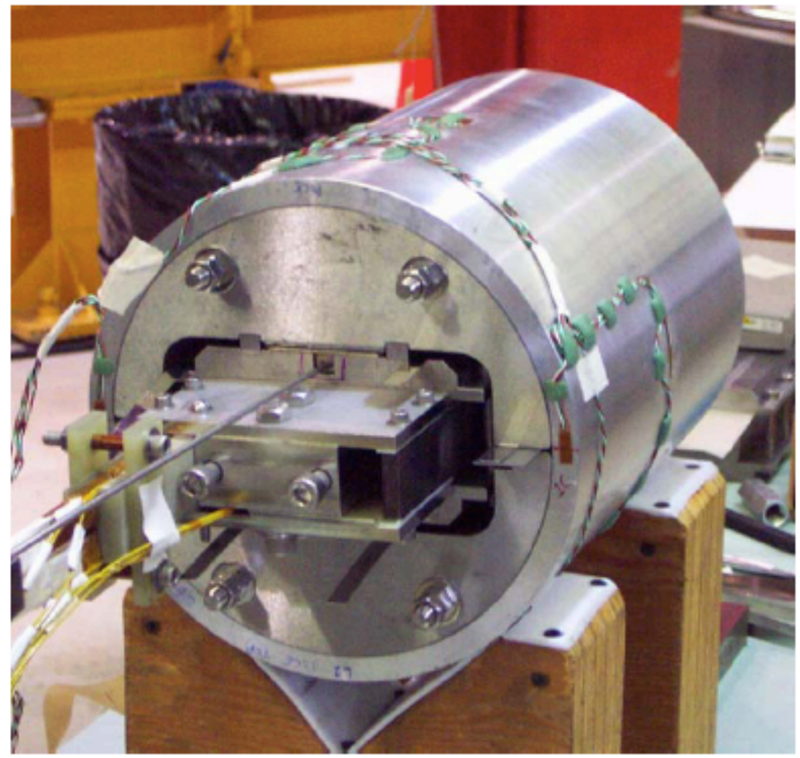
Common Coil Magnets Built at BNL, FNAL, LBNL

BNL

LBNL



FNAL



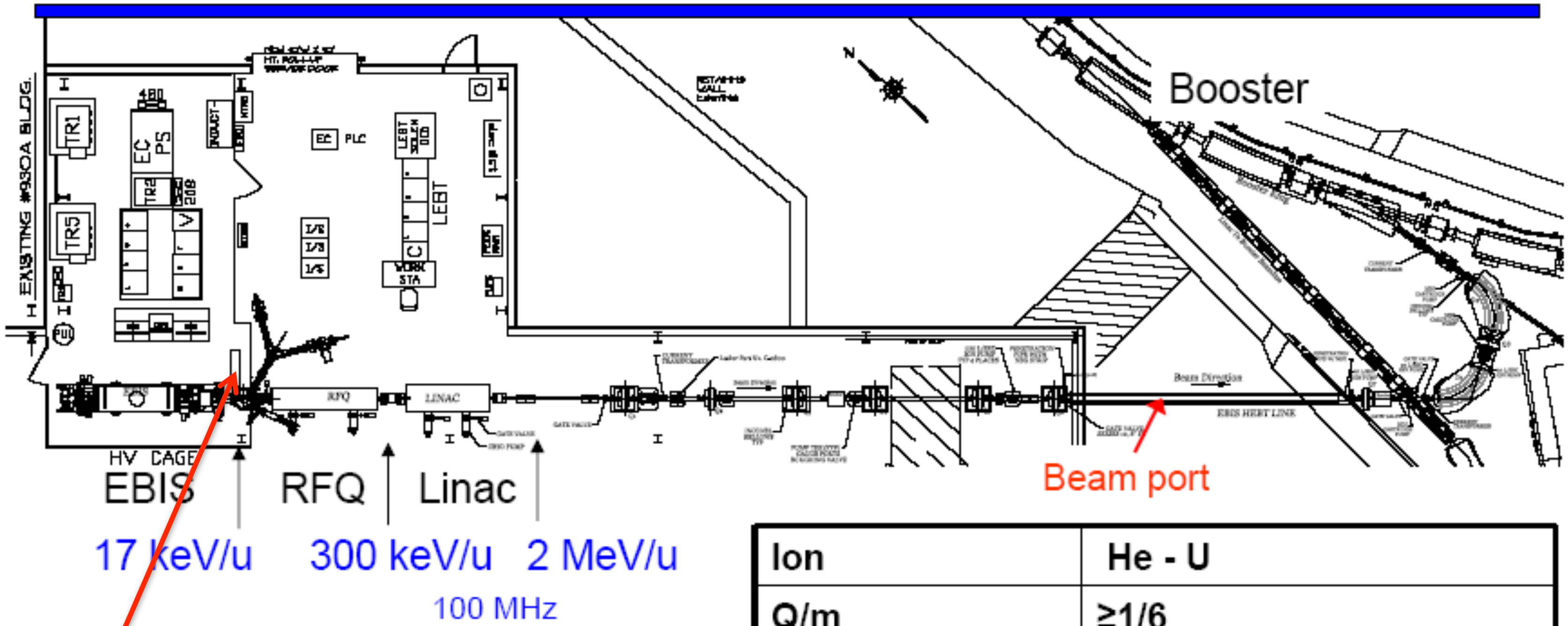
The dEDM ring parameters

Table 1: Deuteron EDM ring parameters

Deuteron Momentum	1.0 GeV/c
Rigidity (B-E/β)R	3.336 Tm
Magnetic field Bv	0.482 T
Radial electric field E0	12.0 MV/m
Length of BE section	3.3 m
Gradient of BE section	0.0101 T/m
BE section radius R	8.406 m
Drift between BE and quads	0.2815m
Drift between two BEs	0.863m
Length of orbit L	85.408 m
Horizontal tune	4.477
Vertical tune	3.469
$\beta_{x,max}$	12.5 m
$\beta_{y,max}$	16.0 m
Dispersion maximum	2.92 m
Momentum compaction factor α	0.149
Focu. quads gradient in bending section, l=0.15m	7.564 T/m
Defocu. quads gradient in bending section, l=0.15m	-6.593 T/m
quads gradient in straight section, l=0.375	12.079 T/m
Drift between quads in s.s.	0.8m

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

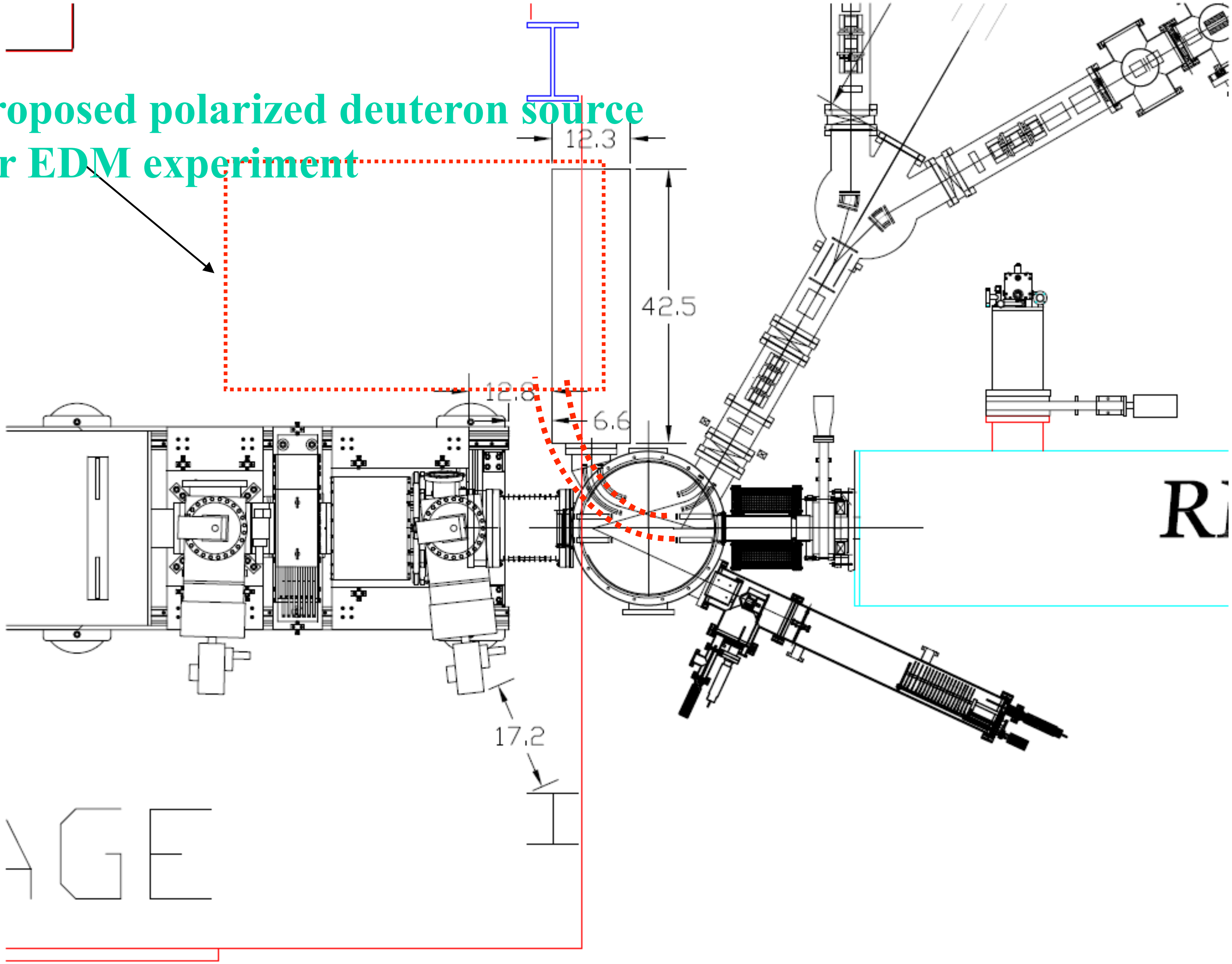
Placement of EBIS Preinjector in lower equipment bay of 200 MeV Linac

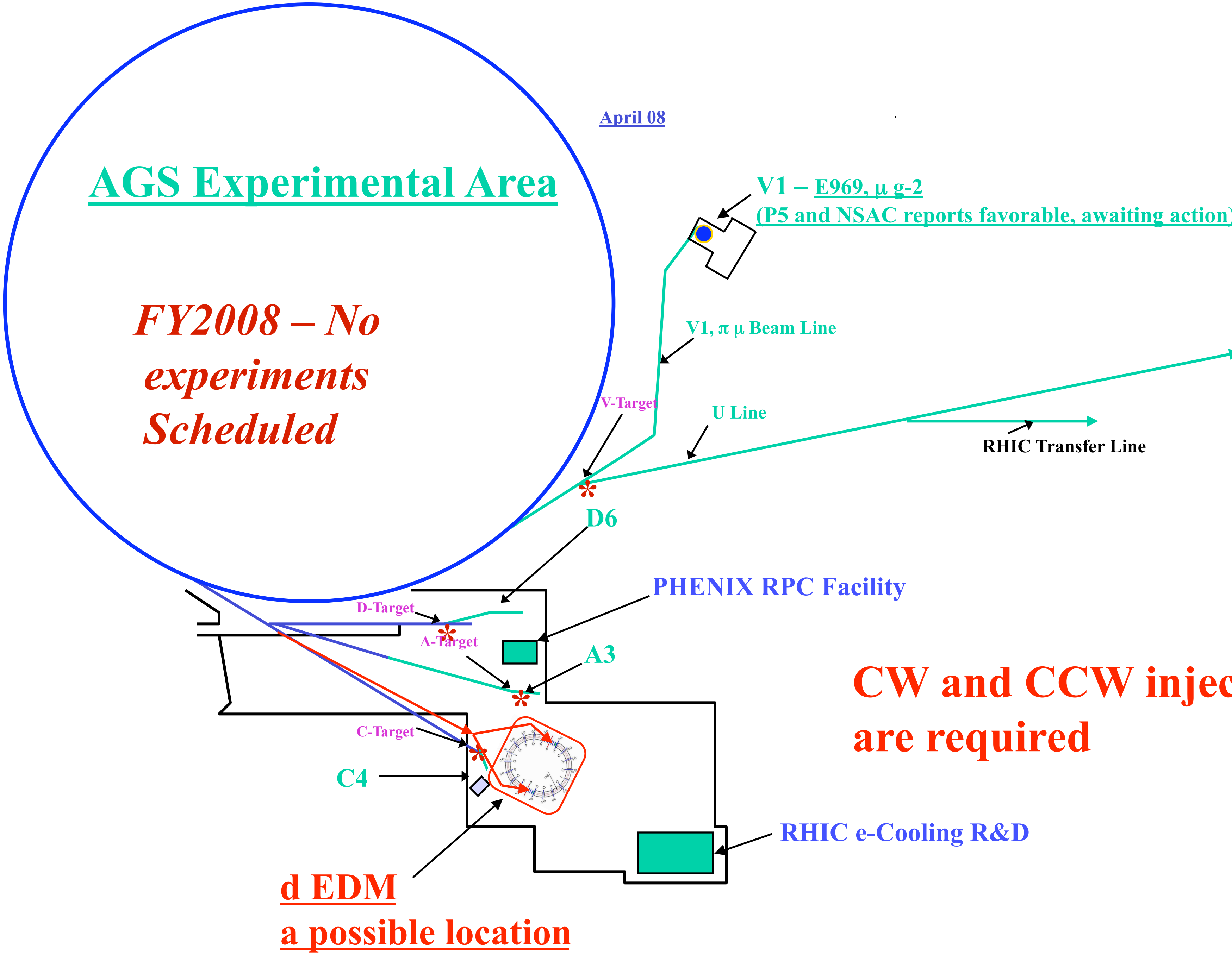


dEDM source location

Ion	**He - U**
Q/m	**≥1/6**
Current	**> 1.5 emA (for 1 turn inj)**
Pulse Length	**10 µs**
Rep. Rate	**5 Hz**
Time to switch species	**1 second**

Proposed polarized deuteron source for EDM experiment





CW and CCW injections are required

From Phil Pile

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

dEDM proposal, Construction Costs

(assumes reduced G&A)

Page 37 in proposal

- Storage Ring $17.7M
- 2 Injection Kickers $2.1M
- Experimental Systems $1.6M
- AGS eCooling $1.7M
- Beam line $7M

Total $30M

From Phil Pile

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

dEDM proposal, Construction Costs – some of what's missing

Mostly guesses

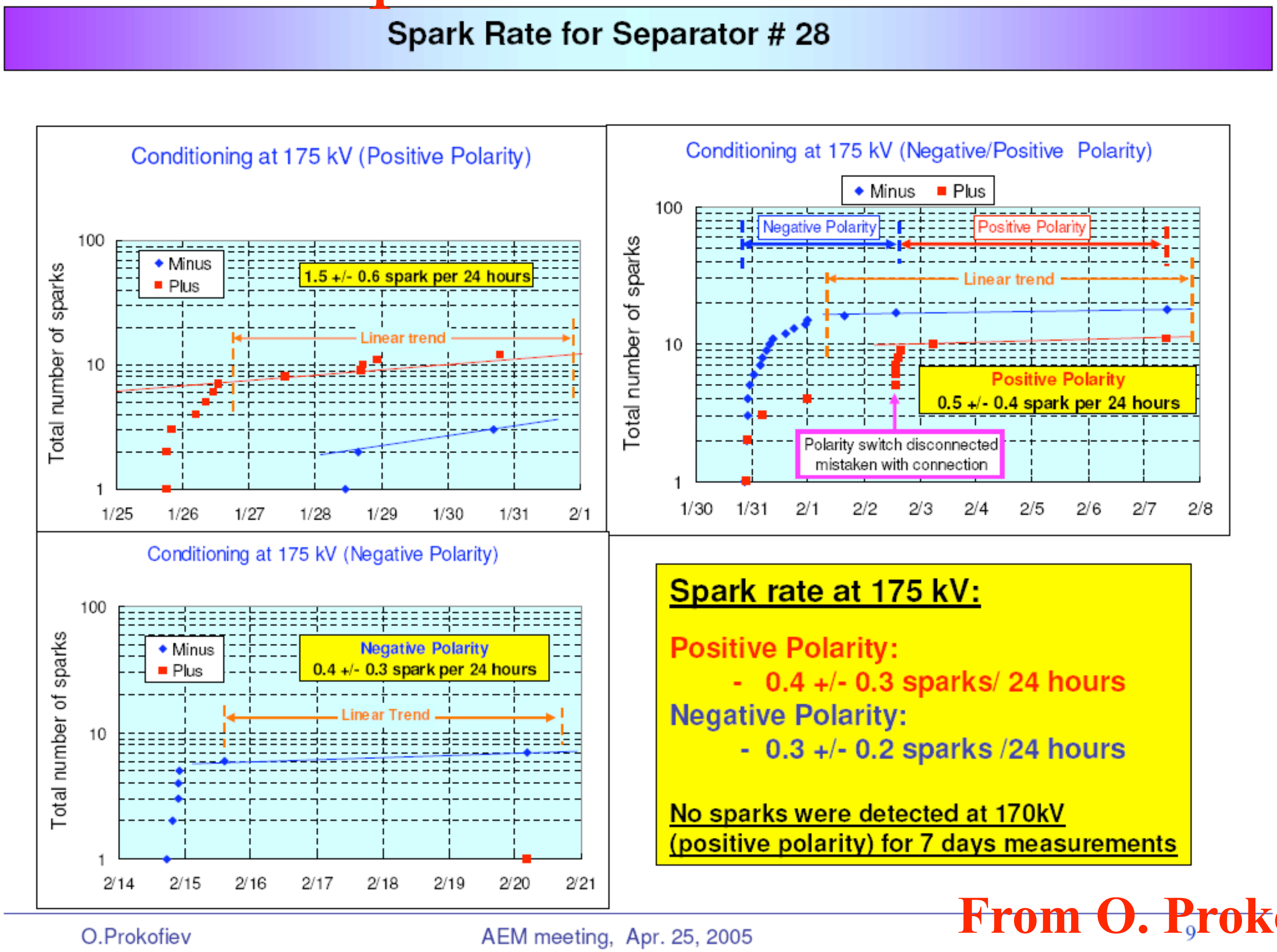
• R&D funds	$0.5M
• Baselining Costs	$0.5M
• Polarized deuteron source	$2M
• Re-establish AGS extraction	$0.2M
• AC solenoids (2)	$0.8
• Two additional injection kickers	$2M
• Reconfigure bldg 912 power and water	$0.5M
• Experiment counting house	$0.2M
• Project Office	$0.4M
• Other	$?

- Total $7M+

From Phil Pile

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

E-field strength, Electrostatic Separators at Tevatron



From O. Prokofiev, FNAL

Summary of Conditioning Tests

- **New process for conditioning at higher voltages was well defined and tested.**
  A procedure became much more quickly (hours vs days).
- **5 beam separators # 4, 6, 8, 27 and 28 were conditioned at 180 kV**
- **A detailed data were obtained on dark current and spark rate dependence vs voltage**
  Conditioning at 10 kV higher decrease spark rate roughly 10 times
- **A measured average spark rate:**
  - at 180 kV → 1.0 +/- 0.2 sparks/day
  - at 175 kV → 0.3 +/- 0.1 sparks/day
- **Estimated spark rate at 150 kV for separators conditioned at 180 kV is ~ 0.6 spark/year.**
  Is it completely meet to technical specs (1 spark/year) requested by AD.
- **Parameter comparison for hand polish and electropolish separators shows:**
  - no big difference in spark rate at 175-180 kV but for 150 kV spark rate for electropolish separator is better for few times
  - a total number of sparks is roughly the same for both hand polish and electropolish separators that indicates an equal number of primary microparticles
  - dark current for electropolish separator almost 10 times better in comparing with handpolish
- **Conditioning separator # 29 with titanium plates is the next**
  Assembly almost completed (waited for HV feedthrough)
  New HV power supply prepared for testing

From O. Prokofiev, FNAL

E-field strength

INITIATION OF ELECTRICAL BREAKDOWN IN VACUUM

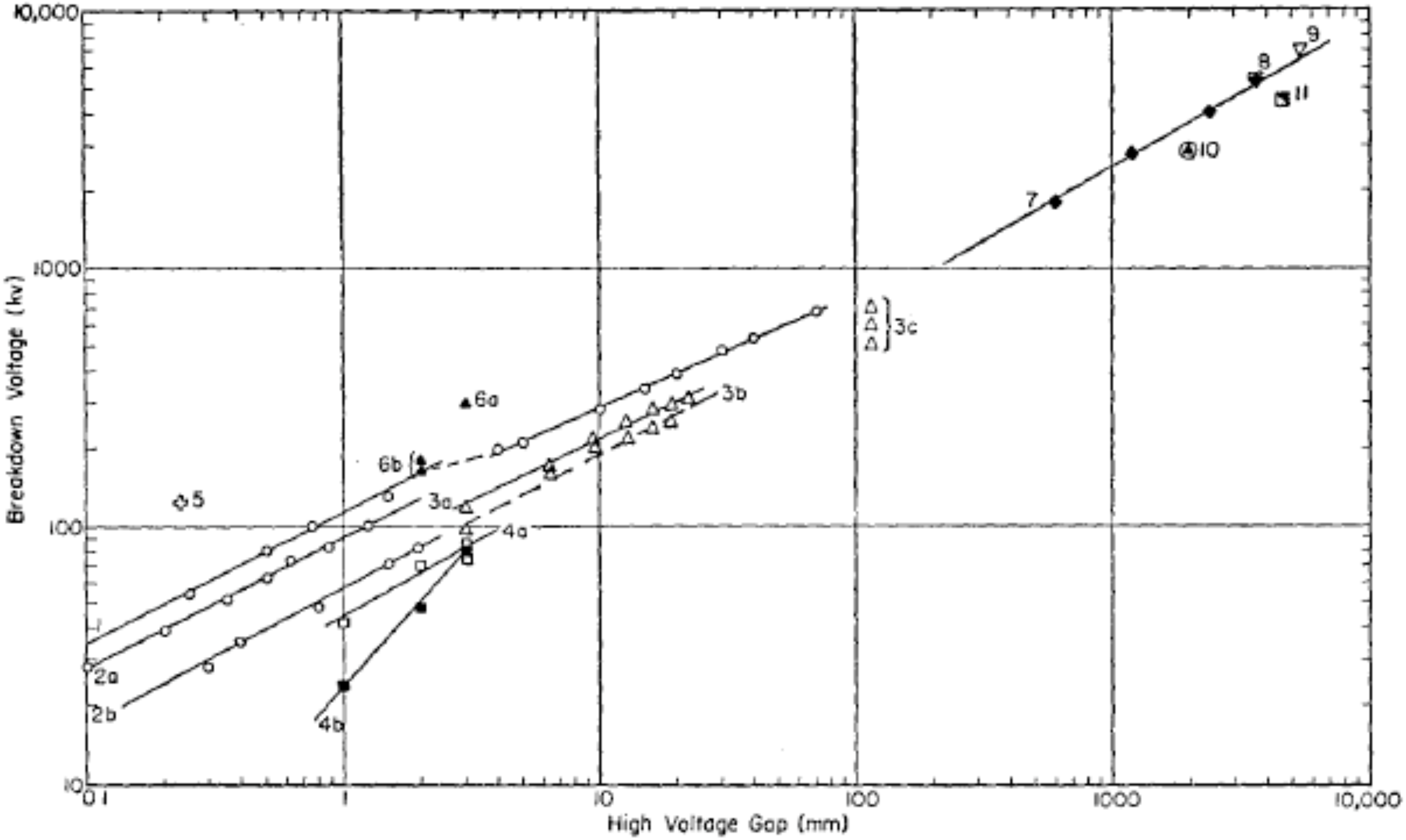
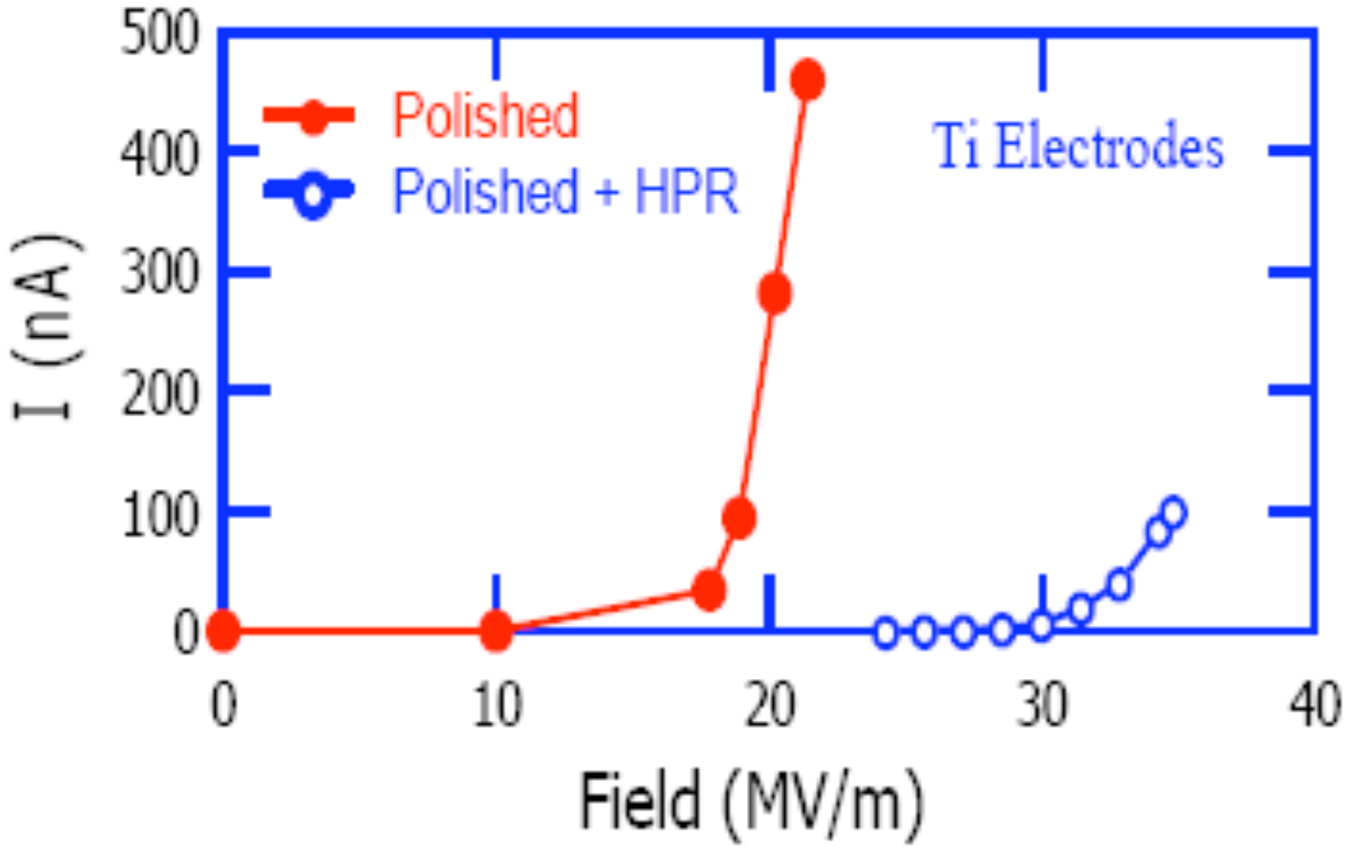


FIG. 1. Plot of data from the literature of breakdown voltage *vs* distance from highest to lowest potential electrode, for uniform-field and near-uniform-field geometry. Numbers on curves indicate sources as listed below.

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

E-field strength



The field emission with and without high pressure water rinsing (H

E-field strength choice: 12MV/m

- E-field strengths scale as 1/sqrt(d)
- Work at FNAL at 60KV/cm with 5cm separation at 5cm gave <1 spark/year.
- Scaled to 2cm (1.4cm): gives 95KV/cm (113KV/cm).

- Developments with high pressure water rinsing (HPR) increased available E-fields by a factor of 3.
- Using HPR we expect to achieve the 120KV/cm strength at 2cm and certainly at 1.4cm with surface area comparable to the FNAL separators.

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

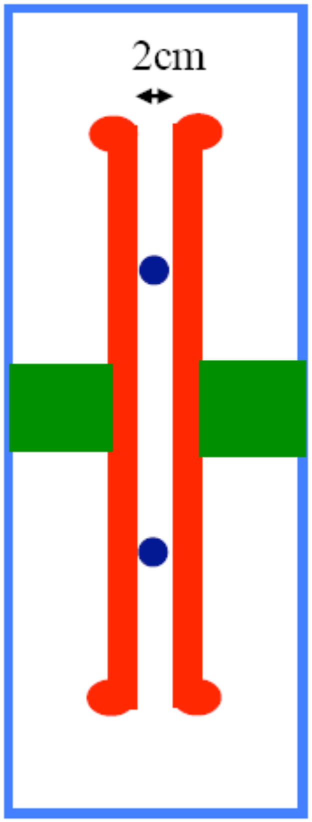
E-field strength choice: 12MV/m

- FNAL 170 KV/plate: no sparks in 7 days.
- Scaled to 2cm: gives 107KV/cm, conditioned at 114KV/cm. Scaled to 1.4cm: 128KV/cm conditioned at 136KV/cm).
- Using HPR we expect to achieve the 120KV/cm strength at 2cm and certainly at 1.4cm.
- O. Prokofiev: It will require work but it can be done.

E-field plan

- First choice: 2cm at 120KV/cm; P.S.:+-120KV.
- 2nd choice: 2cm → 1.4cm at 120KV/cm; P.S.: +-84KV
- 3rd choice: Lower E-field to match up to 0.7 GeV/c. At 0.7 GeV/c the E-field is less by more than a factor of 2. Now need to change the ring radius.

Support the vacuum chambers directly to ground; decouple from magnet



Goal: **chamber position independent of CW-CCW operations**
Verify: **Monitor with a Fabry-Perot resonator the CW and CCW chamber position, position of plates.**

Furthermore the magnetic forces are independent of field direction (except one!)

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

E-plate Specs

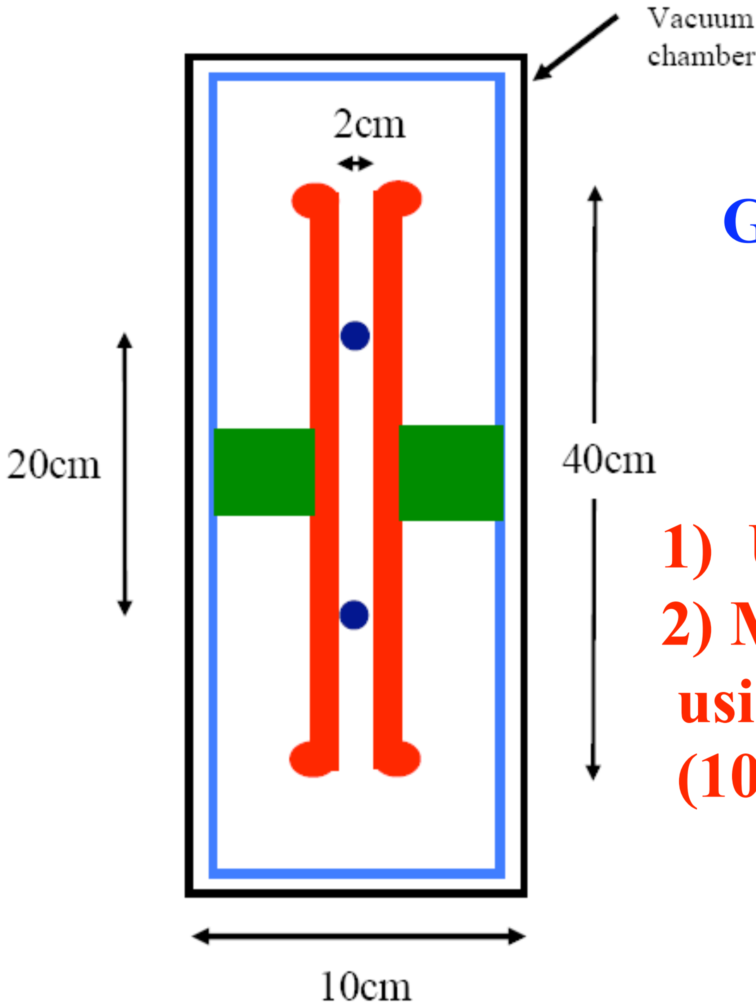


Figure 1. The electrostatic plates (red) are 40cm high separated by 2cm and are supported by the structure support shown in light blue, with high voltage insulators shown in green. This structure is enclosed in the vacuum chamber. The storage beam regions are shown in dark blue, 20 cm apart vertically.

Goal: Align the plates to 1μrad

1) **Use plate leveling with lasers**
2) **Monitor their distance stability using Fabry-Perot resonator (10^{-14} m resolution)**

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

E-field stability

- Requirement: Vacuum chamber (V.C.) bakeable (high vacuum requirements)

- Assumption: V.C. wobbles with ~1μrad amplitude (day-night)

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

E-field stability and other effects

- Plate weight
- Leakage current (<1μA; two effects)
- Eddy current heat on plates, cage, v.c.

- E-field force on plates and its stability
- Temperature uniformity (<10^{-3} K)
- Geometrical phases (combination of different direction fields)

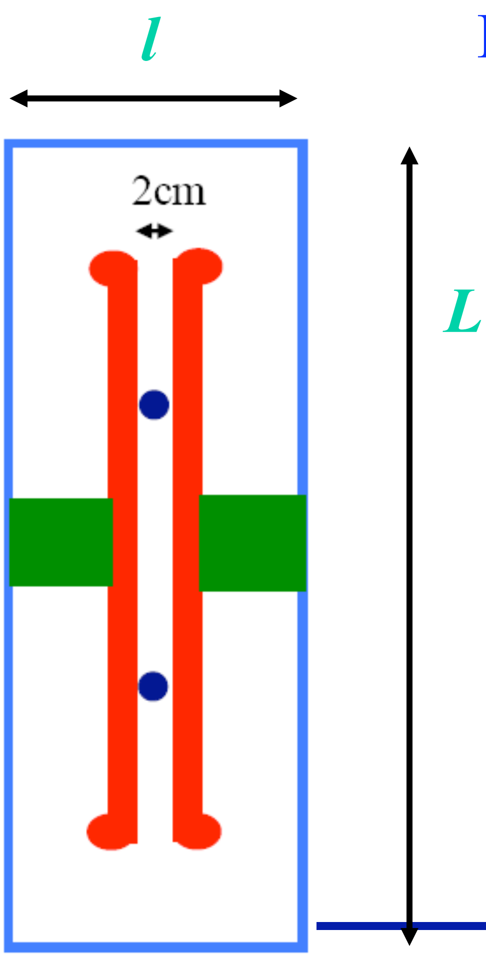
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

E-field force and its stability

- Assuming insulators every 50cm
- Half plate capacitance: ~50pF/50cm
- Charge: Q~5μC
- E-field force: F=QE~60N; ~6Kg. Plates bend <5nrad.
- Typical P.S. stability:10^{-4}, hence plate vertical stability~ .5prad of rms. Running 10000 times CW and CCW cancels goes down to $<5\times10^{-15}$rad. Feedback on P.S.?
- The beam itself causes a small bend on the plates which cancels between CW and CCW.

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

E-plate Specs, temperature uniformity (the DC terms cancel CW and CCW, only the varying effects are considered here)



If top plate expands more than the bottom plate due to temperature difference (for 10000 CW and CCW injections and the average over 1000s):

$$\frac{\Delta l}{L} = 10^{-12} \Rightarrow \frac{\Delta l}{l}\frac{l}{L} = 10^{-12} \Rightarrow 10^{-5}\Delta T \frac{l}{L} = 10^{-12}$$

$$\Rightarrow \frac{\Delta T}{L}\frac{l}{L} L = 10^{-7} \Rightarrow \frac{\Delta T}{L} \leq 10^{-6} \text{ K/m}$$

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

Systematic Error Symmetries
(+) Same as EDM; (-) is opposite

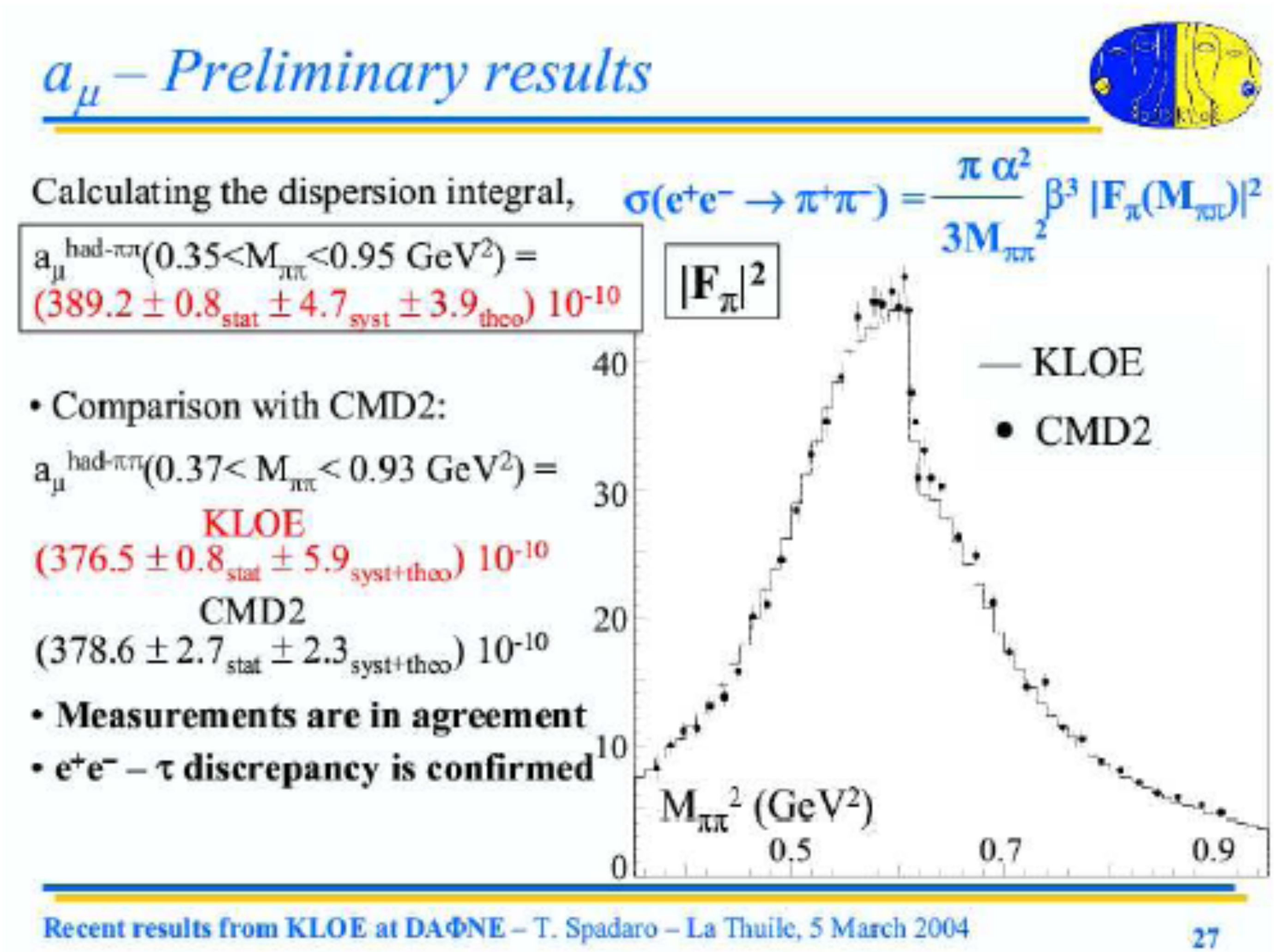
Spin Related

Systematic Effect	cc/ ccw	Ring	Flip P_i	$\delta\omega_a$ rate	$\delta\omega_a$ φ	Error (e cm)
Non-planar Electric Field	-	+	+	+	+	$\approx 10^{-27}$
$B_L \sin(k\omega_c t) \times \Delta B \cos(k\omega_c t)$	-	+	+	+	+	$<10^{-29}$
$B_L \sin(k\omega_c t) \times \delta\omega_a$	-	-	-	-	-	$<10^{-29}$
$(E \bullet B \neq 0) \times \delta\omega_a$	+	-	+	-	-	$<10^{-29}$

Polarimeter Related

Systematic Effect	cw/ ccw	Ring	Flip P_i	$\delta\omega_a$ rate	$\delta\omega_a$ f and φ	Error (e cm)
Source T_{21}	+	+	-	-	-	$<10^{-29}$
Source P_y	-	+	+	-	-	$<10^{-29}$
Polarimeter Rotation	-	-	+	-	+	$<10^{-29}$
Off axis beam	-	-	-	-	-	$<10^{-29}$
PMT rate dependence	-	-	+	-	+	$<10^{-29}$

Recent KLOE Results



S (provided by Juliet Lee-Franzini)

$\times \vec{E}$

$a\iota$

Theory of a_μ

- a_μ(theo) = a_μ(QED)+a_μ(had)+a_μ(weak)
  + a_μ(new physics)

- a_μ(QED) = 11 658 470.6 (0.3) $\times 10^{-10}$
- a_μ(had) = 694.9 (8.) $\times 10^{-10}$ (based on e^+e^-)
- a_μ(had) = 709.6 (7.) $\times 10^{-10}$ (based on τ)
- a_μ(weak) = 15.4 (0.3) $\times 10^{-10}$

- a_μ(SM) = 11 659 181(8)$\times 10^{-10}$ (based on e^+e^-)
- a_μ(SM) = 11 659 196(7)$\times 10^{-10}$ (based on τ)

Muon EDM Letter of Intent to J-PARC/Japan, 2003

J-PARC Letter of Intent: Search for a Permanent Muon Electric Dipole Moment at the $10^{-24}\,e\cdot\mathrm{cm}$ Level.

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January 9, 2003

- †Spokesperson
- # Resident Spokesperson

Expected Muon EDM Value from a_μ

$$L_{DM} = \frac{1}{2}\left[D\bar{\mu}\sigma^{\alpha\beta}\frac{1+\gamma_5}{2} + D^*\bar{\mu}\sigma^{\alpha\beta}\frac{1-\gamma_5}{2}\right]\mu F_{\alpha\beta},$$

where $\sigma^{\alpha\beta} = \frac{1}{2}\left[\gamma^\alpha, \gamma^\beta\right]$ and

$$a_\mu \frac{e}{2m_\mu} = \Re D,$$

$$d_\mu = \Im D,$$

$$D^{SUSY} = \left|D^{SUSY}\right| e^{i\phi_{CP}}$$

Probe this phase to 1%

$$d_\mu = 2\times 10^{-22}\ \mathrm{e\cdot cm}\ \frac{a_\mu^{\mathrm{SUSY}}}{25\times 10^{-10}}\tan(\phi_{CP})$$

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