Center for Axion and Precision Physics Research
Institute for Basic Science
KAIST

13 February 2015
FCC WG on exp. With the CERN injectors

Current Status of our S.R. EDM exp.; Plans.

Yannis Semertzidis, CAPP/IBS and KAIST

The experiment and prospects

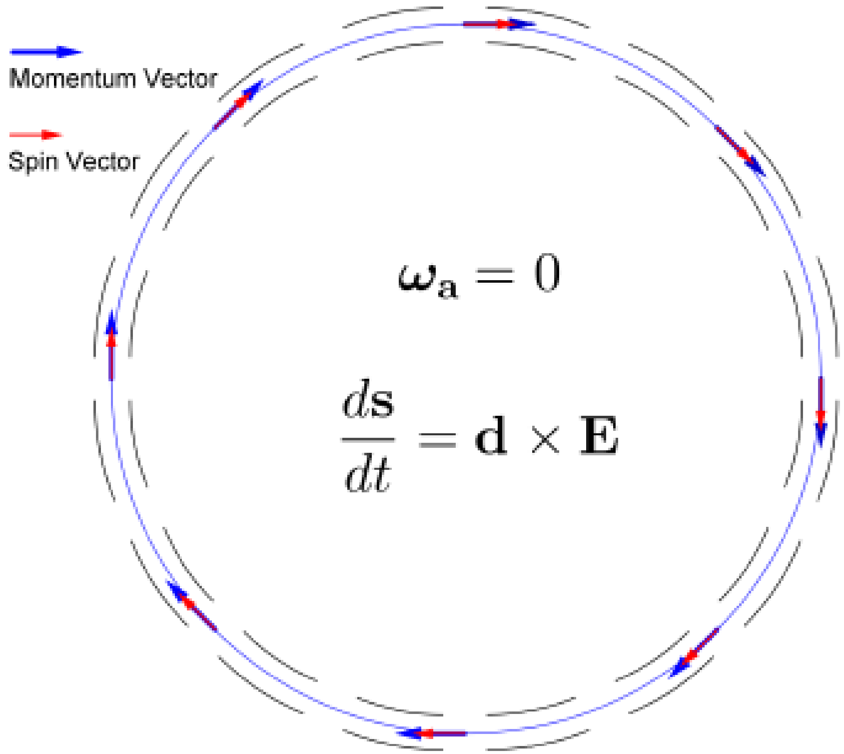
- Ready to write a CDR for 10^{-29} e-cm
- DOE visit to finalize the development plan
- Opportunities for CERN

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

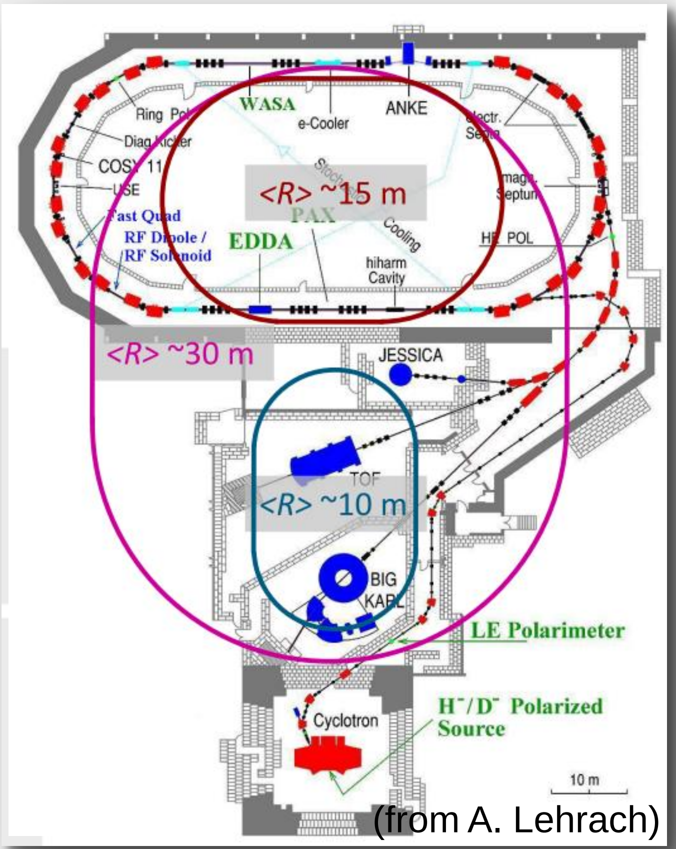
EDMs: Storage ring projects

pEDM in all electric ring at BNL or FNAL

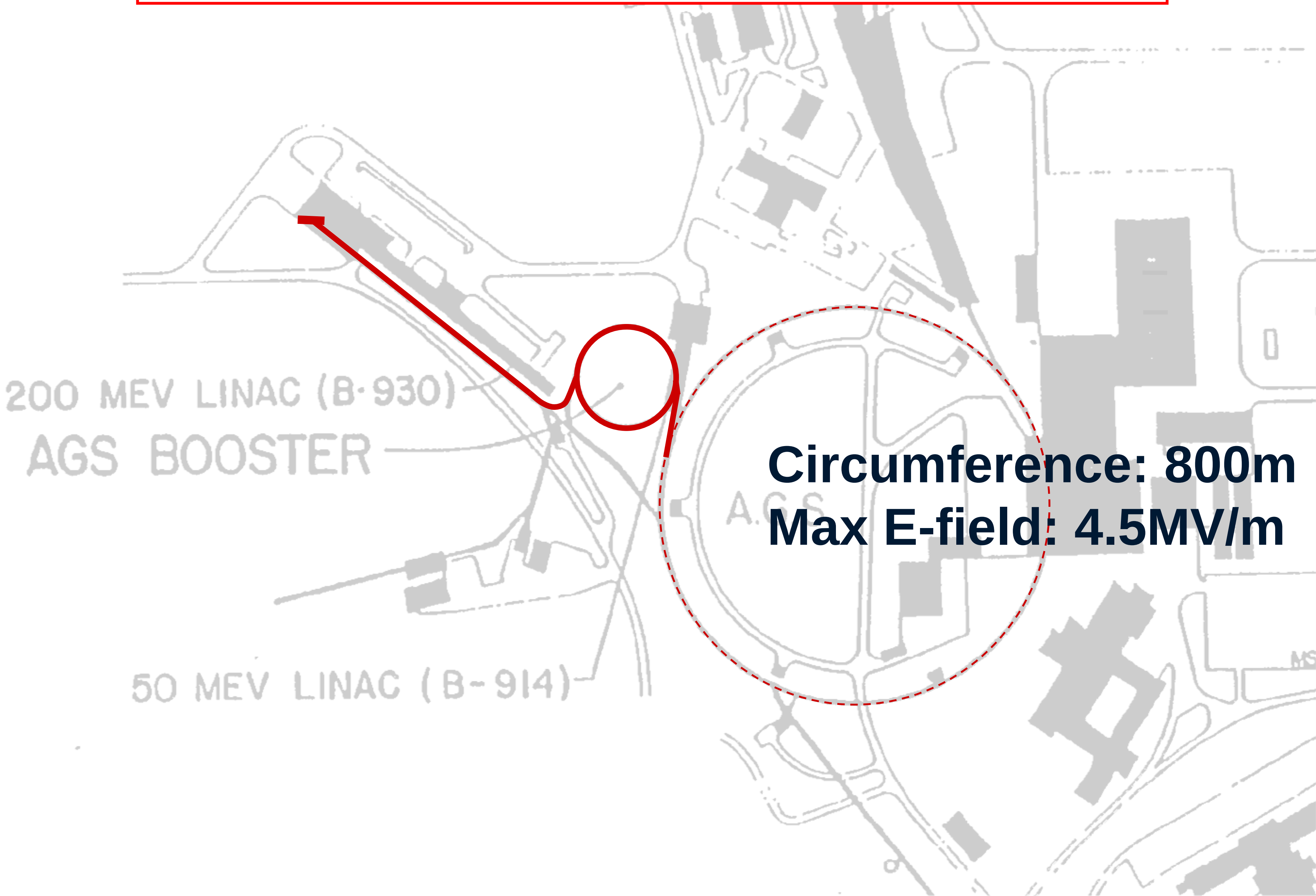


CW and CCW stored beams

Jülich, focus on deuterons, or a combined machine



The proton EDM in the AGS tunnel at BNL



Circumference: 800m
Max E-field: 4.5MV/m

John Benante, Bill Morse in AGS tunnel

Residual Magnetic Field (in Gauss) with Hall Probe

(Measured by John Benante)

Location E20 upstream

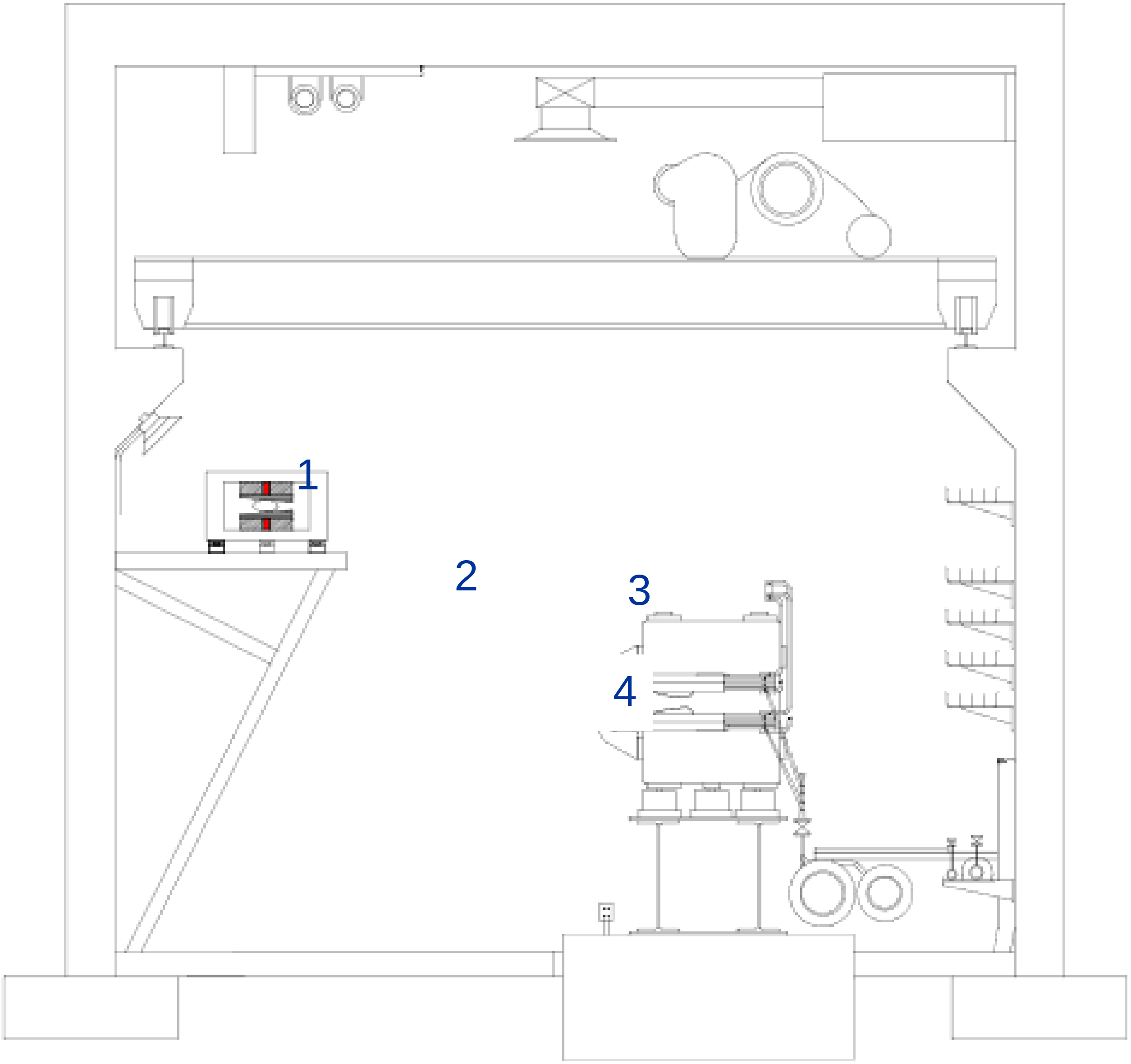
	180°	90°
1	0.14	0.18
2	0.20	0.19
3	0.23	0.17
4	0.52	0.44

Location F12 upstream

	180°	90°
1	0.07	0.07
2	0.06	0.07
3	0.26	0.21
4	0.88	0.80

Location L5 upstream

	180°	90°
1	0.03	0.06
2	0.05	0.06
3	0.26	0.26
4	0.25	0.28

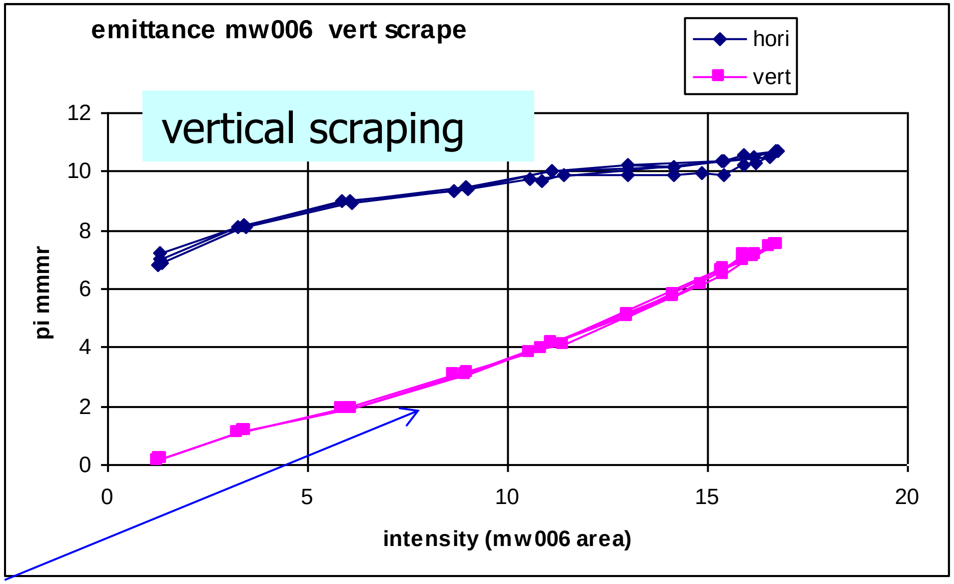


The relative low fields justifies to use AGS tunnel.

Emittance out of Booster

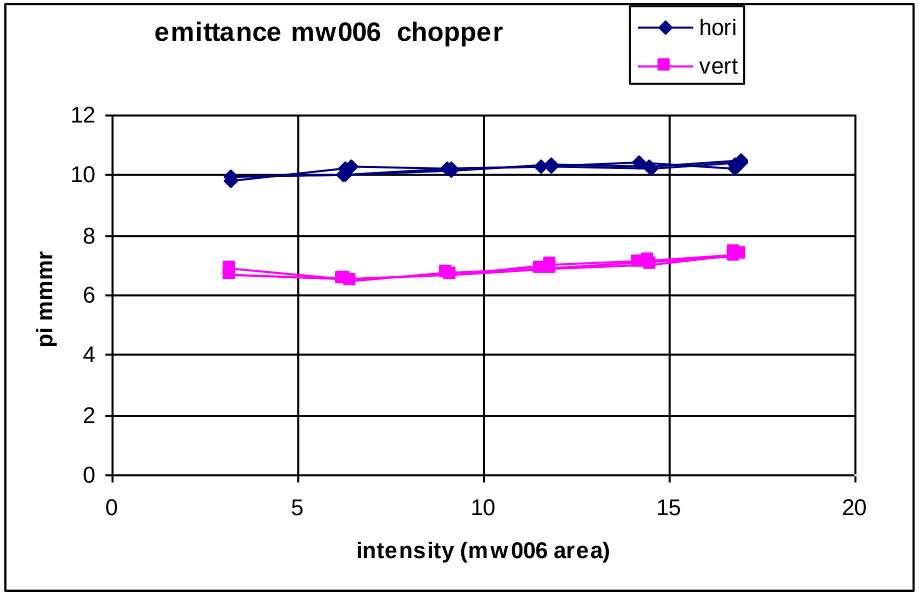
These intensity scan was done in 2009 with Booster input $3*10^{11}$. Not much horizontal scan was done since then. The vertical scale is normalized 95% emittance.

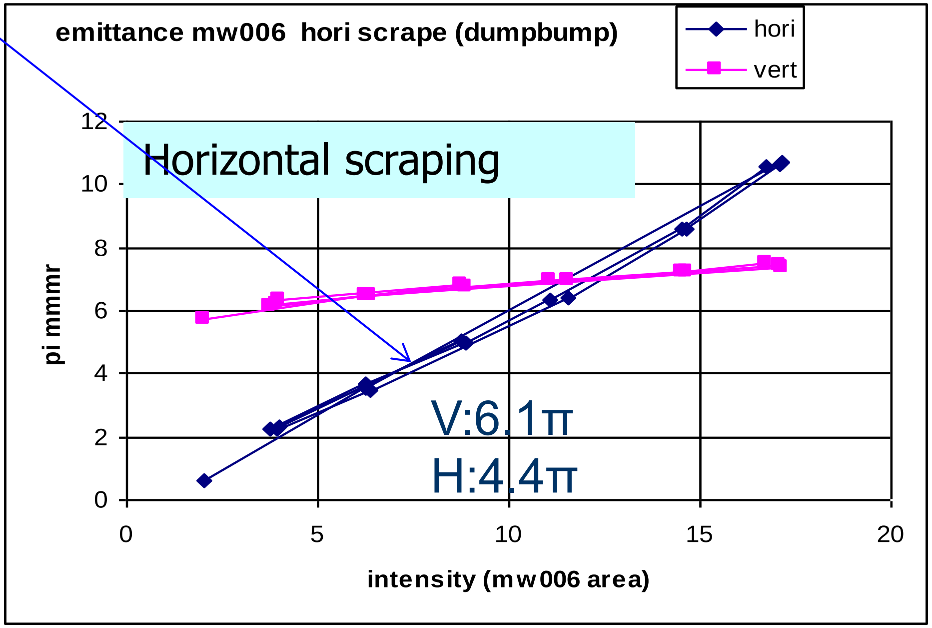
The corresponding normalized rms emittance at 10^{11} is 0.7π horizontal, 1.0π vertical for horizontal scraping.



@10^{11}

Intensity: 15~2e11 protons





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

- Previous muon g-2 Experiment at Brookhaven National Laboratory

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

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

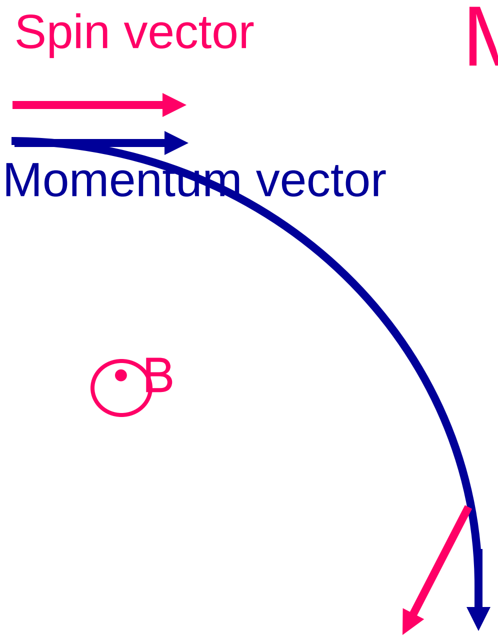
Muon g-2 focusing is electric: The spin precession due to E-field is zero at "magic" momentum (3.1GeV/c for muons, 0.7 GeV/c for protons,…)

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

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

The Principle of g-2

At rest: $\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B}$



Moving: Non-relativistic case

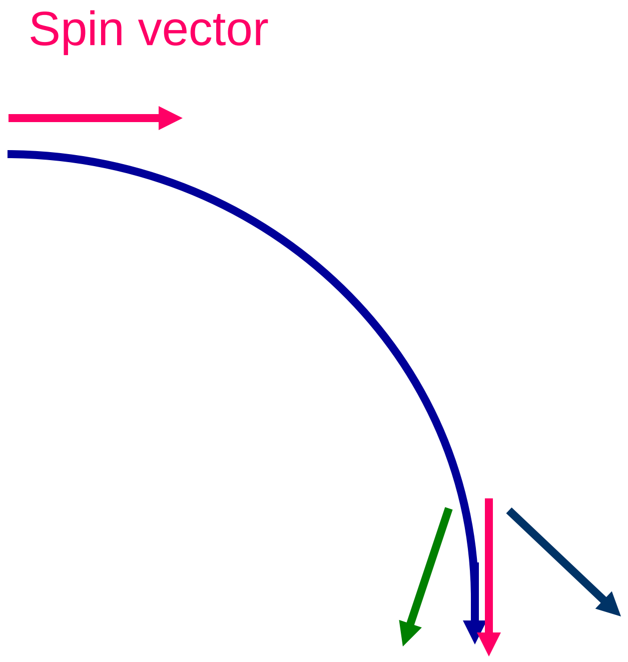
$$\omega_c = \frac{eB}{m}$$

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

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

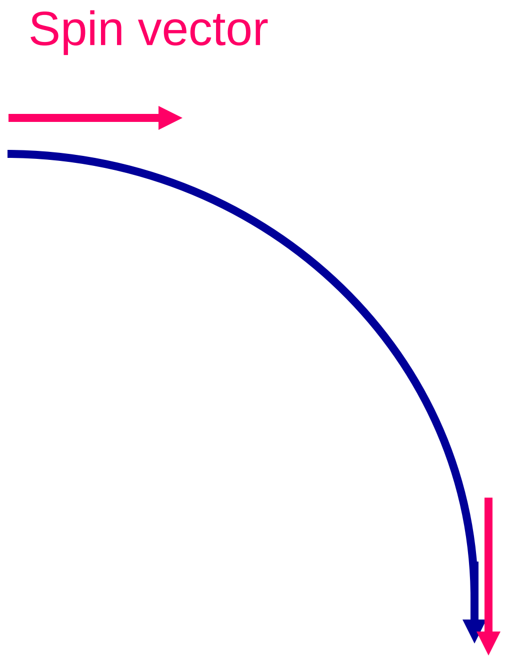
Effect of Radial Electric Field

E-field are used to focus the beam vertically



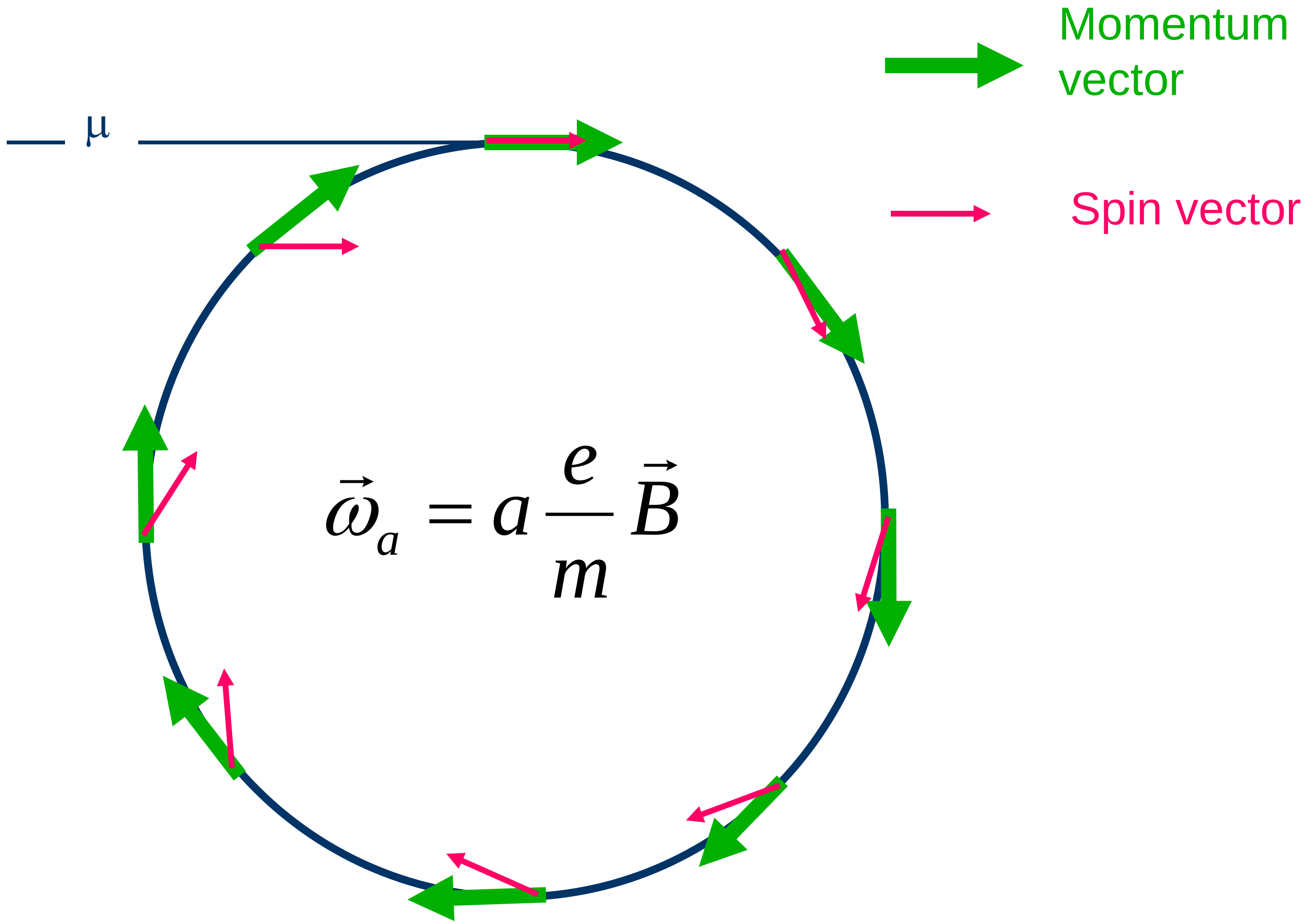
- Low energy particle
- …just right
- High energy particle

Effect of Radial Electric Field



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

Spin Precession in g-2 Ring (Top View)

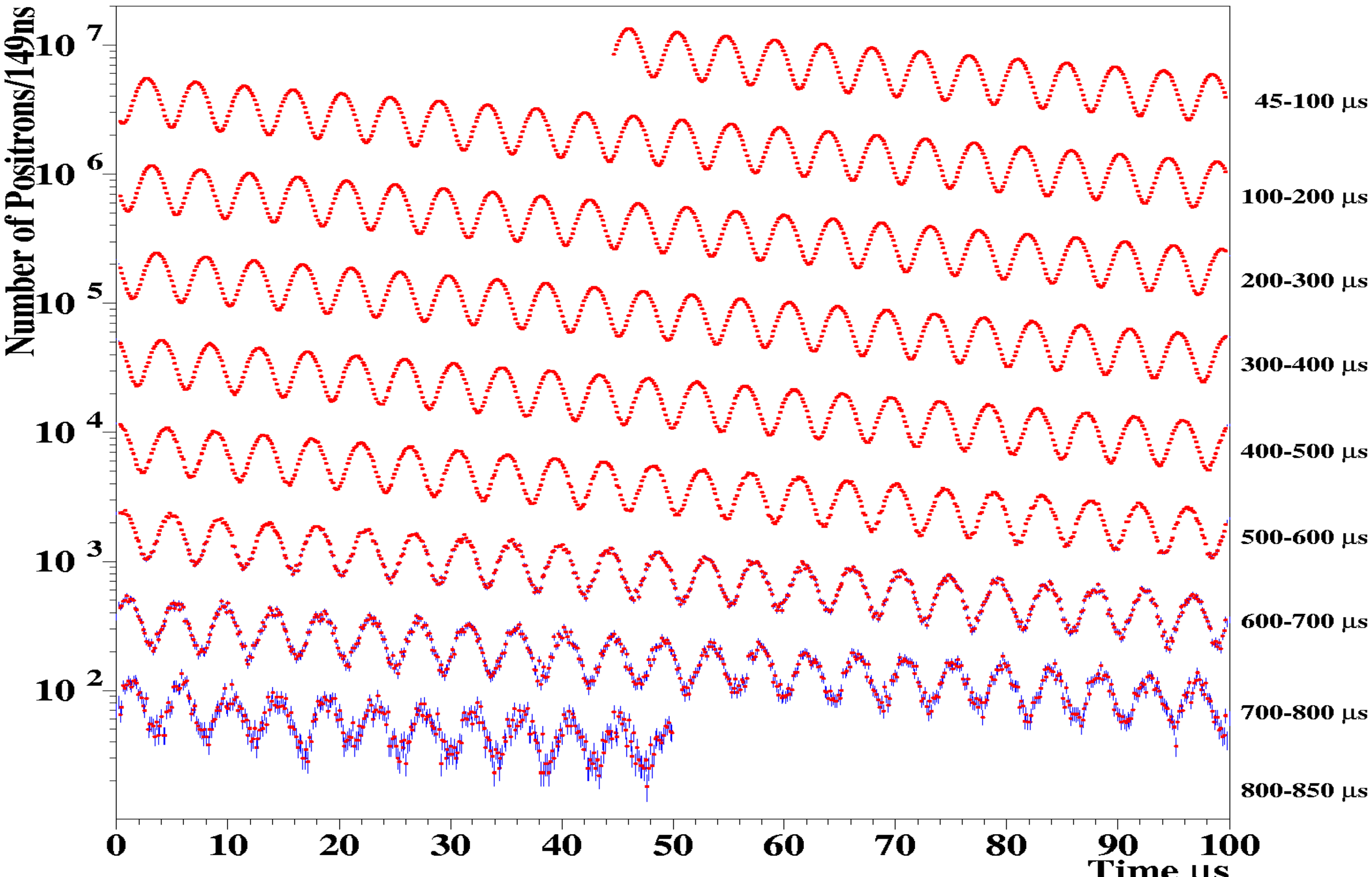


$$\vec{\omega}_a = a \frac{e}{m} \vec{B}$$

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

4 Billion e^+ with E>2GeV

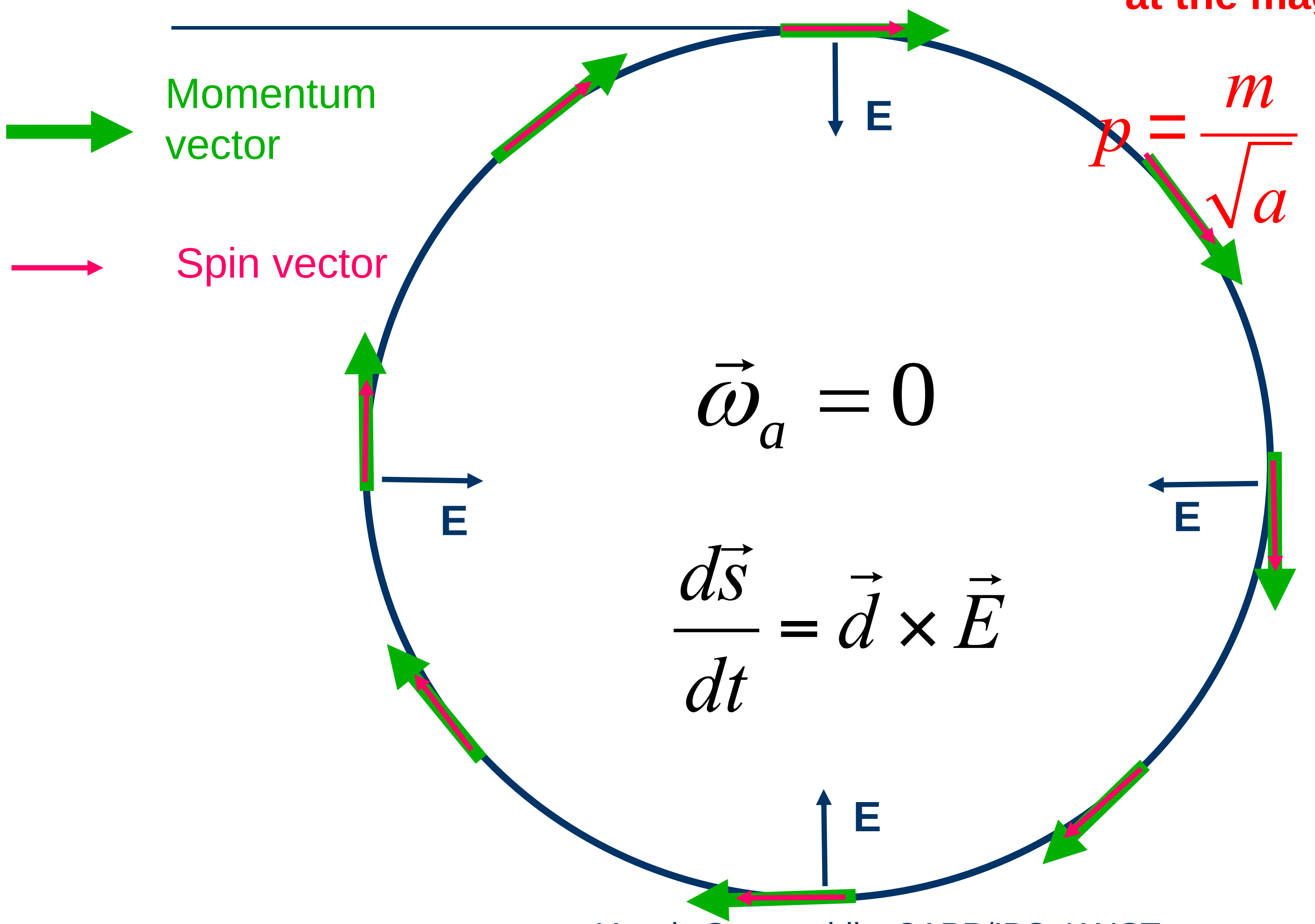
$$dN/dt = N_0 e^{-\frac{t}{\tau}} \left[1 + A\cos(\omega_a t + \phi_a)\right]$$



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

at the magic momentum

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



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

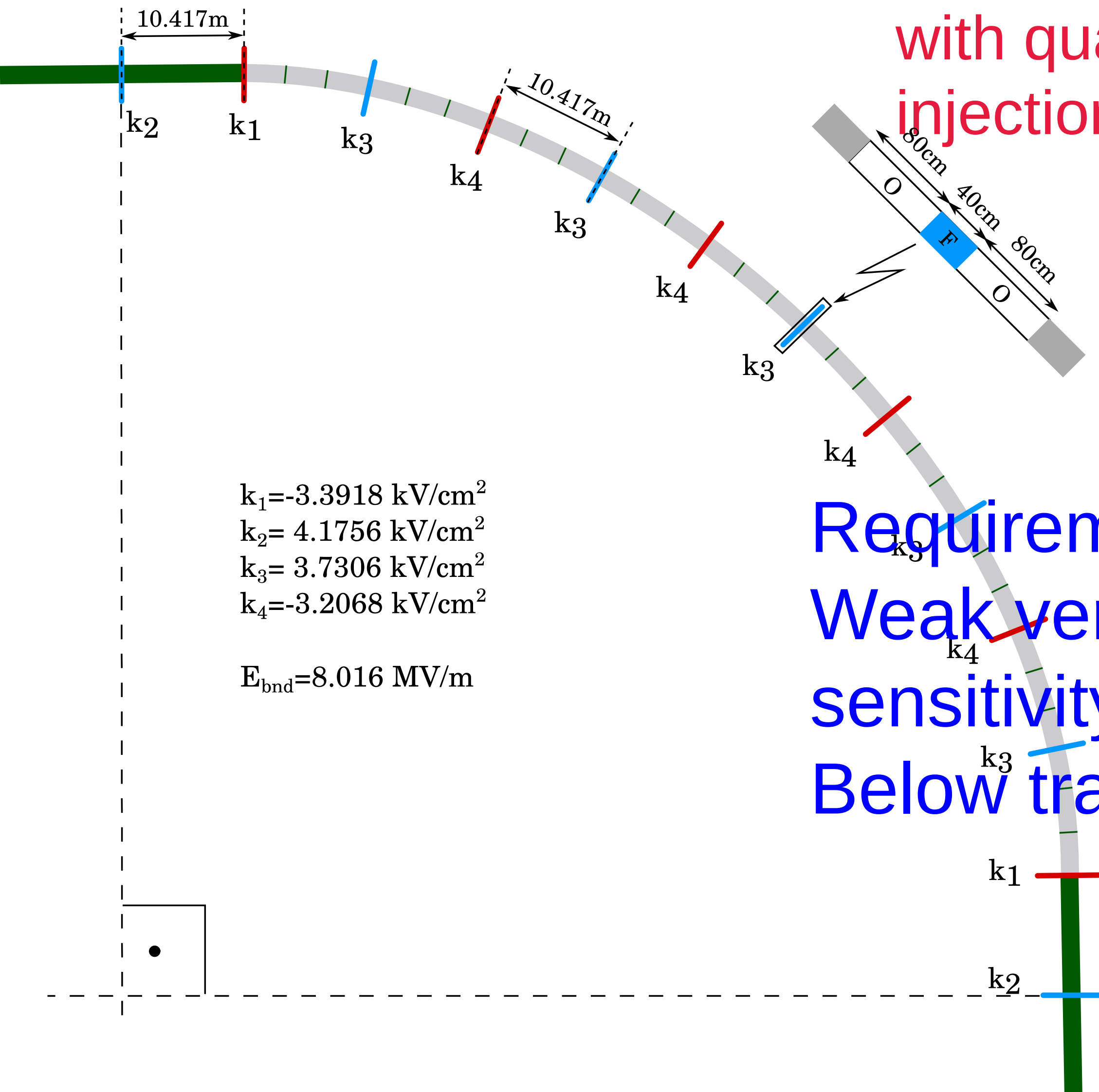
$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$

As in muon g-2 experiment at BNL and FNAL

The proton EDM ring (alternate gradient)

Total circumference: 500 m

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



Requirements:

Weak vertical focusing (B-field sensitivity)

Below transition (reduce IBS)

The proton EDM ring evaluation
Val Lebedev (Fermilab)

Beam intensity 10^{11} protons limited by IBS

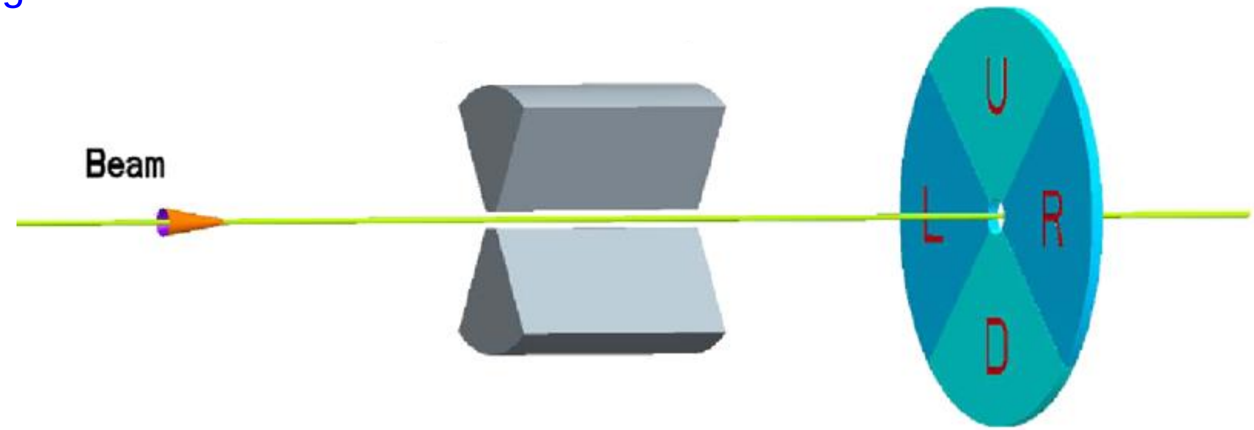
	Soft focusing	Strong focusing
Circumference, m	263	300
Qx/Qy	1.229/0.456	2.32/0.31
Particle per bunch	$1.5 \cdot 10^8$	$7 \cdot 10^8$
Coulomb tune shifts, $\Delta Q_x/\Delta Q_y$	0.0046/0.0066	0.0146/0.0265
Rms emittances, x/y, norm, μm	0.56/1.52	0.31/2.16
Rms momentum spread	$1.1 \cdot 10^{-4}$	$2.9 \cdot 10^{-4}$
IBS growth times, x/y/s, s	300/(-1400)/250	7500
RF voltage, kV	13	10.3
Synchrotron tune	0.02	0.006

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, MRPC, GEMS or Si.

Extraction: lowering the vertical focusing



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

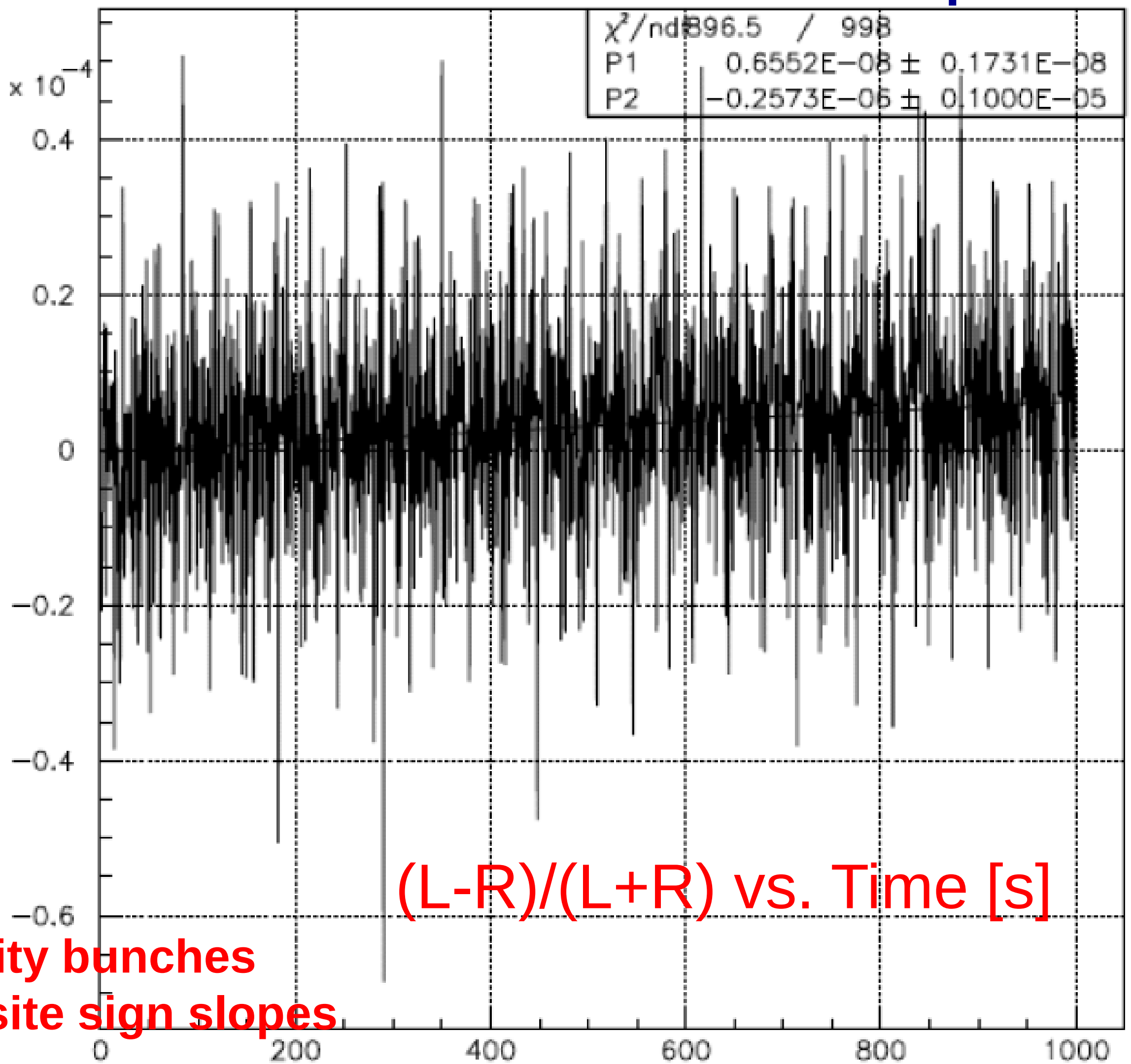
carries EDM signal increases slowly with time

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

carries in-plane (g-2) precession signal

The EDM signal: early to late change

- Comparing the (left-right)/(left+right) counts vs. time we monitor the vertical component of spin



M.C. data

Opposite helicity bunches result to opposite sign slopes.

Large polarimeter analyzing power at P_{magic}!

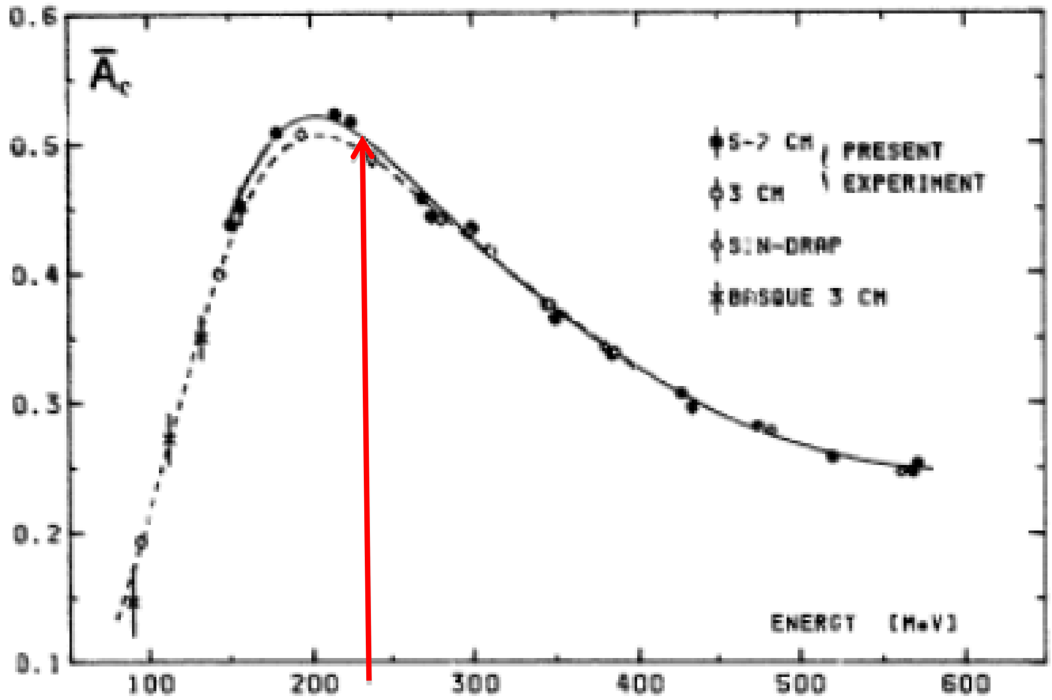


Fig. 4. Angle-averaged effective analyzing power. Curves show our fits. Points are the data included in the fits. Errors are statistical only

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.

Proton Statistical Error (230MeV):

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

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

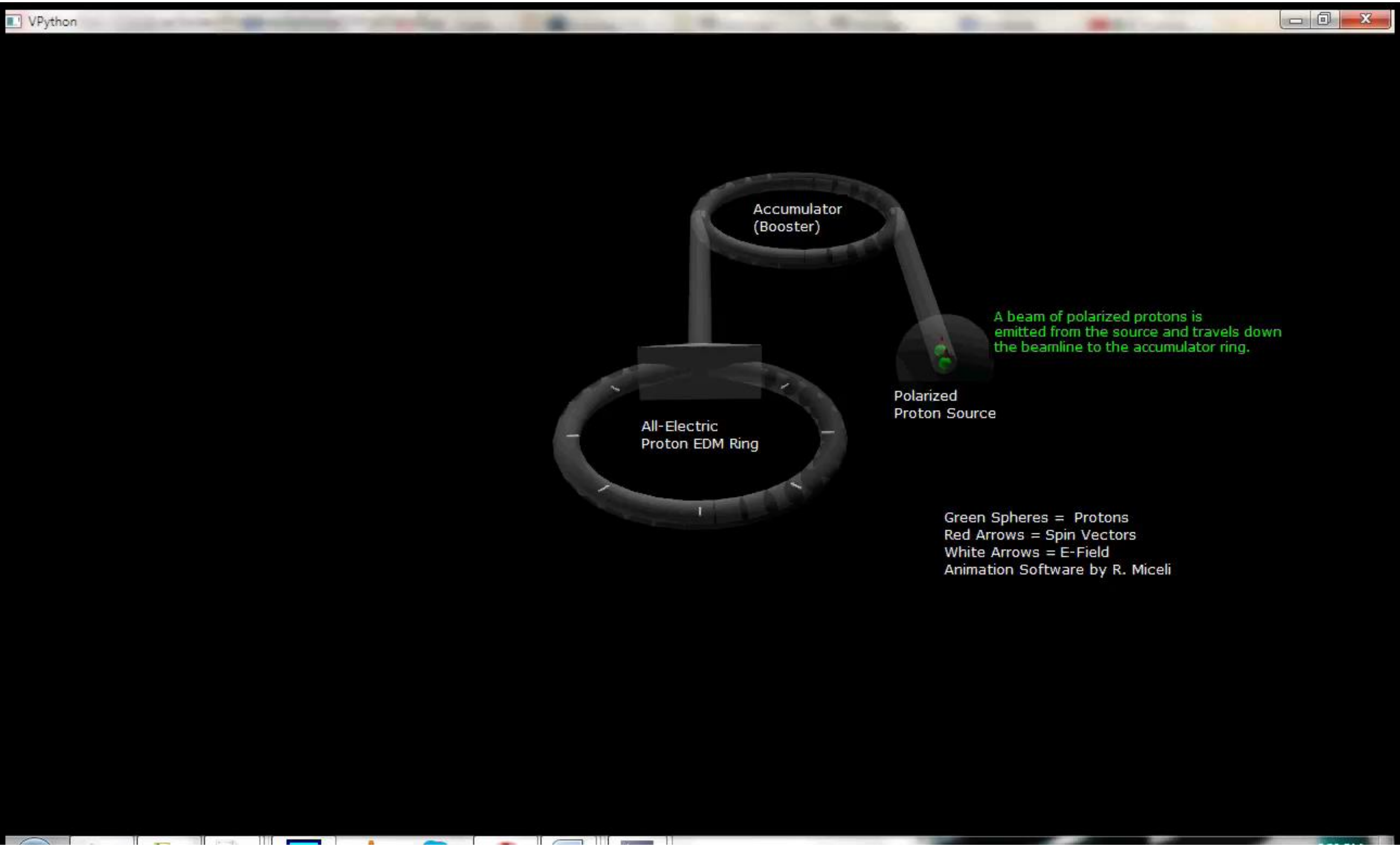
T_{Tot}: 10^7s Total running time per year

f : 0.5% Useful event rate fraction (efficiency for EDM)

E_R : 10.5 MV/m Radial electric field strength (83% azim. cov.)

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

Proton EDM animation

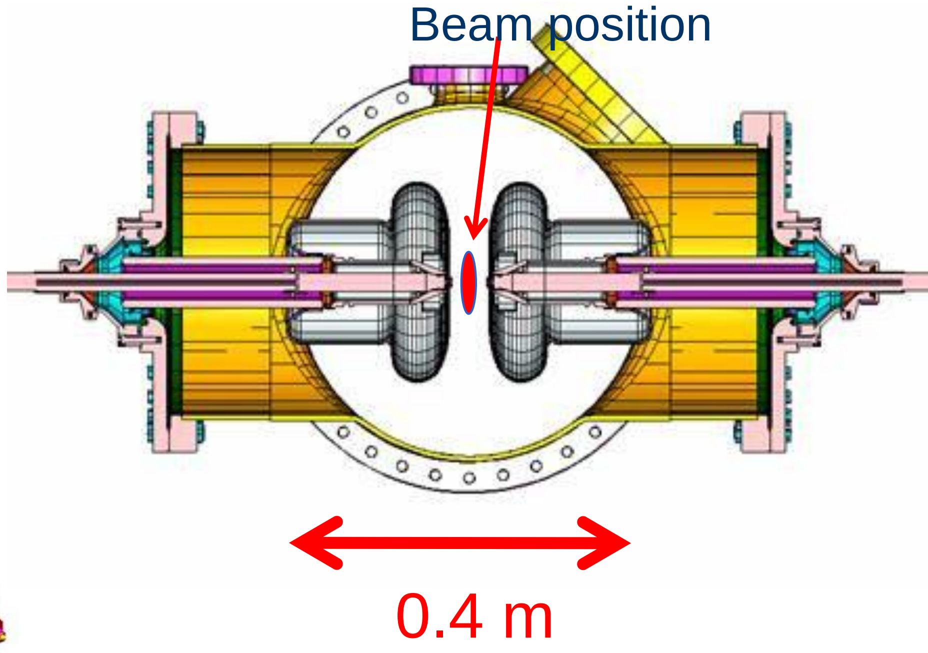


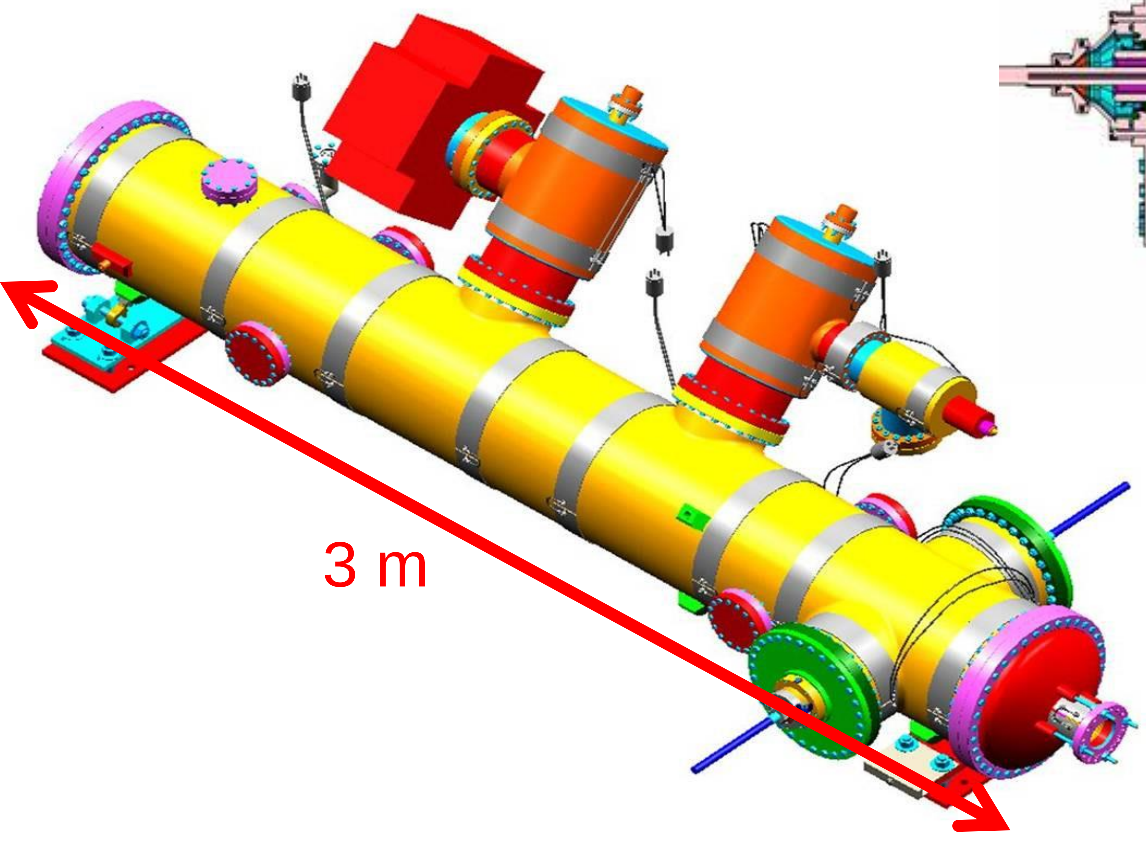
Logistics

- Large ring radius:
- Moderate E-field 4.5MV/m (eliminates risk of bad current leak…)
- Can have TiN coated aluminum (cheap).

- Need 800m of magnetic shielding to 10-100nT. Current state of art.
- State of the art SQUID-based magnetometers

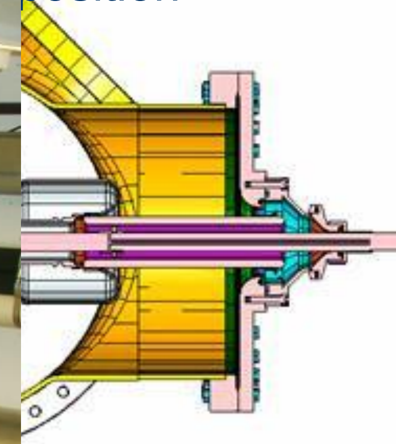
E-field plate module: Similar to the (26) FNAL Tevatron ES-separators





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

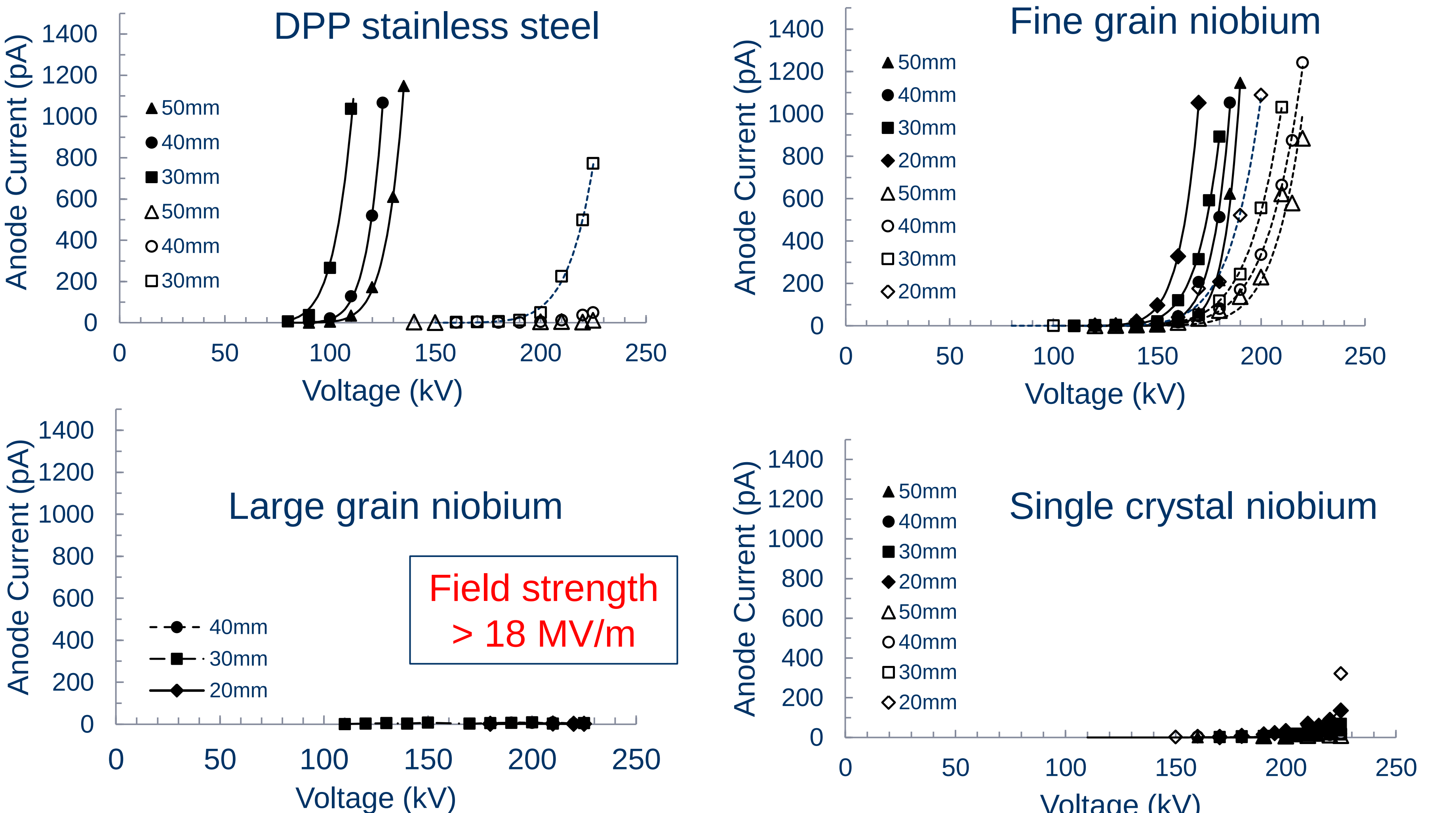
position



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

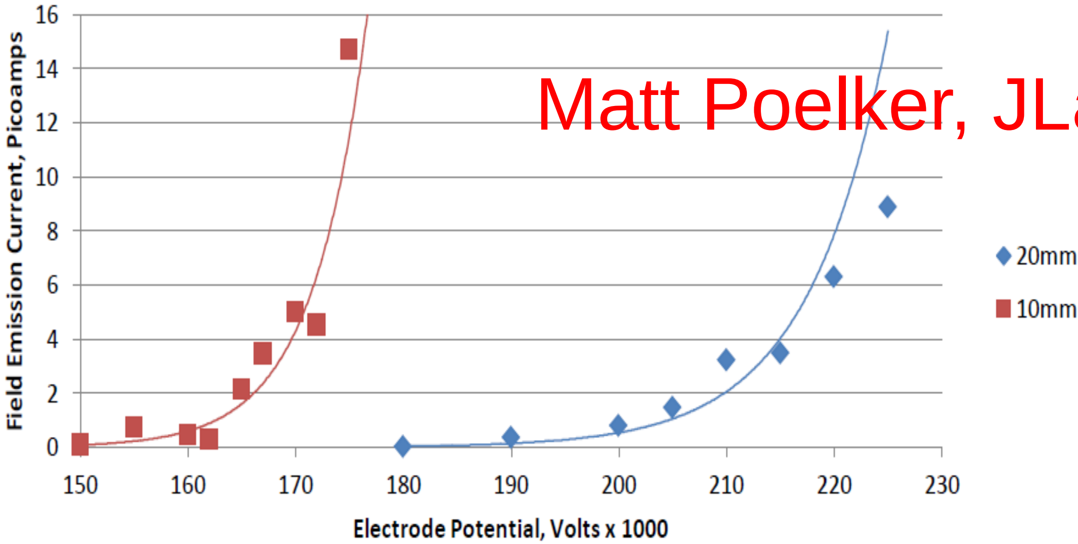


Conventional High Voltage processing: solid data points
After Krypton Processing: open data points

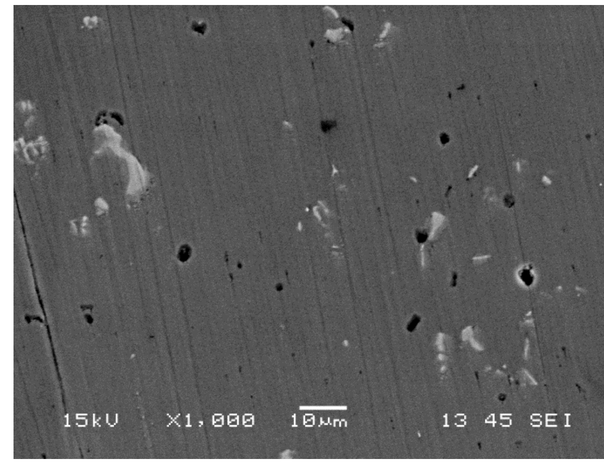
JLab results with TiN-coated Aluminum

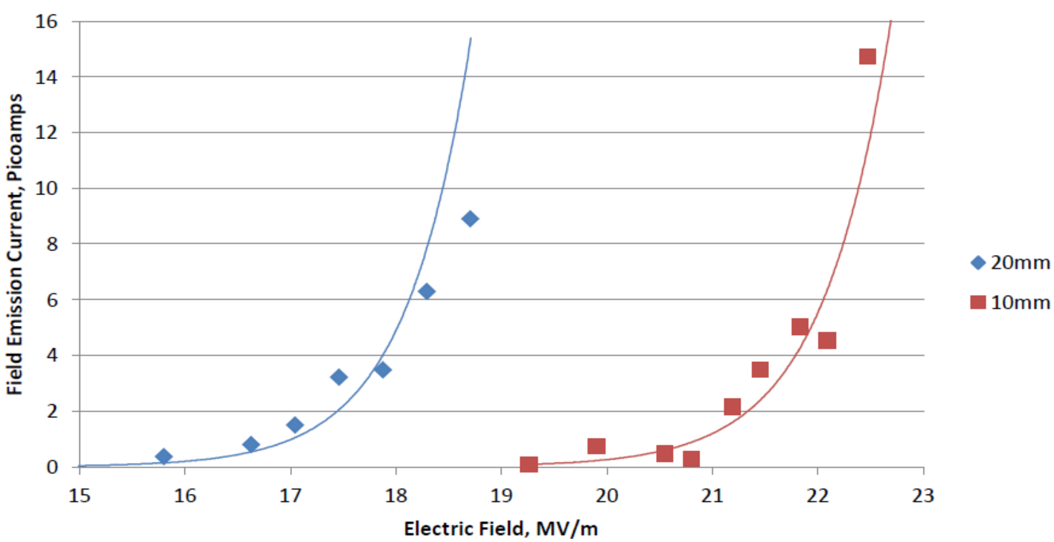
No measureable field emission at 225 kV for gaps > 40 mm, happy at high gradient

Matt Poelker, JLab

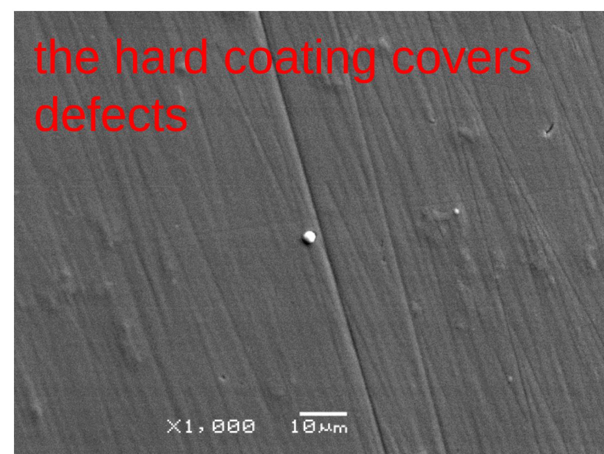


Bare Al





TiN-coated Al



150 kV/cm 200 kV/cm

Work of Md. A. Mamun and E. Forman

Why a large radius ring?

1. Electric field needed is moderate. New techniques with coated Aluminium is a cost savings opportunity.

2. Horizontal Spin Coherence Time. The EDM effect is acting for time ~SCT.

3. Most ideal shape: circular with several straight sections.

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

The storage ring Proton EDM method has it all!

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 <5 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.)

Systematic errors

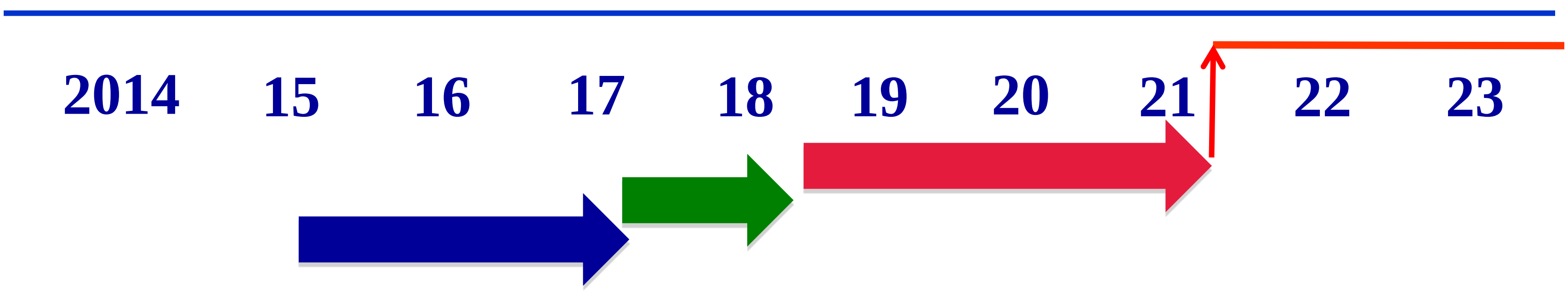
TABLE III. Main systematic errors of the experiment and their remediation.

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.

Opportunities for CERN

- Electric field strength issues, dark currents
- Beam-based alignment, E-field plate alignment
- Beam impedance reduction.

Technically driven pEDM timeline



- Two years systems development (R&D); Ring design; Installation.
- Cost (2011, 2012 engineering cost): $70M + tunnel.
- Proposed cost-sharing with AGS tunnel:
  - Owned by DOE-HEP; DOE-NP partner with running costs.
- Foreign contributions: electric field plates, vacuum chambers, SQUID-based magnetometers

Let's indulge on 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
- >50% efficient polarimeter

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

Spin Coherence Time: need >10^2 s

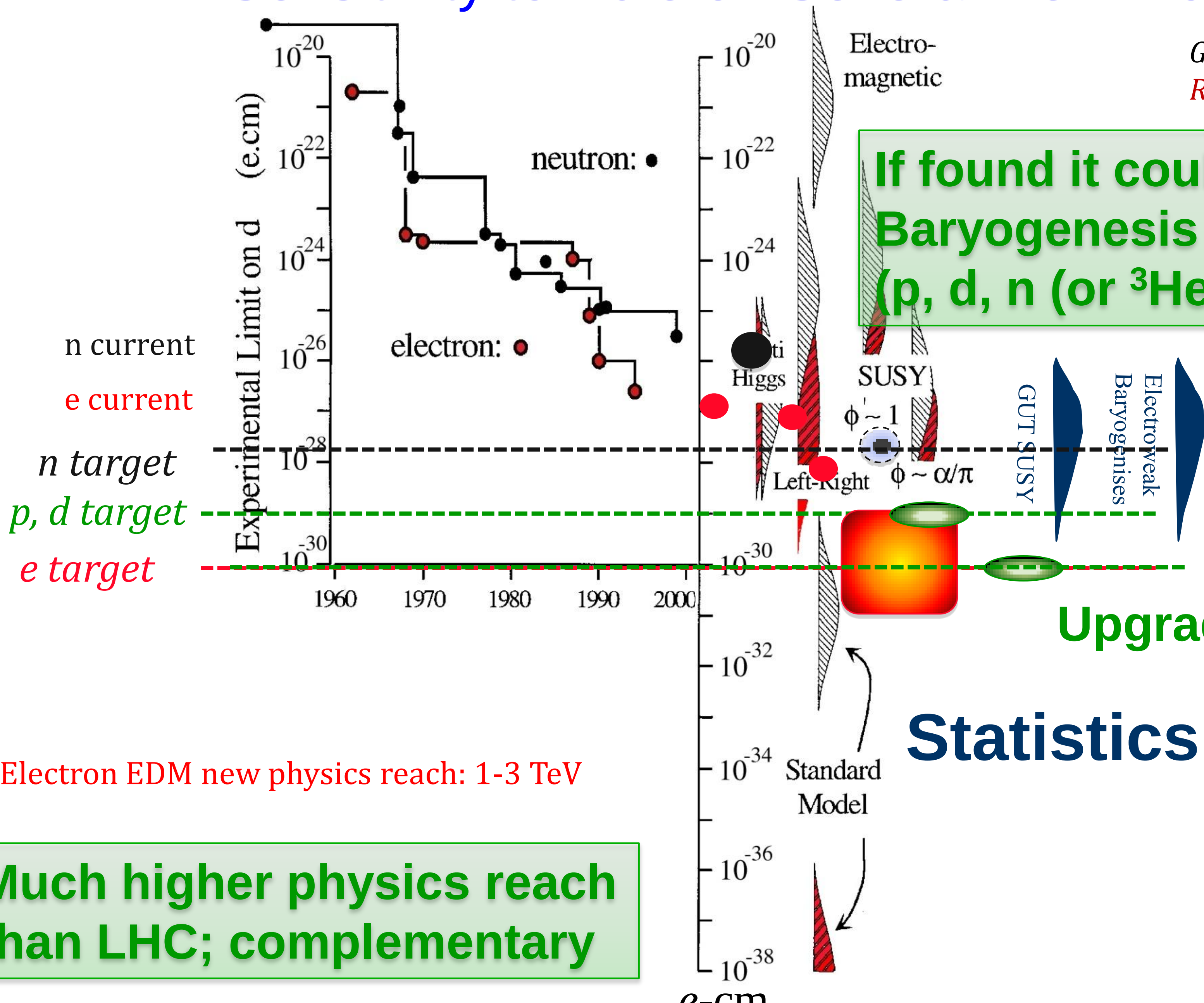
- Not all particles have same deviation from magic momentum, or same horizontal and vertical divergence (all second order effects)

- 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.)

Sensitivity to Rule on Several New Models



Gray: Neutron
Red: Electron

If found it could explain Baryogenesis (p, d, n (or ^{3}He))

Upgrade?

Statistics limited

Electron EDM new physics reach: 1-3 TeV

Much higher physics reach than LHC; complementary

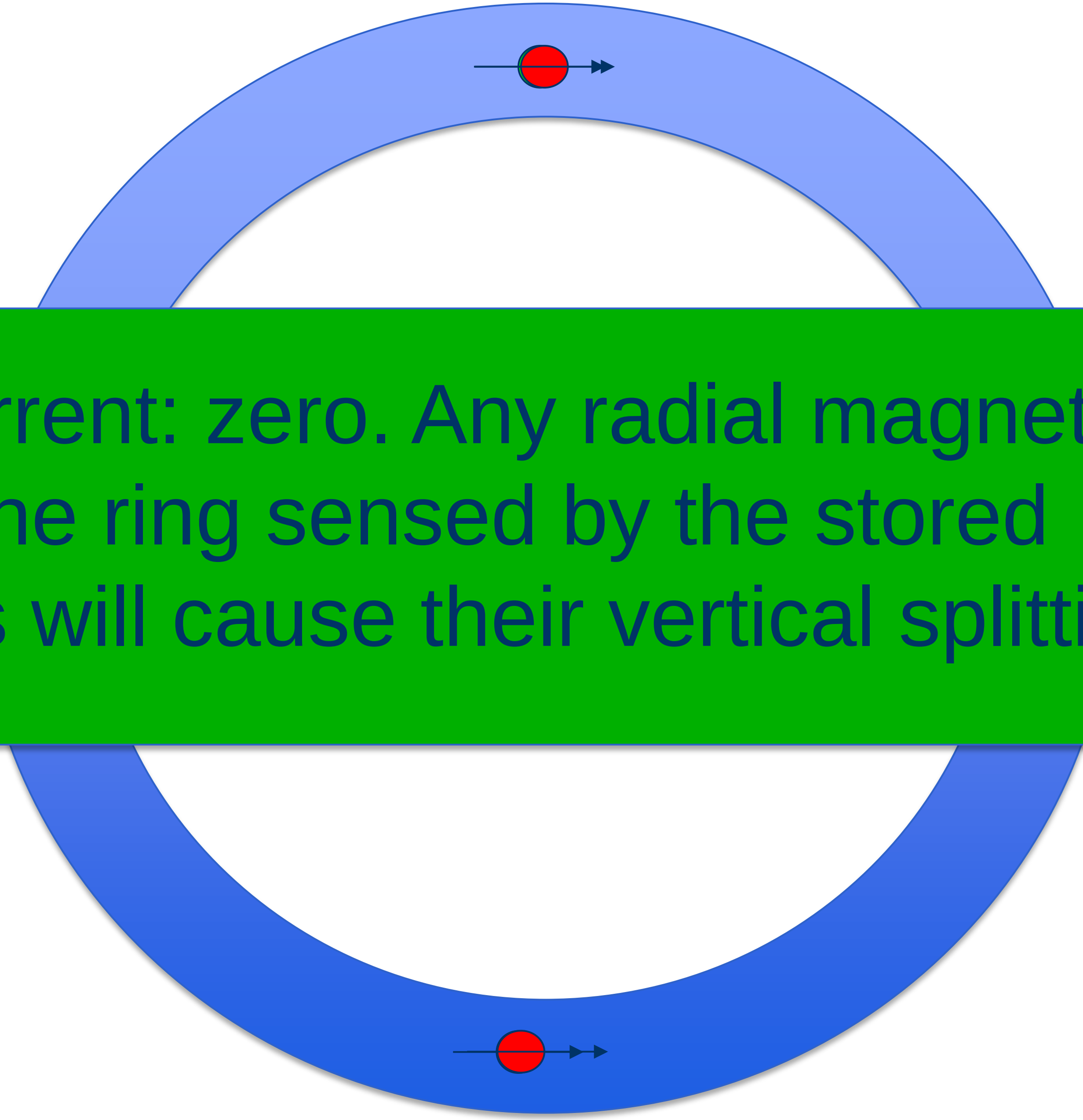
J.M.Pendlebury and E.A. Hinds, NIMA 440 (2000) 471

Summary

- Complementary to LHC; probes New Physics >10^3 TeV.
- The experiment is owned by HEP. Run by NP, hosted by CAD/BNL.
- Work on the open questions. Opportunities for CERN impact.
- Visit DOE OHEP with the plan.

Extra slides

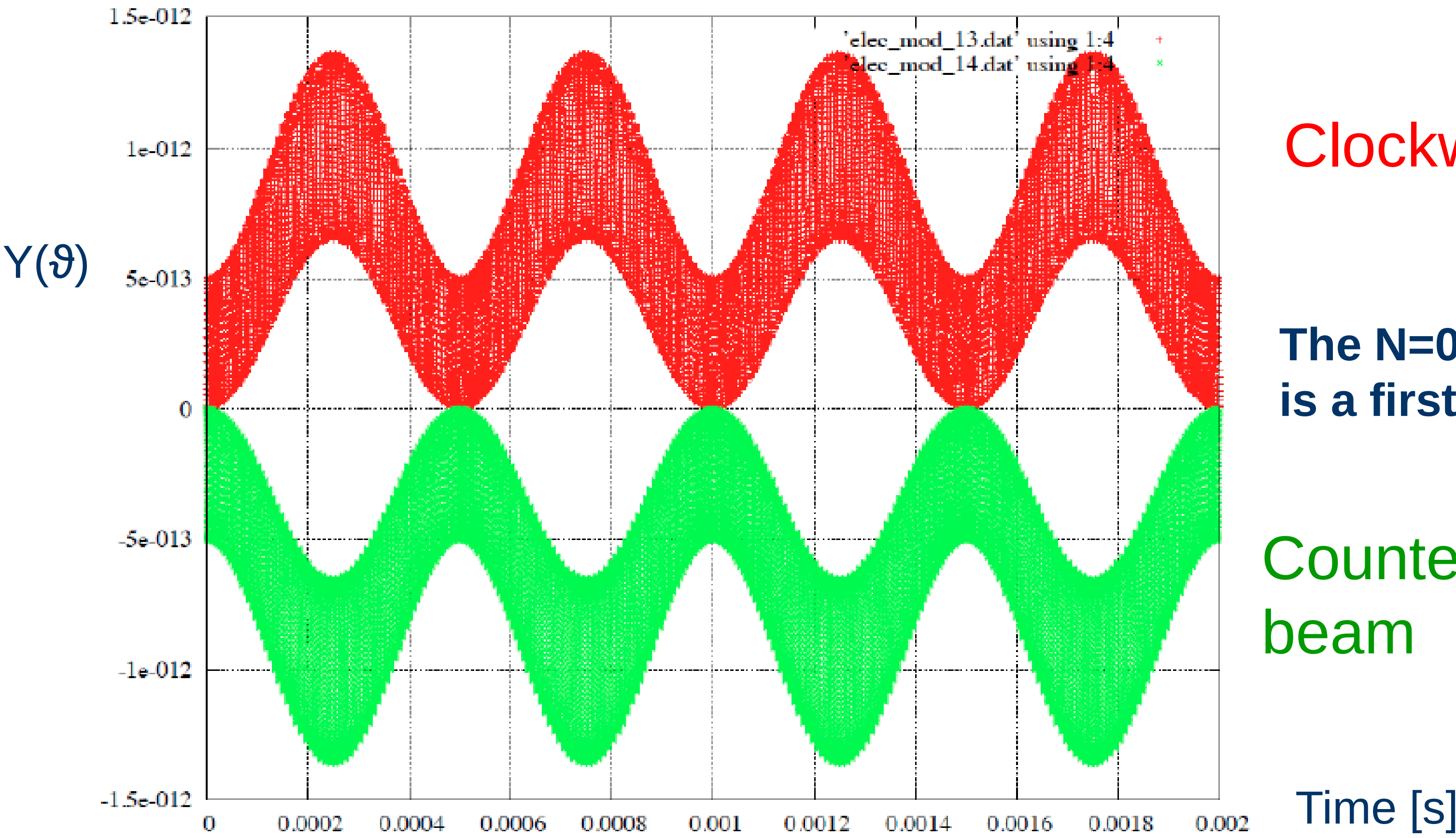
Clock-wise (CW) & Counter-Clock-wise Storage



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

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

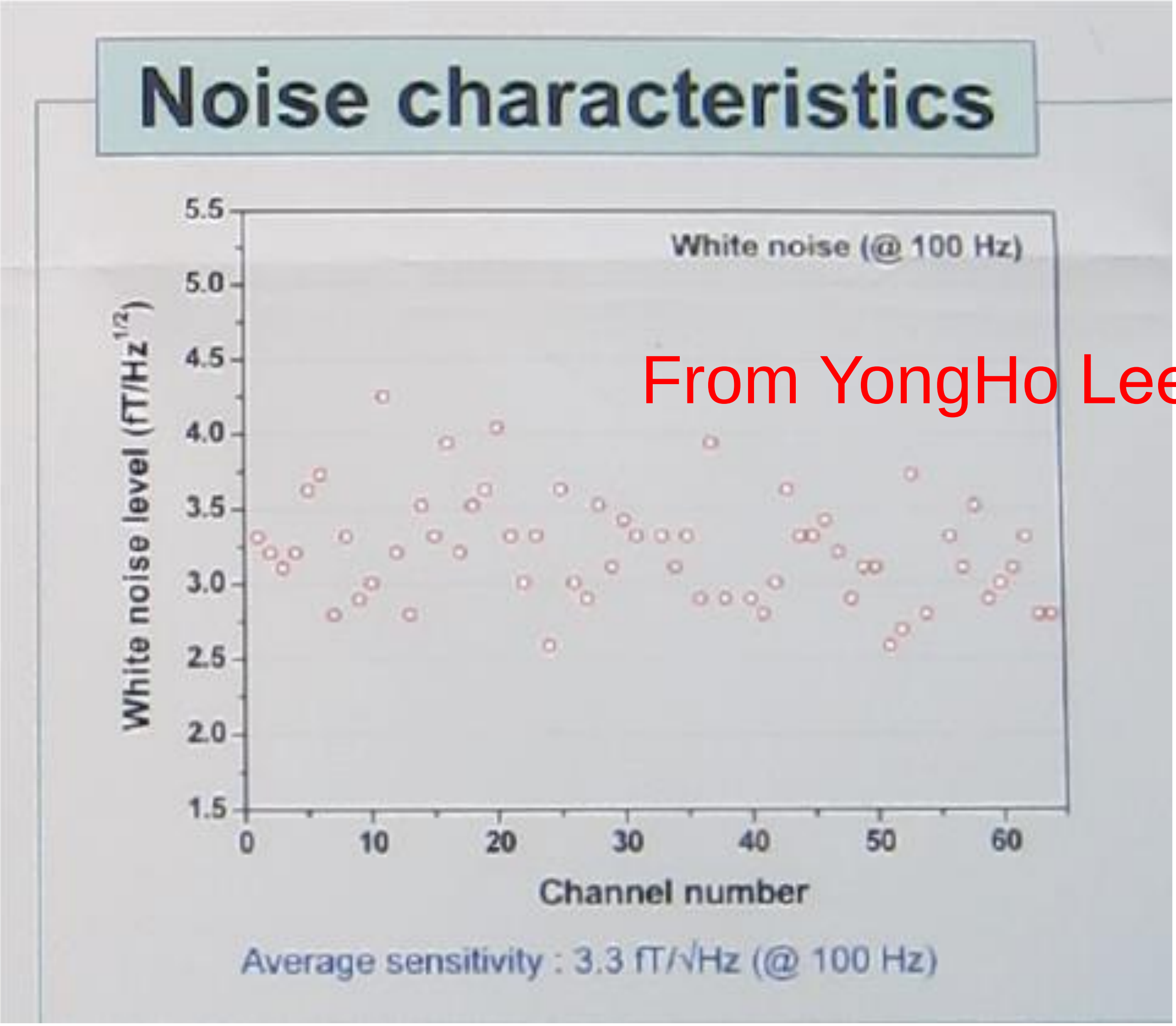


Clockwise beam

The N=0 component is a first order effect!

Counter-clockwise beam

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

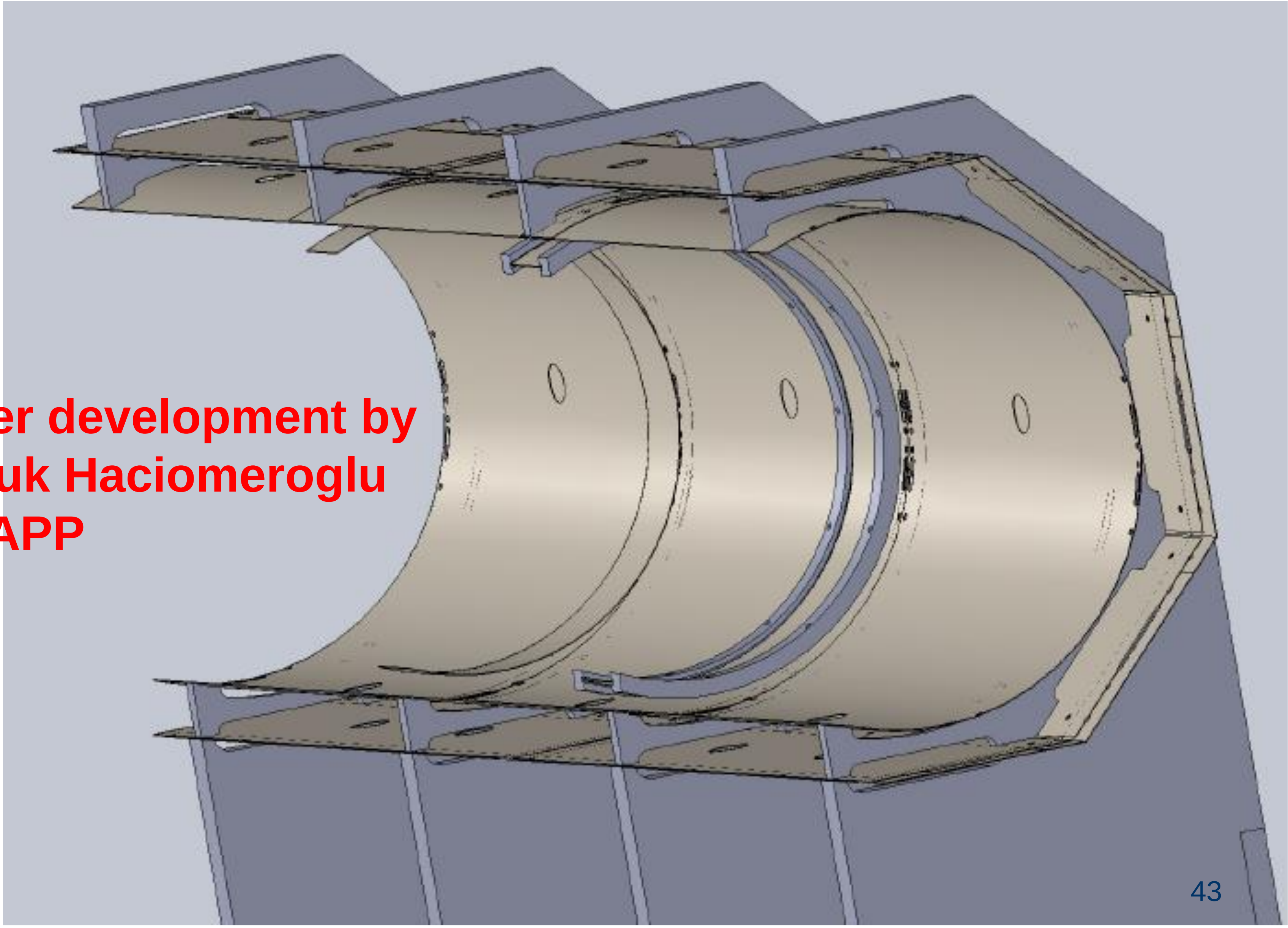


From YongHo Lee's group

B-field Shielding Requirements

- **<u>No need for shielding:</u>** In principle, with counter-rotating beams.
- **<u>However:</u>** BPMs are located only in straight sections $\rightarrow$ sampling finite. Nyquist theorem limits sensitivity to low harmonics of B_r. Most importantly the $<B_r>$ may not be the true average when $N= N_{SQUIDS}$
- Plan: B_r-field needs to be less than (1nT) everywhere and pay attention to $N=80$ B_r. (See Selcuk's talk).

Peter Fierlinger, Garching/Munich



Under development by Selcuk Haciomeroglu at CAPP

To do list: EDM ring in AGS tunnel

- Lattice. Alternate gradient. Operations below transition.

- IBS lifetime estimation. Beam parameters: Intensity, polarization.

- Ring impedance issues.

- Feasibility of LHe line in the EDM ring. Need a cryo-engineer to evaluate.

Marciano from CM9/Korea, last week

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

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

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

Marciano from CM9/Korea, last week Outlook:

<u>Heavy Leptons…</u>

EDMs may soon be discovered: $d_e, d_n, d_p \ldots d_D$

Or significantly constrain "New Physics"

Eg CP violation in ***H→γγ*** ***(Contemporary topic)***

CP violation better explored by 2 loop edms

than all diboson (*γγ, ZZ, WW…)* modes at the LHC!

Atomic, Molecular. Neutron, ***<u>Storage Ring</u>*** (All Complementary)

45

Feasibility of an all-electric ring

- First all-electric ring (AGS-analog) proposed/built 1953-57. It worked!
- Two encouraging technical reviews performed at BNL: Dec. 2009, March 2011.
- Fermilab comprehensive review: Fall 2013.
  Val Lebedev considers the concept to be sound.

- Cost (2011, 2012 engineering cost): $70M + tunnel.
- Proposed cost-sharing if existing tunnel is used:
- DOE-HEP $35M; DOE-NP $20M (+ running costs).
- Foreign contributions: electric field plates, vacuum chambers, SQUID-based magnetometers.