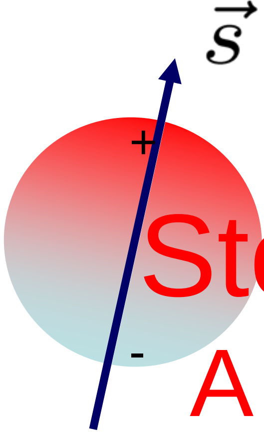
EDM-review meeting
BNL, 7 & 8 December 2009

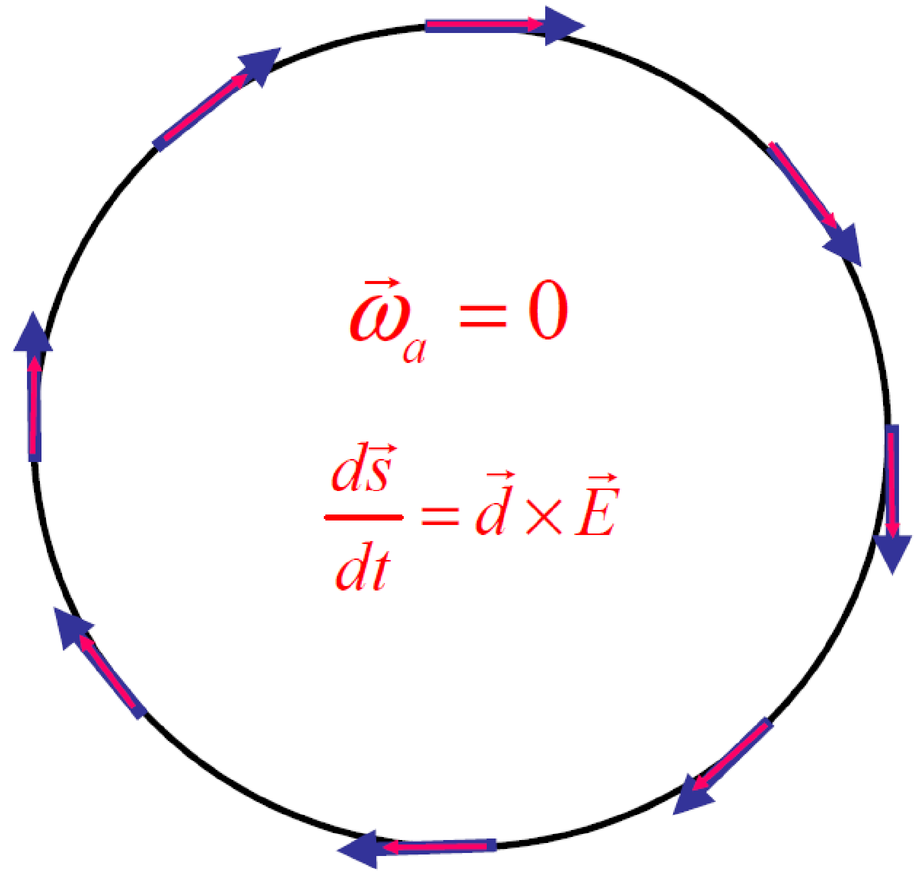


Storage ring EDM experiment.

A Magic Proton Ring for 10^{-29}e·cm.

Yannis K. Semertzidis

- Goals
- Status
- Request



Well defined goals:

- Beam intensity with 2×10^{10} polarized protons per ~10^3s storage (P≥80%), $(dp/p)_{rms}=2.5 \times 10^{-4}$, emitt. (95%, un-norm.): 3μm hor. and 10 μm ver.
- Long Spin Coherence Time (SCT) of ~10^3s, statistics, (R&D)
- Beam Position Monitors (BPM), 10nm, 1Hz BW, eliminates main systematics, (R&D)
- Internal Polarimeter to monitor the proton spin as a function of time, systematics < 1ppm, (R&D)
- E-field gradient of ~17MV/m for 2 cm plate separation, ~240 m ring circumference, (R&D)

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**

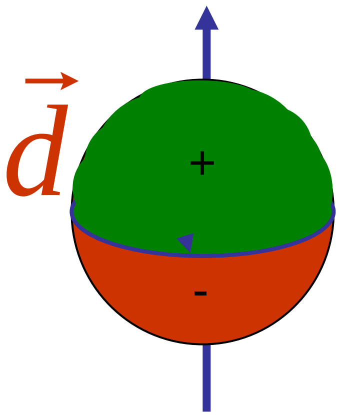
- **Sensitivity to SUSY-type new Physics:**

$$pEDM \approx 10^{-24}\,\mathrm{e}\cdot\mathrm{cm}\ \times \sin\delta \times \left(\frac{0.1\ \mathrm{TeV}}{M_{\mathrm{SUSY}}}\right)^2$$

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

The deuteron EDM sensitivity is similar.

The Electric Dipole Moment precesses in an Electric field

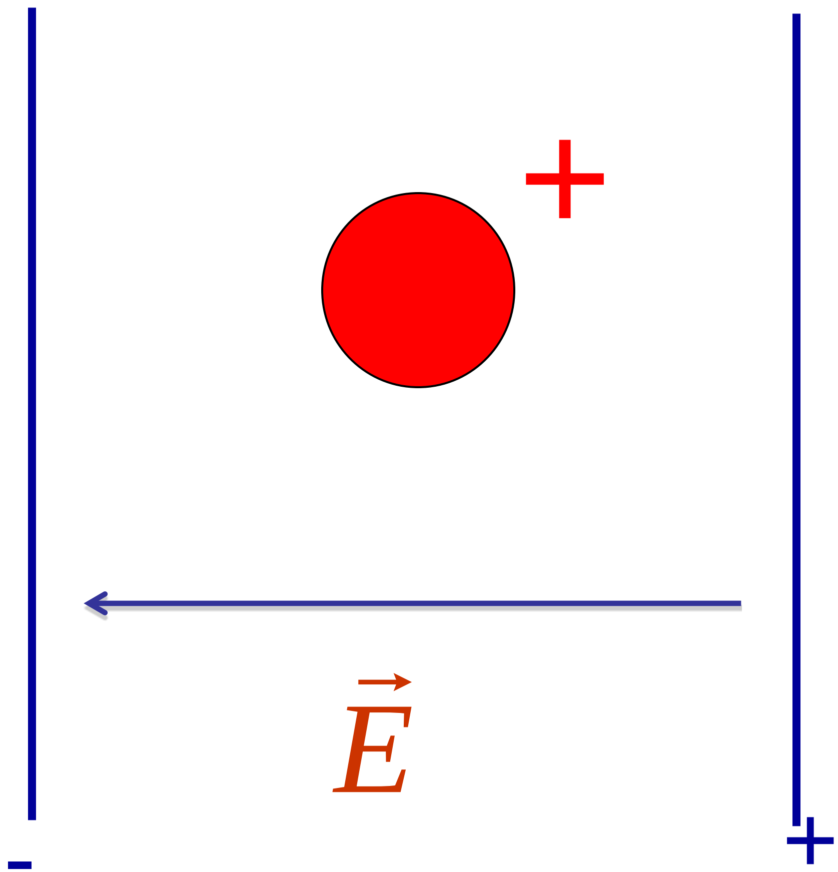


The EDM vector *d* is along the particle spin direction

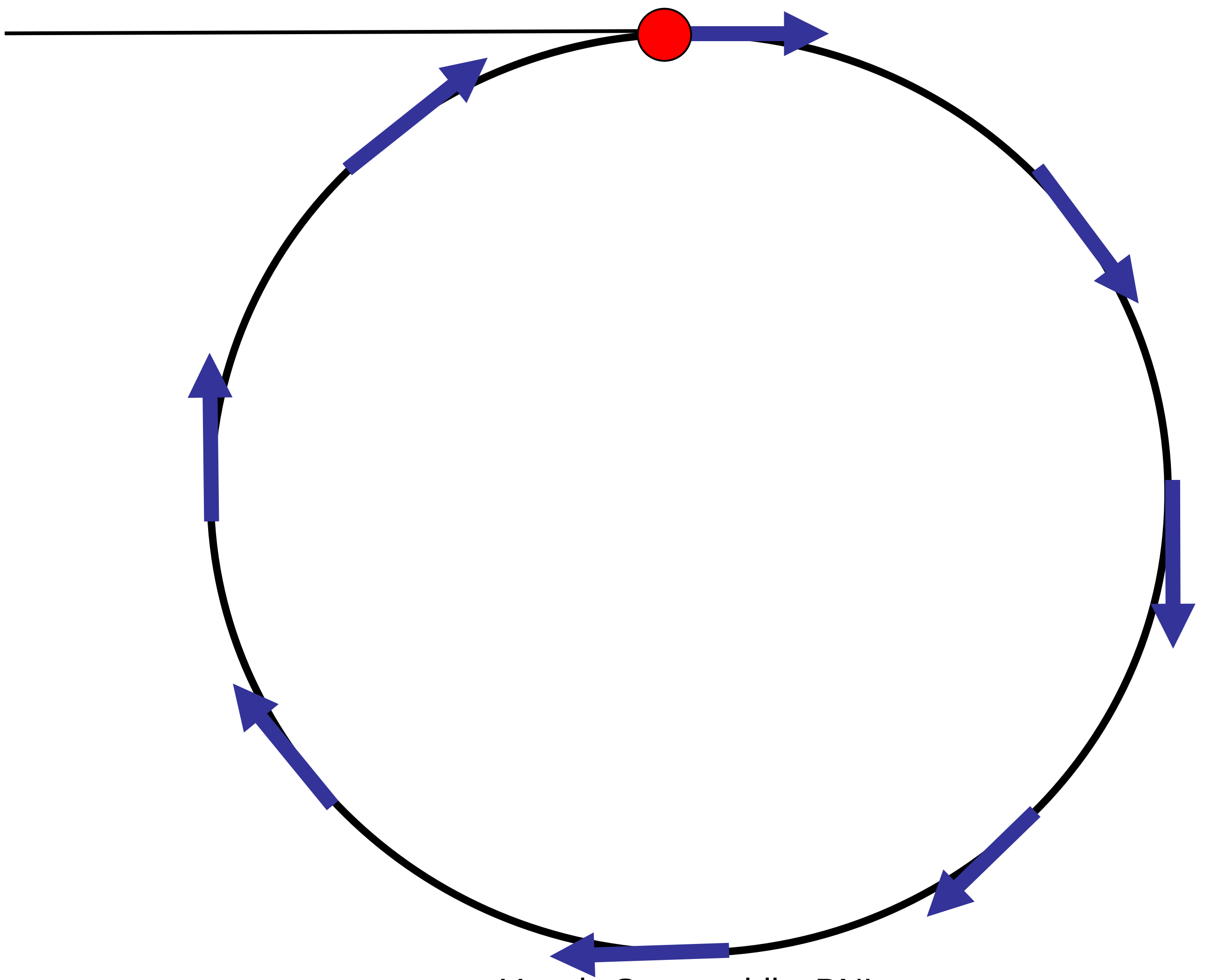
$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$

Yannis Semertzidis, BNL

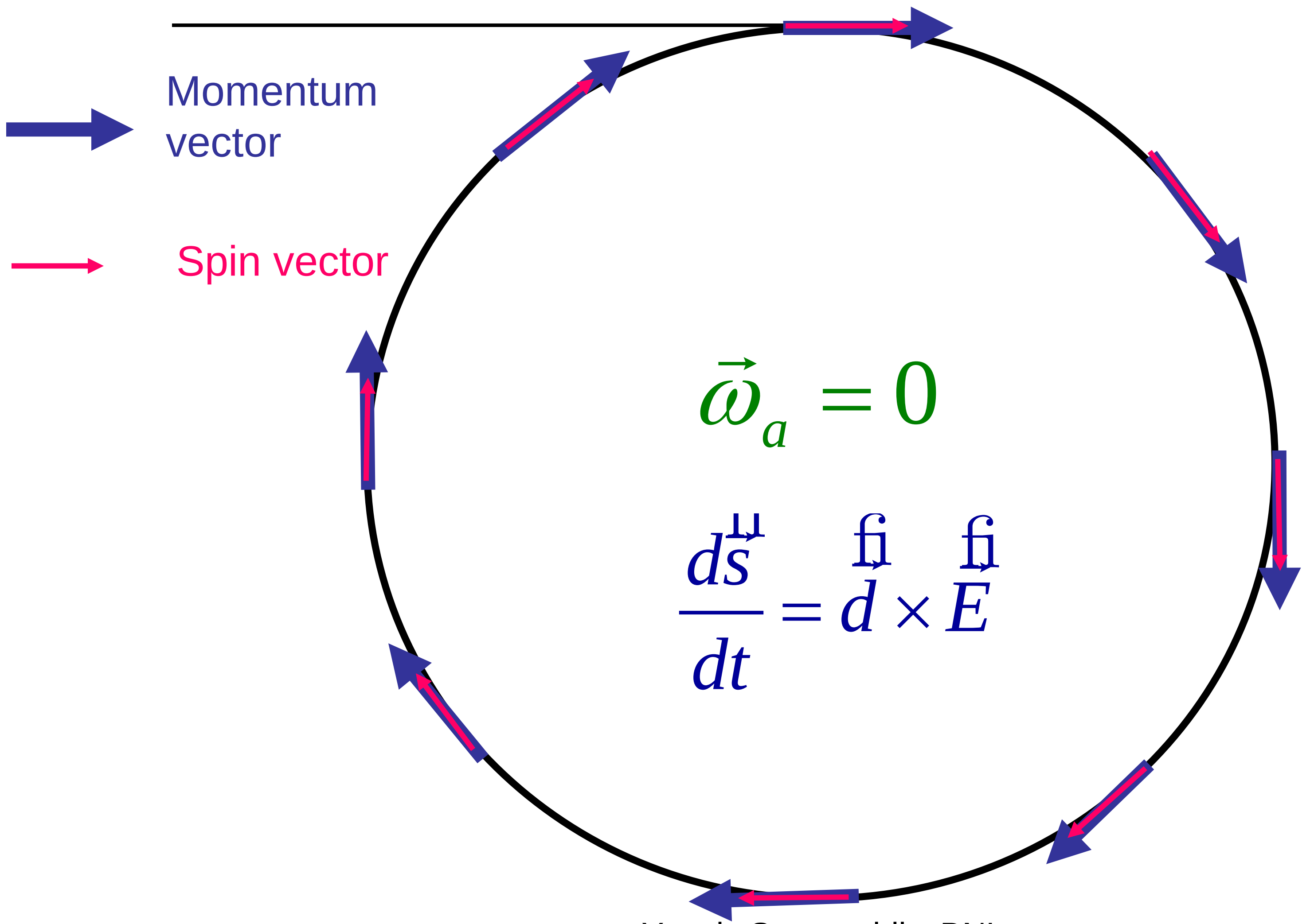
A charged particle between Electric Field plates would be lost right away…



…but can be kept in a storage ring for a long time



The sensitivity to EDM is optimum when the spin vector is kept aligned to the momentum vector



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

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

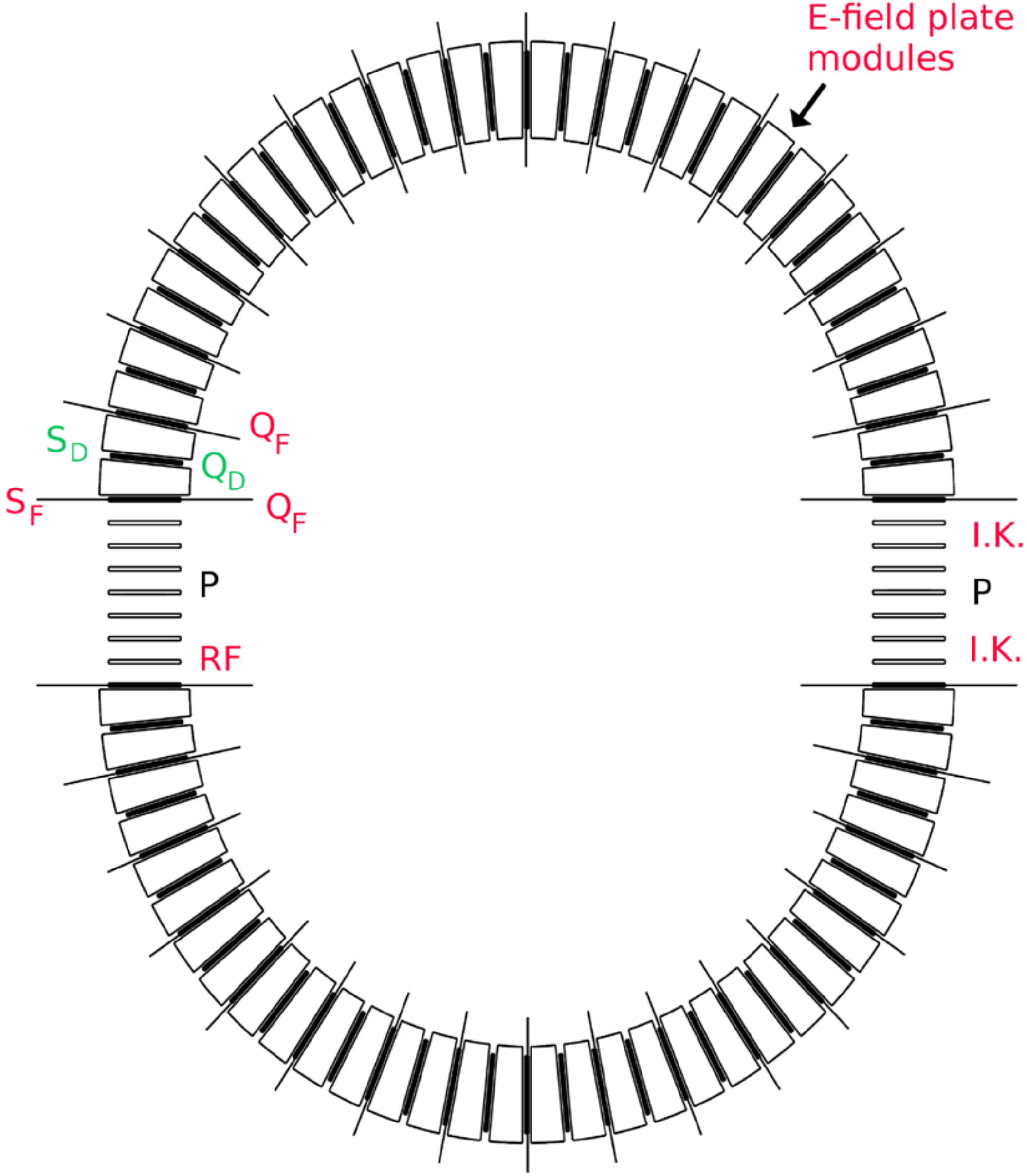
Freezing the horizontal spin precession

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

- The spin precession is zero at “magic” momentum (0.7 GeV/c for protons, 3.1GeV/c for muons,…)

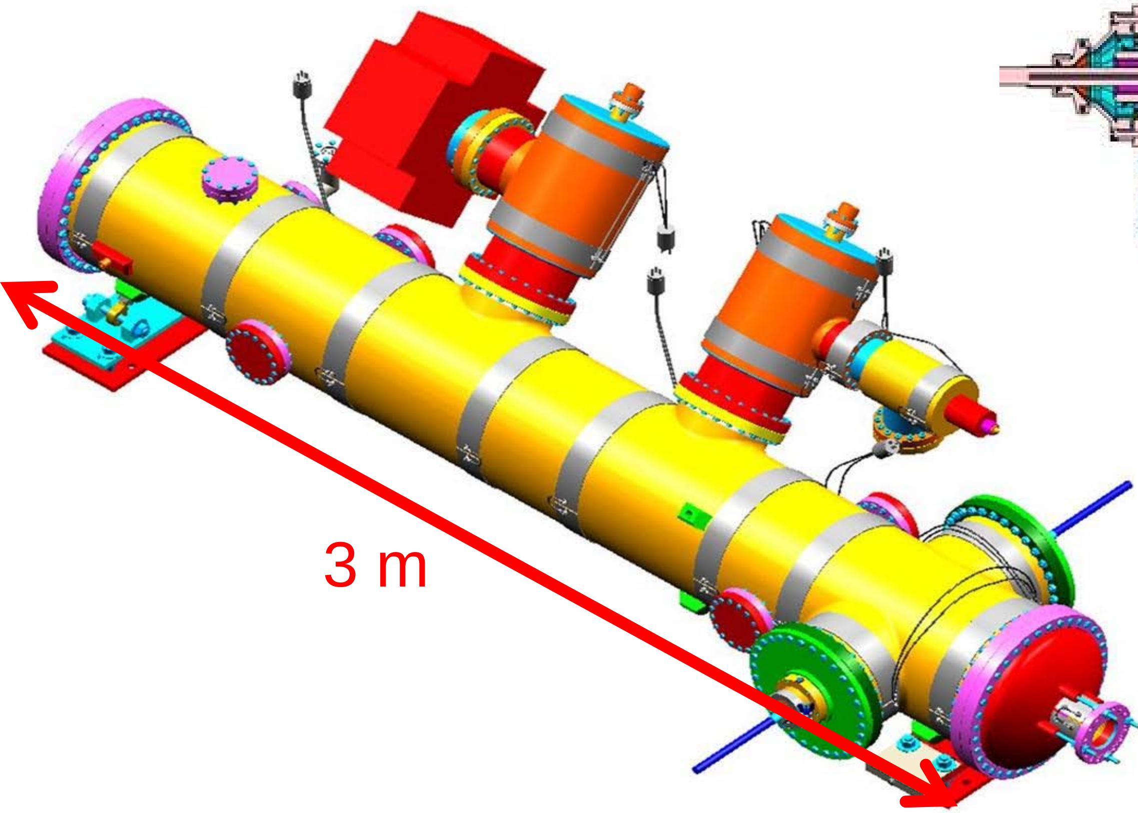
$$p = \frac{m}{\sqrt{a}}, \text{ with } a = \frac{g-2}{2}$$

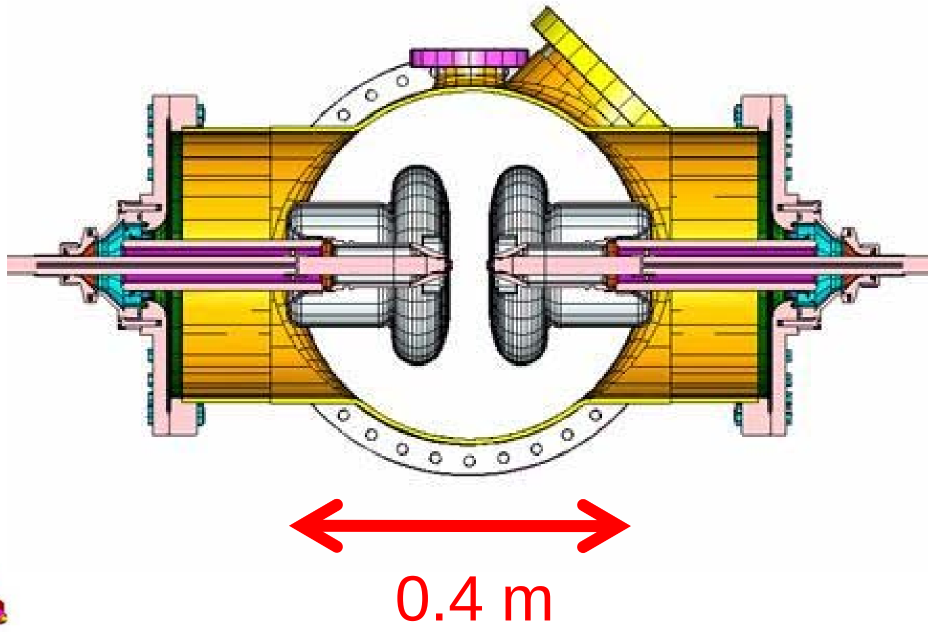
A possible magic proton ring lattice:
~240m circumference with ES-separators.



- I.K.: Injection Kickers
- P: Polarimeters
- RF: RF-system
- S: Sextupoles
- Q: Quadrupoles
- BPMs: ~70 Beam Position Monitors

E-field plate module: The (26) FNAL Tevatron ES-separators would do





Vertical plates are placed everywhere around the ring to minimize vertical electric fields from image charges

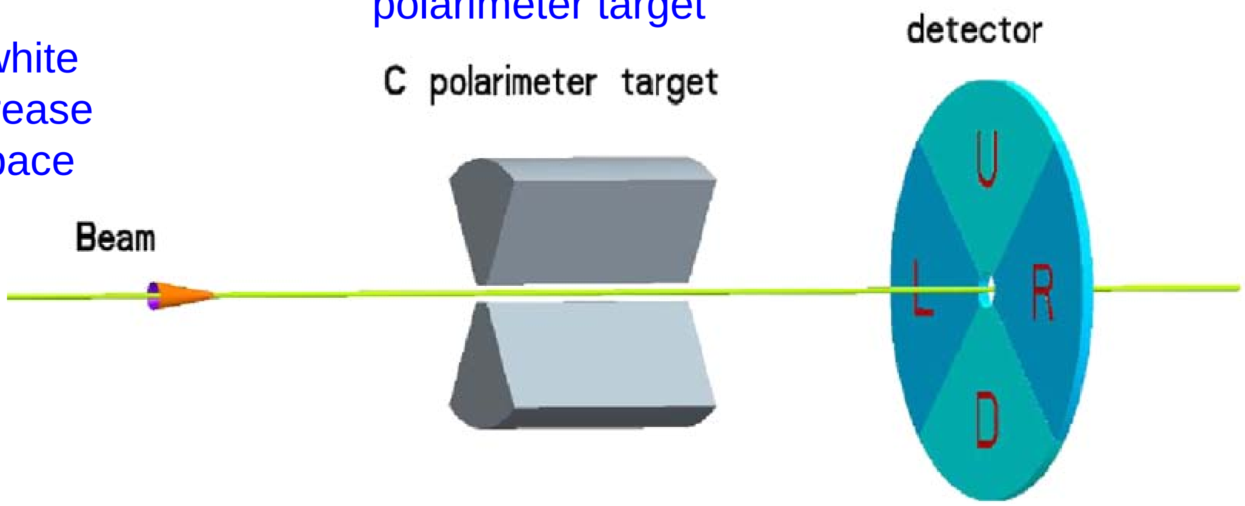
Magic Proton EDM ring includes:

- Injection
- Bunch capture with RF
- Vertical to horizontal spin precession
- Slow extraction onto an internal target for polarization monitoring
- Use RF-feedback from polarimeter to keep spin longitudinal

pEDM polarimeter principle: probing the proton spin components as a function of storage time

“defining aperture”
polarimeter target

extraction adding white noise to slowly increase the beam phase space



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

carries EDM signal
small
increases slowly with time

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

carries in-plane precession signal

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

Analyzing power can be further optimized (E. Stephenson)

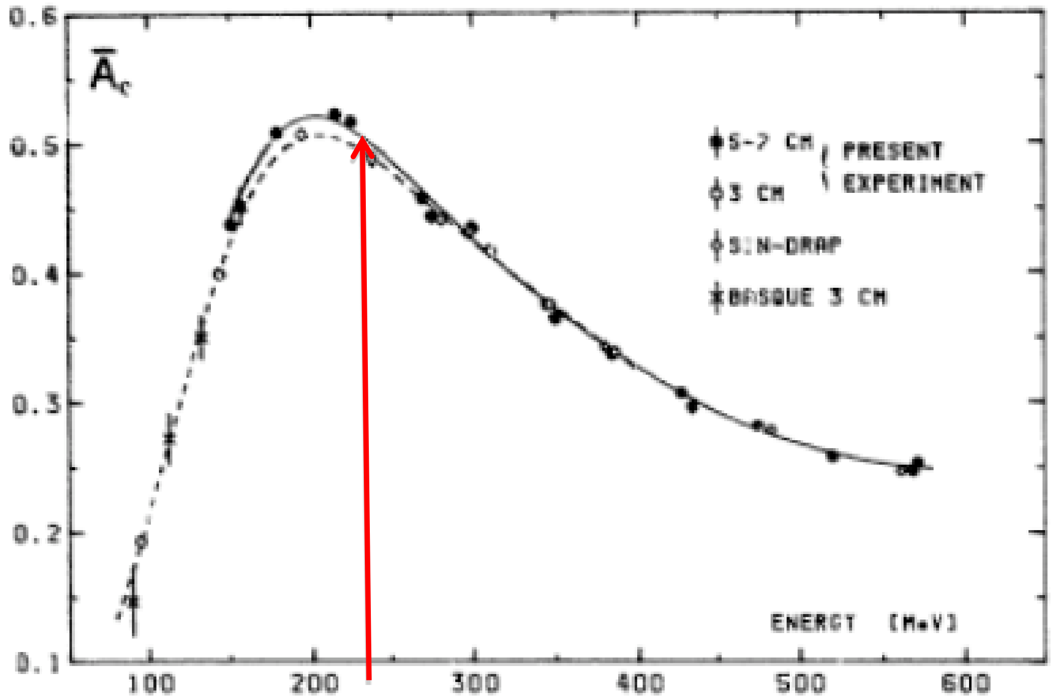
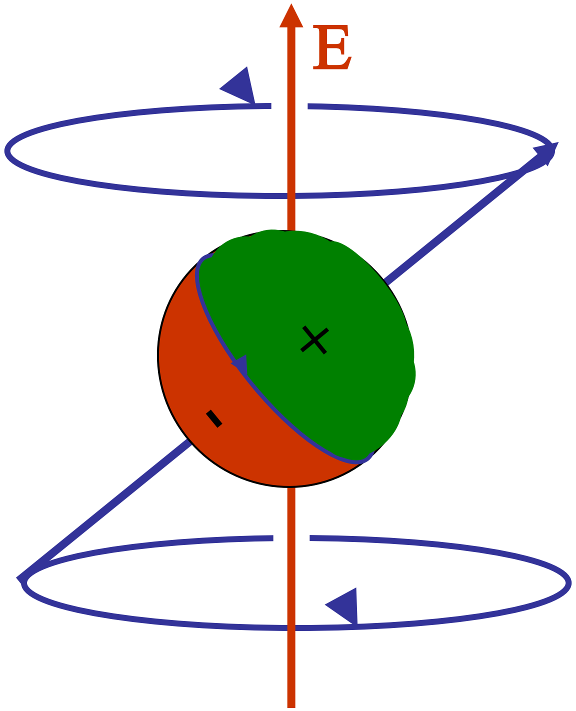


Fig. 4. Angle-averaged effective analyzing power. Curves show our fits. Points are the data included in the fits. Errors are statistical only

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 precession at rest

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



Compare the Precession Frequencies with E-field Flipped:

$$\hbar\left(\omega_1 - \omega_2\right) = 4dE$$

$$\sigma_d \propto \frac{1}{EPA}\frac{1}{\sqrt{N\tau T}}$$

Main Systematic Error: particles have non-zero magnetic moments!

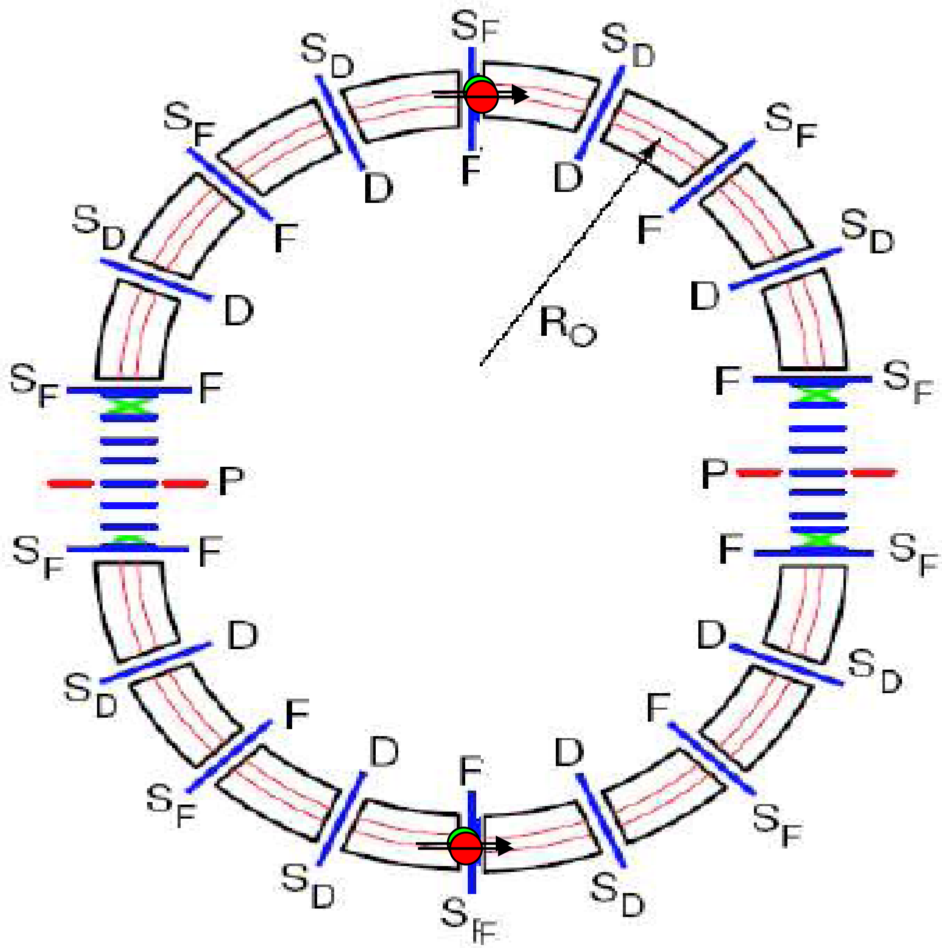
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

- For the nEDM experiments a co-magnetometer or SQUIDS are used to monitor the B-field
- For the magic proton ring we plan to use simultaneous clockwise (CW) & counter-clockwise (CCW) beam storage

Certain (main) systematic errors easier to handle if CW & CCW is done at the same time (Coincident BeamS: CBS)

In a ring with Electric field bending it is possible to store protons CW & CCW at the same time in the same place

Clock-wise (CW) & Counter-clock-wise (CCW) storage



Two different focusing options for the magic proton ring

- Magnetic focusing. The direct magnetic field effect is eliminated. Need to limit vertical forces other than magnetic. BPMs critical to eliminate the fields from the counter-rotating beams.
- Electric focusing. Vertical forces other than magnetic are irrelevant. BPMs critical to eliminate low level radial B-fields.

Systematic errors are very different in the above two focusing systems.

Proton EDM parameters during storage

1. Proton EDM with a statistical goal of 10^{-29} e·cm within ~4×10^7s.
2. Proton momentum 0.7 GeV/c, kinetic energy: 232MeV, beta~0.6.
3. Two simultaneously counter-rotating beams in one ring (same place).
4. $2\text{x}10^{10}$ particles per storage
5. The beam is bunched with h=120, f=90 MHz
6. We will have resonant cavities and/or striplines for position monitoring (BPMs).

CBS: All major previous field issues have been ~eliminated (intensity independent) and greatly reduced (intensity dependent)

- At a price: Need BPMs with 10nm, 1 Hz BW *relative* resolution → 1pm on average around the ring, over ~10^7s.
- The good news: CBS can resolve the dynamic range and stability issues because the needed information is *relative*.

- BPM Players so far: M. Blaskiewicz, P. Cameron, B. Morse. A BPM team is needed.

CBS: Main effects that don't automatically cancel (remedy)

1. Self fields. Need: horizontal to vertical coupling per store < 10^{-4}, and on average (10^7s) < 10^{-6}. We plan to use beam-based alignment (BBA).
2. Fields from the counter-rotating beams (BPMs)
3. RF-cavity fields, if there is a substantial energy loss/turn (longitudinal impedance <1-10 KΩ)
4. Polarimeter: proved <1ppm (mostly done-see talk by E. Stephenson)

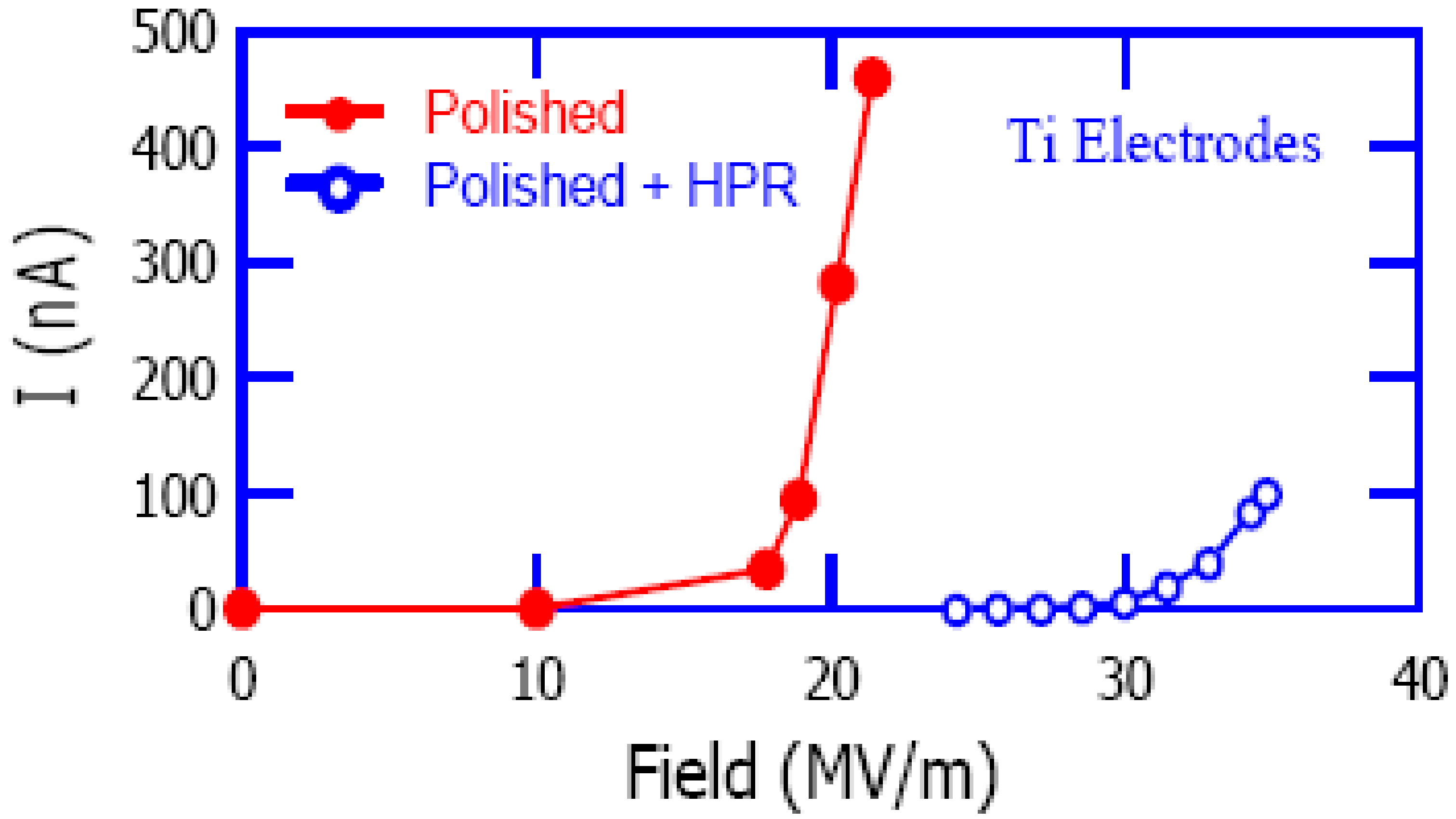
R&D outline and Milestones for the proton EDM.

Duration of R&D: up to 3 years

Goals and considerations

- E-field strength: 170kV/cm, 2cm plate distance
- Polarimeter systematic errors to 1ppm (early to late times-not absolute!). The EDM signal is ~3ppm early to late change in (L-R)/(L+R) counts.
- Spin Coherence Time (SCT): ~10^3s
- BPMs: 10 nm, 1Hz BW resolution

E-field strength (see talk by Morse)



The field emission without and with high pressure water rinsing (HPR) for 0.5cm plate separation.

Recent developments in achieving high E-field strengths with HPR treatment (from Cornell ILC R&D)

Polarimeter Systematic errors: off-axis/angle motion (See talk by Stephenson)

Observable: L-R counting rate asymmetry as a function of time (expected signal level is ~3ppm). Possible syst. error sources:

a) Target position changes from early (~1s) to late times (10^3s).

b) The beam axis changes from early to late times

c) …

Polarimeter team

Polarimeter work

- The Polarimeter team run at the COSY storage ring (Juelich/Germany) with stored polarized deuteron beams and compared signals from opposite (large) vertical polarizations.

- The systematic error is extrapolated to be <1ppm for pEDM

- Candidate detector technologies based on Multi Resistive Plate Chambers (MRPC) and Micro-Megas (MM) are under development in Frascati/Rome and Dimokritos/Athens respectively.

Simulations team

Spin Coherence Time

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

$$d\omega_a \approx \left(\frac{dP}{P}\right)^2 \times 10^7 \,\text{rad/s}$$

- Due to beam momentum spread dP/P there is spread in the horizontal spin precession.
- The linear part of the spread is canceled by using RF-cavity. The quadratic part by using compensating sextupole magnets.
- We expect to demonstrate (with simulation) ~10^3s by end of 2010 using realistic fields.

Cancelling the 2nd order effects with sextupoles

$$\Delta\omega_a \approx a_x A_x^2 + a_y A_y^2 + a_p \left(\frac{dP}{P}\right)_{\max}^2$$

- Strategically placed sextupoles around the ring will cancel the effect from dp/p, horizontal and vertical betatron oscillations. Method applied at Novosibirsk. Our case is analyzed by Y. Orlov who estimated SCT of 10^3s should be possible.

SCT Plan: two tracking programs for cross-checking

- COSY-Infinity (developed expertise and need to support running the interesting cases). See talk by G. Onderwater (KVI)
- UAL-based tracking program (in-house development). See talk by F. Lin (BNL)
- Analytical estimations by Yuri Orlov (Cornell)
- In addition: We need realistic tracking for

  a) magic proton ring lattice optimization,
  b) systematic error checking

Status of Tracking Program development

Name	2^{nd} order effects included (pitch effect, …)	Electric-fields included	Correct energy oscillations	Stable trajectories	Fringe field capability
COSY-Infinity	√	√	√	√	√
UAL_SPINK	√	√	√	(2^{nd} order) TBD	TBD

Spin and Beam Dynamics team

SCT(1&2), Analytical Estimations, Systematic errors

- Working Lattice
- SCT
- Systematic errors
- Include fringe fields and position errors
- Re-estimate SCT
- Re-estimate Systematic errors
- Lattice optimization
- Simulate COSY-ring, observe SCT & compare w/ exp.
- Simulate/optimize BPM-based feedback system, Beam Based Alignment, etc.

BPMs (a possible program)

- Observe Signals at a collision point at RHIC using existing BPMs
- Design resonant cavities
- Build cavities & electronics
- Test cavities in the lab
- Test cavities at an accelerator
- Test cavities at a collision point in an accelerator

Proton Statistical Error (230MeV):

$$\sigma_{d_p} \approx \frac{3\hbar}{E_R A P \sqrt{N_c f T_{Tot} \tau_p}}$$

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 : 2×10^{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)

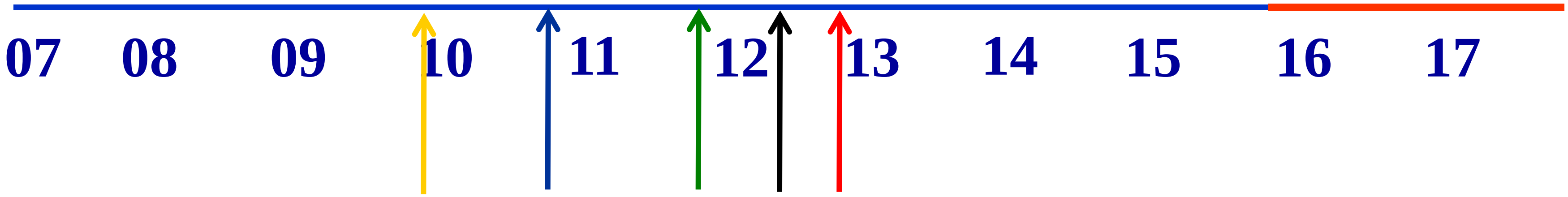
E_R : 17 MV/m Radial electric field strength (65% azim. cov.)

$$\sigma_{d_p} \approx 2.5\times10^{-29}\,\mathrm{e}\cdot\mathrm{cm/year}$$

Need support to develop (fully loaded costs) Total: ~$4M

- SCT (statistics), improve the state of the art by ~10^2; COSY-INF.:$1M, UAL+SPINK: $0.5M
- BPMs (systematics), eliminate the main systematic errors. Need ~10 nm, 1 Hz BW resolution; $0.45M + hardware
- Polarimeter (statistics and systematics). Build and test a full scale polarimeter detector; $1M
- E-field gradient: 17MV/m for 2 cm plate distance. Larger E-field → smaller ring & higher sensitivity → cheaper ring; $0.6M

Technically driven Milestones



- ✓ Spring 2008, Proposal to the BNL PAC
- 2010-2013 R&D phase; ring design

- Fall 2010: E vs. gap studies; simulation and design of polarimeter; 1st phase of SCT studies; design of BPM cavity
- Fall 2011: Polarimeter construction; SCT including placement errors & fringe fields; BPM cavity construction and electronics development, test in lab.
- Spring 2012: Finish first full scale E-field module test
- Fall 2012: Finish commissioning and calibration of polarimeter detector at COSY; Full scale tracking simulation package for EDM ring in place; Test cavity BPMs at a collision point using stored beams

What we have accomplished

1. Have developed the magic proton EDM ring concept. CBS: Simplest SR EDM experiment. It may be expandable to greatest sensitivity: p, d.
2. Developed expertise on COSY-Infinity: a high accuracy/efficiency spin tracking software to study the SCT and systematic errors and developing a second (in house) tracking program for comparison.
3. Polarimeter development runs at COSY/Germany are providing great results.

Possible Upgrade

Modify EDM ring to do the deuteron EDM experiment with similar sensitivity (major upgrade)

If a non-zero EDM value is found in one of them we will have a good idea of the CP-violation source (theta-QCD or new physics)

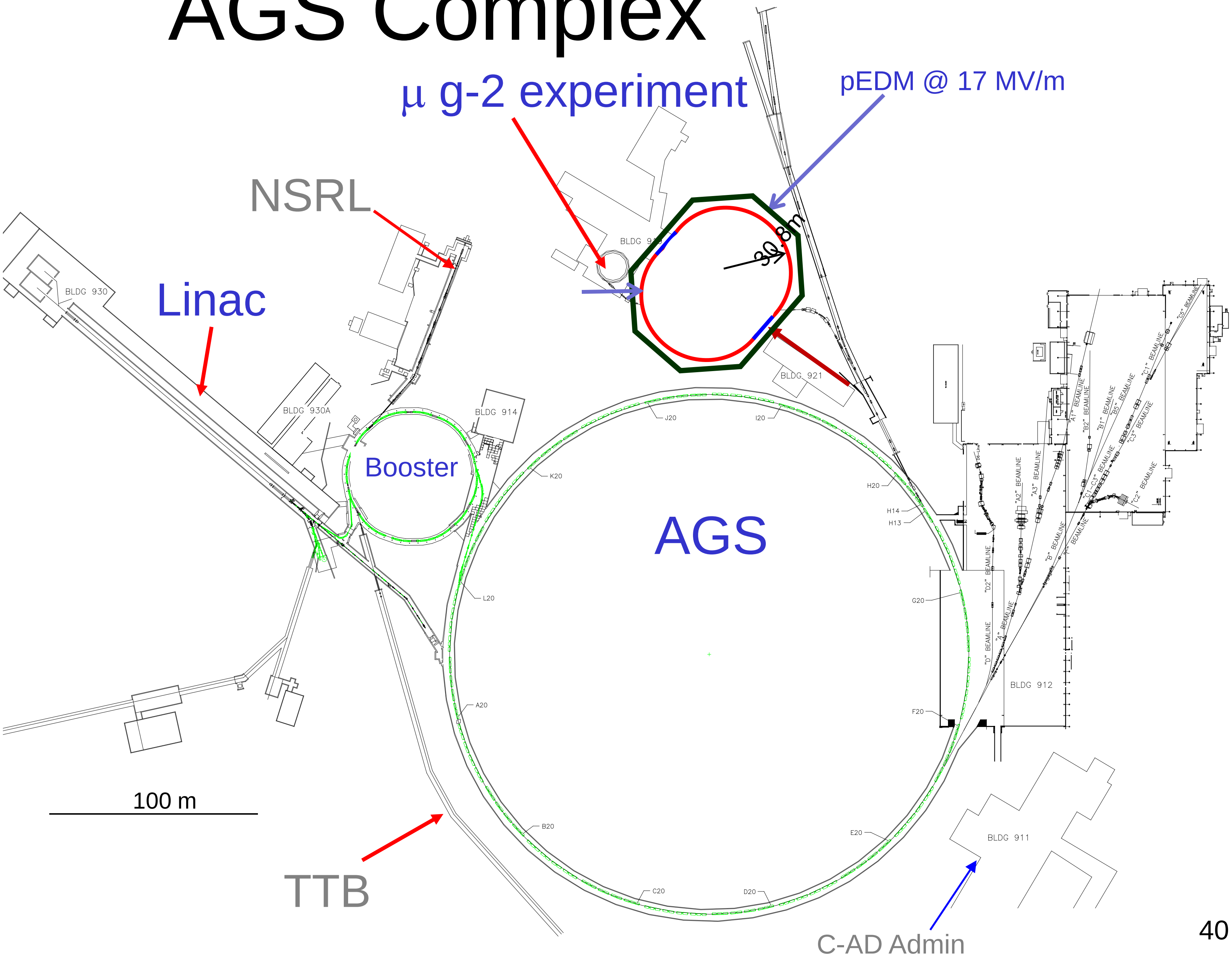
Why does the world need another EDM experiment?

1. The proton, deuteron and neutron combined can pin-down the source should a non-zero EDM value is discovered.
2. Critical: they can differentiate between a theta-QCD source and beyond the SM.
3. The proton and deuteron provide a path to the next order of sensitivity.

Summary

- The success of the proton EDM experiment hangs on our ability to develop BPMs with a *relative* position resolution better than 10 nm for 1 Hz BW, SCT of ~10^3s, highly efficient and low systematic errors Polarimeter detector, and a reliable E-field with E~17 MV/m for 2 cm plate separation. We believe those are all well defined, manageable goals. We need a very strong endorsement to move forward.
- At 10^{-29} e-cm the proton EDM experiment will have the best sensitivity for beyond the SM CP-violation.

AGS Complex



μ g-2 experiment
pEDM @ 17 MV/m
NSRL
Linac
30.8m
BLDG 930
BLDG 930A
BLDG 914
BLDG 921
BLDG 912
BLDG 911
Booster
AGS
J20
I20
K20
H20
H14
H13
G20
L20
A20
F20
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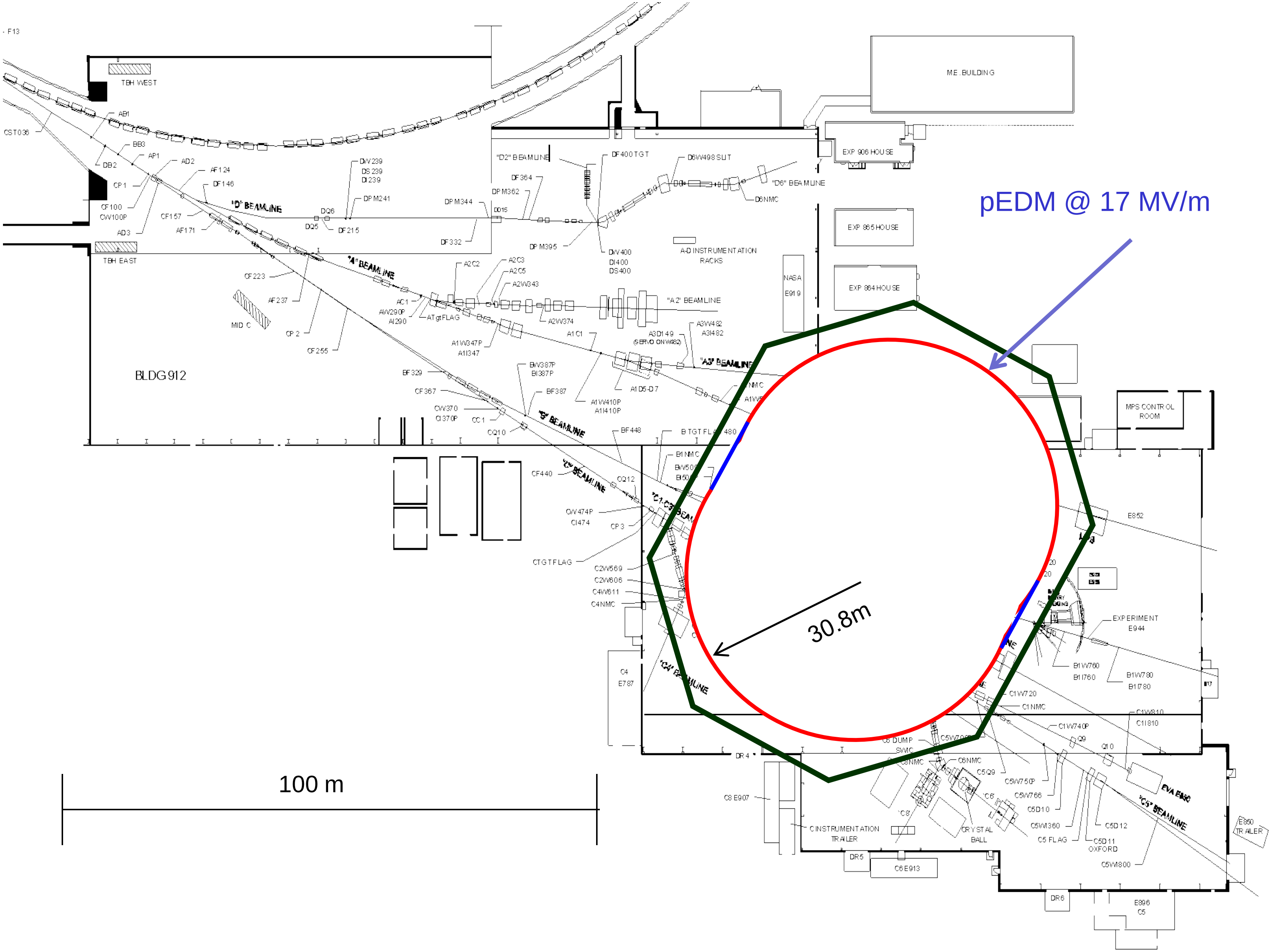
E20
C20
D20
100 m
TTB
C-AD Admin


pEDM @ 17 MV/m
30.8m
100 m
BLDG 912
M.E. BUILDING
EXP 906 HOUSE
EXP 865 HOUSE
EXP 864 HOUSE
MPS CONTROL ROOM
"D" BEAMLINE
"A" BEAMLINE
"A2" BEAMLINE
"A3" BEAMLINE
"B" BEAMLINE
"C" BEAMLINE
"C4" BEAMLINE
"C5" BEAMLINE
TBH WEST
TBH EAST
A-D INSTRUMENTATION RACKS
EXPERIMENT E944
C INSTRUMENTATION TRAILER

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

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

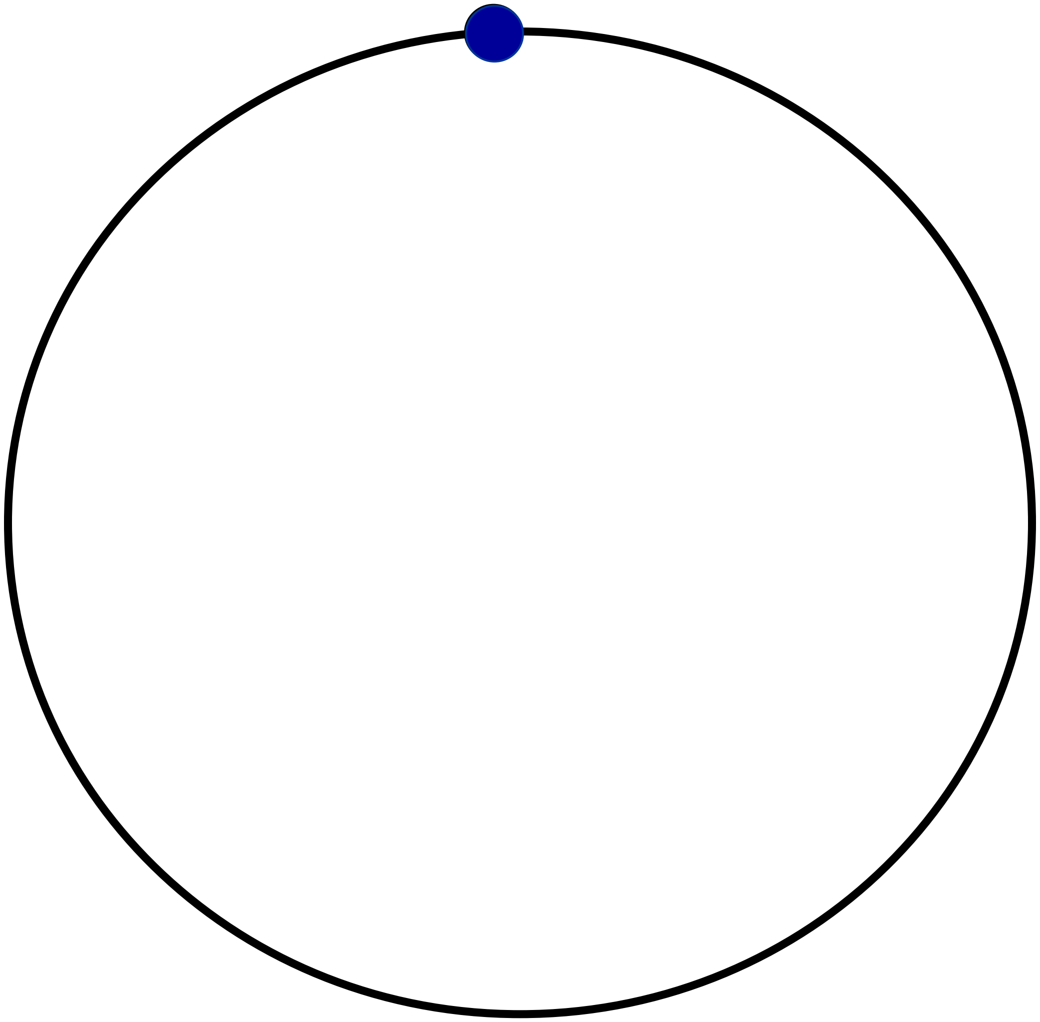
$$\vec{d} = \eta\left(\frac{q}{2mc}\right)\vec{s}$$

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

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

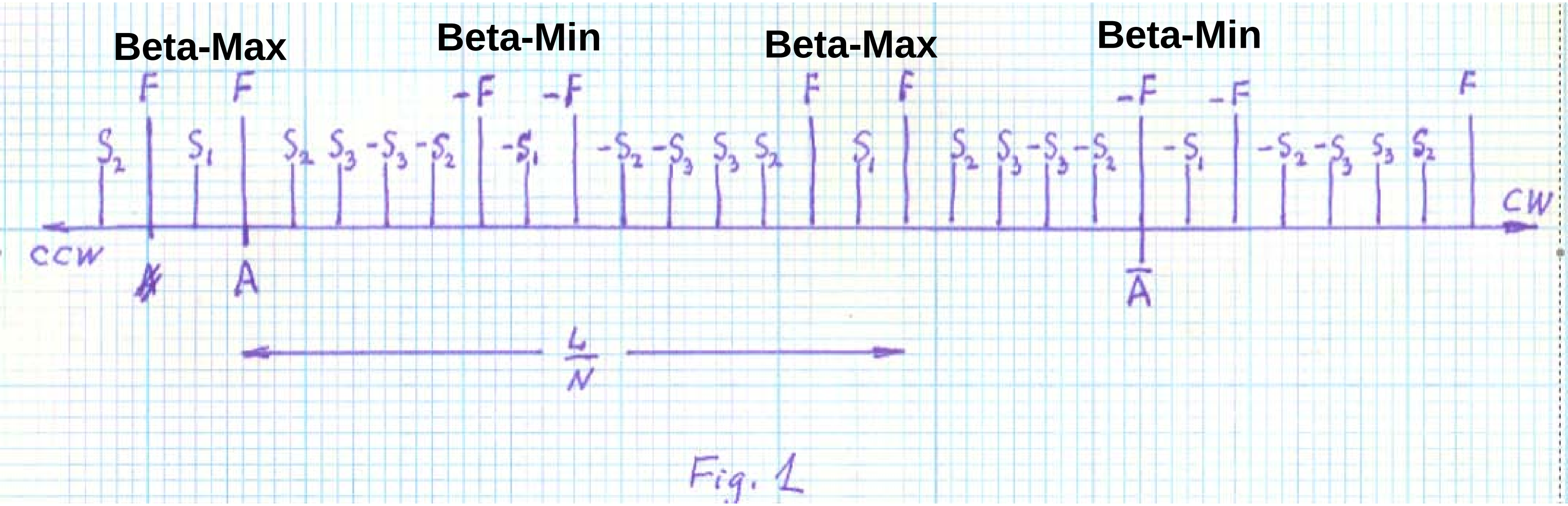
T-violation (under CPT conservation) implies CP-violation, which is needed to explain why matter is dominating over anti-matter in our universe

CW and CCW injections in the magic proton ring



Yannis Semertzidis, BNL

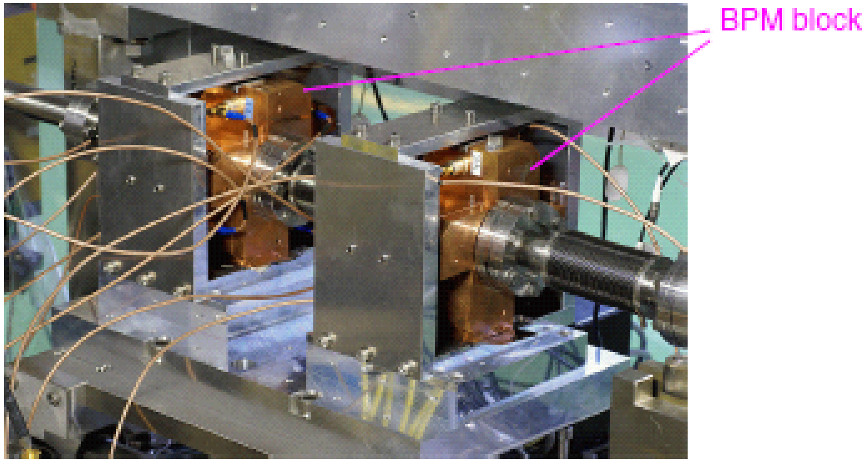
A possible solution for simultaneous CW and CCW beams (Yuri Orlov)



Motivation (Peter Cameron's slide)

- pEDM Coincident Beam Scheme (CBS) requires
  - one picometer measurement of relative positions of the two beams
  - with a bandwidth of one year
  - see BNL pEDM web site for further details
- This can be accomplished with (obsolete, cumbersome, and expensive) COTS electronics (Libera Brilliance)
- We want to get to 1pm in the first month, refine the experiment from there
- In principle, and as the problem is presently understood, this can be accomplished
- Development effort for pickups and electronics is underway
- As a first step in exploring possible unknown systematics of the measurement we propose an APEX experiment

Prior work



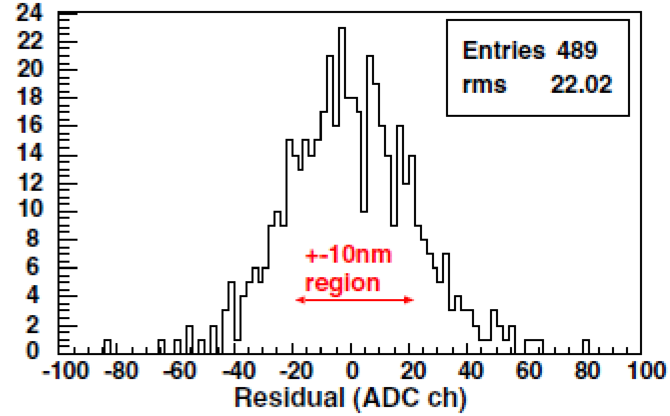


FIG. 17. (Color) Resolution measurement data. The top figure shows a scatter plot of the prediction and measurement. The bottom figure is the distribution of the residual of the prediction.

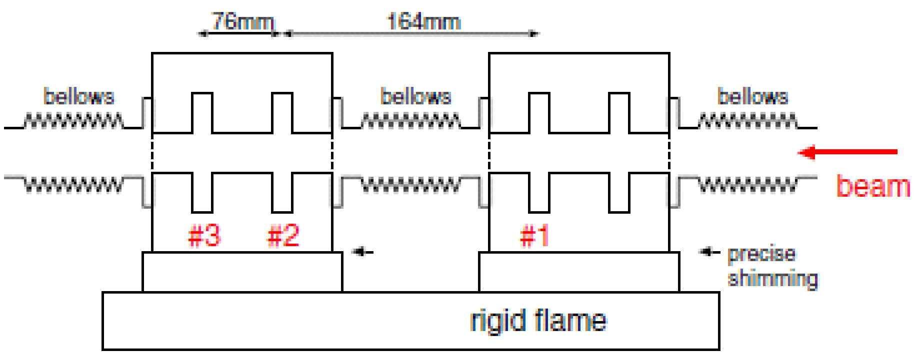


FIG. 6. (Color) BPM support system installed in the beam line. Two blocks were rigidly mounted in the system. The three cavities named 1, 2, and 3 were used in this test. Distances between cavities were 164 and 76 mm. They determine the geometrical factor that appears in the resolution analysis to be 0.799.

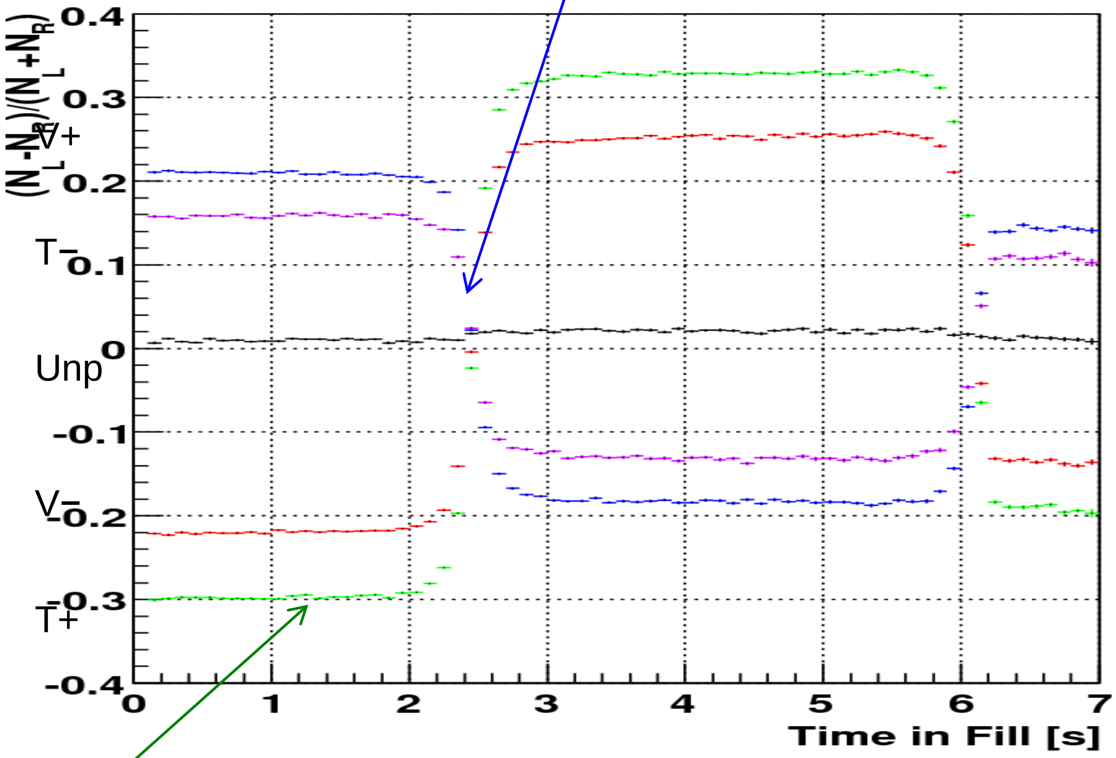
PRST , Accel & Beams, 11, 062801 (2008).
Achieved res. ~8nm per ~10^10 electrons/bunch

From the September 2008 run at COSY

Polarimeter team

Resonance crossing using RF-solenoid (full spin flip)

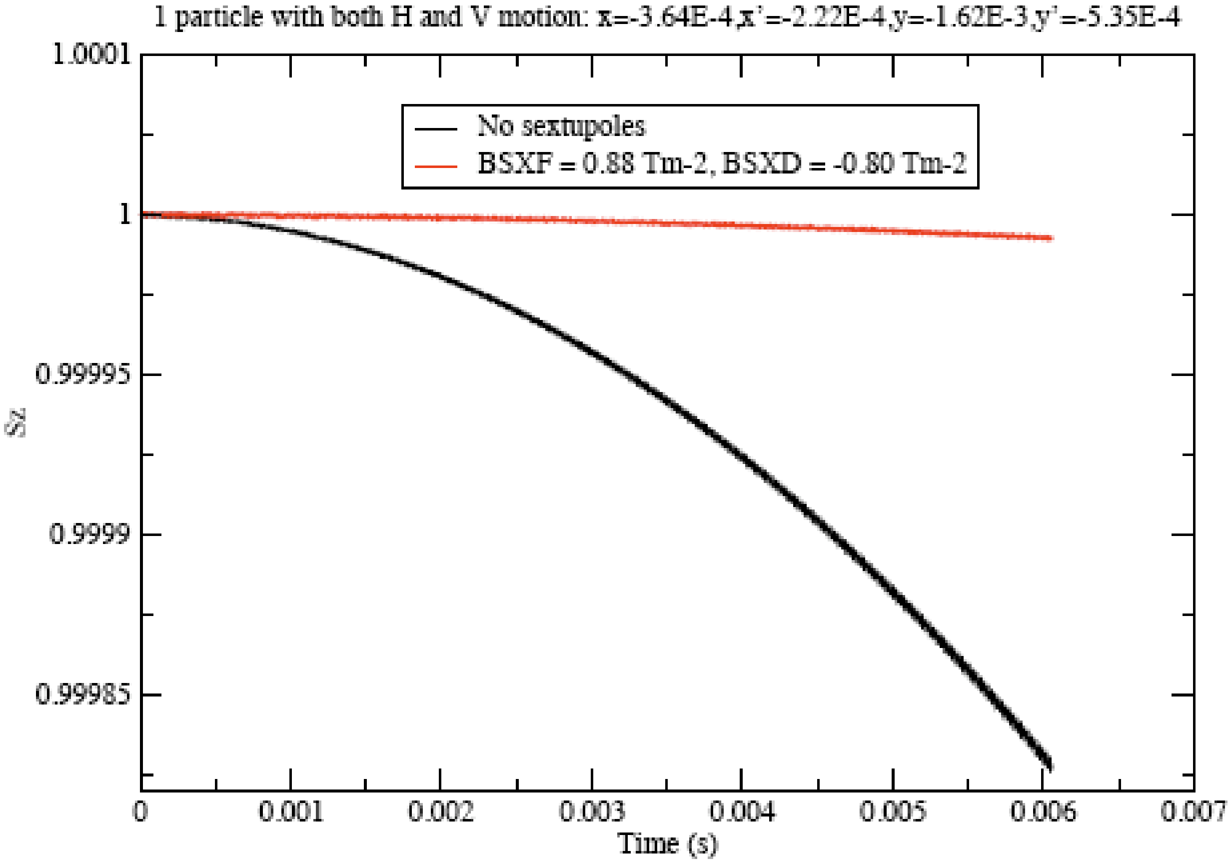
Vector asymmetry



Slowly extracting the beam while monitoring its polarization as a function of time

Searching for optimum sextupoles (Preliminary res.)

SCT team, F. Lin et al.



Two sets of sextupoles are next to focusing and defocusing quads.
Both horizontal and vertical motions are included.

Technically driven pEDM Timeline

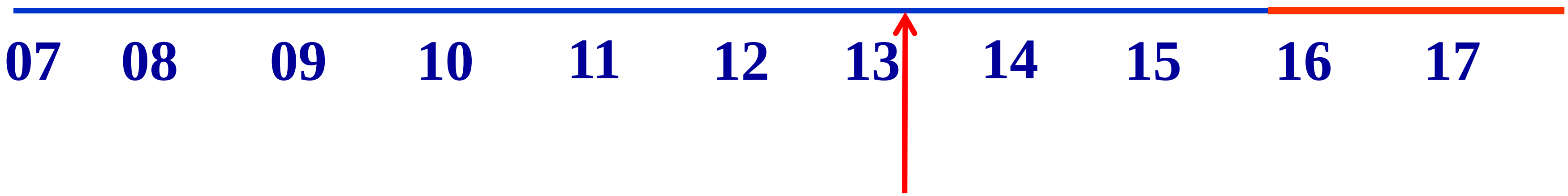
07 08 09 10 11 12 13 14 15 16 17

- ✓ Spring 2008, Proposal to the BNL PAC
- 2008-2012 R&D phase; ring design
- Fall 2009 Conceptual Technical Review at BNL

- Fall 2012, Finish R&D studies:
  a) Develop BPMs, 10 nm, 1 Hz BW resolution
  b) spin/beam dynamics related systematic errors.
  c) Polarimeter detector development and prepare for testing
  d) Finalize E-field strength to use
  e) Establish Spin Coherence Time, study systematic errors, optimize lattice

- FY 2013, start ring construction
- FY 2015, pEDM engineering run starts
- FY 2016, pEDM physics run starts

Technically driven pEDM Timeline



- June 2010 CD0
- June 2011 CD1
- Fall 2012 CD2
- Fall 2014 CD3

- Start of 2012, finish pEDM detailed ring design

- FY 2013, start ring construction
- FY 2015, pEDM engineering run starts
- FY 2016, pEDM physics run starts