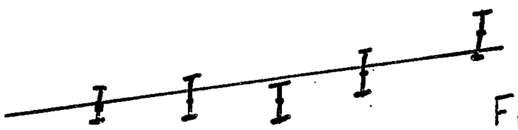
The Case for a Solid Target

YKS
9/12/03



Fitting for the slope

— Statistical sensitivity is greater when counting rate is flat.

— Re-gain the factor $\frac{1}{6\times10^{-4}}$ due to losses (Coulomb scattering).

Possible overall gain ~ 30 in statistical sensitivity.

EDM news

YKS
9/12/03

- Muon EDM LOI
  to J-PARC Jan 2003

- Presentation of LOI
  @ KEK June 2003

- Response from director
  of the J-PARC Project Shoji Nagamiya ✓
  August 2003

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

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R.M. Carey, V. Logashenko, K.R. Lynch, J.P. Miller*, B.L. Roberts

Boston University

G. Bennett, D.M. Lazarus, L.B. Leipuner, W. Marciano,

W. Meng, W.M. Morse, R. Prigl, Y.K. Semertzidis*

Brookhaven National Lab

V. Balakin, A. Bazhan, A. Dudnikov, B. Khazin, I.B. Khriplovich, G. Sylvestrov

BINP, Novosibirsk

Y. Orlov, **Cornell University**

K. Jungmann, **Kernfysisch Versneller Instituut, Groningen**

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M. Auzinsh, **University of Latvia**

P. Cushman, Ron McNabb, **University of Minnesota**

N. Shafer-Ray, **University of Oklahoma**

K. Yoshimura, **KEK, Japan**

M. Aoki, Y. Kuno#, A. Sato, **Osaka, Japan**

M. Iwasaki, **RIKEN, Japan**

F.J.M. Farley, V.W. Hughes, **Yale University**

January 9, 2003

* Spokesperson, # Resident Spokesperson

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August 22, 2003

Professor Y.K. Semertzidis,
Physics Department,
Broonkaven National Laboratory,
PO Box 5000,
Upton, NY 11973-5000,
USA.

Dear Professor Semertzidis:

Thank you for the submission of Letter of Intent to J-PARC for an experiment at the 50 GeV. The project office formed the committee to discuss a) scientific merit, b) suggested schedule, c) comments and suggestions to each experimental proposal. In addition, the project office asked the committee to recommend necessary arrangements to be made at this stage of the project for all the proposals.

Enclosed please find the committee's opinions and comments on your Letter of Intent. The evaluation and comments are carefully written and I fully endorse the enclosed description by the committee. In addition, I would like to inform you that, although it is not 100% clear, it is very likely that the project office will arrange to call for full proposals on Day-1 experiments within a year. Of course, if the system to call for full proposals is established, the call for proposals will be arranged every year in the subsequent years.

According to the committee, your proposal is regarded as one of the highlight experiments at J-PARC. Although it is not feasible to start your experiment now, I encourage you strongly to proceed into the full proposal at an appropriate time.

I thank you for your enthusiasm toward J-PARC. Please write me any comments, questions, requests, etc., if you have.

Thank you again for your submission of the Letter of Intent at this early stage of the project.

Sincerely yours,

Shoji Nagamiya
Director of the J-PARC Project

L22

Search for a Permanent Muon Electric Dipole Magnet at the 10^{-24} e-cm Level

Contact Persons: J. P. Miller, Y. K. Semertzidis, and Y. Kuno

Schedule: Phase 2+

Comments:

The EDM of the muon is a fundamental property, and if it is found at the 10^{-24} e-cm level, it is a clear signature of physics beyond the standard model. The LOI proposes the first dedicated experiment to measure the muon EDM using a muon storage ring.

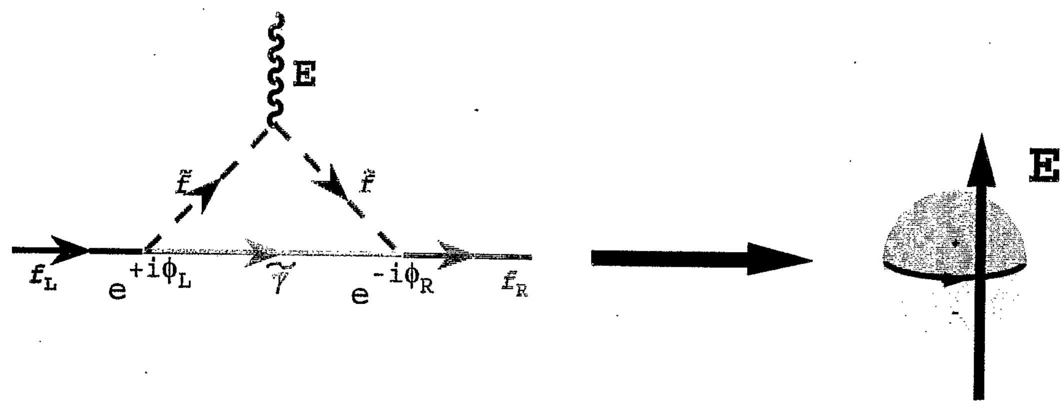
This new idea is still at a conceptual level, but some studies have been started. The Committee encourages the group to study further, including potential systematic errors, accelerator design and detector issues, and prepare a full proposal.

Also, the experimental study of this concept using deuterons is important for backing up the proposal.

N. Fortson
"Lepton Moments"
5/2003

Supersymmetry generates EDM naturally; Standard Model does not.

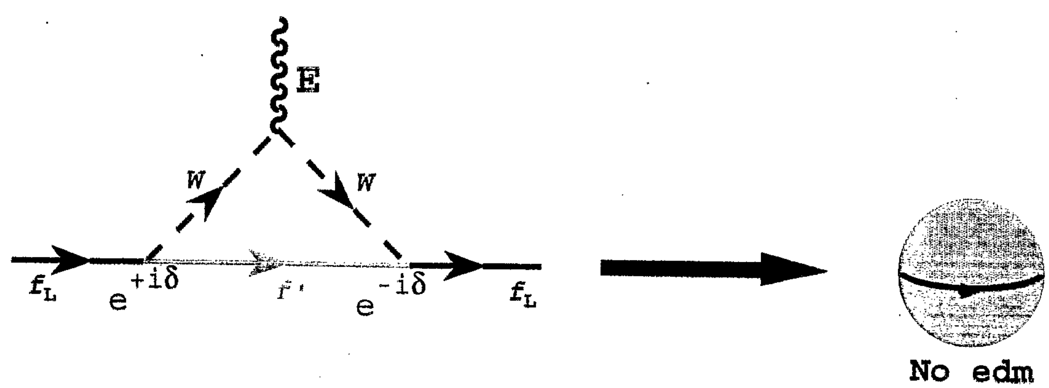
(a) SUSY: Generates edm in virtual cloud.



— $\exists > 40$ ~~CP~~ phases

— Coupling to r.h. fermions not e (W. Marciano)

(b) Standard Model: Edm cancels.



— $\exists$ 1 phase (CKM which cancels

— no coupling to r.h. fermions

Deuteron EDM

CP-violation Experts

✓ W. Marciano	H.E.P.		
✓ I. Khriplovich	Nuclear	EDMs	Did a lot of work on it.
✓ M. Pospelov	"	"	working on it
V. Flambaum	"	"	
M. Ramsey-Musolf	H.E.P.		working on it

M. Pospelov @ "Lepton Moments" Cape Cod 2003:

"The deuteron EDM is the most important and most promising EDM exp."

ELSEVIER

Nuclear Physics B 560 (1999) 3–22

NUCLEAR PHYSICS B

www.elsevier.nl/locate/npe

MSSM predictions for the electric dipole moment of the ^{199}Hg atom

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Received 23 April 1999; accepted 5 August 1999

Abstract

The Minimal Supersymmetric Standard Model can possess several CP-violating phases beyond the conventional Cabibbo–Kobayashi–Maskawa phase. We calculate the contribution of these phases to T-violating nuclear forces. These forces induce a Schiff moment in the ^{199}Hg nucleus, which is strongly limited by experiments aimed at the detection of the electric dipole moment of the mercury atom. The result for d_{Hg} is found to be very sensitive to the CP-violating phases of the MSSM and the calculation carries far fewer QCD uncertainties than the corresponding calculation of the neutron EDM. In certain regions of the MSSM parameter space, the limit from the mercury EDM is stronger than previous constraints based on either the neutron or electron EDMs. We present combined constraints from the mercury and electron EDMs to limit both CP-violating phases of the MSSM. We also present limits in mSUGRA models with unified gaugino and scalar masses at the GUT scale.

PACS: 11.30.Pb; 11.30.Er

Keywords: Electric dipole moment; Schiff moment; CP-violation; Supersymmetry

Deuteron EDM to 10^{-27} e•cm Sensitivity Level is 100 times better than ^{199}Hg

- T-odd Nuclear Forces: $\boldsymbol{d_d = 2\times10^{-22}\,\xi}$ **e·cm** with the best limit for $\boldsymbol{\xi < 0.5\times10^{-3}}$ coming from the ^{199}Hg EDM limit (Fortson, *et al.*, PRL 2001), i.e. $\boldsymbol{d_d < 10^{-25}}$ **e·cm.**

(Sushkov, Flambaum, Khriplovich Sov. Phys. JETP, **60**, p. 873 (1984) and Khriplovich and Korkin, Nucl. Phys. **A665**, p. 365 (2000)).

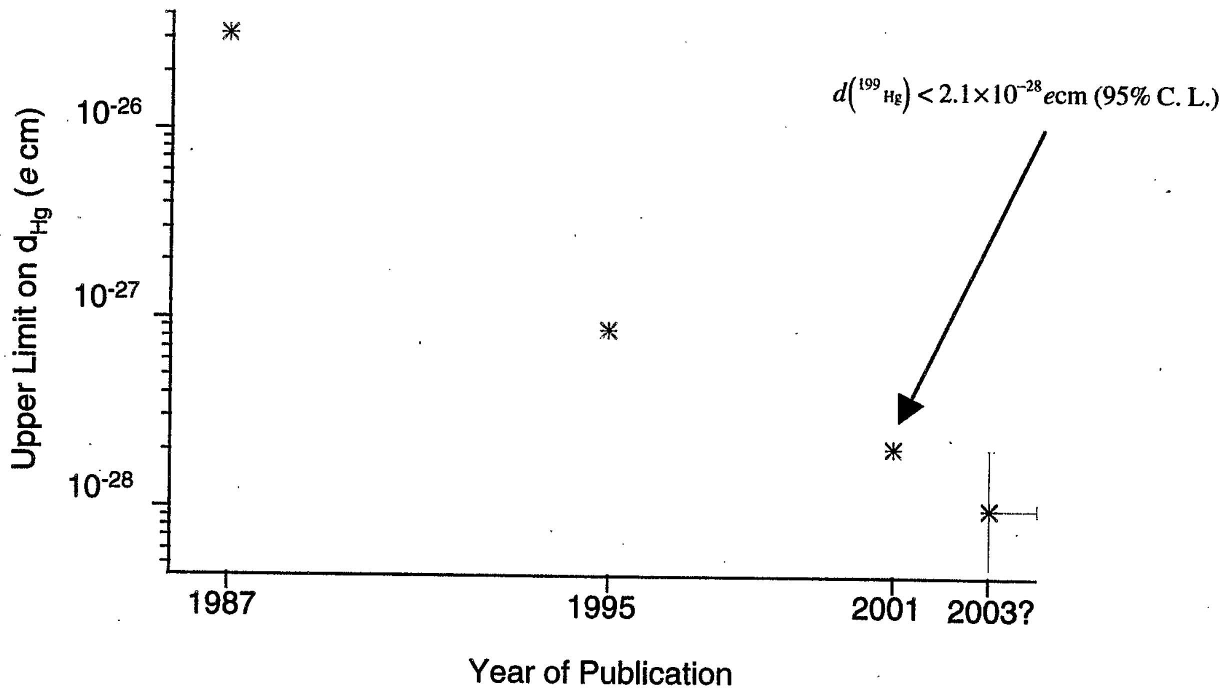
- The current
- neutron sensitivity to T-odd nucl forces 10 × less than ^{199}Hg

$d_d = d_p + d_n$ (I. Khriplovich)

It Improves the Current Proton EDM Limit by a Factor of ~100,000 and a Factor 60-100 on Neutron.

N. Fortson "Lepton Moments

UW ^{199}Hg EDM Limit – Historical

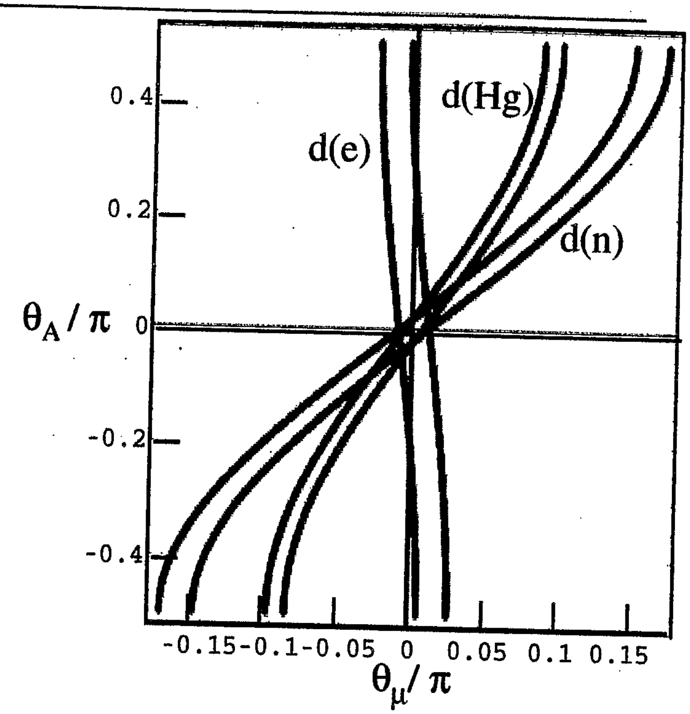


1987: S.K. Lamoreaux, J.P. Jacobs, B.R. Heckel, F.J. Raab, and E.N. Fortson, Phys. Rev. Lett. **59**, 2275 (1987).
1995: J.P. Jacobs, W.M. Klipstein, S.K. Lamoreaux, B.R. Heckel, and E.N. Fortson, Phys. Rev. A **52**, 3521 (1995)
2001: M.V. Romalis, W.C. Griffith, J.P. Jacobs, and E.N. Fortson, Phys. Rev. Lett. **86**, 2505 (2001).

from N. Fortson "Lepton Moments

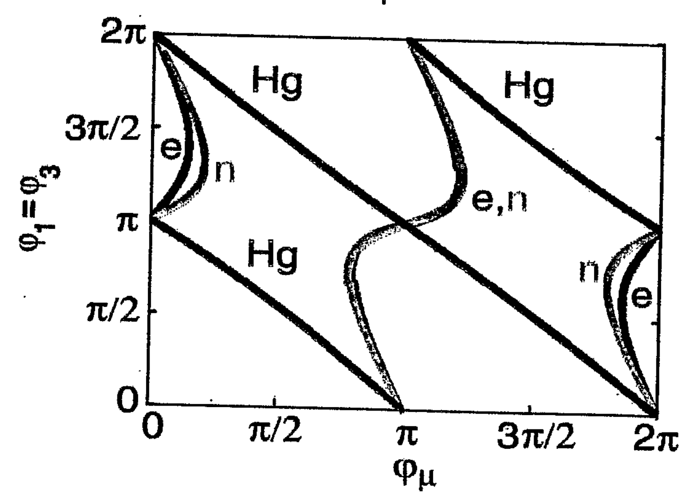
Limits on CP violation in Supersymmetry

MSSM CP-violating phases:
All masses = 500 GeV, $\tan\beta = 2$



T. Falk, K. Olive, M. Pospelov, R. Roiban, Nucl. Phys. B560 3 (1999). Update M. Pospelov.

Models allowing cancellations for d_e and d_n fail when the ^{199}Hg constraint is applied. ($m_{3,2}$= 750 GeV, $\tan\beta = 2$)



S. Abel , S. Khalil, and O. Lebedev, Nucl.Phys. B606, 151 (2001).

Statistical Error Derivation for the Muon and Deuteron EDM Experiments

YKS
9/12/03

Signal $\quad S(t) = \frac{U-D}{U+D}(t) = P\,A\,\vartheta_t$

P: polar.
A: asymm.
ϑ_t: angle due to EDM $\qquad \frac{d\bar{S}}{dt} = \bar{d} \times \bar{E}^*$

$$\vartheta_t = \frac{d \cdot E^*}{\frac{\hbar}{2}\,\cancel{B}}\, t \qquad \text{muons}$$

$$\vartheta_t = \frac{d \cdot E^*}{\hbar}\, t \qquad \text{deuterons}$$

$$\bar{E}^* = \bar{E}_R + \bar{v} \times \bar{B}$$

$$\Rightarrow S(t) = P \cdot \rho \cdot d \cdot t$$

μ: $\quad \rho = \frac{A\,E^*}{\hbar/2}$

d: $\quad \rho = \frac{A\,E^*}{\hbar}$

The error in $S(t)$ is $\sigma_S(t) = \sqrt{\dfrac{1-S^2}{U+D}} \simeq \dfrac{1}{\sqrt{N_0 e^{-t/\tau}}}$

$$\chi^2 = \sum_{i=1}^{n} \left[\frac{P \cdot \rho \cdot d \cdot t - N_i}{\sigma_S} \right]^2$$

minimizing χ^2

$\vdots$

$$\frac{\partial^2 \chi^2}{\partial d^2} = 2 \sum_{i=1}^{n} \left[\frac{P \rho t_i}{\sigma_S} \right]^2 = 2 P^2 \rho^2 N_0 \sum_{i=1}^{n} e^{-t_i/\tau} t_i^2$$

$$\hookrightarrow \int_0^\infty e^{-t/\tau} t^2 \, dt = 2\tau^3$$

$$N_0 \tau = N_{tot,c}$$

$$\Rightarrow \mu: \quad \sigma_d = \frac{1}{\sqrt{8}} \frac{\hbar}{\tau P A E^* \sqrt{N_{tot,c}}}$$

$$d: \quad \sigma_d = \frac{1}{\sqrt{2}} \frac{\hbar}{\tau P A E^* \sqrt{N_{tot,c}}}$$

For 1-par. fit, only slope.

Fitting for a DC-offset $\rightsquigarrow \sqrt{2}$ loss in stat. sens.

— Finite Polarization Lifetime

$$P = P_0 \, e^{-t/\tau_p}$$

then $\frac{1}{\tau} \rightarrow \frac{1}{\tau} + \frac{2}{\tau_p}$

and

μ: $$\sigma_d = \frac{1}{\sqrt{8}} \frac{\hbar}{\tau \left[\frac{\tau_p}{\tau_p + 2\tau} \right]^{3/2} P_0 \, A \, E^* \sqrt{N_{tot,c}}}$$

d: $$\sigma_d = \frac{1}{\sqrt{2}} \frac{\hbar}{\tau \left[\frac{\tau_p}{\tau_p + 2\tau} \right]^{3/2} P_0 \, A \, E^* \sqrt{N_{tot,c}}}$$

for 1-par. fit

— Finite Measurement Time compared to lifetime.

Bill: when storage time is longer than the machine cycle time what is the optimum measurement time?

$$\int_0^{t_m} e^{-t/\tau} t^2 \, dt = \int_0^{\infty} e^{-t/\tau} t^2 \, dt - \int_{t_m}^{\infty} e^{-t/\tau} t^2 \, dt$$

$\uparrow$

$t \rightarrow t' + t_m$

$$\int_0^{t_m} e^{-t/\tau} t^2 \, dt = 2\tau^3 \left\{ 1 - e^{-b}\left[1 + b + \frac{b^2}{2}\right] \right\} = 2\tau^3 D$$

$b = \dfrac{t_m}{\tau}$

$$\mu: \quad \sigma_d = \frac{1}{\sqrt{8}} \frac{\hbar}{\tau D^{1/2} P A E^* \sqrt{N_{tot,c}}}$$

$$d: \quad \sigma_d = \frac{1}{\sqrt{2}} \frac{\hbar}{\tau D^{1/2} P A E^* \sqrt{N_{tot,c}}}$$

1-par. fit

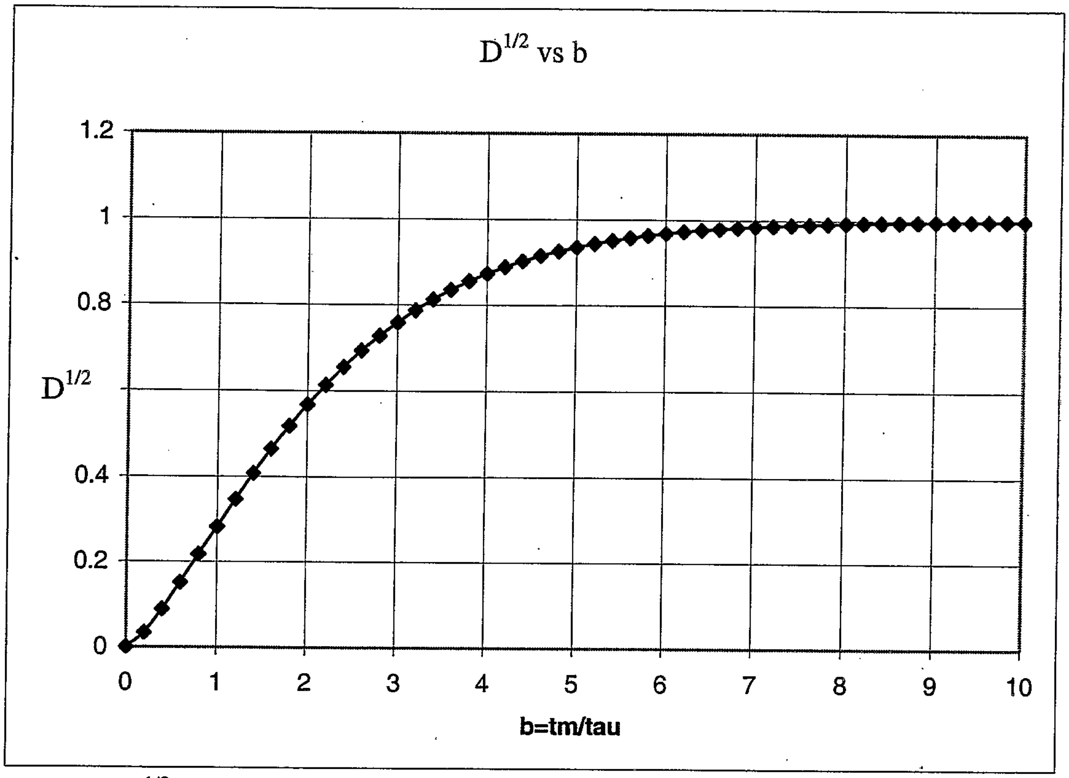


Figure 1. $D^{1/2}$ vs b using the analytical function (see text).

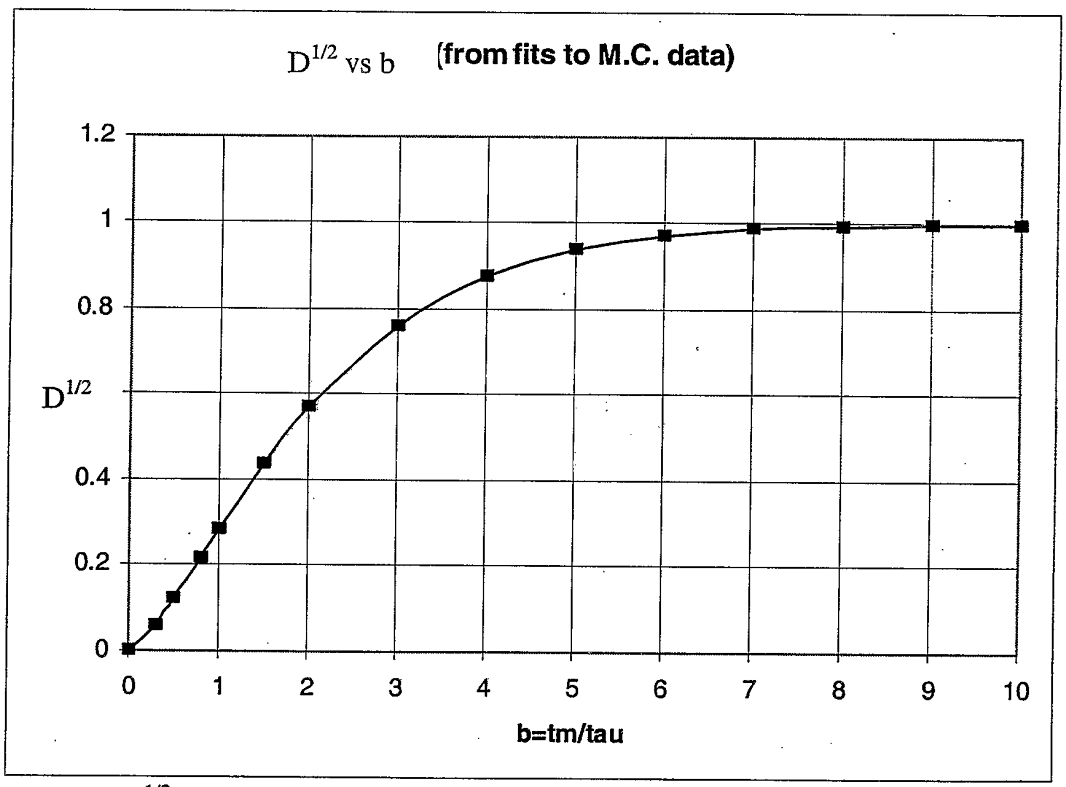
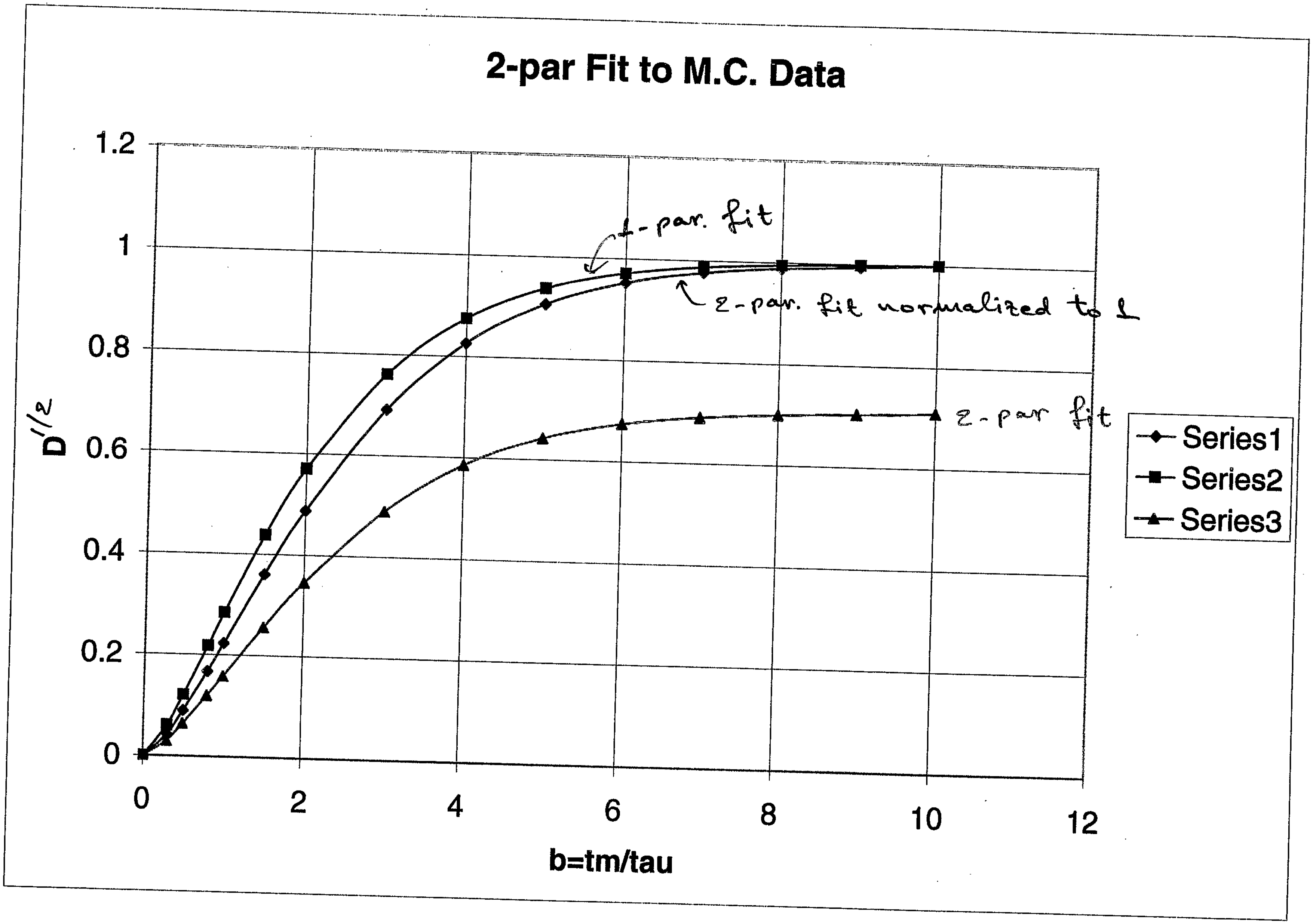


Figure 2. $D^{1/2}$ vs b from one parameter fits to M.C. data.


2-par Fit to M.C. Data
1.2
1
0.8
0.6
0.4
0.2
0
$D^{1/2}$
0
2
4
6
8
10
12
b=tm/tau
Series1
Series2
Series3
1-par. fit
2-par. fit normalized to 1
2-par fit

what happens w/ 2-par. fit?

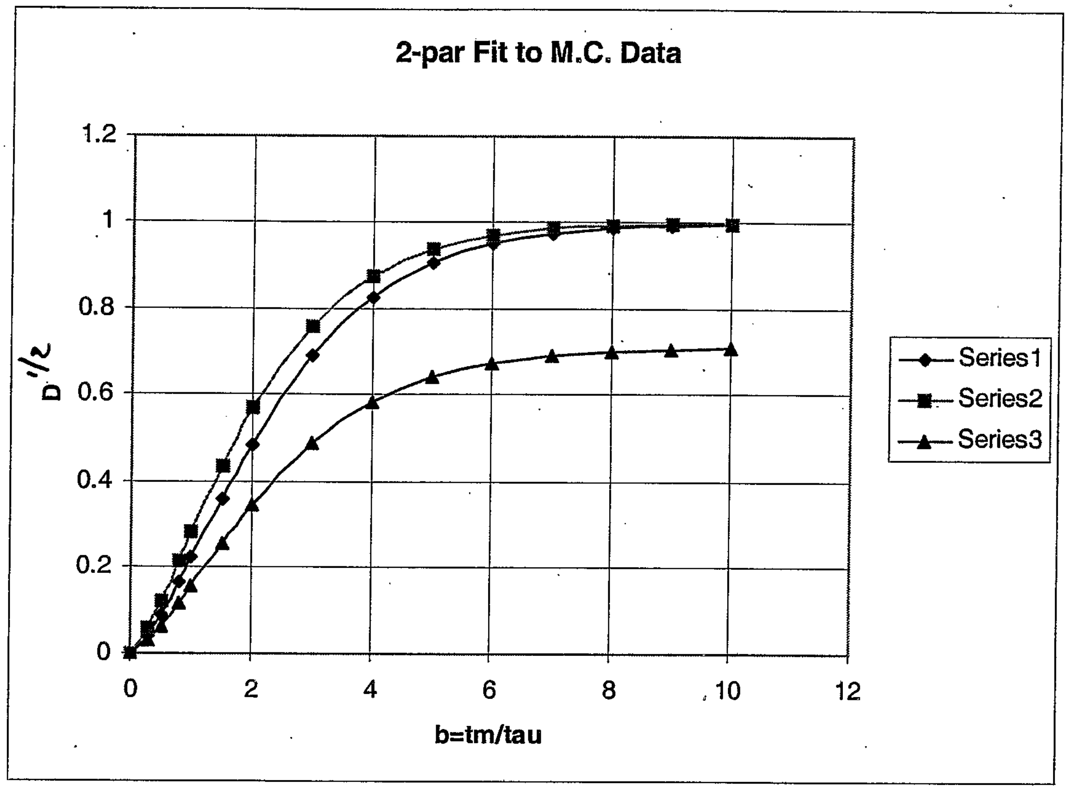


Figure 3. Series 3 corresponds to two-parameter MINUIT fits on M.C. data. For large measurement times the loss of statistical sensitivity is a factor of $\sqrt{2}$. Series 1 is the same graph as series 3 only normalized to 1 at 10 lifetimes for comparison with the 1 parameter fit behavior shown as series 2. The loss of sensitivity is somewhat larger than $\sqrt{2}$ for measuring times less than 10 lifetimes.

Case IV: Finite Measurement Time and Finite Polarization Lifetime.

The combination of the above cases II and III, i.e. combining equations (12), (13), (17) and (18) we get:

$$\boxed{\sigma_d = \frac{1}{\sqrt{8}} \frac{\hbar}{\tau\left(\frac{\tau_p}{\tau_p + 2\tau}\right)^{3/2} D_x^{1/2} P_0 A E^* \sqrt{N_{tot,c}}}} \qquad 20)$$

for the muons and

$$\boxed{\sigma_d = \frac{1}{\sqrt{2}} \frac{\hbar}{\tau\left(\frac{\tau_p}{\tau_p + 2\tau}\right)^{3/2} D_x^{1/2} P_0 A E^* \sqrt{N_{tot,c}}}} \qquad 21)$$

for the deuterons for one parameter fit. The parameter D_x is given by

Combining <u>all</u> and using N_{cycles}:

$$\frac{1}{\sigma_T^2} = \frac{1}{\sigma_{d1}^2} + \frac{1}{\sigma_{d2}^2} + \cdots + \frac{1}{\sigma_{dN}^2} = \frac{N_{cycles}}{\sigma_d^2}$$

$$N_{cycles} = \frac{T_{tot}}{t_m} \quad , \quad w/ \; T_{tot} = 10^7 \text{ s}$$

$$\Rightarrow \sigma_T = \frac{\sigma_d}{\sqrt{N_{cycles}}} = \frac{\sigma_d}{\sqrt{T_{tot}/t_m}}$$

$\Downarrow$ a little algebra

μ:
$$\sigma_T = \frac{1}{\sqrt{8}} \frac{(1+2\kappa)^{3/2} \hbar \sqrt{b}}{D_x^{1/2} P_0 A E^* \sqrt{N_{tot,c} T_{ot} \, \tau}}$$

$$D_x = 1 - e^{-b_m}\left[1 + b_m + \frac{b_m^2}{2}\right]$$

$$b_m = b(1+2\kappa)$$

$$b = \frac{t_m}{\tau} \, , \quad \kappa = \frac{\tau}{\tau_p}$$

optimum (broad) $\kappa = \frac{1}{2}$, i.e. beam lifetime τ is half of τ_p.

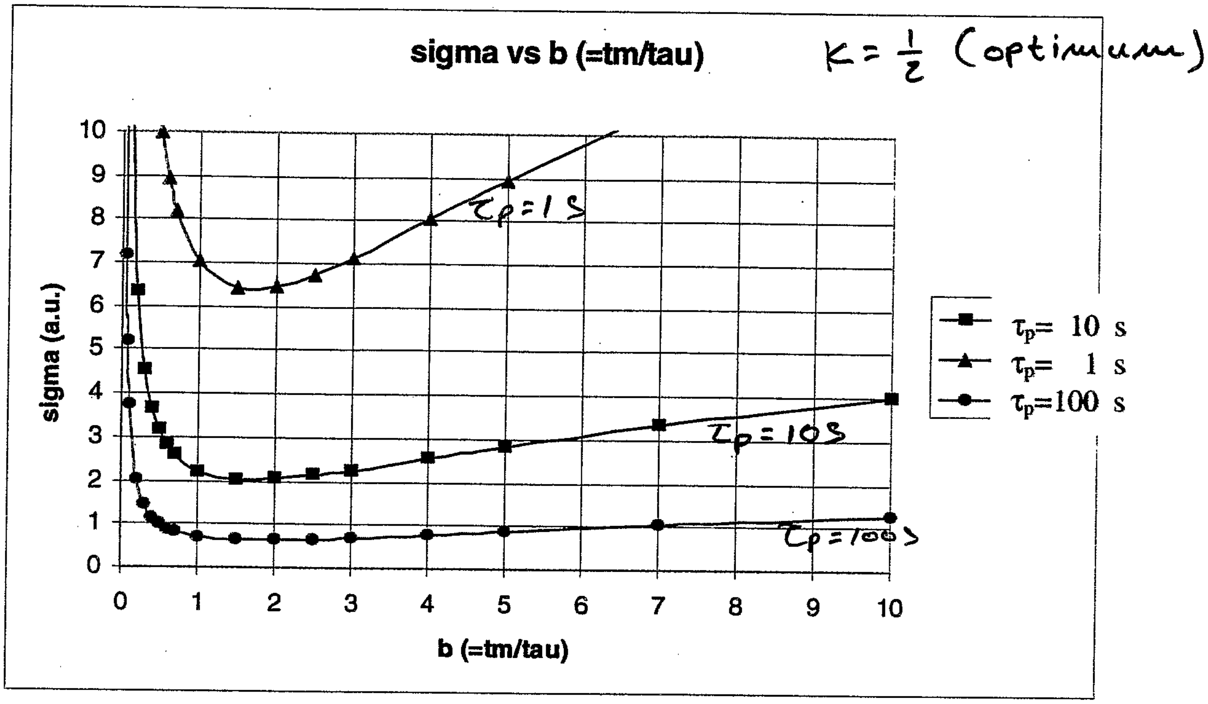


Figure 4. The statistical error (sigma) as a function of b for $k = \frac{\tau}{\tau_p} = \frac{1}{2}$. The minimum is around b=2, where the measuring time is equal to the polarization lifetime. One also can see that going from 1 s to 100 s polarization lifetime there is a gain of a factor of 10 in statistical sensitivity as expected.

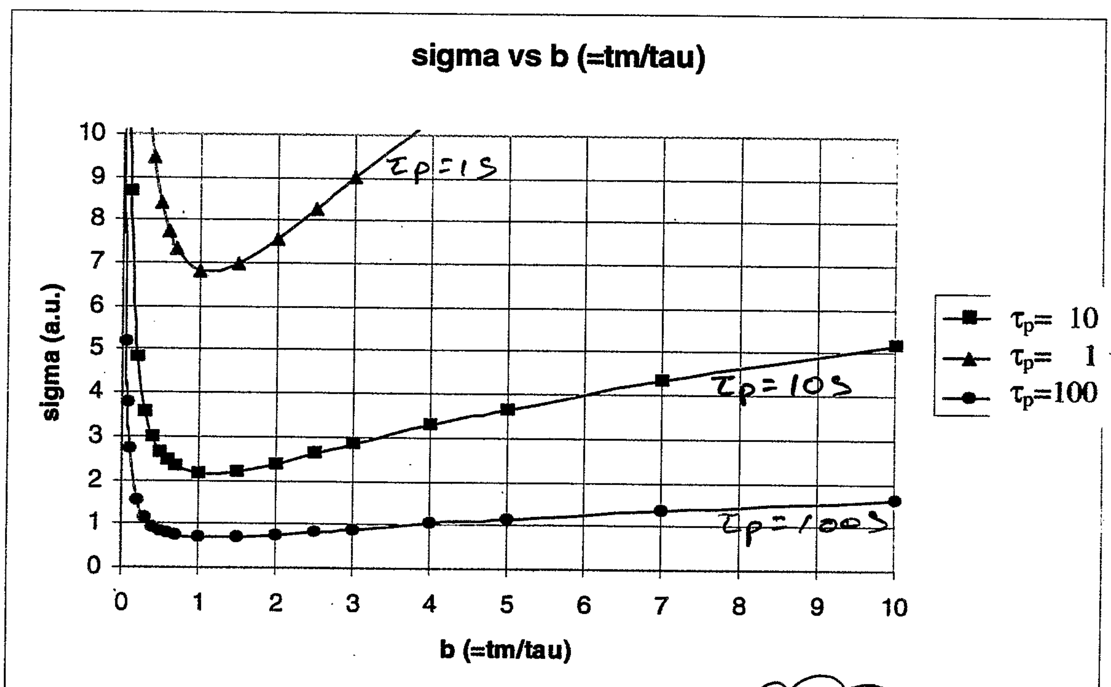


Figure 5. The statistical error (sigma) as a function of b for $k = \frac{\tau}{\tau_p} = 1$. The minima are

slightly higher than those shown in figure 4. The minimum is around $b=1.2$, where the measuring time is about equal to the polarization lifetime.

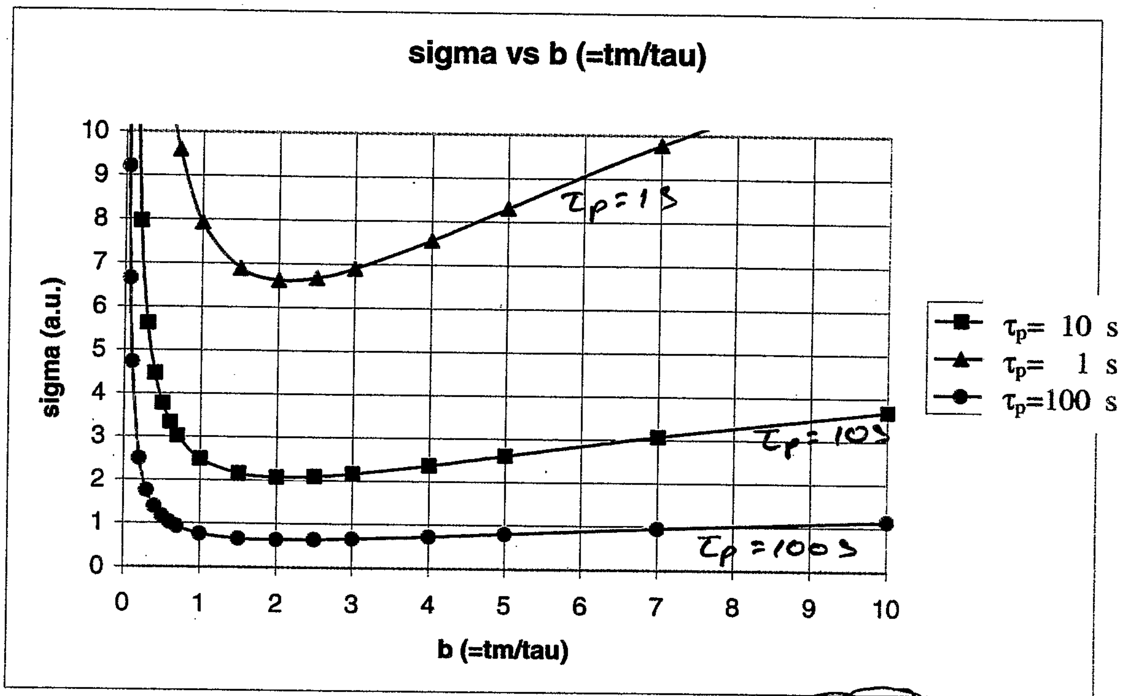


Figure 6. The statistical error (sigma) as a function of b for $k=\frac{\tau}{\tau_p}=0.3$. The minima are slightly higher than those shown in figure 4. The minimum is around $b=2.2$, where the measuring time is about equal to the 2/3 of the polarization lifetime.

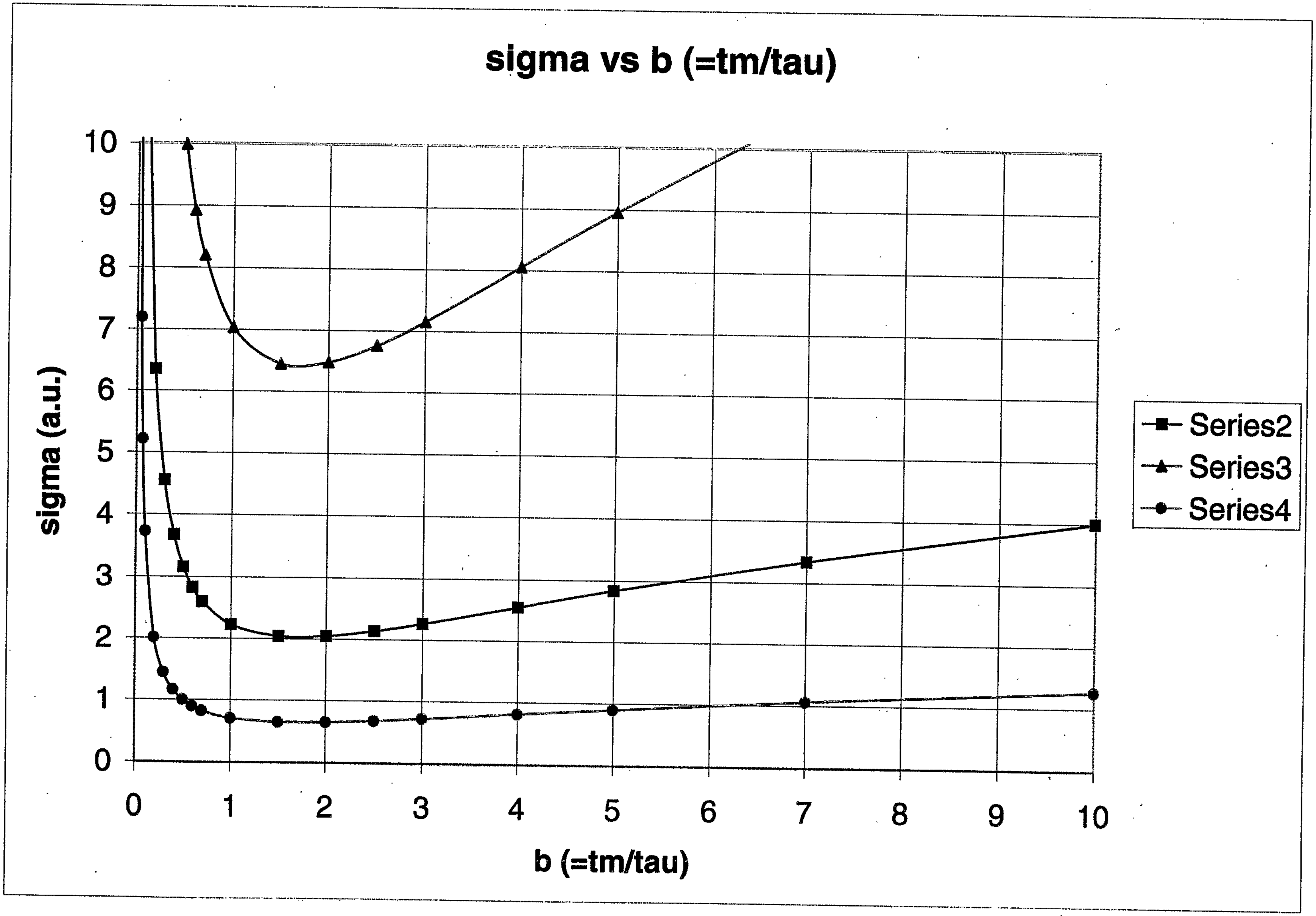
Simplifying the Equations

1) Muon Case

Equation (26) is a very general one for the one parameter fit. Since it is expected that the machine cycle is going to be much longer than the muon lifetime it is expected that the measuring time is also going to be much longer than the muon (beam) lifetime. Also it is expected that the polarization lifetime is going to be much longer than the muon (beam) lifetime. The equation (27) becomes:

$$\boxed{\sigma_T = \frac{1}{\sqrt{8}} \frac{\hbar}{\tau P_0 A E^* \sqrt{N_{tot,c} N_{cycles}}}} \qquad 28)$$

where $N_{tot,c}$ is the total number of muons detected per cycle and N_{cycles} is the total number of cycles. $N_{tot,c} \times N_{cycles} = N_{tot}$, is the total number of detected particles over the course of the experiment. For the two-parameter fit there is an increase in the error by a factor of $\sqrt{2}$ and the equation becomes:



sigma vs b (=tm/tau)
sigma (a.u.)
b (=tm/tau)
0
1
2
3
4
5
6
7
8
9
10
Series2
Series3
Series4

Finally!

μ: $$\sigma_T = \frac{1}{2} \frac{\hbar}{\tau P_0 A E^* \sqrt{N_{tot}}}$$ 2-par. fit

$\sqrt{2}$ higher than before

d: $$\sigma_T = 6.5 \frac{\hbar}{P_0 A E^* \sqrt{N_{tot,c} \cdot T_{tot} \cdot \tau_p}}$$ 2-par. fit

a factor of 9 higher than before...

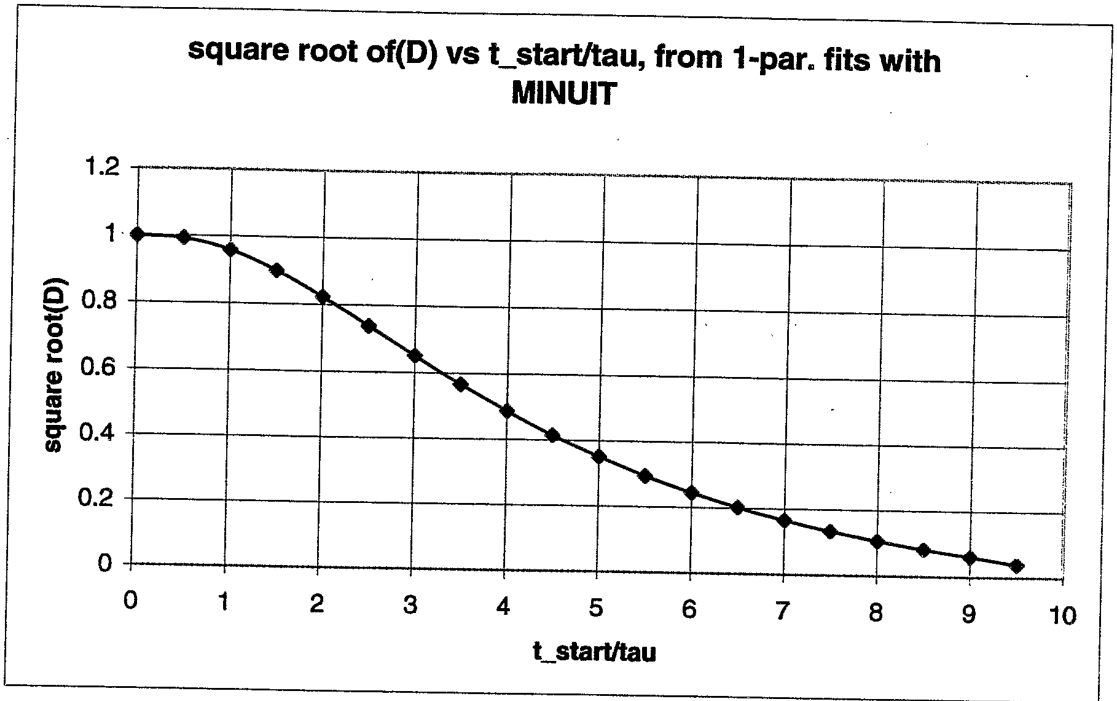


Figure 8. $D_x^{1/2}$ versus the ratio of t_s/τ from 1-parameter fits with MINUIT to M.C. data. The agreement with the prediction (figure 7) is very good.

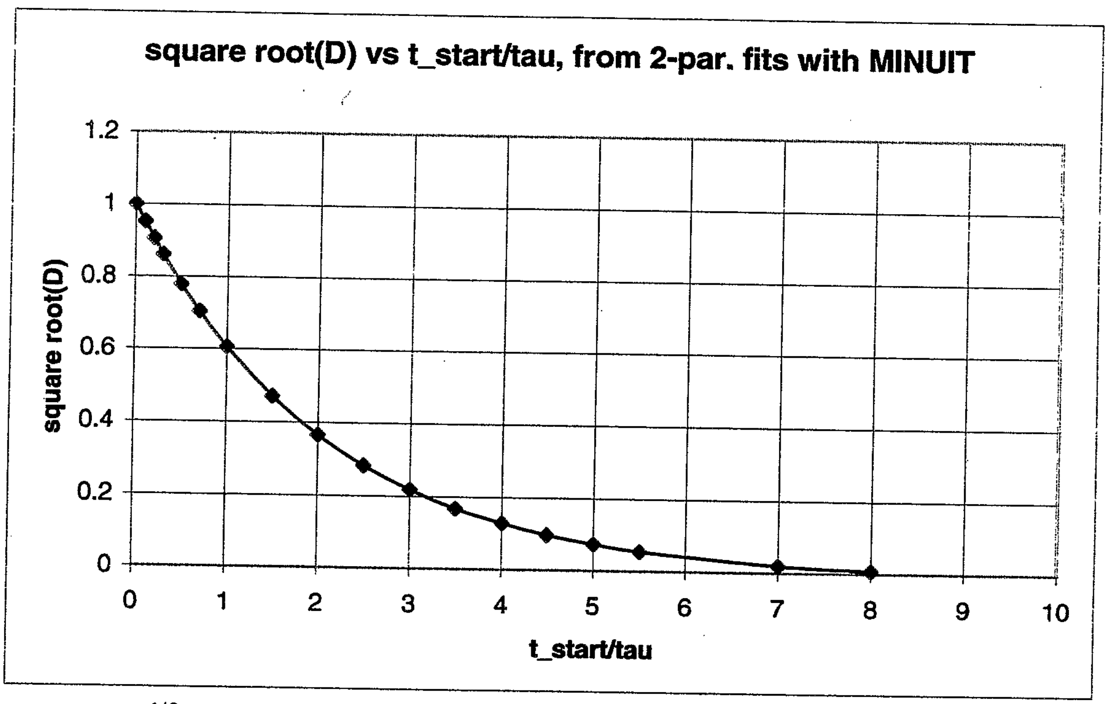


Figure 9. $D_x^{1/2}$ versus the ratio of t_s/τ from 2-parameter fits with MINUIT to M.C. data. The loss of statistical sensitivity is much faster now, compared to 1-parameter fit.

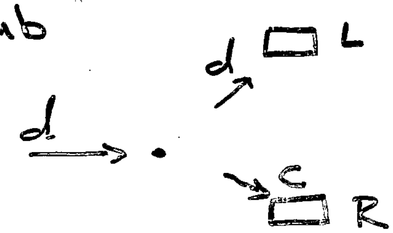
Can we take the rates @ the AGS tunnel?

YKS
9/12/03

Beam intensity: $12 \times 10^{11}\, d / 10\, s$

Loss factor: $f = 6 \times 10^{-4}$ (Coulomb scatt.)

useful cross section: 40 mb



detect d, c in coincidence

$$\sigma_d \simeq 6.5 \frac{\hbar a \gamma^2 (1 + a\beta^2\gamma^2)}{\sqrt{\tau_p}\, E_R \left[1 + a\gamma^2(1 + a\beta^2\gamma^2)\right] A P_0 \sqrt{N f T_{tot}}}$$

$E_R \simeq 4\, MV/m$

$A \simeq 0.35$

$P_0 \simeq 0.56$

$N \simeq 12 \times 10^{11}$

$T_{tot} = 10^7\, s$

$\tau_p \simeq 10\, s$

$\gamma^2 \simeq 2$

$$\Rightarrow \boxed{\sigma_d \simeq 8 \times 10^{-28}\, e \cdot cm}$$

Rates: $1.5 \times 10^{8}/s$

100 polarimeters

$R = 1.5 \times 10^{6}/s$

Time resol.: $\Delta t \simeq 10 s$

$P_i = 2 \Delta t R \simeq 3\%$

Polarimeter segm. by 10

$\rightarrow P_i = 0.3\%$

L/R accept. diff. 10%, 100 polarimeters

$\boxed{A(P_i) = 3 \times 10^{-5}}$ w/ time coincidence

Signal:

$$\frac{d\bar{s}}{dt} = \bar{d} \times \bar{E}^* \Rightarrow \bar{\omega} = \frac{\bar{d} \times \bar{E}^*}{\hbar} \simeq 3 \times 10^{-7}\ \text{rad/s}$$

$\rightarrow 3\ \mu\text{rad} / 10\ \text{s}$

where $\bar{E}^* = \bar{E}_R + \bar{v} \times \bar{B}$

$$d = 10^{-27}\ e \cdot \text{cm}$$

Asymmetry due to EDM (early to late)

$$\Theta \times A \times P_0 = 3\ \mu\text{rad} \times 0.35 \times 0.56 \simeq 6 \times 10^{-7}$$

50 × smaller than the asymm. caused by pileup when using the time coincidence.

- Possible resolution: Beam polarization in the 12 bunches

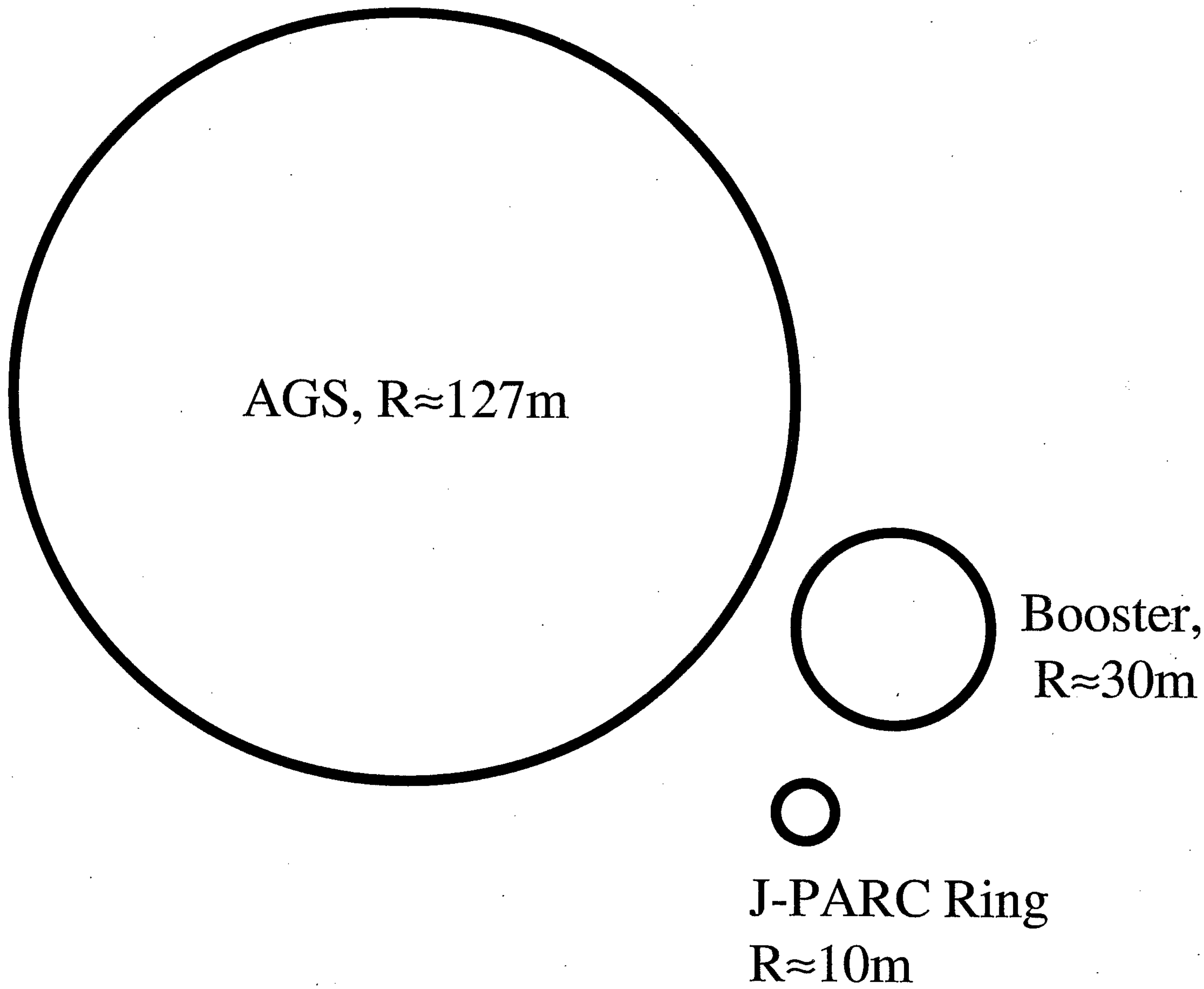
$\rightarrow \leftarrow \rightarrow \leftarrow \rightarrow \leftarrow \rightarrow \leftarrow \rightarrow \leftarrow \rightarrow \leftarrow$

Subtract to 2%.

- Integrate the current and only monitor (time coinc.) a fraction of the breakups (E.S.)

  Asymmetry: 0.35 → 0.15 could improve...

Possible Deuteron EDM Ring Size:



Bill Morse
9/12/03

Deuteron Quadrupole Moment

From ref. 1, the electric dipole moment is defined as:

$$d = \int z\,\rho(r,z)\,dz \qquad (1)$$

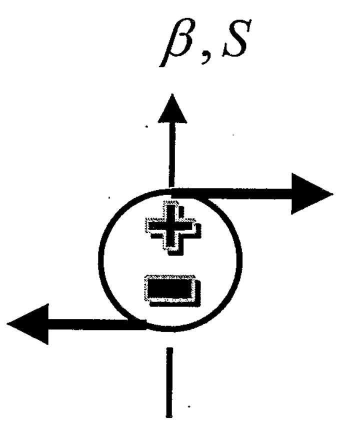
violates T,P

where we use cyclindrical coordinates with the spin pointing in the z direction, and ρ is the charge distribution. The electric quadrupole moment is defined as:

$$Q = \frac{1}{e}\int (3z^2 - r^2)\rho(r,z)d^3x \qquad (2)$$

The deuteron is a bound state of the neutron and proton with spins aligned in an S wave with a small 7% component of the $^3D_1$ state [2]. The deuteron quadrupole moment has been measured to be:

$$Q = 2.86\,mb \qquad (3)$$



$$\vec{F} = qc\vec{\beta}\times\vec{B}$$

FIGURE 1. Cartoon of a relativistic particle in a vertical magnetic field showing the torque on the spin due to an edm.

Fig. 1 shows a cartoon of a relativistic particle in a vertical magnetic field illustrating the torque on the spin due to an edm:

$$\frac{d\vec{S}}{dt} = \vec{d}\times\left(c\,\vec{\beta}\times\vec{B}\right) \qquad (4)$$

The torque causes the spin to precess vertically. Fig. 2 shows a cartoon of a relativistic particle in a vertical magnetic field illustrating the torque on the spin due to an electric quadrupole moment:

$$\frac{dS}{dt} = Qc\beta\frac{\partial B}{\partial z}\cos(2\varphi) \qquad \hat{\beta}\bullet\hat{S} = \cos\varphi \qquad (5)$$

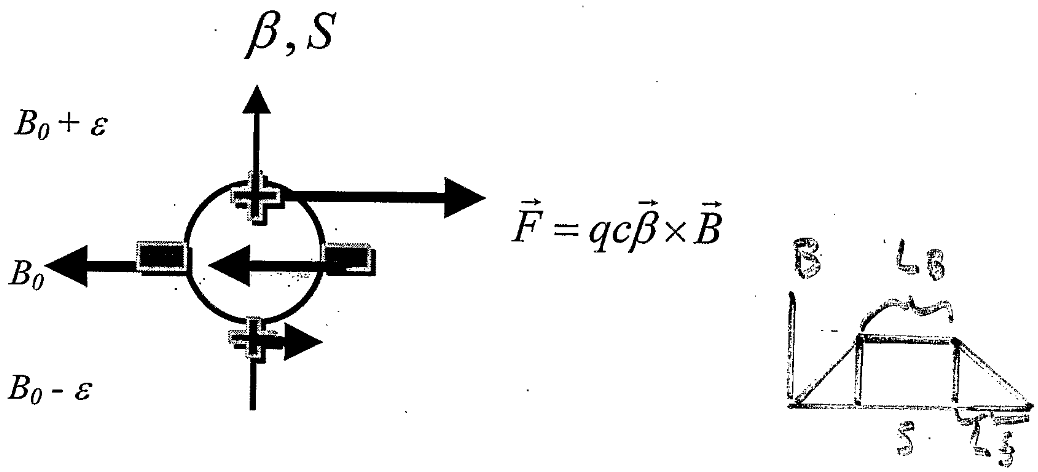


FIGURE 2. Cartoon of a relativistic particle in a longitudinally changing magnetic field showing the torque on the spin due to an electric quadrupole moment.

Fig. 2 shows the case when the magnetic field is increasing along the direction of travel, ie. the deuteron is entering a dipole magnet. The torque direction is the same as for an edm. If the spin is frozen in the forward direction, there would be no error due to the quadruple moment as the torque direction reverses when the deuteron leaves the magnet. However, if the g-2 precession is $\pi/2$ as the deuteron passes through the magnet, then the ΔS_y would accumulate; see equ. 5. The change in the vertical component of the spin after passing through a magnet with magnetic length L_B and fringe field $dB/dz = B_0/L_f$ is:

$$\Delta S_y = dB_0 c\beta\frac{L_B}{c\beta} = dB_0 L_B \quad (6)$$

$$\Delta S_y = Qc\beta\frac{B_0}{L_f}\frac{L_f}{c\beta}\Delta\cos(2\varphi) = 2QB_0\sin(2\varphi)\Delta\varphi \quad (7)$$

$\frac{dB}{ds} = \frac{B}{L_f}$

from the electric dipole and quadrupole moments respectively. The ratio is:

$$R = \frac{2Q\sin(2\varphi)\Delta\varphi}{dL_B} \quad (8)$$

For the JPARC lattice, $L_B = 2.62$m, and our goal is to limit $\Delta\varphi$ to $10^{-\cancel{7}\,6}$ radians, ie. ± 1 radian after passing through ~~ten~~ 1 million times. Then

$$R < \frac{2(2.86\times10^{-27}\,e-cm^2)10^{-\cancel{7}\,6}}{d\,(262cm)} \qquad (8)$$

Setting $R < 10\%$ and solving for d gives $\approx 10^{-3\cancel{3}\,4}$ e-cm, as a level where the quadrupole moment is still an acceptable systematic error. Of course, from equ. 5, dS/dt varies as $\cos(2\phi)$, not $\cos\phi$, so by fitting the angular dependence, the systematic error could be even less. Therefore, it does not represent an important systematic error.

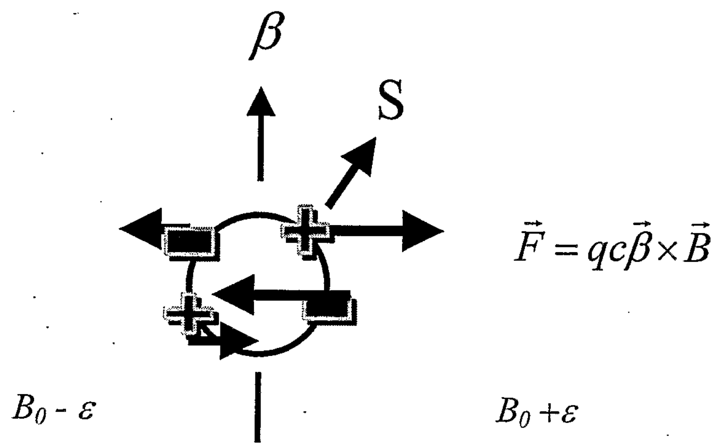


FIGURE 3. Cartoon of a relativistic particle in a radially changing magnetic field showing the torque on the spin due to an electric quadrupole moment.

Fig. 3 shows the case for a radially changing magnetic field. The ratio of background from Q to signal from d would be:

$$R = \frac{Q(\partial B/\partial r)}{dB_0} = \frac{Qn}{dR_0}$$

$n \equiv \frac{R}{B}\frac{\partial B}{\partial r}$

Setting R = 10%, gives d = 10^{-30} e-cm.

References

1. J. D. Jackson, Classical Electrodynamics.

2. I. B. Khriplovich, Variations on the Deuteron, Nucl-th/0007009.

1

Yuri F. Orlov
EDM Workshop,
BNL, 9/13/03

One more effect responsible for the spin depolarization (dephasing) — a correction to BM calculations.

In addition to the $\delta\omega_a/\omega_a$ term, connected with the dependence of $E_R = R_0 E_{R0}/R$ and caused by radial betatron oscillations, there are other terms caused by ~~these~~ these radial oscillations.

Bill's term:

$$\langle E_R \rangle = E_{R0} + \langle E_R (x/R_0)^2 \rangle .$$

JPARC LOI Ring off the Booster or Ring in AGS Tunnel?

Guesstimate of de-polarization time due to E/B non-cancellation for small ring with p ≈ 0.5 GeV/c and large ring with p ≈2 GeV/c (see edm note).

To cancel g-2: $E \approx aBc\beta\gamma^2$

$\delta\omega/\omega$	**R = 6.5 m**	**R = 10^2 m**
$(x/R_0)^2$ term	10^{-6}	0.03×10^{-7}
$(d\beta)^2$ term	3×10^{-7}	1×10^{-7}
E/B uniformity n = 2, 4, ...	2×10^{-7}	2×10^{-7}
Others	1×10^{-7}	1×10^{-7}
Total	10^{-6}	2.5×10^{-7}
De-polarization time constant	≈1s	≈10s

Spin motion due to edm:

$$\Delta S = d \times (E + \beta cB)\Delta T = d\beta cB(1 + a\gamma^2)\Delta T \approx d\Delta T(1 + a\gamma^2)\frac{E}{a\gamma^2}$$

Guesstimate of figure of merit for statistical sensitivity (does not include polarimeter considerations - see Yannis talk).

	p ≈ 0.5 GeV/c	**p ≈ 2 GeV/c**
ΔT	1s	10s
$a + \gamma^{-2}$	0.79	0.33
$N^{0.5}$	1	3
$\Delta T \times \gamma^{-2} \times$ **$N^{0.5}$**	0.79	9.9

The spin motion due to the non-planar electric field (systematic error) is:

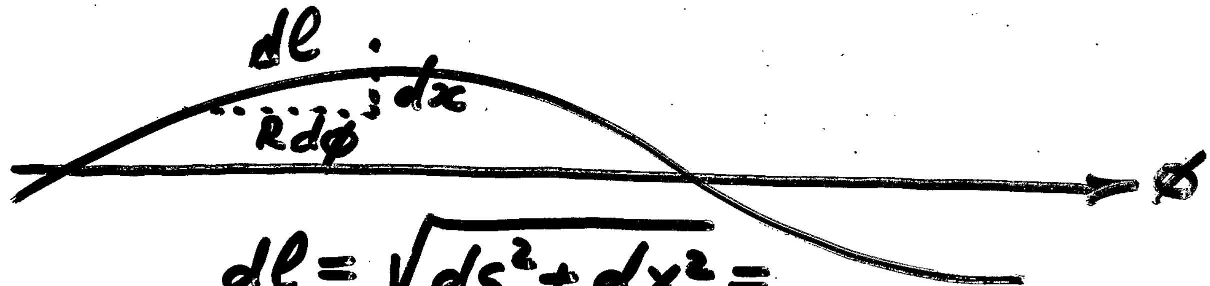
$$\frac{dS}{dt} = \mu B_R \approx \frac{\mu E \vartheta}{ac\beta\gamma^2}$$

The ratio of the spin motion from the non-planar electric field to the edm is:

$$R \approx \frac{\mu\vartheta}{d\beta}$$

The factor of β^{-1} is better by a factor of about three for the large ring.

Betatron oscillations change the length L of the orbit:



$$d\ell = \sqrt{ds^2 + dx^2} =$$
$$= ds\left(1 + \frac{1}{2}\theta_x^2\right)$$

As a result, <u>in the presence of the synchrotron RF</u> (not taken into account in my EDM Note 10), particles change their p, R, v

$$\frac{1}{N} f_{RF} = \frac{v}{L} = \text{constant!}$$

$$L = L_0\left(1 + \frac{1}{2}\left\langle\theta_x^2\right\rangle + \left\langle\frac{\Delta R}{R}\right\rangle\right)$$

$$\left\langle\frac{\Delta R}{R}\right\rangle = \alpha \frac{\Delta p}{p}$$

compaction

4

Thanks to $\frac{v}{L} = \text{const}$

$$\overline{\frac{\Delta v}{v}} = \overline{\frac{\Delta L}{L}} = \frac{1}{2}\overline{\theta_x^2} + \overline{\frac{\Delta R}{R}}$$

But

$$\overline{\frac{\Delta v}{v}} = \frac{1}{\gamma^2}\overline{\frac{\Delta p}{p}}, \quad \overline{\frac{\Delta R}{R}} = \alpha\overline{\frac{\Delta p}{p}}$$

$$\Rightarrow \left(\alpha - \frac{1}{\gamma^2}\right)\overline{\frac{\Delta p}{p}} = \frac{1}{2}\overline{\theta_x^2} = \frac{1}{4}\overline{\theta_{max}^2}$$

$$\overline{\frac{\Delta p}{p}} = \frac{\overline{\theta_{max}^2}}{4\left(\frac{1}{\gamma^2} - \alpha\right)}$$

$$\overline{\frac{\Delta v}{v}} = \frac{\overline{\theta_{max}^2}}{4\gamma^2\left(\frac{1}{\gamma^2} - \alpha\right)}$$

$$\overline{\frac{\Delta R}{R}} = \frac{\alpha\,\overline{\theta_{max}^2}}{4\left(\frac{1}{\gamma^2} - \alpha\right)}$$

And then (from eqs for x),

$$\overline{\frac{\Delta B_v}{B_v}} = \left(\frac{L_m}{L} - \alpha\right)\frac{\Delta p}{p}$$

Rates @ BNL w/ a Booster size ring - statistical sensitivity

YKS
9/12/03

10^{11} d / cycle

$P \simeq 1\ \text{GeV}/c$, $E_{kin} \simeq 250\ \text{MeV}$
$R \simeq 32\ m$
$B = 1.3\ \text{KG}$ (80% coverage)
$E \simeq 3.5\ \text{MV/m}$ (80% 〃)
$\beta \simeq 0.5$
$\gamma \simeq 1.15$
$\tau_p \simeq 3\ s$

$$\sigma_d \simeq 6.5 \frac{\hbar a \gamma^2}{\sqrt{\tau_p}\, E_R (1 + a\gamma^2) A P \sqrt{N f T_{tot}}} = \frac{2.4 \times 10^{-29}\ e \cdot cm}{A \sqrt{f}}$$

$$\Rightarrow \sigma_d = \frac{2.4 \times 10^{-29}\ e \cdot cm}{A \sqrt{f}} = 2.8 \times 10^{-27}\ e \cdot cm$$

$A = 0.35$
$f = 6 \times 10^{-4}$

$$5 \times 10^{-28}\ e \cdot cm$$

$A = 0.15$
$f = 0.1$

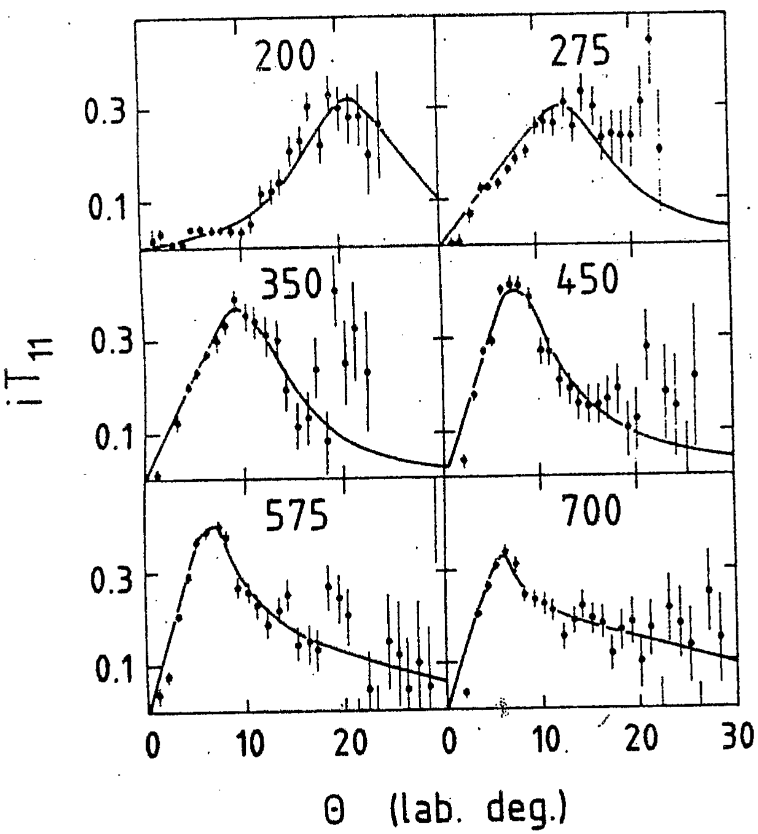


Fig. 4. The vector analyzing power iT_{11}. The dotted line corresponds to the parametrization discussed in the text.

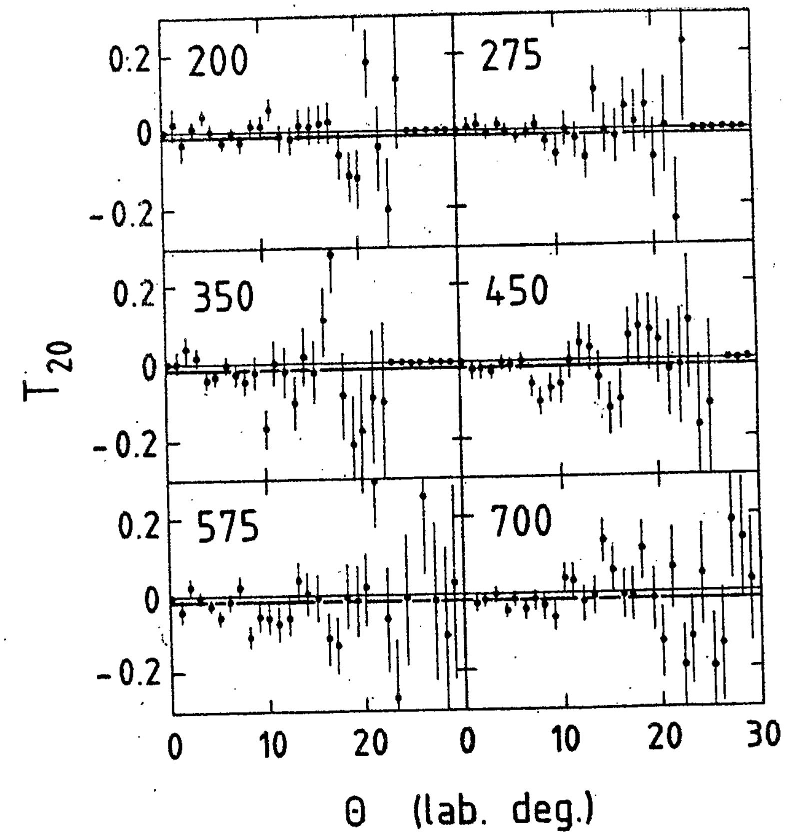


Fig. 5. The tensor analyzing power T_{20}. The dotted line corresponds to the parametrization discussed in the text.

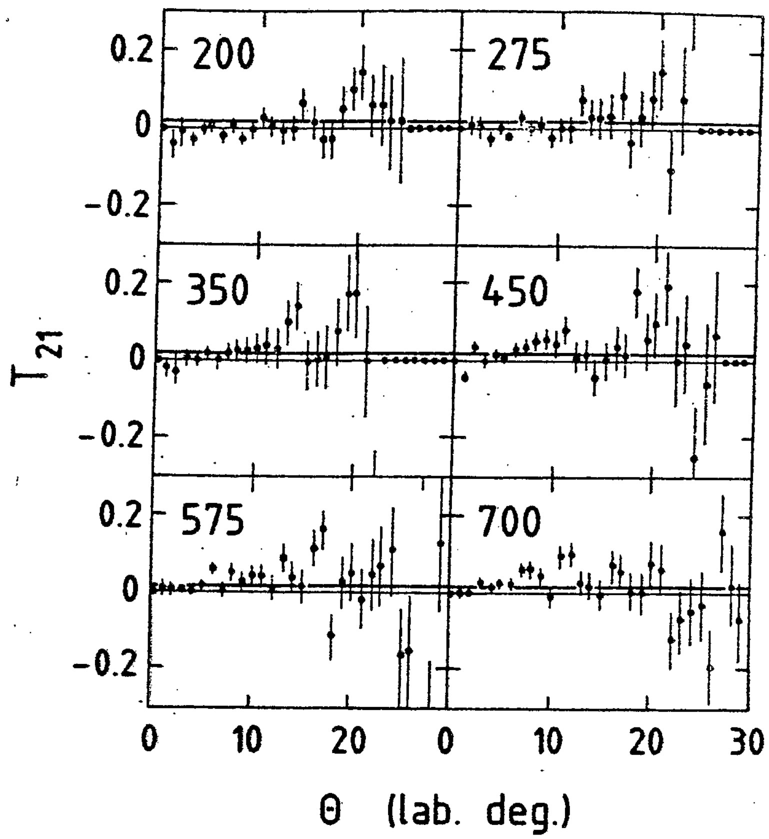


Fig. 6. The tensor analyzing power T_{21}. The dotted line corresponds to the parametrization discussed in the text.

Assuming a factor of 16 "loss" in running time due to systematics (see E.S. talk)

$$\Rightarrow \sigma_d \begin{cases} \rightarrow 1.1 \times 10^{-26}\ e\cdot cm \\ \rightarrow 2 \times 10^{-27}\ e\cdot cm \end{cases}$$

Proton sensitivity to $<E_v>$

9/12/03
YKS

$E \simeq 3.5$ MV/m , 80% coverage
$B \simeq 270$ Gauss " "
$R \simeq 32$ m (Booster size ring)

$P \simeq 0.2$ GeV/c
$\beta \simeq 0.2$

$$\frac{P(\text{Background})}{d(\text{Background})} = \frac{\mu_p / (\beta_p \gamma_p^2)}{\mu_d / (\beta_d \gamma_d^2)} = \frac{2.8/(0.2 \times 1.02^2)}{0.85/(0.5 \times 1.15^2)} \simeq 10.5$$

Statistical sensitivity:

d: $\tau_p \simeq 3$ S $\underset{(a\gamma)}{\Longrightarrow}$ 0.25 S a factor of 3.5 loss

Beam intensity $\xrightarrow{\times 10}$ (LINAC) gain back

d: 16 × for syst. due to tensor part

$\Rightarrow$ $\simeq 6{,}000$ s $\to$ 1.6 hours for 2×10^{-27} e.cm
Background check.

J. Alessi / K. Brown 2/03 Yannis idea last month. B. Morse

JPARC LOI Ring off the Booster or Ring in AGS Tunnel?

Guesstimate of de-polarization time due to E/B non-cancellation for small ring with $p \approx 0.5$ GeV/c and large ring with $p \approx 2$ GeV/c (see edm note 31). **revised.**

To cancel g-2: $E \approx aBc\beta\gamma^2$

$\delta\omega/\omega$	less expensive **R = 6.5 m**	more expensive **R = 10^2 m**
$(x/R_0)^2$ term	10^{-6}	0.03×10^{-7}
$(d\beta)^2$ term	3×10^{-7}	1×10^{-7}
E/B uniformity n = 2, 4, ...	2×10^{-7}	2×10^{-7}
Others	1×10^{-7}	1×10^{-7}
Total	10^{-6}	2.5×10^{-7}
De-polarization time constant	≈1s	≈10s

Y.O. θ_x^2
" θ_y^2

Spin motion due to edm:

$$\Delta S = d \times (E + \beta cB)\Delta T = d\beta cB(1 + a\gamma^2)\Delta T \approx d\Delta T(1 + a\gamma^2)\frac{E}{a\gamma^2}$$

Guesstimate of figure of merit for statistical sensitivity (does not include polarimeter considerations - see Yannis talk).

	p ≈ 0.5 GeV/c	**p ≈ 2 GeV/c**
$(\Delta T)^{0.5}$	1	3.2
$a + \gamma^{-2}$	0.79	0.33
$N^{0.5}$	1	3
$\Delta T^{0.5} \times a\gamma^{-2} \times N^{0.5}$	0.79	3.2

$\frac{3.2}{0.79} = 4.$

The spin motion due to the non-planar electric field (systematic error) is:

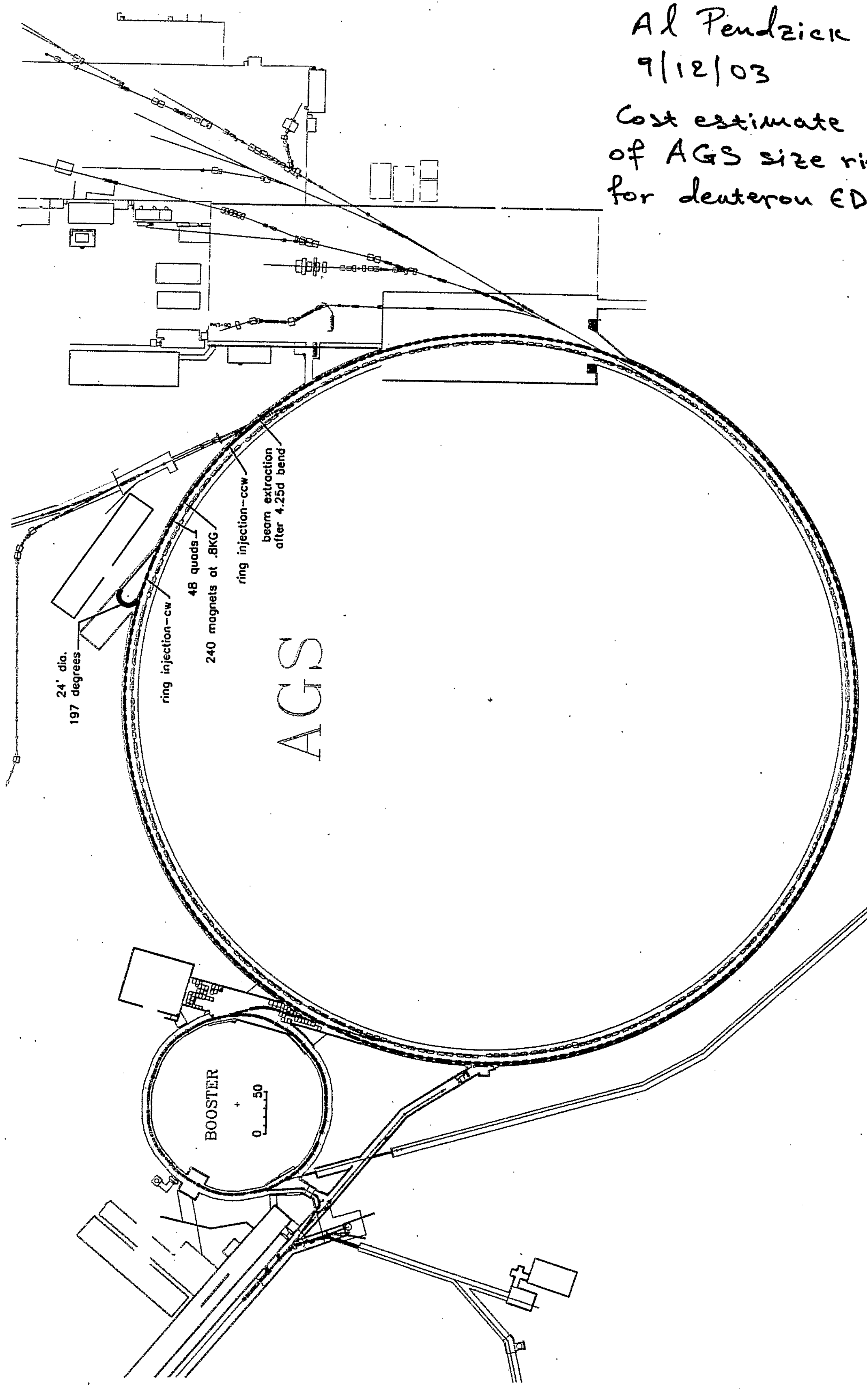
$$\frac{dS}{dt} = \mu B_R \approx \frac{\mu E \vartheta}{ac\beta\gamma^2}$$

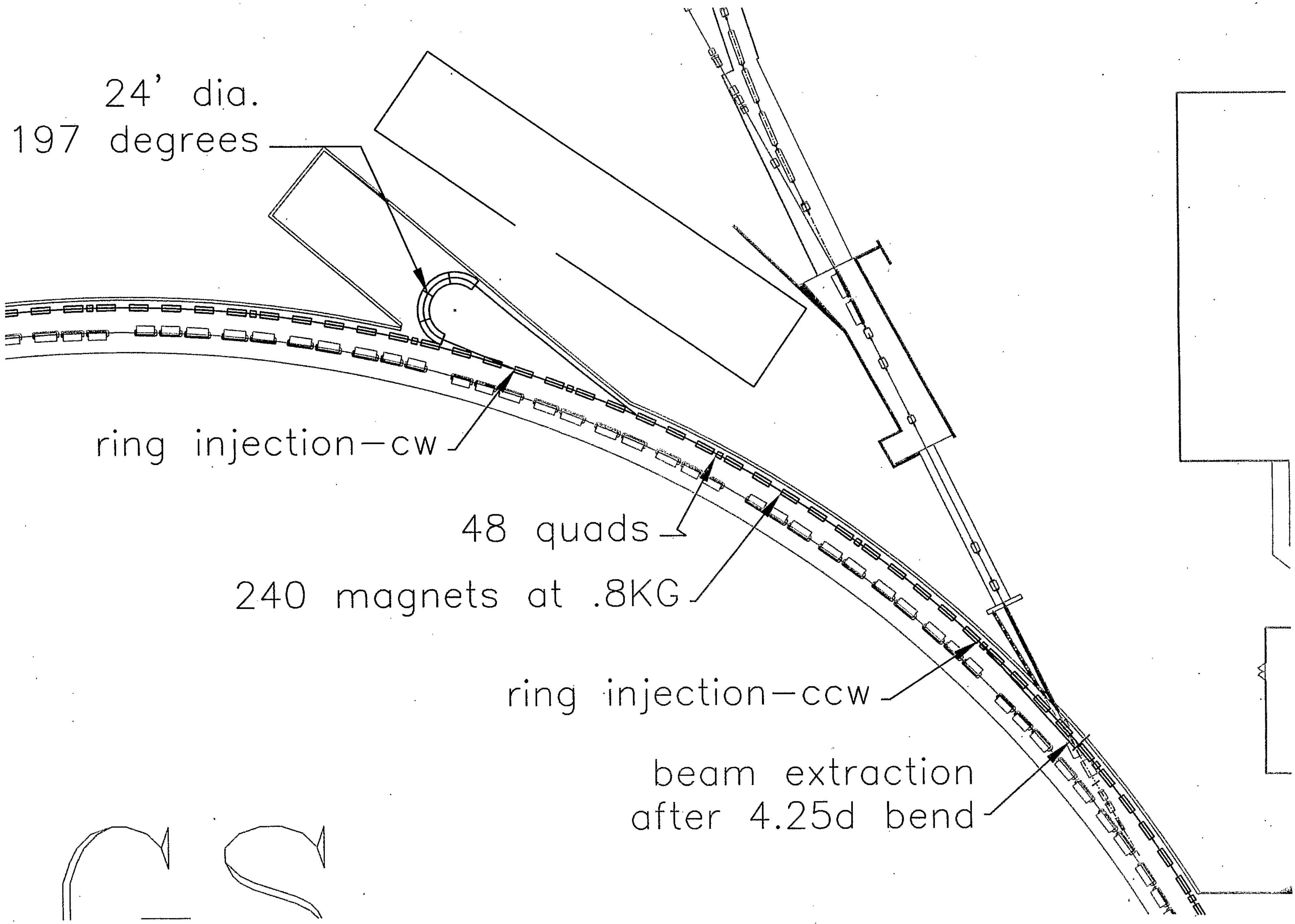
The ratio of the spin motion from the non-planar electric field to the edm is:

$$R \approx \frac{\mu\vartheta}{d\beta}$$

The factor of β^{-1} is better by a factor of about three for the large ring.

Al Pendzick
9/12/03
Cost estimate
of AGS size ring
for deuteron EDM




24' dia.
197 degrees
ring injection—cw
48 quads
240 magnets at .8KG
ring injection—ccw
beam extraction
after 4.25d bend

Cost Estimate

Main Ring

240 dipoles @ 25K	6000 K
48 Quads @ 25K	1200 K
Dipole PS @ 250K	250 K
Quad PS @ 200K	200 K
Vacuum & Vacuum Intr (700' @ 4K/ft)	2800 K
Instrumentation	1000 K
Controls	500 K
Injection Kickers & PFN	2000 K

Turn-Around

4-sector dipoles @ 200K	800 K
Power Supply	400 K
Vacuum (42' @ 4500$/ft)	189 K

INJECTION LINES

CCW	
4 diPoles @ 25K	100K
3 Power supplies @ 35K	105K
CW	
8 diPoles @ 25K	200K
5 Power supplies @ 35K	175K
VACUUM 200' @ 2500^{00}	500K
6 QUADS @ 25K	150K
6 Power supplies @ 35K	210K

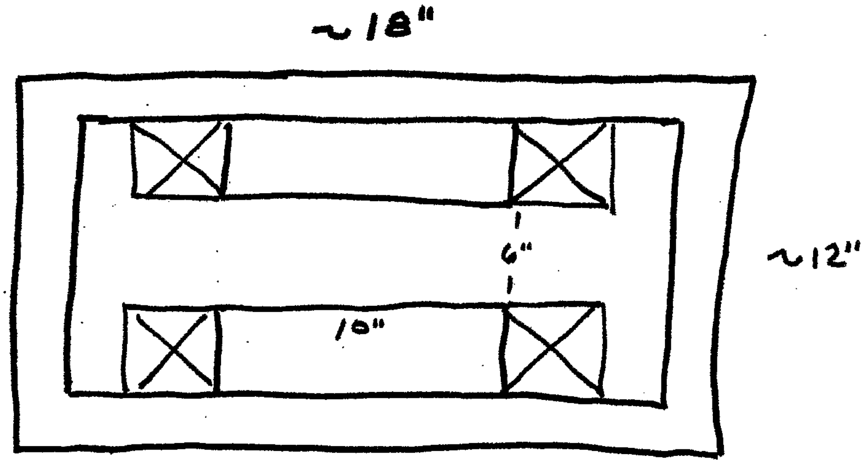
UTILITIES

Power	1000 K
WATER	850 K
TRAY - 3000' @ 10^{00}	300 K
Building 40 x 100 @ 150^{00}	600 K

Materials	19,529
LAbor @ 75%	14,647
E&D @ 15%	5,126
CONT @ 25%	9,825
TOTAl direct COSTS	49,127 K
Burdens @ 17%	8,353 K
TOTAl Project Cost	57,480 K

$\boxed{\text{SAY} \quad 57.5\ \text{M}}$

Main Ring Magnet



B_{max} = 1 Kg
I = 1000 A
V = 2.2 V
weight = 2600#

Tom Russo
9/12/03

Nominal dimensions are:
Chamber 6x12 inches
Plates 4 inches x 10 feet for each chamber

# of high voltage sections: 240/5 = 48

Each section could be 50 feet long, area is 2400 in^2
(2GeV separator is 1585 in^2)

Gradient is 200kV in 2 inches (~40kV/cm)
(2GeV separator is 75 kV/cm)

Cathode material is anodized aluminum.

Anode material is Stainless Steel.

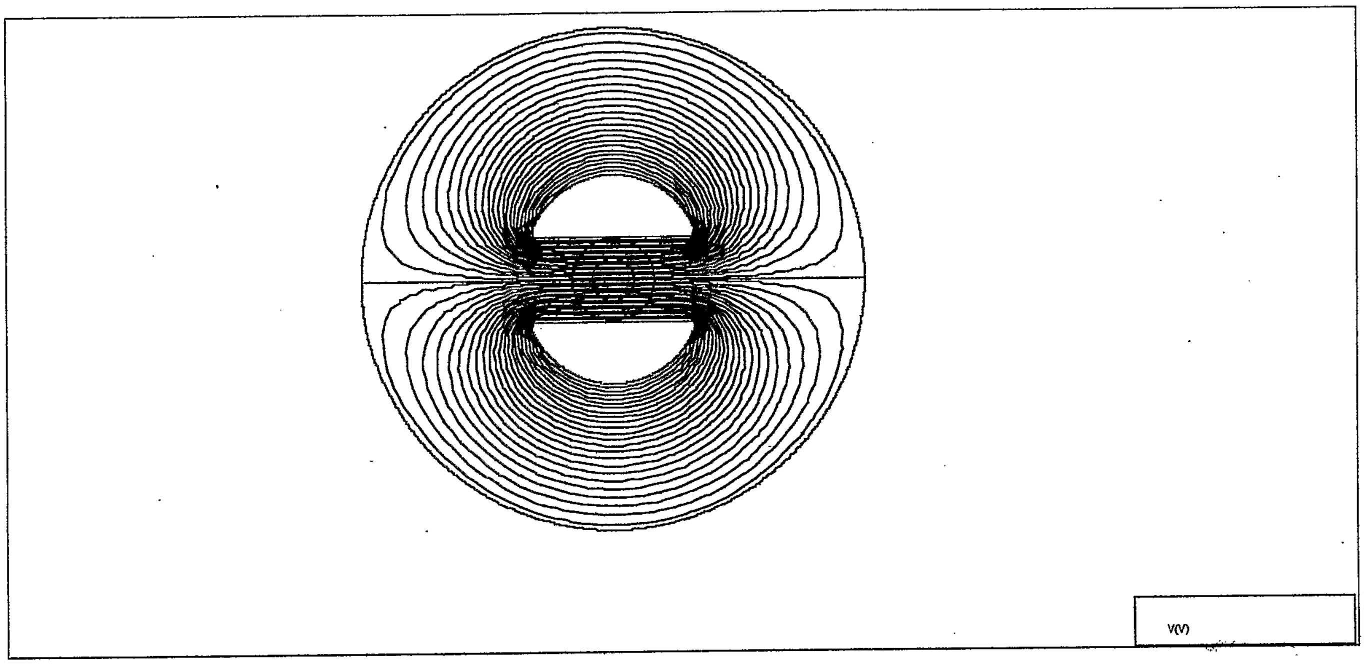
Power will utilize a "split" design. Power Section is separate from high voltage section.

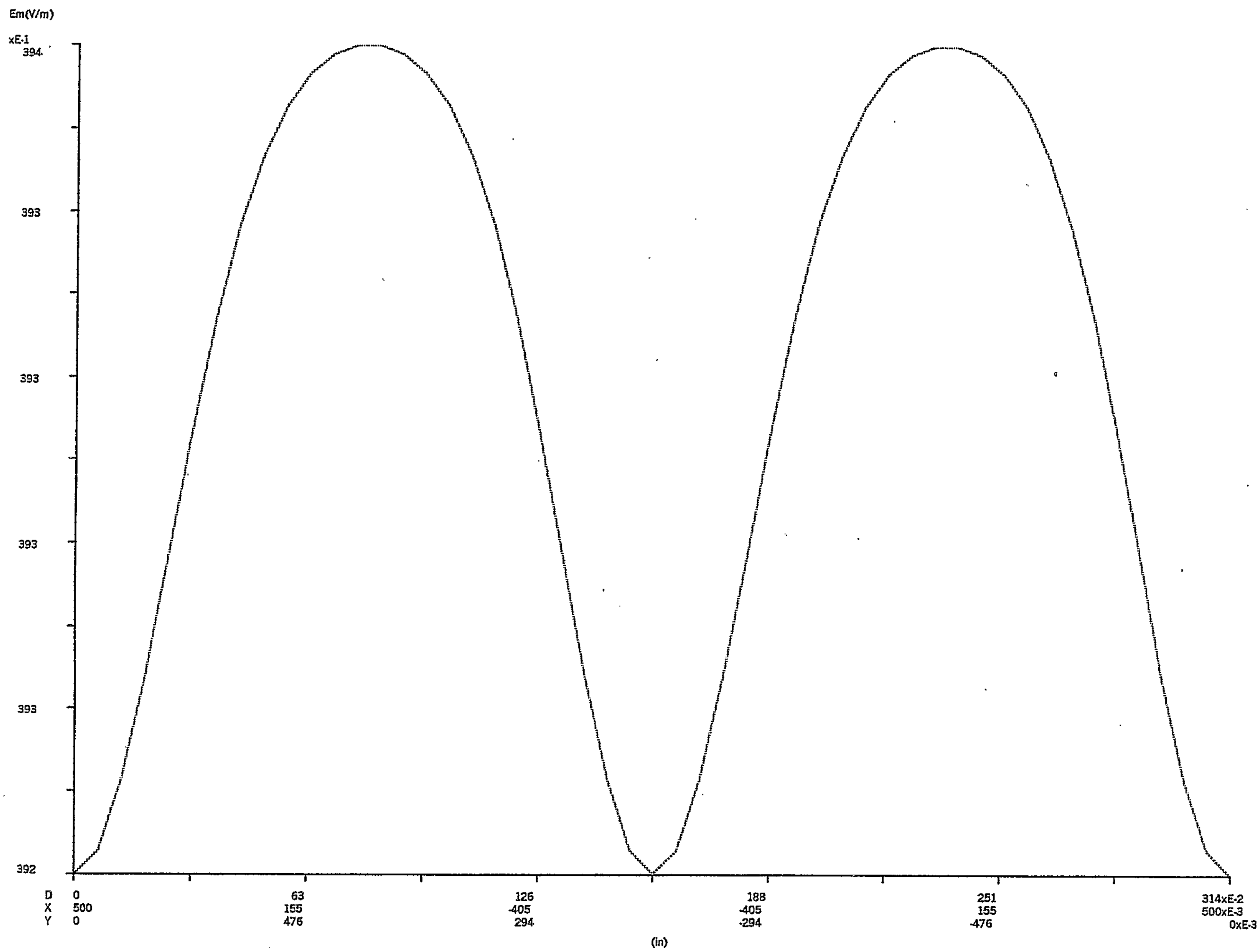
High voltage section is mounted directly to the chamber

Commercial 125kV 2 mA power supplies 96 @ $5k each = $480,000

We may need to develop a high voltage section to be oil-free and plug directly into the chamber socket.

Not clear if we need to leak gas into the chamber with this geometry.

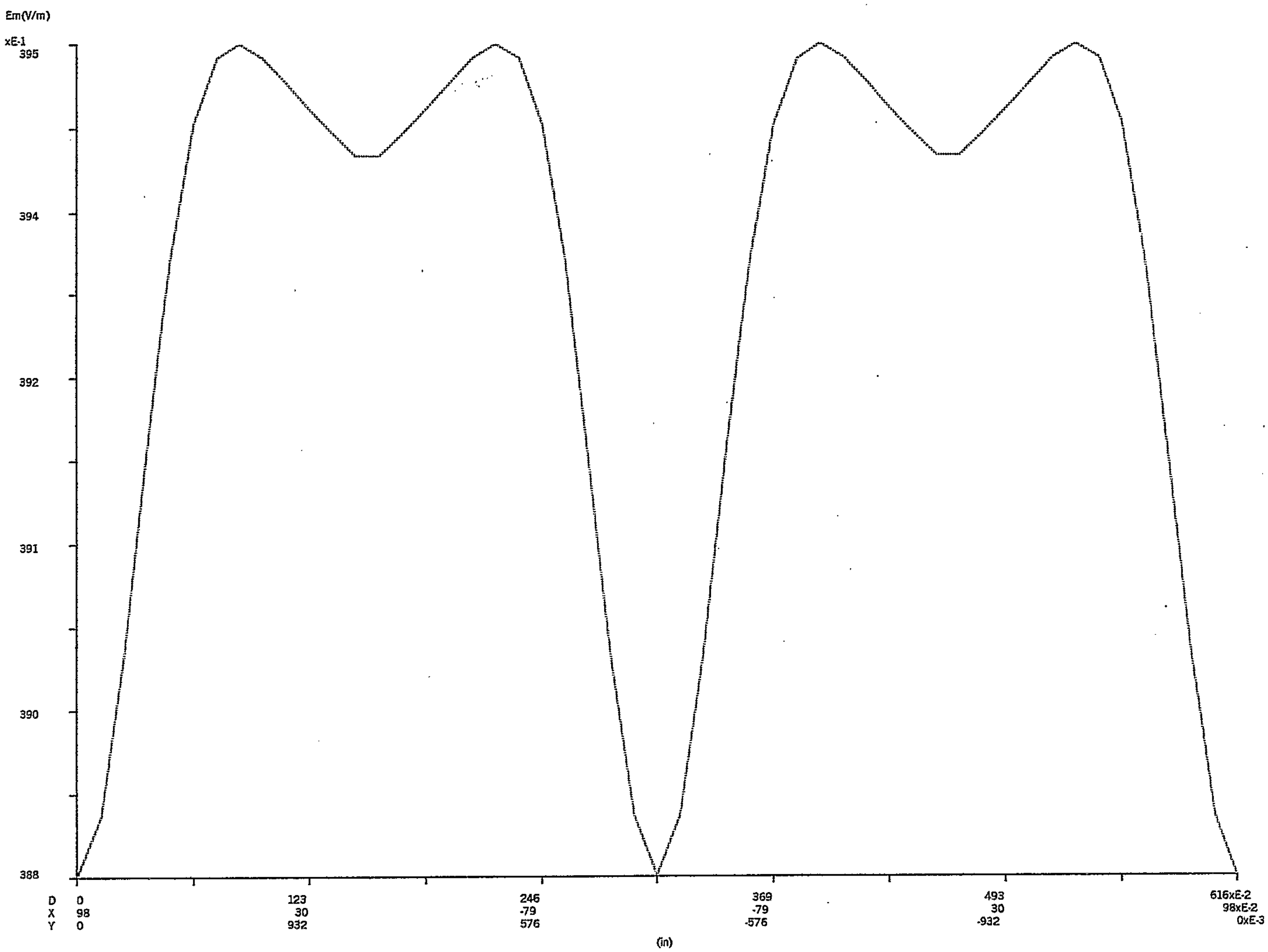

V(V)



4 inch plates 2" Gap 12" pipe

Difference ≈ 2 / 400 ≈ .5%

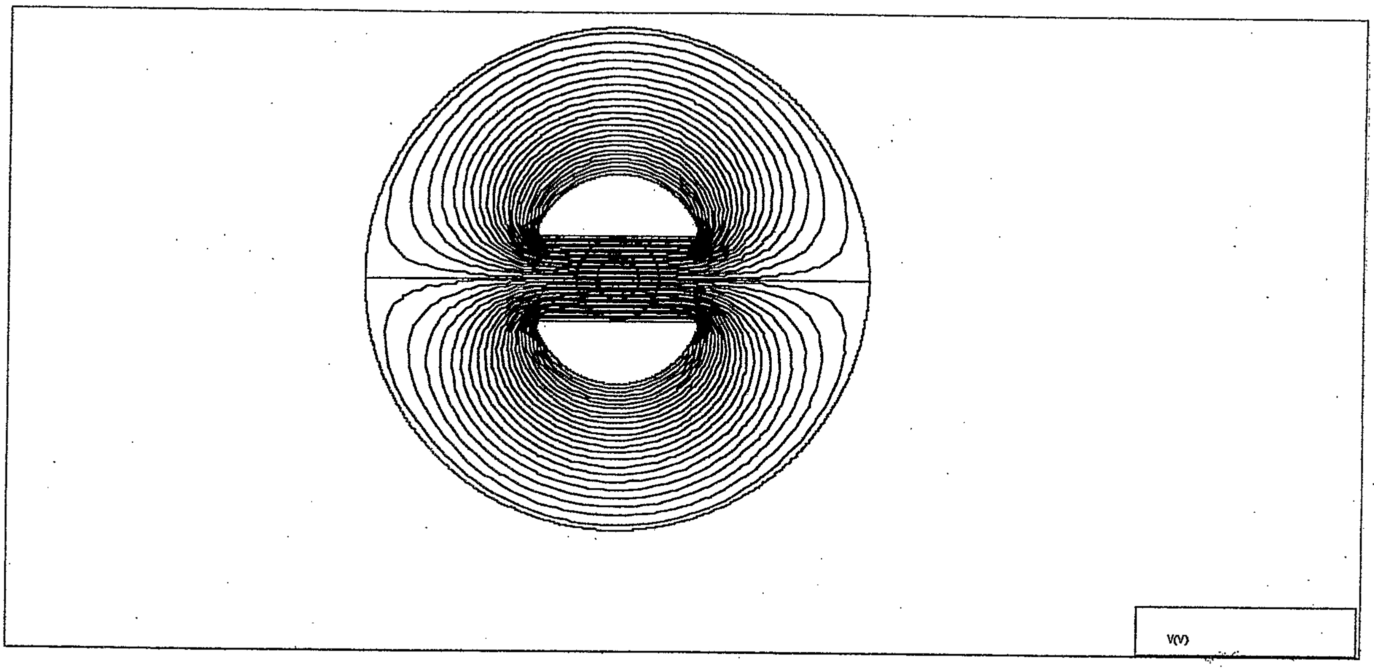
Electron field flatness on a 1 inch circle



4" plates 2" Gap 12" pipe

difference ≈ 10/400 ≈ 2.5%

Electric Field Flatness on a 2 inch circle


V(V)