Joint Experimental-Theoretical Physics (W&C) seminar
Fermilab, 20 April 2012


# Storage ring Electric Dipole Moment experiment for the proton

Yannis K. Semertzidis, BNL

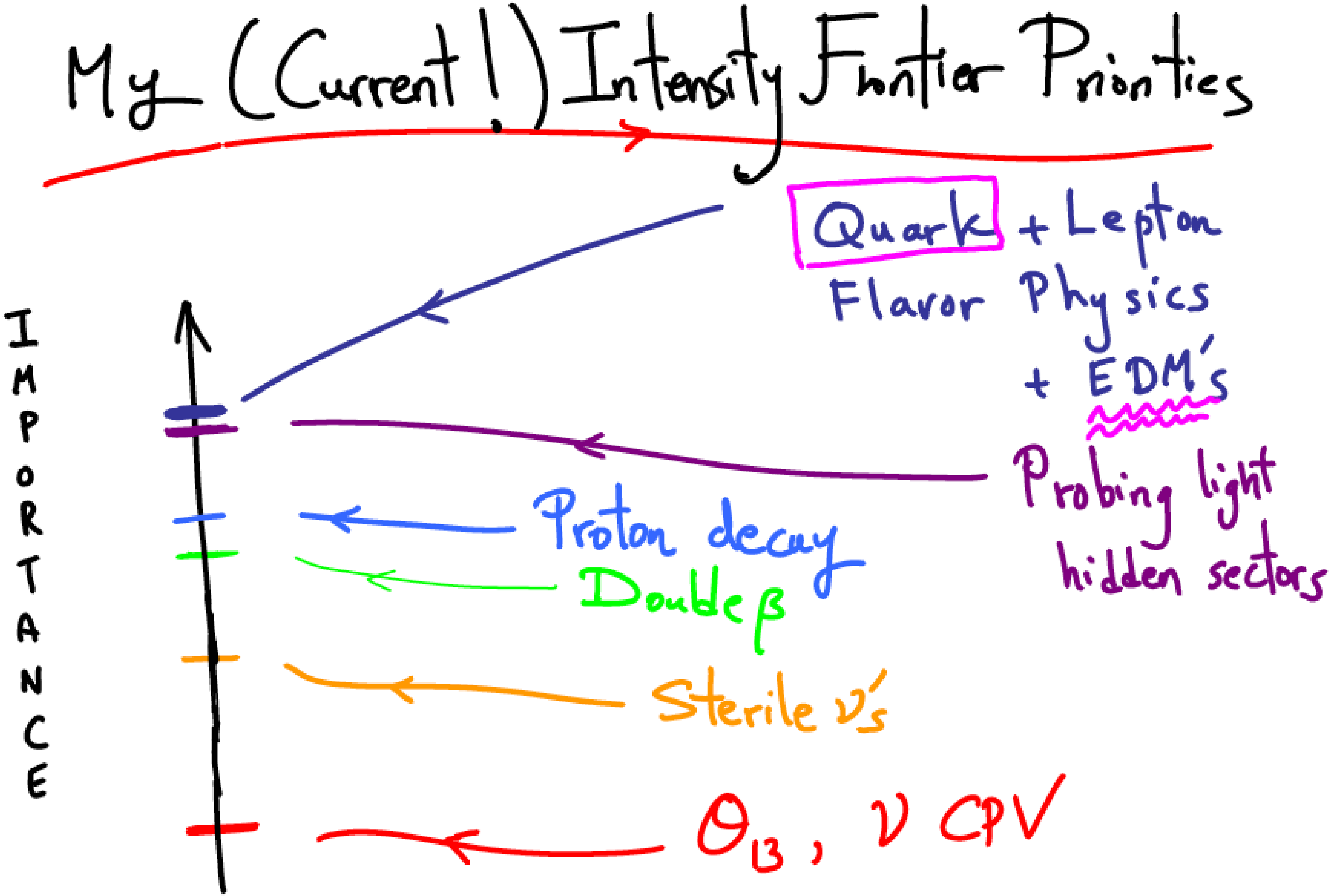
✓High precision experiment: $10^{-29}$e·cm

✓High sensitivity to New Physics, ~$10^3$ TeV

✓Few $\times 10^{10}$ Polarized protons in a storage ring every 20 min can provide the statistics.

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

Talk by Nima Arkani Hamed at the Intensity Frontier meeting, Nov. 2011



# 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**

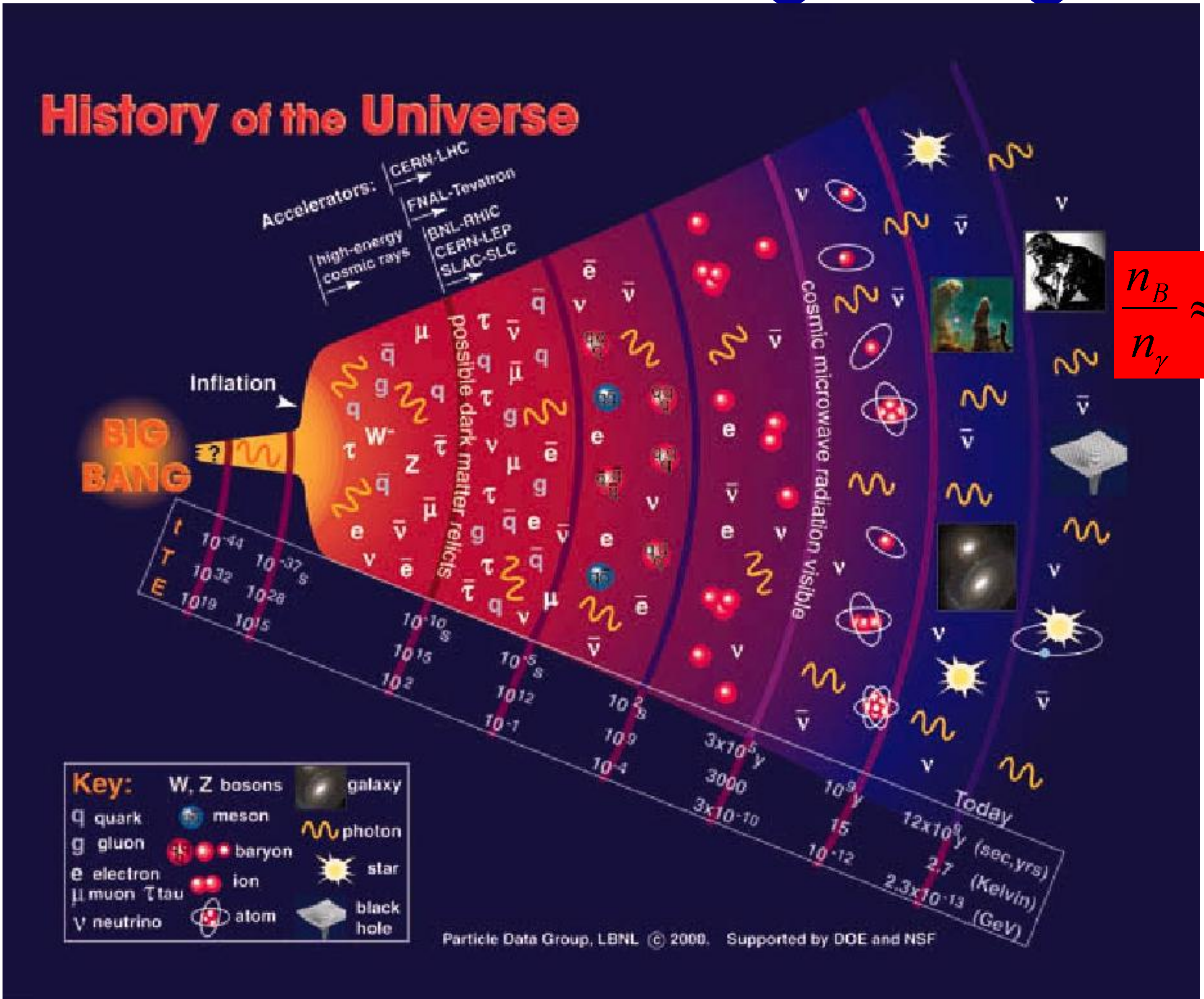
- **Sensitivity to SUSY-type new Physics:**

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

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.

# Why is there so much matter after the Big Bang;



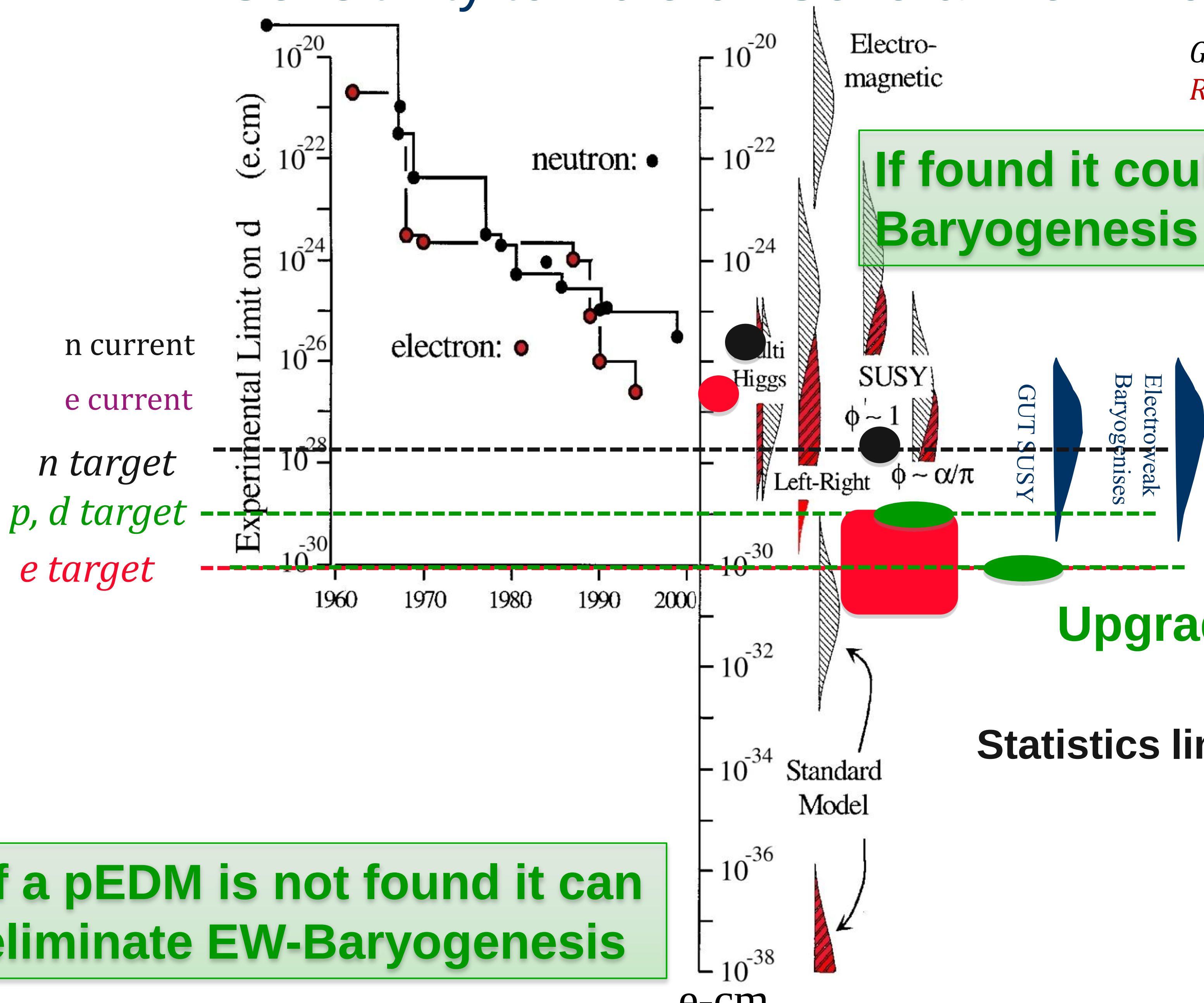

We see:

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

From the SM:

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

# Sensitivity to Rule on Several New Models

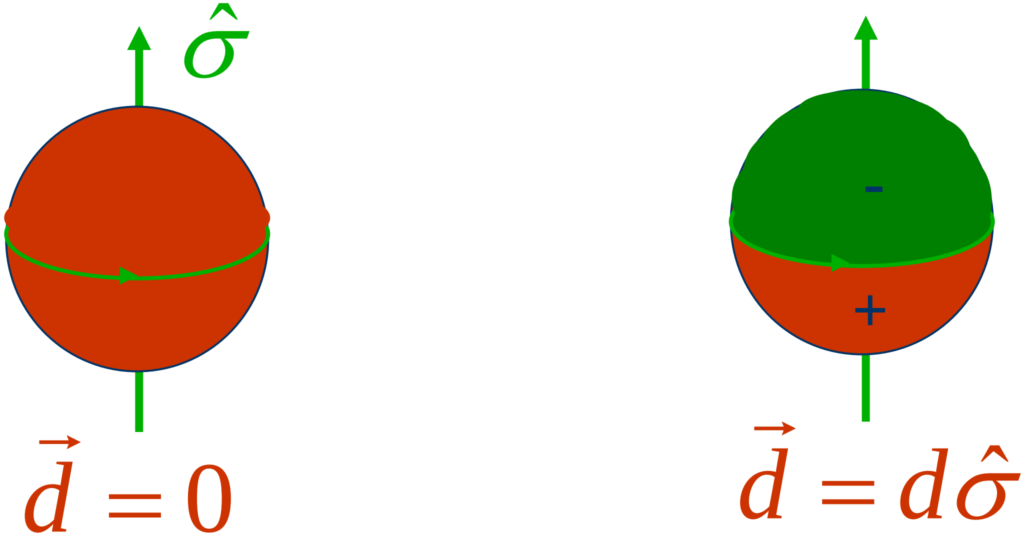



**If found it could explain Baryogenesis**

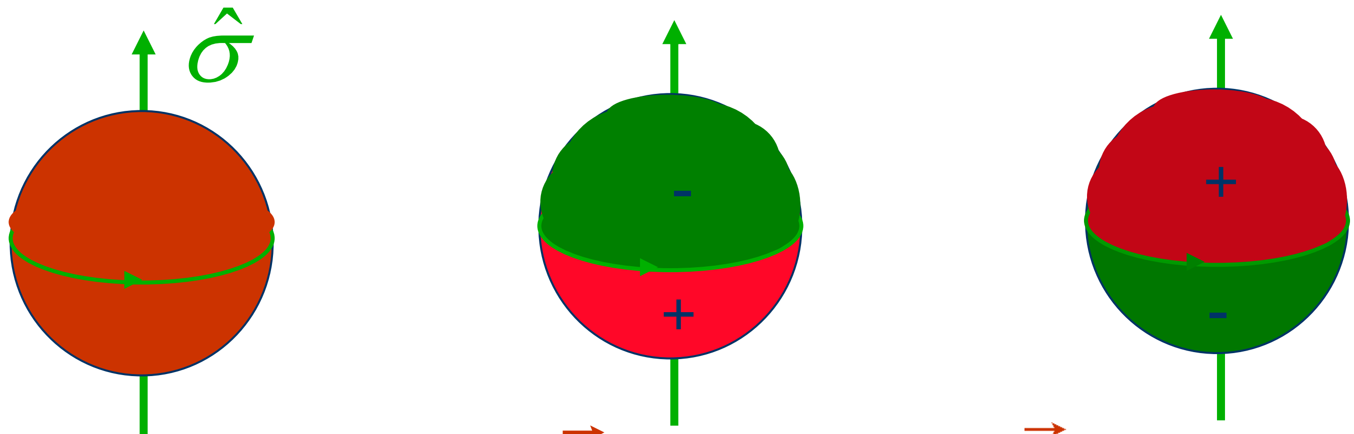
**If a pEDM is not found it can eliminate EW-Baryogenesis**

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

# Spin is the only vector defining a direction of a “fundamental” particle with spin



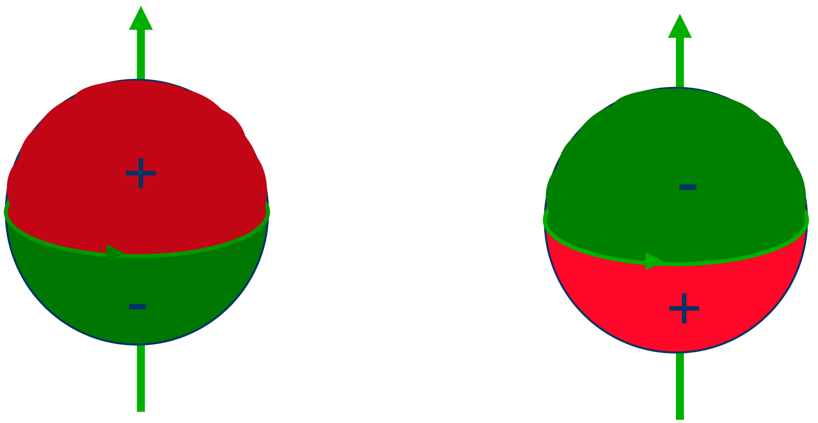
# Electric Dipole Moment: two possibilities




$$\vec{d} = 0 \qquad \vec{d} = d\hat{\sigma} \qquad \vec{d} = -d\hat{\sigma}$$

# If we discover that the proton

- Has a non-zero EDM value, i.e. prefers only one of the two possible states:




- Then P and T symmetries are violated and through CPT, CP-symmetry is also violated.
- CP-violation is one of three necessary conditions to obtain a matter dominated universe starting from a symmetric one…

# 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)

# Short History of EDM

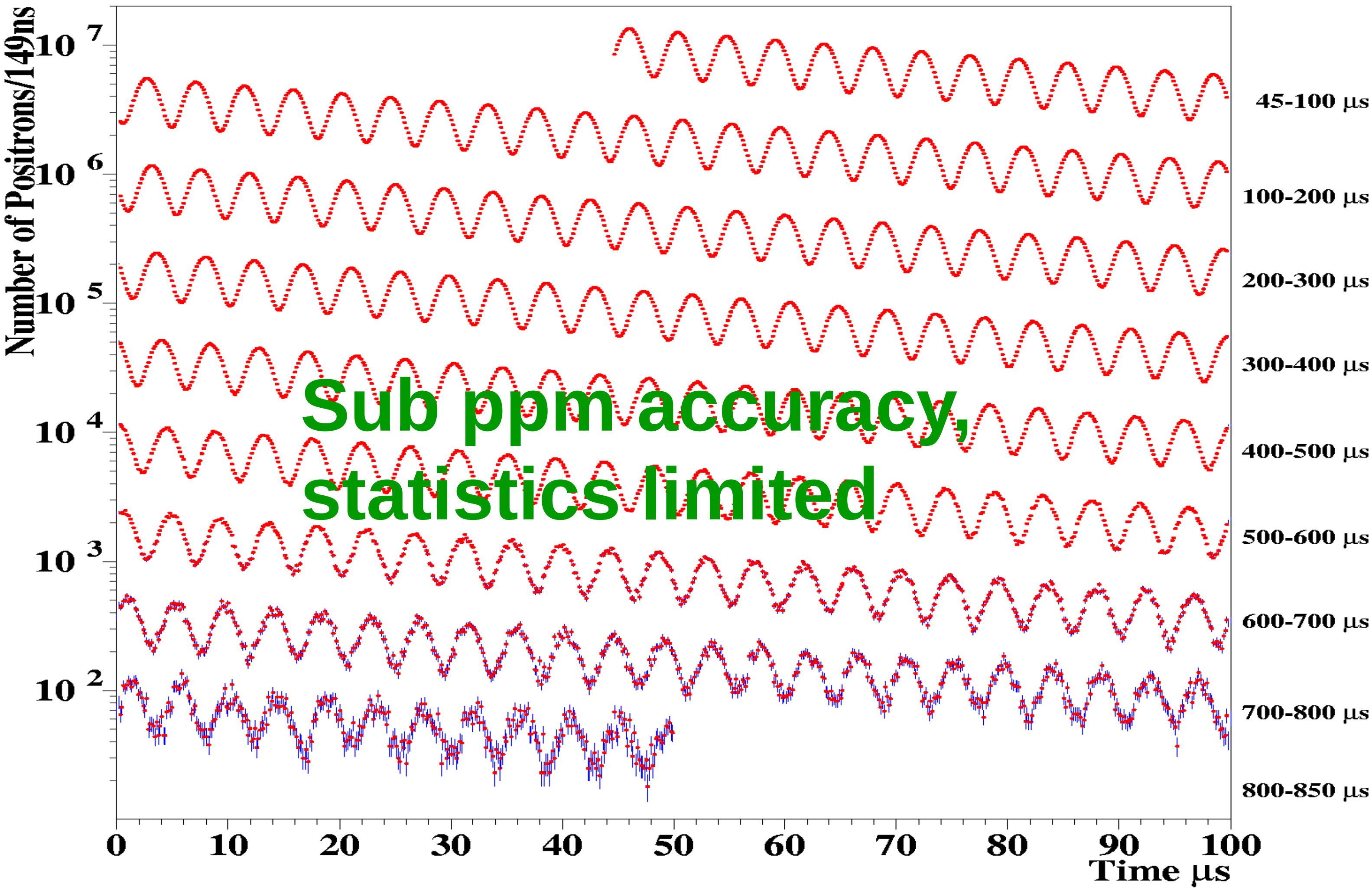
- 1950's neutron EDM experiment started to search for parity violation (Ramsey and Purcell).
- After P-violation was discovered it was realized EDMs require both P,T-violation
- 1960's EDM searches in atomic systems
- 1970's Indirect Storage Ring EDM method from the CERN muon g-2 exp.
- 1980's Theory studies on systems (molecules) w/ large enhancement factors
- 1990's First exp. attempts w/ molecules. Dedicated Storage Ring EDM method developed
- 2000's Proposal for sensitive dEDM exp. developed.

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

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

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

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




**Sub ppm accuracy, statistics limited**

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

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

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.

# Important Stages in an EDM Experiment

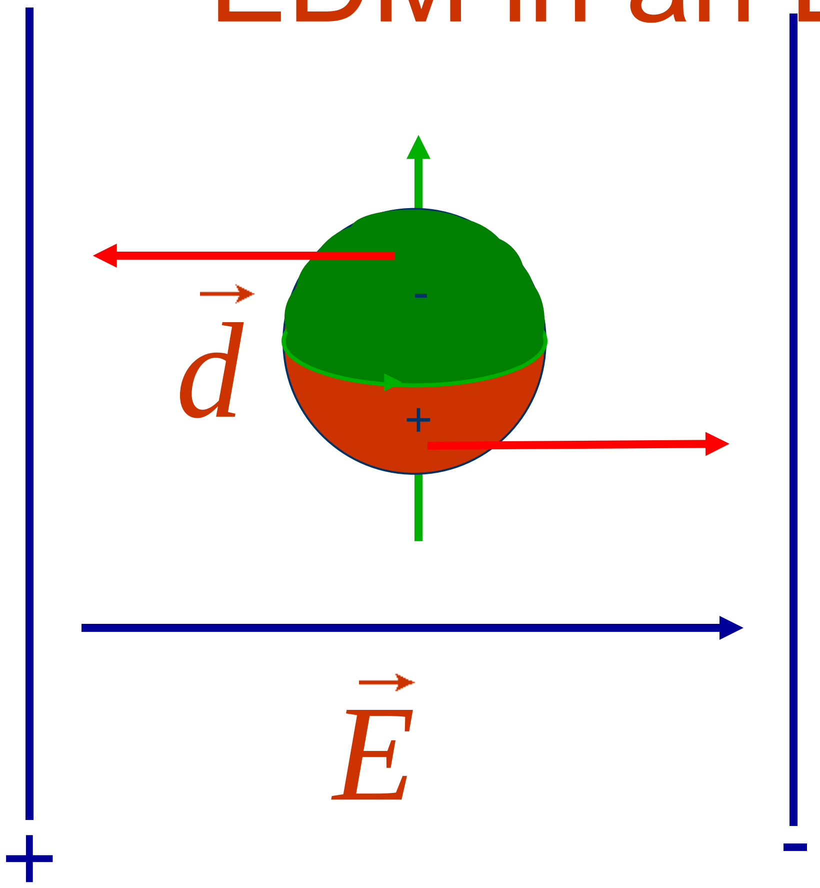
1. Polarize: state preparation, intensity of beams

2. Interact with an E-field: the higher the better

3. Analyze: high efficiency analyzer

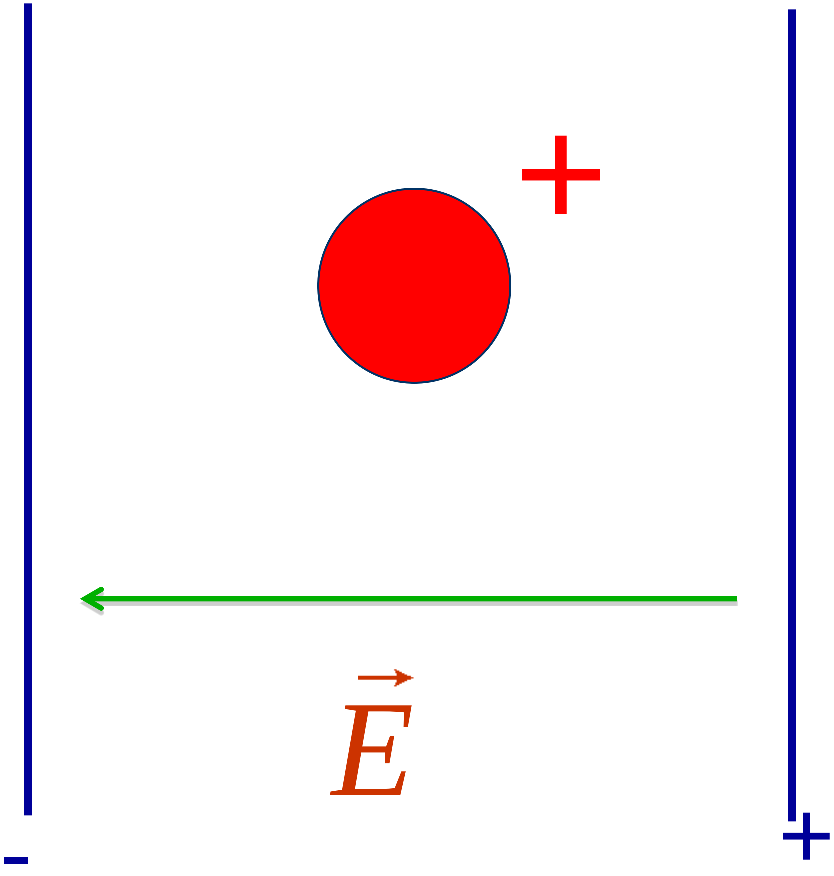
4. Scientific Interpretation of Result! Easier for the simpler systems

# EDM in an Electric Field…

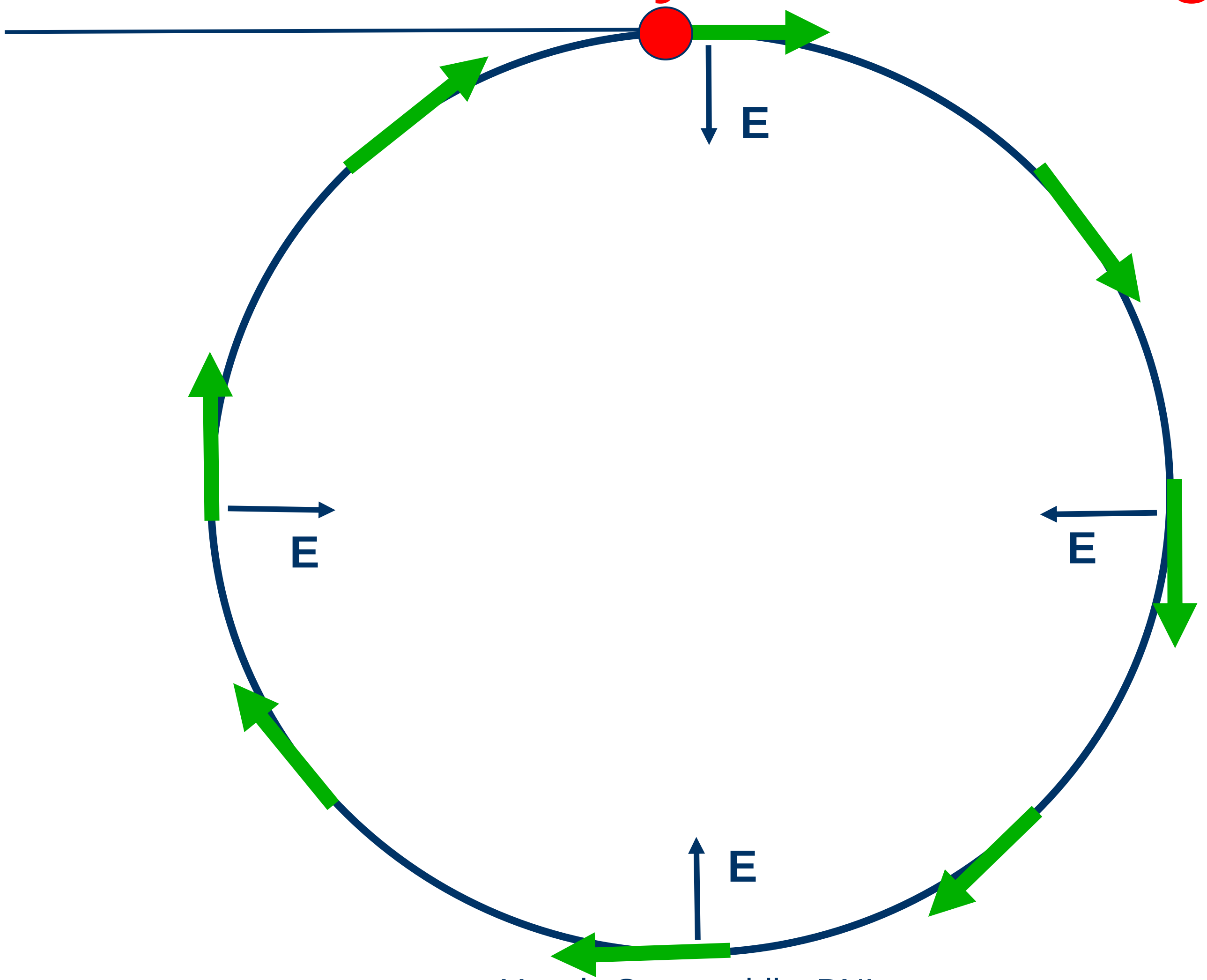



$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$

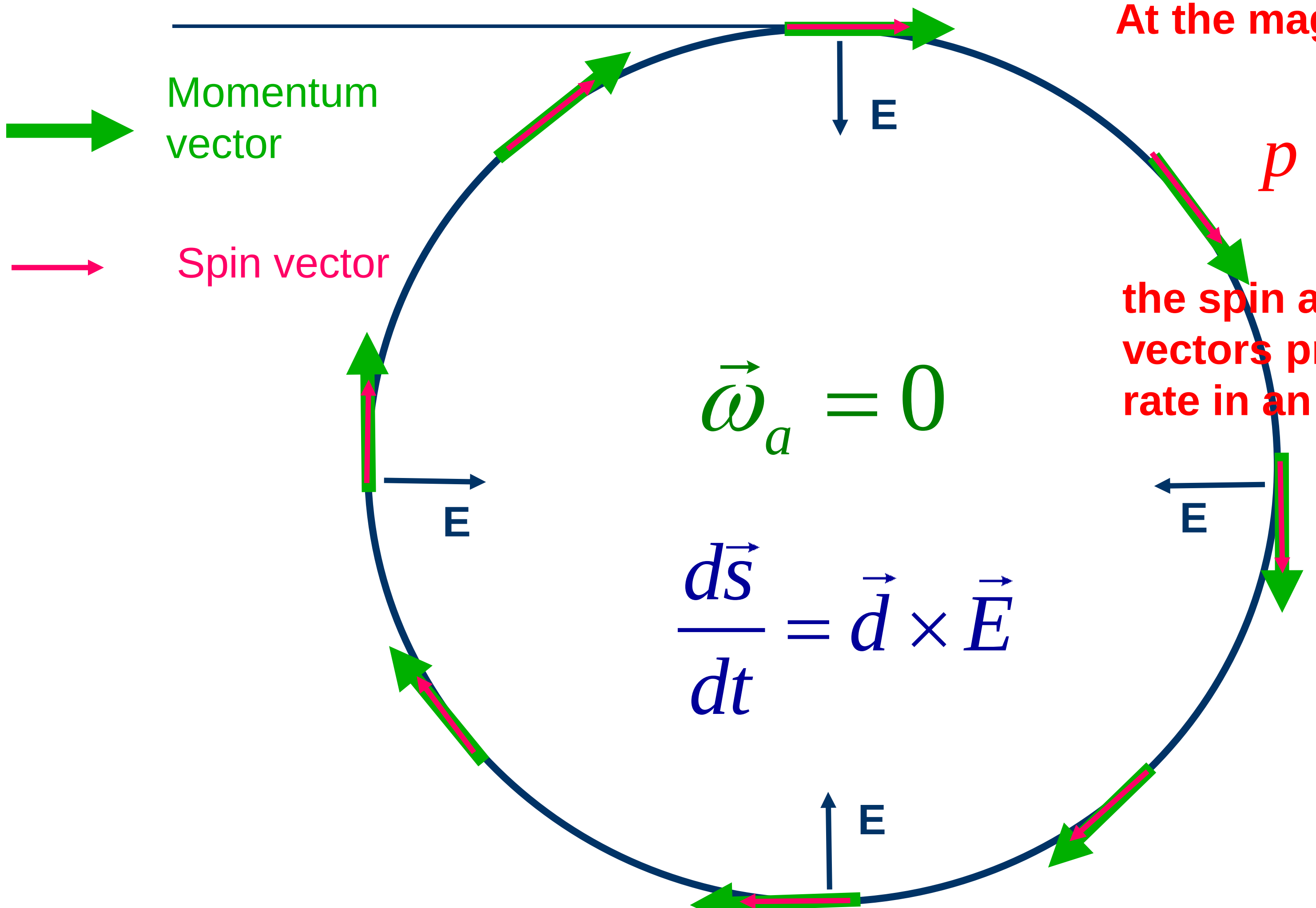
A charged particle between Electric Field plates would be lost right away…



…but can be kept in a storage ring for a long time. The force due to the radial E-field is balanced by the centrifugal force.



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




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

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

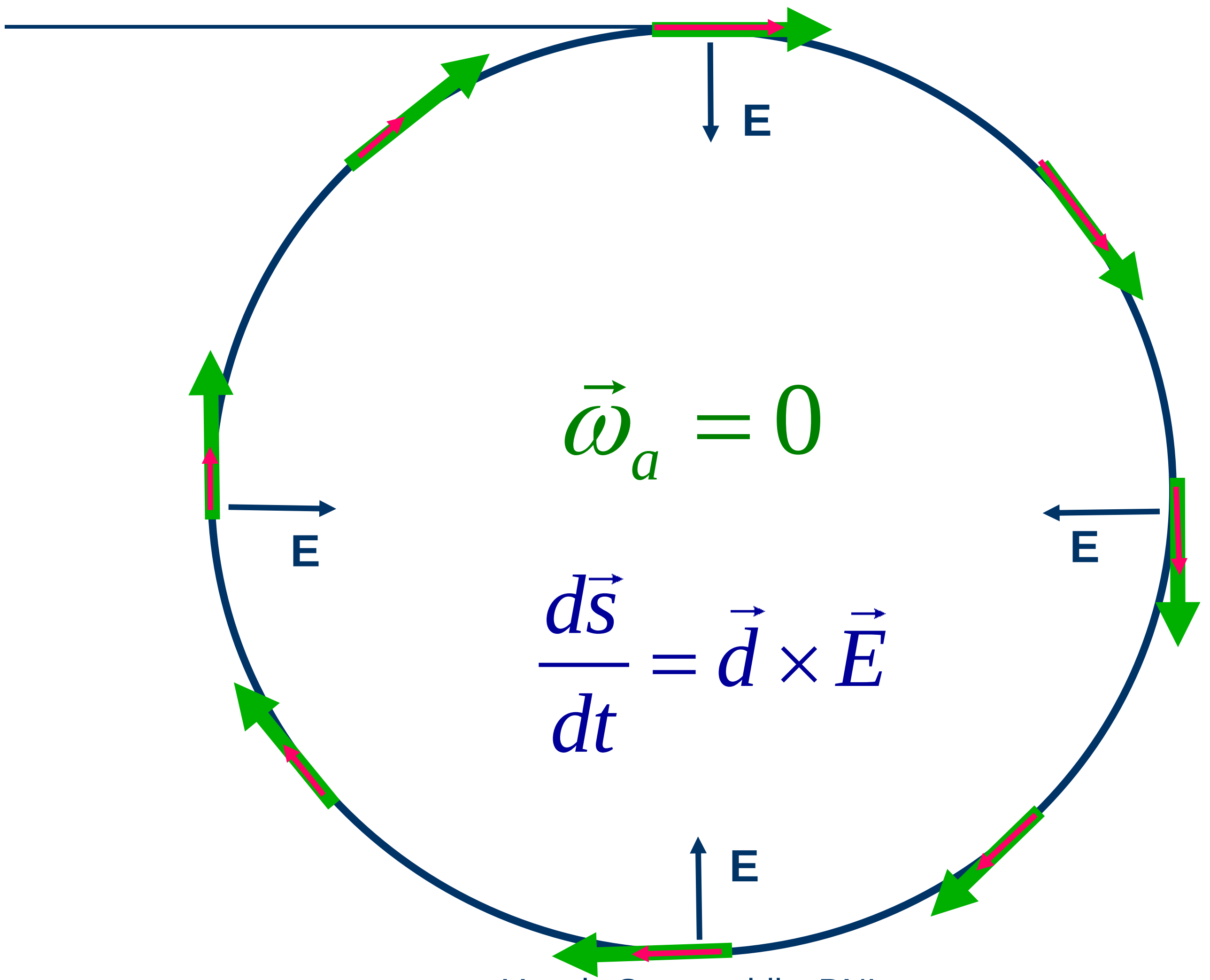
**At the magic momentum**

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

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

Yannis Semertzidis, BNL

# The spin precession relative to momentum in the plane is kept near zero. A vert. spin precession vs. time is an indication of an EDM (*d*) signal.




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

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

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

Analyzing power can be further optimized

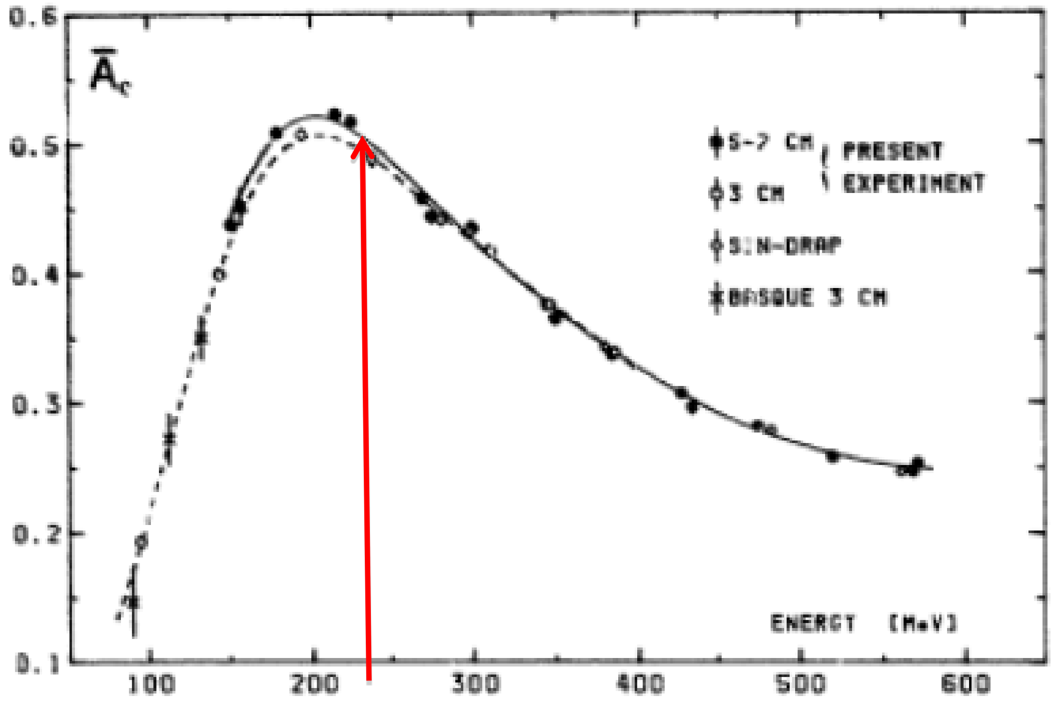
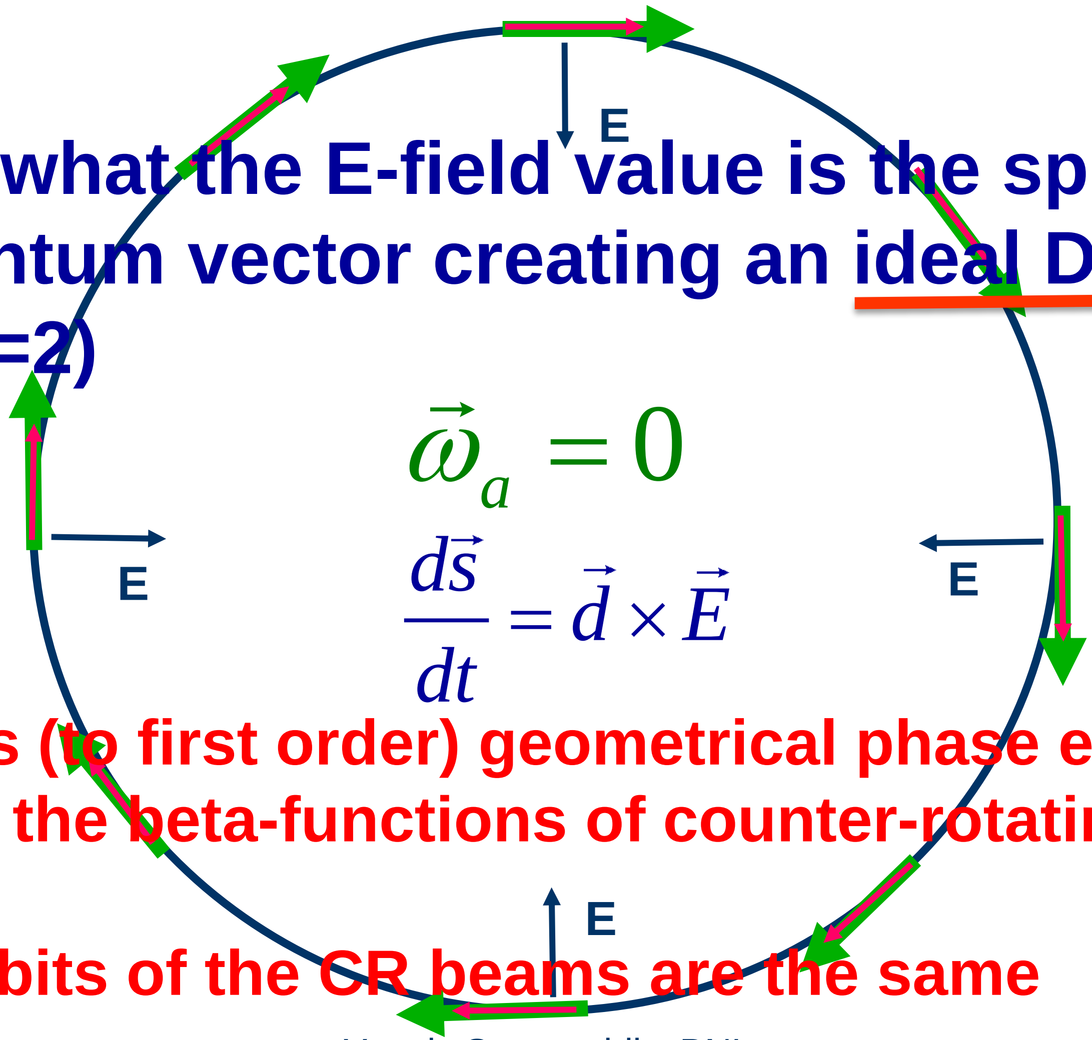



Fig. 4. Angle-averaged effective analyzing power. Curves show our fits. Points are the data included in the fits. Errors are statistical only

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.

# When $P=P_{magic}$ the spin follows the momentum

**No matter what the E-field value is the spin follows the momentum vector creating an ideal Dirac-like particle (g=2)**




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

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

1. **Eliminates (to first order) geometrical phase effect**
2. **Equalizes the beta-functions of counter-rotating (CR) beams**
3. **Closed orbits of the CR beams are the same**

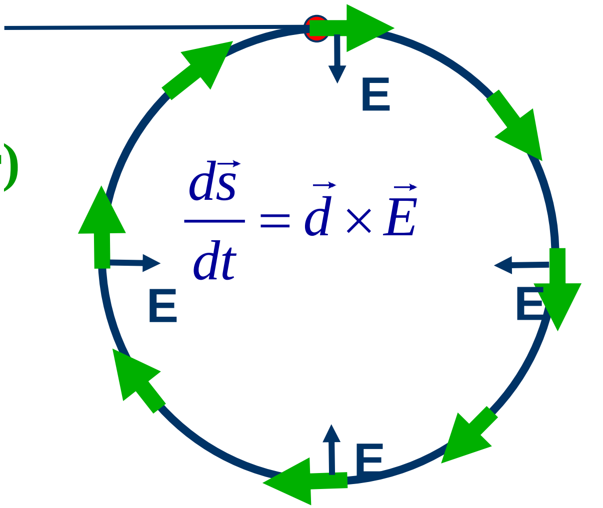
# The power of a dedicated storage ring EDM method: proton EDM

**Statistics:**

- **High intensity ($4\times10^{10}$), highly polarized beams (>80%)**
- **Keep spin along the momentum, radial E-field (10MV/m) acts on proton EDM**
- **Spin coherence time (SCT) adequate for ~$10^3$s storage**
- **High efficiency (0.5%), with large analyzing power (>50%)**

**Systematics:**

- **Magnetic field shielding + feedback to keep vertical spin <0.3mrad/storage**
- **Store counter-rotating beams + BPMs to probe $<B_r>$**
- **Longitudinal impedance: <10KΩ**
- **Forward/backward bunch polarizations (polarimeter)**

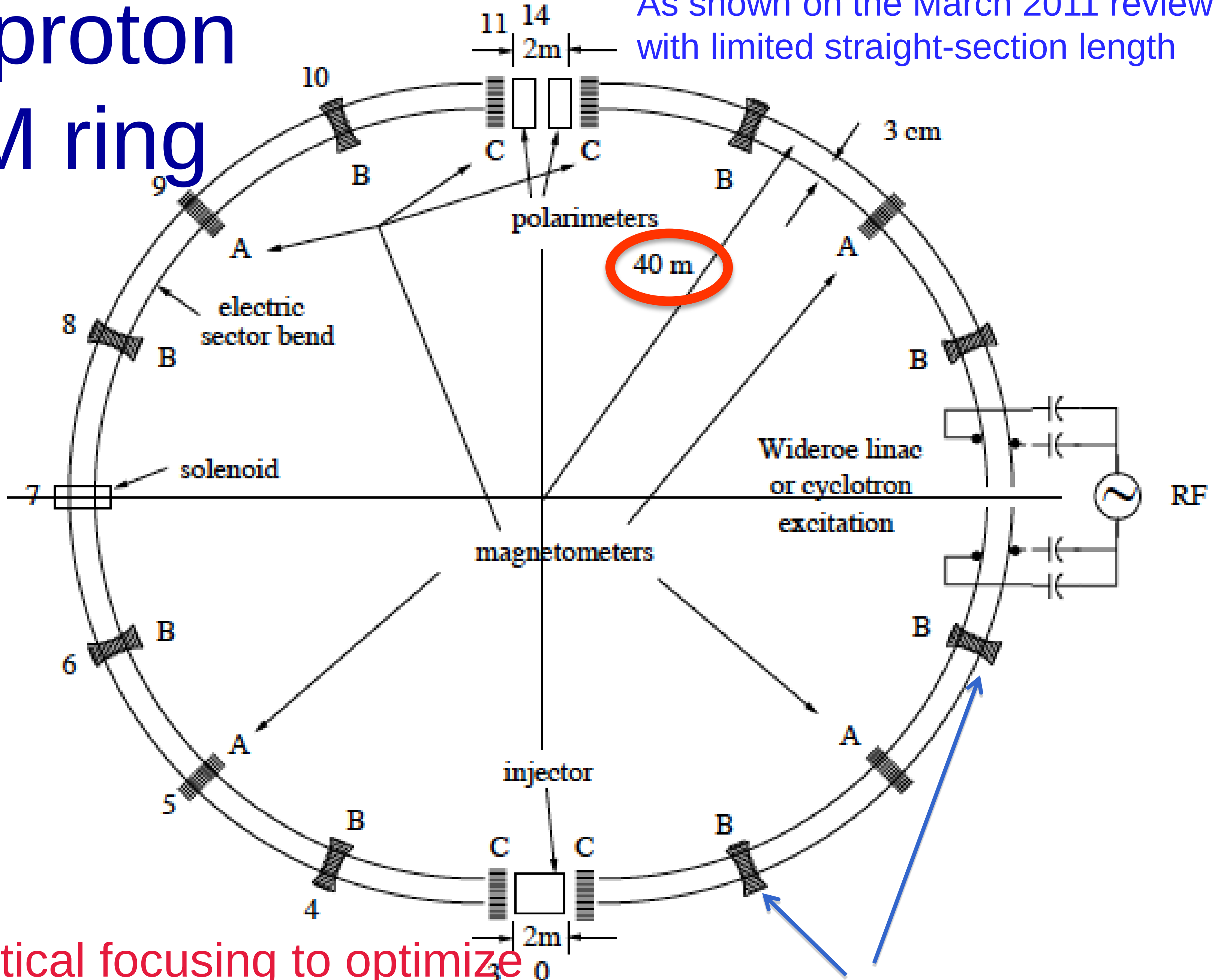



**Software development:**

- **Benchmarking at COSY with stored beams**
- **At least two different approaches, speed, accuracy…**

# 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

# Proton Statistical Error (230MeV):

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

$\tau_p$ : $10^3$s Polarization Lifetime (Spin Coherence Time)

$A$ : 0.6 Left/right asymmetry observed by the polarimeter

$P$ : 0.8 Beam polarization

$N_c$ : $4\times10^{10}$p/cycle Total number of stored particles per cycle

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

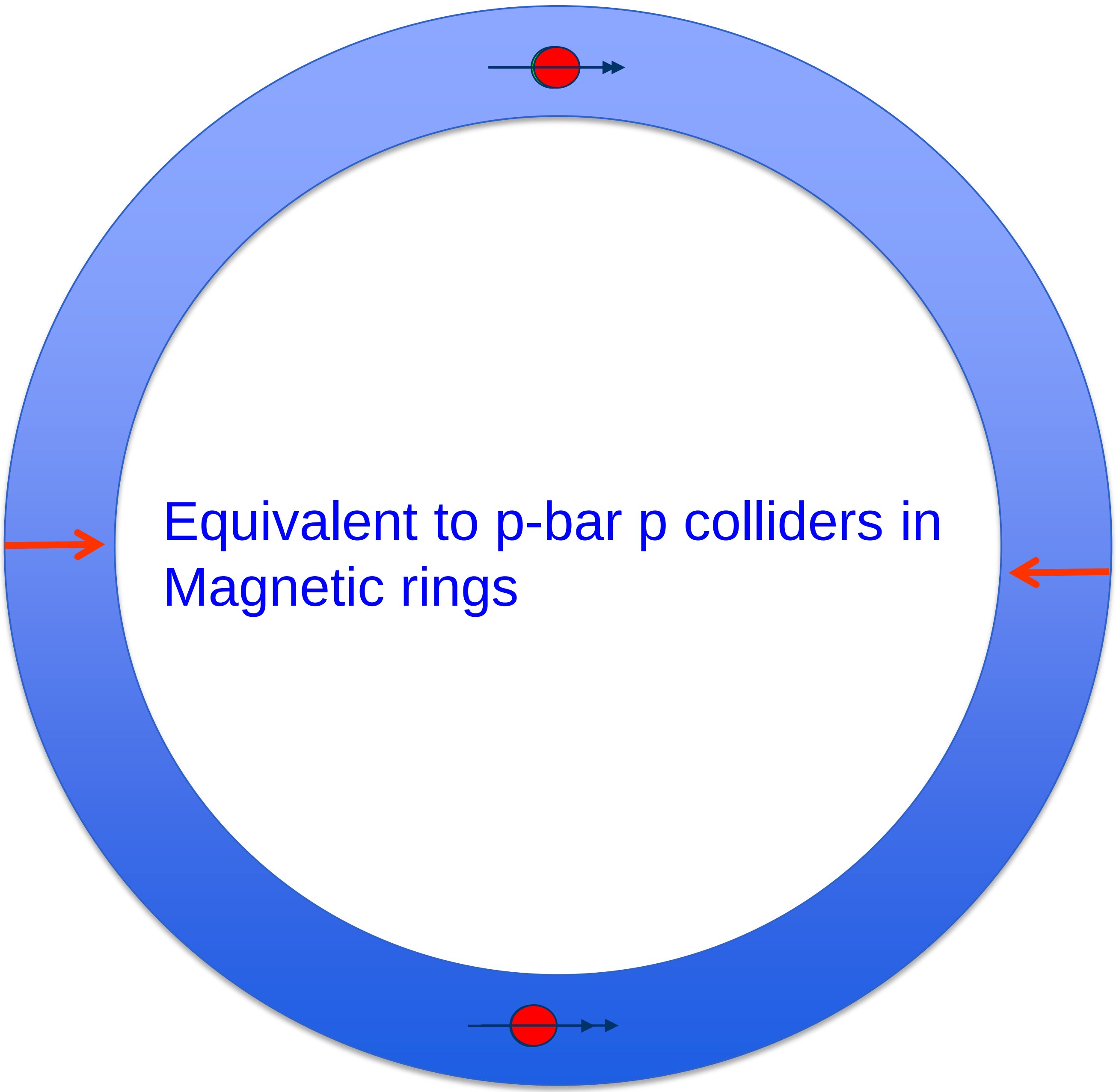
$f$ : 0.5% Useful event rate fraction (efficiency for EDM)

$E_R$ : 10.5 MV/m Radial electric field strength (95% azim. cov.)

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

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

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



# 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): horizontal depolarization due to spread in g-2 frequencies; Software development for an all-electric ring: SCT and systematic error studies
4. Electric field development for large surface area plates

# Main systematic error

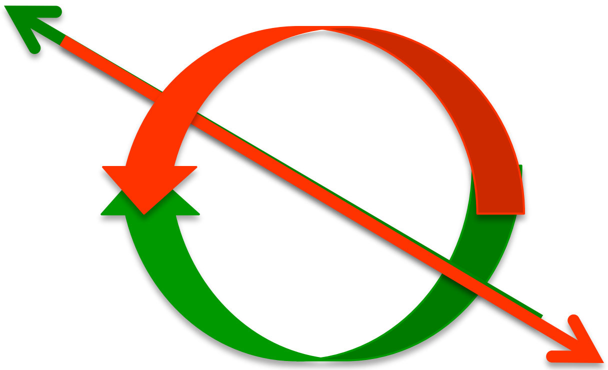
- A net radial magnetic field integrated around the ring.
- Ambient noise: nT/√Hz at 0.01-1 Hz → 10pT/√Hz at 100 Hz. We plan a shielding factor (passive plus active) of $>10^8$.

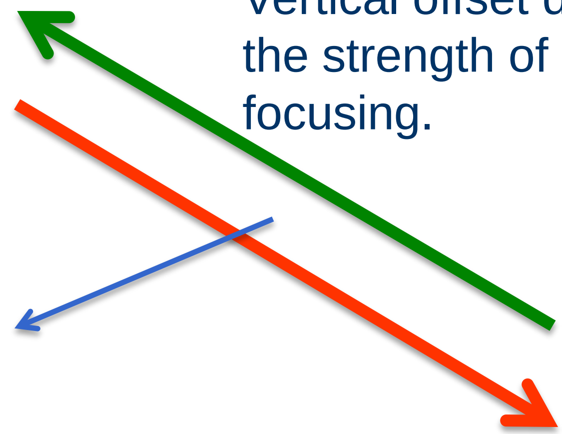
- We plan to use the beams to tell us what radial B-fields they “see”.

# Oscillating B-field background

- Let's say there is a 10mG oscillating B-field at 10Hz (averaged over the ring).
- Dynamic shielding (currents), assume $10^1$ reduction → 1mG
- Passive shielding of $10^5$, reduces it to 10nG.
- Another reduction factor from oscillations: 10Hz/0.001Hz = $10^4$, reduces it to 1pG
- $10^4$ injections (not in phase): reduction of $10^2$ → 0.01pG, i.e. negligible.

# B-field from (same sign) CR beams





Vertical offset depends on the strength of the vertical focusing.

- A single beam creates ~20nT *vertical* B-field, 2cm (radially) away. For $\delta y$~10nm relative vertical offset we get ~10fT *horizontal* B-field.
- Modulate the vertical focusing (tune) by ~10%
- Commercially available SQUIDS reach ~1fT/√Hz at >$10^2$ Hz

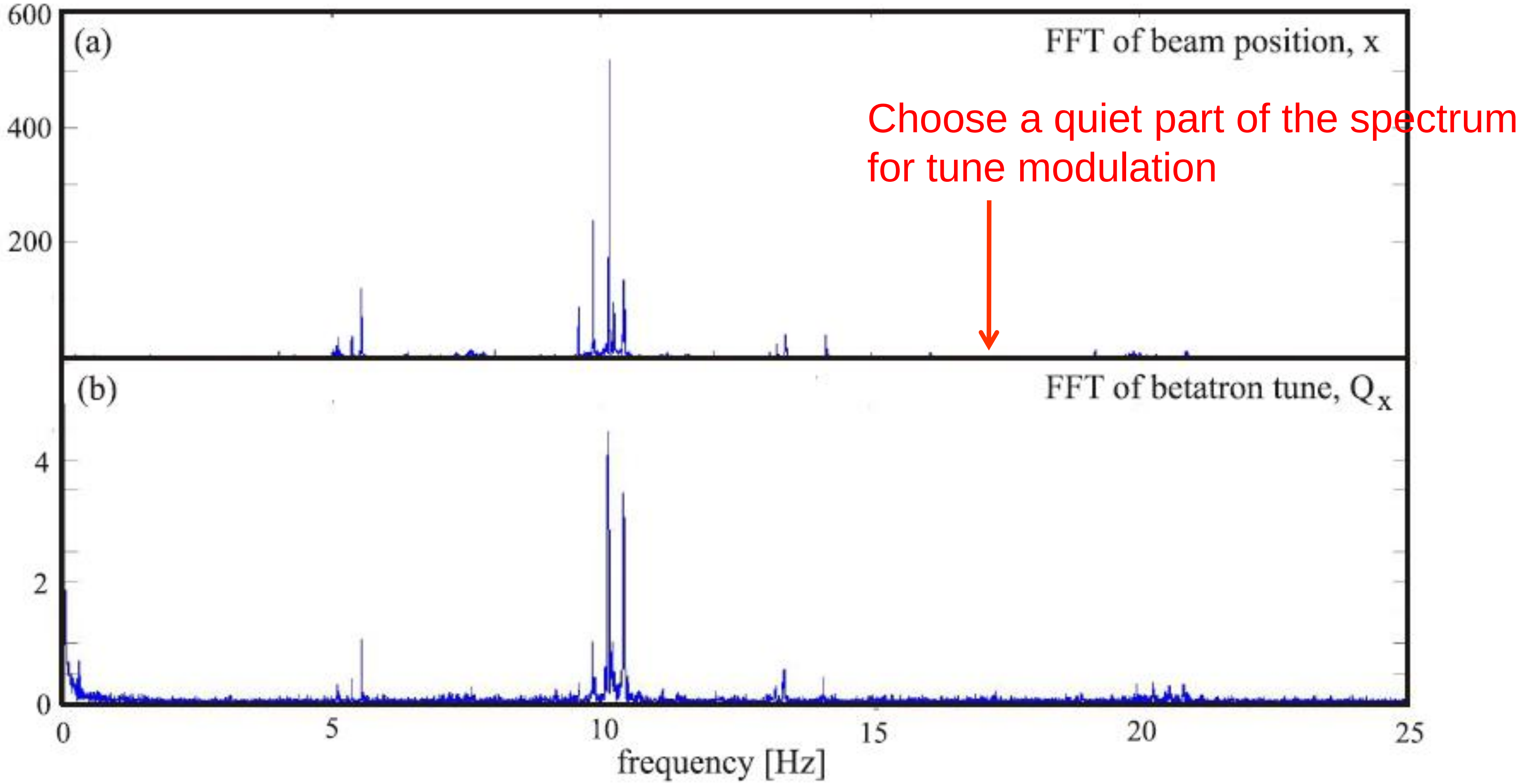
# B-field from (same sign) CR beams

- Dynamic range is not an issue.
- Need to demonstrate in an accelerator environment
- Two years R&D, $0.6M

# Advantages of SQUID magnetometers for (same sign) counter-rotating beams

- Non-destructive
- Large dynamic range:
- Counter-rotating beams cancel B-fields to first order
- Only a *relative* vertical offset creates a horizontal B-field.
- By modulating the vertical tune we modulate the vertical separation and hence the horizontal B-field as well ($10^2$-$10^4$Hz).

# Fourier transforms of the horizontal beam position and betatron tune as measured in the blue ring (RHIC)



**Designed by D. Kawall, UMASS, based on existing technology, optimized for the storage ring**

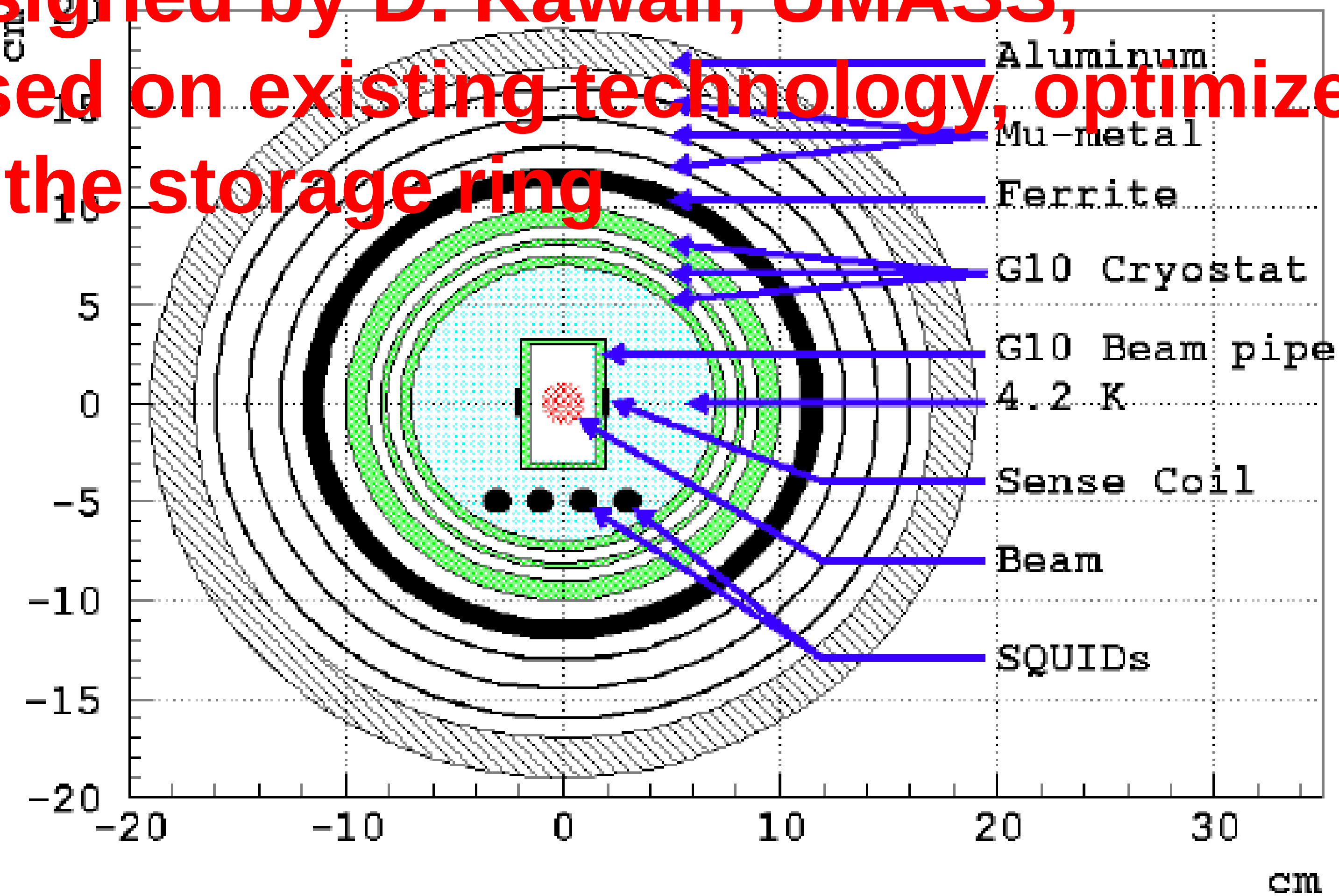



Figure 1: Schematic of a possible SQUID BPM station. The beams are in the innermost G10 beam pipe, which also includes a very thin grounded conductor to attenuate high (MHz) frequency fields. The horizontal $B$ field is picked up by the sense coils which are attached by shielded superconducting wire (not shown) to the SQUIDs, which are shielded with a superconducting foil. The system is carefully shielded by a room temperature low-noise ferrite shield and several layers of $\mu$-metal.

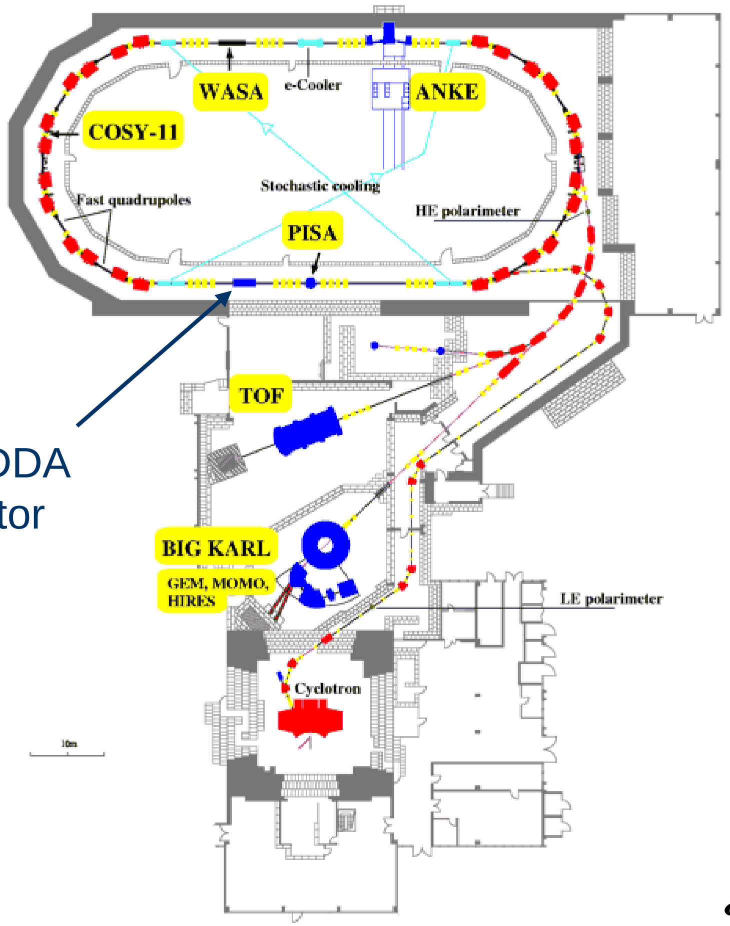
# 1. Beam Position Monitors

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

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

# Polarimeter Development
## COSY in Jülich/Germany tests

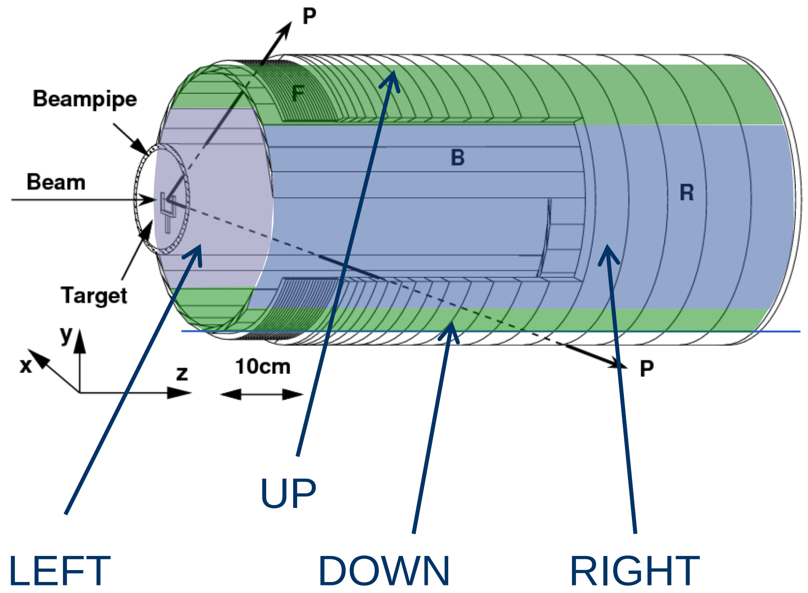
COSY ring:




Use EDDA detector

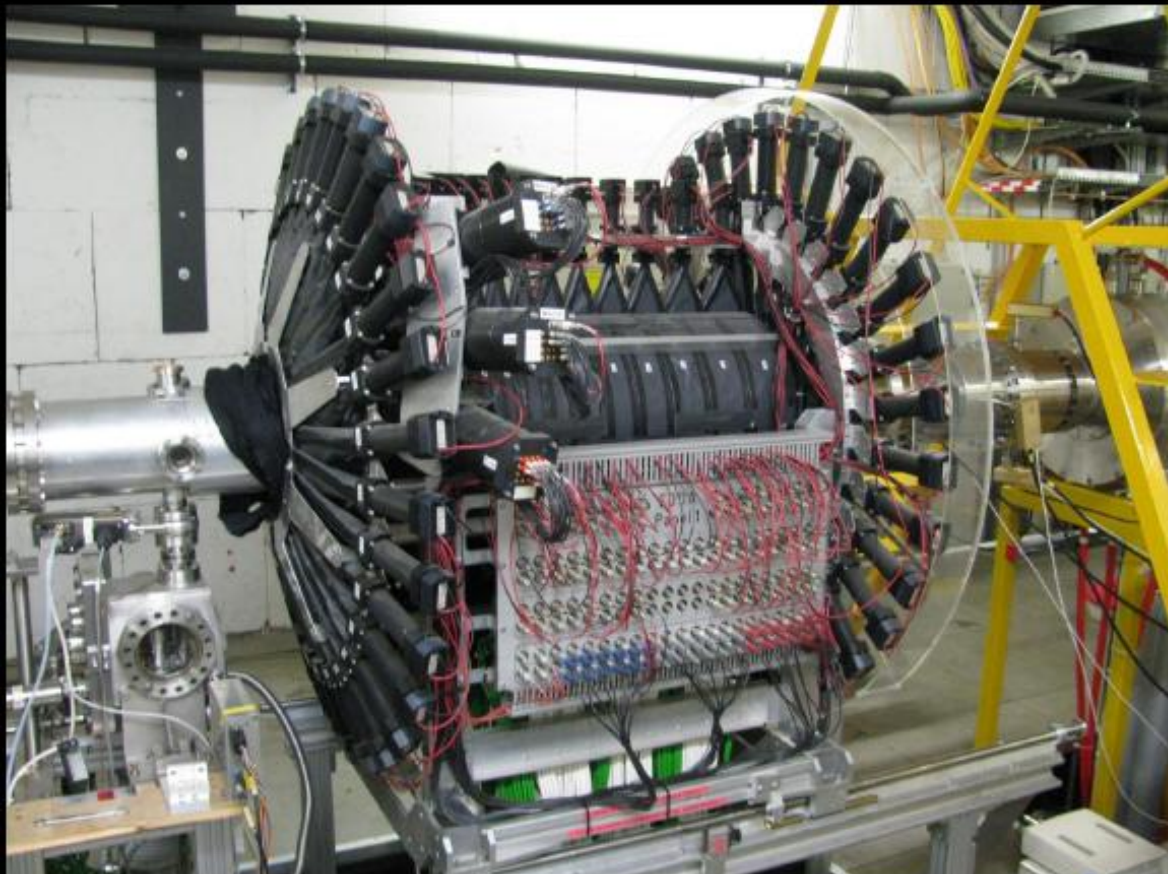
EDDA detector:

Rings and bars to determine angles.




Azimuthal angles yield two asymmetries:

$$\varepsilon_{EDM} = \frac{L-R}{L+R} \qquad \varepsilon_{g-2} = \frac{D-U}{D+U}$$

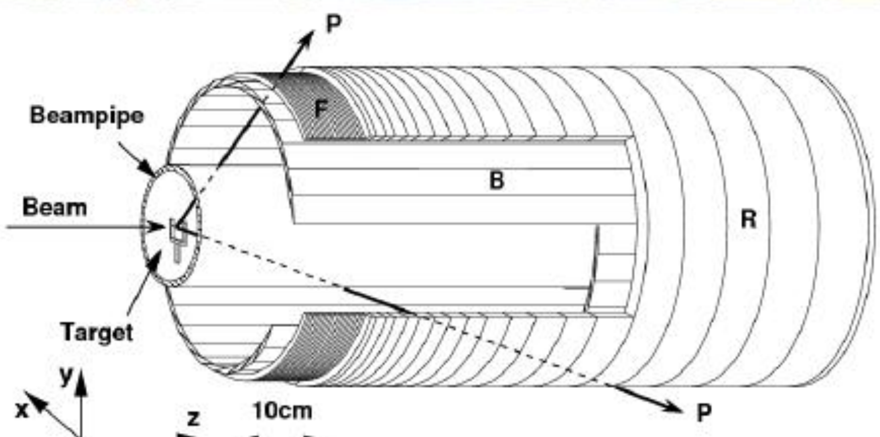


EDDA detector

32 bars measure azimuthal angle

rings measure scattering angle

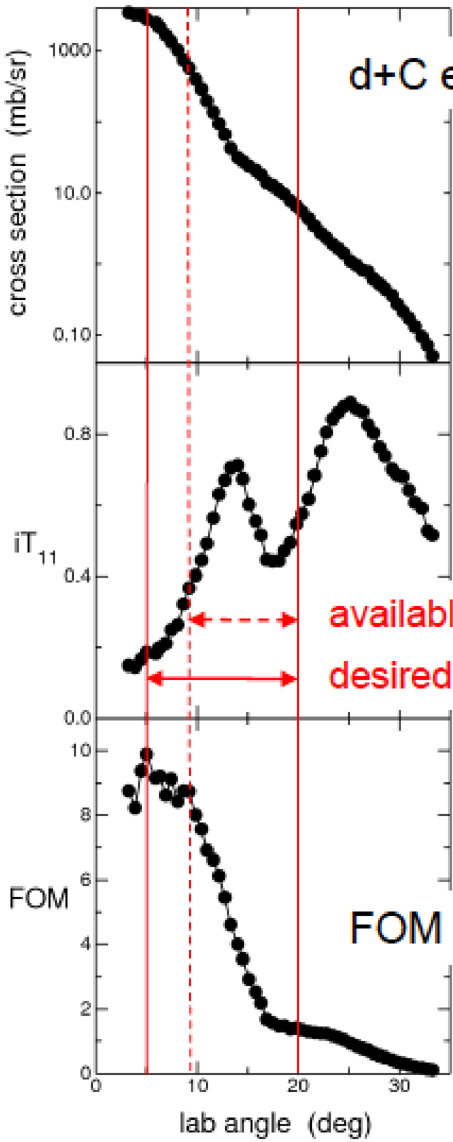
Operate as stopping detector for deuterons, sets beam momentum to be p = 0.97 GeV/c




Thick carbon target used for continuous extraction and high efficiency

## Deuteron case

Y. Satou, PL B 549, 307 (2002)




d+C elastic, 270 MeV

available at COSY

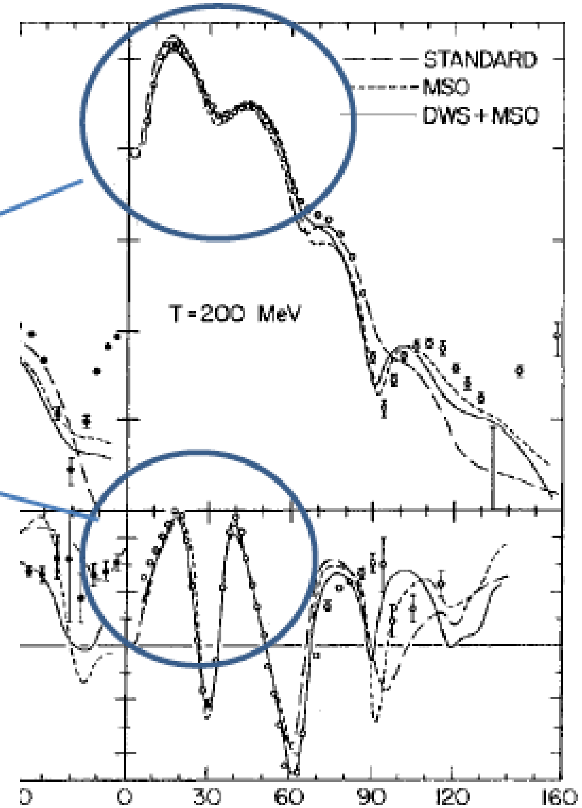
desired range

FOM = $\sigma A^2$

## Proton case

Similarity to deuteron case means results apply to both.

Near 230 MeV the forward cross section and analyzing power are favorable.




We can expect:

efficiency ~ 1.1 % (over $2\pi$)

analyzing power ~ 0.6

with some selection on elastics

# 2. Polarimeter Development

- Polarimeter tests with runs at COSY (Germany) demonstrated << 1ppm level systematic errors: N. Brantjes et al., NIM A664, 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 (under evaluation as an 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

- First tests at COSY (January 2011) are very encouraging.

- Bonus: Electric ring with weak vertical focusing SCT is long enough for $10^3$s storage

# Beam/spin dynamics simulations (precise 2nd order description)

Describe beam/spin dynamics in electric rings

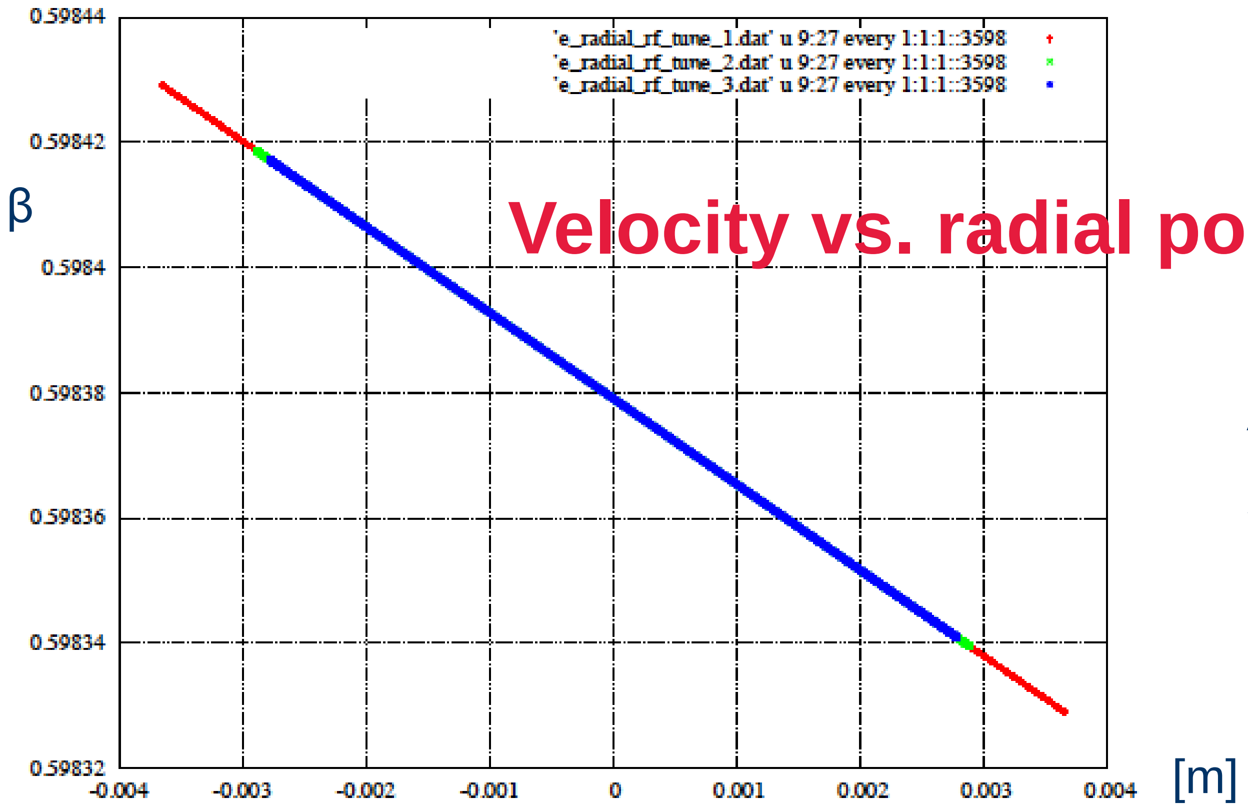
1. Slow and accurate using 4th order Runge-Kutta integration. At production stage. Shown to be accurate to sub-ppb (muon g-2).

2. Fast and accurate ETEAPOT (R. Talman et al.): Advanced stage.

3. Accurate description of COSY ring (magnetic)

# Electric ring software development

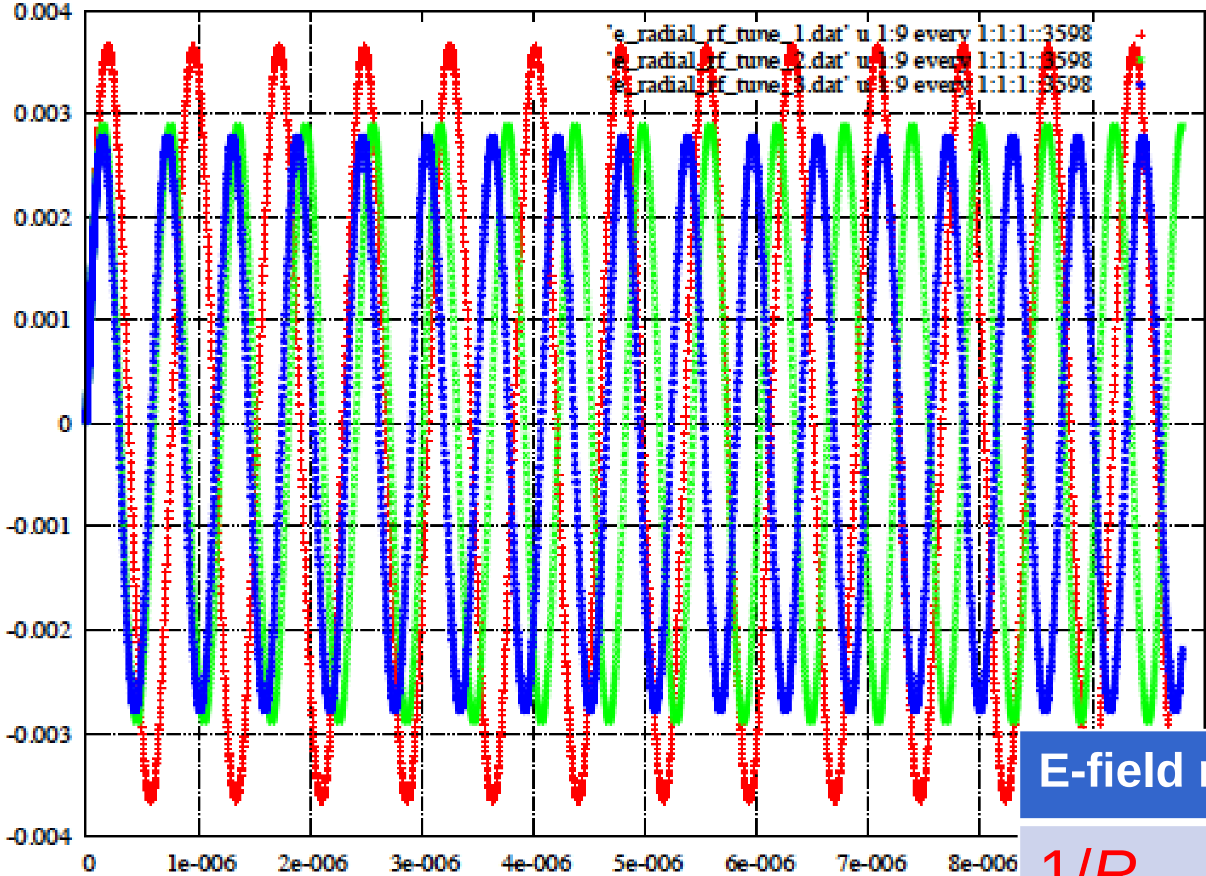
E-field complication: Kinetic energy changes with radial oscillations → additional horizontal focusing




Analytical work by
S. Mane,
Y. Orlov,
R. Talman,
M. Conte,
etc.

# Software development

- 4th order R.K. integrator (accurate and slow)




**Radial motion [m] vs. time [s]**

Three different E-field radial dependences:
1/*R*
Constant
$R^{0.2}$

Consistent with analytical estimations:

| E-field radial dep. | Horizontal tune |
|---|---|
| 1/*R* | 1.275 |
| Constant | 1.625 |
| $R^{0.2}$ | 1.680 |

# 4. Electric Field Development

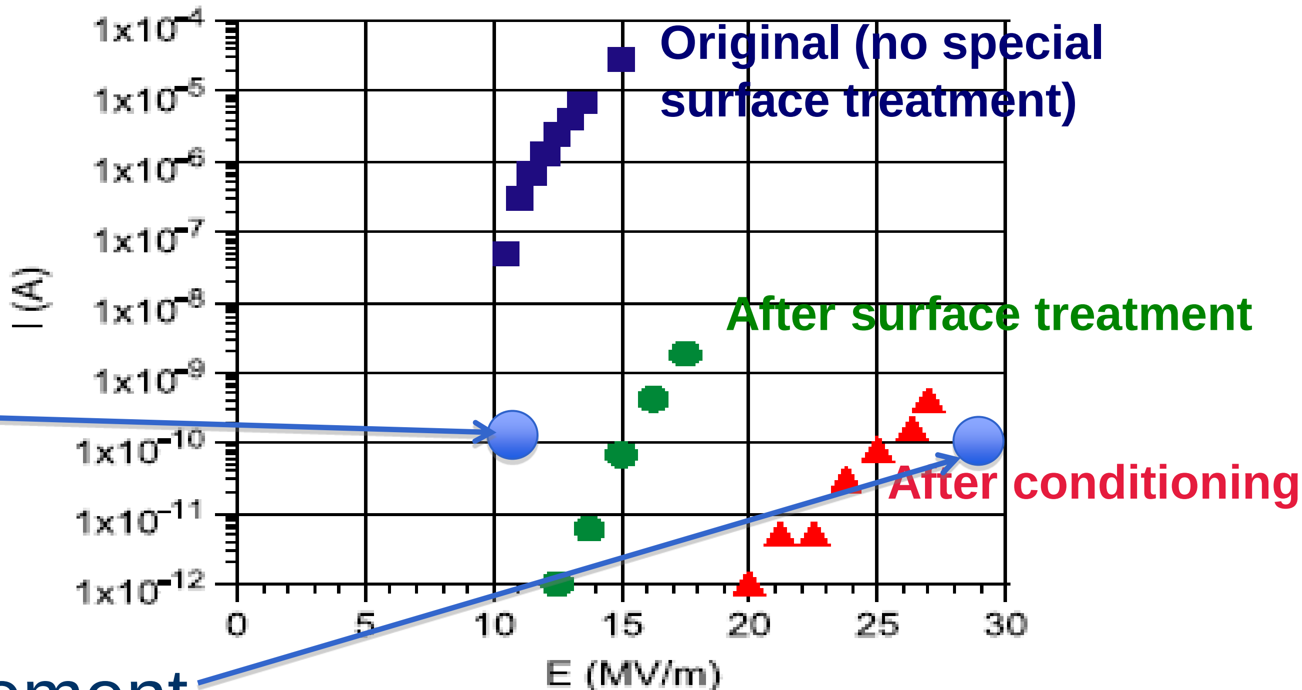
- Reproduce Cornell/JLAB results with stainless steel plates treated with high pressure water rinsing (part of ILC/ERL development work)
- Determine:

1. E-field vs. plate distance
2. Develop spark recovery method

- Develop and test a large area E-field prototype plate module (Cornell Univ. just got involved)

# Recent Progress from ILC/ERL R&D (~4.5mm gap tests) Cornell/JLab

Our goal
(3cm plate separation)



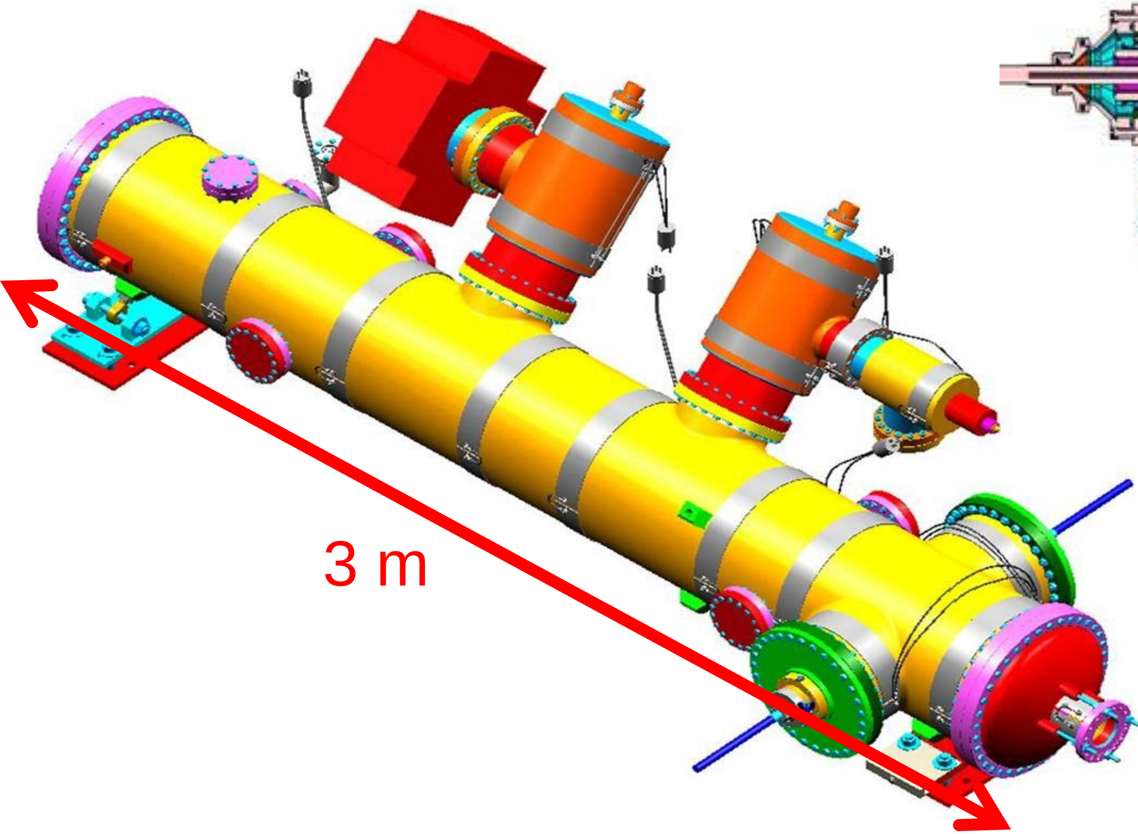

Our achievement
(4mm plate separation)

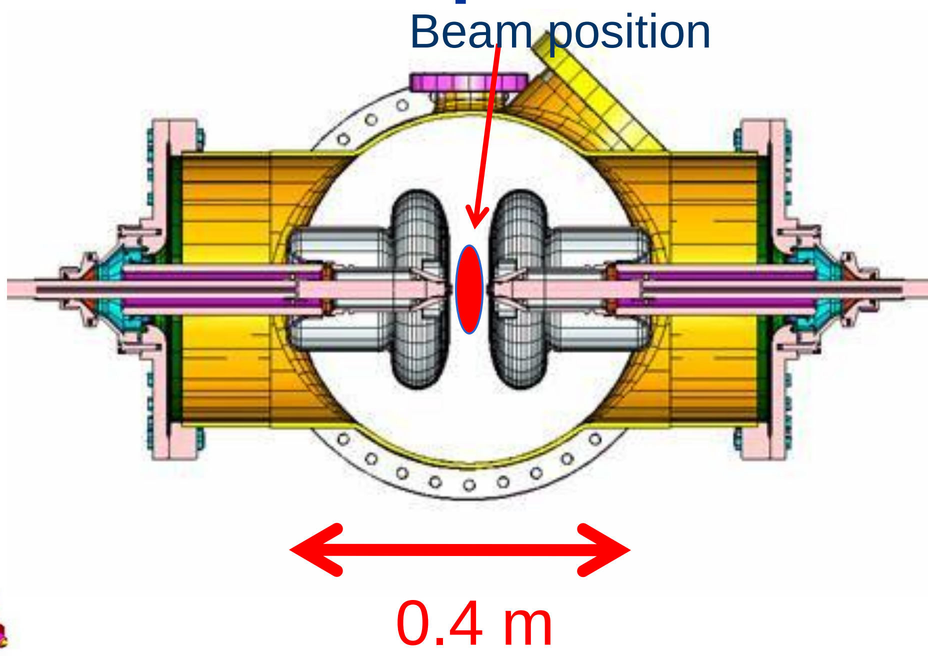
Fig. 4. Field emission current as a function of applied gradient for a 150-mm-diameter stainless steel electrodes: (squares) a typical untreated sample, (circles) first measurement of GCIB treated sample, (triangles) re-measurement of GCIB treated sample after high-voltage conditioning [14].

# 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 | 84 |
| Max. HV | ±180KV | ±200KV | ±150KV |

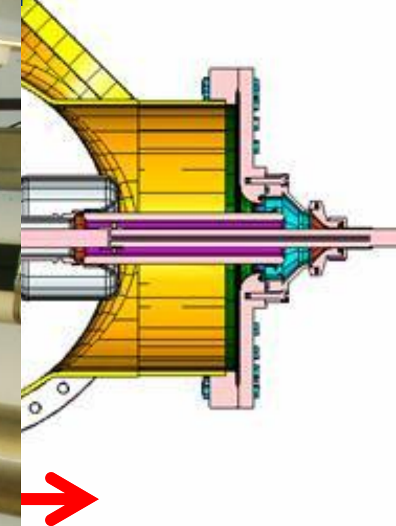
# E-field plate module: Similar to the (26) FNAL Tevatron ES-separators



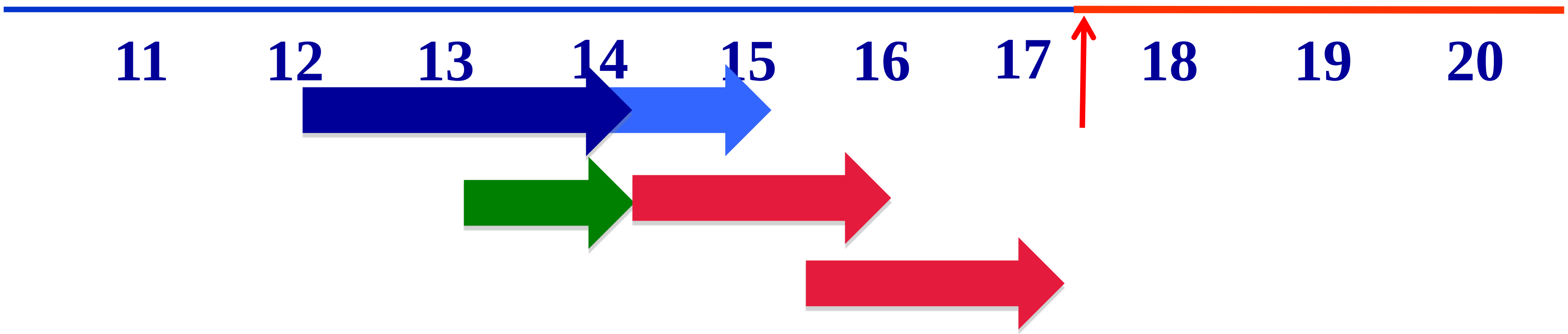



# E-field plate module: Similar to the (26) FNAL Tevatron ES-separators

position



# Technically driven pEDM timeline

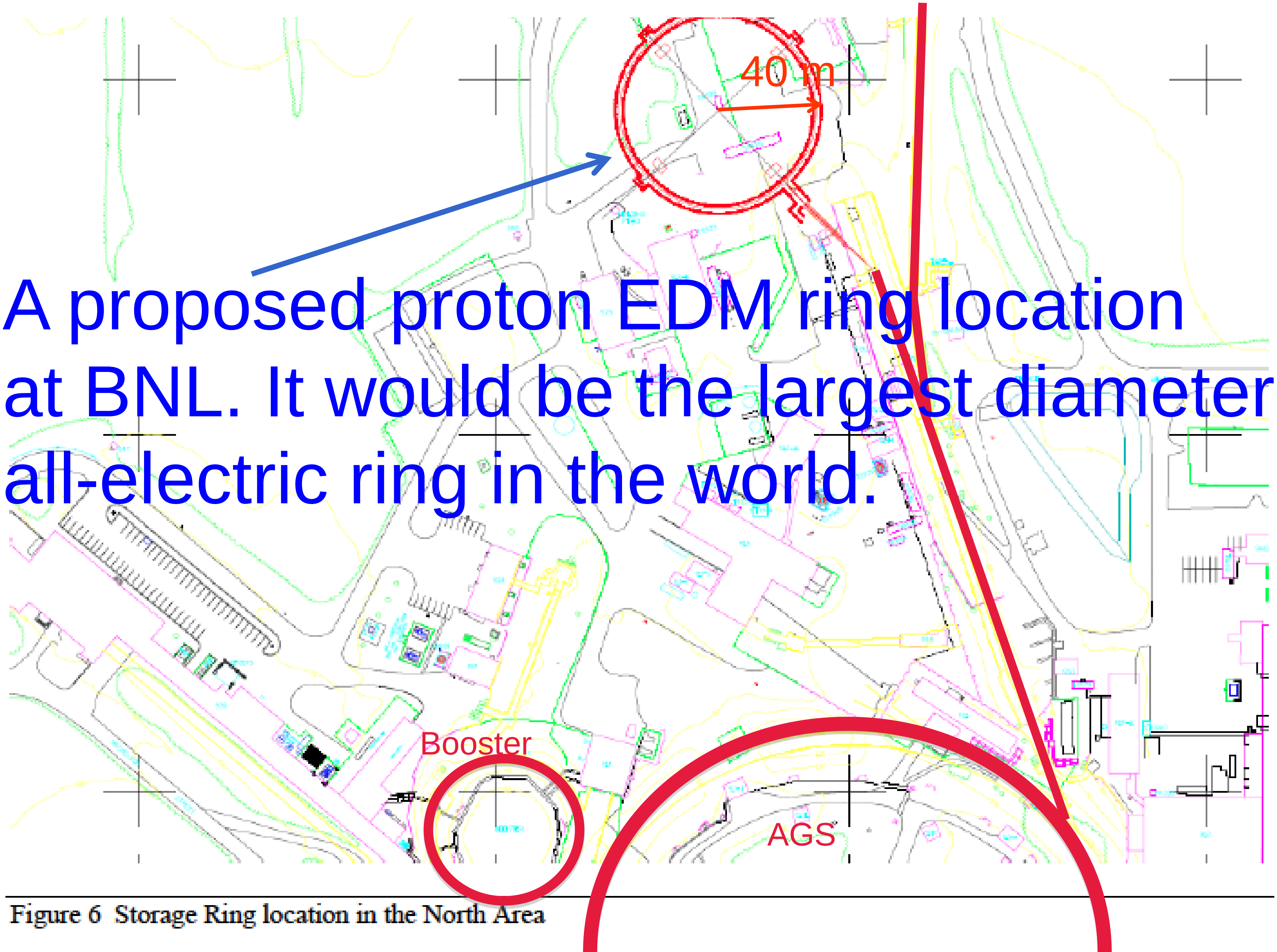



- Two years R&D
- One year final ring design
- Two years ring/beam-line construction
- Two years installation
- One year "string test"

# The bottom line

- The proton EDM in its magic momentum proposal is at an advanced stage: ready for prime time
- Two technical reviews (Dec 2009 and March 2011) were very successful encouraging the collaboration to proceed to the proposal stage

- BPM magnetometer concept is based on proven techniques. We plan to prove it in a storage ring environment.
- Other issues are low/medium risk




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

- 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

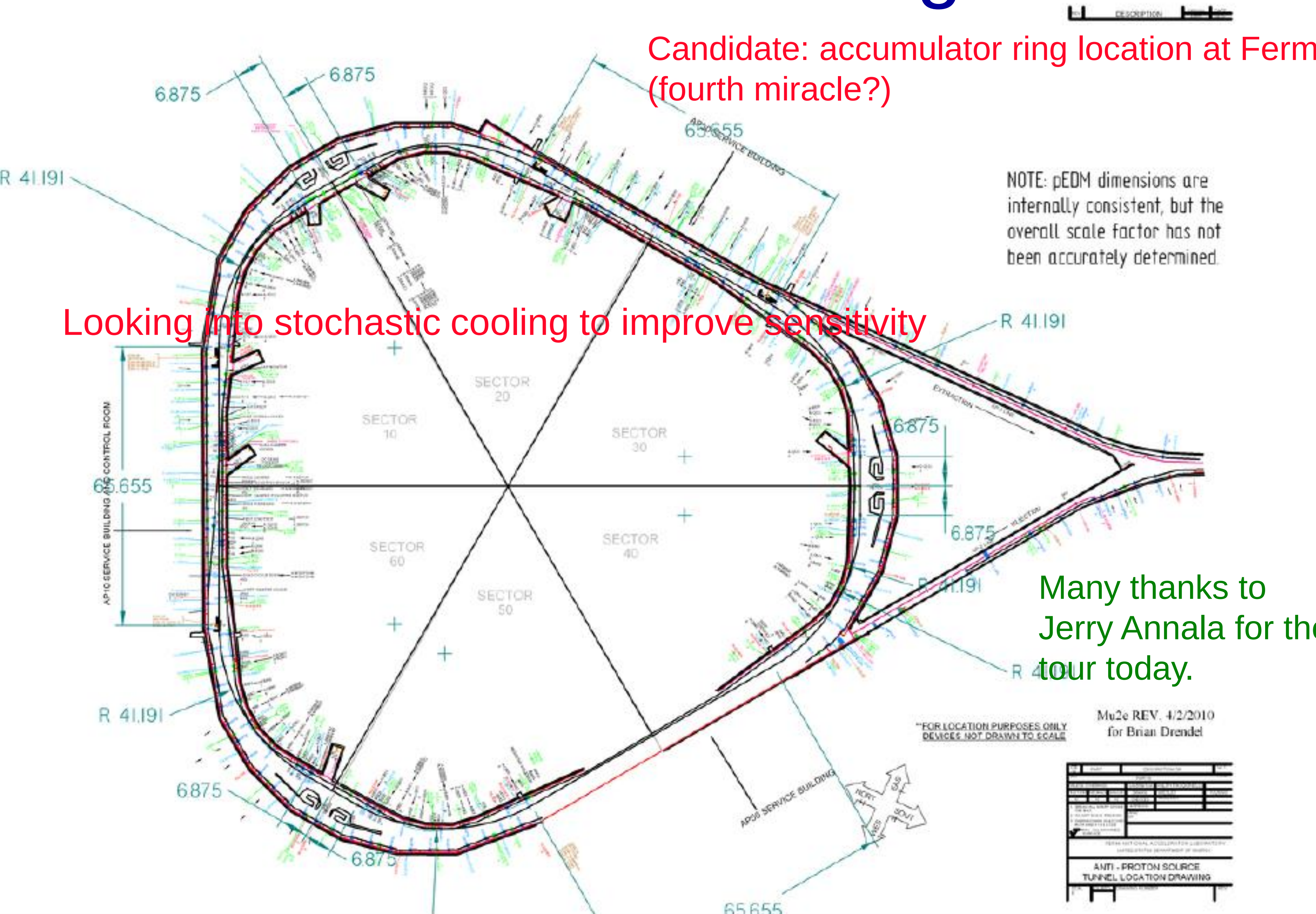
http://www.bnl.gov/edm

# Could it fit in an existing tunnel?

Candidate: accumulator ring location at Fermi (fourth miracle?)

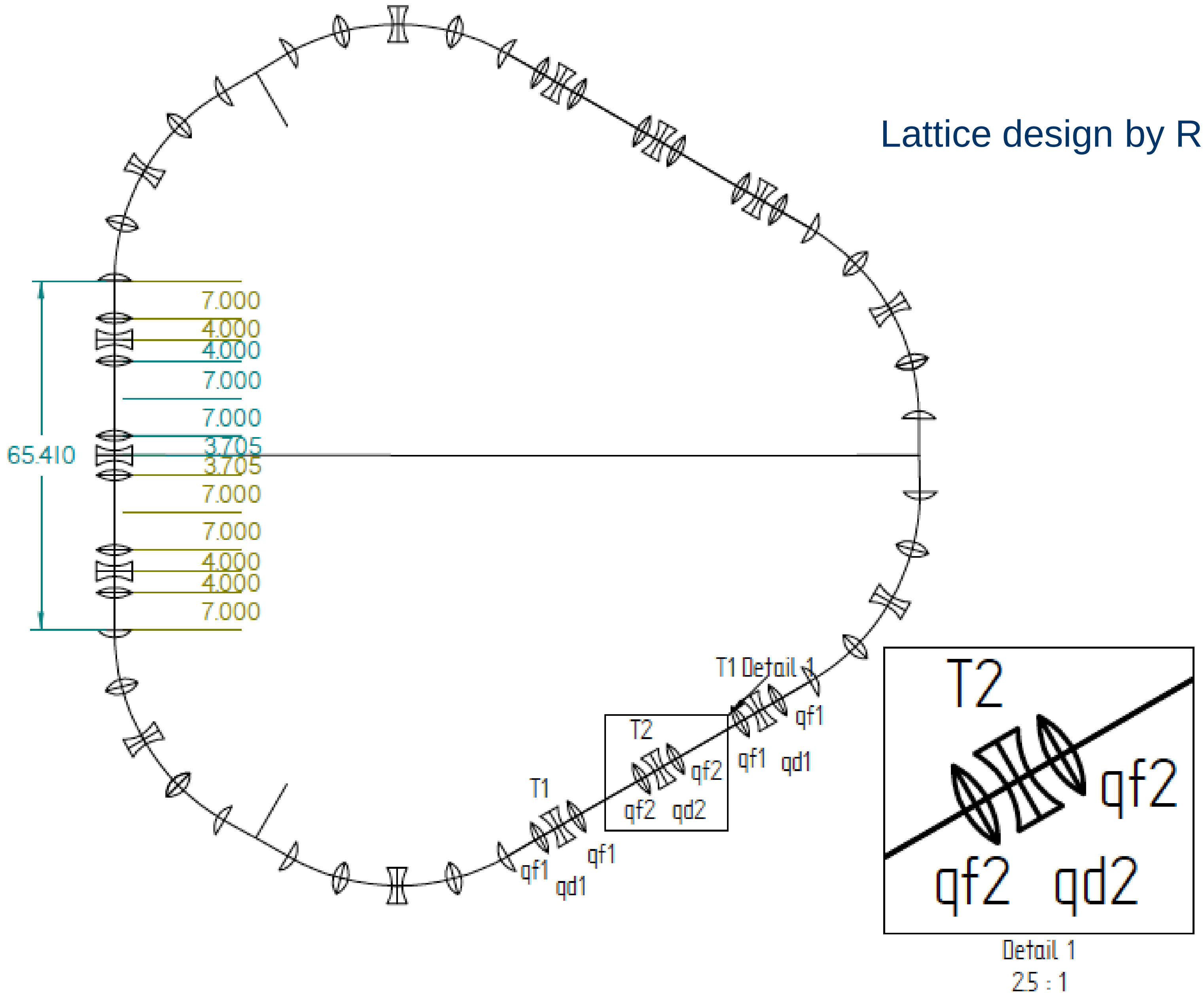
Looking into stochastic cooling to improve sensitivity

Many thanks to Jerry Annala for the tour today.



# At the old accumulator tunnel location

Lattice design by R. Talman



# Beam parameters

| | | | |
|---|---|---|---|
| C.R. proton beams | 0.7 GeV/c | ≥80% polariz.; ↑ | ~$4 \times 10^{10}$ protons/store |
| ~$10^2$ m base length | Repetition period: 20 minutes | Beam energy: ~1J | Average beam power: ~1mW |
| Beam emittance: 95%, norm. | Horizontal: 2 mm-mrad | Vertical: 6 mm-mrad | $(dp/p)_{rms}$~ $2 \times 10^{-4}$ |

- CW & CCW injections: Average emittance parameters: same to ~10% at injection.

Fermi would need to get into polarized beams physics

# The current status

- Have developed R&D plans for 1) BPM magnetometers, 2) Tests at IKP/Jülich using stored polarized beams at COSY, 3) E-field development, and 4) Polarimeter prototype
- We had two successful technical reviews: Dec 2009, and March 2011.
- Exp. Method and R&D plan blessed by both review committees.
- Sent a proposal to DOE NP for a proton EDM experiment at BNL: November 2011

# 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 ($1.3 \times 10^{-29}$ e•cm/year)
- ✓ Polarimeter work
- Planning BPM-prototype demonstration including tests at RHIC
- Old accumulator ring could house the proton EDM ring at Fermi; significant cost savings. Upgrade possibilities...

# From Marciano's presentation at the review

## Conclusion

1. Measurements of $d_n$ & $d_p$ with similar sensitivity essential to unfold underlying physics. Explain Baryogenesis
2. $d_p$ has potential to do (10x) better than $d_n$
3. $d_p$ at $10^{-29}$e-cm ***must do*** experiment
   **Explores physics up to scales O(3000TeV) for $\phi^{NP}$~O(1) i.e. beyond LHC or $\phi^{NP}$~$10^{-7}$ at LHC discovery scales!**
4. Sets stage for $d_D=d_n+d_p+d$(2 body), d($^3$He)…