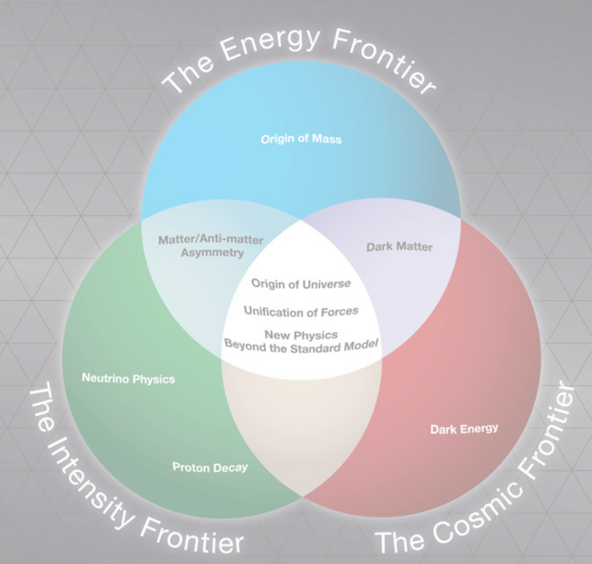
CAPP
Center for Axion and Precision Physics Research

Storage ring EDM experiments

Yannis Semertzidis, CAPP/IBS and KAIST

Proton, deuteron, electron

- Storage ring p,e,d EDMs @ $<10^{-29}$*e*-cm level
- Probing NP $\sim 10^3$-10^4 TeV
- Status of the storage ring precision physics field: good!



Center for Axion and Precision Physics (CAPP)

http://capp.ibs.re.kr/html/capp_en/

CAPP / IBS, October 2014


CAPP / IBS, May 2015

KUSP

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KUSP KOREA UNDERGRADUATE/GRADUATE/H.S. SCIENCE PROGRAM

Center for Axion & Precision Physics

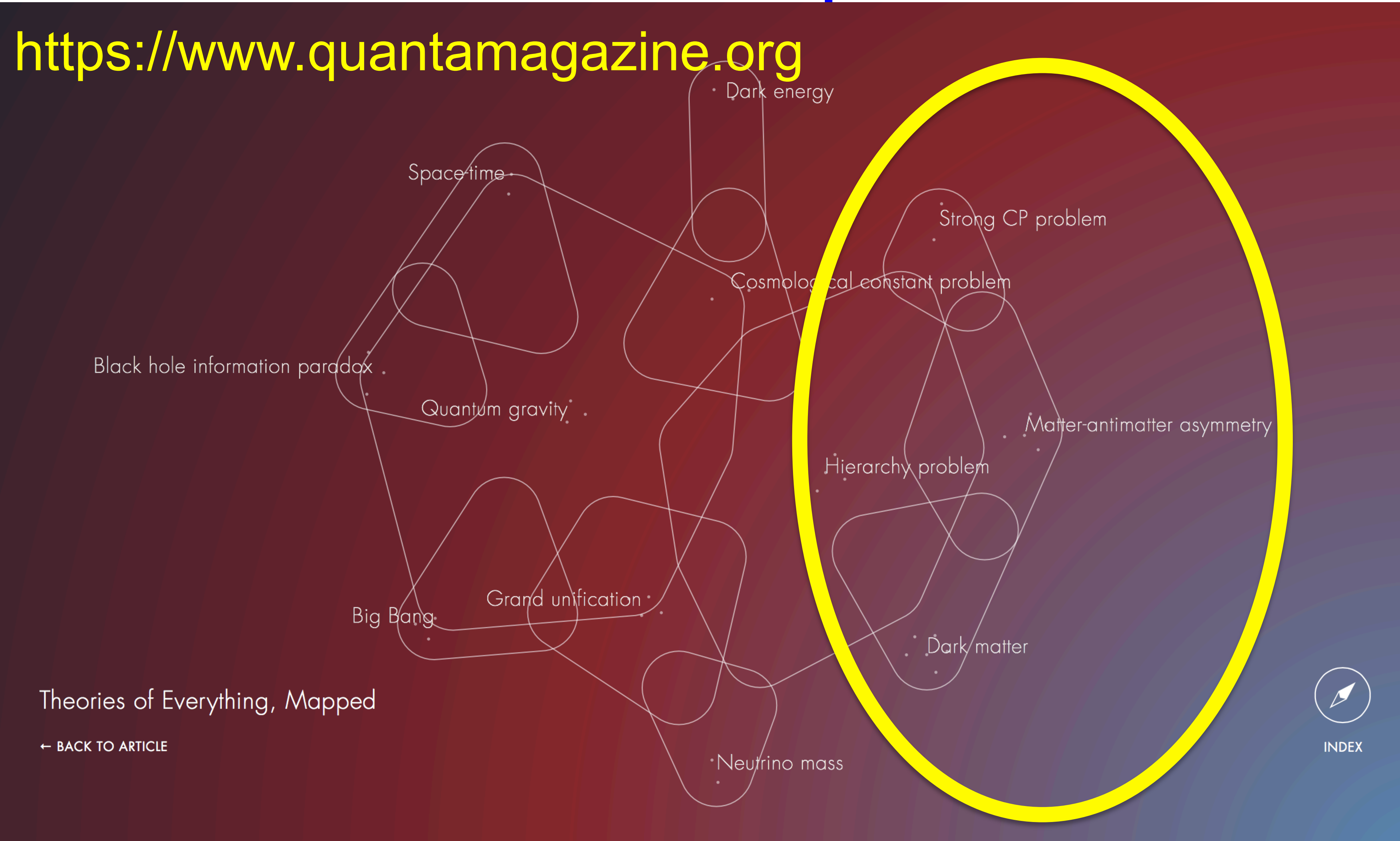
CAPP-Physics

- Establish Experimental Particle Physics group.

Involved in important physics questions:

- Strong CP problem
- Cosmic Frontier (Dark Matter axions)
- Storage ring proton EDM (most sensitive hadronic EDM experiment, flavor conserving CP-violation, BAU)
- Muon g-2; muon to electron conversion (flavor physics)

CAPP/IBS's Physics goals address some of the most important issues



Status in HEP-NP

1. LHC discovered the Higgs
2. No sight of SUSY yet at LHC (~1TeV)
3. No EDM discovered so far (fine tuning ~1%)
4. What's next?

A balanced approach is best…!

Fig. 1: 95% of the universe are made of two mysterious substances, dark matter and dark energy that cannot be explained in the Standard Model. By their very names it is clear that these things are somehow hidden from our view. New particles could hide by being very massive or by having extremely feeble interactions. It is clear that we need to look in all possible directions. In our quest for new physics high energy and low energy/high precision experiments nicely complement each other and together hopefully answer our questions to Nature.
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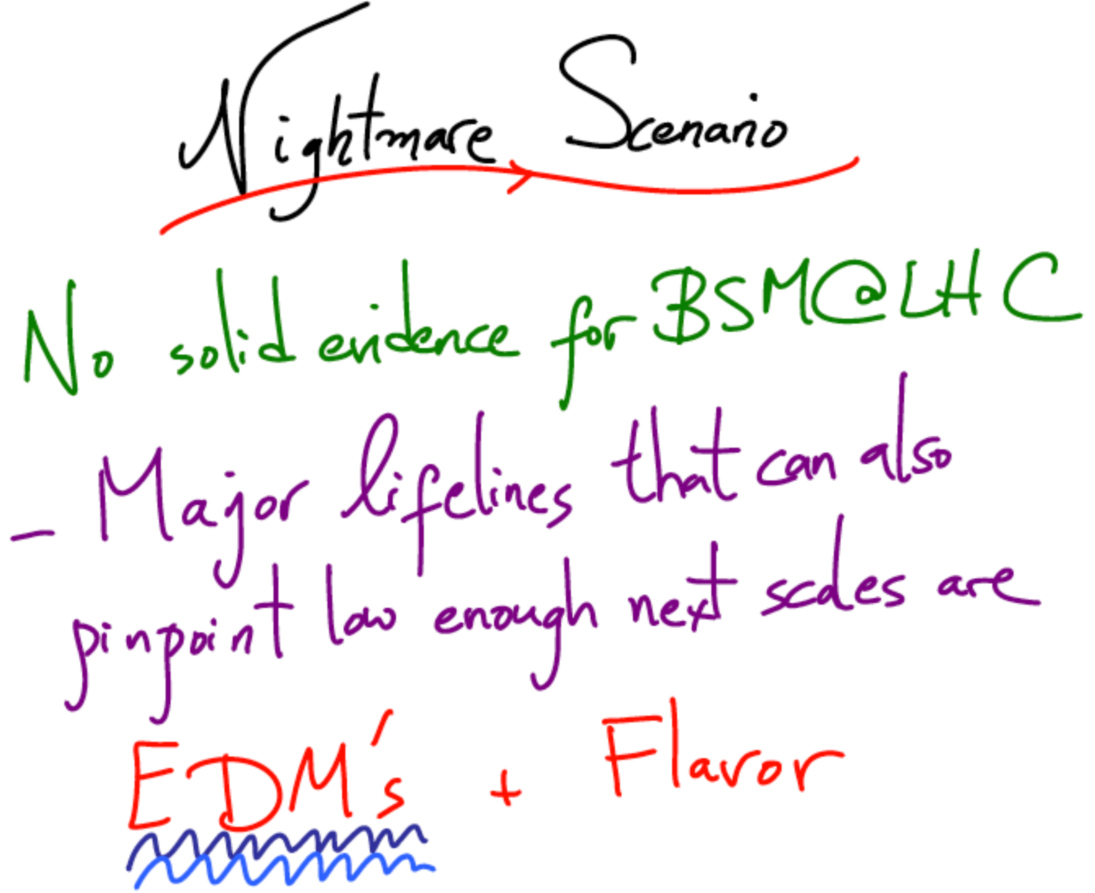
Physics of EDM of fundamental particles.

Proton EDM: $>10^3$ TeV for SUSY-like New Physics



Nima Arkani-Hamed, Intensity Frontier, Rockville, 2011

Storage Ring Muon g-2: Rigorous Test of the Standard Model

Spin Precession Rate at Rest

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

There is a large asymmetry in this equation: *μ* is relatively large, *d* is compatible with zero

Breakthrough concept: Freezing the horizontal spin precession due to E-field

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

Muon g-2 focusing is electric: The spin precession due to E-field is zero at "magic" momentum (3.1GeV/c for muons, 0.7 GeV/c for protons,…)

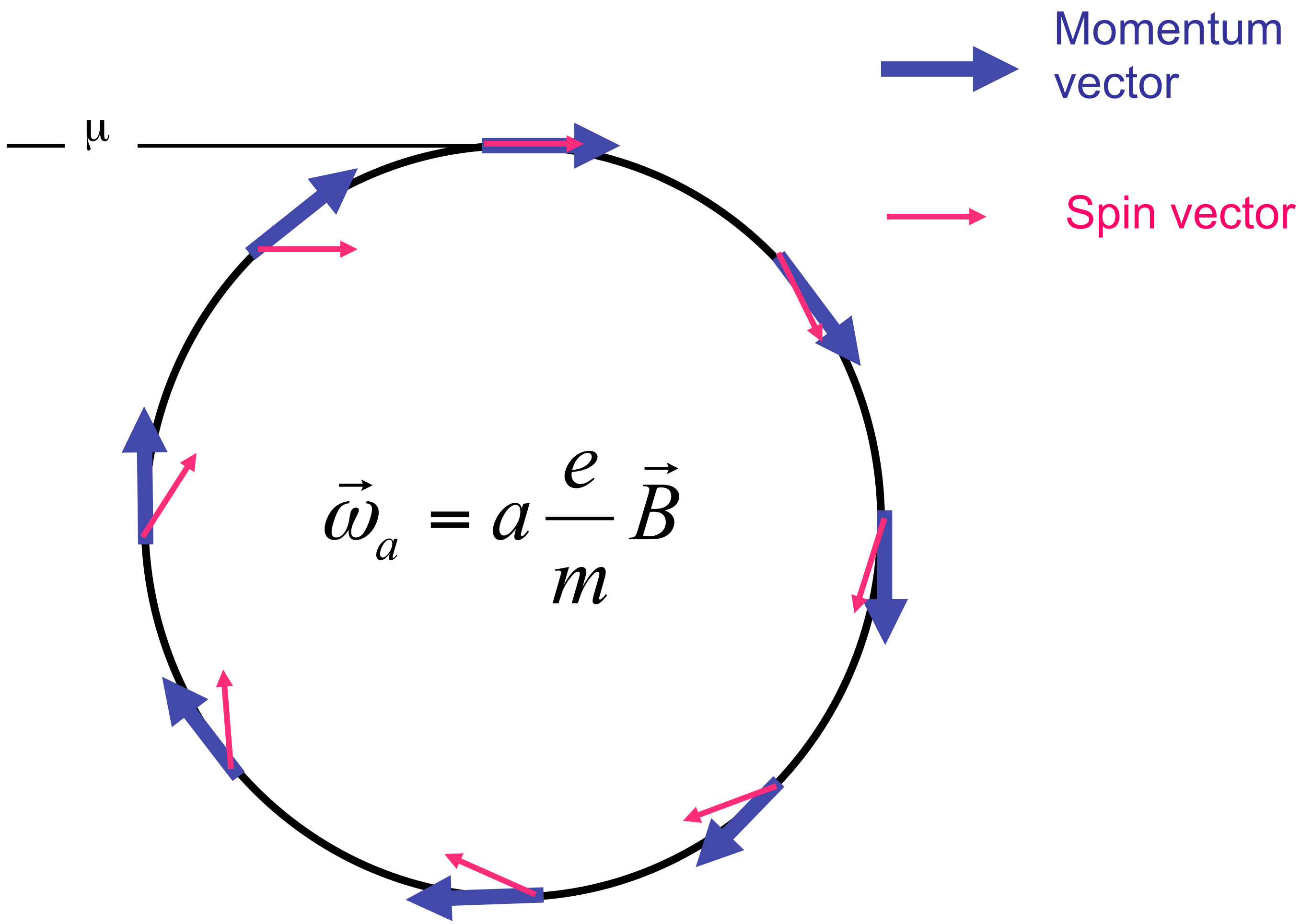
$$p = \frac{mc}{\sqrt{a}}, \text{ with } G = a = \frac{g-2}{2}$$

The "magic" momentum concept was used in the muon g-2 experiments at CERN, BNL, and …next at FNAL.

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

- Previous muon g-2 Experiment at Brookhaven National Laboratory

Spin Precession in g-2 Ring (Top View)



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

The electric focusing does not influence the g-2 precession rate

4 Billion e^+ with E>2GeV

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

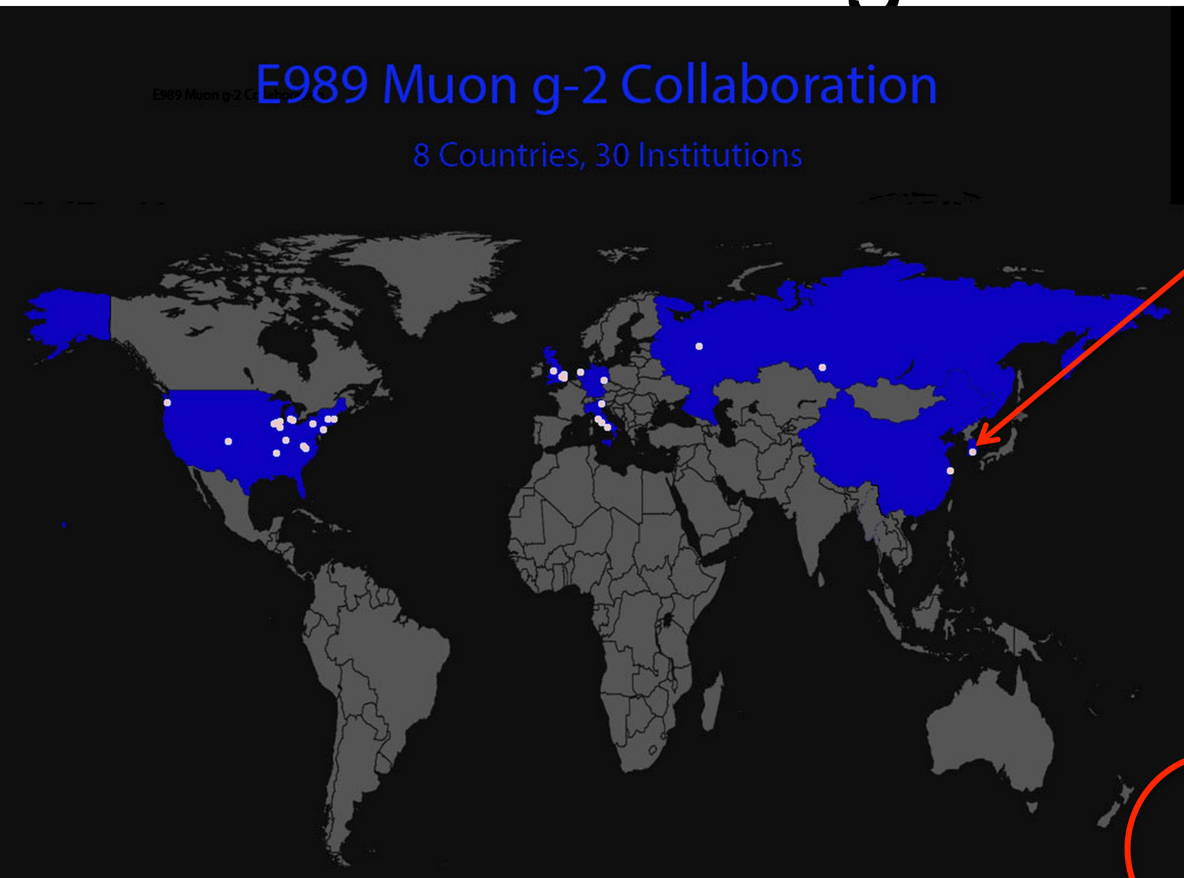
The result is 3.5 s.d. away from theory! What is it?

The muon g-2 coil moved to Fermilab for more intense beam

Contacts: C. Polly – Project Manager (polly@fnal.gov)
K.W. Merritt – Deputy Project Manager (wyatt@fnal.gov)
D. Hertzog – Co-Spokesperson (hertzog@uw.edu)
B. L. Roberts – Co-Spokesperson (roberts@bu.edu)

The ring has been reassembled and fully powered to 1.45T! First data: 2017

E989 muon g-2 collaboration



CAPP/IBS

CAPPers

Collaboration meeting, Nov. 2014

Fundamental particle EDM: study of CP-violation beyond the Standard Model

Electric Dipole Moments: P and T-violating when $\vec{d}$ // to spin

$$\vec{\mu} = g\left(\frac{q}{2m}\right)\vec{s},$$

$$\vec{d} = \eta\left(\frac{q}{2mc}\right)\vec{s}$$

$$\mathcal{H} = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E}$$

	$\vec{E}$	$\vec{B}$	$\vec{\mu}$ or $\vec{d}$
P	$-$	$+$	$+$
C	$-$	$-$	$-$
T	$+$	$-$	$-$

Electric Dipole Moments: P and T-violating when $\vec{d}$ // to spin

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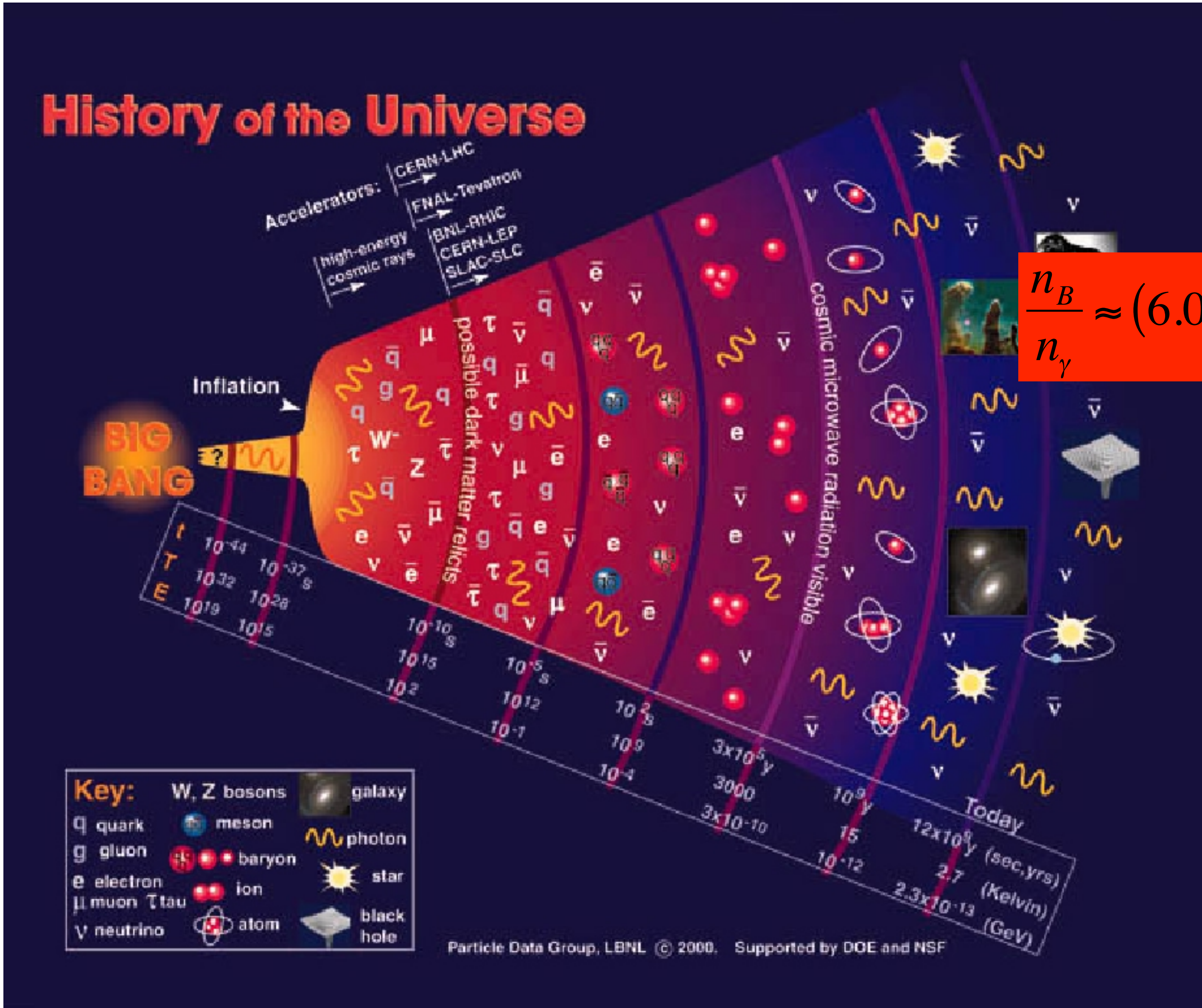
	$\vec{E}$	$\vec{B}$	$\vec{\mu}$ or $\vec{d}$
P	$-$	$+$	$+$
C	$-$	$-$	$-$
T	$+$	$-$	$-$

T-violation: assuming CPT cons. → CP-violation

Why is there so much matter after the Big Bang:



We see:

$$\frac{n_B}{n_\gamma} \approx (6.08 \pm 0.14) \times 10^{-10}$$

From the SM:

$$\frac{n_B}{n_\gamma} \approx 10^{-18}$$

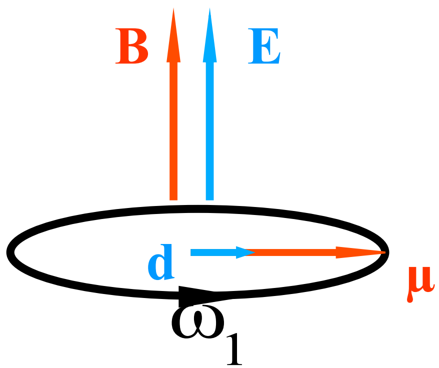
Purcell and Ramsey:

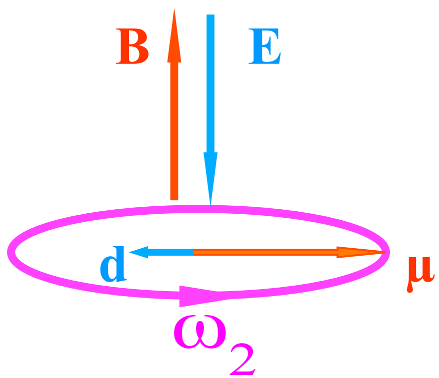
"The question of the possible existence of an electric dipole moment of a nucleus or of an elementary particle…becomes a purely experimental matter"

Phys. Rev. 78 (1950)

Measuring an EDM of Neutral Particles

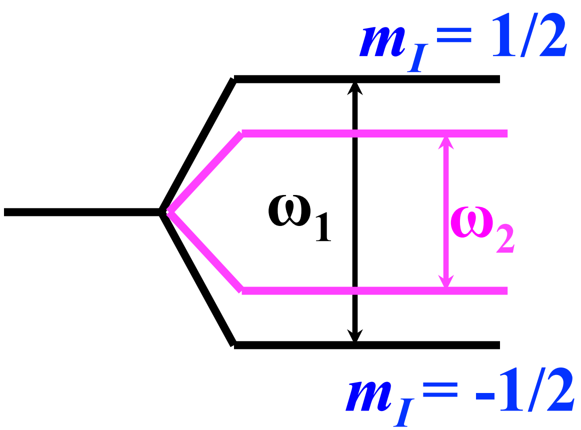
$$H = -(d\,\mathbf{E} + \mu\,\mathbf{B}) \bullet \mathbf{I}/I$$





$$\omega_1 = \frac{2\mu B + 2dE}{h}$$

$$\omega_2 = \frac{2\mu B - 2dE}{h}$$

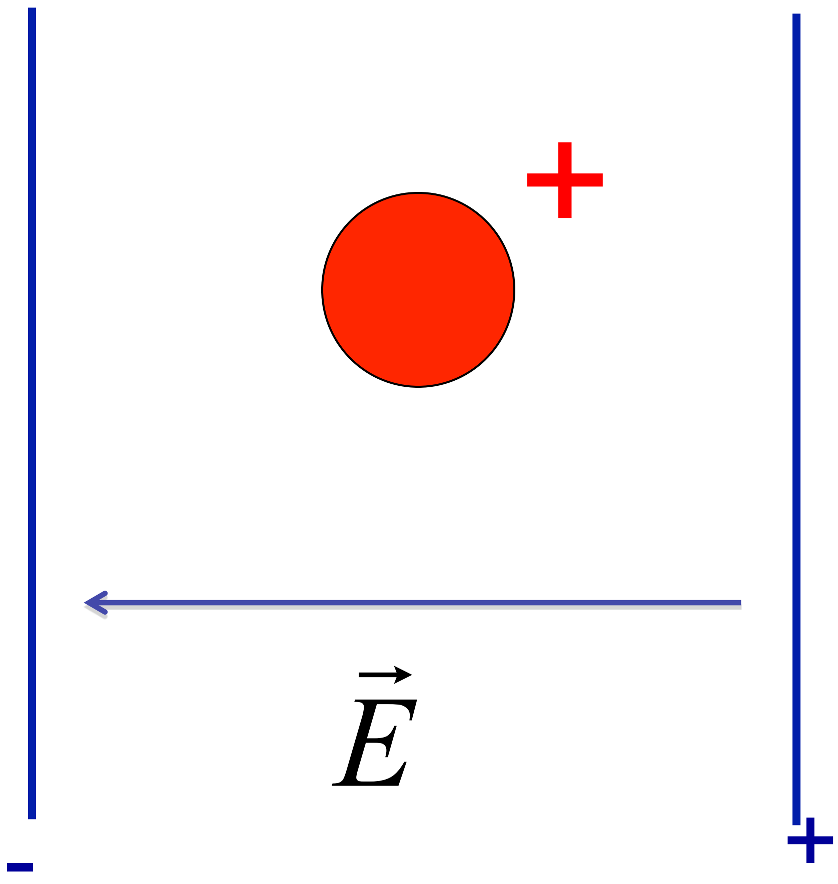


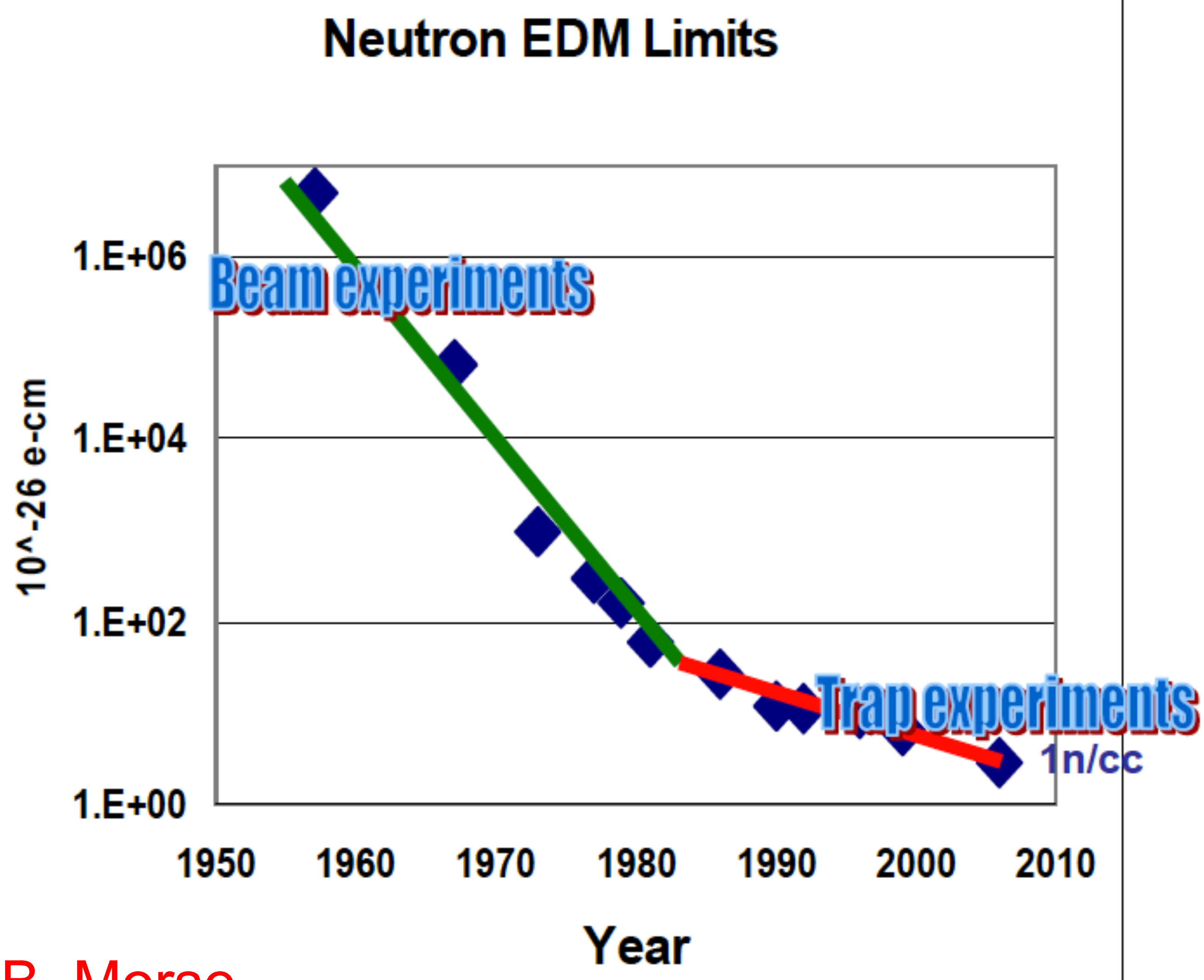
$$d = \frac{h(\omega_1 - \omega_2)}{4E}$$

$d = 10^{-29}$ e cm
E = 100 kV/cm

$\Rightarrow$ **ω = 5 nrad/s**

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




Neutron EDM Limits
1.E+06
1.E+04
1.E+02
1.E+00
10^-26 e-cm
Beam experiments
Trap experiments
1n/cc
1950
1960
1970
1980
1990
2000
2010
Year

B. Morse

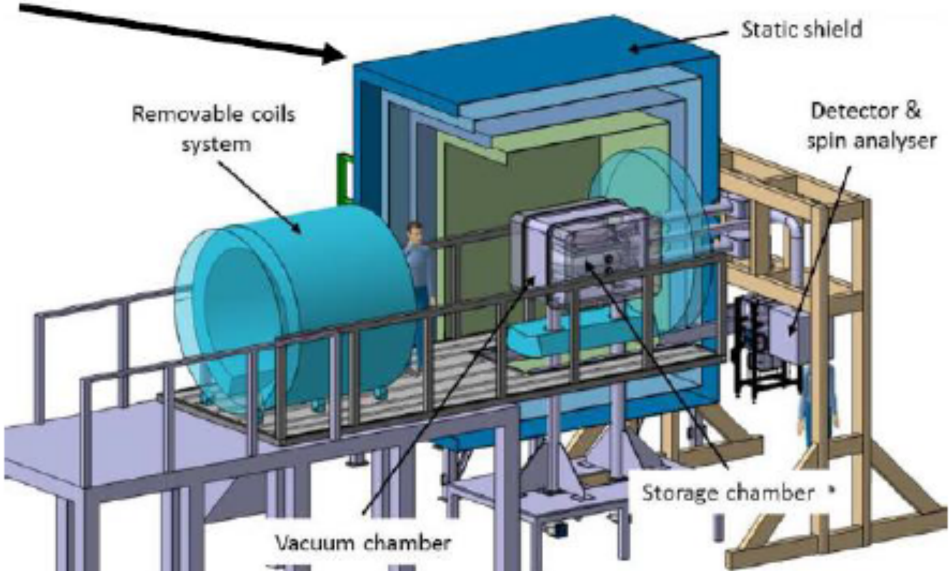
K. Kirch

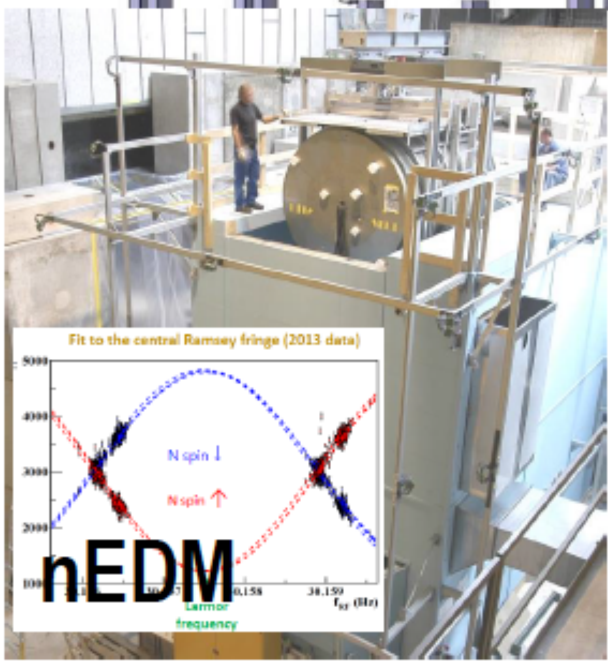
The nEDM@PSI collaboration

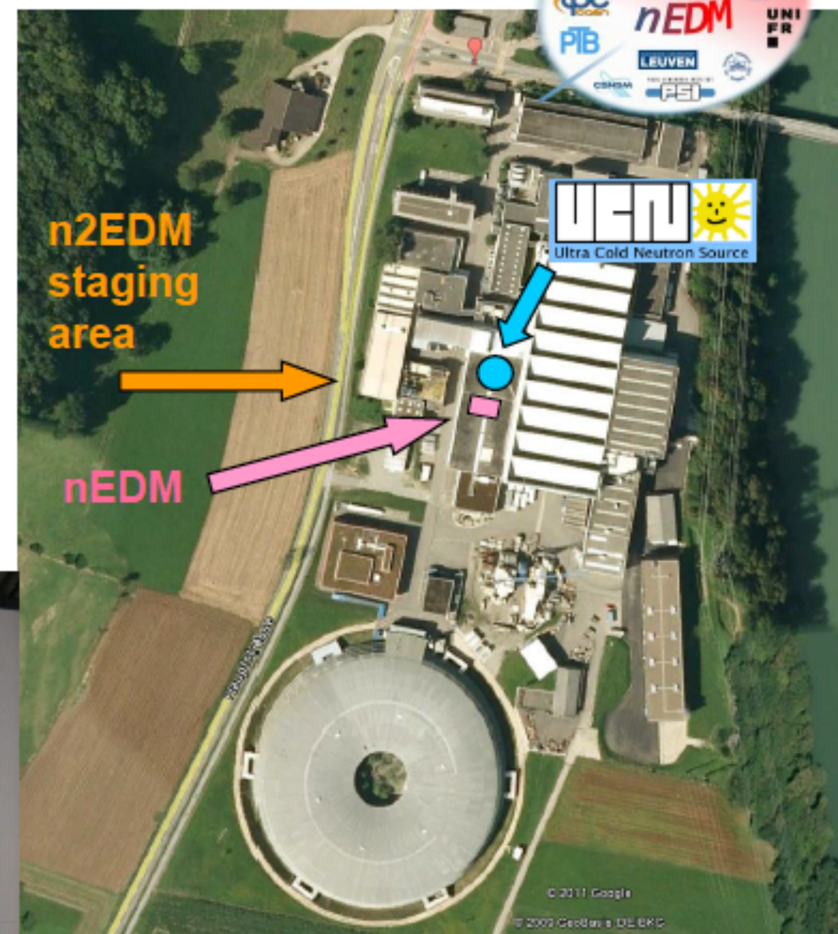
13 Institutions, 7 Countries, 50 individuals

PAUL SCHERRER INSTITUT

n2EDM







The target sensitivity for nEDM is 10^{-26}ecm or better, for n2EDM 10^{-27}ecm or better

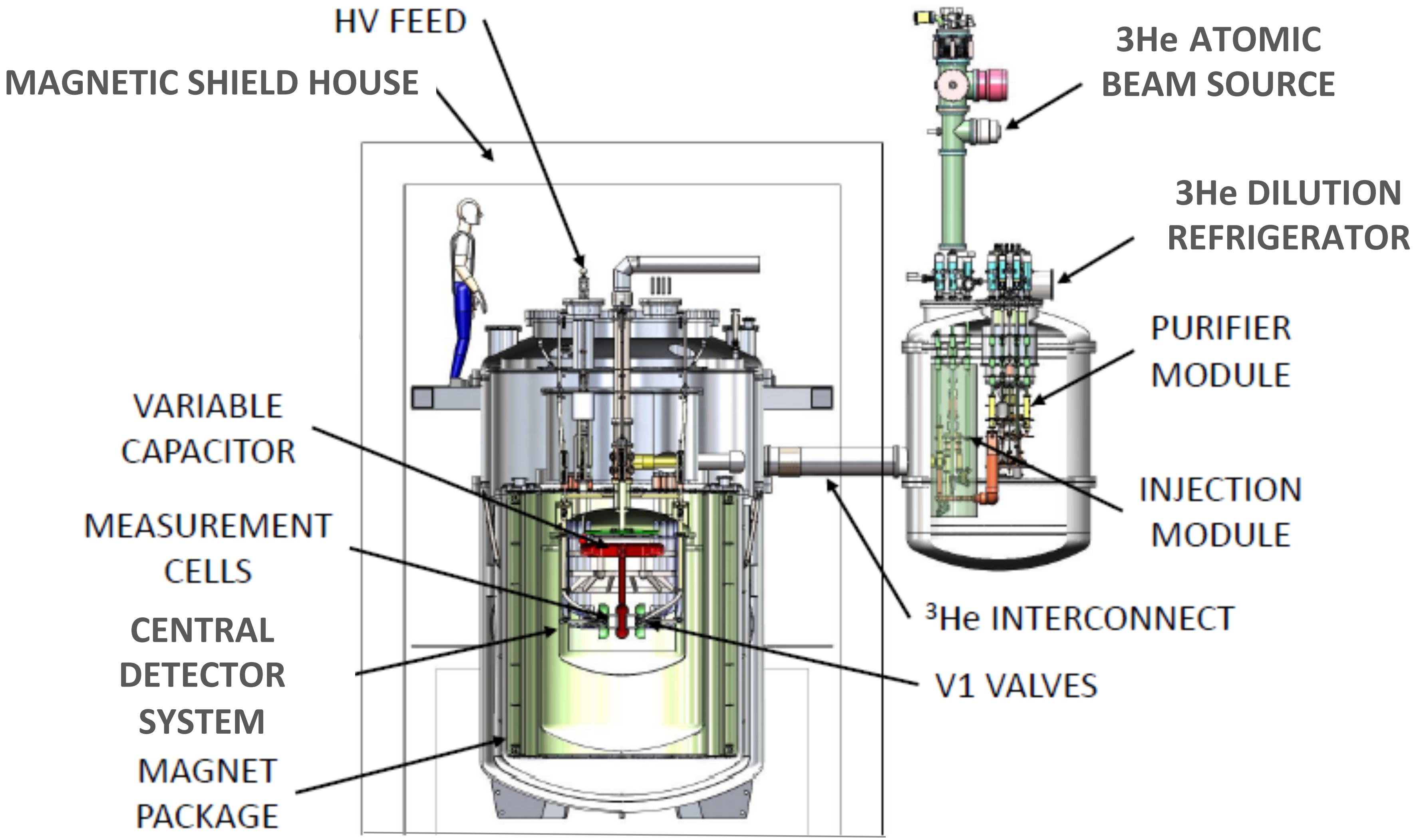
Key Features of nEDM@SNS

Brad Filippone

- Sensitivity: ~2×10^{-28} e-cm, 100 times better than existing limit
- In-situ Production of UCN in superfluid helium (no UCN transport)
- **Polarized ^{3}He co-magnetometer**
  - Also functions as neutron spin precession monitor via spin-dependent n-^{3}He capture cross section using wavelength-shifted scintillation light in the LHe
  - Ability to vary influence of external B-fields via “dressed spins”
    - Extra RF field allows synching of n & ^{3}He relative precession frequency
- Superconducting Magnetic Shield
- Two cells with opposite E-field
- Control of central-volume temperature
  - Can vary ^{3}He diffusion (mfp)- big change in geometric phase effect on ^{3}He

Arguably the most ambitious of all neutron EDM experiments

SNS-nEDM Experiment



Neutron beam
is into page

History/Status of nEDM@SNS

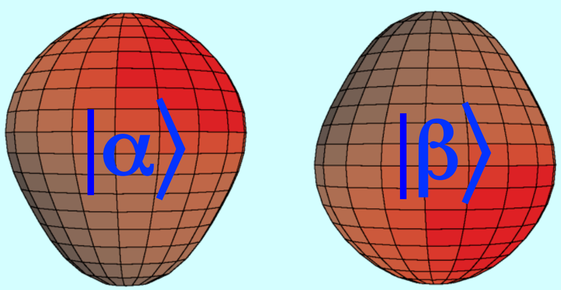
- **2011:** NSAC Neutron Subcommittee
- **2013:** Critical R&D successfully demonstrated
- **2014-2017:** Critical Component Demonstration (CCD) phase begun
  - Build working, full-scale, prototypes of technically-challenging subsystems (use these in the full experiment)
  - 4yr NSF proposal for 6.5M$ CCD funded
  - DOE commitment of $\approx$ 1.8M$/yr for CCD
- **2018-2020:** Large scale Integration and Conventional Component Procurement
- **2021:** Begin Commissioning and Data-taking

EDM of ^{225}Ra enhanced and more reliably calculated

Z.T. Lu

- Closely spaced parity doublet – Haxton & Henley, PRL (1983)
- Large Schiff moment due to octupole deformation – Auerbach, Flambaum & Spevak, PRL (1996)
- Relativistic atomic structure (^{225}Ra / ^{199}Hg ~ 3) – Dzuba, Flambaum, Ginges, Kozlov, PRA (2002)

Parity doublet



$$\Psi^- = (|\alpha\rangle - |\beta\rangle)/\sqrt{2}$$

55 keV

$$\Psi^+ = (|\alpha\rangle + |\beta\rangle)/\sqrt{2}$$

$$Schiff\_moment = \sum_{i\neq 0} \frac{\langle \psi_0 | \hat{S}_z | \psi_i \rangle \langle \psi_i | \hat{H}_{PT} | \psi_0 \rangle}{E_0 - E_i} + c.c.$$

Enhancement Factor: EDM (^{225}Ra) / EDM (^{199}Hg)

	Isoscalar	Isovector
Skyrme SIII	300	4000
Skyrme SkM*	300	2000
Skyrme SLy4	700	8000

Schiff moment of ^{225}Ra, Dobaczewski, Engel, PRL (2005)
Schiff moment of ^{199}Hg, Dobaczewski, Engel *et al.*, PRC (2010)

"[Nuclear structure] calculations in Ra are almost certainly more reliable than those in Hg."

– Engel, Ramsey-Musolf, van Kolck, Prog. Part. Nucl. Phys. (2013)

Constraining parameters in a global EDM analysis.

– Chupp, Ramsey-Musolf, arXiv1407.1064 (2014)

^{225}Ra:

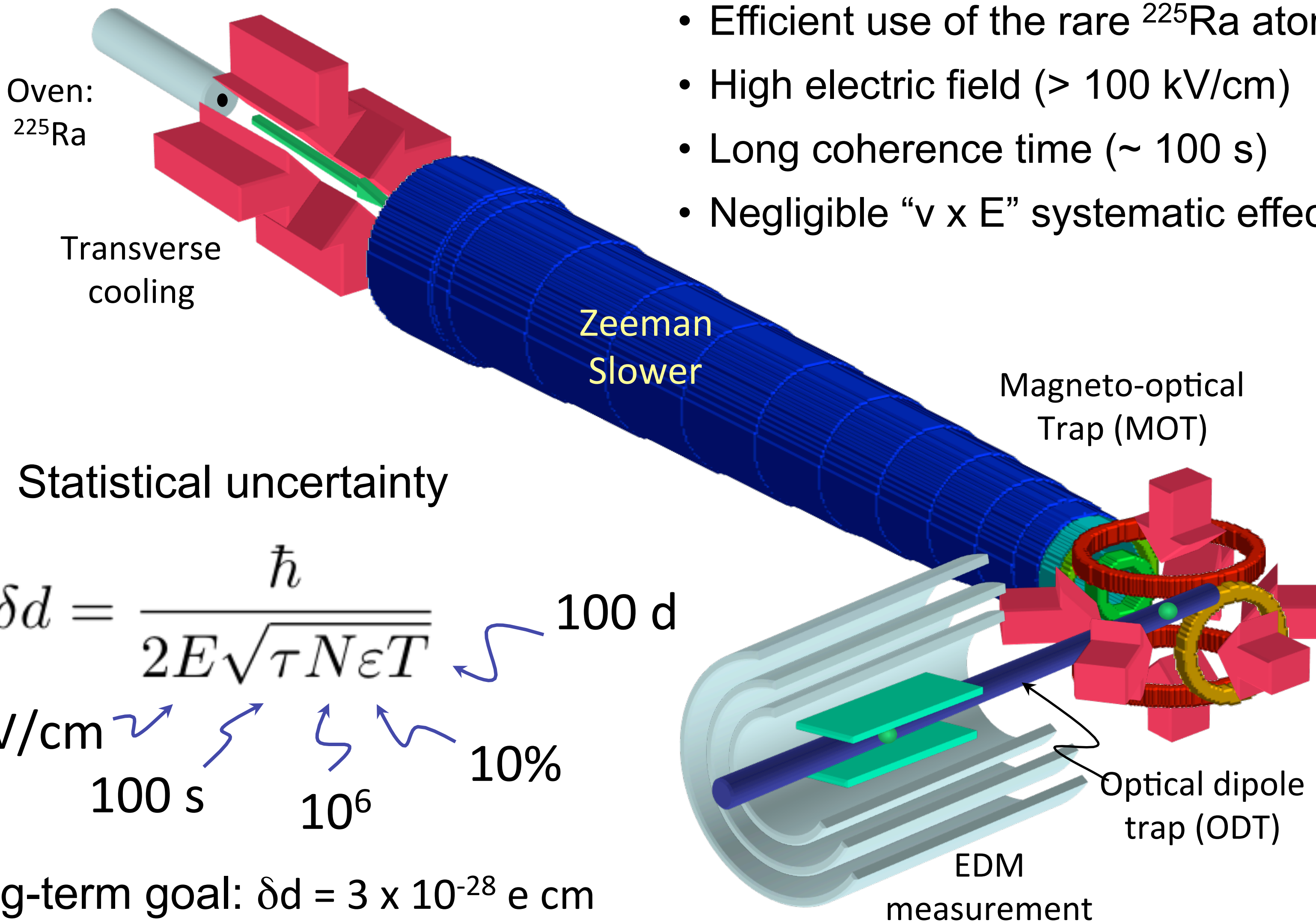
I = ½

$t_{1/2}$ = 15 d

EDM measurement on ^{225}Ra in a trap

Collaboration of Argonne, Kentucky, Michigan State

- Efficient use of the rare ^{225}Ra atoms
- High electric field (> 100 kV/cm)
- Long coherence time (~ 100 s)
- Negligible "v x E" systematic effect



Statistical uncertainty

$$\delta d = \frac{\hbar}{2E\sqrt{\tau N \varepsilon T}}$$

100 d

100 kV/cm

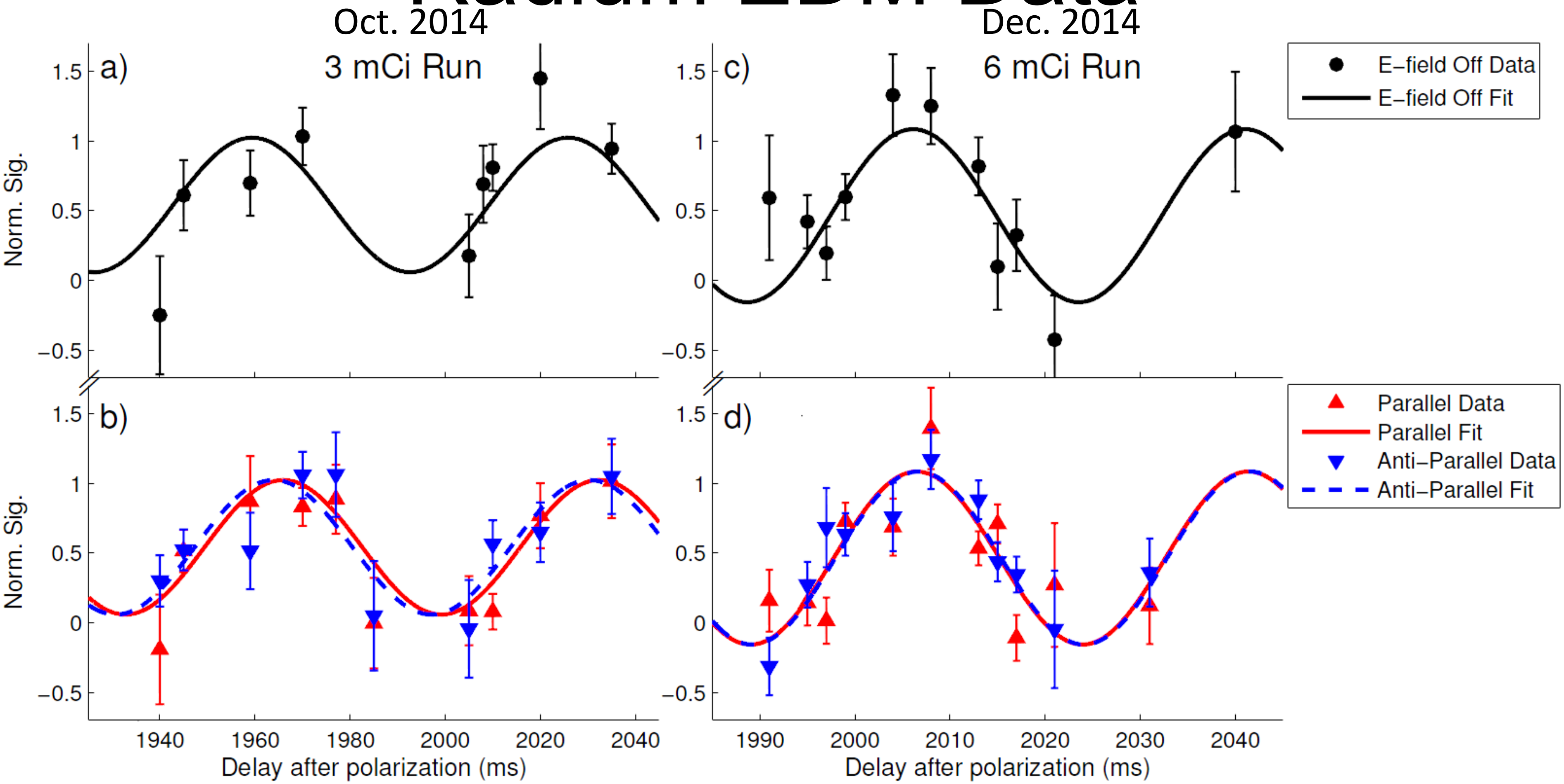
100 s

10^6

10%

Long-term goal: δd = 3 x 10^{-28} e cm

Radium EDM Data



$$d_{Ra\text{-}225} = (-0.5 \pm 2.5_{stat} \pm 0.2_{syst}) \times 10^{-22}\ \text{e-cm}$$

$$|d_{Ra\text{-}225}| < 5.0 \times 10^{-22}\ \text{e-cm (95\% confidence)}$$

R. H. Parker *et al.*, submitted (2015)

P. Fierlinger

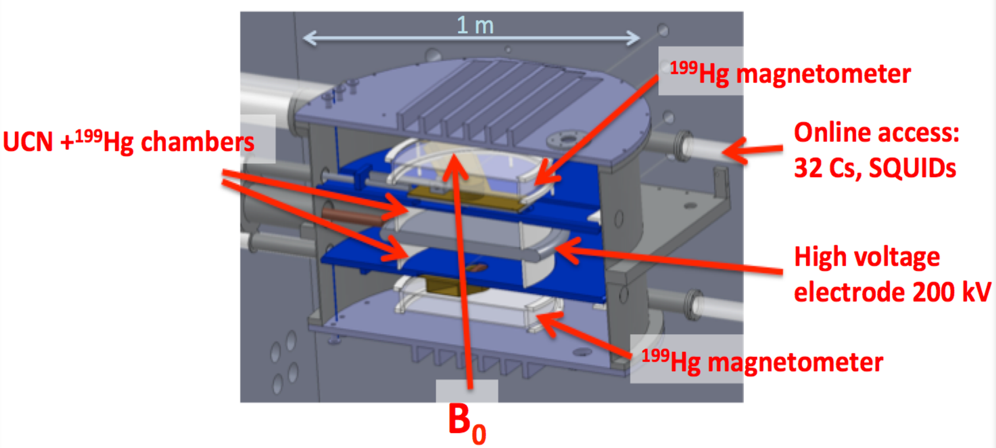
The TUM EDM experiment

SLOW NEUTRONS
DFG SPP 1491

EDM
nedm.ph.tum.de

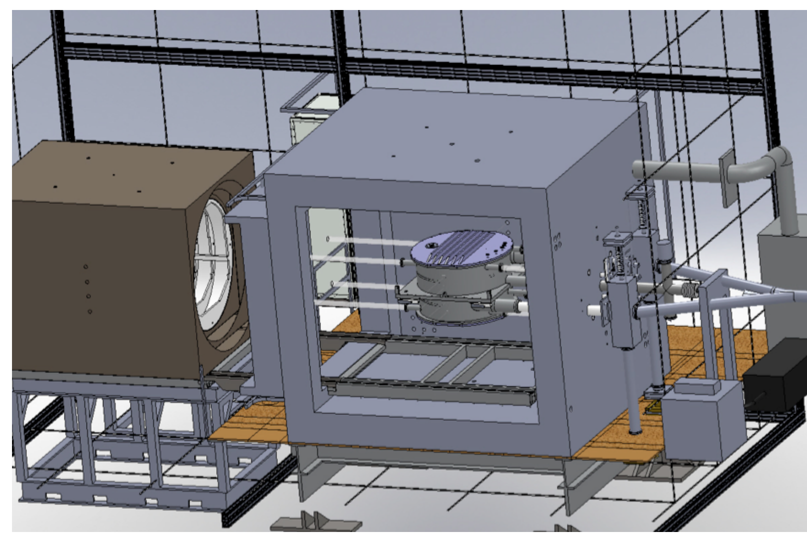
- Initially a ‘conventional’ Ramsey experiment
- UCN trapped at room temperature, ultimately cryogenic trap
- Double chamber with co-magnetometer option
- ^{199}Hg, Cs, ^{129}Xe, ^{3}He, SQUID magnetometers
- Portable and modular setup, including magnetically shielded room
- Ultimate goal: 10^{-28} ecm sensitivity, staged approach (syst. and stat.)

Double chamber in SF6 container



I. Altarev et al., Il Nuovo Cimento 35 C 122 (2012)

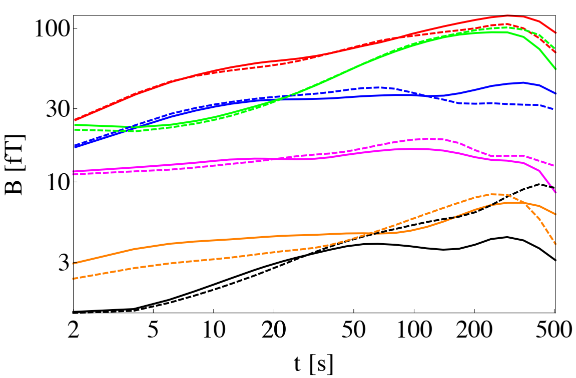
Modular shield setup

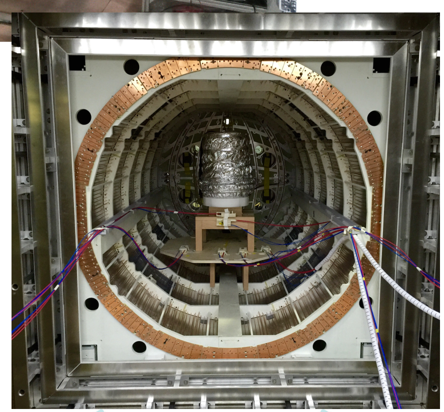


Most hardware built & tested

E.g.: passive magnetic shielding factor > 6 million @ 1 mHz (without ext. compensation coils!)

I.Altarev et al., arXiv:1501.07408
I. Altarev et al., , arXiv:1501.07861

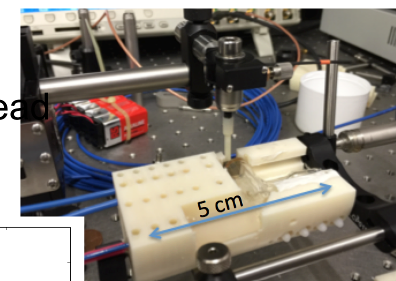


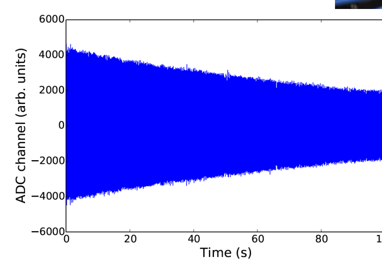


1.5m

- The smallest gradients over an extended volume ever realized: < 50 pT / m stable gradient over EDM cell volume
- Residual field drift < 5 fT in typical Ramsey cycle time
- Hg and Cs magnetometery on < 20 fT level:

Cs sensor head assembly





Raw 199-Hg FPD signal

- Basically all magnetic field related systematics under control

Storage Ring Proton EDM: study of CP-violation beyond the Standard Model

Storage Ring EDM Collaboration

- Aristotle University of Thessaloniki, Thessaloniki/Greece
- Research Inst. for Nuclear Problems, Belarusian State University, Minsk/Belarus
- Brookhaven National Laboratory, Upton, NY/USA
- Budker Institute for Nuclear Physics, Novosibirsk/Russia
- Royal Holloway, University of London, Egham, Surrey, UK
- Cornell University, Ithaca, NY/USA
- Institut für Kernphysik and Jülich Centre for Hadron Physics Forschungszentrum Jülich, Jülich/Germany
- Institute of Nuclear Physics Demokritos, Athens/Greece
- University and INFN Ferrara, Ferrara/Italy
- Laboratori Nazionali di Frascati dell'INFN, Frascati/Italy
- Joint Institute for Nuclear Research, Dubna/Russia
- Indiana University, Indiana/USA
- Istanbul Technical University, Istanbul/Turkey
- University of Massachusetts, Amherst, Massachusetts/USA
- Michigan State University, East Lansing, Minnesota/USA
- Dipartimento do Fisica, Universita' "Tor Vergata" and Sezione INFN, Rome/Italy
- University of Patras, Patras/Greece
- CEA, Saclay, Paris/France
- KEK, High Energy Accel. Res. Organization, Tsukuba, Ibaraki 305-0801, Japan
- University of Virginia, Virginia/USA

>20 Institutions
>80 Collaborators

http://www.bnl.gov/edm

Storage ring proton EDM proposal to DOE NP, Nov 2011

Why now?

- Exciting progress in electron EDM using molecules.
- Several neutron EDM experiments under development to improve their sensitivity level.
- Proton EDM has large STATISTICAL sensitivity; great way to handle SYSTEMATICS.

Storage ring proton EDM method

- All-electric storage ring. Strong radial E-field to confine protons with "magic" momentum. The spin vector is aligned to momentum horizontally.

- High intensity, polarized proton beams are injected Clockwise and Counter-clockwise with positive and negative helicities. Great for systematics

- Great statistics: up to ~10^{11} particles with primary proton beams and small phase-space parameters.

PAC/Snowmass strong endorsement

- BNL PAC on EDM proposal (2008): “enthusiastic endorsement of the physics…need to demonstrate feasibility of systems”

- Snowmass writeup: “…Ultimately the interpretability of possible EDMs in terms of underlying sources of CP violation may prove sharpest in simple systems such as neutron and proton,…”

- FNAL PAC EDM EOI (2012): “The Physics case for such a measurement is compelling since models with new physics at the TeV scale (e.g., low energy SUSY) that have new sources of CP-violation can give contributions of this order…. The PAC recommends that Fermilab and Brookhaven management work together, and with potential international partners, to find a way for critical R&D for this promising experiment to proceed.”

Importance and Promise of Electric Dipole Moments

Frank Wilczek

January 22, 2014

Support letter to P5 for the proton EDM

The additional symmetry has another remarkable consequence. It predicts the existence of a new very light, very weakly interacting spin 0 particle, the *axion*. The possible existence of axions raises the stakes around these ideas, because it entails major cosmological consequences. Indeed, if axions exist at all, they must provide much of the astronomical "dark matter", and quite plausibly most of it.

Better bounds on θ, or especially an actual determination of its value, would allow us to sharpen these considerations considerably. Better measurements of fundamental electric dipole moments are the most promising path to such bounds, or measurement.

P5: Particle Physics Project Prioritization Panel setup by DOE and NSF. It took more than a year for the HEP community to come up with the report.

In 2014 we have received the P5 endorsement for the proton EDM experiment under all funding scenarios!

Marciano, CM9/KAIST/Korea, Nov 2014

Generic Physics Reach of $d_p \sim 10^{-29}$e-cm

$d_p \sim 0.01(m_p/\Lambda_{NP})^2 \tan\phi^{NP} e/2m_p$

$\mathbf{\sim 10^{-22}(1TeV/\Lambda_{NP})^2 \tan\phi^{NP} e\text{-}cm}$

If ϕ^{NP} is of O(1), $\Lambda_{NP} \sim$ 3000TeV Probed!

If $\Lambda_{NP} \sim$ O(1TeV), $\phi_{NP} \sim 10^{-7}$ Probed!

Unique Capabilities!

CP-violation phase from Higgs

EDMs will eventually be discovered: $d_e, d_n, d_p \ldots d_D$

Magnitudes of ≈ -10^{-28} expected for Baryogenesis

Atomic, Molecular, Neutron, ***Storage Ring*** (All important)

Marciano

CP violation phase in***: Hee, H$\gamma\gamma$, Htt,   2HD Model…***

Uniquely explored by 2 loop edms! Barr-Zee effect

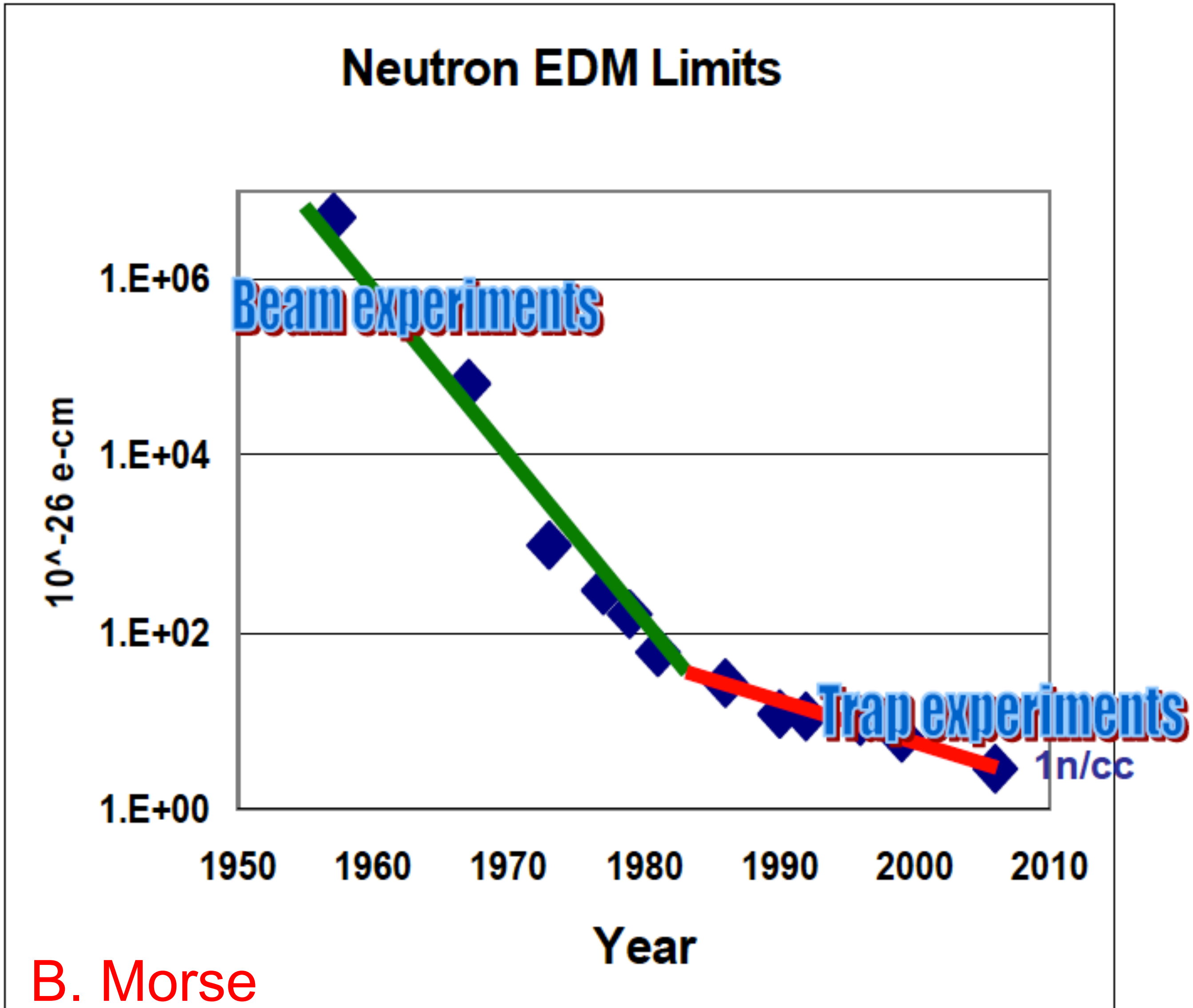
May be our only window to Hee, Huu and Hdd couplings

Guided by experiment: ***H→$\gamma\gamma$***   ***(H→$\tau^+\tau^-$, $\mu^+\mu^-$) etc.***

Updates Anxiously Anticipated!

The Higgs may be central to our existence!

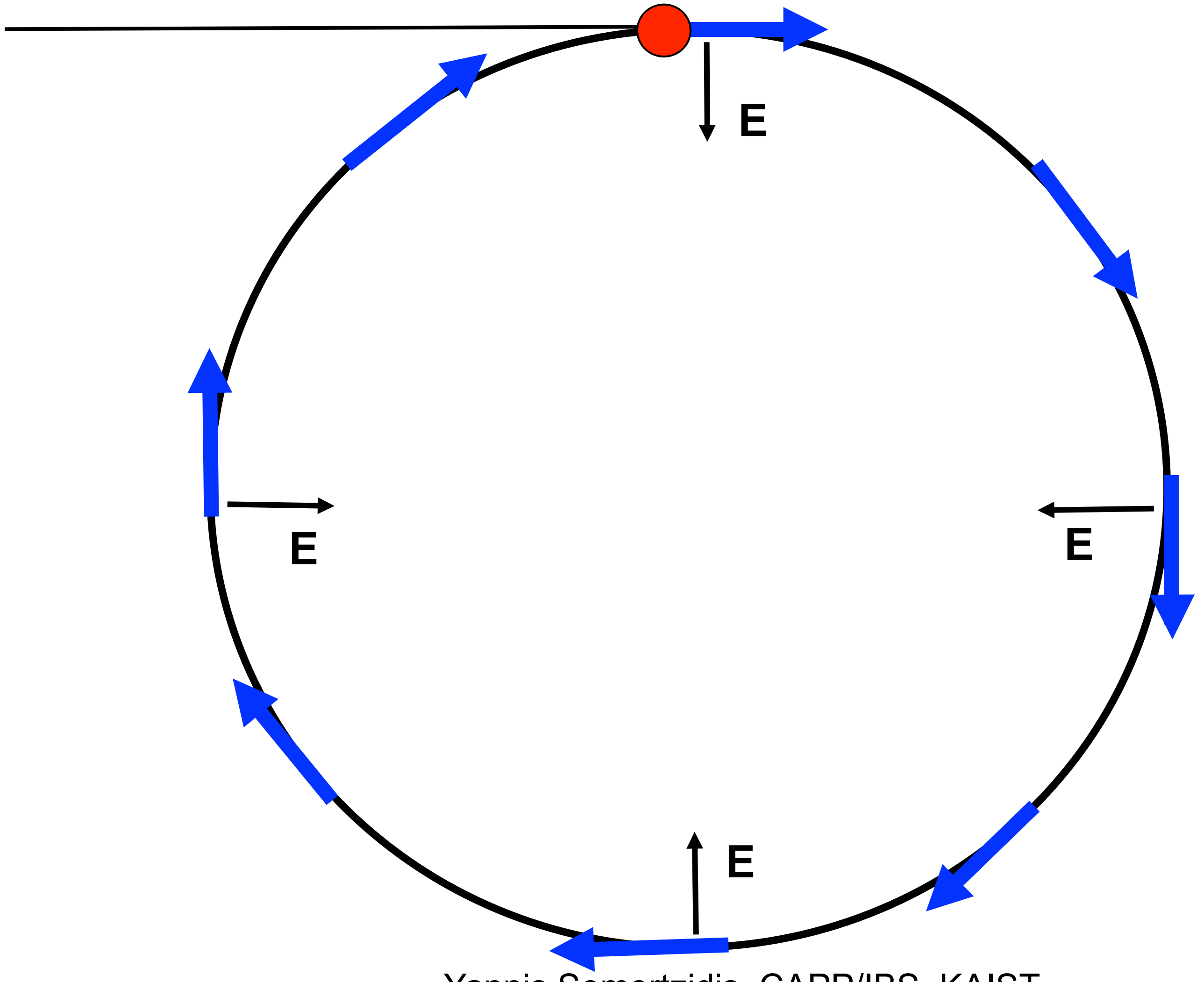
Proton storage ring EDM experiment is combination of beam + a trap



Storage ring EDM method

Or… how do you turn a weakness into an opportunity?

Stored beam: The radial E-field force is balanced by the centrifugal force.



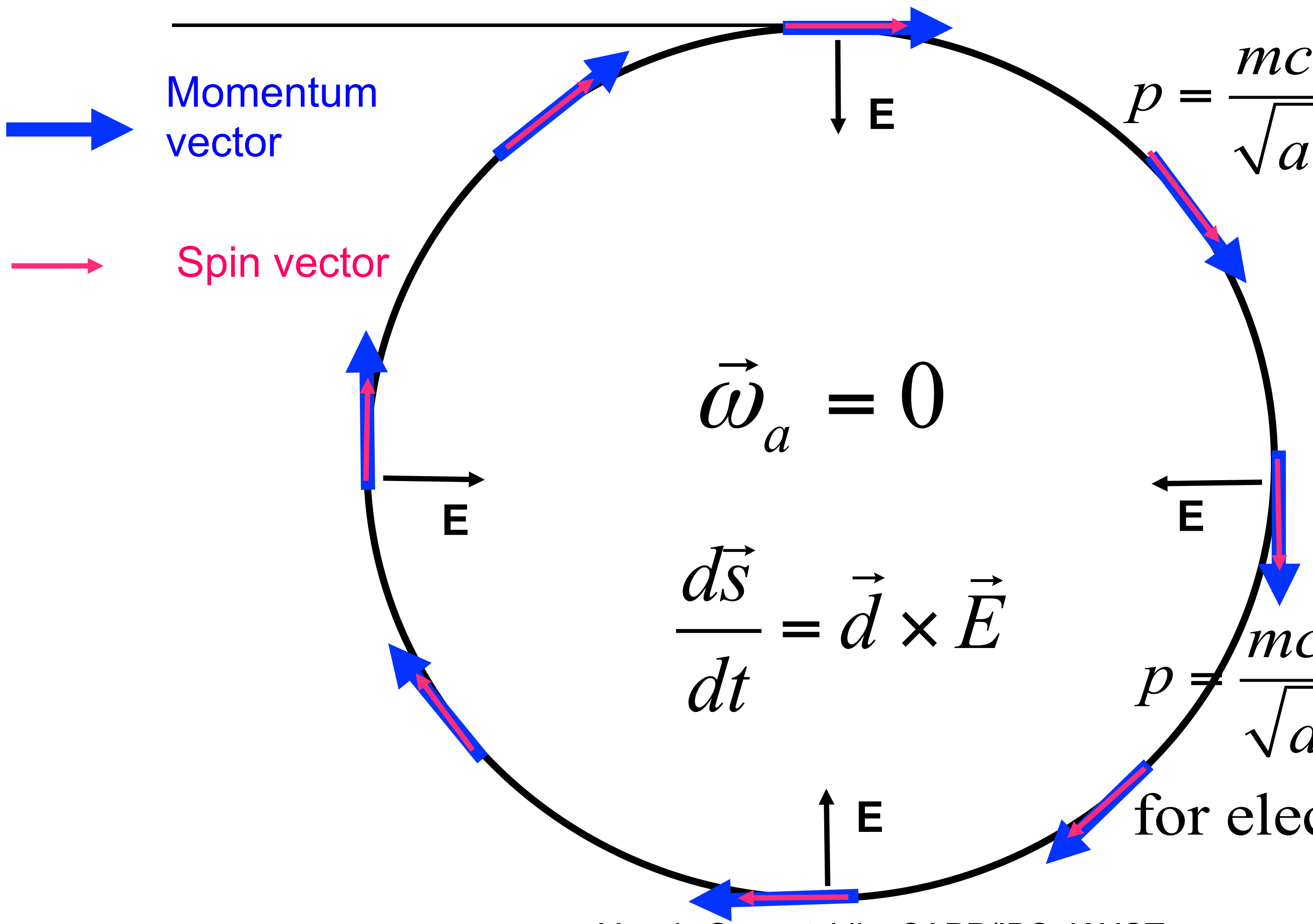
The Electric Dipole Moment precesses in an Electric field

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

The proton EDM uses an ALL-ELECTRIC ring: spin is aligned with the momentum vector

at the magic momentum

$$p = \frac{mc}{\sqrt{a}} = 0.7\ \text{GeV/c}$$



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

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

$$p = \frac{mc}{\sqrt{a}} = 15\text{MeV/c}$$

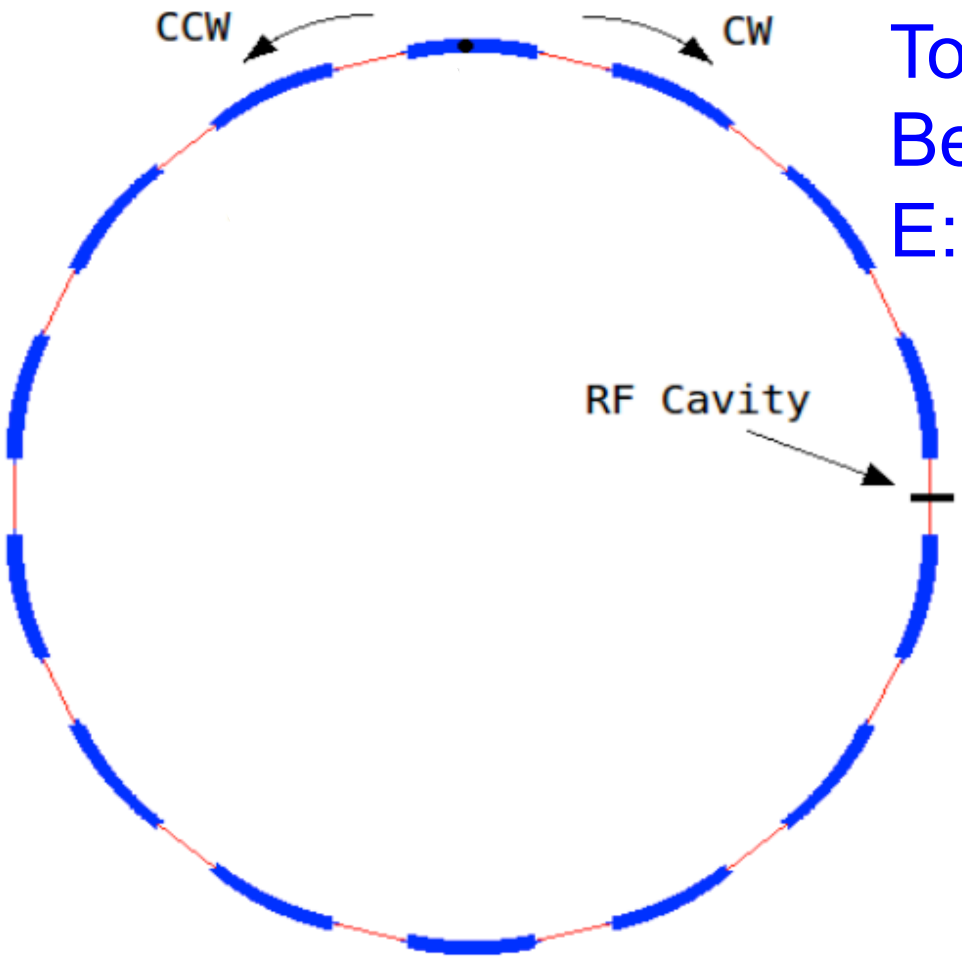
for electrons!

The proton EDM ring evaluation Val Lebedev (Fermilab)

Beam intensity 10^{11} protons limited by IBS

	Soft focusing	Strong focusing
Circumference, m	263	300
Qx/Qy	1.229/0.456	2.32/0.31
Particle per bunch	$1.5\cdot10^{8}$	$7\cdot10^{8}$
Coulomb tune shifts, $\Delta Q_x/\Delta Q_y$	0.0046/0.0066	0.0146/0.0265
Rms emittances, x/y, norm, µm	0.56/1.52	0.31/2.16
Rms momentum spread	$1.1\cdot10^{-4}$	$2.9\cdot10^{-4}$
IBS growth times, x/y/s, s	300/(-1400)/250	7500
RF voltage, kV	13	10.3
Synchrotron tune	0.02	0.006

Example: The proton EDM ring

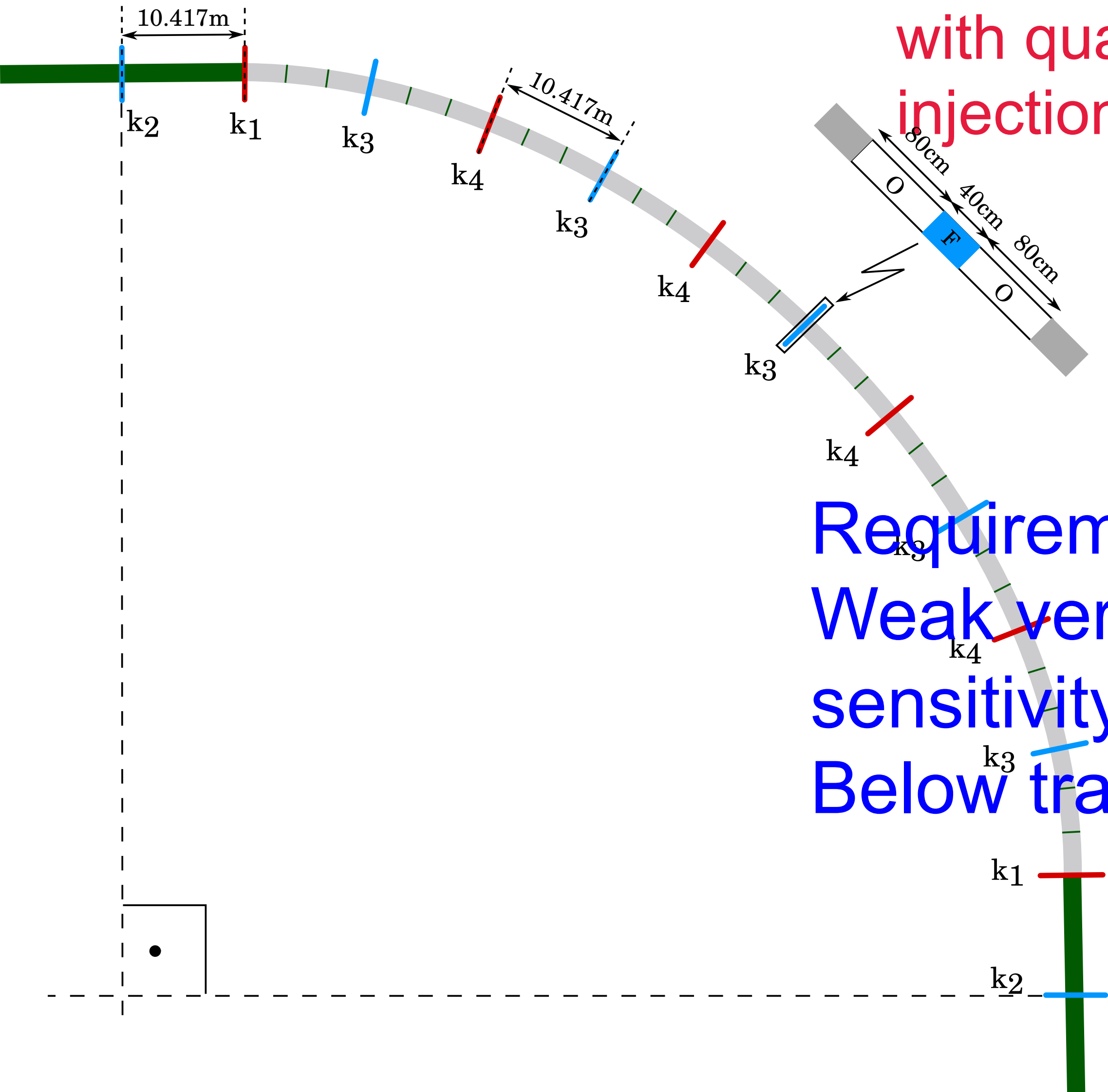


Total circumference: 300 m
Bending radius: 40 m
E: 10 MV/m

Weak vertical focusing
Stronger horizontal focusing

The proton EDM ring (alternate gradient)

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



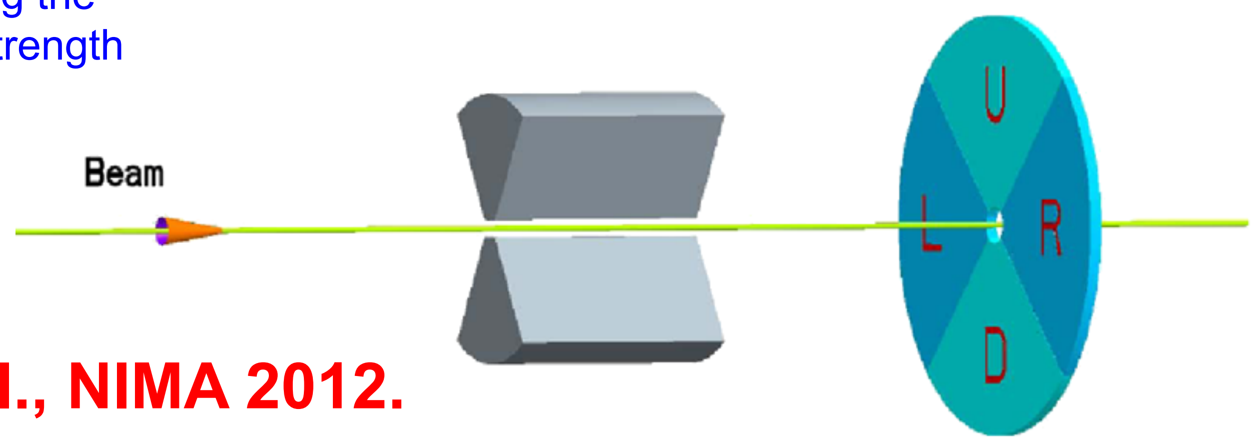
Requirements:
Weak vertical focusing (B-field sensitivity)
Below transition (reduce IBS)

pEDM polarimeter principle (placed in a straight section in the ring): probing the proton spin components as a function of storage time

“defining aperture” polarimeter target

Micro-Megas detector, GEMs, MRPC or Si.

Extraction: lowering the vertical focusing strength



Brantjes et al., NIMA 2012.

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

carries EDM signal increases slowly with time

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

carries in-plane (g-2) precession signal

Large polarimeter analyzing power at P_{magic}!

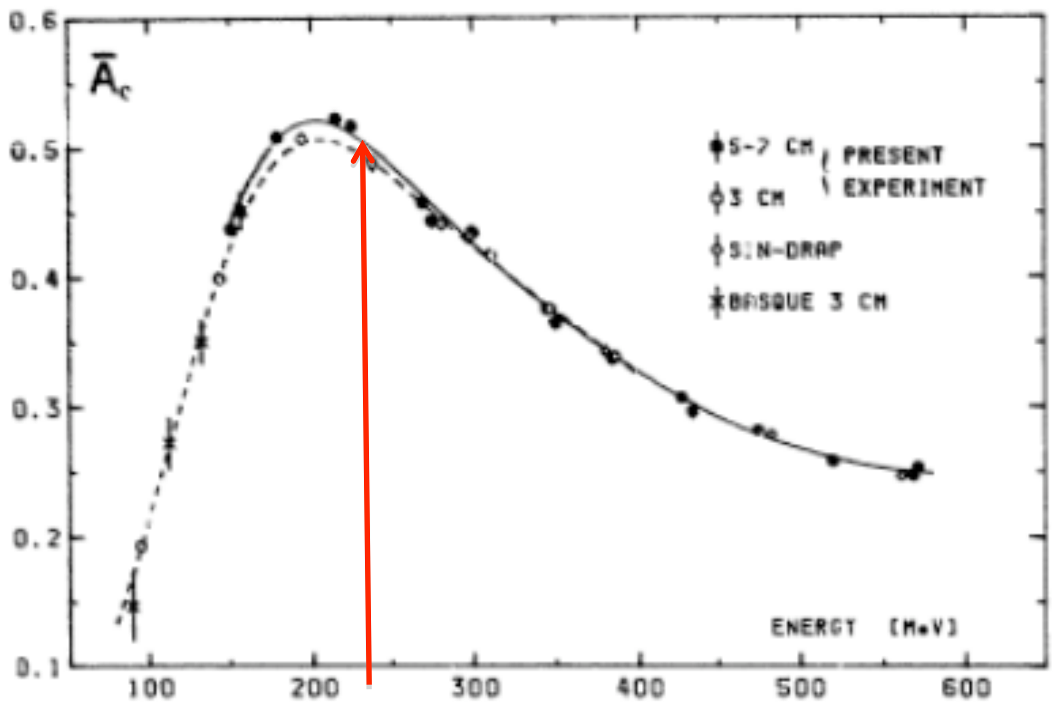


Fig. 4. Angle-averaged effective analyzing power. Curves show our fits. Points are the data included in the fits. Errors are statistical only

Fig.4. The angle averaged effective analyzing power as a function of the proton kinetic energy. The magic momentum of 0.7GeV/c corresponds to 232MeV.

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:

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

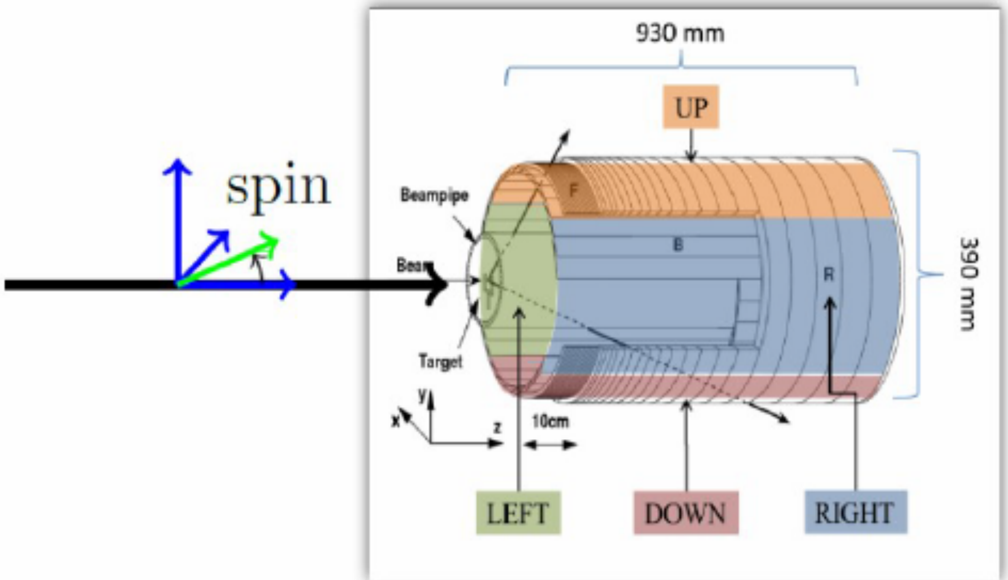
- Present design parameters allow for 10^3 s.
- Much longer SCT with thermal mixing (S.C.)?

Main Devices

Martin Gaisser/CAPP

COSY:
- ≈184m circumference
- (Un)polarized proton/deuteron beams
- Momentum range: 0.3-3.7GeV/c
- Electron/stochastic cooling

Edda Polarimeter:
- Scintillator rings and bars
- Carbon target
- Polarimeter not ideal but best we have!



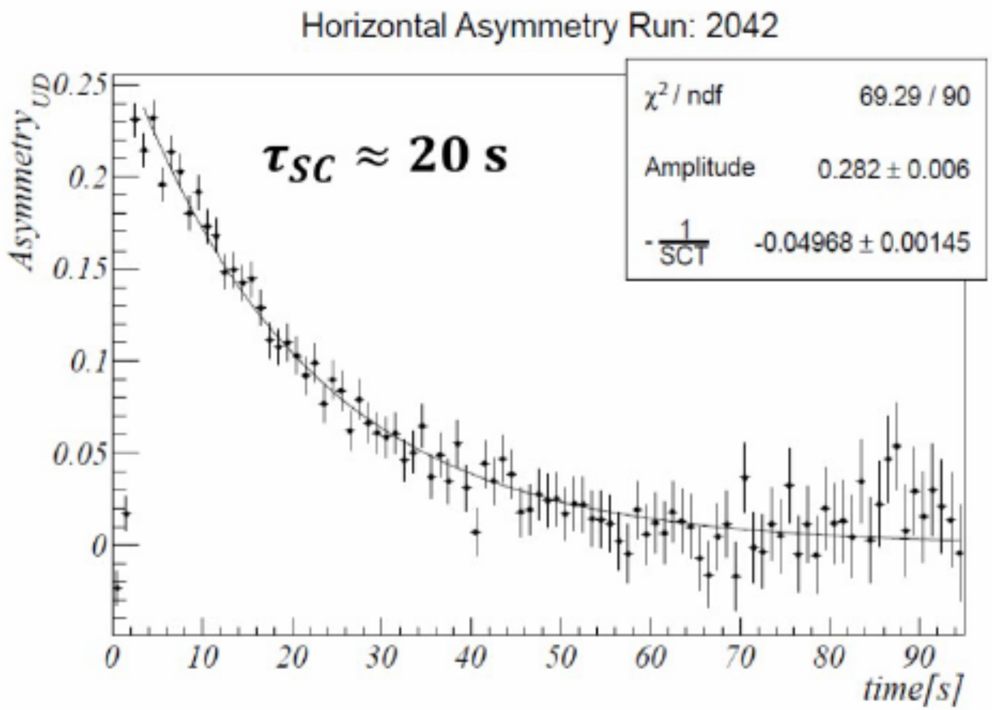
Measurement Principle

Martin Gaisser/CAPP

Beam Preparation:

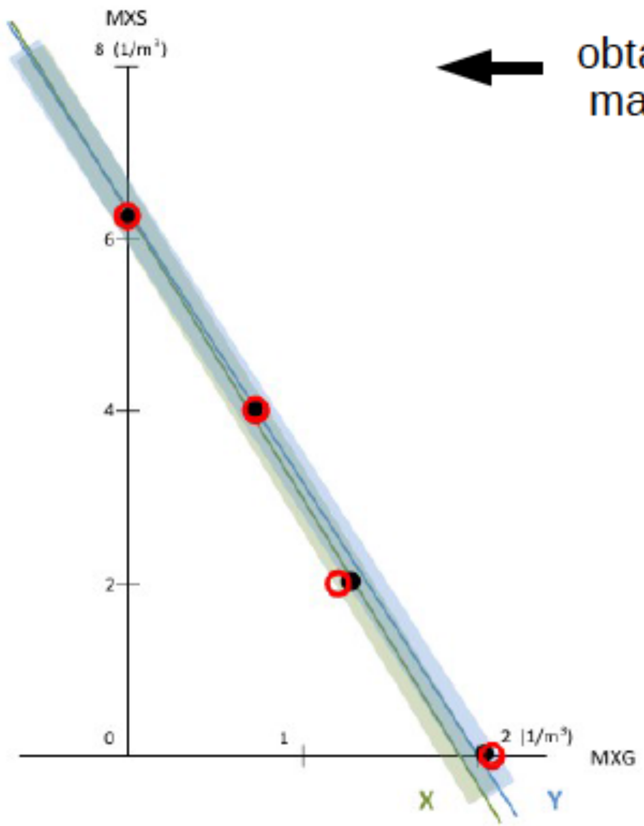
- Inject vertically polarized deuteron beam
- Accelerate
- Cool (with e-cooler) and bunch
- Put spin into horizontal plane (with rf-solenoid on spin tune resonance)

Watch decay of up-down asymmetry (horizontal polarization)

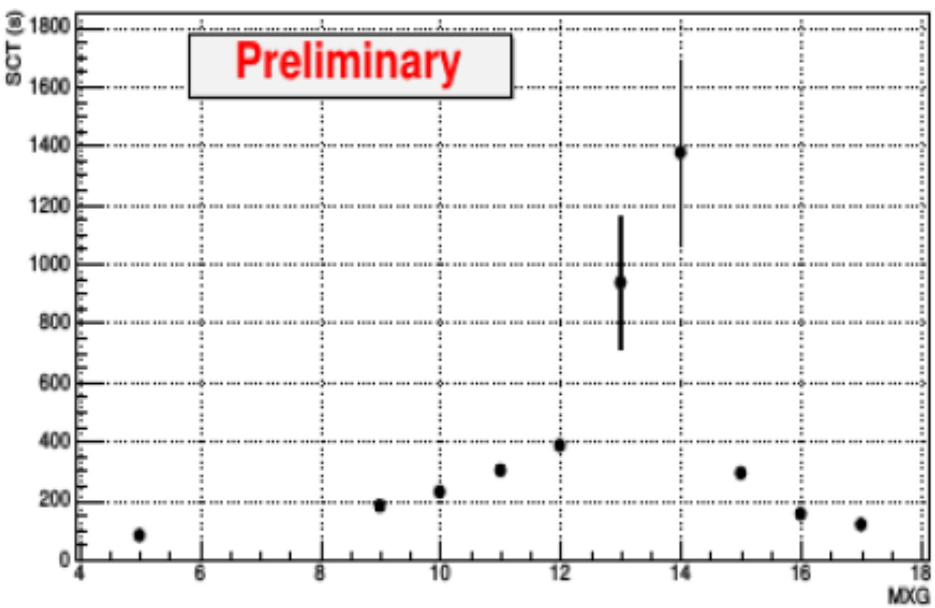


Sextupole Scans

Martin Gaisser/CAPP



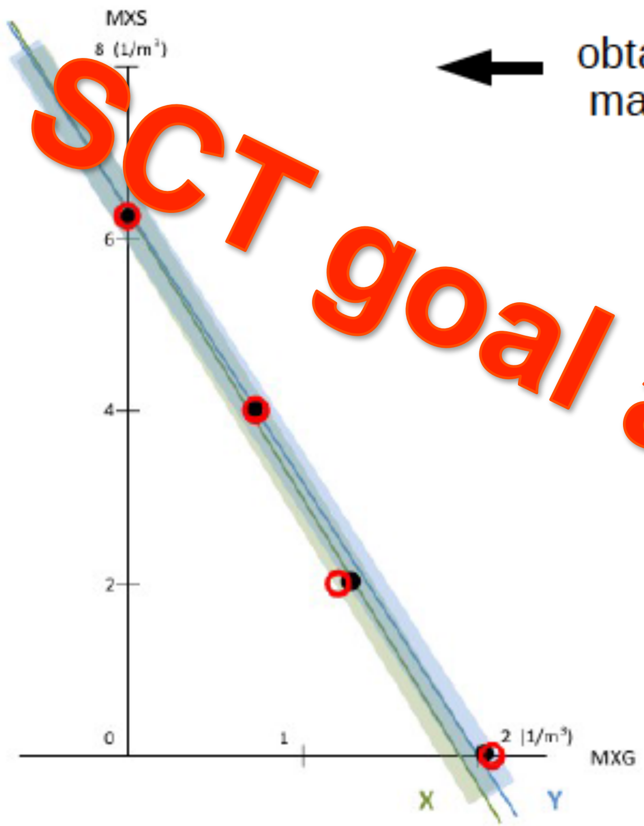
obtain this picture by rastering the MXS-MXG plane,
maximum SCT lies on zero chromaticity lines



Sextupole strength

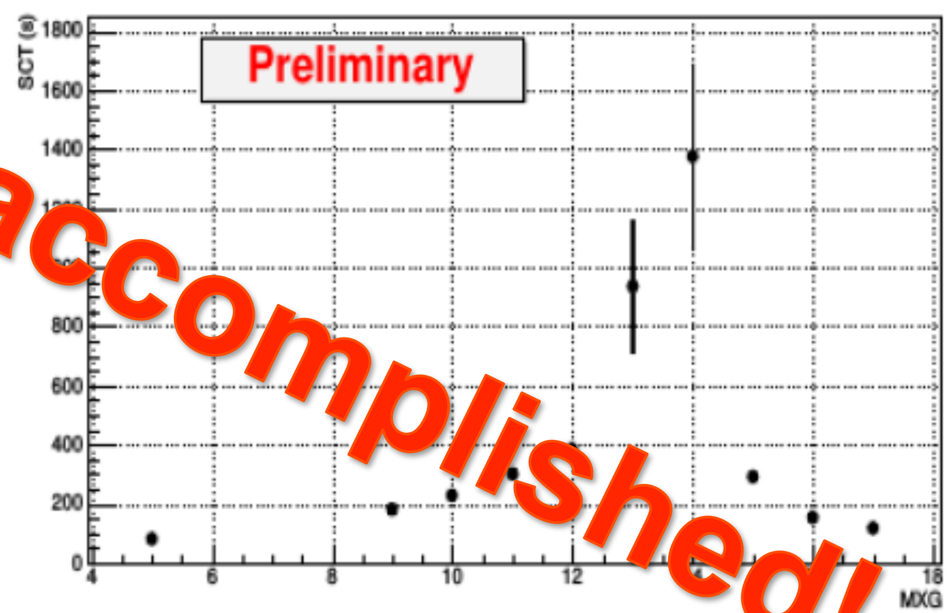
Sextupole Scans

Martin Gaisser/CAPP



obtain this picture by rastering the MXS-MXG plane, maximum SCT lies on zero chromaticity lines

SCT goal accomplished!



Sextupole strength

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 Radial electric field strength

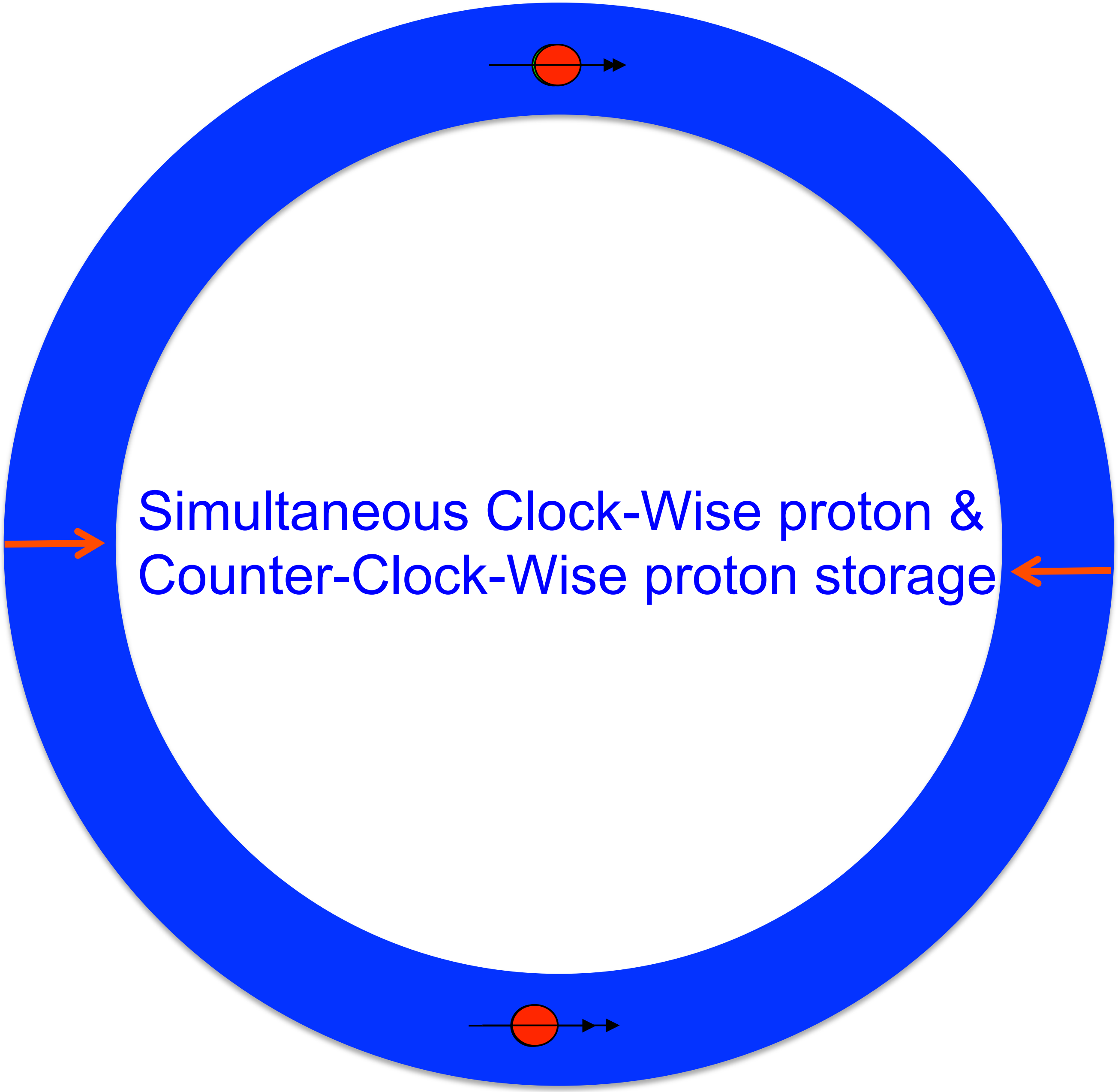
$\sigma_d = 1.0\times10^{-29}$ e-cm / year

Systematic errors

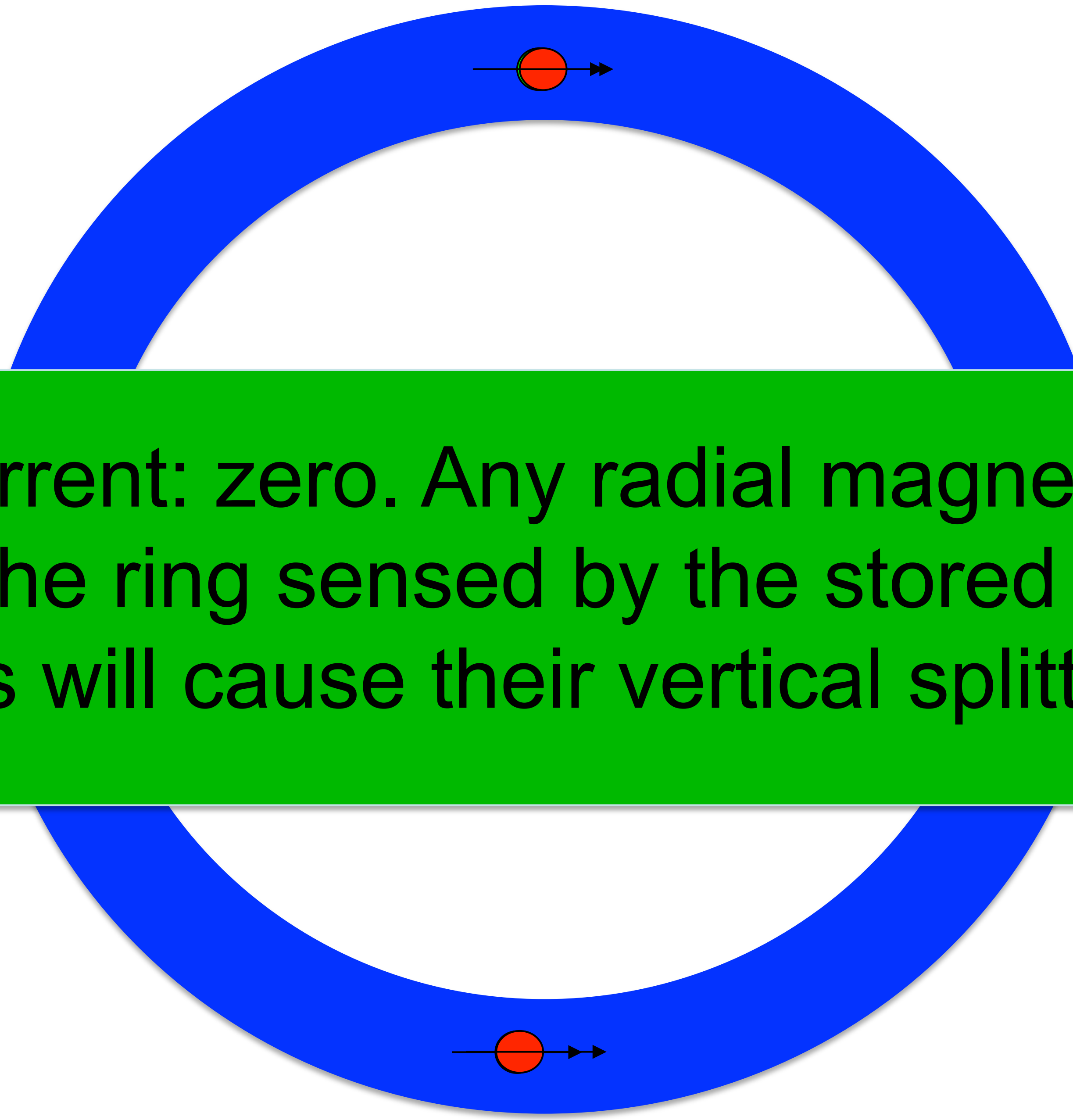
TABLE III. Main systematic errors of the experiment and their remediation.

Effect	Remediation
Radial B-field	SQUID BPMs with 1 fT/$\sqrt{\mathrm{Hz}}$ 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.

Clock-wise (CW) & Counter-Clock-wise Storage



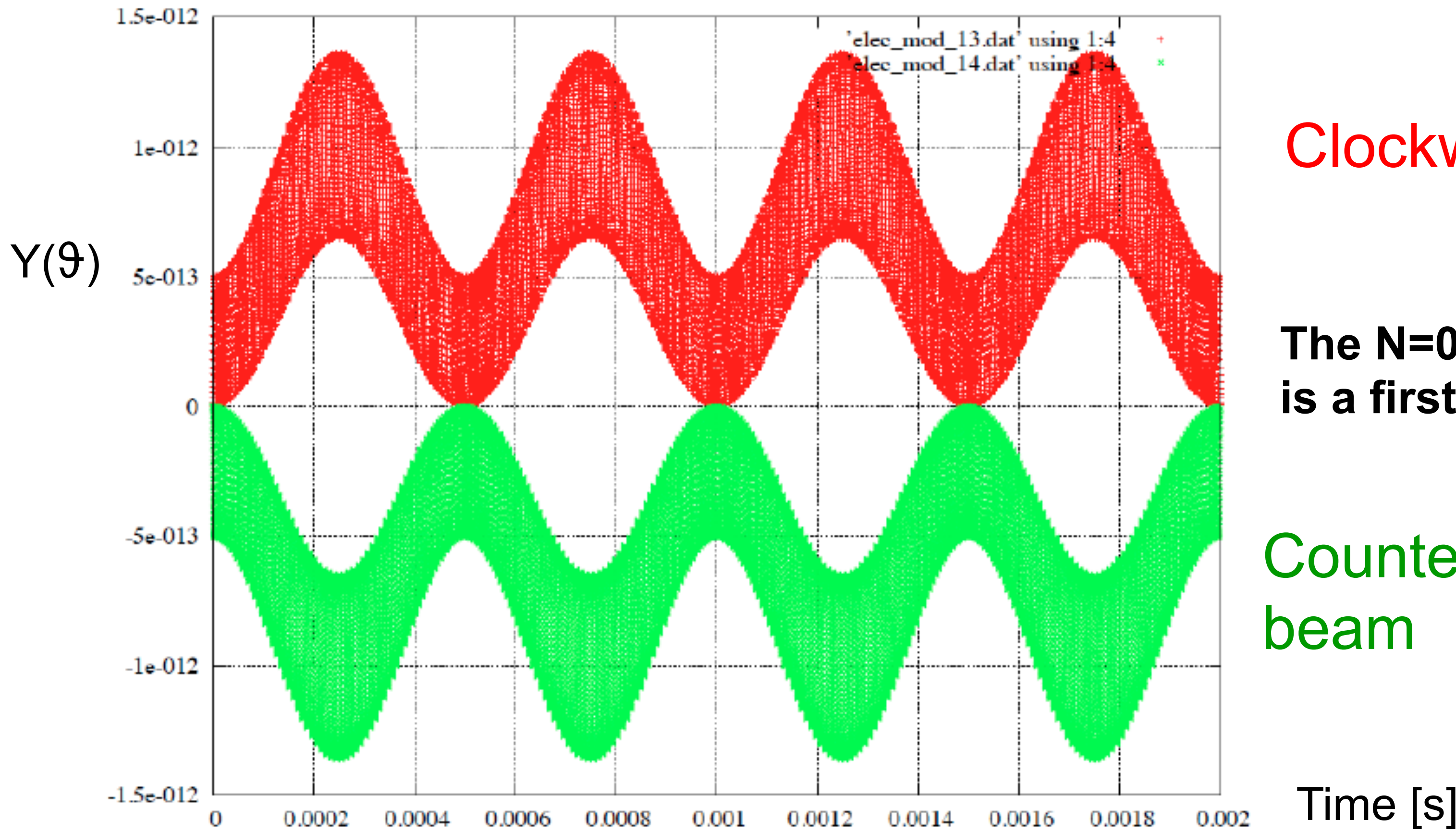
Clock-wise (CW) & Counter-Clockwise Storage



Total current: zero. Any radial magnetic field in the ring sensed by the stored particles will cause their vertical splitting.

Distortion of the closed orbit due to N^{th}-harmonic of radial B-field

$$y(\vartheta) = \sum_{N=0}^{\infty} \frac{\beta R_0 B_{rN}}{E_0\left(Q_y^2 - N^2\right)} \cos\left(N\vartheta + \varphi_N\right)$$



Clockwise beam

The N=0 component is a first order effect!

Counter-clockwise beam

SQUID BPM to sense the vertical beam splitting at 1-10kHz

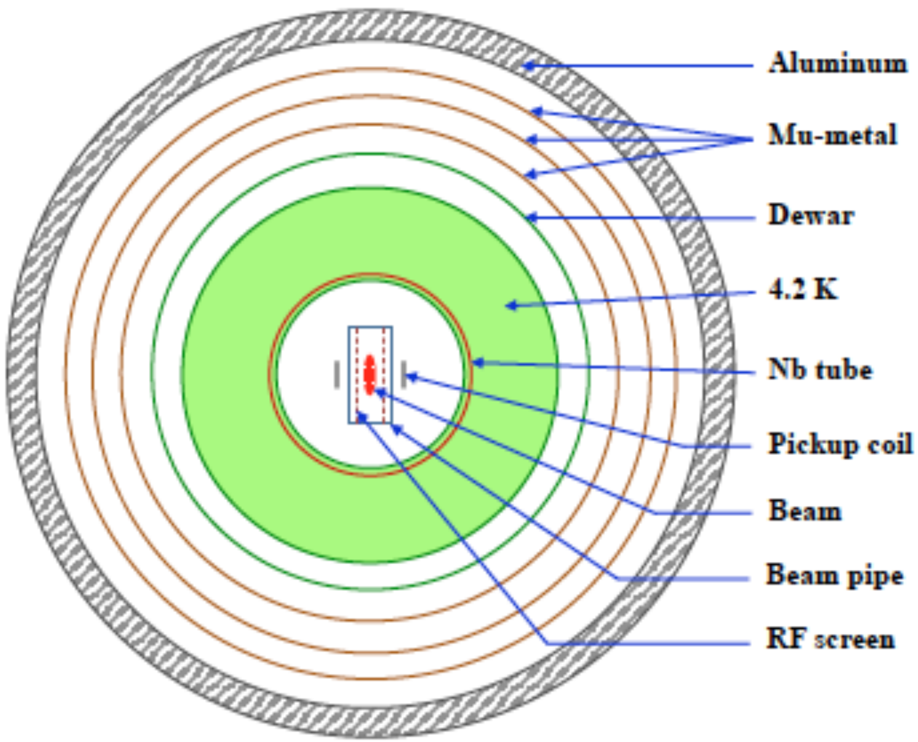
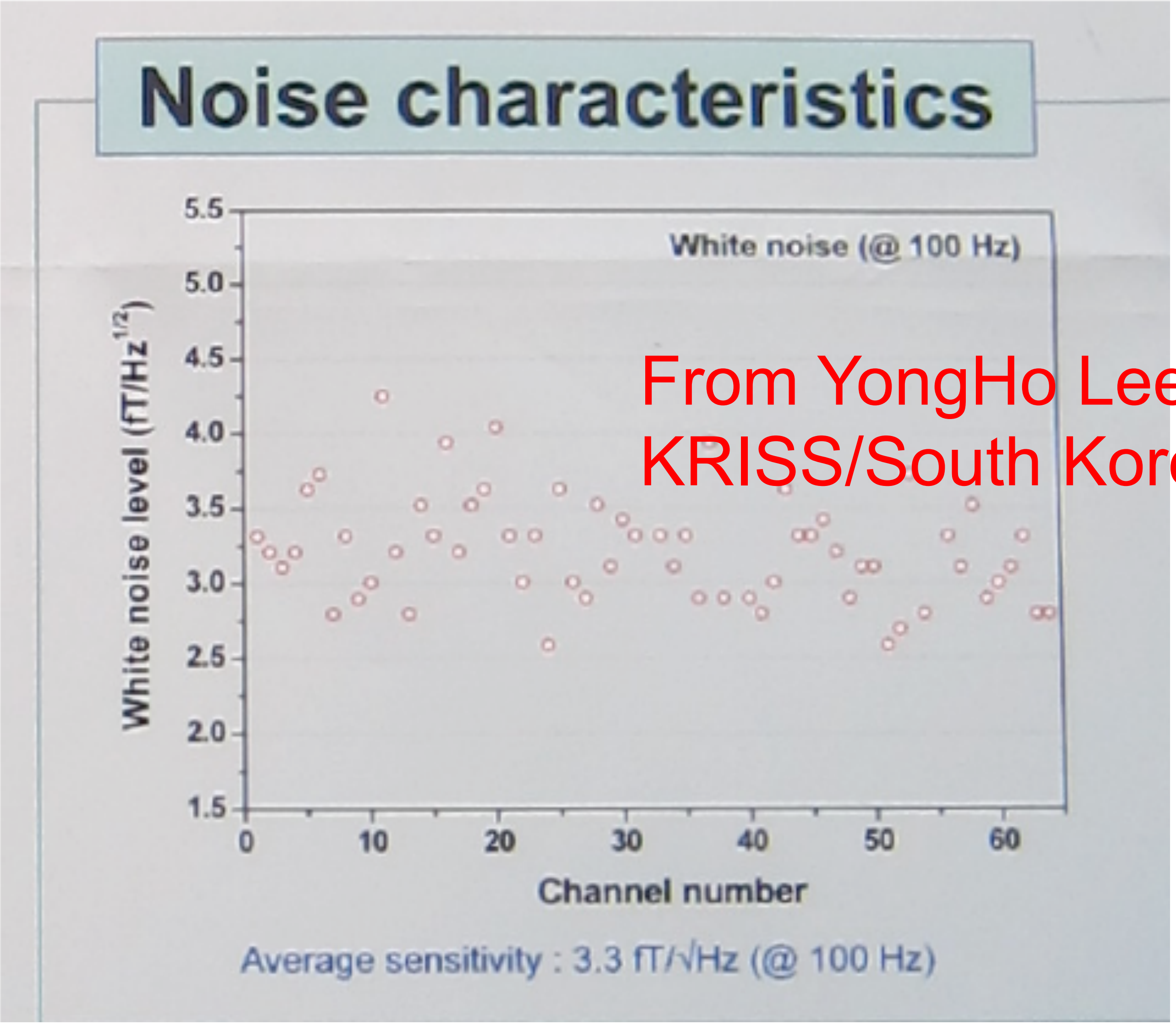


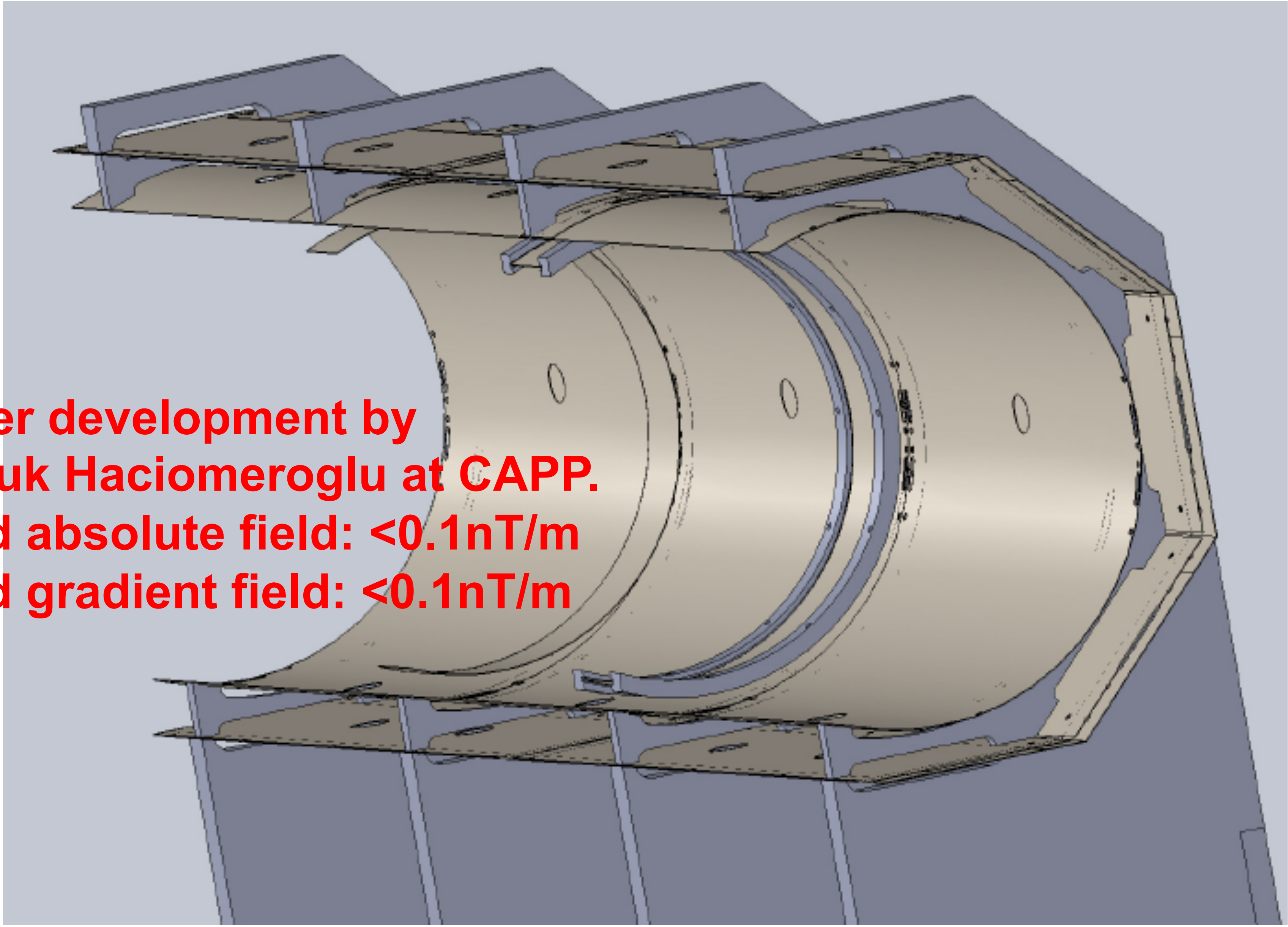
FIG. 3. A schematic of a possible SQUID BPM station. The system is shielded with a superconducting Nb tube, Al tube for RF-shield, and several mu-metal layers.

Total noise of (65) commercially available SQUID gradiometers at KRISS



From YongHo Lee's group
KRISS/South Korea

Peter Fierlinger, Garching/Munich



Under development by
Selcuk Haciomeroglu at CAPP.
Need absolute field: <0.1nT/m
Need gradient field: <0.1nT/m

Peter Fierlinger, Garching/Munich

Shipped to Korea for integration

What has been accomplished?

- ✓ Polarimeter systematic errors (with beams at KVI, and stored beams at COSY).
- ✓ Precision beam/spin dynamics tracking.
- ✓ Stable lattice, IBS lifetime: ~10^4s (Lebedev, FNAL)
- ✓ Spin coherence time 10^3 s; role of sextupoles understood (using stored beams at COSY).
- ✓ Feasibility of required electric field strength >10 MV/m, 3cm plate separation (JLab, FNAL)
- ✓ Analytic estimation of electric fringe fields and precision beam/spin dynamics tracking. Stable!
- ✓ (Paper already published or in progress.)

Major characteristics of a successful Electric Dipole Moment Experiment

- Statistical power:
  - High intensity beams
  - Long beam lifetime
  - Long Spin Coherence Time

- An indirect way to cancel B-field effect
- A way to cancel geometric phase effects
- Control detector systematic errors
- Manageable E-field strength, negligible dark current

Major characteristics of a successful Electric Dipole Moment Experiment

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- A way to cancel geometric phase effects
- Control detector systematic errors
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The storage ring Proton EDM method has it all!

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

Two different labs could host the storage ring EDM experiments

- AGS/BNL, USA: proton "magic" (simpler) ring
- COSY/IKP, Jülich/Germany: deuteron or a combination ring

Two different labs could host the storage ring EDM experiments

- ~~AGS/BNL, USA: proton "magic" (simpler) ring~~

Opportunity opening for another lab!

- COSY/IKP, Jülich/Germany: deuteron or a combination ring

Various options for EDM@COSY, Juelich

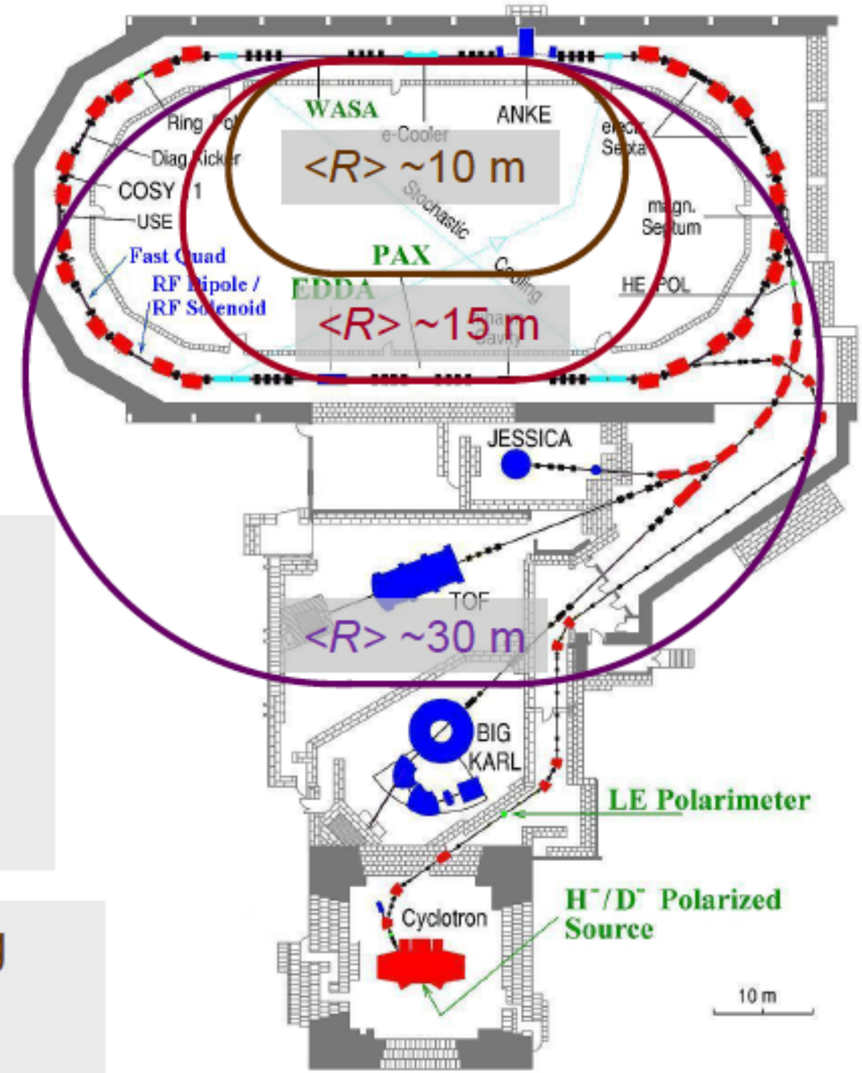
EDM with E- and B-Fields for different Particles

„all-in-one“ storage ring

Protons: p_p = 0.701 GeV/c
E_R = 16.8 MV/m, B_V = 0 T

Deuterons: p_d = 1.0 GeV/c
E_R = -4.0 MV/m, B_V = 0.16 T

Helium-3: p_{3He} = 1.285 GeV/c
E_R = 17.0 MV/m, B_V = -0.05 T



„all-in-one“ storage ring

Protons: p_d = 0.527 GeV/c
E_R = 16.8 MV/m, B_V = 0.02 T

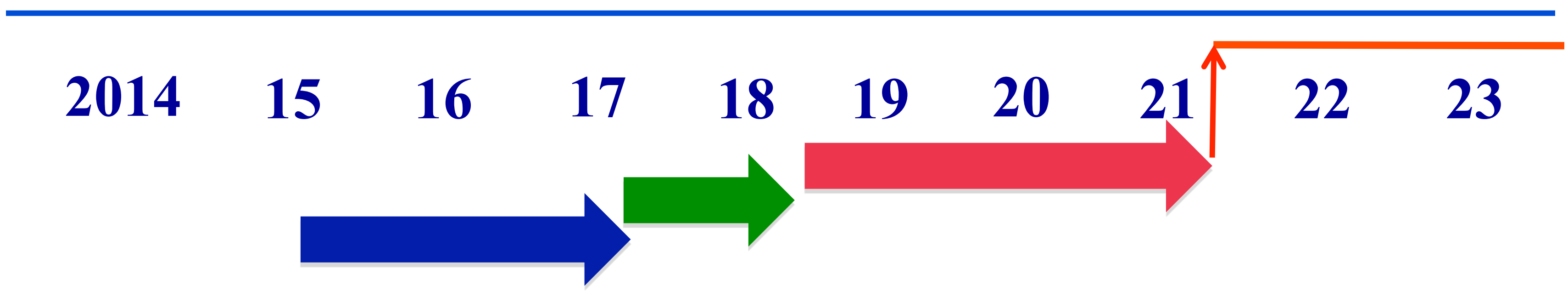
Deuterons: p_d = 1.0 GeV/c

Helium-3: p_{3He} = 0.946 GeV/c

Dedicated deuteron storage ring

Deuterons: p_d = 1.0 GeV/c
E_R = -12.0 MV/m, B_V = 0.48 T

Technically driven pEDM timeline



- Two years systems development (R&D); CDR; ring design, TDR, installation
- CDR by end of 2016
- Proposal to a lab: fall 2016

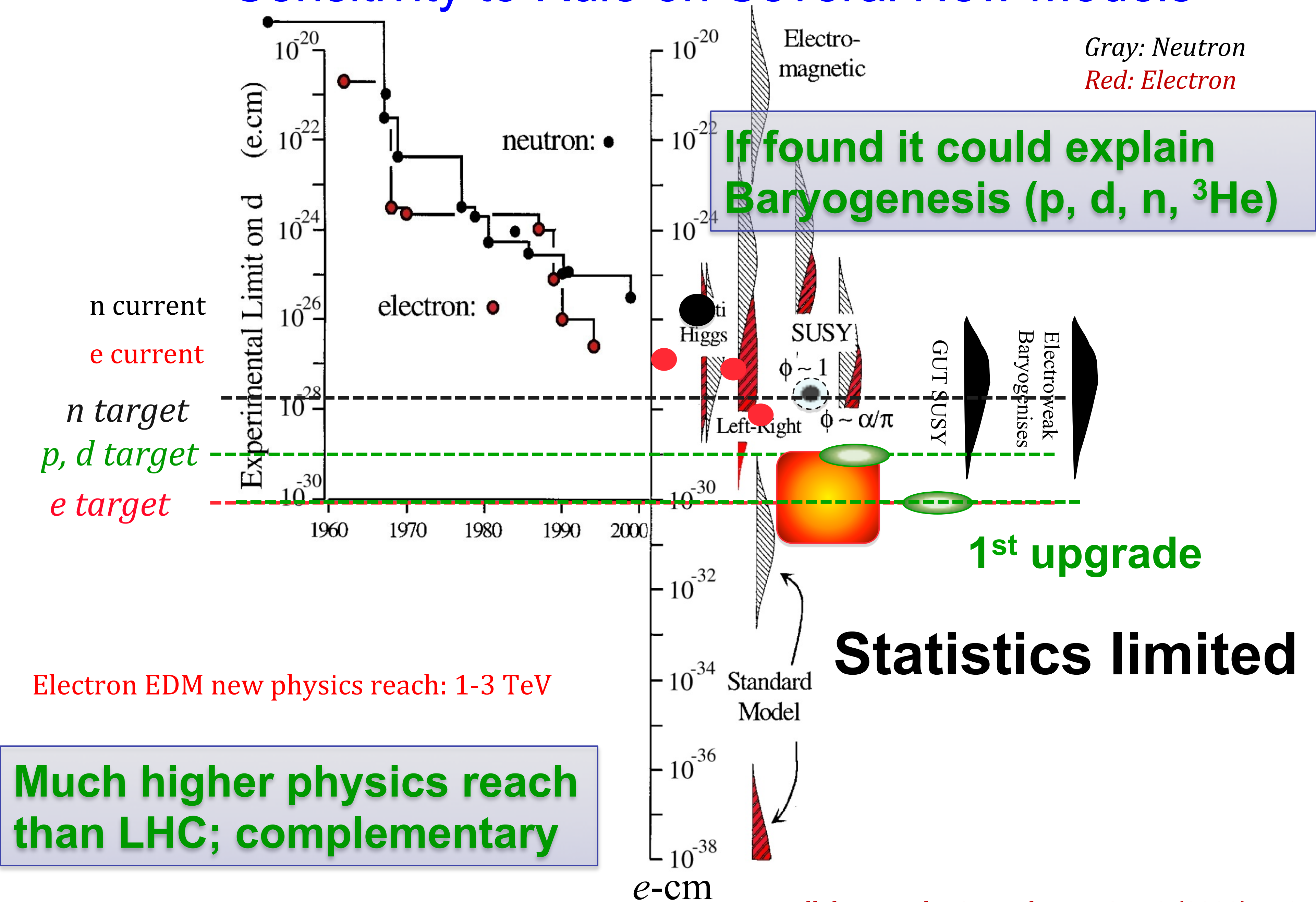
Let's indulge on proton sensitivity

- Spin coherence time (10^4 seconds), stochastic cooling-thermal mixing, …
- Higher beam intensity, smaller IBS

- Reliable E-field 15 MV/m with negligible dark current
- >5% efficient polarimeter, run longer

- Potential gain $>10^2$ in statistical sensitivity: $\sim 10^{-30}$-10^{-31} e-cm!

Sensitivity to Rule on Several New Models



Electron EDM new physics reach: 1-3 TeV

Much higher physics reach than LHC; complementary

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

Physics strength comparison (Marciano)

System	Current limit [e·cm]	Future goal	Neutron equivalent
Neutron	$<1.6\times10^{-26}$	$\sim10^{-28}$	10^{-28}
^{199}Hg atom	$<3\times10^{-29}$		10^{-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}
Proton nucleus	$<7\times10^{-25}$	$\sim10^{-29}$-10^{-30}	10^{-29}-10^{-30}

EDM status

- The EDM experiments are gearing up, getting ready:

- ^{199}Hg EDM <10^{-29} e-cm sensitivity, imminent

- nEDM at PSI 10^{-26} e-cm sensitivity, 2015 - 2017
- nEDM at PSI 10^{-27} e-cm sensitivity, 2018 - …

- nEDM at SNS ~$2{\times}10^{-28}$ e-cm starting data taking 2021

EDM status (cont'd)

- ThO, current limit on eEDM: 10^{-28} e-cm, next $\times 10$ improvement.

- TUM nEDM effort, making progress in B-field shielding, met B-field specs. It moves to ILL in 2015, goal: 10^{-28} e-cm, staged approach, starting in 2016.
- ^{225}Ra EDM, $\sim 5\times 10^{-22}$ e-cm now, $\sim 3\times 10^{-28}$ e-cm w/ FRIB

- Storage ring EDM: p,dEDM goals $\sim 10^{-29}$ e-cm Strength: statistics. Proton w/ upgrade $\sim 10^{-30}$ e-cm

The Storage Ring electron EDM!
What can we learn from it?

Build an electron storage ring

1. Electron magic momentum: 15MeV. Small ring (*R*=2.5 m) required, cost ~$5M.

2. Start simple. Run it with CW and CCW stored beams (all-electric) at magic momentum. Simulate storage ring proton EDM. Limited Physics reach on eEDM. Great for systematics studies on the Storage ring proton EDM.

3. Run it in spin-wheel mode with resonant electron-polarimeter at magic momentum (R. Talman, **arXiv: 1508.04366**).
4. EDM sensitivity (if limited by systematics: B-field stability) $<10^{-27}$ *e.*cm, possibly much better.

Storage ring EDM

- High precision experiments: deuteron, electron, proton are finding host labs

- Complementary approach to:
  - LHC in Europe
  - ILC in Japan
  - Very large hadron collider (FCC) in China
  - Neutrino Physics in the USA

Summary

- Storage ring EDM effort is timely

- Can start simple, with all electric eEDM ring, study all-electric ring concepts, apply to proton.

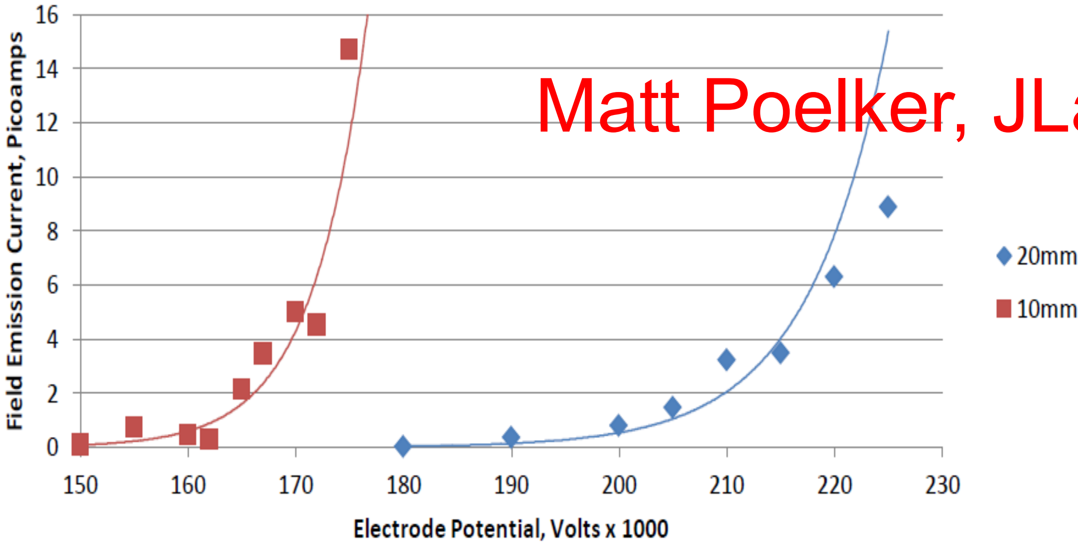
- Ultimate sensitivity for e, p, d < 10^{-29}-10^{-30} e-cm

- SUSY-like physics reach: 10^3-10^4TeV, it can show the way ahead.

Extra slides

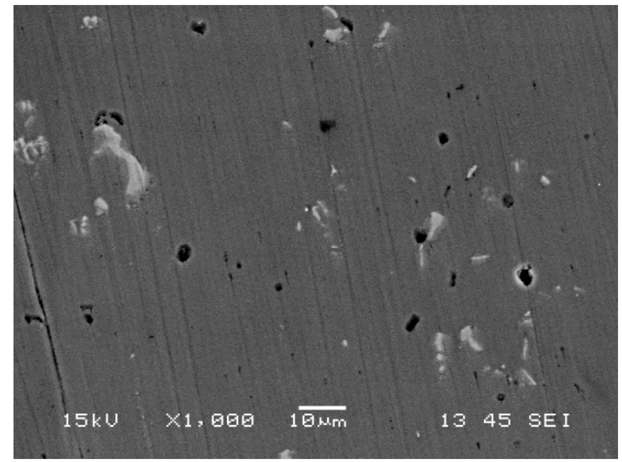
JLab results with TiN-coated Aluminum

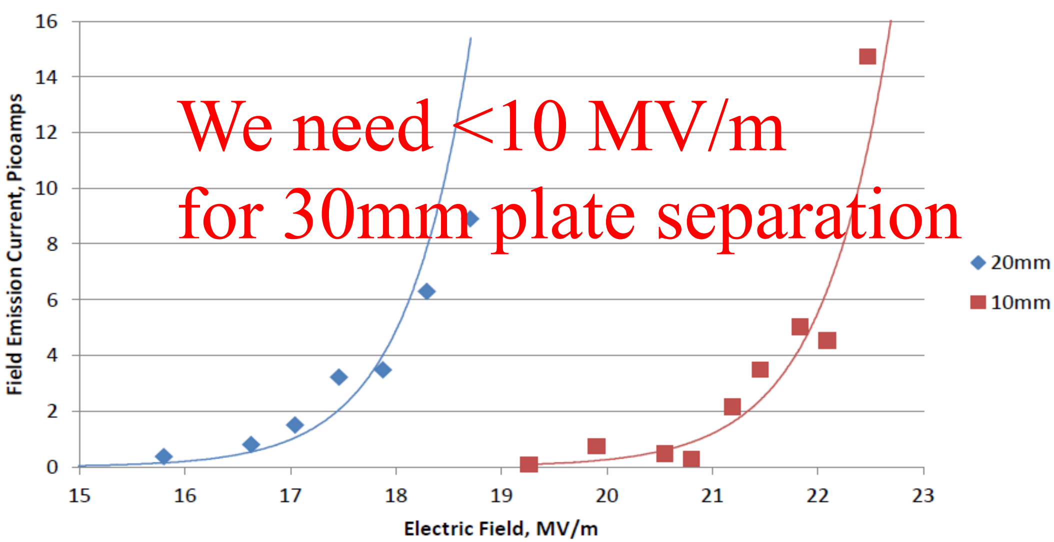
No measureable field emission at 225 kV for gaps > 40 mm, happy at high gradient



Matt Poelker, JLab

Bare Al

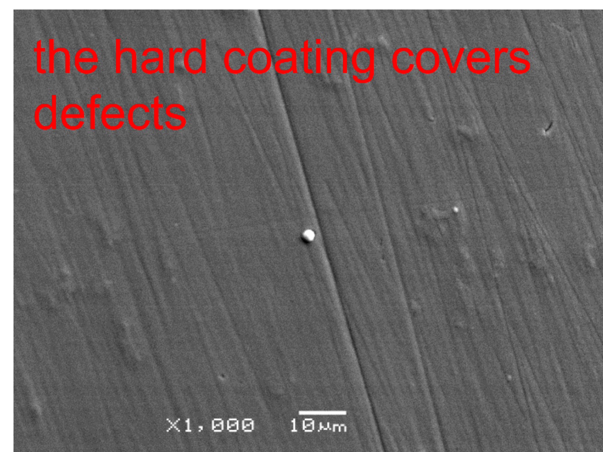




We need <10 MV/m
for 30mm plate separation

15 MV/m 20 MV/m

TiN-coated Al



Work of Md. A. Mamun and E. Forman

Fringe fields

1. E-field lattices with straight sections. The issues:
   a) Multipoles
   b) Radial E-field (due to left-right asymmetry)

2. See Eric Metodiev et al., for a complete study of fringe fields: Phys. Rev. ST Accel. Beams 17 (2014) 5, 074002, available at http://journals.aps.org/prstab/pdf/10.1103/PhysRevSTAB.17.074002

Fringe fields

$$x = \frac{d}{2\pi}(u + 1 + e^u \cos v), \qquad y = \frac{d}{2\pi}(v + e^u \sin v),$$

$$E_x = \frac{2V_0}{d} \frac{e^u \sin v}{(1 + 2e^u \cos v + e^{2u})},$$

$$E_y = -\frac{2V_0}{d} \frac{1 + e^u \cos v}{(1 + 2e^u \cos v + e^{2u})}.$$

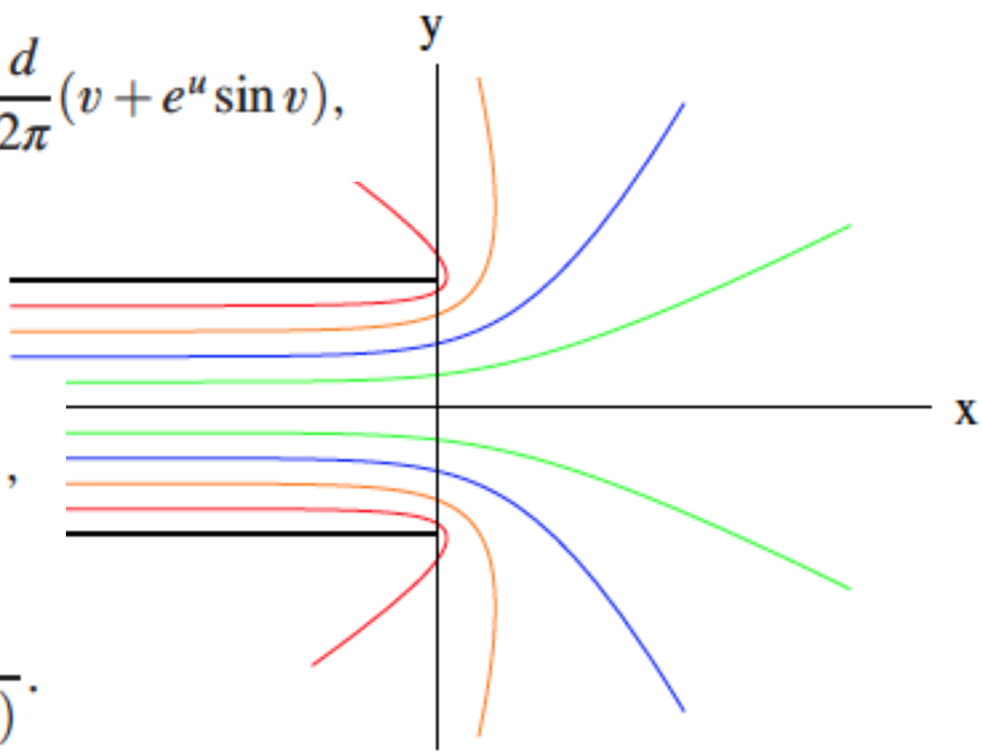
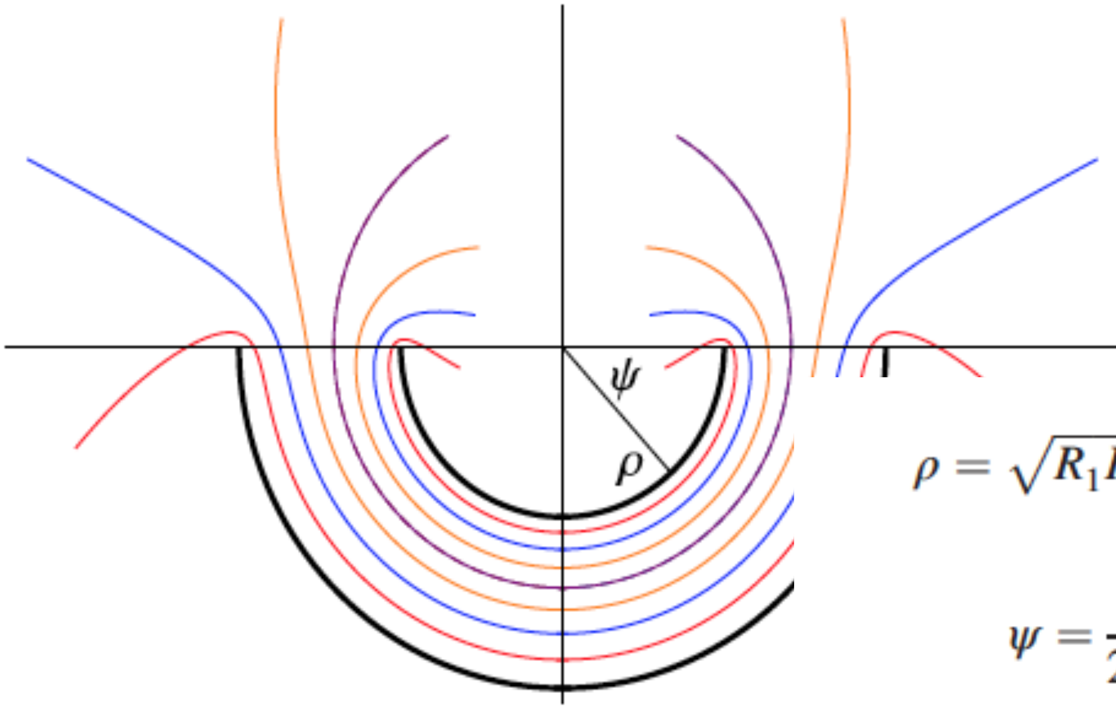


FIG. 1. Equipotential lines, equally spaced in voltage, at the fringes of flat parallel plates.

Electric fringe-fields from straight plates are left/ right symmetric

Fringe fields



$$\rho = \sqrt{R_1 R_2} \exp\left[\frac{1}{2\pi} \ln \frac{R_2}{R_1} (e^u \sin v + v)\right],$$

$$\psi = \frac{1}{2\pi} \ln \frac{R_2}{R_1} (1 + e^u \cos v + u),$$

FIG. 3. Equipotential lines, equally spaced in voltage, of concentric semicircles found using the methods mentioned [2] for cylindrical plates by reflecting about the vertical axis. Figure shown is for semicircular plates where $R_2/R_1 = 2$.

Electric fringe-fields from bend plates are left/right asymmetric

Fringe fields

1. We have solved the problem analytically (exactly) and have implemented the exact solution to the tracking program.

2. Time step used: 1-100ps.

3. Assumed infinitely high plates.

Fringe fields, coordinate inversion

Now we solve for $u(\rho, \psi)$ and $v(\rho, \psi)$ in the same way through the equivalence described above. We thus arrive at the u and v expressions for the finite cylindrical plates:

$$u = \Re\left\{-1 + \frac{2\pi z}{\ln(\frac{R_2}{R_1})} - W\left[\exp\left(-1 + \frac{2\pi z}{\ln(\frac{R_2}{R_1})}\right)\right]\right\}, \quad (19)$$

$$v = \Im\left\{-1 + \frac{2\pi z}{\ln(\frac{R_2}{R_1})} - W\left[\exp\left(-1 + \frac{2\pi z}{\ln(\frac{R_2}{R_1})}\right)\right]\right\}, \quad (20)$$

where $z = \psi + i\ln(\rho/\sqrt{R_1 R_2})$ and the branch of the Lambert W function is $\kappa(z) = \lceil[\Im(\frac{2\pi z}{\ln(R_2/R_1)}) - \pi]/2\pi\rceil$.

Fringe fields, Getting the E-fields for tracking

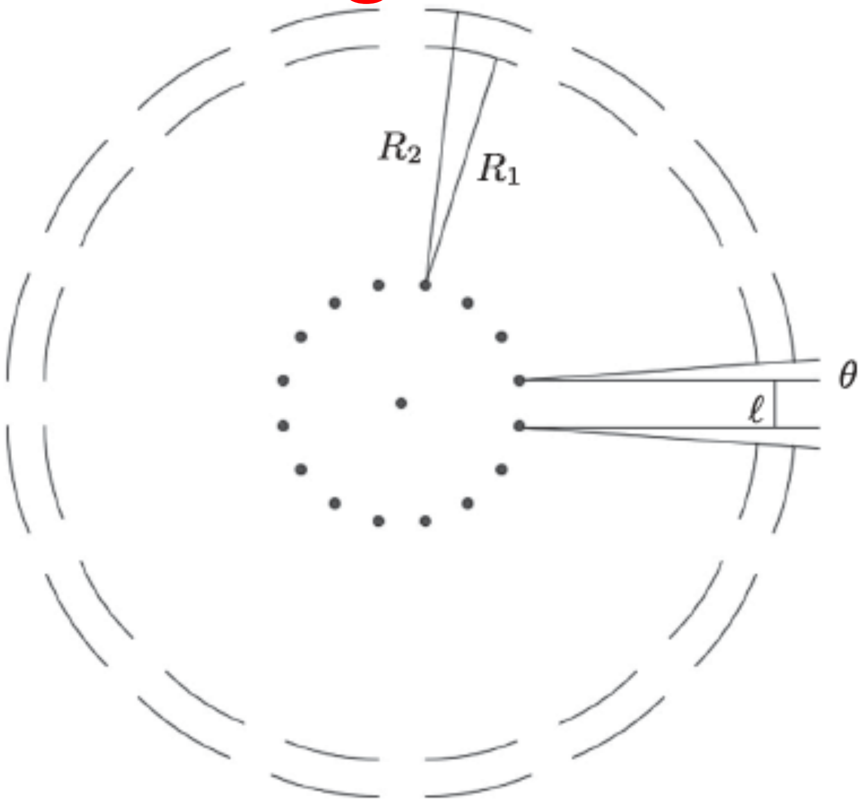
$$E_\rho = -\frac{2V_0(1+e^u\cos v)\exp\left[-\frac{1}{2\pi}\ln\frac{R_2}{R_1}(e^u\sin v+v)\right]}{\ln(\frac{R_2}{R_1})\sqrt{R_1R_2}(1+2e^u\cos v+e^{2u}),} \tag{9}$$

$$E_\psi = \frac{2V_0e^u\sin v\exp\left[-\frac{1}{2\pi}\ln\frac{R_2}{R_1}(e^u\sin v+v)\right]}{\ln(\frac{R_2}{R_1})\sqrt{R_1R_2}(1+2e^u\cos v+e^{2u})}. \tag{10}$$

The expressions above can be represented, like the field expressions for the flat plates, in a further simplified form. We take E to be the negatively signed magnitude of the electric field:

$$E = -\frac{2V_0\exp\left[-\frac{1}{2\pi}\ln\frac{R_2}{R_1}(e^u\sin v+v)\right]}{\ln(\frac{R_2}{R_1})\sqrt{R_1R_2}\sqrt{1+2e^u\cos v+e^{2u}}}. \tag{11}$$

Fringe fields: to get stability



Biggest effect: cut off a θ=1mrad from every plate. (R_0 ~ 40m, 16 sections)

FIG. 6. The Proton EDM storage ring geometry. The ring consists of 16 sections of concentric cylindrical deflectors separated by some distance ℓ. Each section spans $2\pi/16 - 2\theta$ radians. The fringe effects occur near the ends of the deflectors.

Fringe fields: radial displacement around the ring, 0.5 mm max.

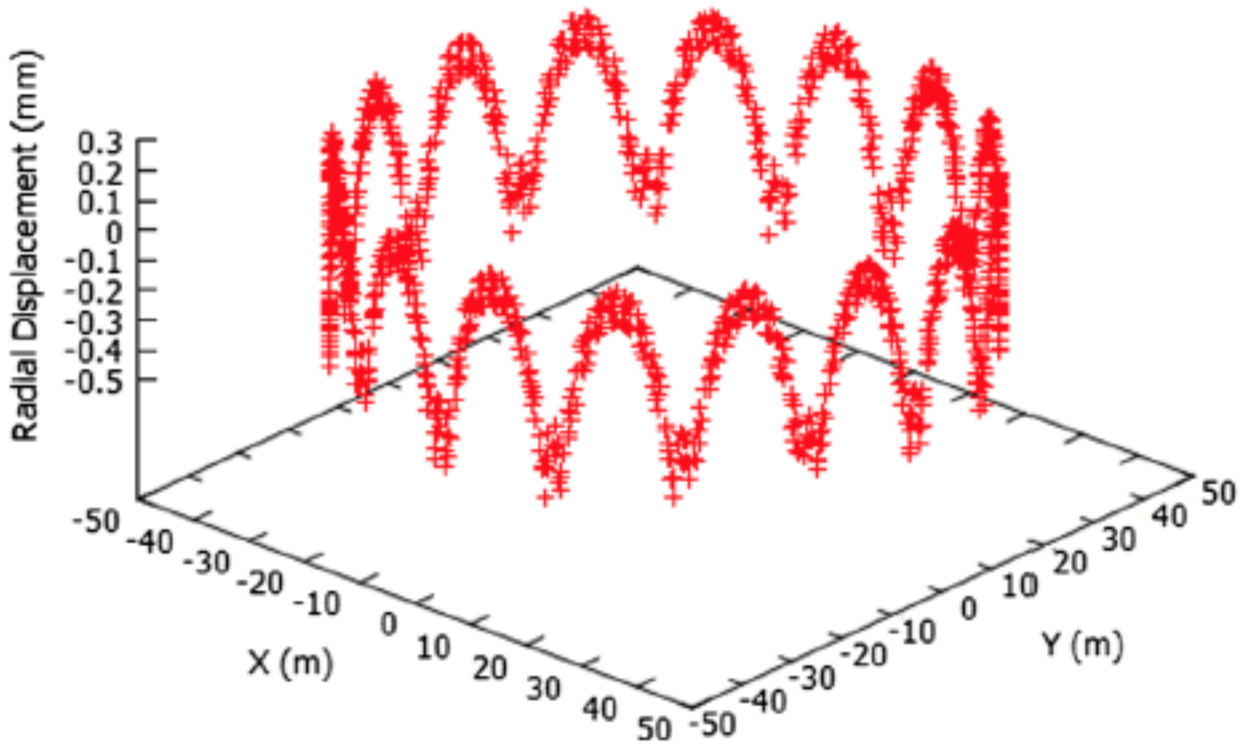
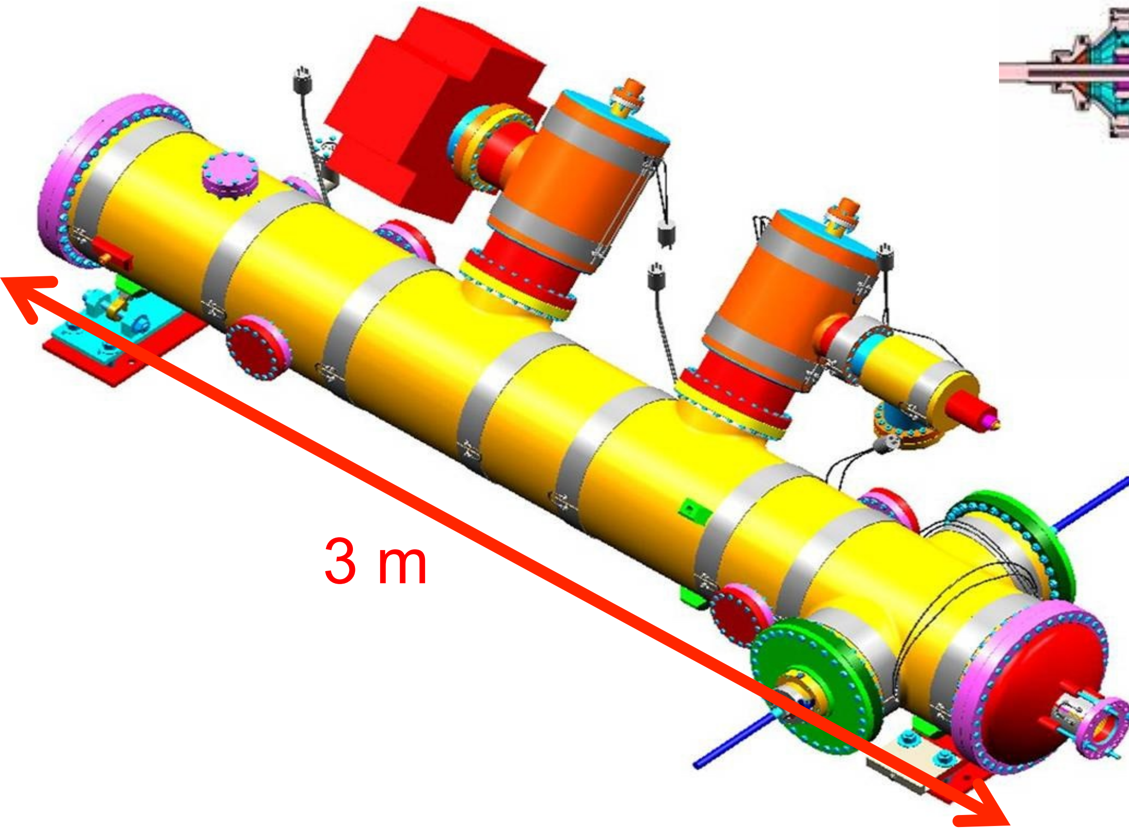
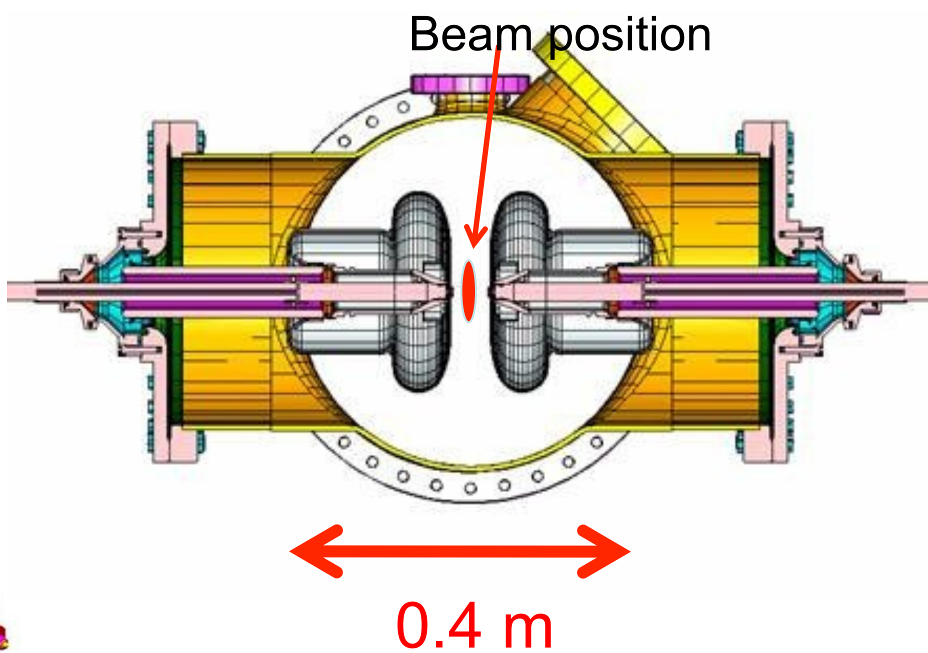


FIG. 7. The radial displacement of a proton with the design momentum around the ring from its hard-edge orbit, starting at an initial position of 45.029 m using an angle $\theta = 1.0$ mrad. The oscillations about this radius are shown as a function of time (top) and of position around the ring (bottom).

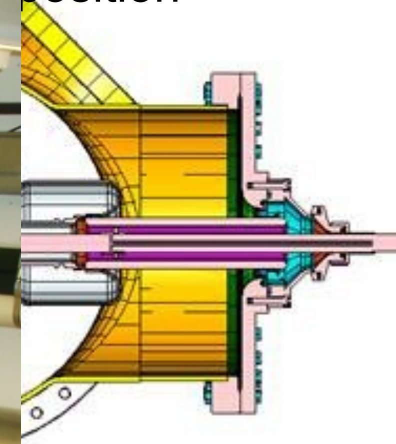
E-field plate module: Similar to the (26) FNAL Tevatron ES-separators





E-field plate module: Similar to the (26) FNAL Tevatron ES-separators

position



Why a large radius ring (sr pEDM)?

1. Electric field needed is moderate (≤10MV/m). New techniques with coated Aluminum is a cost savings opportunity.

2. Long horizontal Spin Coherence Time (SCT) w/out sextupoles. The EDM effect is acting for time ~SCT.

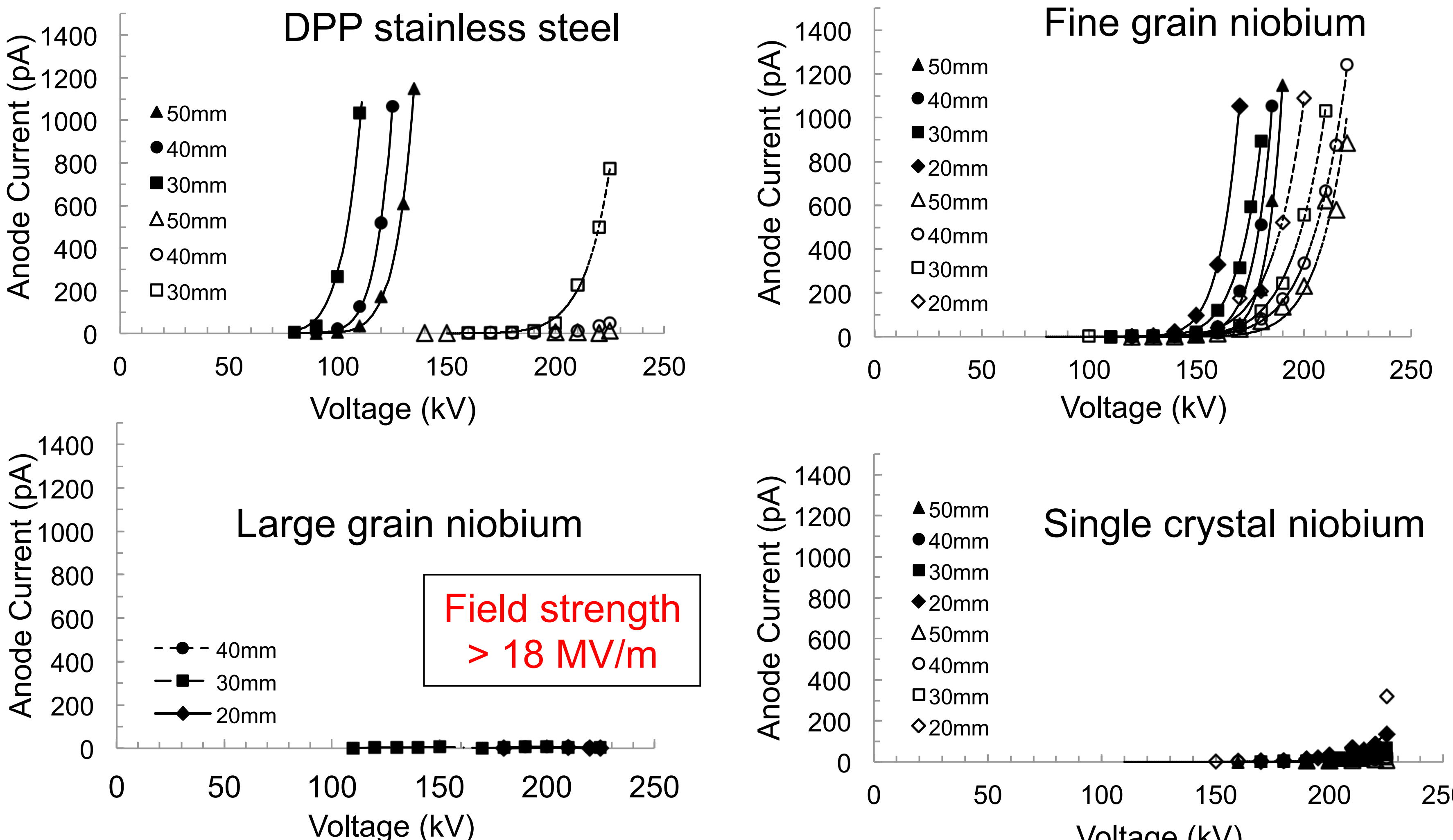
JLab E-field breakthrough

- ✓ Large grain Nb, no detectable dark current up to 18 MV/m and 3cm plate gap.
- ✓ TiN coated Al plates reach high E-field strength
- JLab to test large surface plates

Field Emission from Niobium

Work of M. BastaniNejad
Phys. Rev. ST Accel. Beams, 15, 083502 (2012)

Buffer chemical polish: less time consuming than diamond paste polishing



Conventional High Voltage processing: solid data points
After Krypton Processing: open data points

EDMs of hadronic systems are mainly sensitive to

- Theta-QCD (part of the SM)

- CP-violating sources beyond the SM

Alternative simple systems are needed to be able to differentiate the CP-violating source (e.g. neutron, proton, deuteron,…).

pEDM at 10^{-29}e•cm is > an order of magnitude more sens. than the best current nEDM plans

Storage ring electron EDM

- All electric ring: electron “magic” momentum: 15MeV/c
  - Originally proposed by Yuri Orlov, circa 2004
  - Polarimeter was the major issue
  - Bill Morse developed on eEDM concepts, 2013
  - Beam-beam scattering major issue (Valerie Lebedev)
  - Richard Talman, 2015: use resonant polarimeter combined with Koop’s spin wheel. Potentially a game changer…!

Richard Talman's electron polarimeter concept

eEDM: Potentially systematics limited at better than 10^{-27} e.cm!

5 Resonant (Longitudinal) Polarimeter

arXiv:1508.04366

Figure: Longitudinally polarized beam approaching a superconducting helical resonator. Beam polarization is due to the more or less parallel alignment of the individual particle spins, indicated here as tiny current loops. The helix is the inner conductor of a helical transmission line, open at both ends. The cylindrical outer conductor is not shown.

Derbenev's electron polarimeter concept

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RF-resonance beam polarimeter
Part I. Fundamental concepts

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The possibility of an RF-resonance polarimeter (RFP) for fast non-destructive measurement of beam polarization in an accelerator ring is considered. In order to accumulate the transition radiation from the free oscillating coherent spin of the beam, a passive superconducting cavity is proposed. The increase of effective voltage in the cavity with time (related to beam polarization) is calculated here. The efficiency of the polarimeter does not decrease with beam energy and is proportional to the average beam current A possible scheme of measurement of the accumulated voltage is presented. The noise limitations are taken into account and evaluated. Siberian snakes can be used in order to provide a sufficiently small value for the spin tune spread. Numerical examples are given

Derbenev's electron polarimeter concept

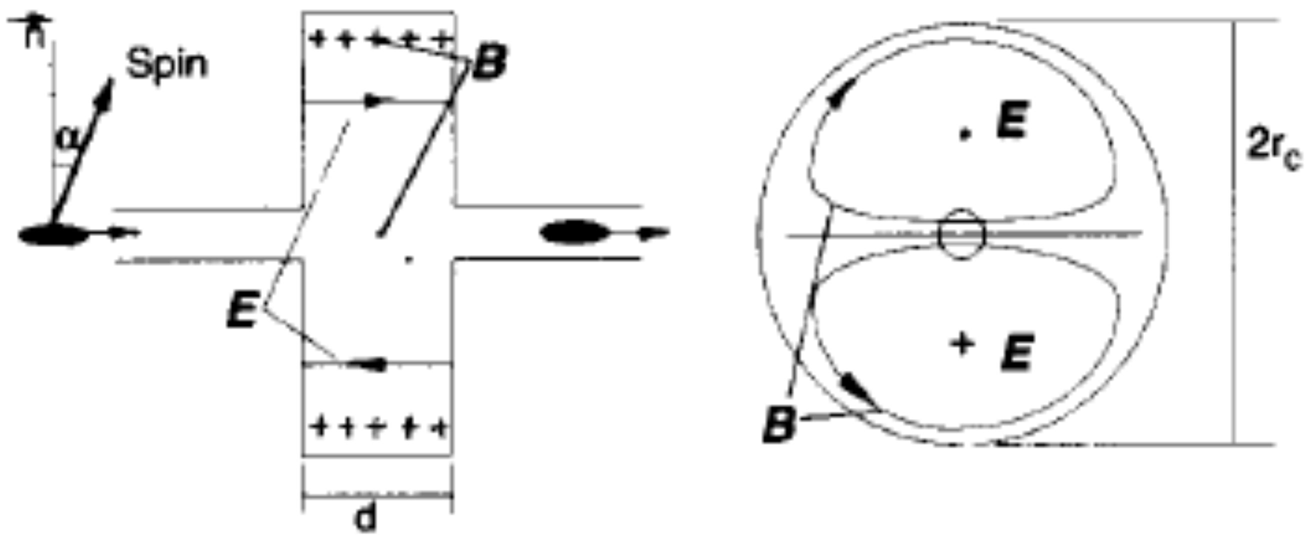

Fig. 1 Scheme of spin interaction with TM_{110} mode.

Opportunities for new collaborators

- Electric field strength issues for large surface plates, dark currents
- Beam-based alignment, E-field plate alignment (pot. syst. error source)
- Beam impedance issues (pot. syst. error source)

Build an electron storage ring

1. Start simple. Run it with CW and CCW stored beams (all-electric) at magic momentum. Simulate storage ring proton EDM. Limited Physics reach on eEDM. Great for systematics studies on the Storage ring proton EDM.

2. Run it in spin-wheel mode with resonant electron-polarimeter at magic momentum. EDM sensitivity (if limited by systematics: B-field stability) $<10^{-27}$*e*.cm

3. Run it in combined electric and magnetic fields configuration below magic momentum. EDM sensitivity (if limited by systematics) $<10^{-29}$*e*.cm

What can we learn from a storage ring electron EDM: all electric

- Probe the free-electron EDM with high accuracy
- “Learn by doing”, a working prototype of a large ring. Install sextupoles to prolong SCT.
- Learn about E-field alignment issues as well as stability issues.

What can we learn from a storage ring electron EDM: all electric

- Study fringe-field effects on SCT & storage time.
- Study wake field issues (beam impedance), coupled with RF-cavity misalignment.

What can we learn from a storage ring electron EDM: all electric

- Store simultaneous CW & CCW beams. Modulate vertical focusing strength. Install SQUID-based BPMs. Study the effects of external B-fields (stability issues, detection sensitivity).

- Install B-field shielding and exercise feedback system (B-field cancellation system).

What can we learn from a storage ring electron EDM: combined ring

- Study all issues related with combined E and B-fields, e.g., fringe-field effects, local cancellations, geometrical phases, low energy e-trapping… Test the storage ring deuteron EDM concepts!

- Probe the electron EDM with high accuracy, better than 10^{-29} *e*.cm.