13 March 2017
Kickoff EDM meeting, CERN

Storage Ring EDM experiments: Proton and Deuteron

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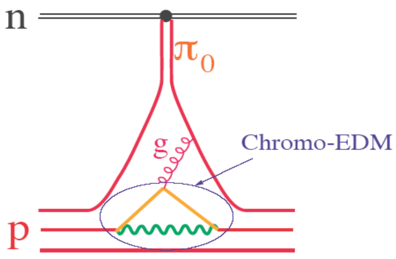
BASICS

- Proton and Deuteron
  - Pros and cons for both. Start with simpler and more ready system. Plan for both.
- Precision physics frontier
  - Estimate R&D period, R&D scope
  - Storage ring EDMs, probing NP ~10^3-10^4 TeV



The Storage Ring EDM

The Electric Dipole Moment precesses in an Electric field

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

Electric Dipole Moments in Magnetic Storage Rings

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

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

Storage Ring Electric Dipole Moments

Fields	**Example**	**EDM term**	**Comments**
Dipole magnetic field **(B)**	Muon g-2	Tilt of the spin precession plane. (Limited sensitivity due to spin precession)	Eventually limited by geometrical alignment. Requires CW and CCW injection to eliminate systematic errors
Combination of electric and magnetic fields **(E, B)**	Deuteron, ^{3}He, proton, etc.	Mainly: $\boxed{\frac{d\vec{s}}{dt} = \vec{d} \times \left(\vec{v} \times \vec{B}\right)}$	Most powerful. Small ring. Need to build combined B and E-field system. Reduce vertical E-field.
Radial Electric field **(E)**	Proton, etc.	$\boxed{\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}}$	Large ring, CW & CCW storage. Simplest to achieve. Reduce radial B-field.

Storage ring EDM: The deuteron

- 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

2. Combined E&B-fields:

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

- Using a combination of dipole B-fields and radial E-fields to freeze the spin. The required E-field is

$$\mathrm{E} \approx a\mathrm{Bc}\beta\gamma^2, \text{ i.e. the smaller the } a \text{ the better!}$$

Deuteron: Momentum 1 GeV/c, B=0.5 T, E=120KV/cm

Deuteron, final sensitivity: few 10^{-29} e-cm

Large a=(g-2)/2 vs. small a value

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

Use a radial E_r-field to cancel the g-2 precession but use the VxB internal E^*-field to precess spin.

For 1 GeV/c deuteron momentum, V/c=0.5, B=0.5T and E^* = 75MV/m equivalent.

Deuteron Statistical Error (250MeV):

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

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

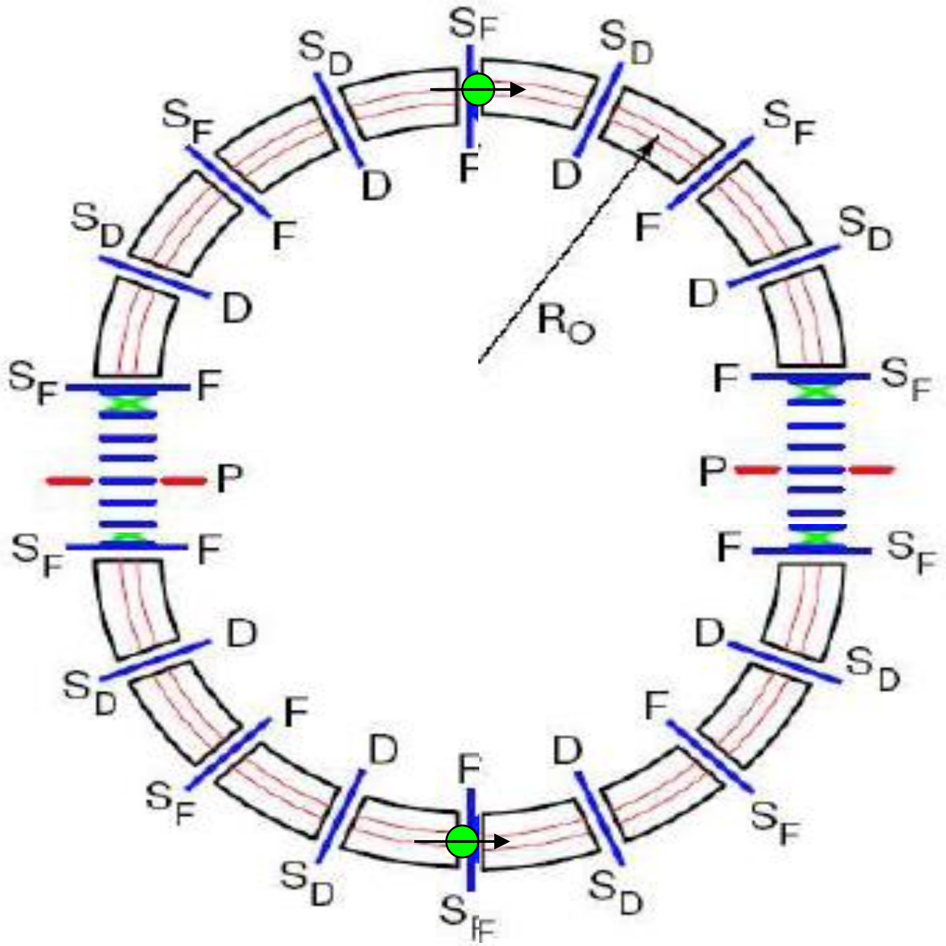
$$\sigma_d \approx 10^{-29}\,\mathrm{e}\cdot\mathrm{cm/year}$$

Main issues

✓ Polarimeter systematic errors <1ppm

- Average vertical electric field very strict (CW and CCW injections require B-field reversals)
- E-field strength: 120kV/cm
- Average E-field alignment: 10^{-7} rad; stability. (?)
- B-field and E-field combined. Geometrical phases: local spin cancellation $\sim 10^{-4}$. Stability; Sensitive Fabry-Perot resonator to be developed. (?)
- So-called patch effect. (?)

✓ Spin Coherence Time: $\sim 10^3$s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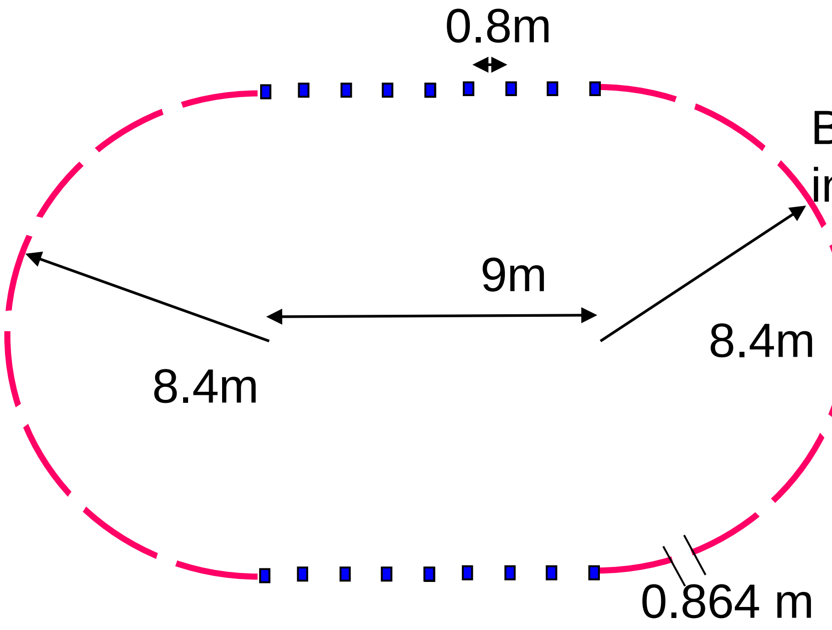
The dEDM ring (old!) lattice



Bend section (BE), Quadrupoles and sextupoles in between BE sections

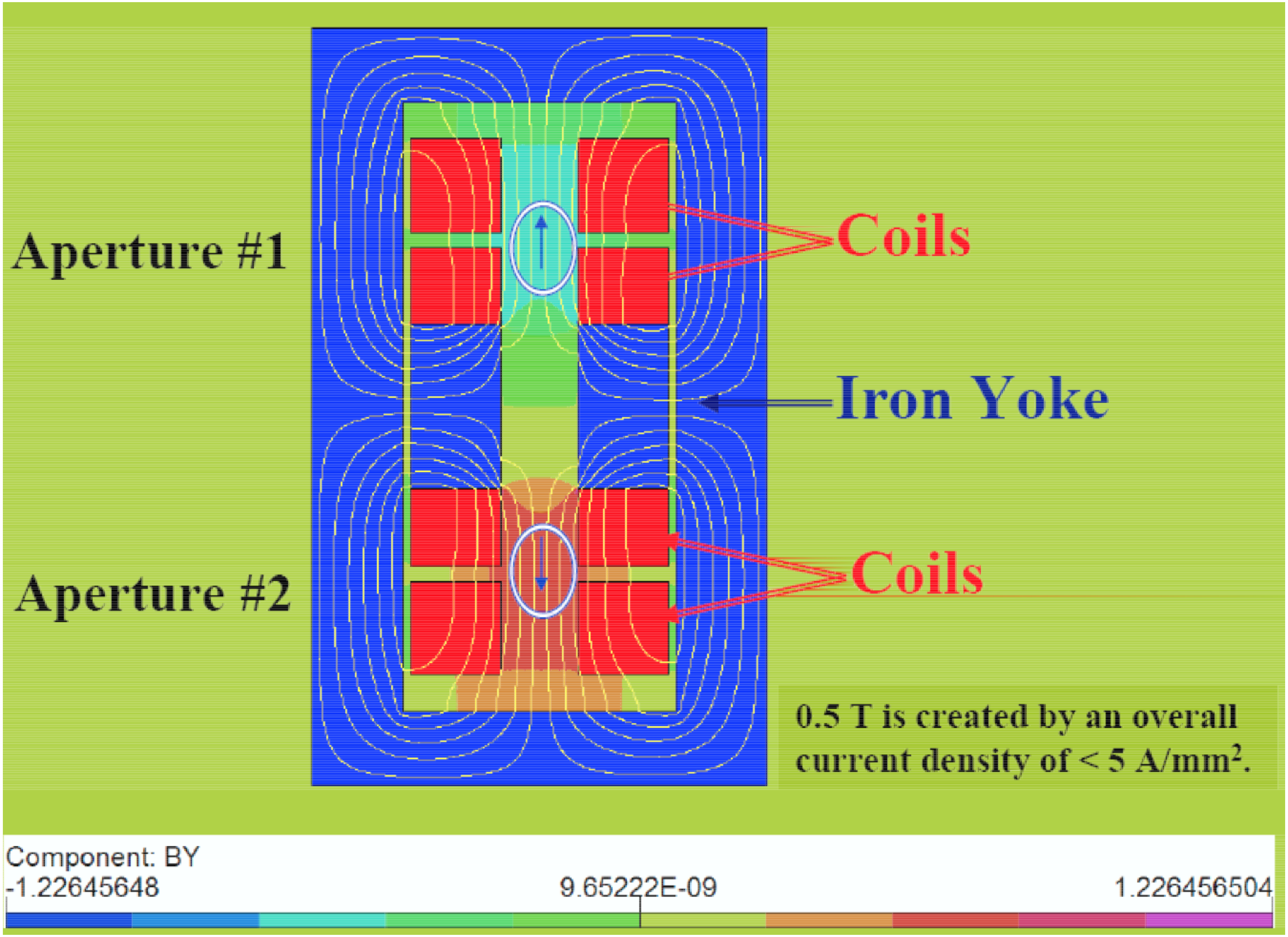
Straight section (s.s.)

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

EDM: vertical spin precession rate ~10nrad/s or ~10^{-14} rad/turn



Aperture #1

Coils

Iron Yoke

Aperture #2

Coils

0.5 T is created by an overall current density of < 5 A/mm^2.

Storage ring deuteron EDM reqs.

Particle	**E-field needed**	**Dipole B-field needed (combined E&B fields)**	**Flipping field for CW, CCW injections**	**Sensitive Fabry-Perot resonator needed**
Deuteron	YES: 12MV/m	YES (Space restrictions; e^- trapping)	B: YES E: No	YES
Proton	Yes: 8MV/m	No	No	No

Storage ring deuteron EDM reqs.

Particle	**Local g-2 phase cancellation**	**Spin Coherence Time**	**Polarimeter**
Deuteron	10^{-4}; E&B balance, requires high stability	Vertical & horizontal pitch effects	Tensor polarization; break-up protons
Proton	10^{-4}, on average. Keeping the magic momentum correct with RF	Radial oscillations	No tensor issues

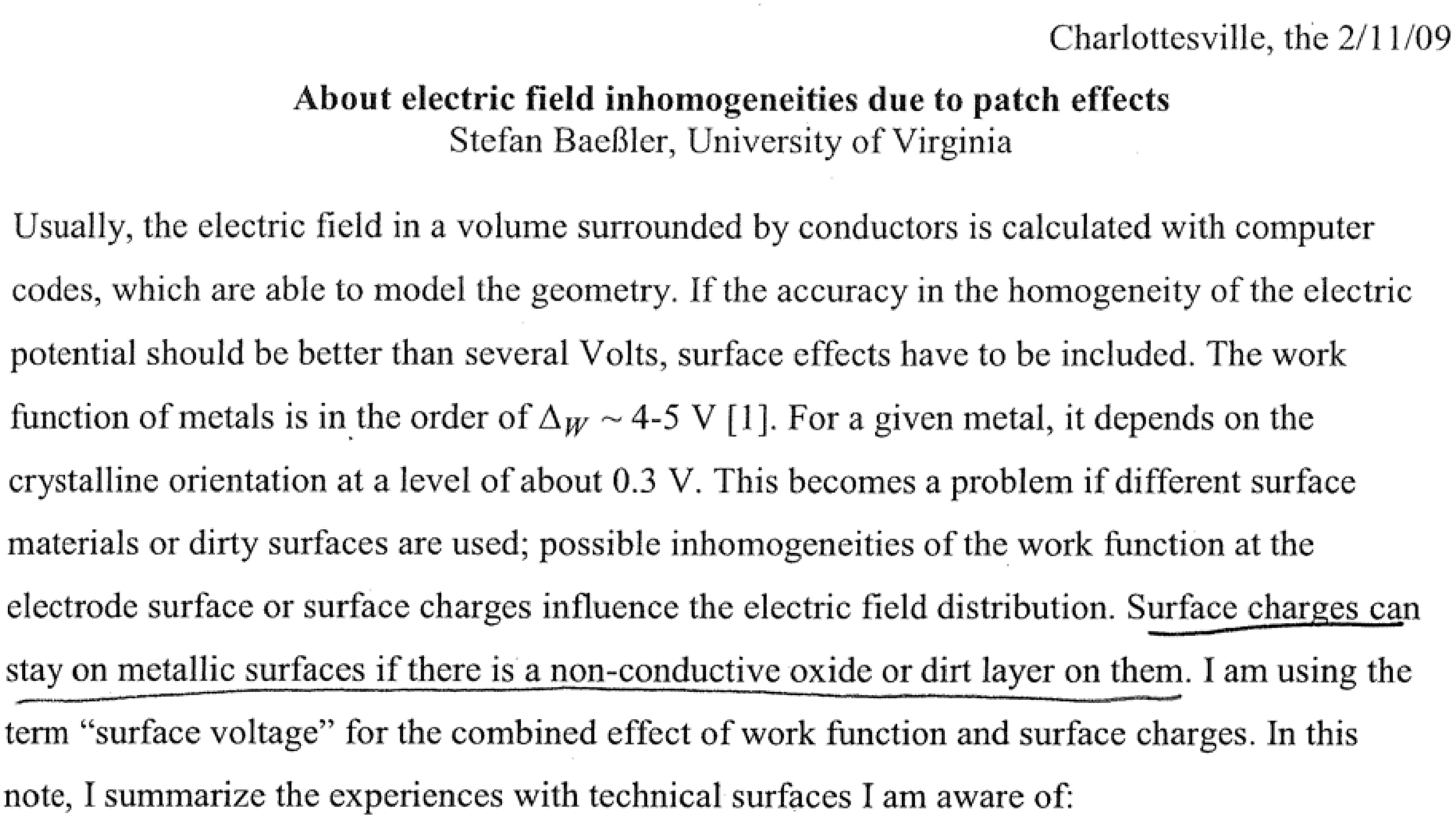
Storage ring deuteron EDM reqs.

Particle	**Ring circumference**	**Running issues**	**Sensitivity**
Deuteron	~85m	Patch effect; Stability of B-field after flip	~2×10^{-29} e-cm /year
Proton	~500m	No patch effect issues; No field flips	~2×10^{-29} *e*-cm/year

Patch effect

- Electric voltages/fields generated on metal surfaces.
- Time constant of some fields: ~100-200s
- Large effects, needs to be studied

Patch effect



Charlottesville, the 2/11/09

About electric field inhomogeneities due to patch effects

Stefan Baeßler, University of Virginia

Usually, the electric field in a volume surrounded by conductors is calculated with computer codes, which are able to model the geometry. If the accuracy in the homogeneity of the electric potential should be better than several Volts, surface effects have to be included. The work function of metals is in the order of $\Delta_W \sim 4\text{-}5$ V [1]. For a given metal, it depends on the crystalline orientation at a level of about 0.3 V. This becomes a problem if different surface materials or dirty surfaces are used; possible inhomogeneities of the work function at the electrode surface or surface charges influence the electric field distribution. Surface charges can stay on metallic surfaces if there is a non-conductive oxide or dirt layer on them. I am using the term “surface voltage” for the combined effect of work function and surface charges. In this note, I summarize the experiences with technical surfaces I am aware of:

Patch effect due to irradiation

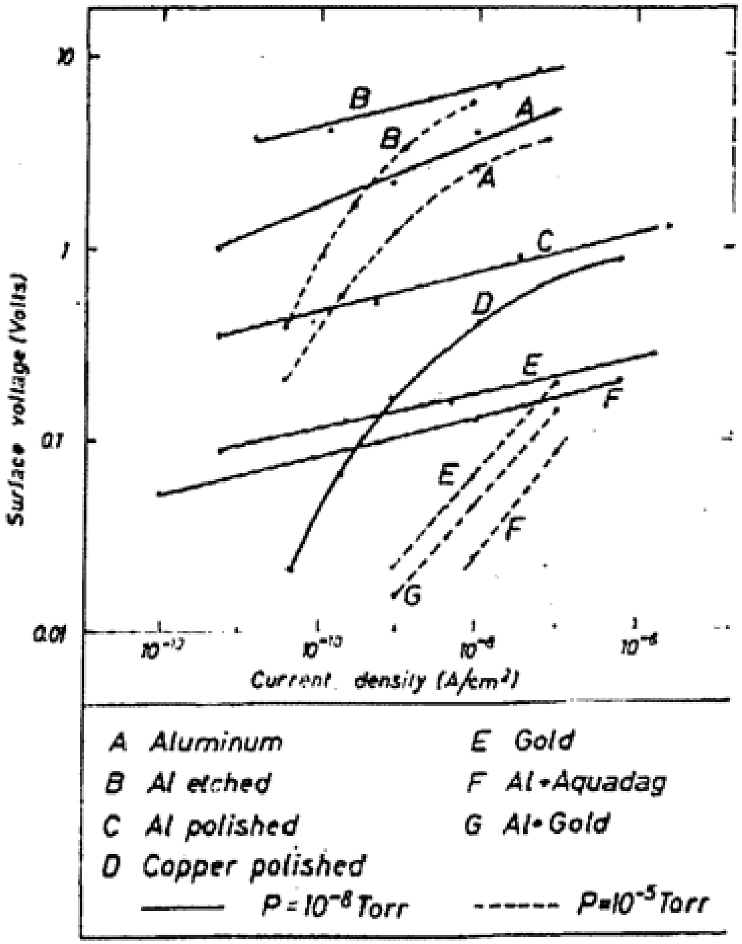


Fig. 1: The measured change of electric potential difference between metal and the surrounding vacuum is called “Surface Voltage”. Aquadag is a kind of colloidal graphite coating (from [1]).

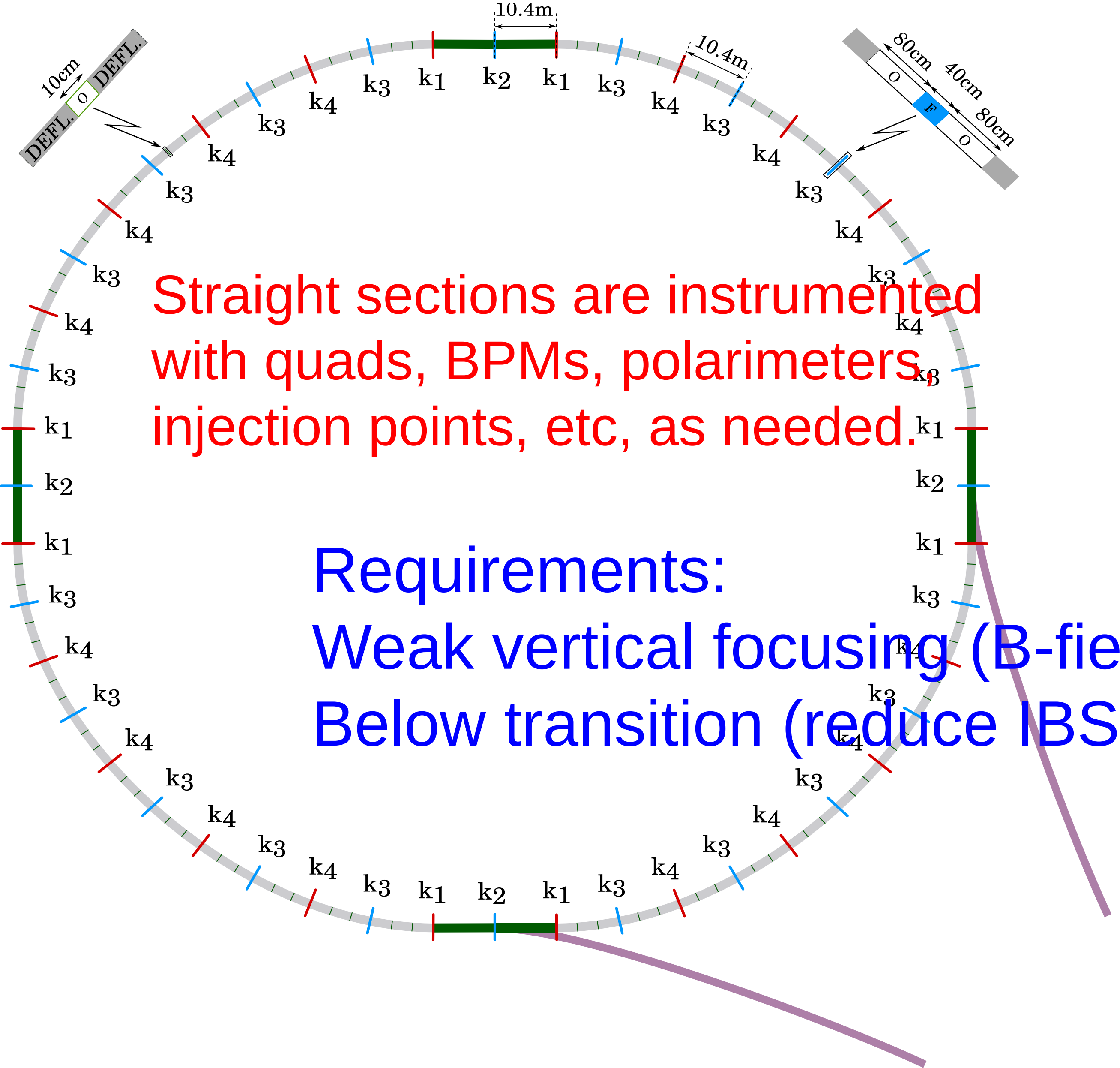
Deuteron EDM issues

- Crucial systematic error studies
  - Stability of E_v, including with B-field reversal
  - Geometrical errors
- Precision beam/spin dynamics simulations
- Accurate combined fringe-field simulation
- E-field strength, low energy e^- trapping in combined (E&B) fields
- Patch effect
- …

Storage ring EDM: The proton

- High intensity sources (~10^{11}/fill)
- High vector polarization (>80%)
- High analyzing power for 0.7 GeV/c (233MeV)
- Long spin coherence time possible (>10^3s)
- Simultaneous CW & CCW storage

The proton EDM electric ring, 500m circ.



Straight sections are instrumented
with quads, BPMs, polarimeters,
injection points, etc, as needed.

Requirements:
Weak vertical focusing (B-field sensitivity)
Below transition (reduce IBS)

Proton Statistical Error (230MeV):

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

τ_p	: 10^3s	Polarization Lifetime (Spin Coherence Time)
A	: 0.6	Left/right asymmetry observed by the polarimeter
P	: 0.8	Beam polarization
N_c	: 10^{11}p/cycle	Total number of stored particles per cycle
T_{Tot}	: 10^7s	Total running time per year
f	: 1%	Useful event rate fraction (efficiency for EDM)
E_R	: 7 MV/m	Average radial electric field strength

$$\sigma_d = 1.0 \times 10^{-29} \text{ e-cm / year}$$

Systematic errors

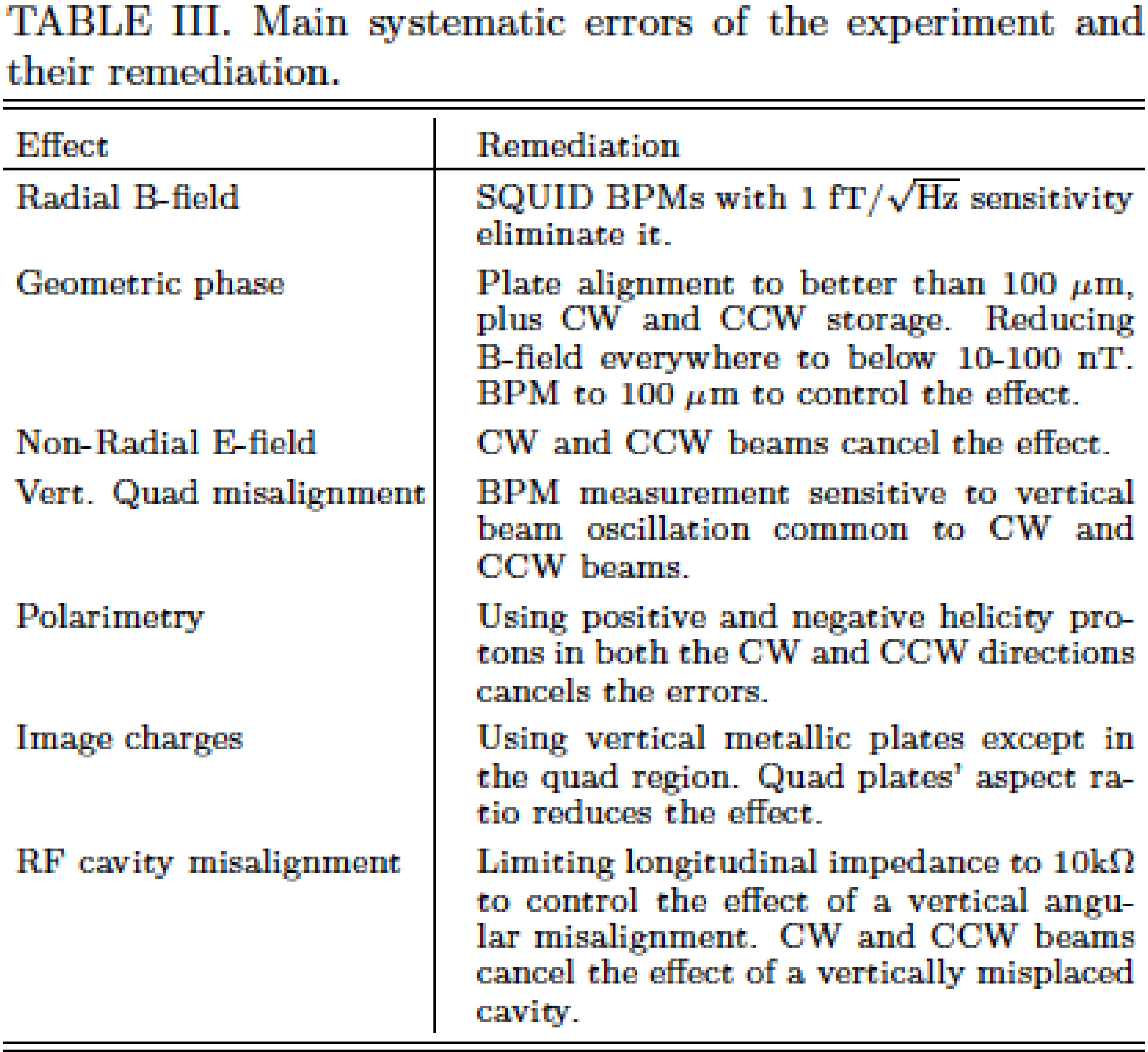
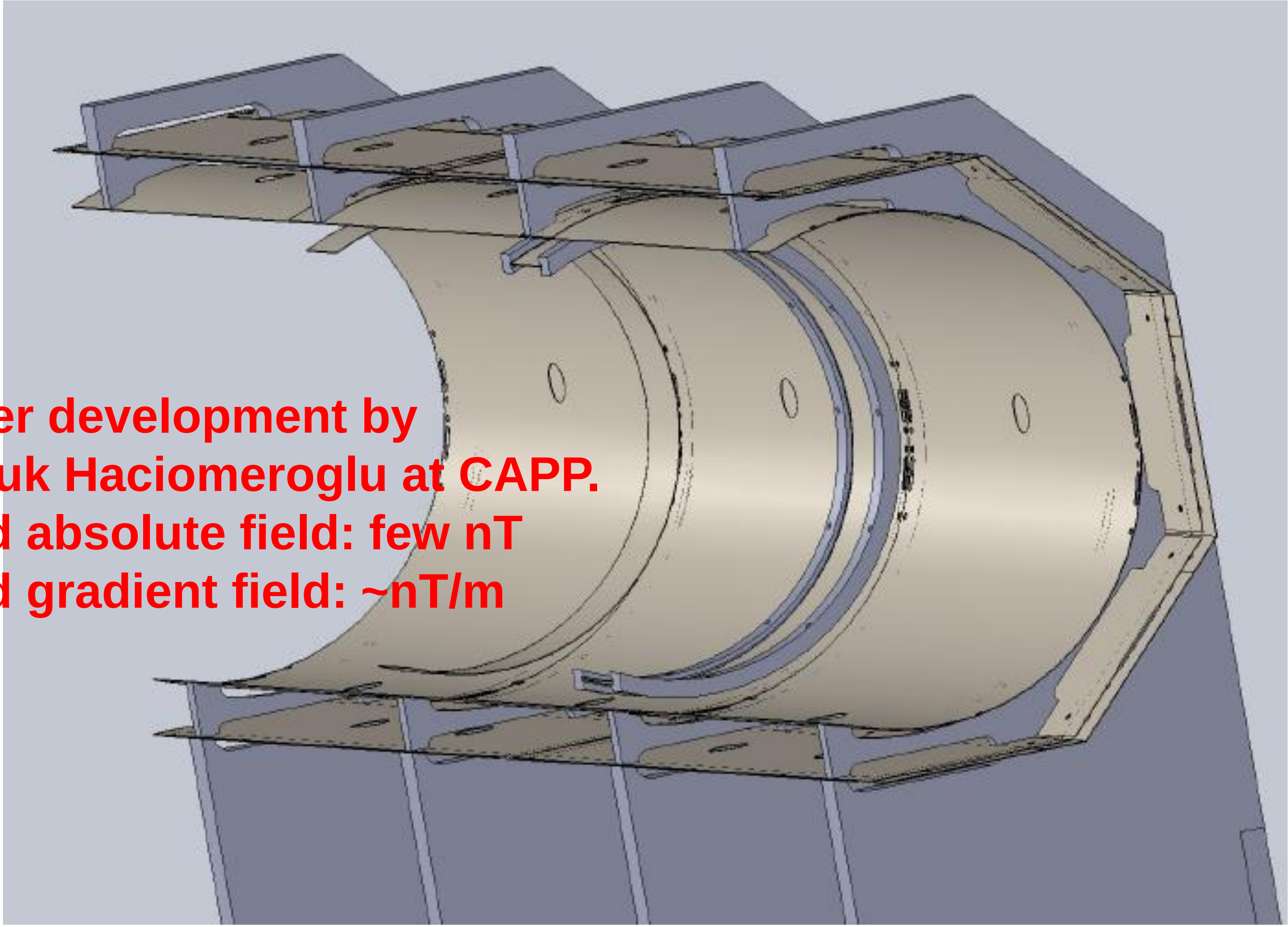


TABLE III. Main systematic errors of the experiment and their remediation.

Effect	Remediation
Radial B-field	SQUID BPMs with 1 fT/$\sqrt{\text{Hz}}$ sensitivity eliminate it.
Geometric phase	Plate alignment to better than 100 μm, plus CW and CCW storage. Reducing B-field everywhere to below 10-100 nT. BPM to 100 μm to control the effect.
Non-Radial E-field	CW and CCW beams cancel the effect.
Vert. Quad misalignment	BPM measurement sensitive to vertical beam oscillation common to CW and CCW beams.
Polarimetry	Using positive and negative helicity protons in both the CW and CCW directions cancels the errors.
Image charges	Using vertical metallic plates except in the quad region. Quad plates' aspect ratio reduces the effect.
RF cavity misalignment	Limiting longitudinal impedance to 10kΩ to control the effect of a vertical angular misalignment. CW and CCW beams cancel the effect of a vertically misplaced cavity.

Peter Fierlinger, Garching/Munich



Under development by
Selcuk Haciomeroglu at CAPP.
Need absolute field: few nT
Need gradient field: ~nT/m

Peter Fierlinger, Garching/Munich

Shipped to Korea for integration

Achieved so far:
Absolute field: <0.5nT
Gradient field: <2.0nT/m
Finishing up!

Proton systematic errors case

1. Main systematic error (radial B-field) is well under control: measure ds_v/dt and vertical split of beams at 1kHz.

2. Geometrical phase for B-field: CW vs CCW cancel!

3. B-field shielding: few nT, well under control

4. E-field specs: 100μm placement, 10μm using beam based alignment?

Summary

1. Proton systematic error studies show great promise, coming to conclusions soon.

2. Deuteron questions:
    1. E_V stability, including when B-field is reversed
    2. Level of local cancellation with mixed E and B-fields (Geometrical phases)
    3. Patch effect from E-field plate surfaces.
    4. Complications from Tensor polarization?

Extra slides

Spin Coherence Time: need ~10^3 s

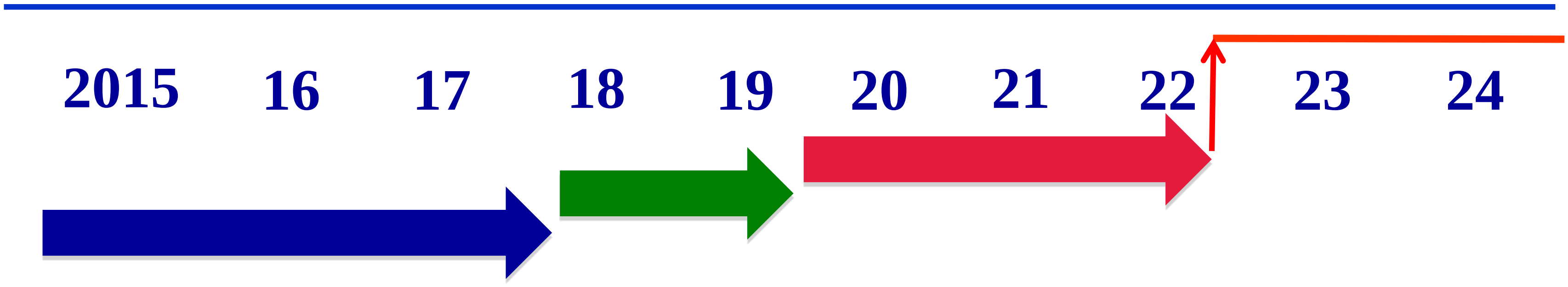
- Not all particles have same deviation from magic momentum, or same horizontal and vertical divergence (all second order effects)

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

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

- Present design parameters allow for 10^3 s.
- Much longer SCT with thermal mixing (S.C.)?

Technically driven pEDM timeline



- Research and systems development (R&D); CDR; final ring design, TDR, installation

- CDR by fall of 2018

- Proposal to a lab: fall 2018

REVIEW OF SCIENTIFIC INSTRUMENTS **87**, 115116 (2016)

A storage ring experiment to detect a proton electric dipole moment

V. Anastassopoulos,[1] S. Andrianov,[2] R. Baartman,[3] S. Baessler,[4] M. Bai,[5] J. Benante,[6]
M. Berz,[7] M. Blaskiewicz,[6] T. Bowcock,[8] K. Brown,[6] B. Casey,[9] M. Conte,[10] J. D. Crnkovic,[6]
N. D'Imperio,[6] G. Fanourakis,[11] A. Fedotov,[6] P. Fierlinger,[12] W. Fischer,[6] M. O. Gaisser,[13]
Y. Giomataris,[14] M. Grosse-Perdekamp,[15] G. Guidoboni,[16] S. Hacıömeroğlu,[13]
G. Hoffstaetter,[17] H. Huang,[6] M. Incagli,[18] A. Ivanov,[2] D. Kawall,[19] Y. I. Kim,[13] B. King,[8]
I. A. Koop,[20] D. M. Lazarus,[6] V. Lebedev,[9] M. J. Lee,[13] S. Lee,[13] Y. H. Lee,[21] A. Lehrach,[5,22]
P. Lenisa,[16] P. Levi Sandri,[23] A. U. Luccio,[6] A. Lyapin,[24] W. MacKay,[6] R. Maier,[5] K. Makino,[7]
N. Malitsky,[6] W. J. Marciano,[6] W. Meng,[6] F. Meot,[6] E. M. Metodiev,[13,25] L. Miceli,[13]
D. Moricciani,[26] W. M. Morse,[6] S. Nagaitsev,[9] S. K. Nayak,[6] Y. F. Orlov,[17] C. S. Ozben,[27]
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H. Kamal Sayed,[6] Y. K. Semertzidis,[13,28,a)] Y. Senichev,[5] A. Sidorin,[29] A. Silenko,[29,30]
N. Simos,[6] A. Stahl,[22] E. J. Stephenson,[31] H. Ströher,[5] M. J. Syphers,[9,32] J. Talman,[6]
R. M. Talman,[17] V. Tishchenko,[6] C. Touramanis,[8] N. Tsoupas,[6] G. Venanzoni,[23] K. Vetter,[33]
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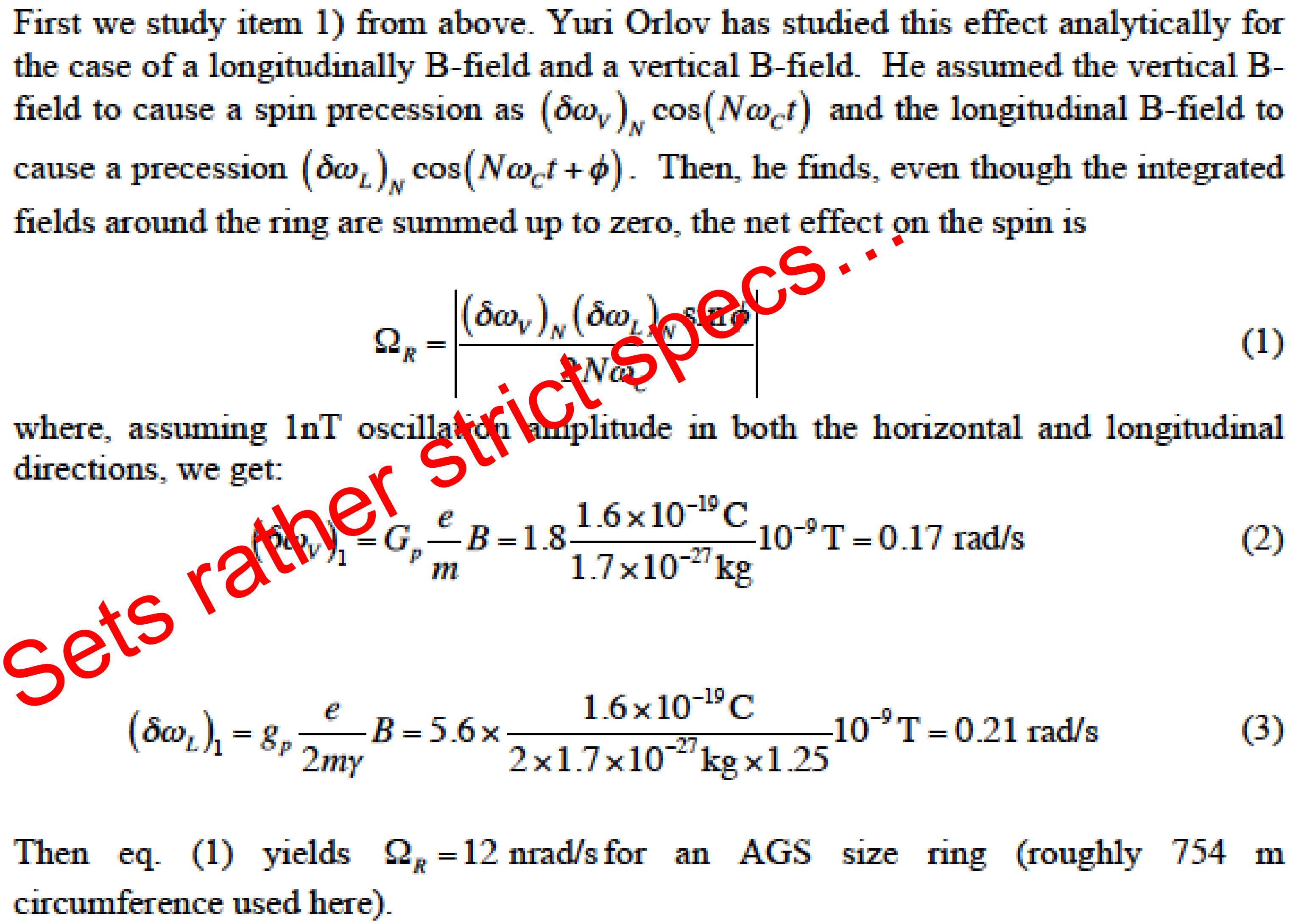
Geometrical Phases in Deuteron EDM

Example from the proton case:



First we study item 1) from above. Yuri Orlov has studied this effect analytically for the case of a longitudinally B-field and a vertical B-field. He assumed the vertical B-field to cause a spin precession as $(\delta\omega_V)_N \cos(N\omega_C t)$ and the longitudinal B-field to cause a precession $(\delta\omega_L)_N \cos(N\omega_C t + \phi)$. Then, he finds, even though the integrated fields around the ring are summed up to zero, the net effect on the spin is

$$\Omega_R = \left| \frac{(\delta\omega_V)_N (\delta\omega_L)_N \sin\phi}{2N\omega_C} \right| \qquad (1)$$

where, assuming 1nT oscillation amplitude in both the horizontal and longitudinal directions, we get:

$$(\delta\omega_V)_1 = G_p \frac{e}{m} B = 1.8 \frac{1.6\times10^{-19}\,\mathrm{C}}{1.7\times10^{-27}\,\mathrm{kg}} 10^{-9}\,\mathrm{T} = 0.17\ \mathrm{rad/s} \qquad (2)$$

$$(\delta\omega_L)_1 = g_p \frac{e}{2m\gamma} B = 5.6\times \frac{1.6\times10^{-19}\,\mathrm{C}}{2\times1.7\times10^{-27}\,\mathrm{kg}\times1.25} 10^{-9}\,\mathrm{T} = 0.21\ \mathrm{rad/s} \qquad (3)$$

Then eq. (1) yields $\Omega_R = 12$ nrad/s for an AGS size ring (roughly 754 m circumference used here).

Sets rather strict specs…

Geometrical Phases in Deuteron EDM

Ground motion:

Coherence up to 90-120m apart.

days – the week of Feb. 7, 2004. One can see that the variance increases with L up to 90-120 m and then flattens out. That indicates lack of coherence (independence) of the motion of the pieces of the tunnel distanced by more than 120 m apart – at the time scale of 1 week. For shorter distances, the ATL law $<dY^2(T,L)>=ATL$ with coefficient $A_{TevB}=(2.2\pm1.2)\cdot10^{-6}$ $\mu m^2/s/m$ gives a good approximation of the data.

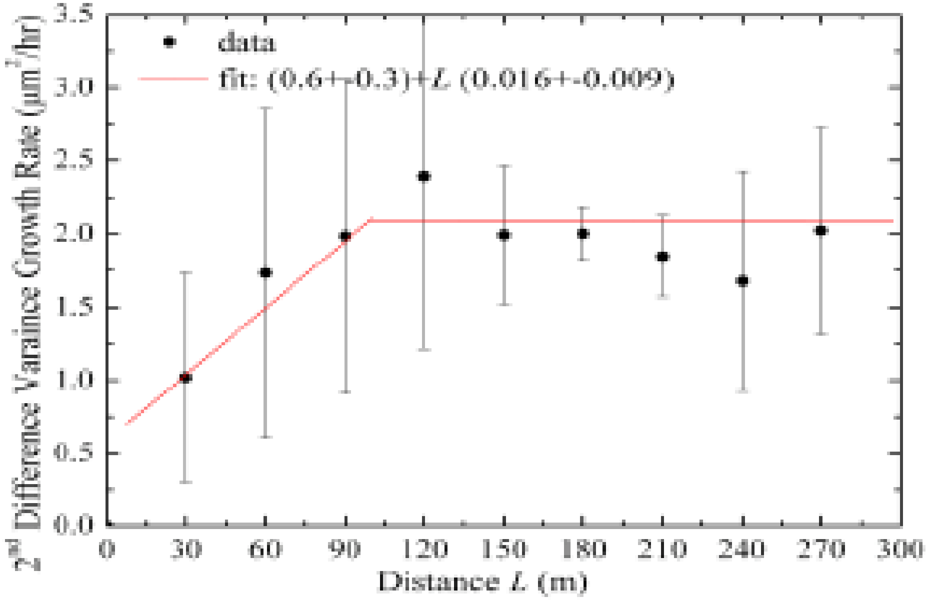


Fig.3. Dependence of the growth rate of the variance of the 2nd difference vs distance between the HLS probes (the Tevatron tunnel, the week of Feb 7,2004).

Geometrical Phases in Deuteron EDM

Ground motion:

FNAL MINOS hall

One can see that some 6 μm amplitude periodic variations due to the Earth tide dominate few μm scale slow drifts over weeks.

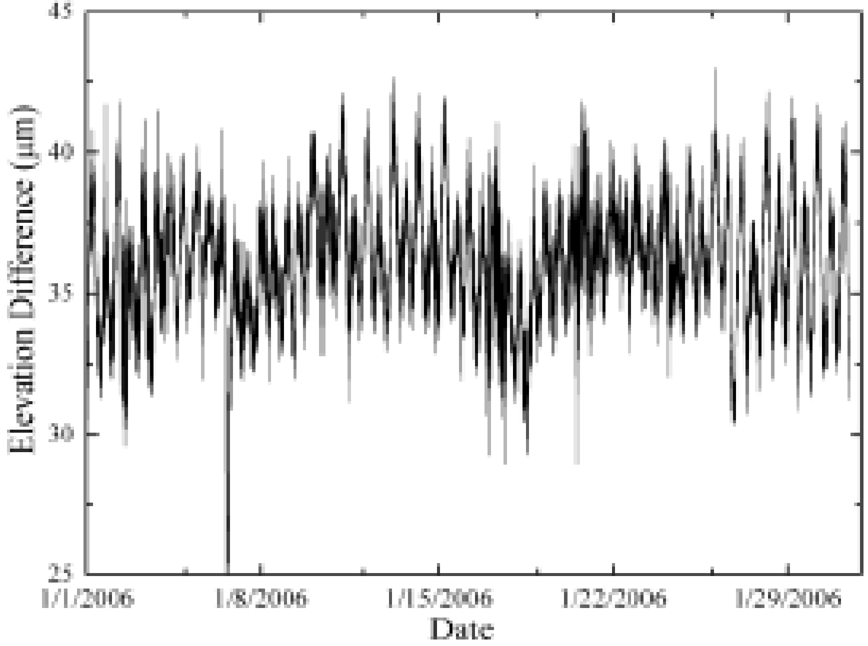


Fig.4. January 2006 record of elevation difference for two HLS probes 90 m apart in the FNAL MINOS hall.

Geometrical Phases in Deuteron EDM

Ground motion:

FNAL MINOS hall

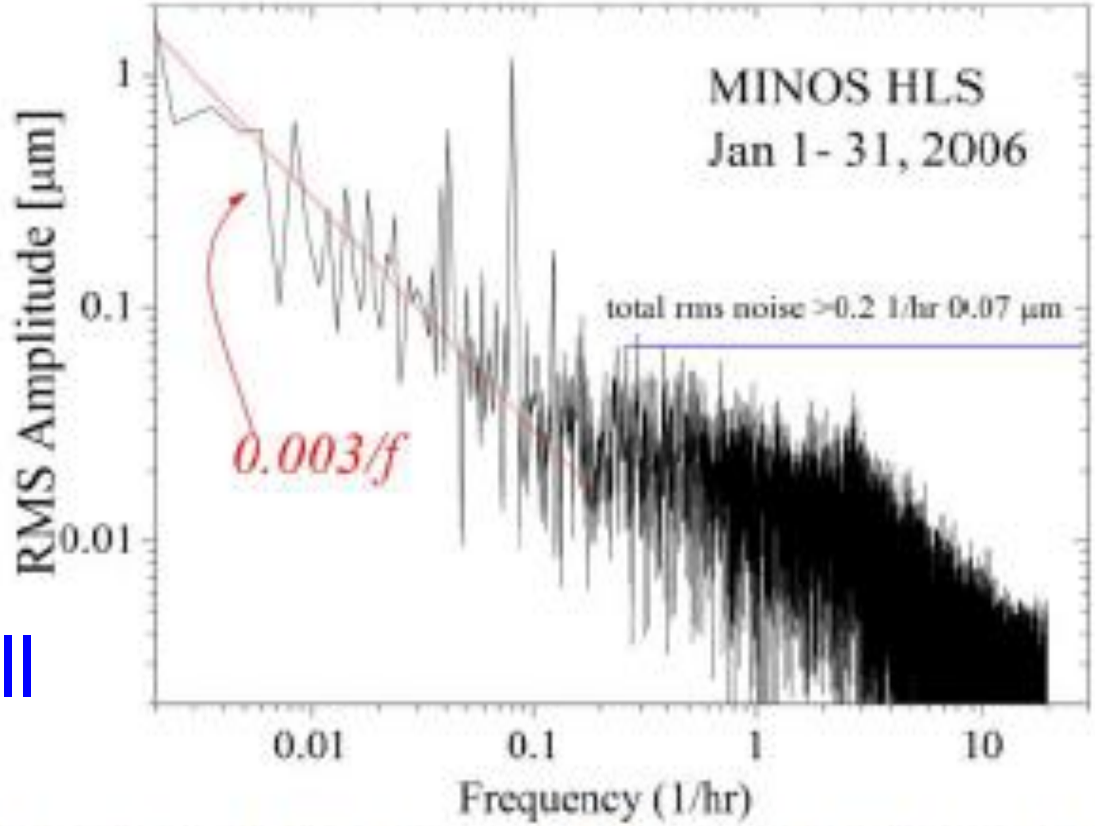


Fig.5. FFT of the elevation difference for HLS probes 90 m apart as measured in the Fermilab's MINOS all.

1. Symmetries

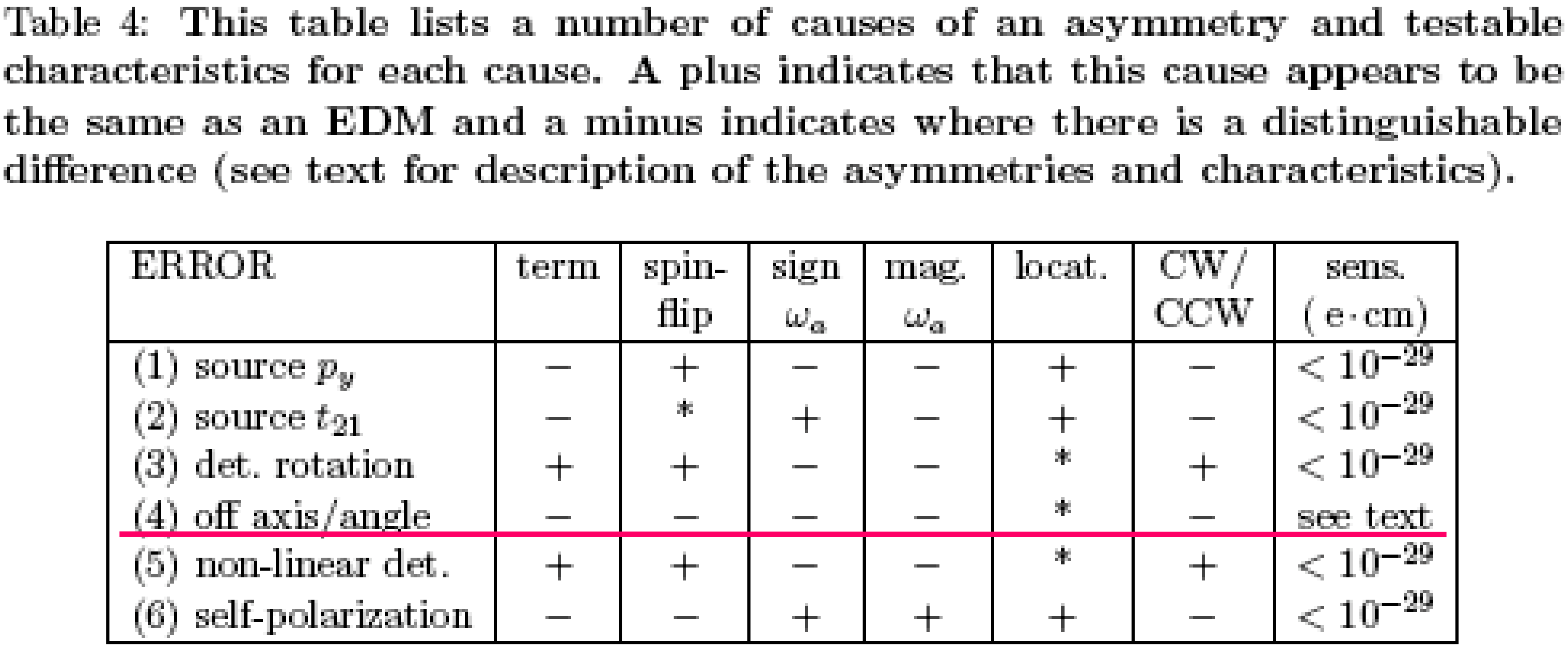


Table 4: **This table lists a number of causes of an asymmetry and testable characteristics for each cause. A plus indicates that this cause appears to be the same as an EDM and a minus indicates where there is a distinguishable difference (see text for description of the asymmetries and characteristics).**

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	$-$	$-$	$+$	$+$	$+$	$-$	$< 10^{-29}$

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