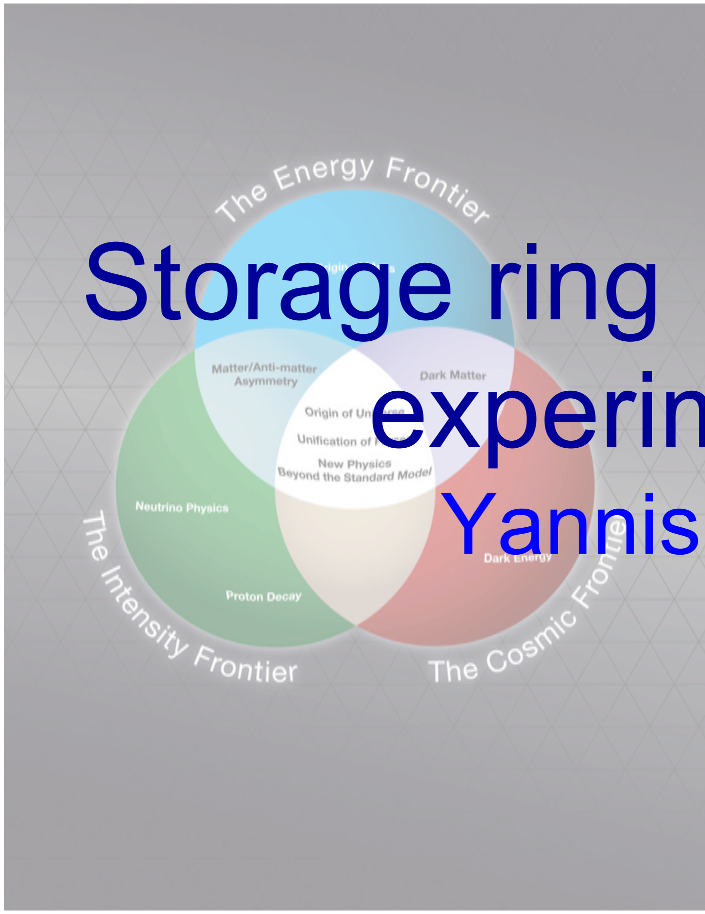
Lattice Computations
BNL, 16 May 2012



Storage ring Electric Dipole Moment experiment for the proton

Yannis K. Semertzidis, BNL

✓Goal: 10^{-29}e•cm; Probe New Physics ~10^3 TeV

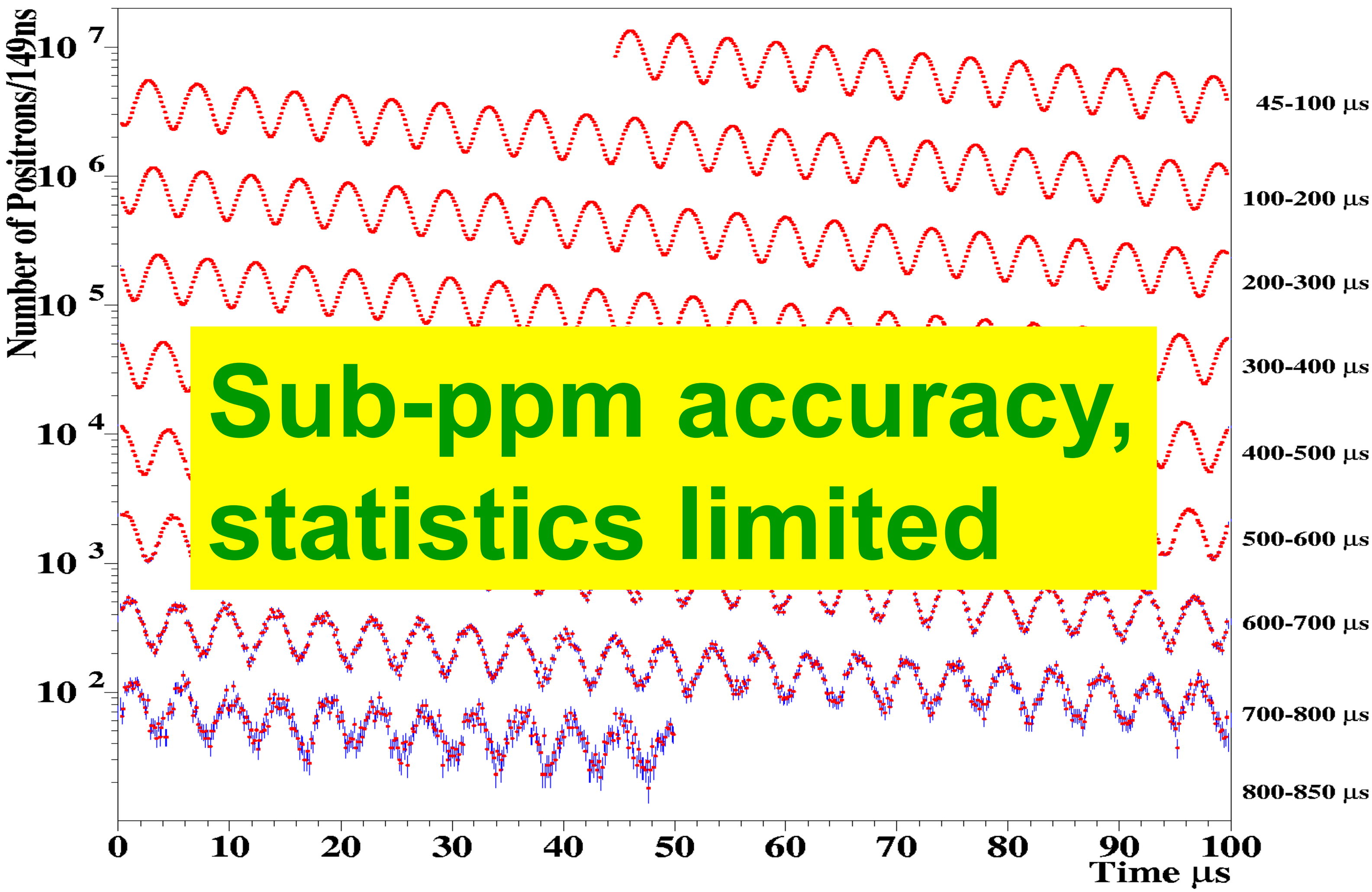
✓Systematics best in an all-electric ring and counter-rotating (CR) beams.

- Muon g-2: Precision physics in a Storage Ring

- Statistics limited… to improve sensitivity by a factor of 4 at Fermilab

Muon g-2: 4 Billion e^+ with E>2GeV

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



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

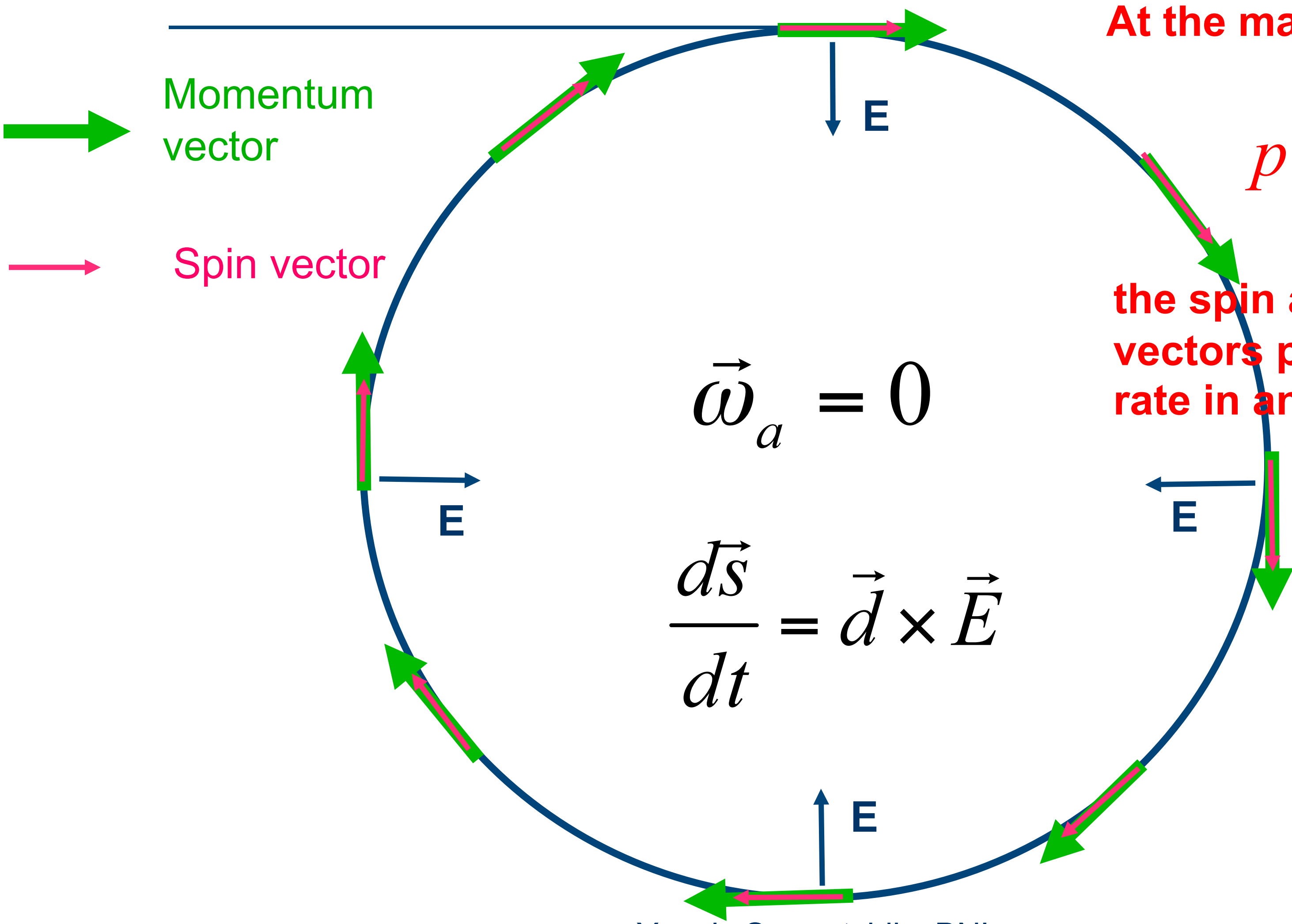
$$\vec{\omega}_a = \frac{e}{m}\left\{ a\vec{B} + \left[a - \left(\frac{m}{p} \right)^2 \right] \frac{\vec{\beta} \times \vec{E}}{c} \right\}$$

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



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

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

At the magic momentum

$$p = \frac{m}{\sqrt{a}}$$

the spin and momentum vectors precess at same rate in an E-field

Yannis Semertzidis, BNL

Is the polarimeter analyzing power good at P_{magic}? YES!

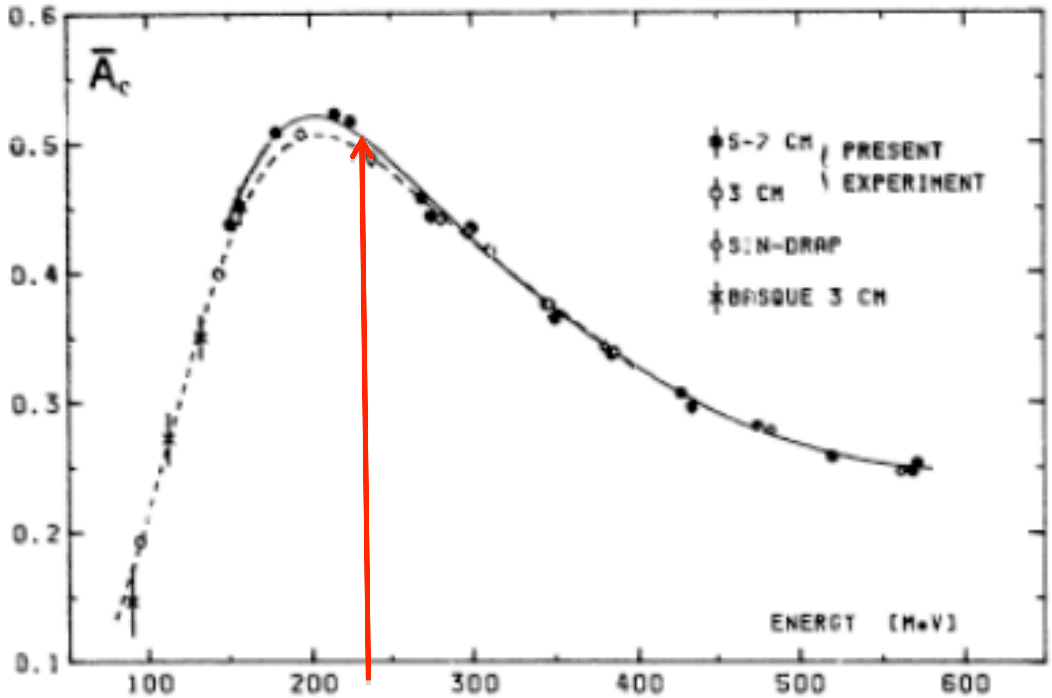
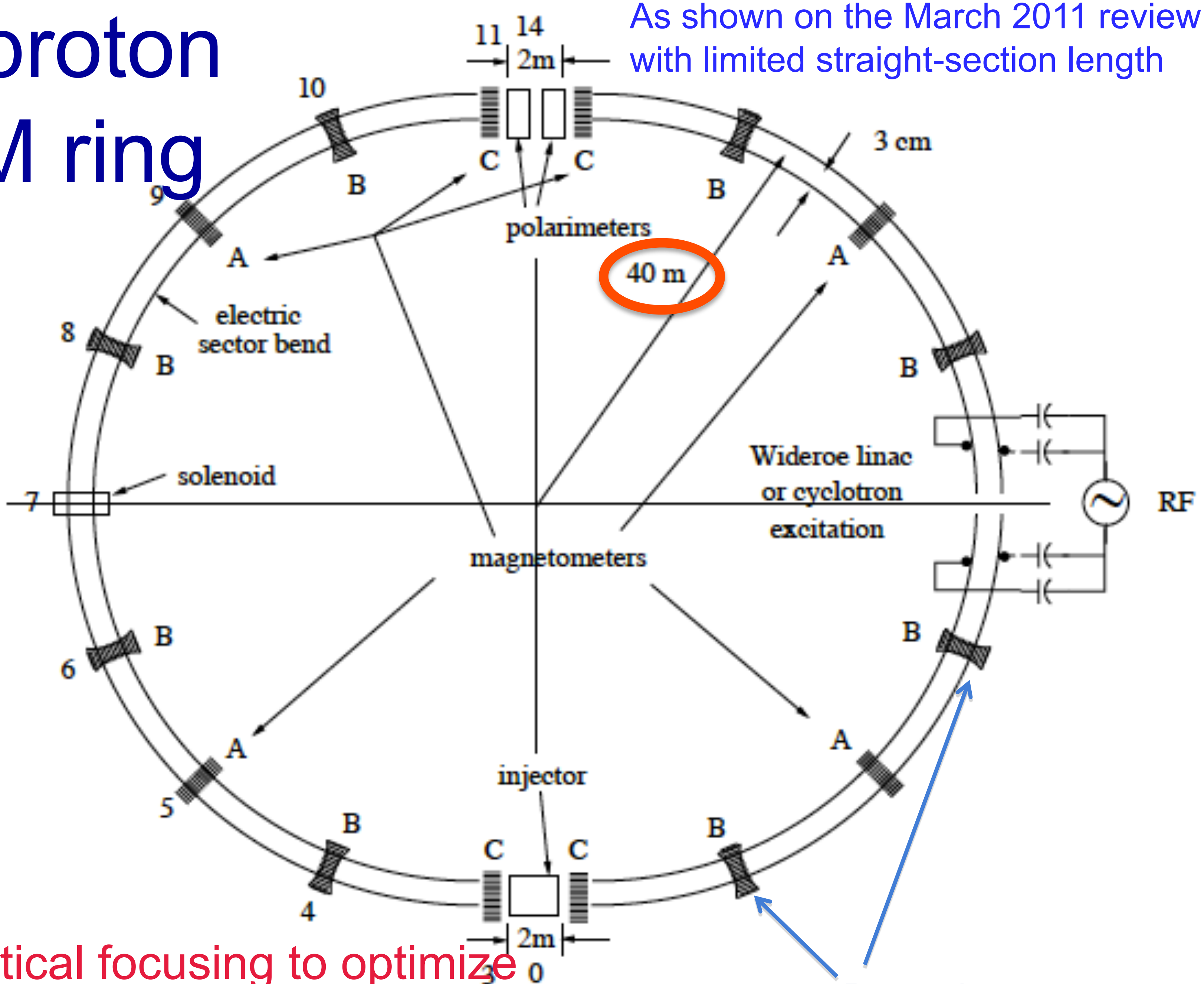


Fig. 4. Angle-averaged effective analyzing power. Curves show our fits. Points are the data included in the fits. Errors are statistical only

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.

The proton EDM ring

As shown on the March 2011 review with limited straight-section length



Weak vertical focusing to optimize SCT and BPM operation

B: quadrupoles

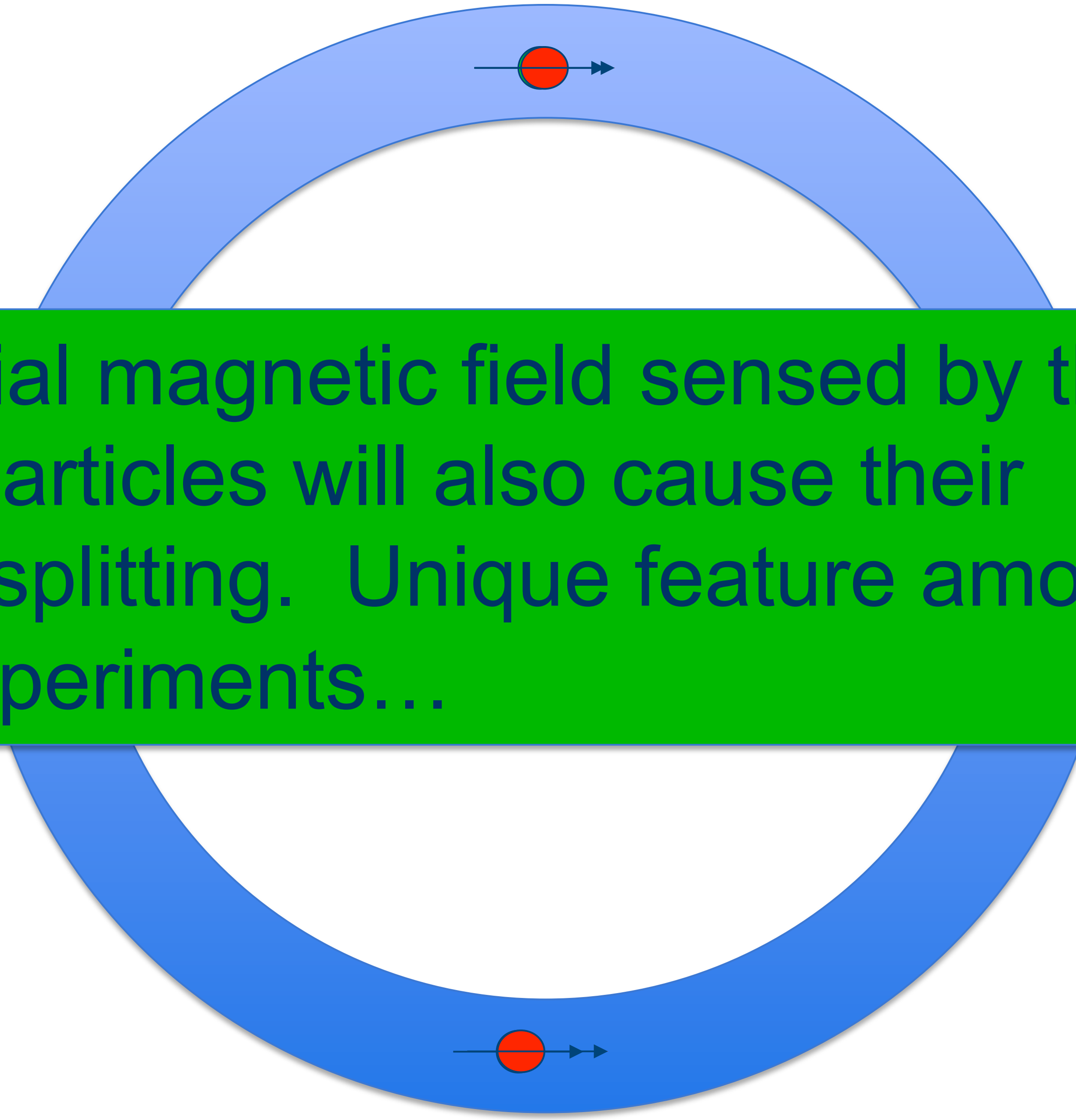
Important Stages in an EDM Experiment

1. Polarize: state preparation, intensity of beams
2. Interact with an E-field: the higher the better
3. Analyze: high efficiency analyzer
4. Scientific Interpretation of Result! Easier for the simpler systems (theory; lattice?)

The grand issues in the proton EDM experiment

1. BPM magnetometers (need to demonstrate in a storage ring environment)
2. Polarimeter development: high efficiency, small systematic errors
3. Spin Coherence Time (SCT): study at COSY/ simulations; Simulations for an all-electric ring: SCT and systematic error studies
4. Electric field development for large surface area plates

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



Any radial magnetic field sensed by the stored particles will also cause their vertical splitting. Unique feature among EDM experiments…

1. Beam Position Monitors

- Technology of choice: Low T_c SQUIDS, signal at 10^2-10^4Hz (10% vertical tune modulation)
- R&D sequence: (First funding from US-Japan)

1. Operate SQUIDS in a magnetically shielded area-reproduce current state of art
2. Operate in RHIC at an IP (evaluate noise in an accelerator environment);
3. Operate in E-field string test

2. Polarimeter Development

- Polarimeter tests with runs at COSY (Germany) demonstrated < 1ppm level systematic errors: N. Brantjes et al., NIM A **664**, 49, (2012)

- Technologies under investigation:

1. Micro-Megas/Greece: high rate, pointing capabilities, part of R&D for ATLAS upgrade
2. MRPC/Italy: high energy resolution, high rate capability, part of ALICE development

3. 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. Cooling/mixing during storage could prolong SCT (upgrade option?).

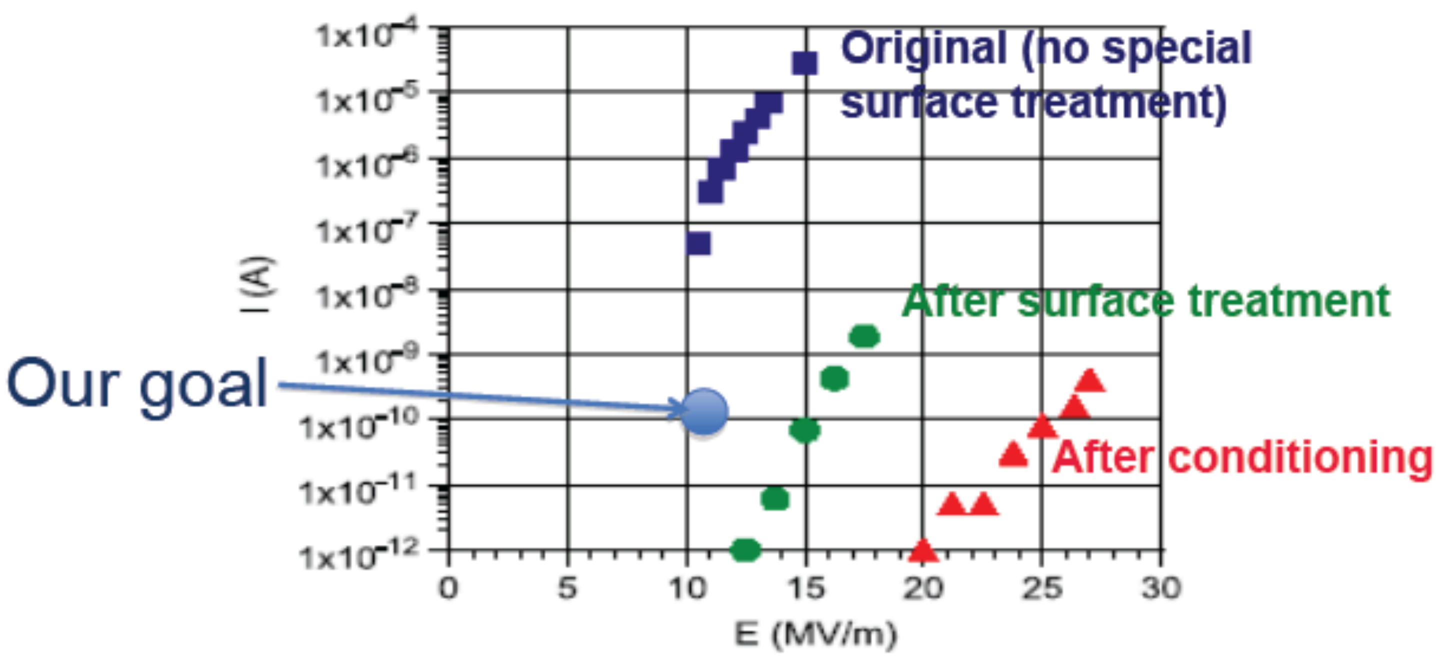
SCT Development

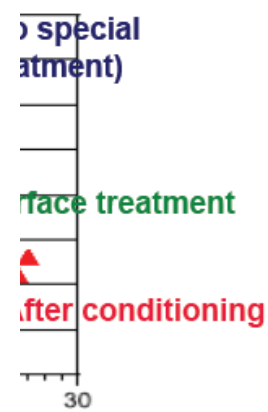
- We have a SCT working solution (precision tracking and analytically-work in progress).
- Tests with polarized deuterons and protons at COSY to benchmark software
- Test runs at COSY are very encouraging.
- Bonus: Electric ring with weak vertical focusing →SCT is long enough for 10^3s storage

4. Electric Field Development

- ✓ Reproduce Cornell/JLAB results of stainless steel plates treated with high pressure water rinsing (part of ILC/ERL development work)

Recent Progress from ILC/ERL R&D (~5mm gap tests) Cornell/JLab

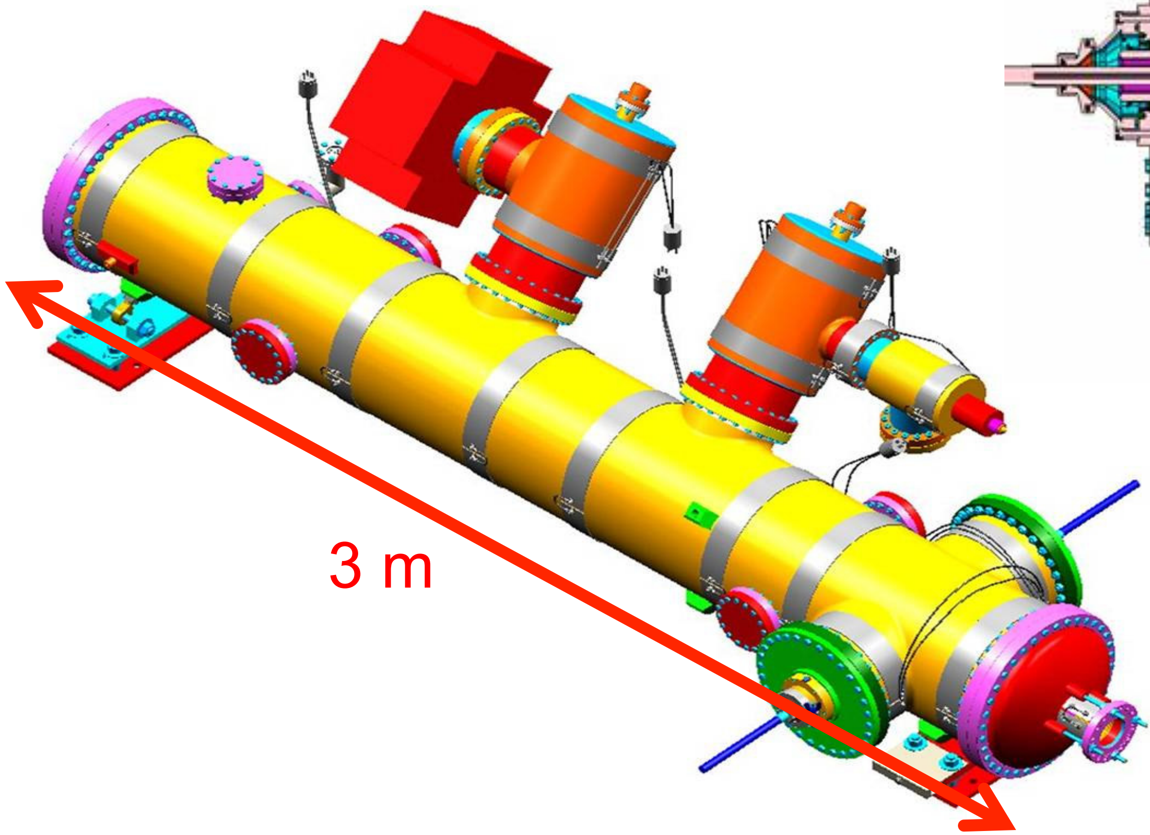


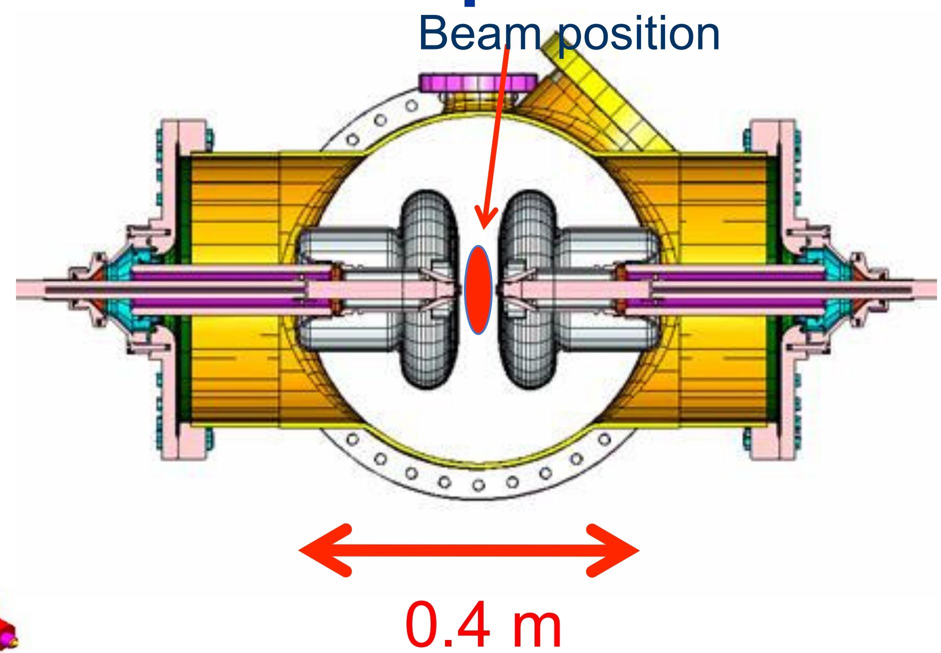


Large Scale Electrodes, New: pEDM electrodes with HPWR

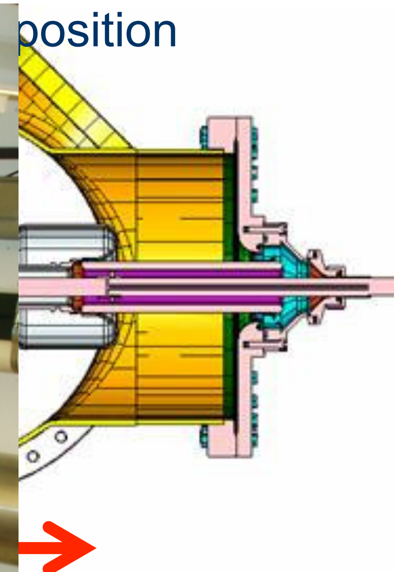
Parameter	Tevatron pbar-p Separators	BNL K-pi Separators	pEDM
Length	2.6m	4.5m	3m
Gap	5cm	10cm	3cm
Height	0.2m	0.4m	0.2m
Number	24	2	10^2
Max. HV	±180KV	±200KV	±150KV

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





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

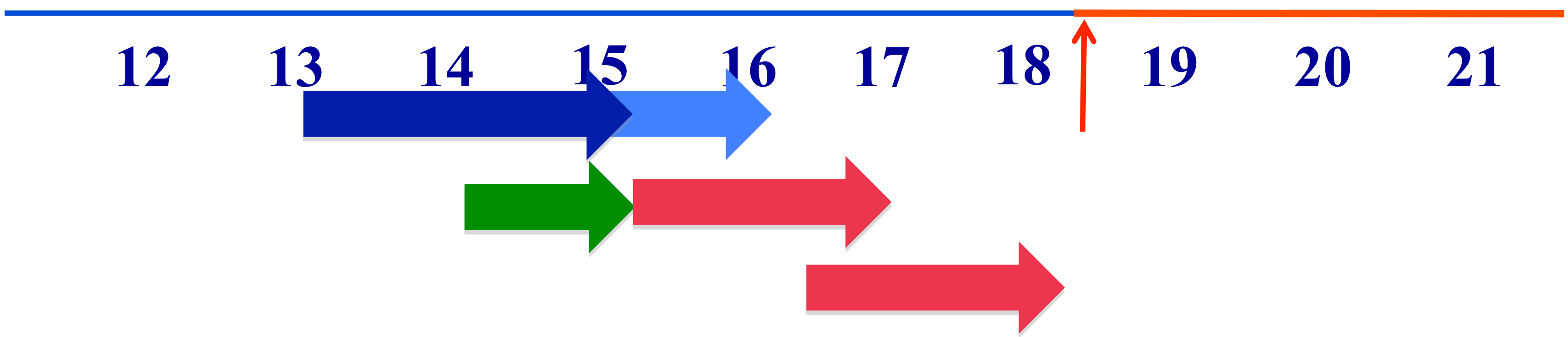


The miracles that make the pEDM

1. Magic momentum (MM): high intensity charged beam in an all-electric storage ring
2. High analyzing power: A>50% at the MM
3. Weak vertical focusing in an all-electric ring: SCT allows for 10^3s beneficial storage; prospects for much longer SCT with mixing (cooling and heating)

4. The beam vertical position tells the average radial B-field; the main systematic error source

Technically driven pEDM timeline



- Two years R&D
- One year final ring design
- Two years ring/beam-line construction
- Two years installation
- One year "string test"

A proposed proton EDM ring location at BNL. It would be the largest diameter all-electric ring in the world.

Figure 6 Storage Ring location in the North Area

Total cost: exp + ring + beamline for two different ring locations @ BNL

System	Experiment w/ indirects	Conventional plus beamline w/ indirects	Total
pEDM at ATR	**$25.6M**	**$20M**	**$45.6M**
pEDM at SEB	**$25.6M**	**$14M**	**$39.6M**

System	Experiment w/ 55% contingency	Conv. & Beamline w/ contingency	Total
pEDM at ATR	$39.5M	$29.2M	**$68.7M**
pEDM at SEB	$39.5M	$22.6M	**$62.1M**

EDM ring

EDM ring+tunnel and beam line

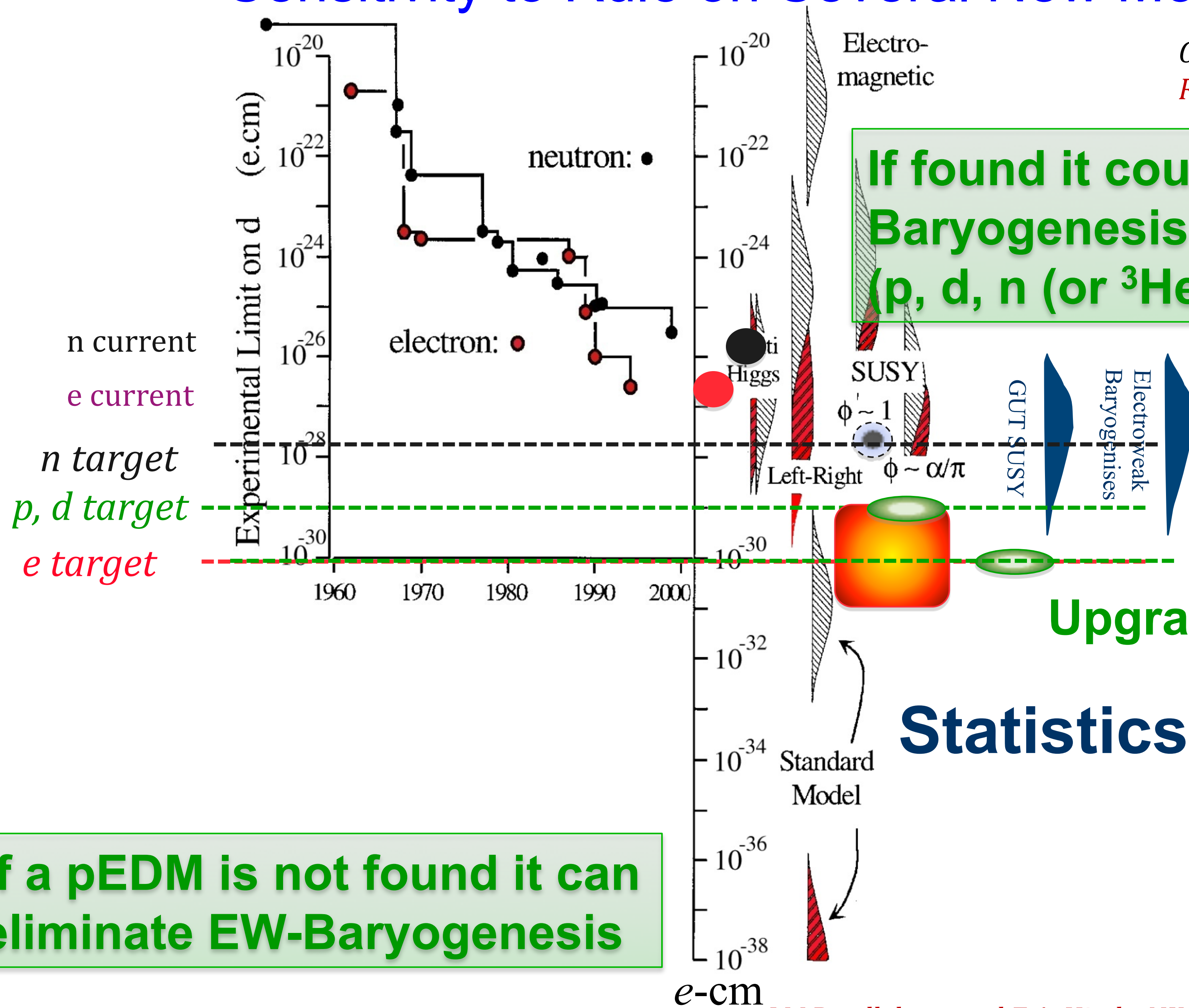
Storage Ring EDM Collaboration

>20 Institutions
>80 Collaborators

- 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

http://www.bnl.gov/edm

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

If a pEDM is not found it can eliminate EW-Baryogenesis

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

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

Measure all three: proton, deuteron and neutron EDMs to determine CPV source

Super-Symmetry (SUSY) model predictions:

$$d_n \simeq 1.4(d_d - 0.25 d_u) + 0.83e(d_u^c + d_d^c) - 0.27e(d_u^c - d_d^c)$$

Theoretical estimation on the lattice?

$$d_N^{I=1} \simeq 0.87(d_u - d_d) + 0.27e(d_u^c - d_d^c) \qquad d_N^{I=1} = (d_p - d_n)/2$$

$$d_N^{I=0} \simeq 0.5(d_u + d_d) + 0.83e(d_u^c + d_d^c) \qquad d_N^{I=0} = (d_p + d_n)/2$$

Physics reach of magic pEDM (Marciano)

- Currently: $\bar{\theta} \leq 10^{-10}$, Sensitivity with pEDM: $\bar{\theta} < 0.3\times 10^{-13}$

- **Sensitivity to new contact interaction: 3000 TeV**

- **Sensitivity to SUSY-type new Physics:**

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

The proton EDM at 10^{-29}e·cm has a reach of >300TeV or, if new physics exists at the LHC scale, $\delta<10^{-7}$-10^{-6} rad CP-violating phase; an unprecedented sensitivity level.

The deuteron EDM sensitivity is similar.

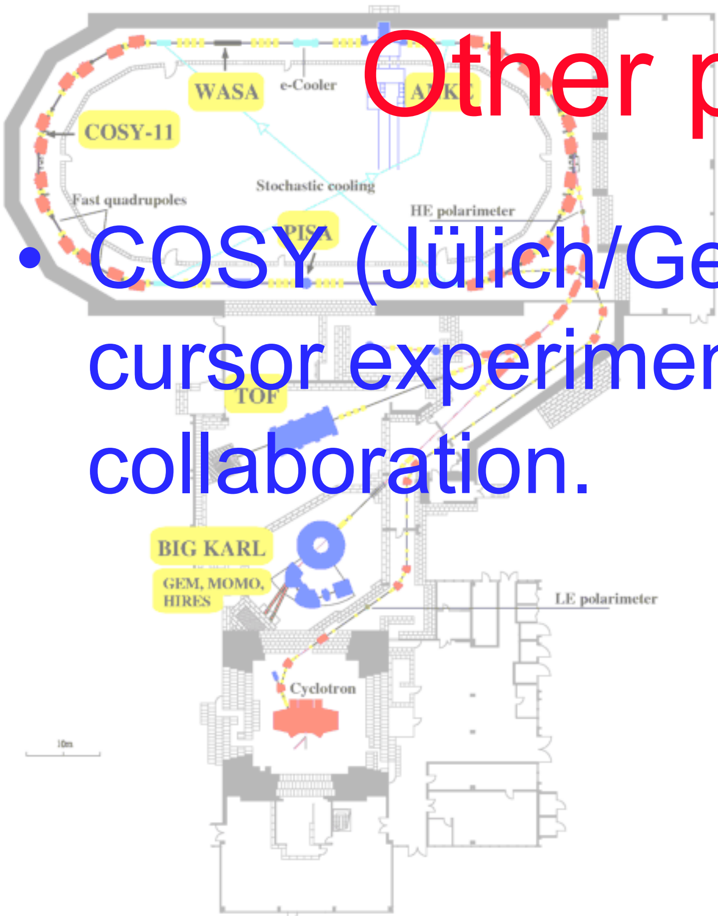
The current status

- Have developed R&D plans (need $1M/year for two years) for

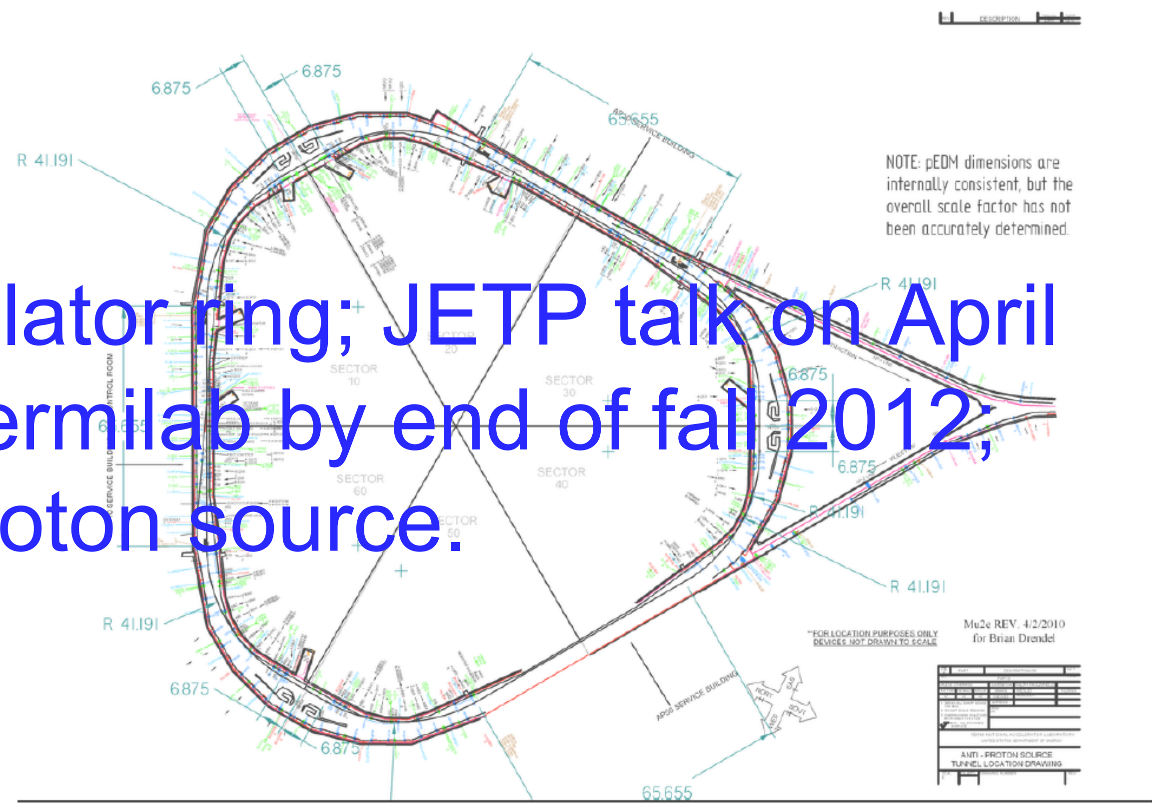
  1) BPM magnetometers, 2) SCT tests at COSY, 3) E-field development, and 4) Polarimeter prototype

- We had two successful technical reviews: Dec 2009, and March 2011.
- Sent a proposal to DOE NP for a proton EDM experiment at BNL: November 2011

Other possible places?



- COSY (Jülich/Germany); proposal for a pre-cursor experiment; we have a common R&D collaboration.



- Fermilab, accumulator ring; JETP talk on April 20; Proposal to Fermilab by end of fall 2012; Need polarized proton source.

Common R&D with COSY

EDM at Storage Rings

JÜLICH FORSCHUNGSZENTRUM

International srEDM Network

Institutional (MoU) and Personal (Spokespersons …) Cooperation

srEDM Collaboration (BNL)	srEDM Collaboration (FZJ)

Common R & D

RHIC
Beam Position Monitors
(…)

EDM-at-COSY
Polarimetry
Spin Coherence Time
Cooling
(…)

Spin Tracking

Slide by H. Stroeher, Director of IKP II

	Study Group
DOE-Proposal	Precursor; Ring Design
CD0, 1, …	HGF Application(s)

Summary

- ✓ Proton EDM physics is a must do, > order of magnitude improvement over the neutron EDM
- ✓ E-field issues well understood
- ✓ Working EDM lattice with long SCT and large enough acceptance (~10^{-29}e•cm/year)
- ✓ Polarimeter work
- Planning BPM-prototype demonstration including tests at RHIC
- Old accumulator ring could house the proton EDM ring at Fermilab; BNL: new tunnel needed
- ✓ At COSY a pre-cursor proposal to PAC

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 : 4×10^{10}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 (95% azim. cov.)

$\sigma_d = 1.6\times10^{-29}\,\mathrm{e\cdot cm/year}$ for uniform counting rate and

$\sigma_d = 1.1\times10^{-29}\,\mathrm{e\cdot cm/year}$ for variable counting rate

Physics/effort comparison

- Physics reach ~10^3 TeV, similar to mu2e (MECO) experiment at FNAL; moreover, it can explain BAU (EW-Baryogenesis)
- SUSY-like new physics at LHC scale, it probes CP-violating phases to sub micro-radian level, complementary to LHC (plus fine-tuned SUSY)
- At 10^{-29}e·cm it's > an order of magnitude better than the best neutron EDM plans anywhere. Statistically superior to neutron EDM exps.
- Method can be applied to proton, deuteron, and ^{3}He to unravel the underlying physics. More than other methods can do.