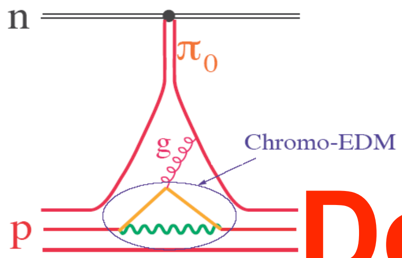


8 May 2008
BNL PAC meeting

Deuteron EDM Proposal:

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

Y. Semertzidis, BNL
for the Storage Ring EDM Collaboration

- 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.
- BNL is a natural place for this experiment.

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)

Physics Motivation of dEDM

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

- Sensitivity to new contact interaction: 3000 TeV

- Sensitivity to SUSY-type new Physics:

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

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.

Physics strength comparison

System	Current limit [e·cm]	Future goal	Neutron equivalent
Neutron	$<1.6\times10^{-26}$	$\sim10^{-28}$	10^{-28}
199Hg 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}

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

- If $\bar{\theta}$ is the source of the EDM, then
  $$d_D(\bar{\theta})/d_n(\bar{\theta}) \approx 1/3 \Rightarrow d_D \approx 3\times 10^{-29}\,\mathrm{e\cdot cm}$$

- If SUSY is the source of the EDM (isovector part of T-odd N-forces), then
  $$d_D(\bar{\theta})/d_n(\bar{\theta}) \approx 20 \Rightarrow d_D \approx 2\times 10^{-27}\,\mathrm{e\cdot cm}$$

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

Experimental Principle of dEDM

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

The Electric Dipole Moment precesses in an Electric field

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

Electric Dipole Moments in Magnetic Storage Rings

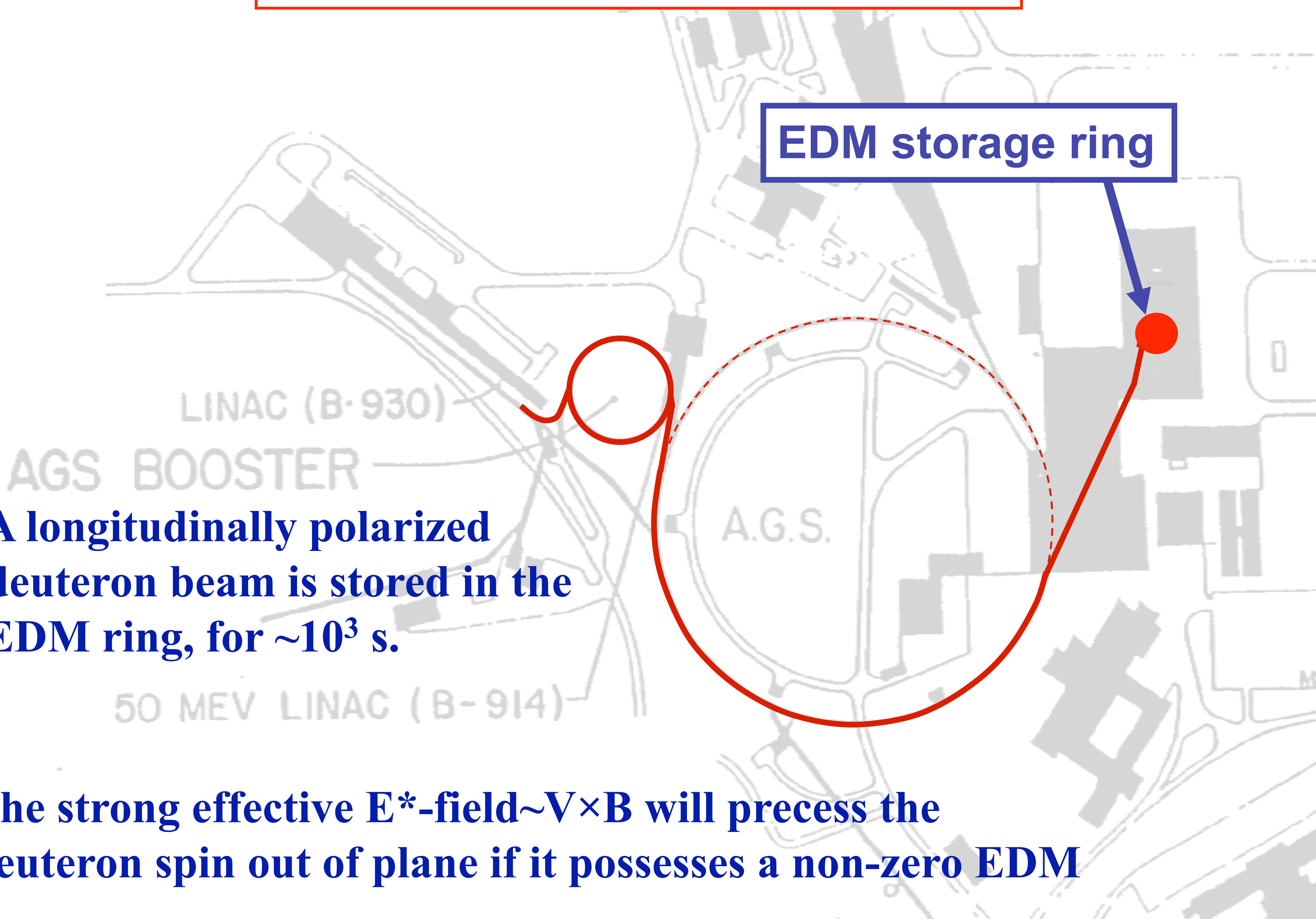
$$\frac{d\vec{s}}{dt} = \vec{d} \times \left(\vec{v} \times \vec{B}\right)$$

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

Storage ring EDM: The deuteron case

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

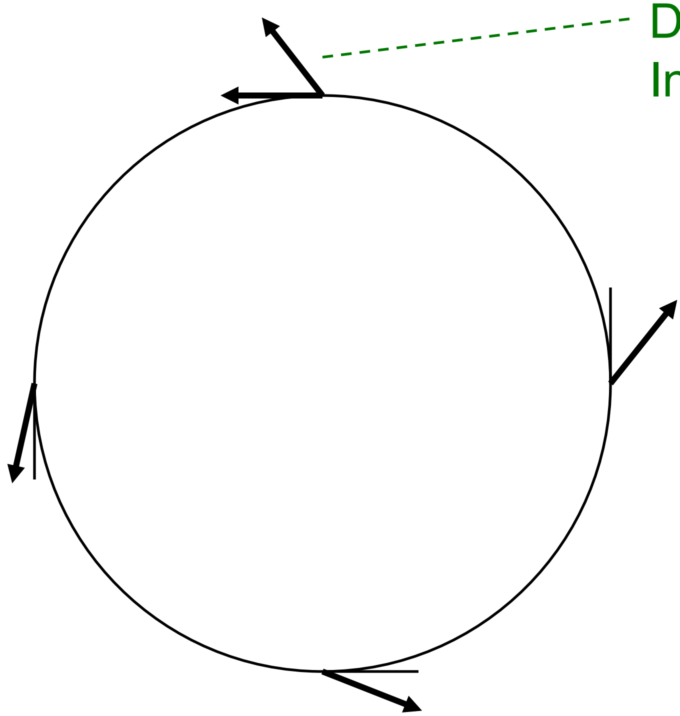
deuteron EDM search at BNL



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…

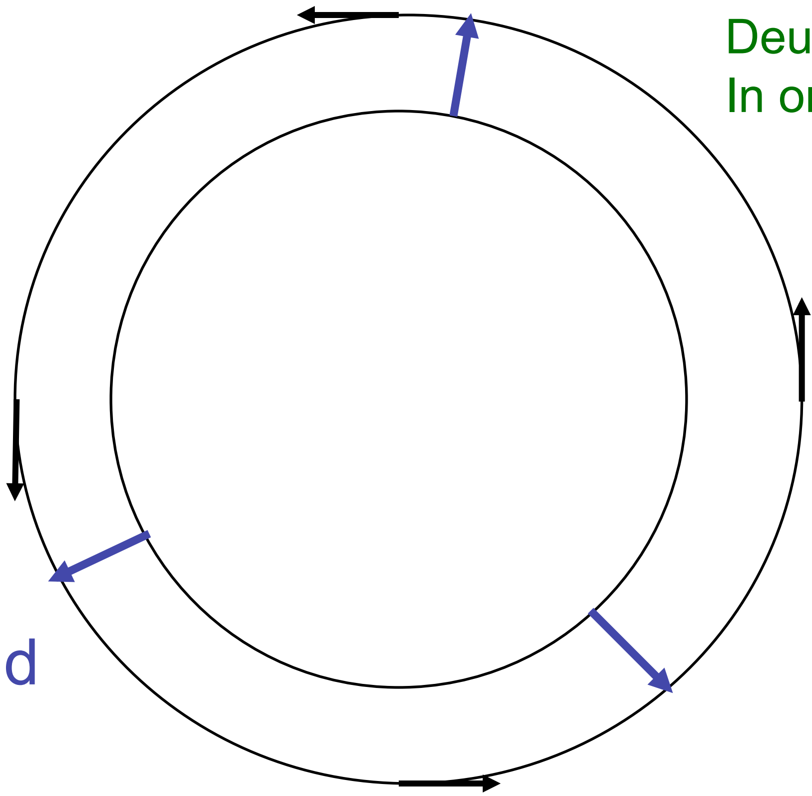


Deuteron anomalous moment = – 0.14.
In one revolution, spin lags momentum.

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…



E field

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

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

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.)

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

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).**

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	−	−	+	+	+	−	$< 10^{-29}$

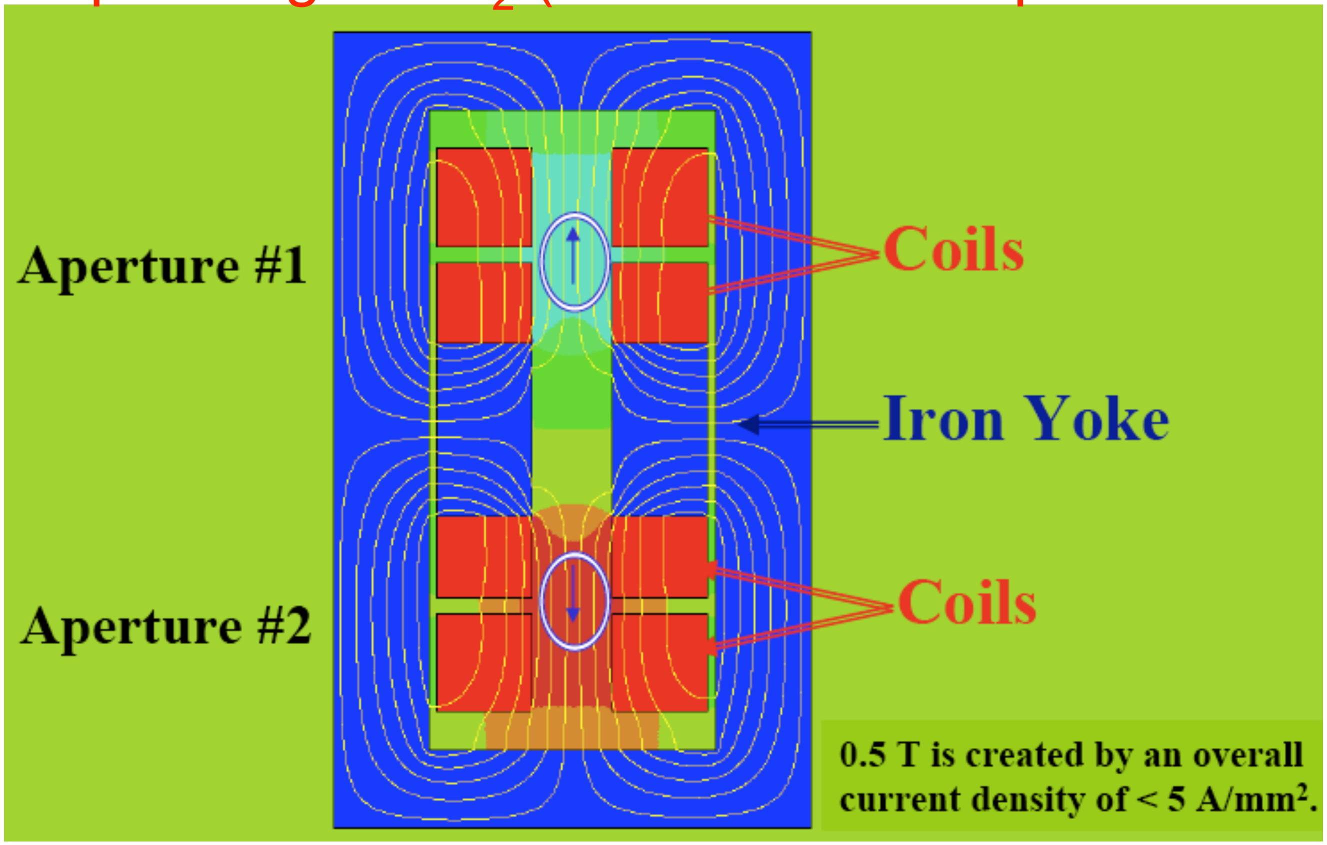
Clock Wise (CW) and Counter Clock Wise (CCW) injections

- 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

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

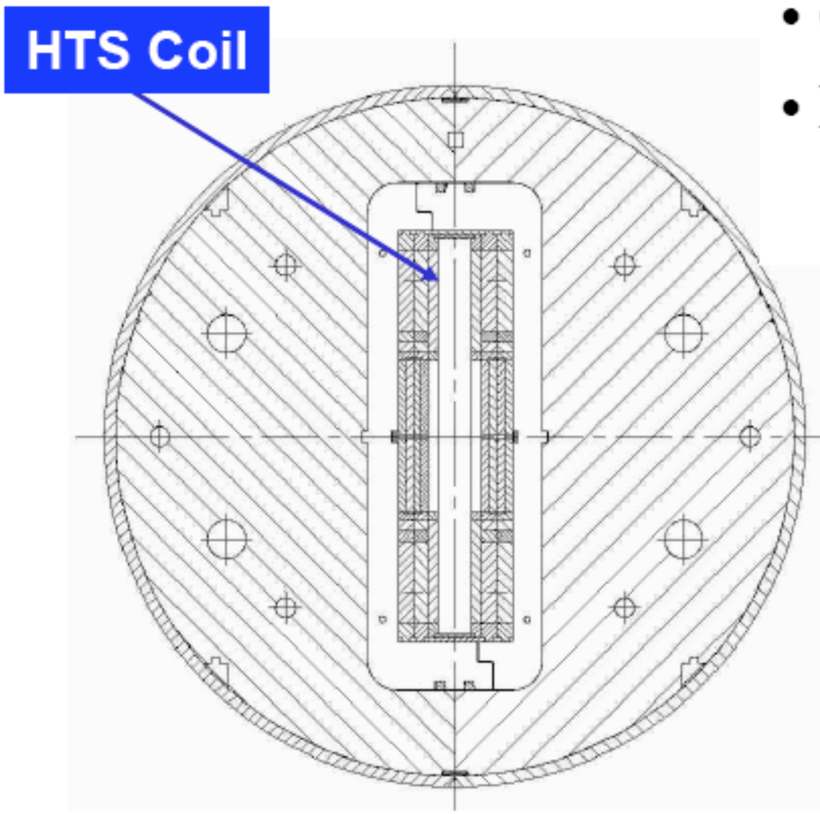
- Solution (Morse): Use the 2-in-1 magnet design for simultaneous CW and CCW storage. R. Gupta considered two options: Normal conducting magnet (design shown here) and high temperature superconducting magnet (in progress) operating at LN_2 (uses much less power than normal magnet).



A Unique Feature of BNL Common Coil Design

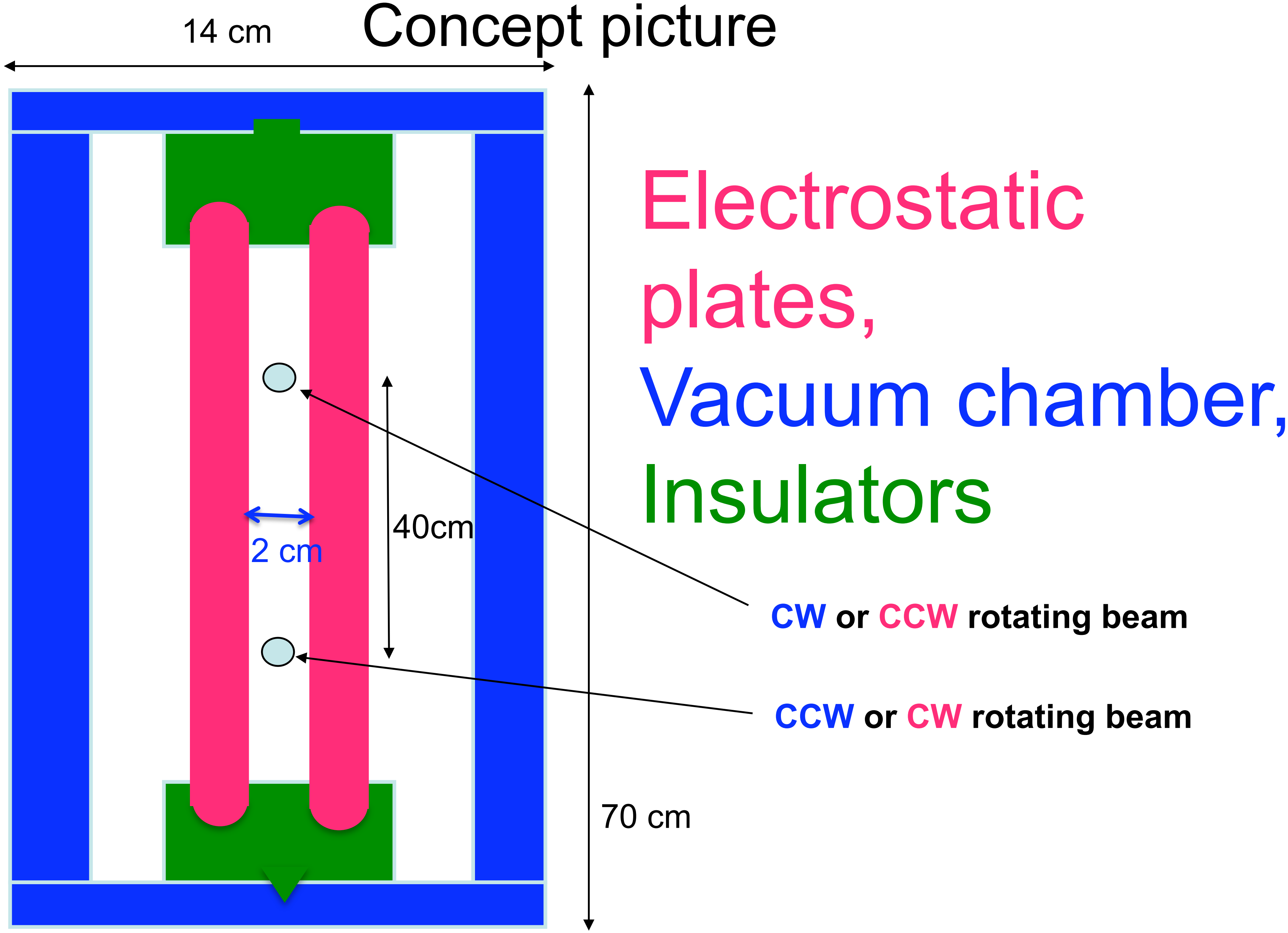
A unique feature of BNL design is a large vertical open space between the two coils.

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

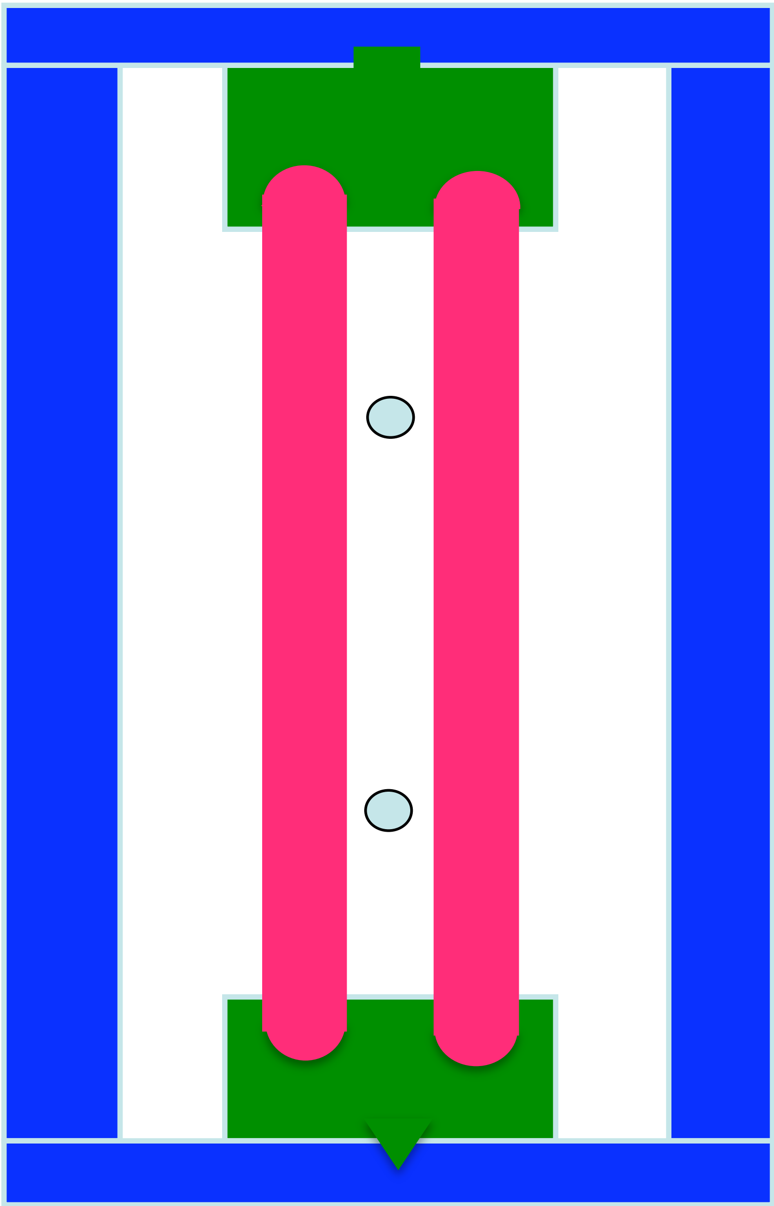


HTS insert coil test configuration (HTS/Nb_3Sn Hybrid magnet)

Concept picture



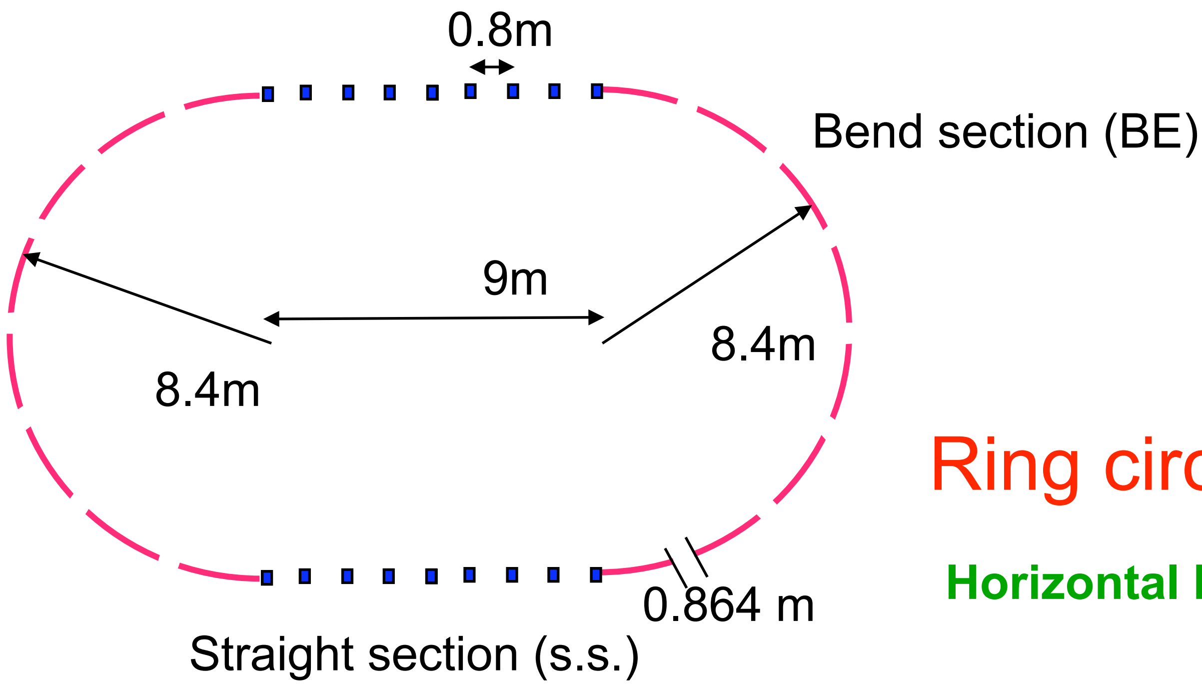
Concept picture



E-field: using well established scaling rules & extrapolating from the FNAL ES separators we should be able to get 120KV/cm. The B-field presence is not a concern…

E-field design: 120 KV/cm at beam locations (smaller everywhere else).

The dEDM ring lattice



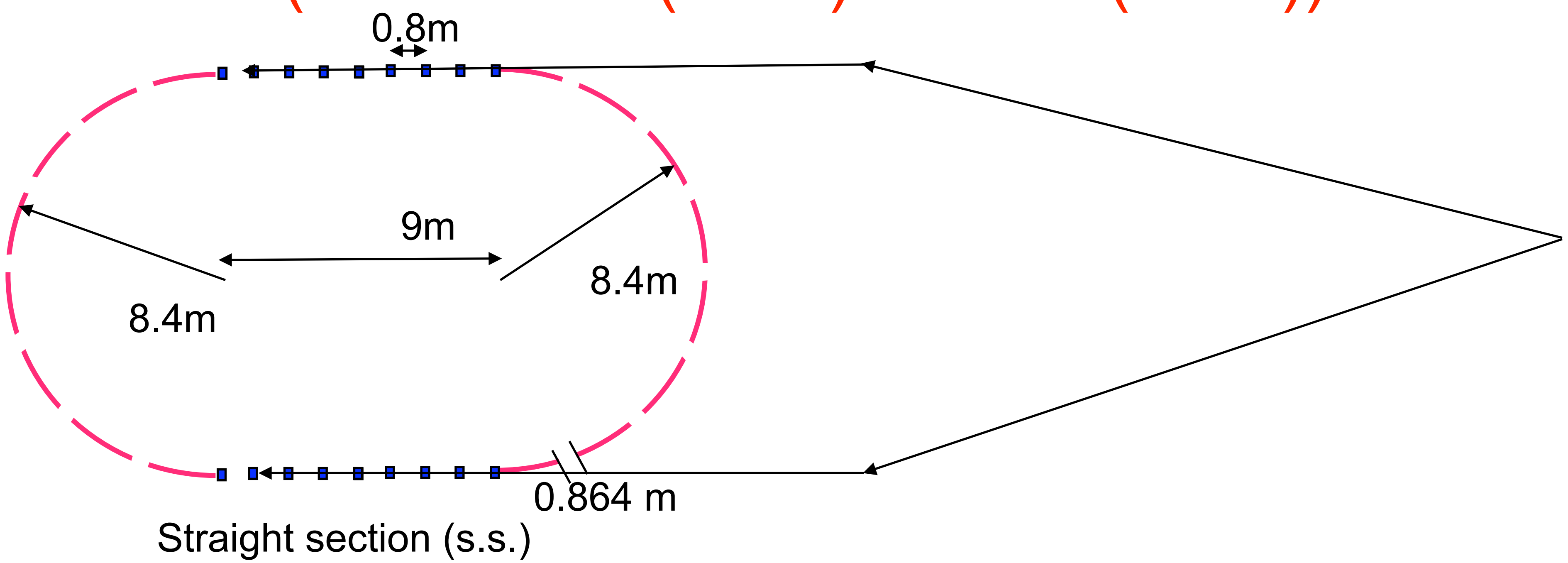
Ring circumference: 85m

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
8 places are free for other needs

Four injection kickers

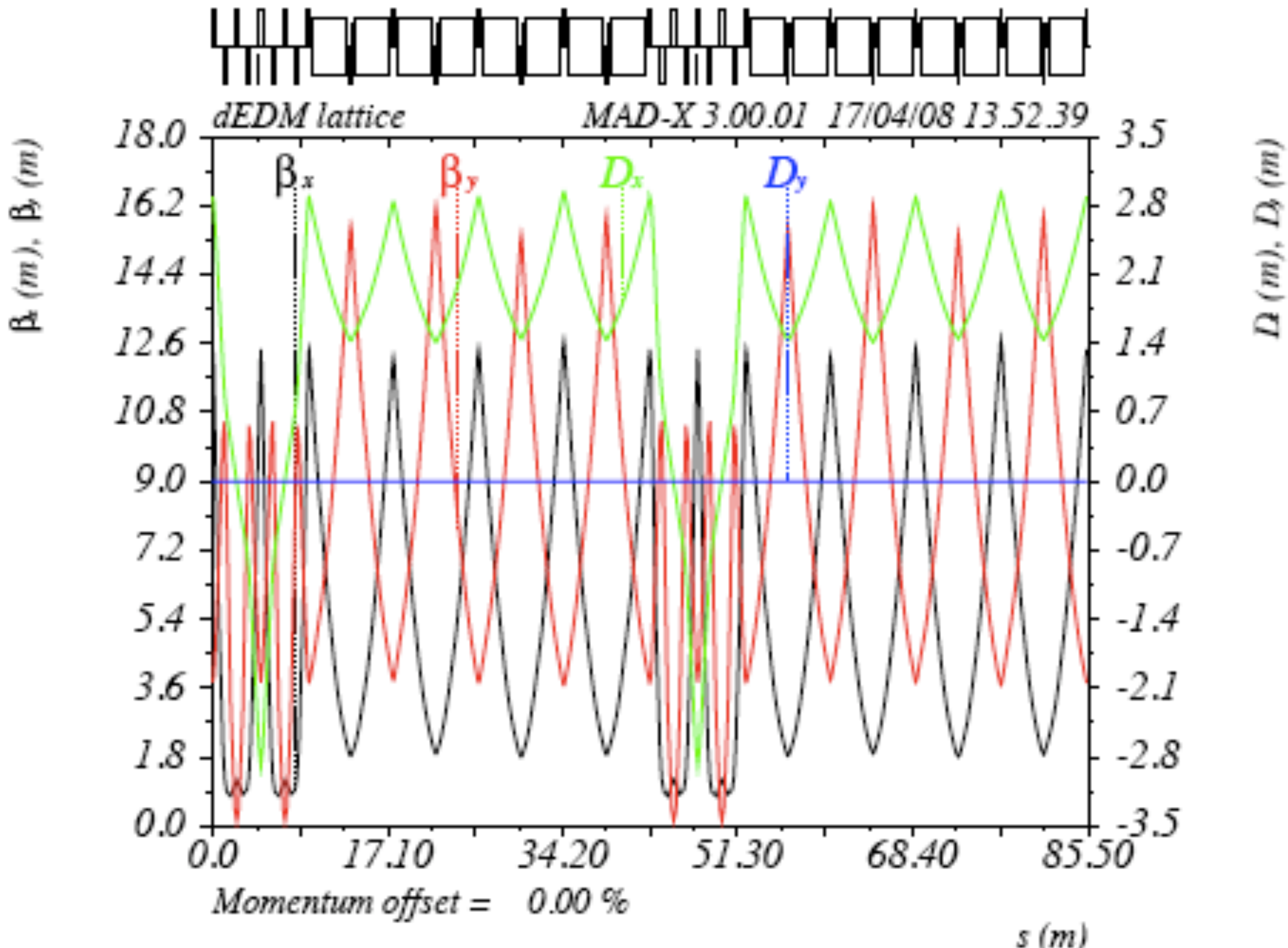
(Arlene Wu (CAD) & J. Mi (CAD))



4 kicker systems are required: two for each ring

~5 mrad kick is needed, 1.6m long plates
Beam horizontal radius (95%): 6mm.
Beam-line matching: F. Lin (Physics), K. Brown (CAD), A. Luccio (CAD)

The dEDM Ring Lattice



Ring Circumference: 85m

Yannis Semertzidis, BNL PAC meeting, May 2008

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.

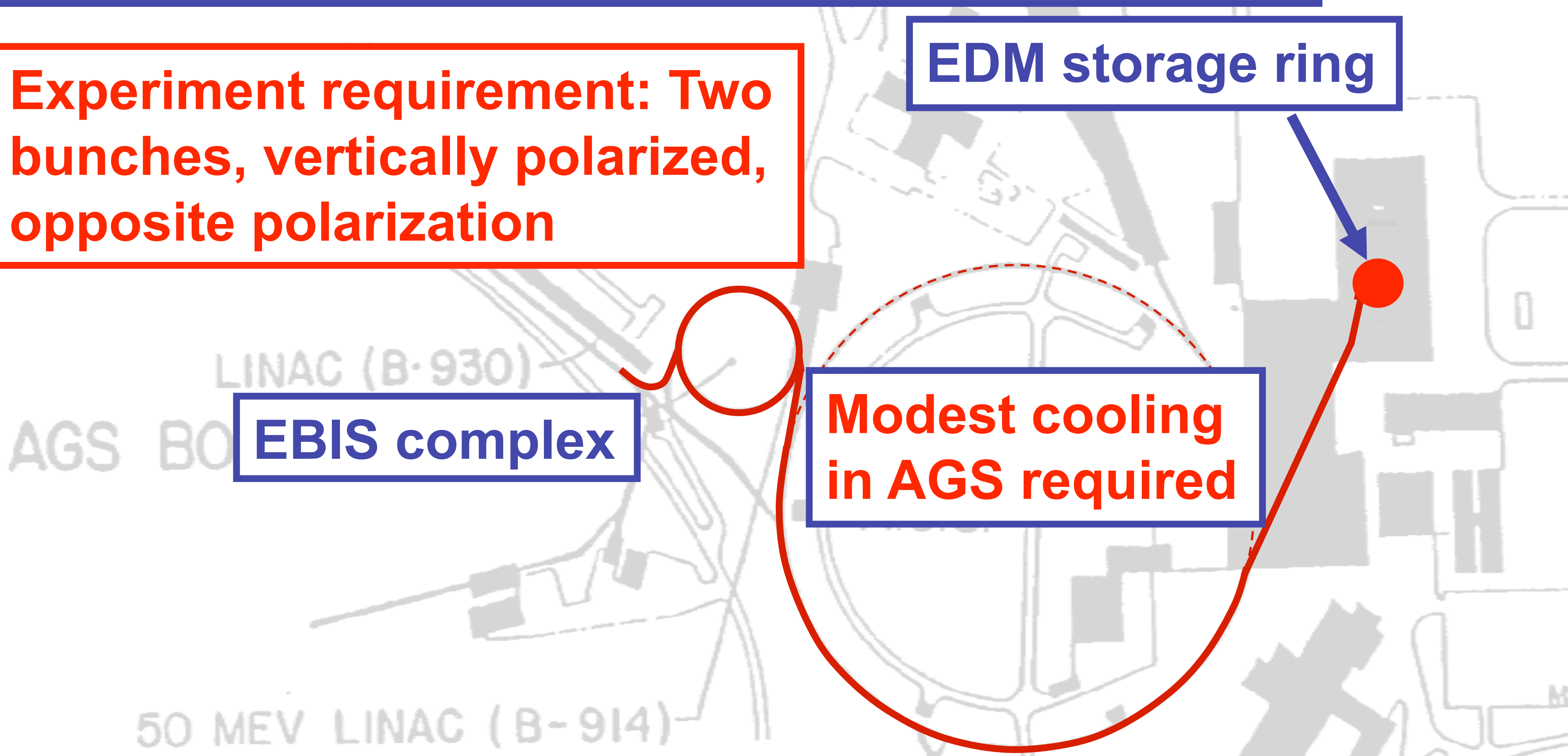
d) Optimize polarimetry using beams at KVI and COSY: A. Imig, M. da Silva e Silva (KVI), G. Onderwater (KVI), E. Stephenson (IUCF), Groups from Italy, Greece, …

Development Plan (cont'd)

e) Electric field testing in the presence of B-field: V. Dzhordzhadze (Physics), R. Larsen (Physics), …
f) Electrostatic plate initial alignment: 50μrad locally, <1-5μrad 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.),…

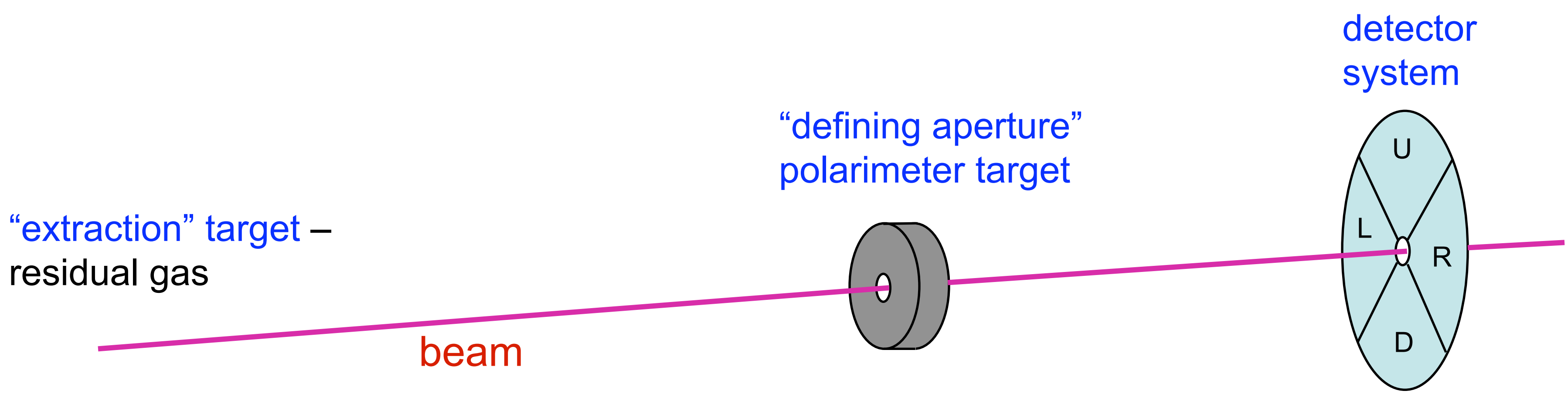
Source parameters: A. Zelenski (CAD)
Emittance numbers: D. Raparia (CAD)
Cooling parameters: A. Fedotov (CAD)

Experiment requirement: Two bunches, vertically polarized, opposite polarization



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

Cross section and analyzing power

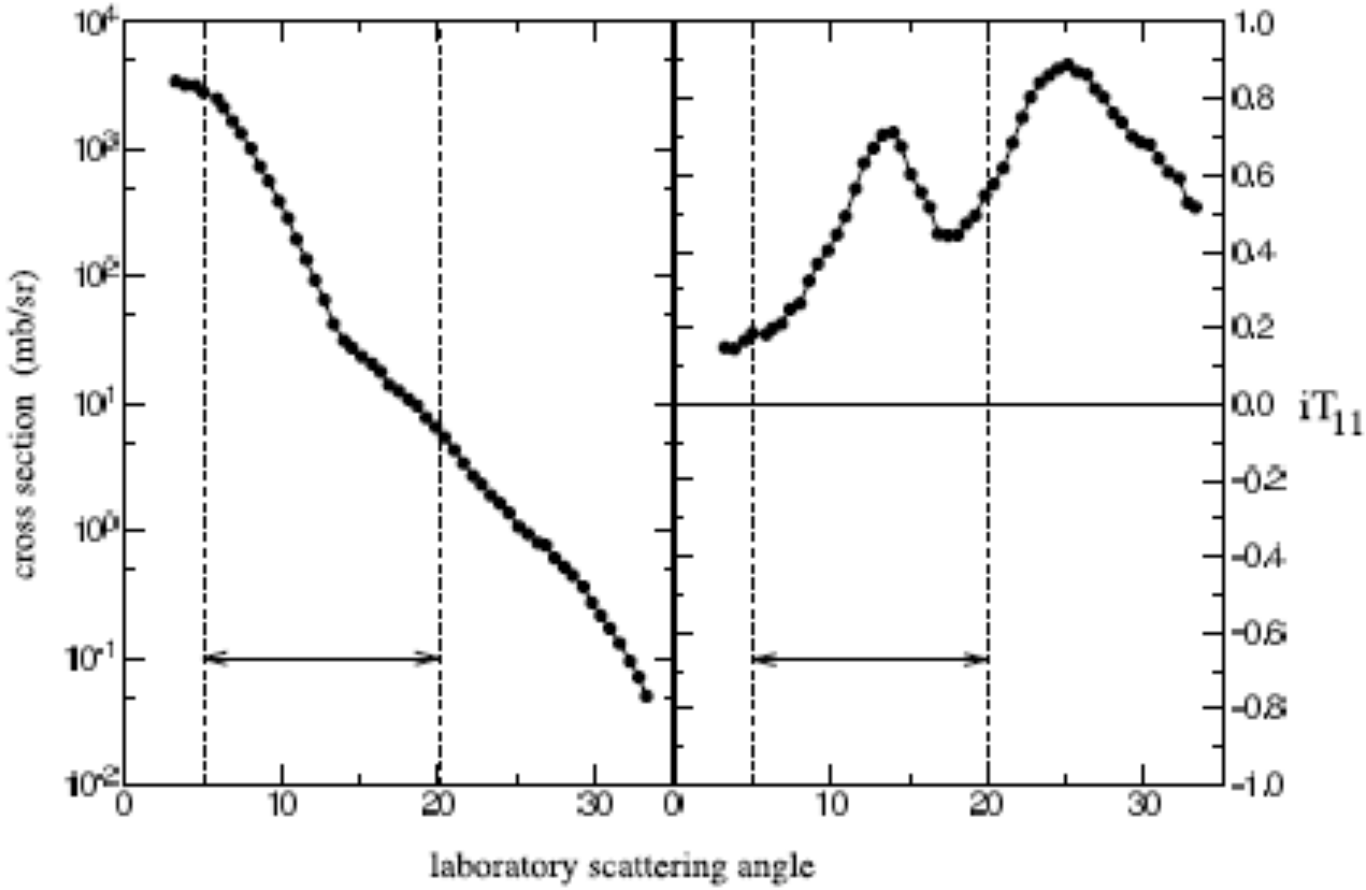


Figure 2: Deuteron elastic cross section and analyzing power at 270 MeV from carbon [29]. The dashed lines indicate the preferred acceptance limits for an EDM polarimeter.

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

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

Systematic Error Strategy

1. Use of Symmetries

2. Determined 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	$-$	$-$	$+$	$+$	$+$	$-$	$< 10^{-29}$

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

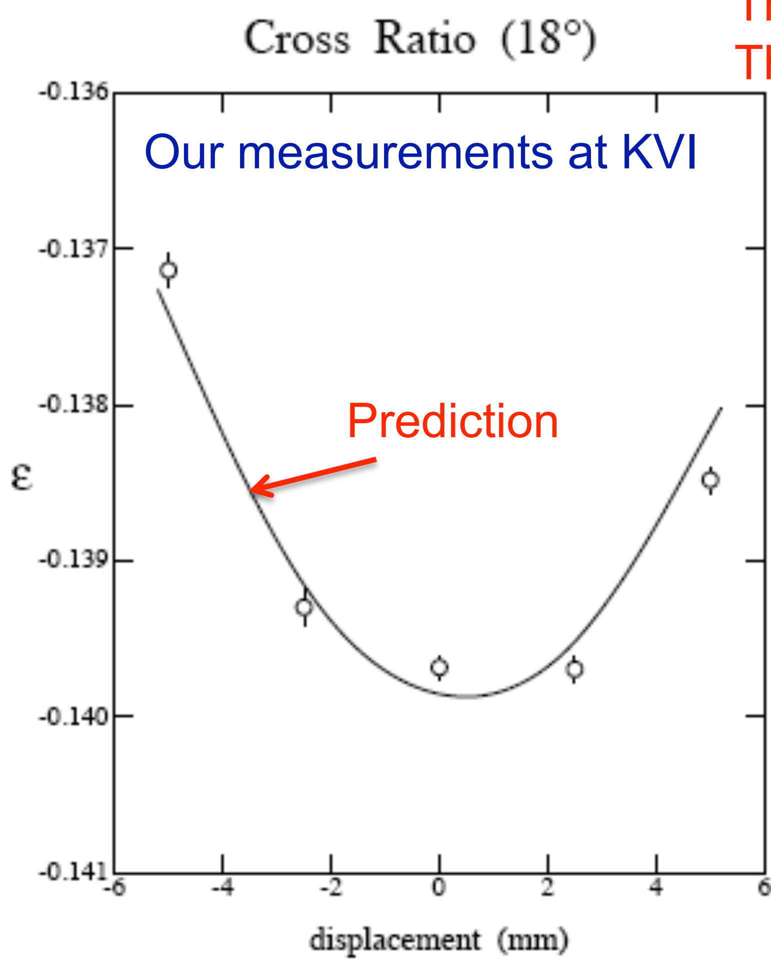


Figure 3: Measurements of the change in left-right asymmetry as the target position is moved horizontally. The solid line is an *a priori* prediction based on the older scattering measurements at 113 MeV. The curve has been offset vertically to match the average asymmetry. The errors shown are statistical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

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.

2. Specs

a) Leakage currents: <1μA
b) Power Supply stability (on average): $<10^{-4}$
c) Net heat source in enclosed ring: <(±20 kwatt)
d) Horizontal B-fields (non-reversible, e.g. earth's magnetic field, leakage currents, current sources): 1^{st} azimuthal harmonic amplitude < 10 mgauss.

Run Plan

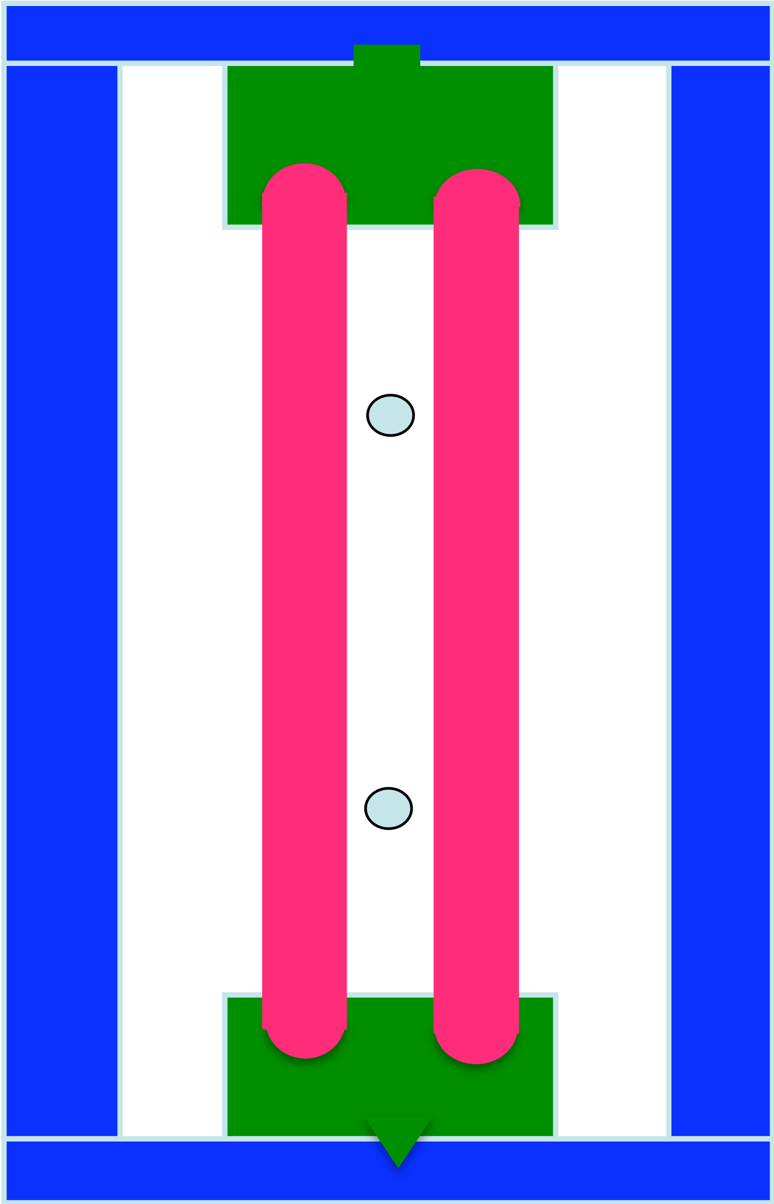
a) Run 1 to shim the ring and study the systematic errors. Collect data for 10^{-28}e•cm

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) Probe horizontal B-fields (1^{st} harmonic) with a sensitivity of 1 ppm using polarized deuterons and controlling the value & phase of ω_a.
e) Collect data for 10^{-28}e•cm

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 beam location needs to repeat to 0.1mm.

Next Run

Collect data for 10^{-29}e•cm

Storage Ring EDM Collaboration

A strong collaboration that seeks a strong endorsement from PAC.

AGS Proposal: Search for a permanent electric dipole moment of the deuteron nucleus at the 10^{-29} e · 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

(technically driven scenario)

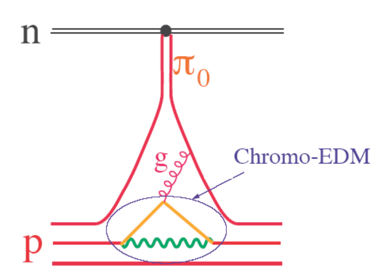
07 08 09 10 11 12 13 14 15 16 17

- Spring 2008, Proposal to the BNL PAC
- Fall 2009, 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 2010, finish dEDM detailed ring design
- Fall 2010, start ring construction
- Fall 2013, dEDM engineering run starts
- Fall 2014, dEDM physics run for three (calendar) years

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 collaboration seeks a strong and clear endorsement by the PAC.

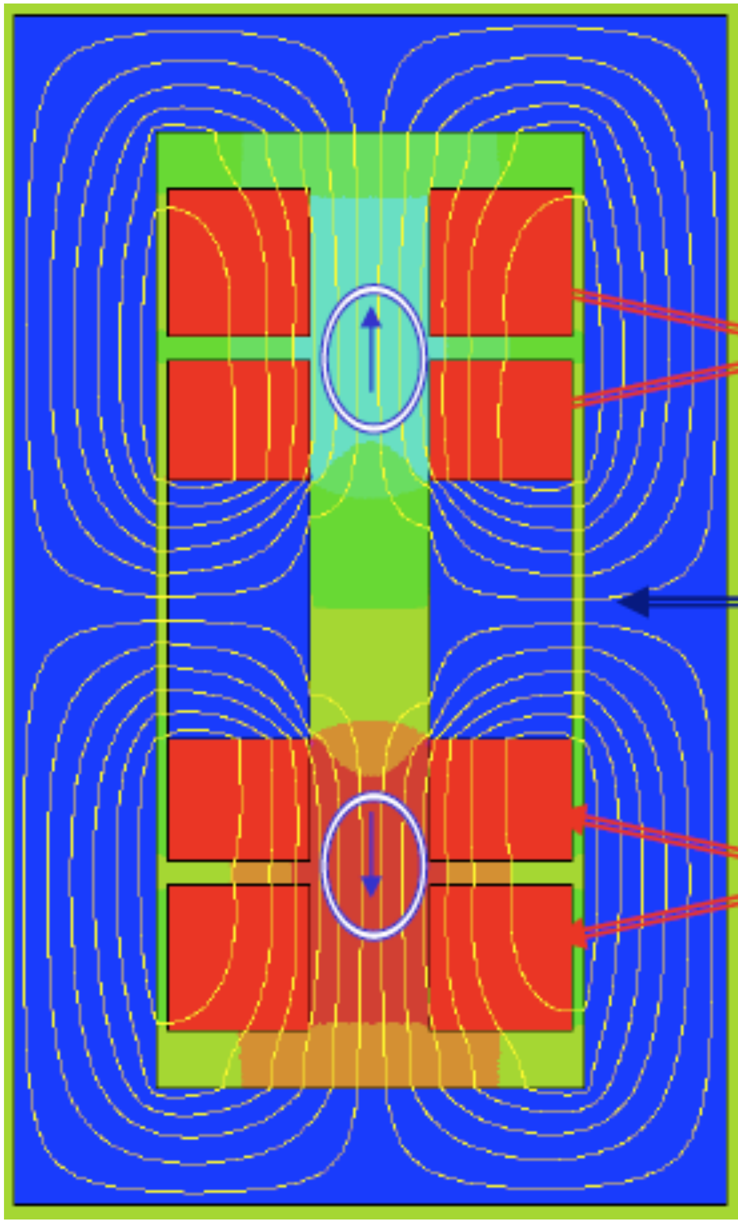


Extra sides

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.

Operating Electric Fields in the Presence of Magnetic Fields



Trapped electrons may cause trouble. They undergo three motions:

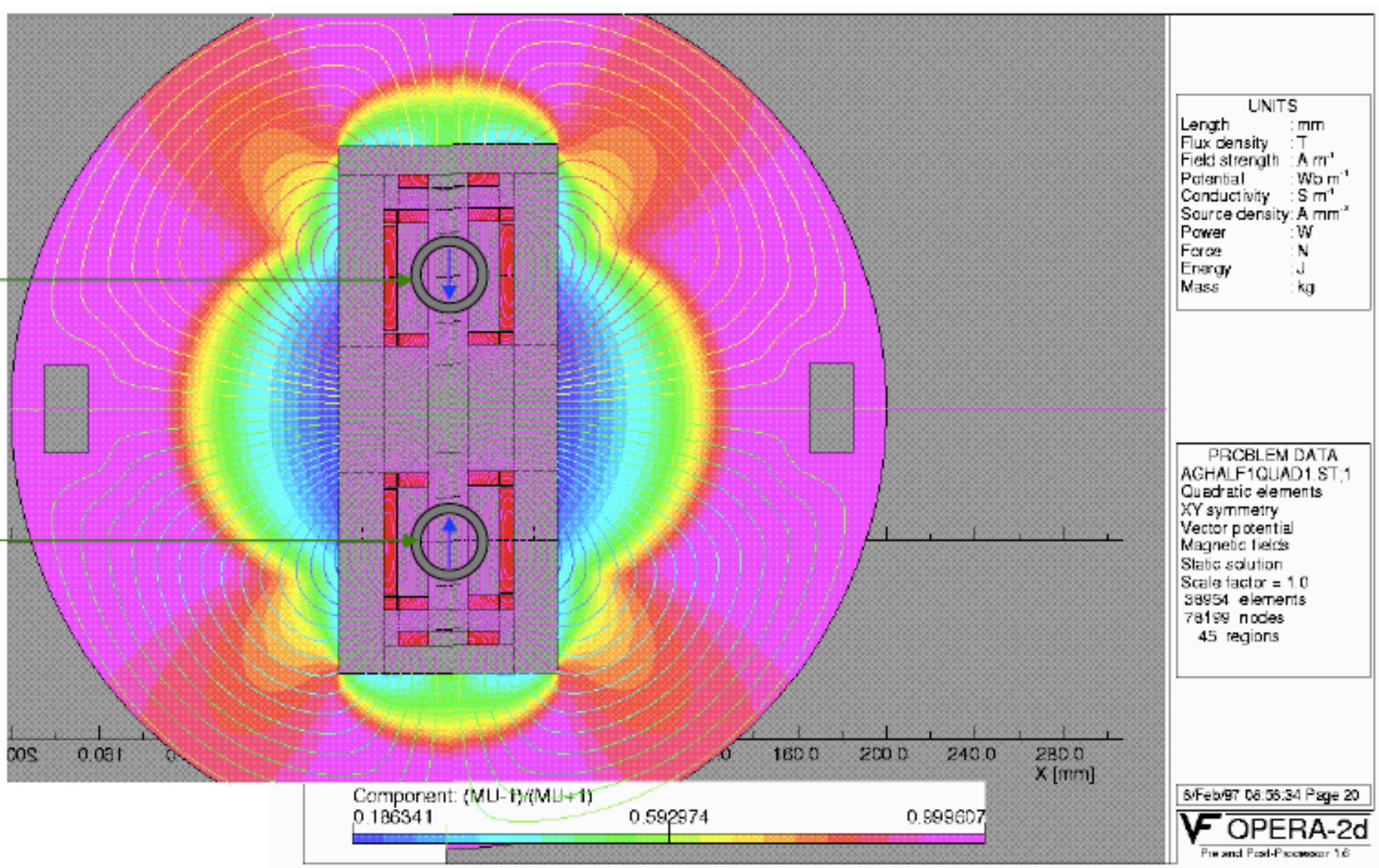
1) cyclotron, 2) Axial (up/down), 3) Magnetron (drift in the E×B direction)

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…

Field Lines at 15 T in a Common Coil Magnet Design

Aperture #1

Aperture #2

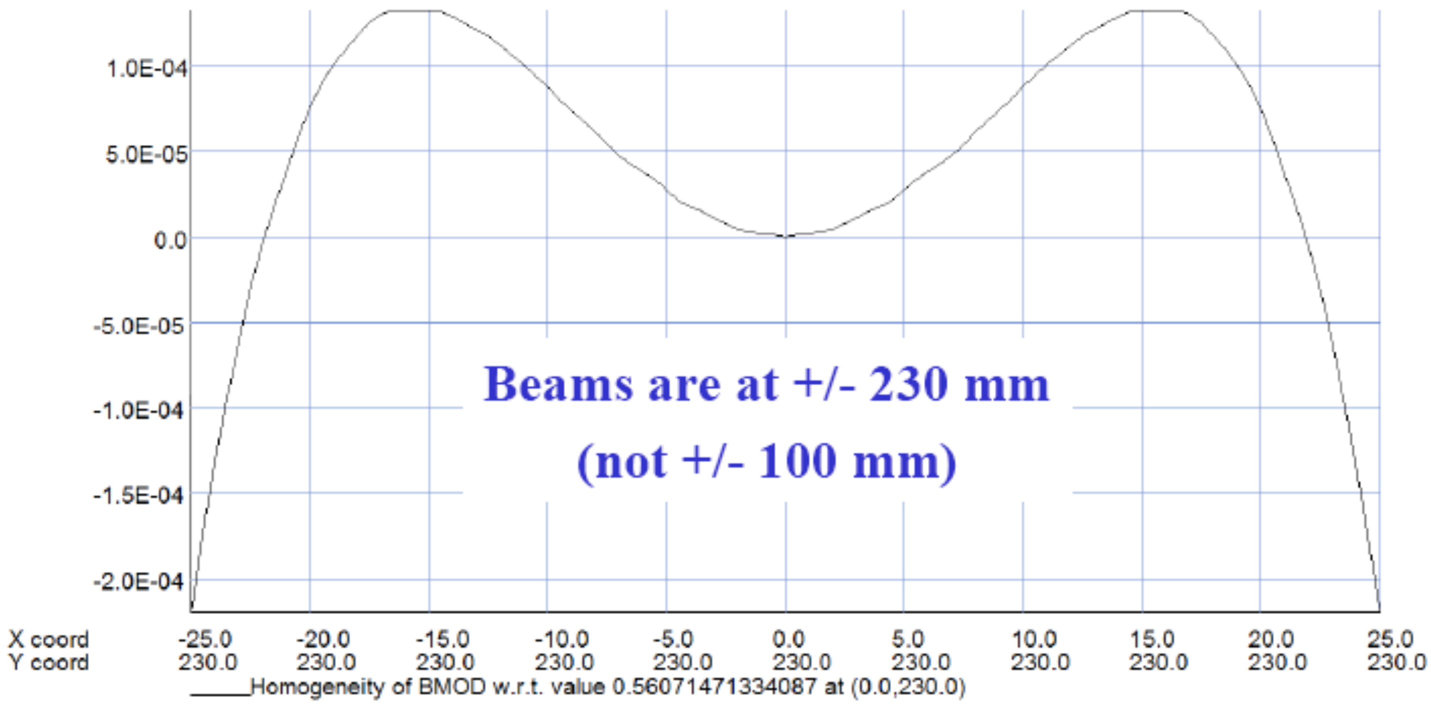


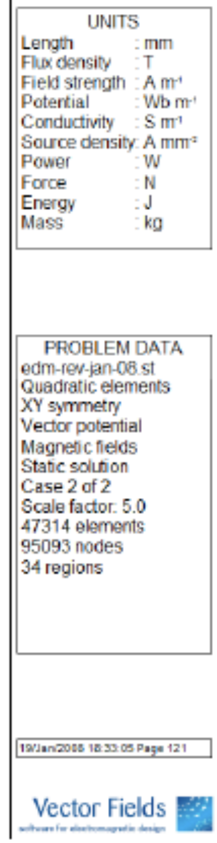
BROOKHAVEN NATIONAL LABORATORY

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.

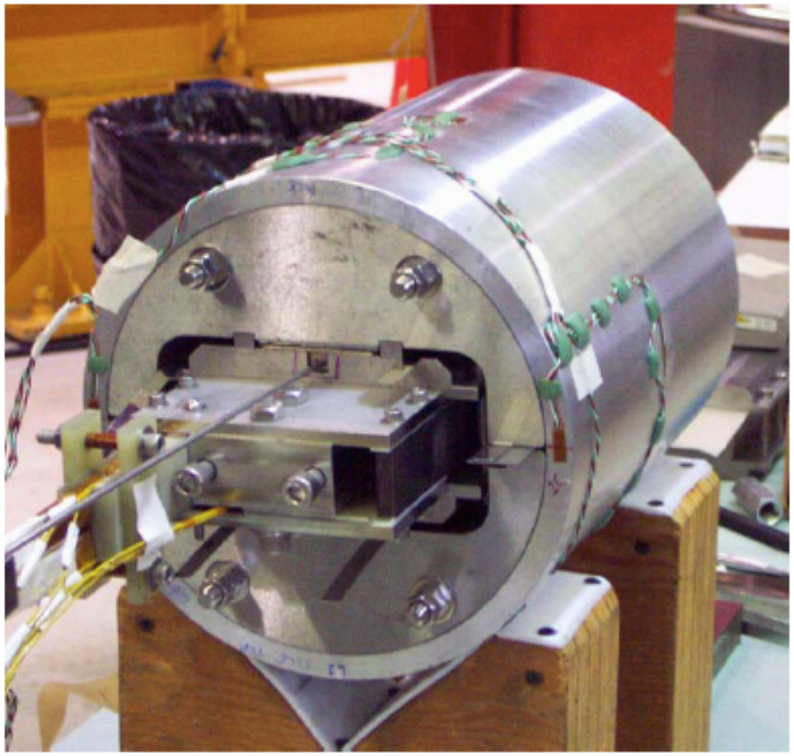
Field errors are displayed for +/- 25 mm. Actual beam size is much smaller.

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.

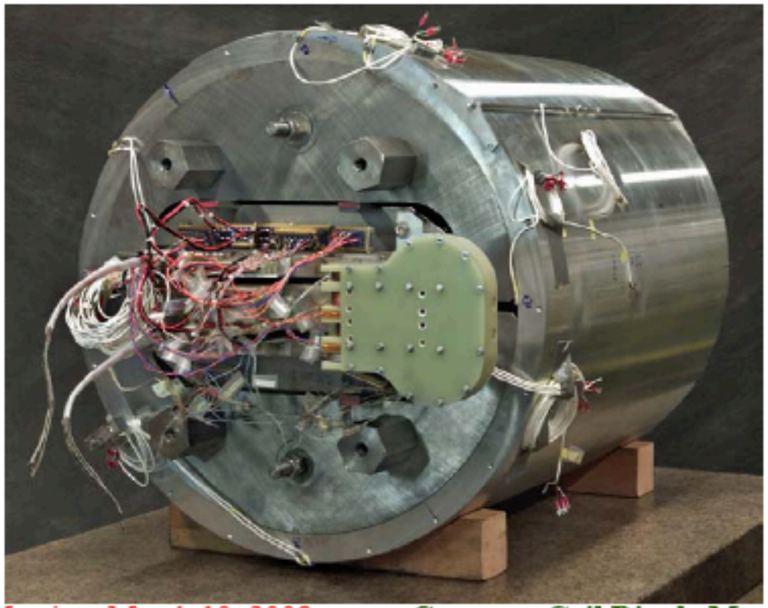
Common Coil Magnets Built at BNL, FNAL, LBNL

BNL

FNAL



LBNL



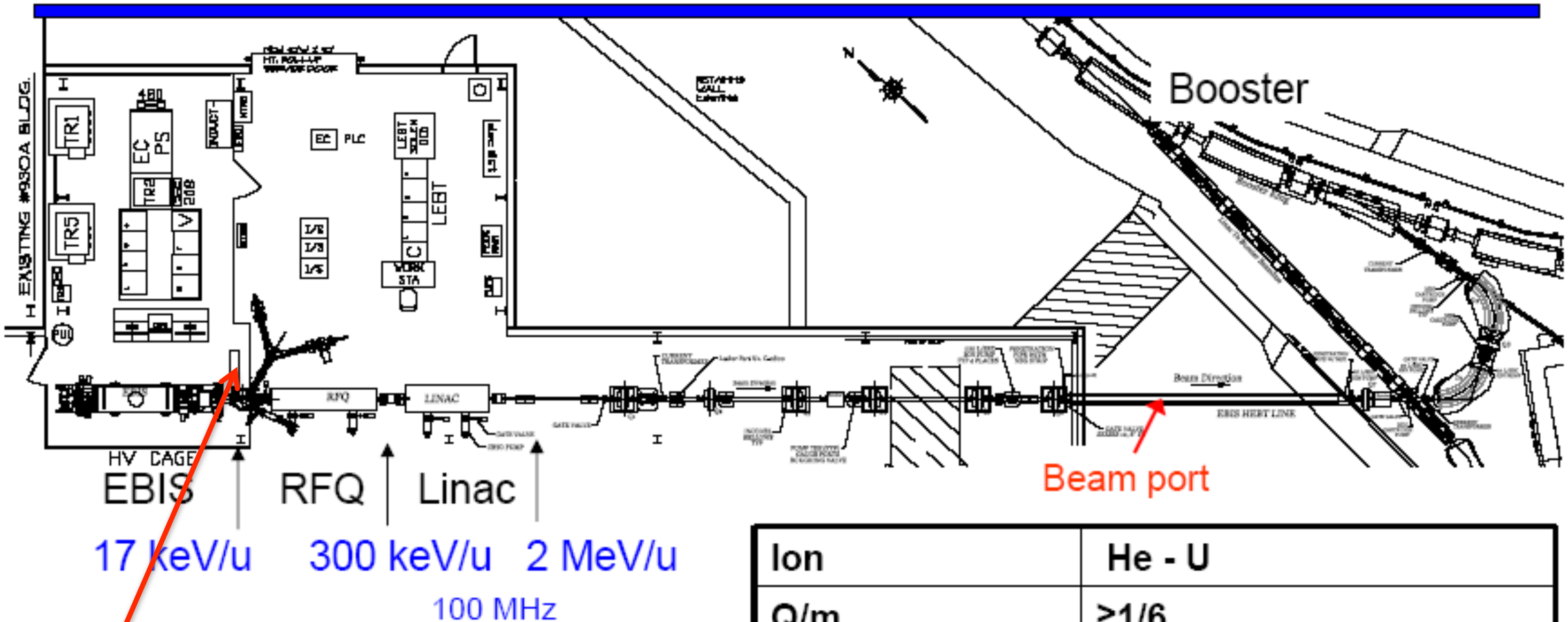
The dEDM ring parameters

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

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

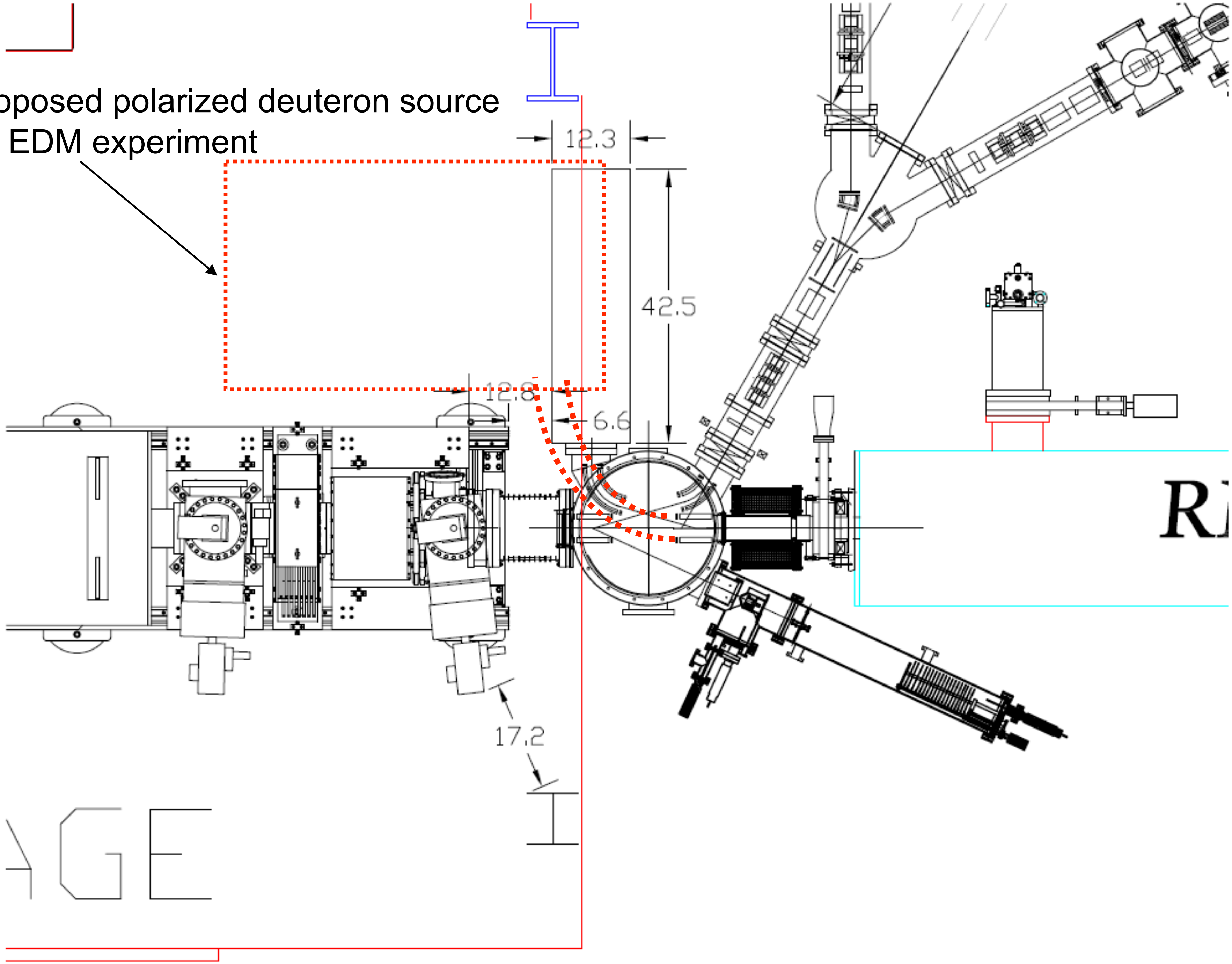
EBIS
ELECTRON BEAM ION SOURCE

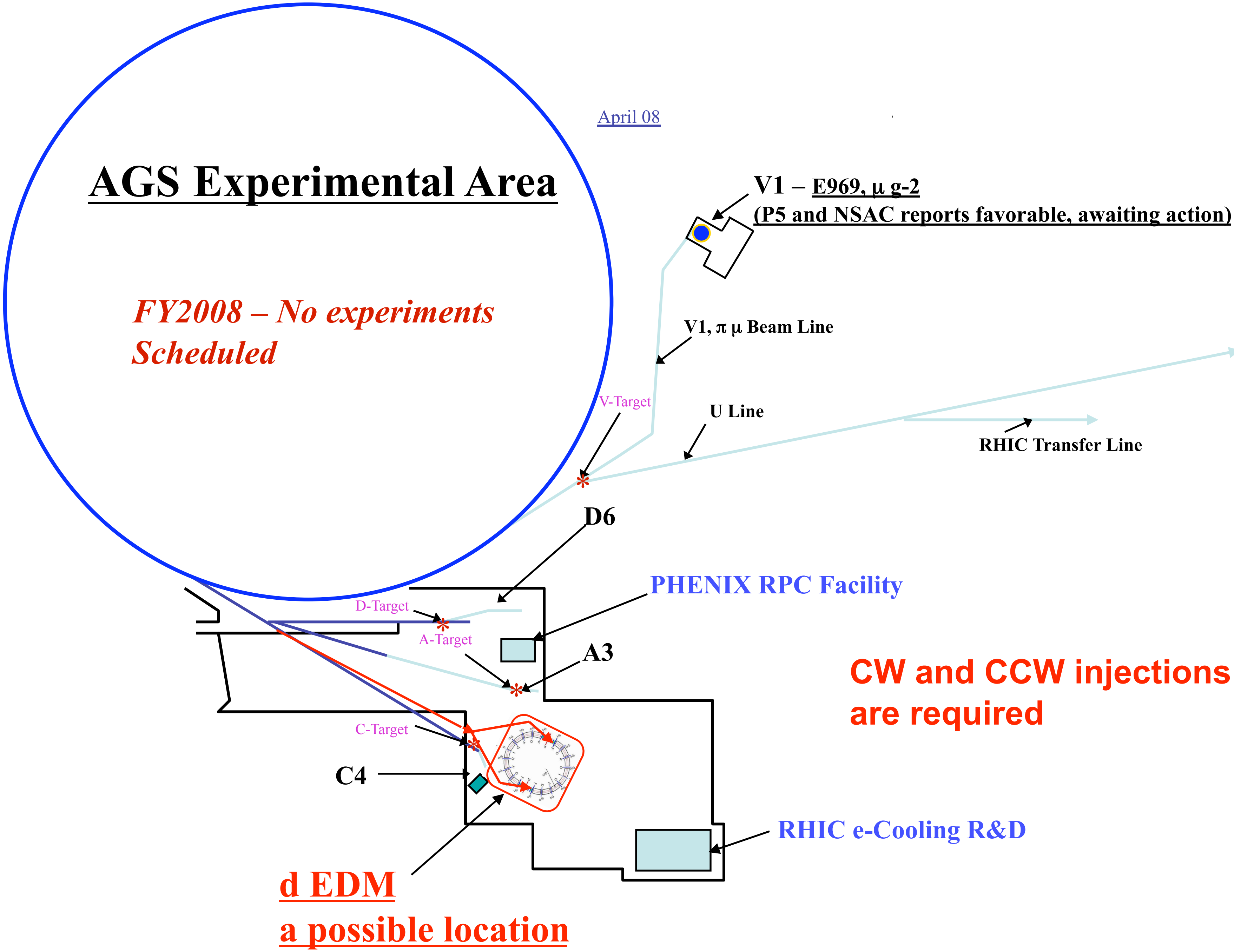


dEDM source location

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





From Phil Pile

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

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

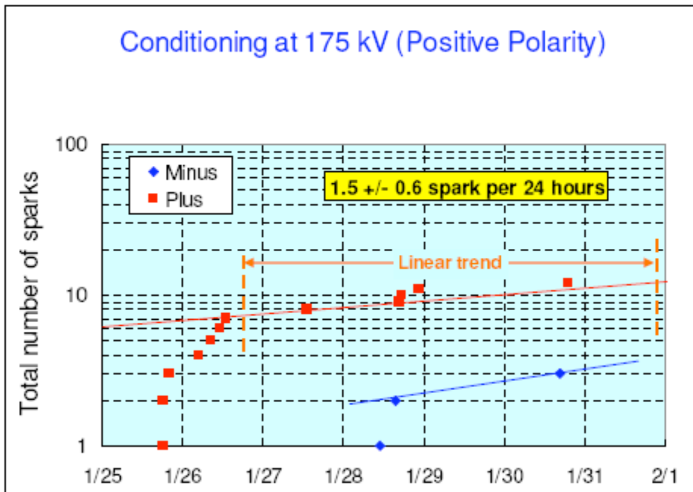
Mostly guesses

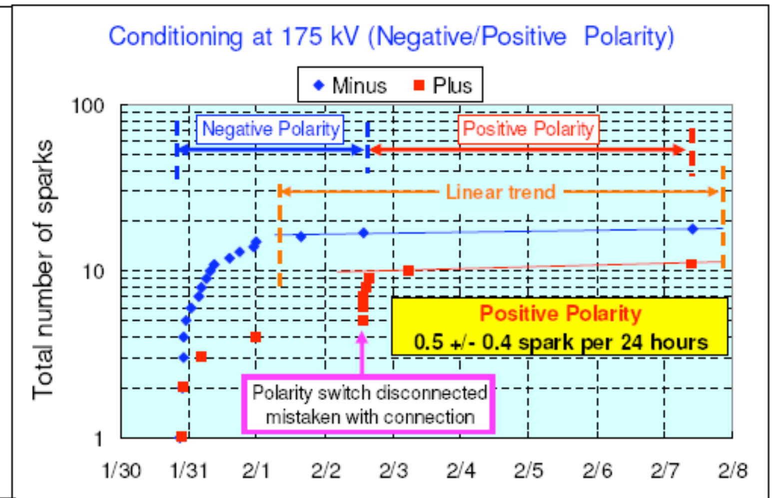
• R&D funds	$0.5M
• Baselining Costs	$0.5M
• Polarized deuteron source	$2M
• Re-establish AGS extraction	$0.2M
• AC solenoids (2)	$0.8
• Two additional injection kickers	$2M
• Reconfigure bldg 912 power and water	$0.5M
• Experiment counting house	$0.2M
• Project Office	$0.4M
• Other	$?
• **Total**	**$7M+**

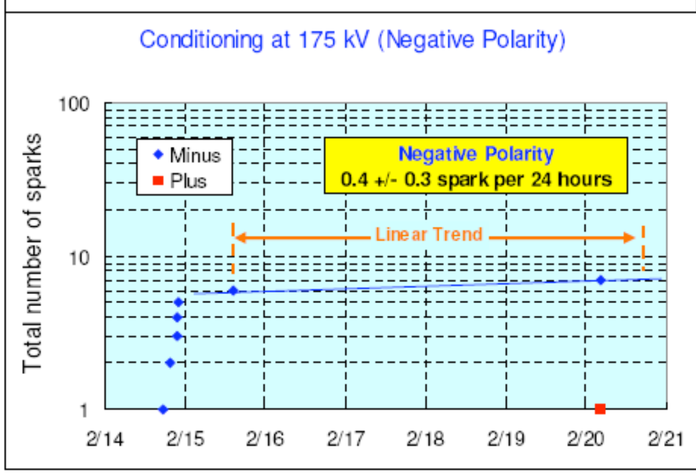
From Phil Pile

E-field strength, Electrostatic Separators at Tevatron

Spark Rate for Separator # 28







<u>Spark rate at 175 kV:</u>

Positive Polarity:

- **0.4 +/- 0.3 sparks/ 24 hours**

Negative Polarity:

- **0.3 +/- 0.2 sparks /24 hours**

<u>No sparks were detected at 170kV (positive polarity) for 7 days measurements</u>

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

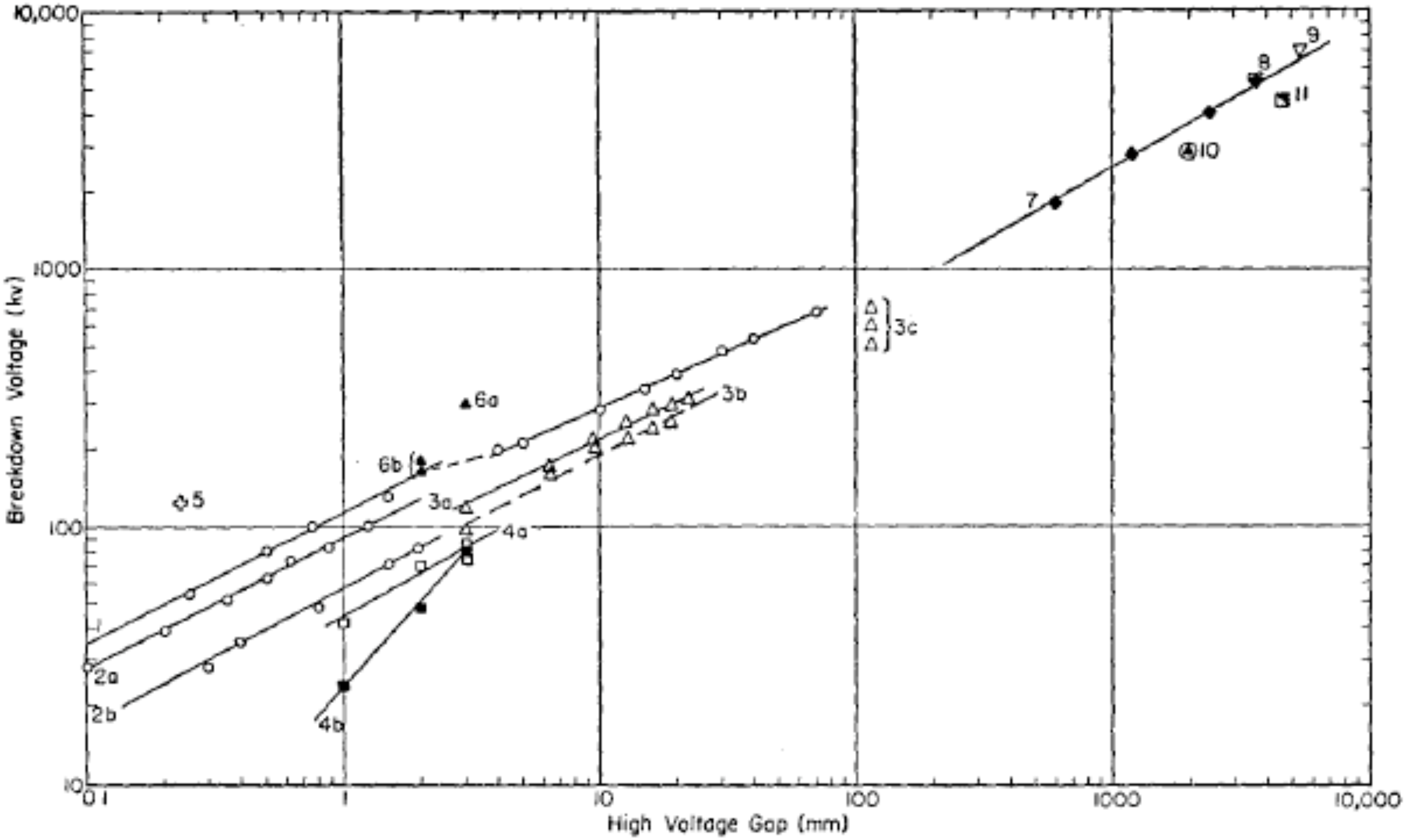
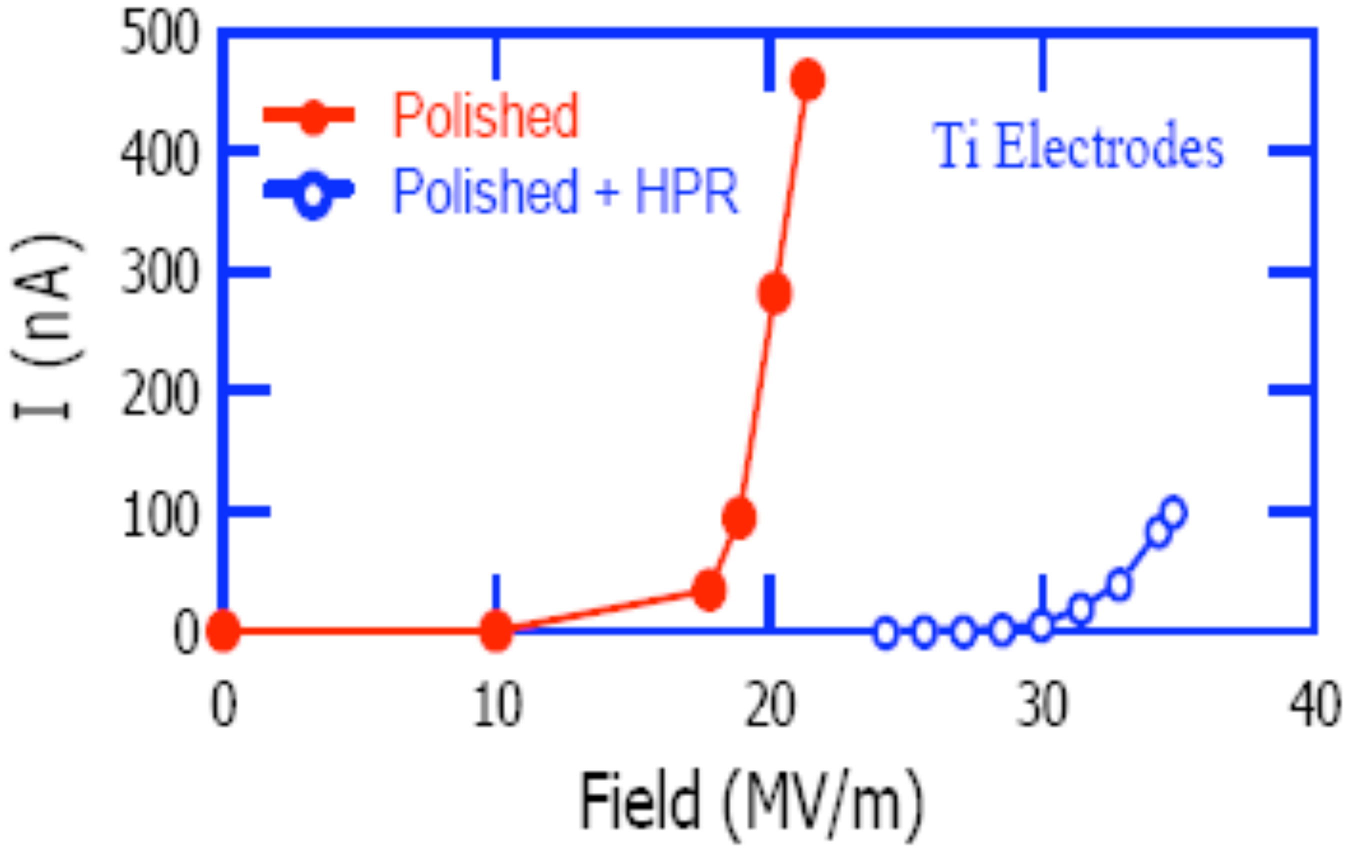


FIG. 1. Plot of data from the literature of breakdown voltage *vs* distance from highest to lowest potential electrode, for uniform-field and near-uniform-field geometry. Numbers on curves indicate sources as listed below.

E-field strength



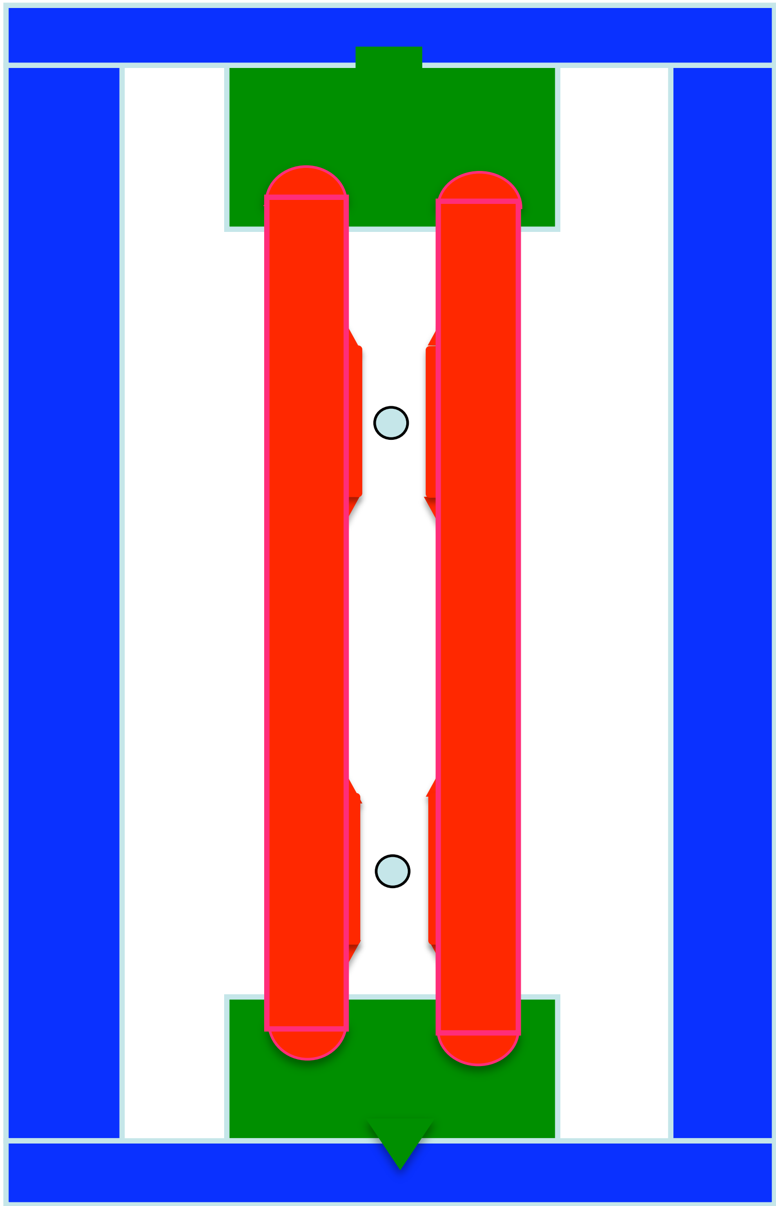
The field emission with and without high pressure water rinsing (HPR).

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.

Concept picture



E-field: 120 KV/cm at beam location (smaller everywhere else by at least 25%).

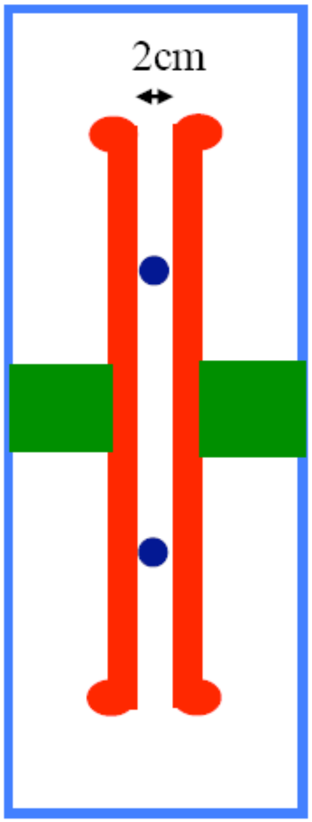
E-field strength choice: 12MV/m

- 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

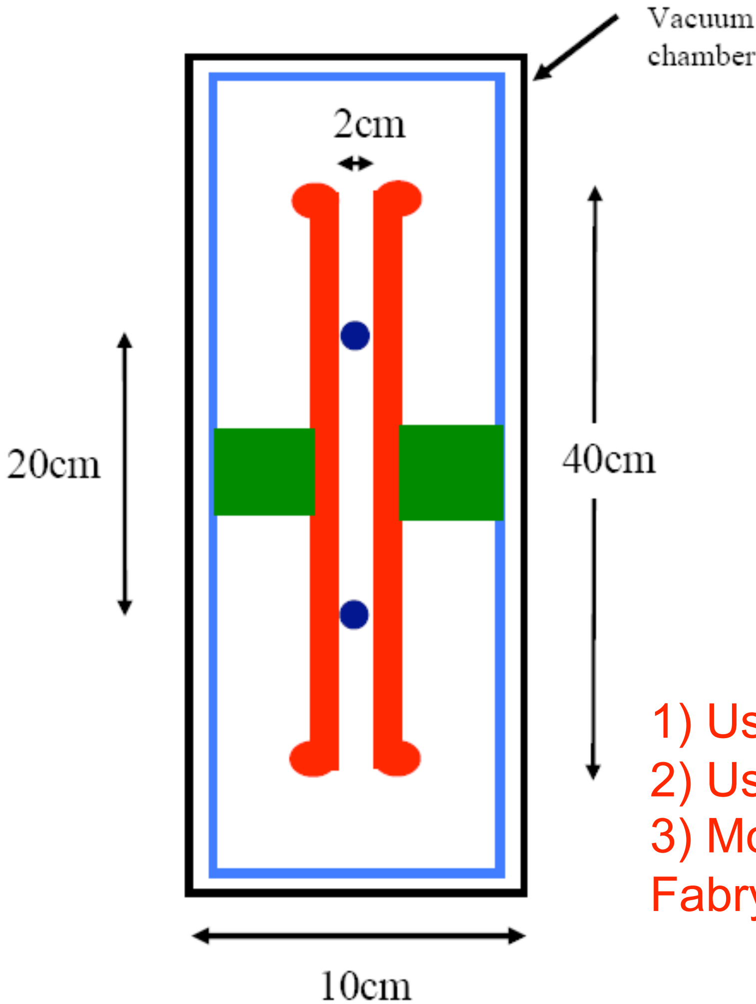


The AGS experimental floor is 1 ft of concrete. Trace the ring on the concrete and mount the vacuum chambers independently of the magnets. (R. Larsen)

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!)

E-plate Specs



Goal: Align the plates to 1μrad

1) Use plate leveling with lasers
2) Use Stark-effect E-field measurement
3) Monitor their distance stability using Fabry-Perot resonator (10^{-14} m resolution)

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.

E-field stability

- Requirement: Vacuum chamber (V.C.) bakeable (high vacuum requirements)
- Assumption: V.C. wobbles with ~1μrad amplitude (day-night)

E-field stability and other effects

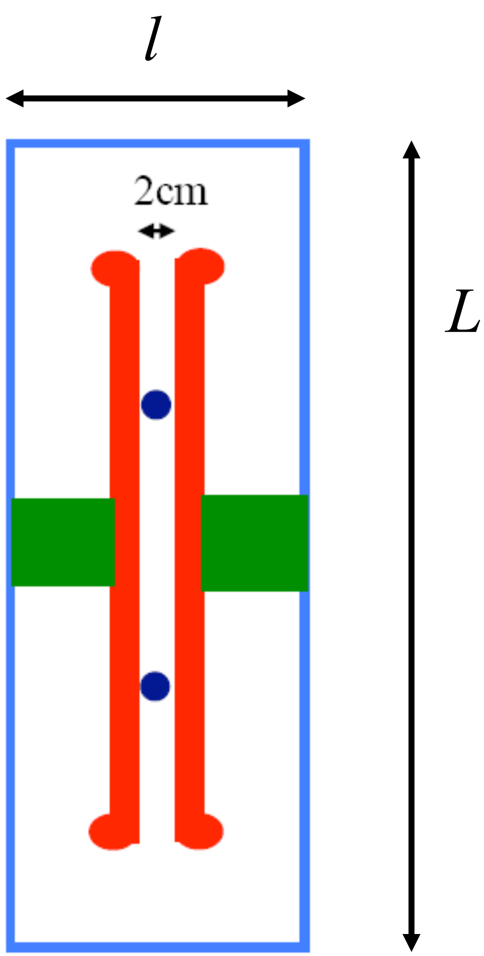
- Plate weight
- Leakage current (<1μA; two effects)
- Eddy current heat on plates, cage, v.c.

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

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.

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

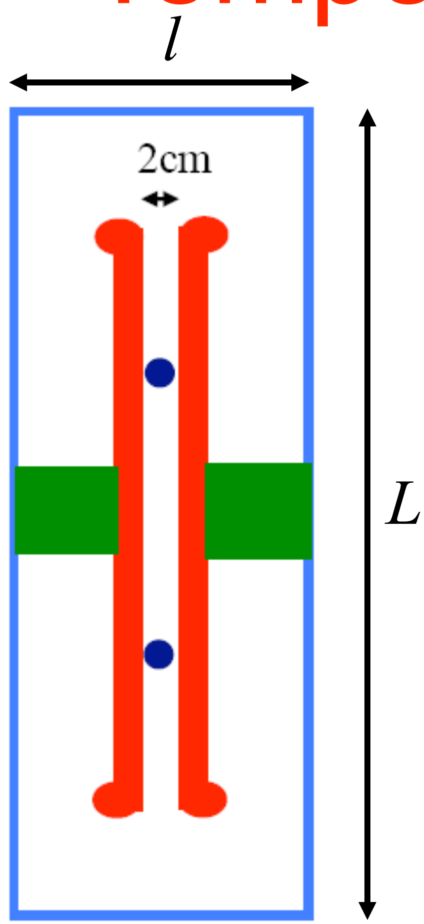


If top plate expands more than the bottom plate due to temperature difference (for 10000 CW and CCW injections and the average over 1000s):

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

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

Temperature uniformity



However, the dipole vertical E-field
is the same for both beams (i.e. it cancels).
It is the quadrupole component that matters:

$$E_y = \frac{V\vartheta}{2d}\left(1+\frac{\delta x}{d}\right) \Rightarrow \frac{E_{y,q}}{E_{y,d}} = \frac{\delta x}{d} = 10^{-4} \Rightarrow$$

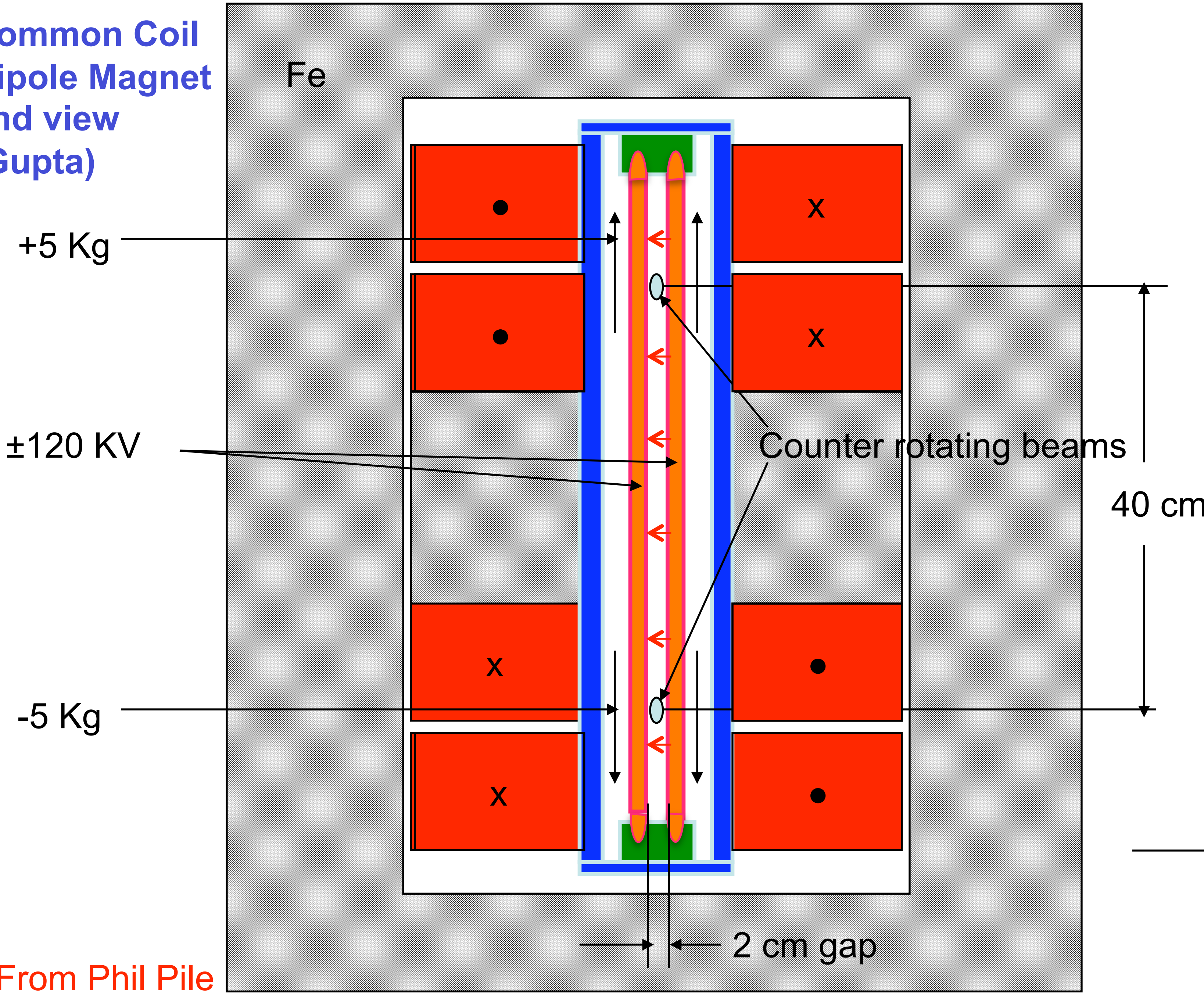
$$\delta x \leq 2\ \mu\text{m}$$

i.e. the two beams need to be in the same
radial position to 2 μm and then

$$\frac{\Delta T}{L} \leq 0.01\ \text{K/m}$$

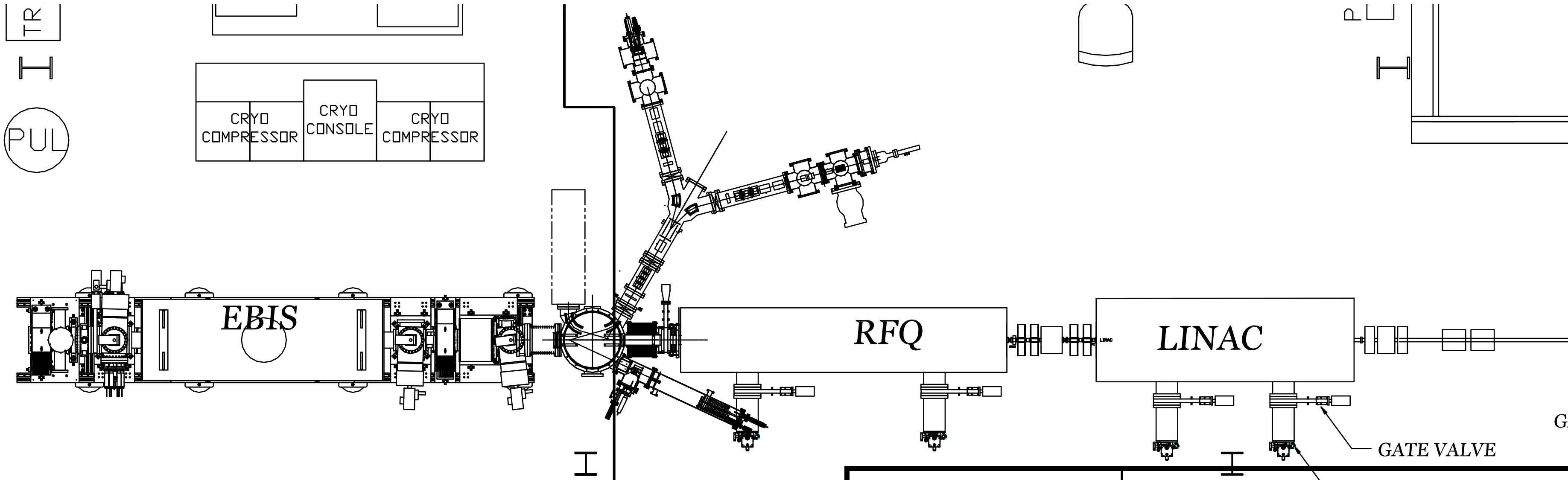
on average over the course of the experiment (top vs bottom cage plates).

Common Coil Dipole Magnet end view (Gupta)



From Phil Pile

Proposed Linac–Based RHIC Preinjector



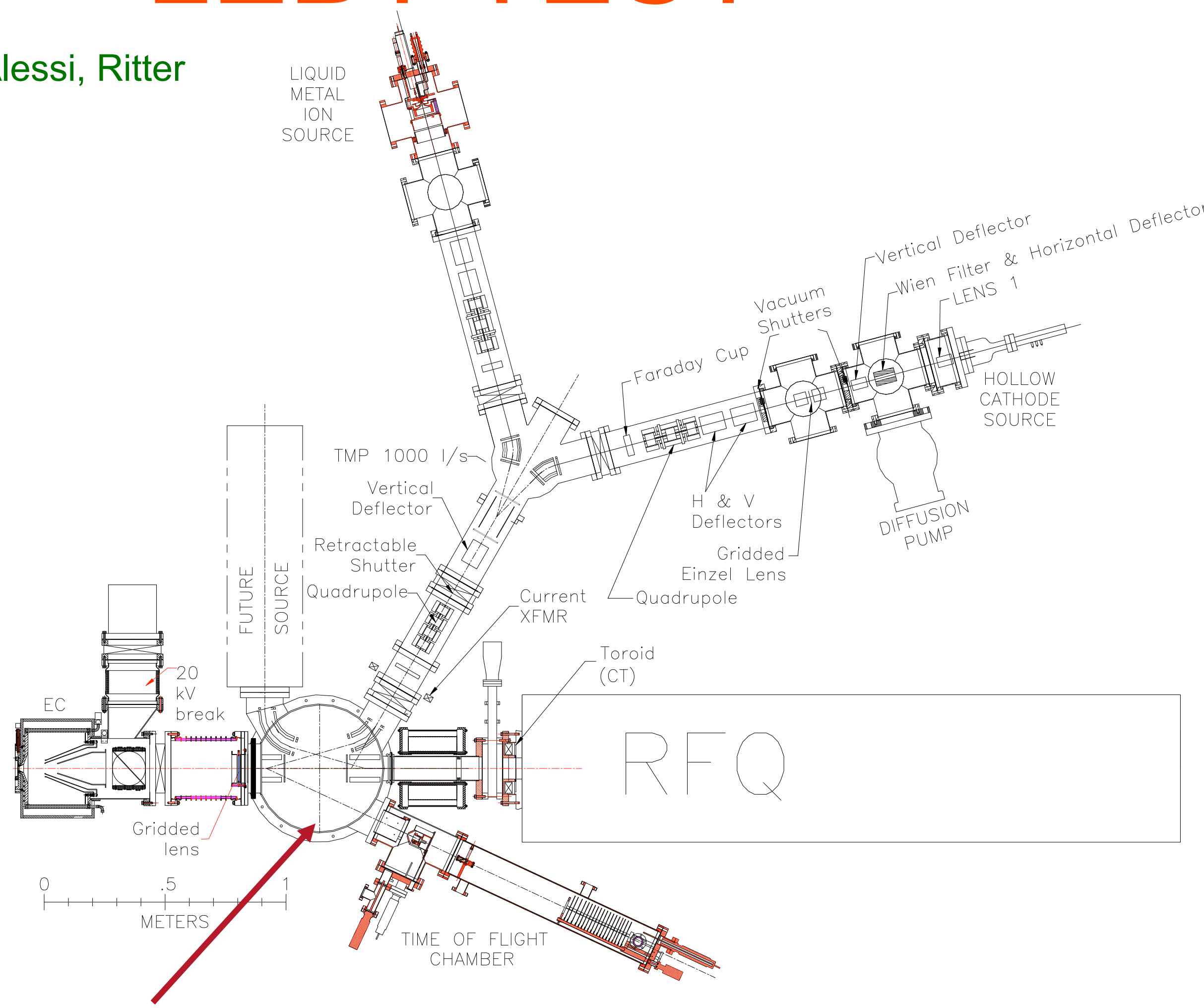
RFQ: 17 - 300 keV/u;
100.625 MHz

IH Linac: 0.3 - 2.0 MeV/u;
100.625 MHz

Ion	U - D
Charge	38 – 1 (q/m =.16-0.5)
Current	1.5 emA (for 1 turn inj)
Pulse Length Rep. Rate Duty Factor	10 μs 5 Hz 0.0005 %
Emittance	0.14 π mm rad (nor, rms)
Energy Spread	2.0 keV/u

LEBT TEST

Pikin, Beebe, Raparia, Alessi, Ritter



LEBT Switch yard

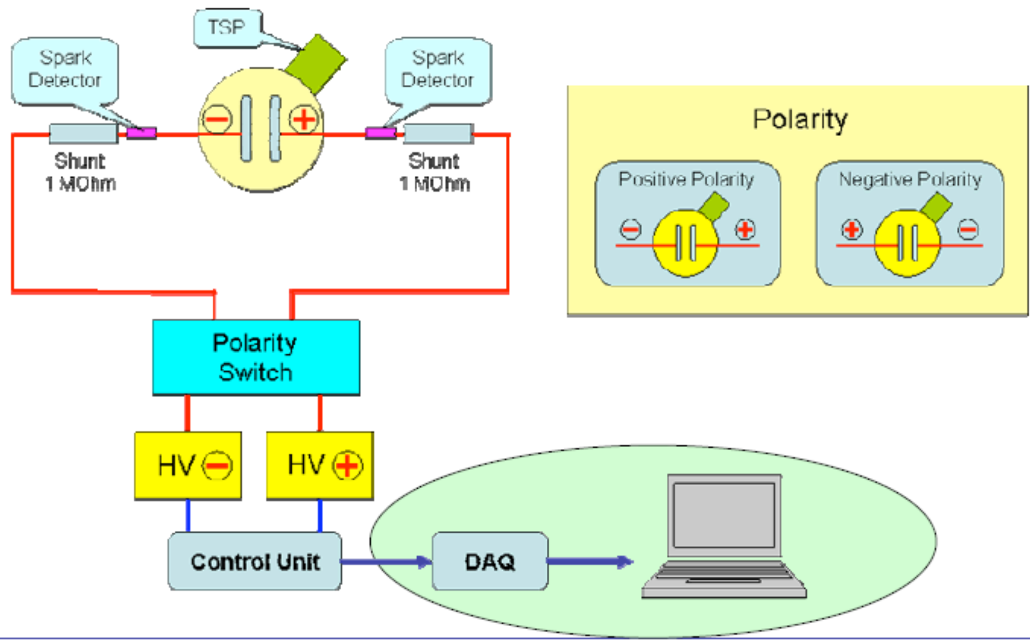
E-field strength, Electrostatic Separators at Tevatron

Conditioning Test Facility at MP-9

New factory (clean room, baking oven, conditioning cave) was constructed at MP-9 for building beam separators (BTeV project).

R&D is being done to improve separator performance and reliability.
Tests new electrode materials, conditioning procedure
Goals: 1 spark/year at 150 kV/plate (60 kV/cm)

Measuring scheme



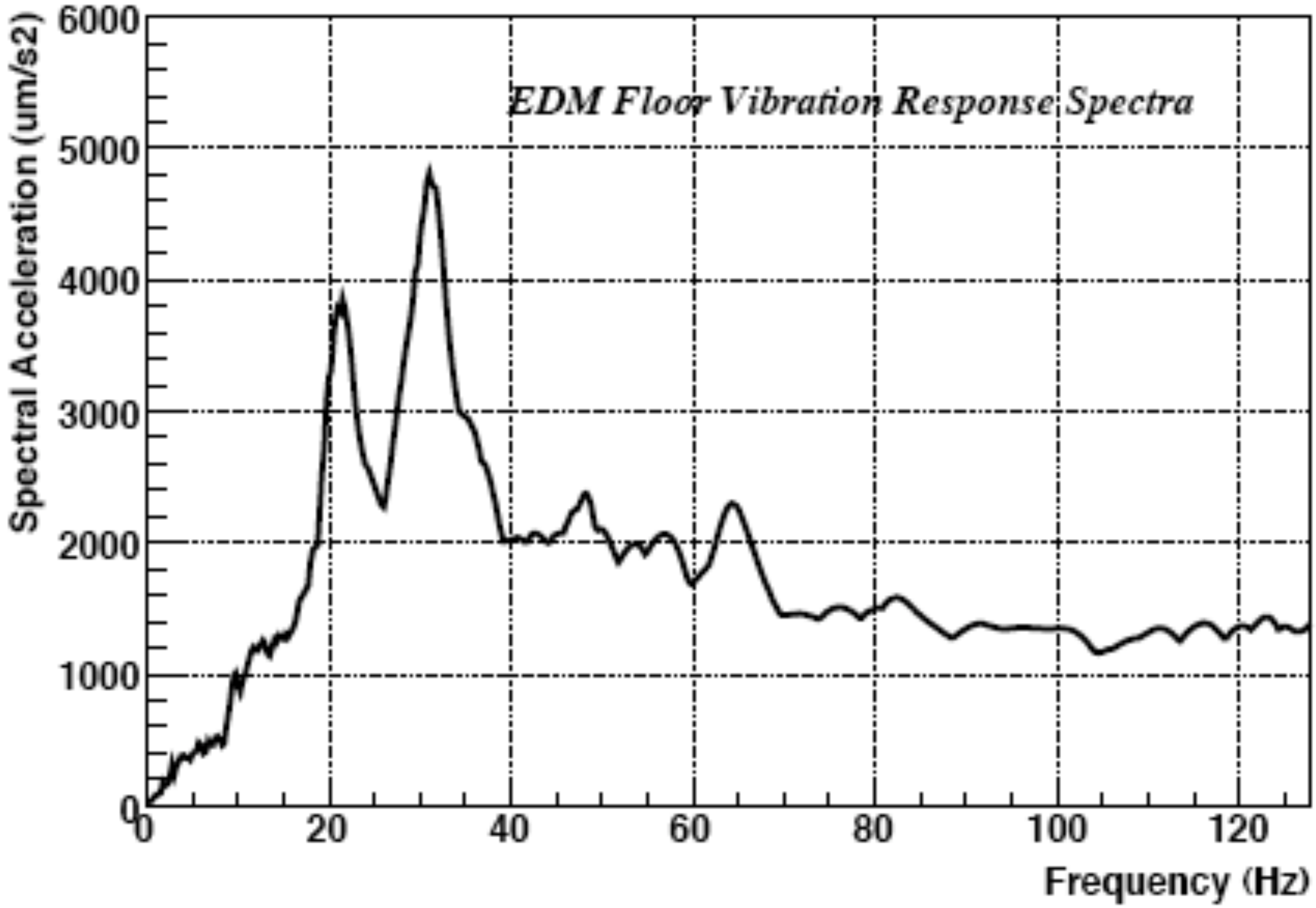


Figure 8: Response function of the AGS experimental floor as a function of frequency.

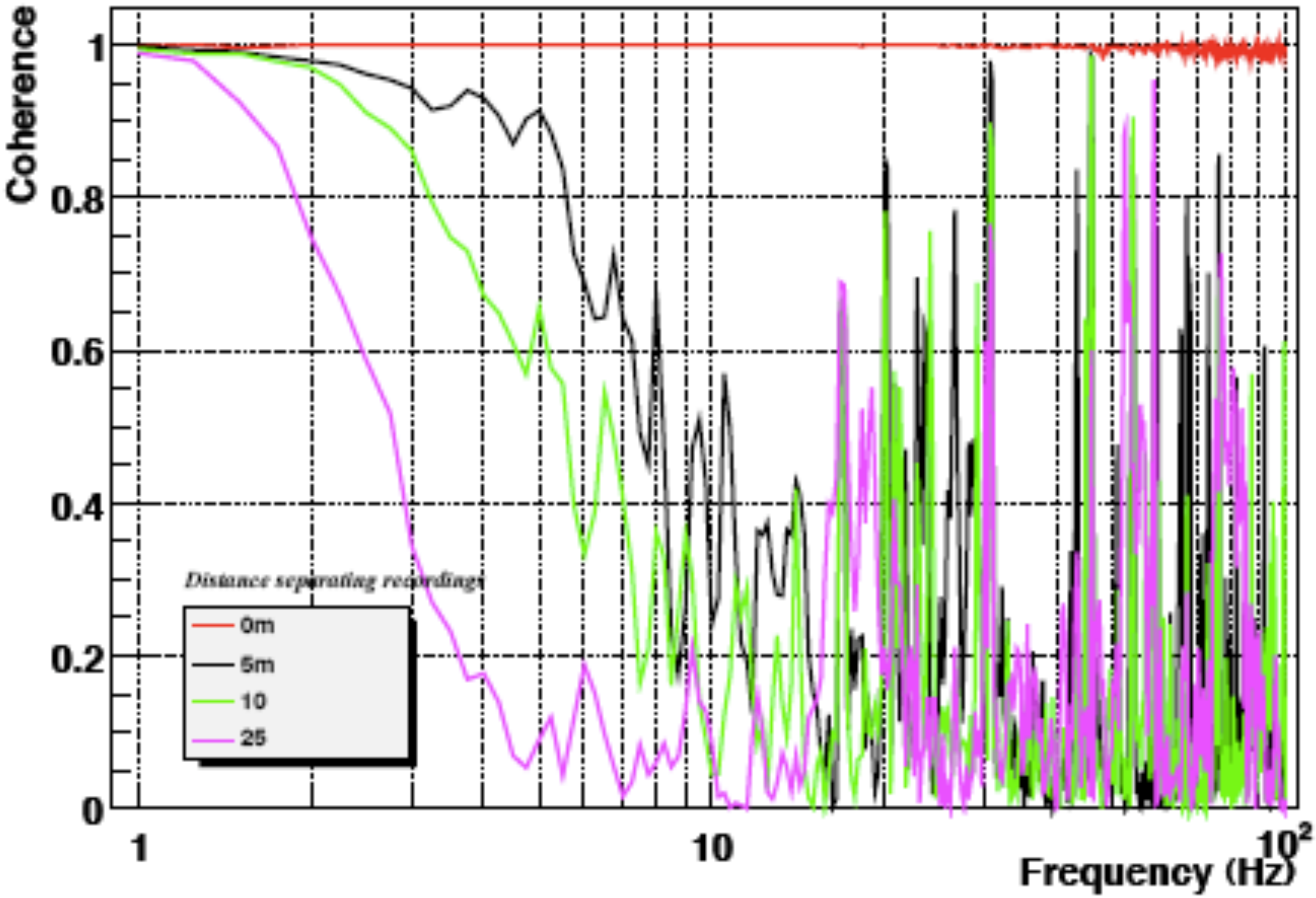


Figure 7: Coherence between various points of the AGS floor as a function of frequency for various distances between the probes.

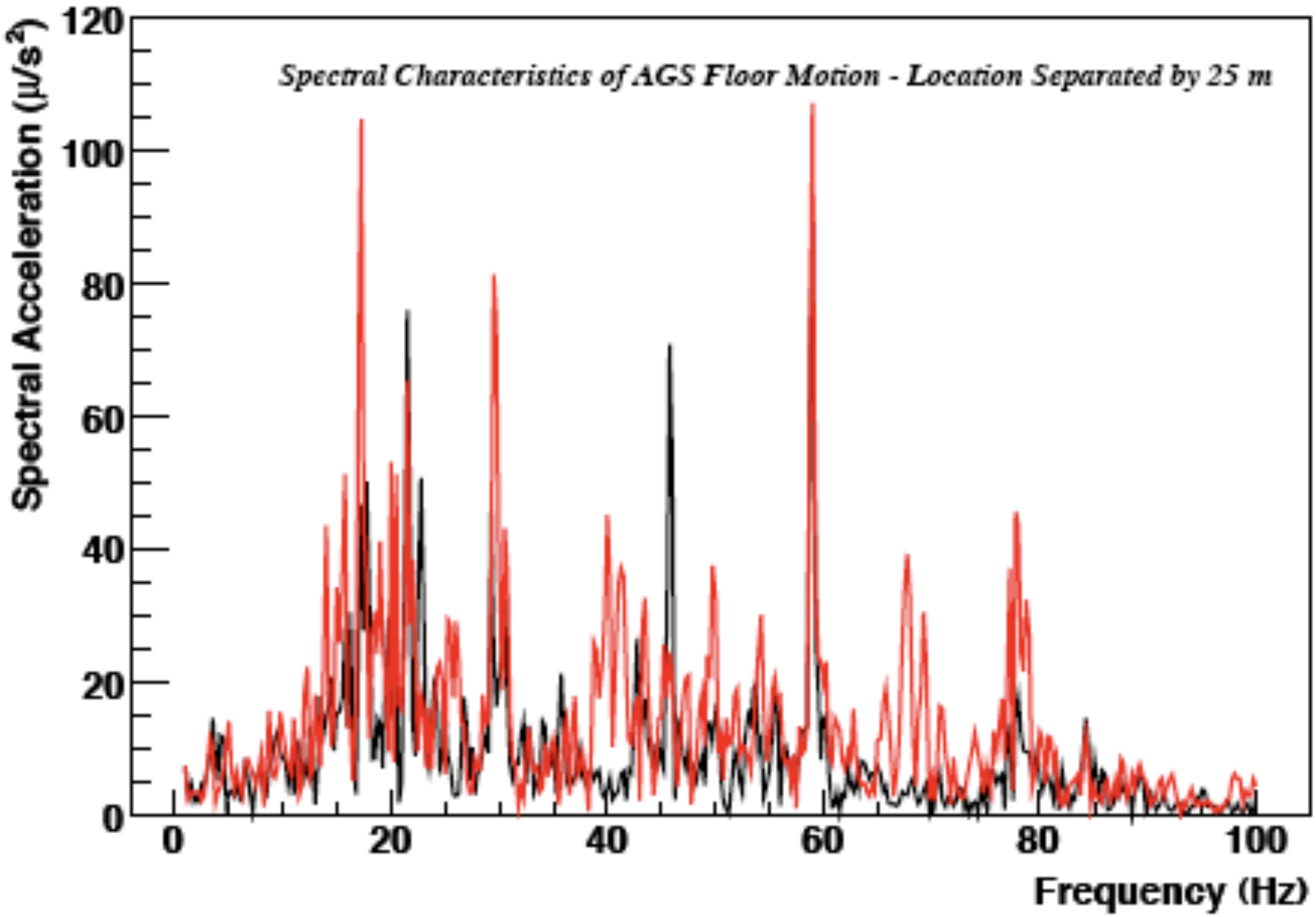
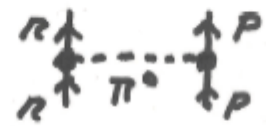


Figure 6: Acceleration data in μm/s^2 vs. frequency in Hz, taken at the AGS experimental floor with two probes separated by 25 m.

Nuclear Theory Clean

$$d_D = d_n + d_p + d_D^{Nuclear}$$



$I=1$

Pion P+S interaction

Violates P+T, Large!

S-P States Mix → d_D

No Electron (Schiff) Shielding (in Atoms)

$$d_{Deuterium} \sim 10^{-7} d_{Deuteron}$$

$d_D^{Nuclear}$ Generally Dominates

Eg. $\bar{\theta}$ of QCD (Currently $\bar{\theta} < 10^{-10}$)

$d_u + d_d$ of quarks

$d_u^c + d_d^c$ color (gluon) edms

$$d_n \simeq 3\times10^{-16}\bar{\theta}\ e\text{-cm} + 1.4(d_d - 0.25 d_u) + 0.83(d_d^c + d_u^c) + 0.27(d_d^c - d_u^c)e$$

$$d_D \simeq -1\times10^{-16}\bar{\theta}\ e\text{-cm} + (d_d + d_u) - 0.20(d_d^c + d_u^c) + \underline{6\ (d_d^c - d_u^c)e}$$

Complementary

$d_D / d_n \simeq -\frac{1}{3} \rightarrow \bar{\theta}$ source $\sim 10^{-13}$ Sensitivity!

$d_D / d_n \simeq 22 \rightarrow d_d^c - d_u^c$ dominates (eg SUSY)

If $d_D \neq 0$, Storage Ring $\rightarrow d_p + d_{He}$ ...

Compelling Probe of SUSY, LR, Multi-Higgs ...

Generic Loop Prediction: $d \sim \frac{eg^2}{16\pi^2} \frac{m_q}{M^2} \sin\delta$

$d \sim 10^{-24}$ e-cm $\times \sin\delta \times \left(\frac{1\,\text{TeV}}{M}\right)^2$

SUSY → $d_n \sim 10^{-25} - 10^{-28}$ e-cm $\sim d_D$ (Observable)

δ very small or $M > 1$ TeV (SUSY CP Crisis)?

If LHC discovers SUSY < 1 TeV

$d_n, d_D \ldots d_p, d_{He^3}$ Sort Phase Structure.. (Complementary)

If LHC Fails To Find SUSY

d_D probes up to $M \sim 1000$ TeV! (Spectacular!)

 W. Marciano

Deuteron EDM Theory

EDMs Violate P+T Symmetries (N. Ramsey d_n)

Standard Model: $|d_n| \sim 10^{-31} - 10^{-32}$ e-cm $|d_e| \sim 10^{-40}$ e-cm

Currently unobservable

Window to "New Physics" (eg Supersymmetry $d_n \sim 10^{-25} - 10^{-28}$ e-cm)

BNL L.O.I. Goal: $d_D \to 10^{-29}$ e-cm! Spectacular!

Competitive (Better) - Other EDM Exps.

Clean (Theory) - Simple pn bound state (No Schiff shielding)

Complementary - LHC + Other EDMs ...

Compelling - $M_{CP} \sim$ 1-1000 TeV (SUSY, LR, Higgs...)

Baryogenesis!

Comparison With Other EDM Efforts

	Current Bound	Future Goal	~d_n Equivalent
Neutron	$d_n < 3\times10^{-26}$ e-cm	$\sim 10^{-28}$ e-cm	10^{-28} e-cm
^{199}Hg atom	$d_{Hg} < 2\times10^{-28}$ e-cm	$\sim 2\times10^{-29}$ e-cm	$10^{-25}-10^{-26}$ e-cm
^{129}Xe atom	$d_{Xe} < 6\times10^{-27}$ e-cm	$\sim 10^{-30}-10^{-33}$ e-cm	$10^{-26}\sim10^{-29}$ e-cm
Deuteron	–	10^{-29} e-cm	$3\times10^{-29}-5\times10^{-31}$ e-cm

Deuteron Competitive - Better!

Marciano 9/2006

dEDM beam Specs

- Intensity: $2x10^{11}$ deuterons stored per ring
- Polarization: ≥ 80%, up and down polarization, in two bunches
- dp/p ≤ 10^{-3}
- Emittance. Horiz.: 3 mm mrad, vertical: 5 mm mrad
- Momentum: 1 GeV/c (total) or 250 MeV kinetic energy
- Running time for 10^{-29} e•cm (statistics): 10^{7} seconds

Cost

8.1 Storage Ring

16 dipole magnets @ $50 K each		800 K
48 quadrupole magnets @ $25 K each		800 K
32 sextupole magnets @ $15 K each		480 K
Dipole power supply		250 K
Quadrupole magnet power supply		250 K
RF cavity & associated equipment		150 K
Vacuum & vacuum instrumentation		750 K
16 electric field regions with power supplies		1,000 K
Controls		160 K
Beam instrumentation		350 K
20 m diameter storage ring shielding		1,000 K
	Sub-Total	**$5,990 K**
	Including Burdens	**$17,670 K**
Injection kicker magnet & PFN		2,123 K
	Sub-Total	**$19,793 K**

8.2 Experimental Systems

Tiltmeters		100 K
Fabry-Perot interferometers		300 K
NMR and Kerr effect system		300 K
4 Polarimeters, including data acquisition system.		929 K
Electron cooling		1,650 K
	Sub-Total	**$3,229 K**

8.3 Total deuteron EDM ring cost

$23,022 K

Cost

8.4 Beamline and Conventional Facilities

In addition to the ring-experiment cost, the total cost of a beamline from the AGS to the deuteron EDM ring is estimated (including full burdens) to be $7M, bringing the total experiment cost to **$30,022K** .

As noted, this cost estimate was prepared for building the deuteron EDM storage ring at BNL. Other sites, such as CERN, FNAL, and J-PARC are under consideration. Cost estimates will likely differ because of differences in the overhead rates, the amount of existing equipment and infrastructure that can be made available, and operating costs.

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[4] Burdens include: Costs for labor (75%), EDIA (Engineering, Design, Installation and Assembly) (15%), contingency (25%) and additional charges (17%). Total costs for items without the indication "Including Burdens" were based on estimates from known costs, including burdens based on recent experience with sufficiently similar devices.

Physics community response

- NP Long Range Plan (NSAC) includes a very strong support of dEDM development recognizing its physics potential (BNL is a NP lab).

- EDMs are part of WG3 of “Flavour in the era of LHC” at CERN. The two volume report just finished, where the dEDM has a very strong presence http://cern.ch/flavlhc