PAC meeting
BNL, 6 June 2011

Storage ring EDM experiments: The status of the proton EDM proposal

Yannis K. Semertzidis, BNL

- Dec 2008, NPP ALD S. Vigdor: suggested to work on a simpler system than the deuteron
- Protons at their magic momentum: All-electric storage ring experiment, eliminate all magnetic fields; much smaller R&D effort needed
- BNL could provide the required beam today!

The current status

- Have developed R&D plans for 1) BPM magnetometers, 2) SCT at COSY and software, 3) E-field development, and 4) Polarimeter
- We had two successful technical reviews: Dec 2009, and March 2011.
- Exp. Method and R&D plan blessed by both review committees. We have greatly benefited from their recommendations

- Preparing a proposal to DOE for CD0 for a proton EDM experiment at BNL: end June 2011

EDMs of hadronic systems are mainly sensitive to

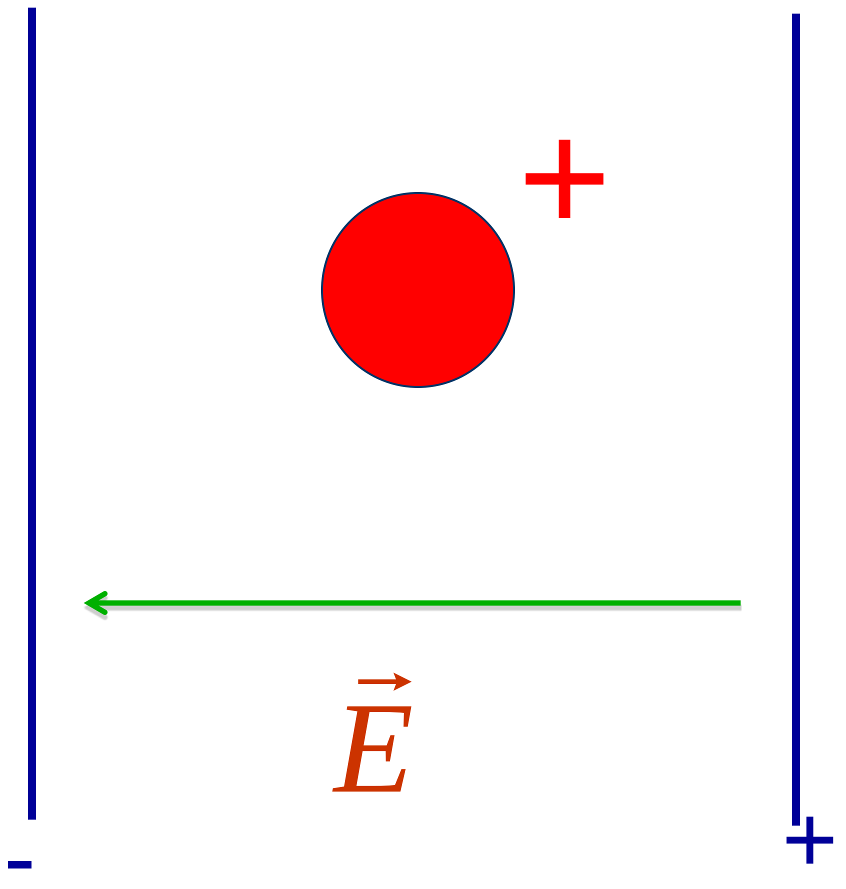
- Theta-QCD (part of the SM)

- CP-violating sources beyond the SM

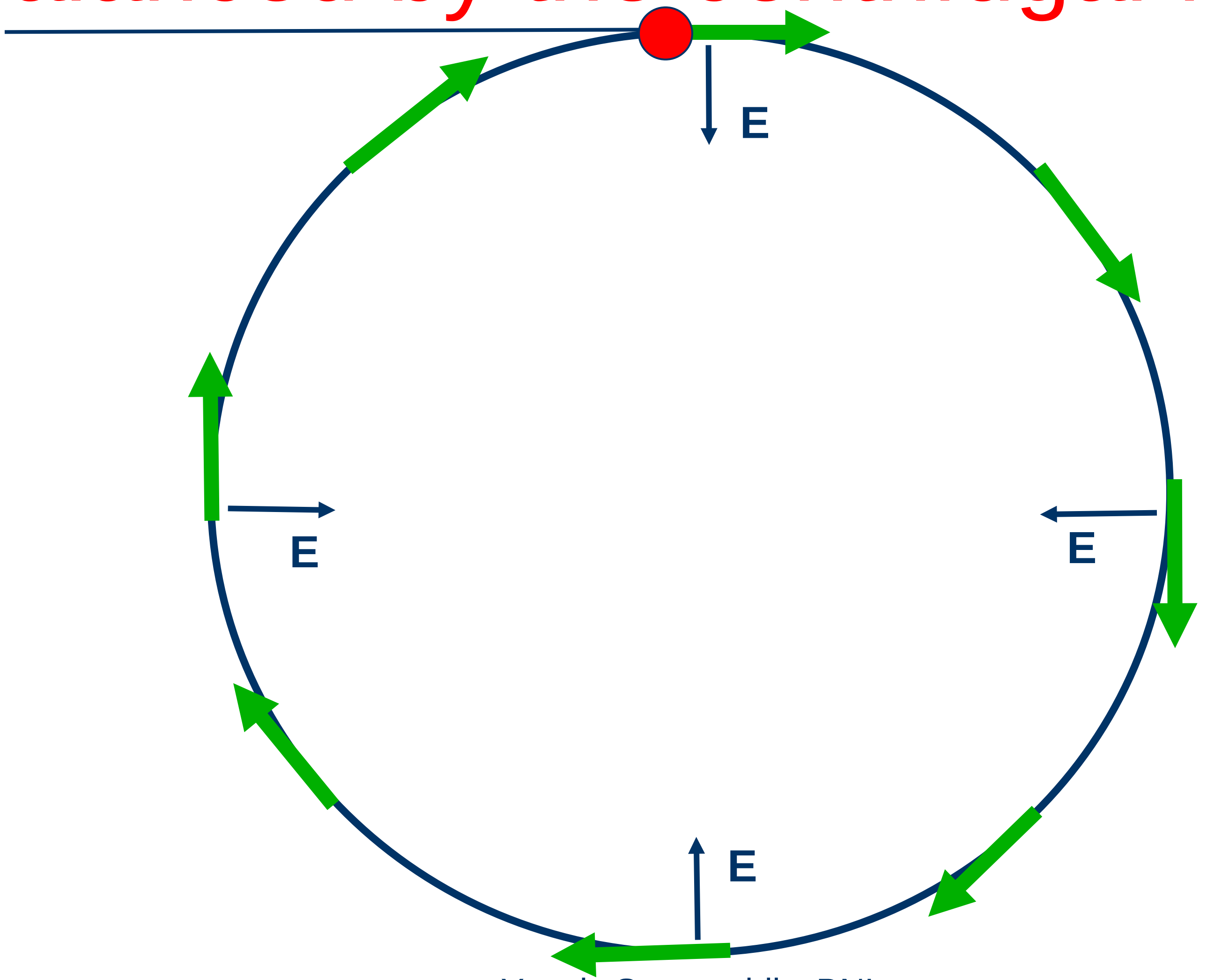
Alternative simple systems are needed to be able to differentiate the CP-violating source (e.g. neutron, proton, deuteron,…).

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

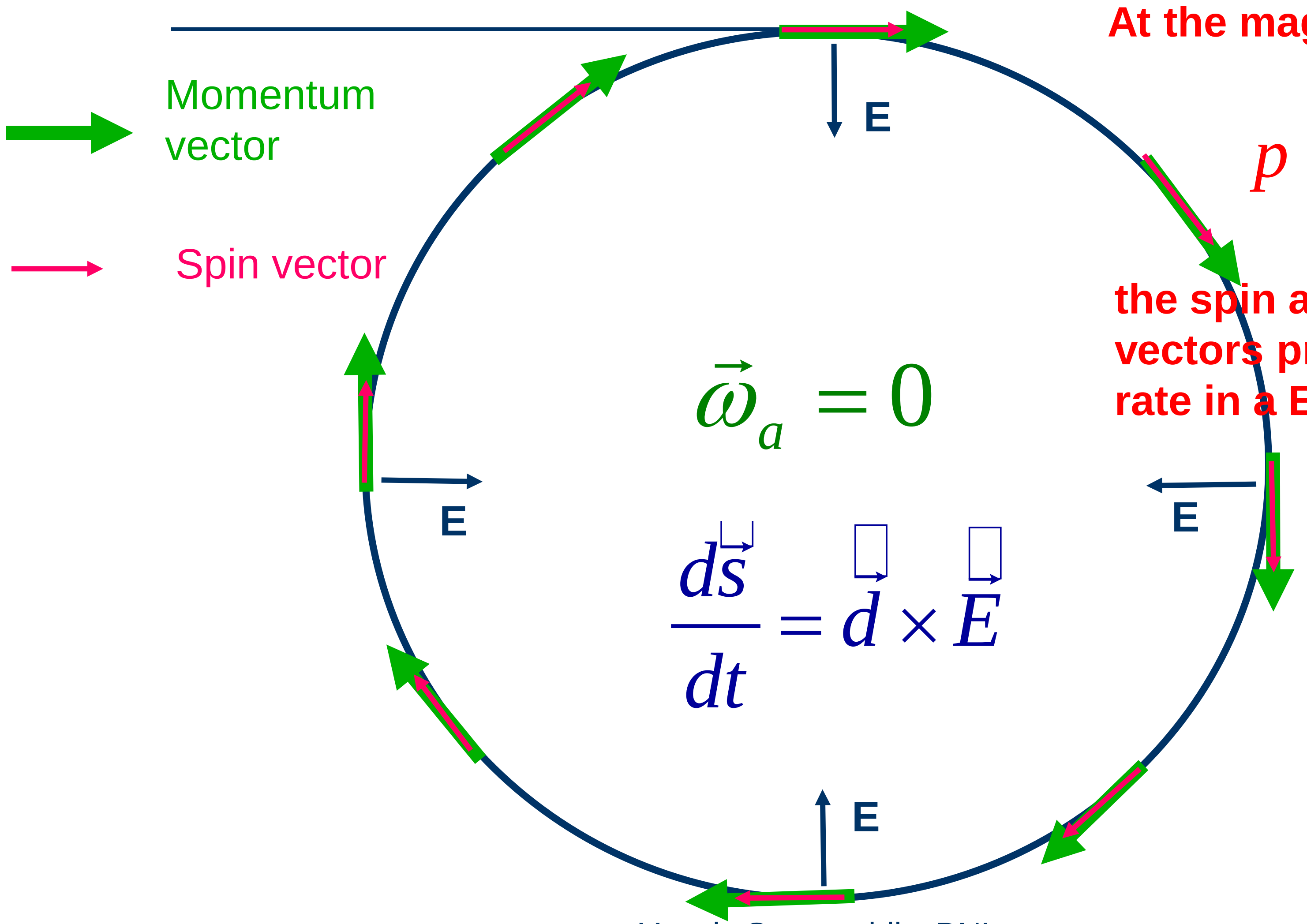
A charged particle between Electric Field plates would be lost right away…



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



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

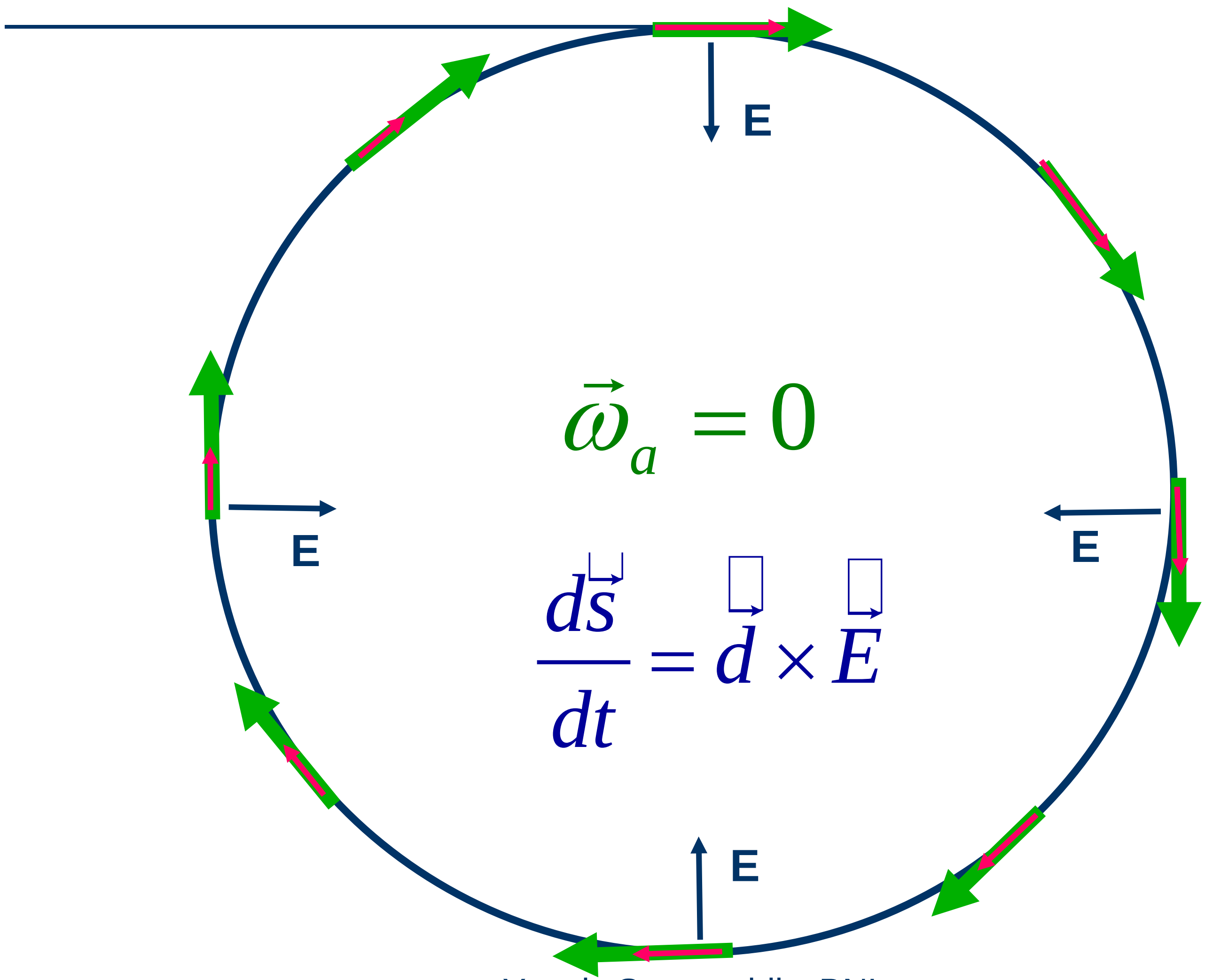
$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$

At the magic momentum

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

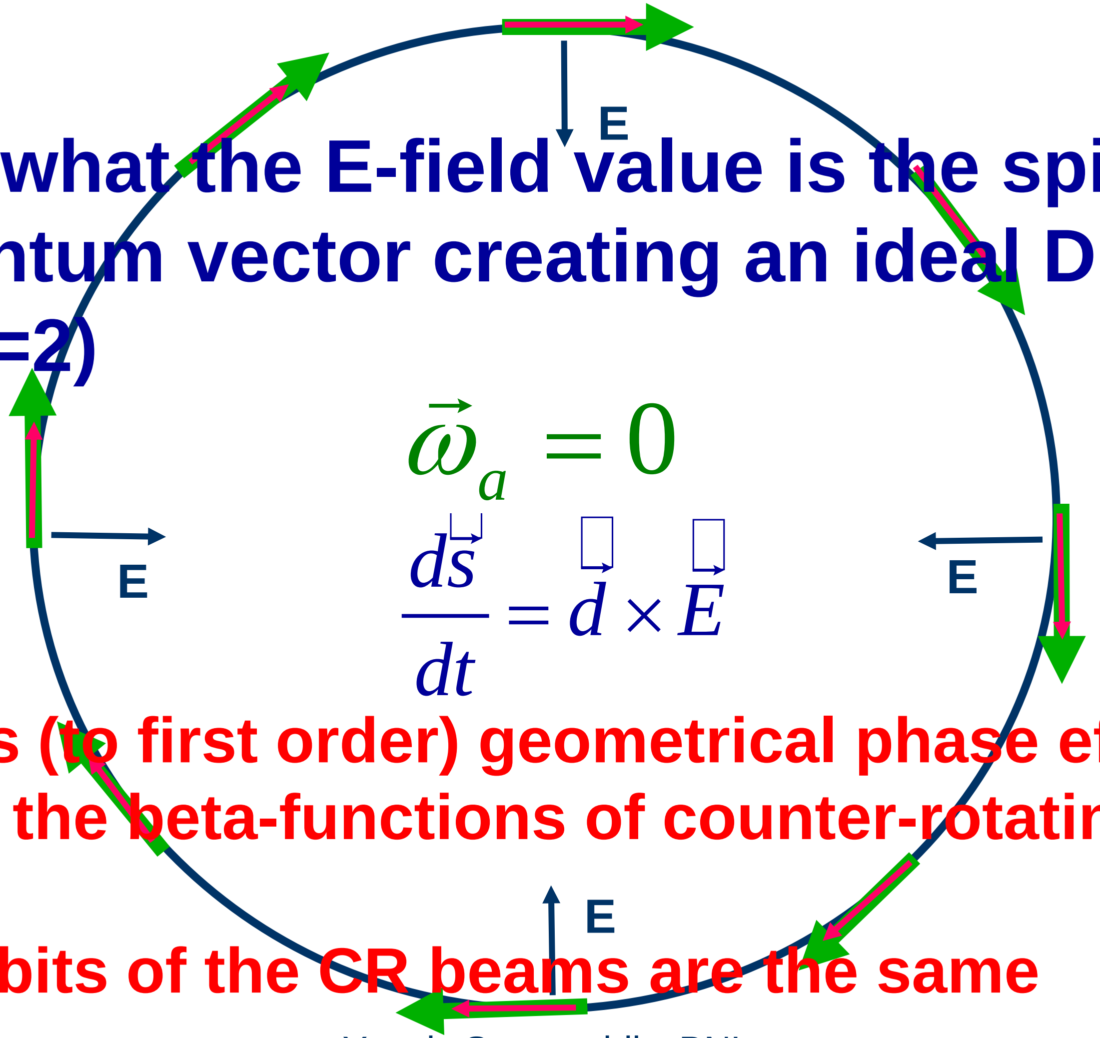
the spin and momentum vectors precess at same rate in a E-field

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.



Yannis Semertzidis, BNL

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**

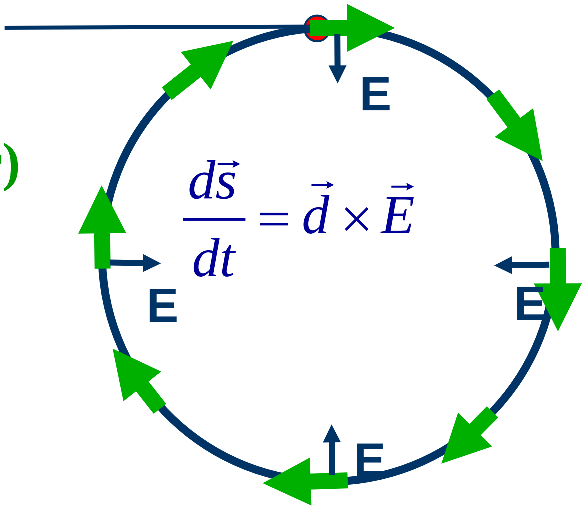
High intensity charged particle beams can be stored for a long time

Statistics:

- **High intensity (4×10^{10}), highly polarized beams (>80%)**
- **Keep spin along the momentum, radial E-field (10MV/m) acts on proton EDM**
- **Long (~10^{3}s) spin coherence time (SCT) is shown**
- **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 $\langle B_r \rangle$**
- **Longitudinal impedance: <10KΩ**
- **Forward/backward bunch polarizations (polarimeter)**



Software development:

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

Review of Dec 2009

- Great Physics; complementary to LHC
- Recommendation: Use all E-field focusing (all-electric ring)

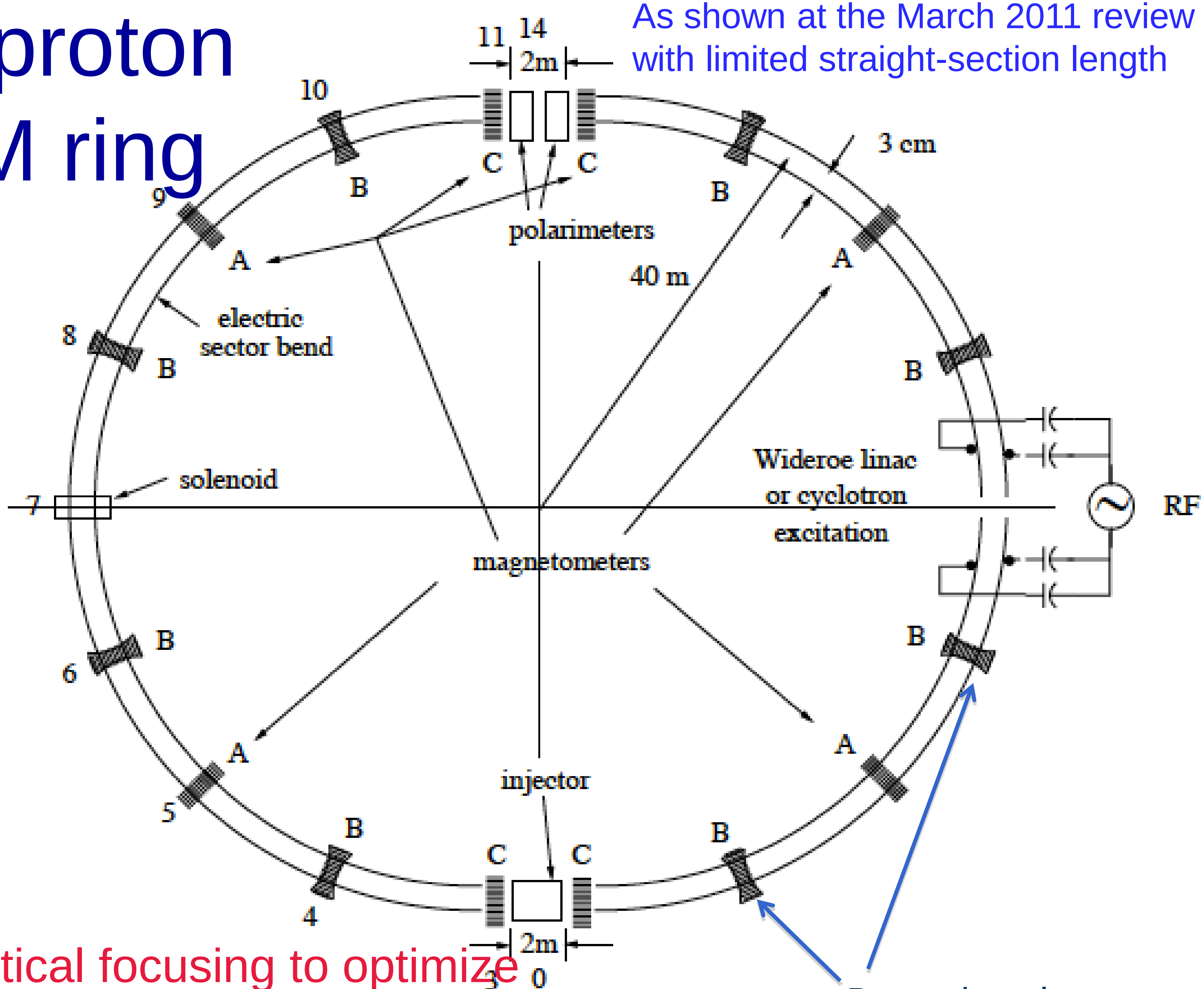
- Critical items:
- 1) SCT (benchmark software with polarized beams at COSY)
- 2) BPMs (test with beams at RHIC)

Since Dec 2009 Review

1. Adopted the E-field focusing option in spring 2010 after studying issues
2. Started a test program at COSY on SCT; longer SCT w/ cooling; software benchmarking
3. Developed significant understanding of the E-field issues for beam dynamics tracking
4. Studied BPM systematics, developed BPM magnetometer based on low T_c SQUIDS

The proton EDM ring

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

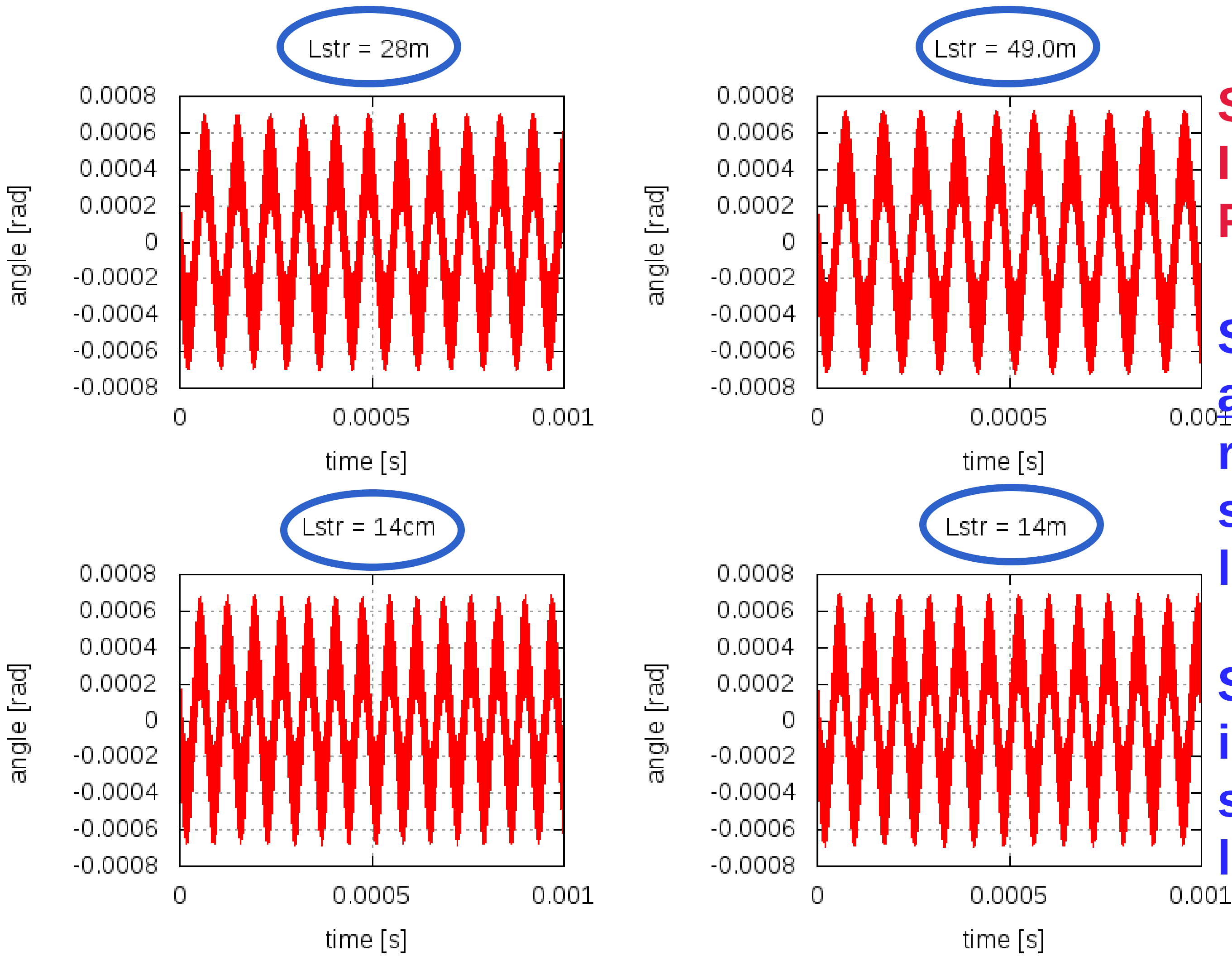


B: quadrupoles

Weak vertical focusing to optimize SCT and BPM operation

Since the March 2011 review

- The straight section length can be much longer than previously thought (>50m if needed!)



S. Haciomeroglu Istanbul T.U., PhD student:

Studying SCT of an all-electric storage ring as a function of straight section length.

SCT is found to be independent of straight section length!

Experimental needs

C.R. proton beams	0.7 GeV/c	≥80% polariz.;	~4×10^{10} protons/store
<10^2 m base length	Repetition period: 10^3s	Beam energy: ~1J	Average beam power: ~1mW
Beam emittance: 95%, norm.	Horizontal: 2 mm-mrad	Vertical: 6 mm-mrad	$(dp/p)_{rms}$~ 2×10^{-4}

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

C-AD can provide a beam with these parameters even today!

The grand issues in the proton EDM experiment

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

1. Beam Position Monitor

- Technology of choice: Low T_c SQUIDS, signal at 10^1-10^4Hz (10% vertical tune modulation)
- Test sequence:

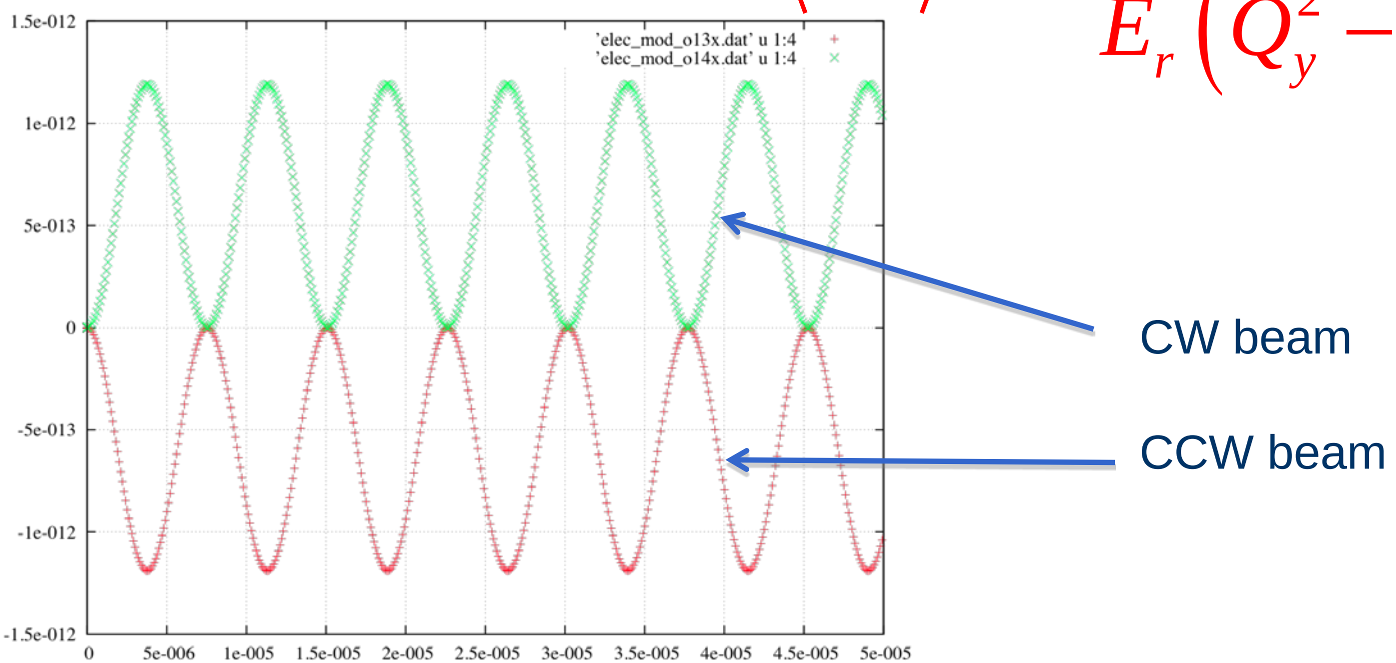
1. Operate SQUIDS in a magnetically shielded area-reproduce current state of art
2. Operate in RHIC ring (evaluate noise in an accelerator environment)
3. Operate in E-field string test

BPMs: CR beams split if $B_r \neq 0$

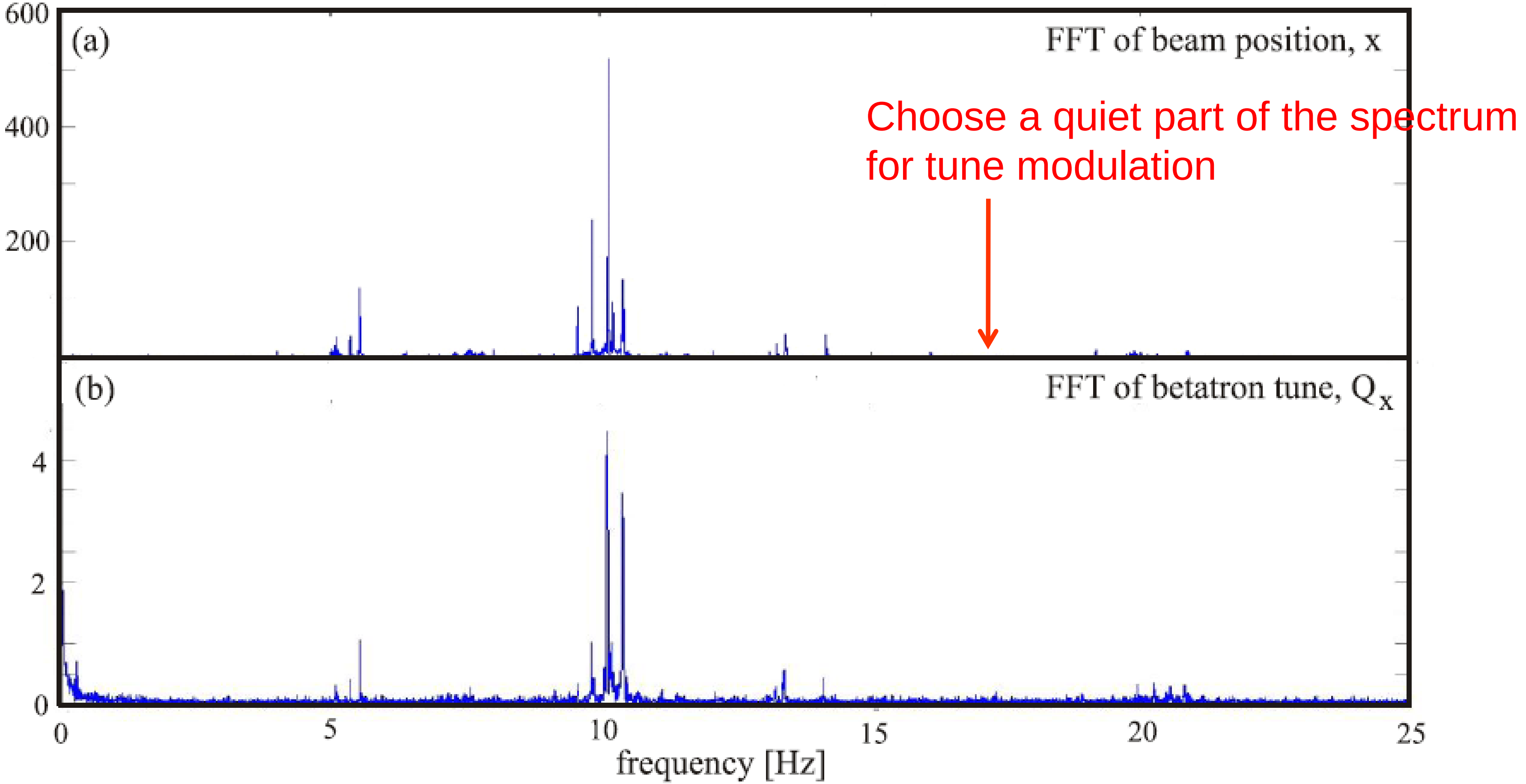
- The splitting depends on the vertical tune Q_y
- Modulating Q_y would create a frequency dependent separation and a B-field at the same frequency.

$$\langle \delta y \rangle = 2 \frac{\beta c R_0 B_{r0}}{E_r \left(Q_y^2 - N^2 \right)} \sim 2\,pm$$

Vertical position vs. time

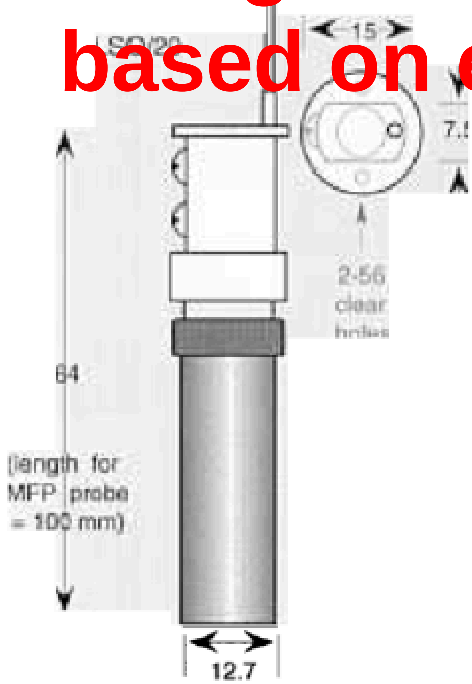


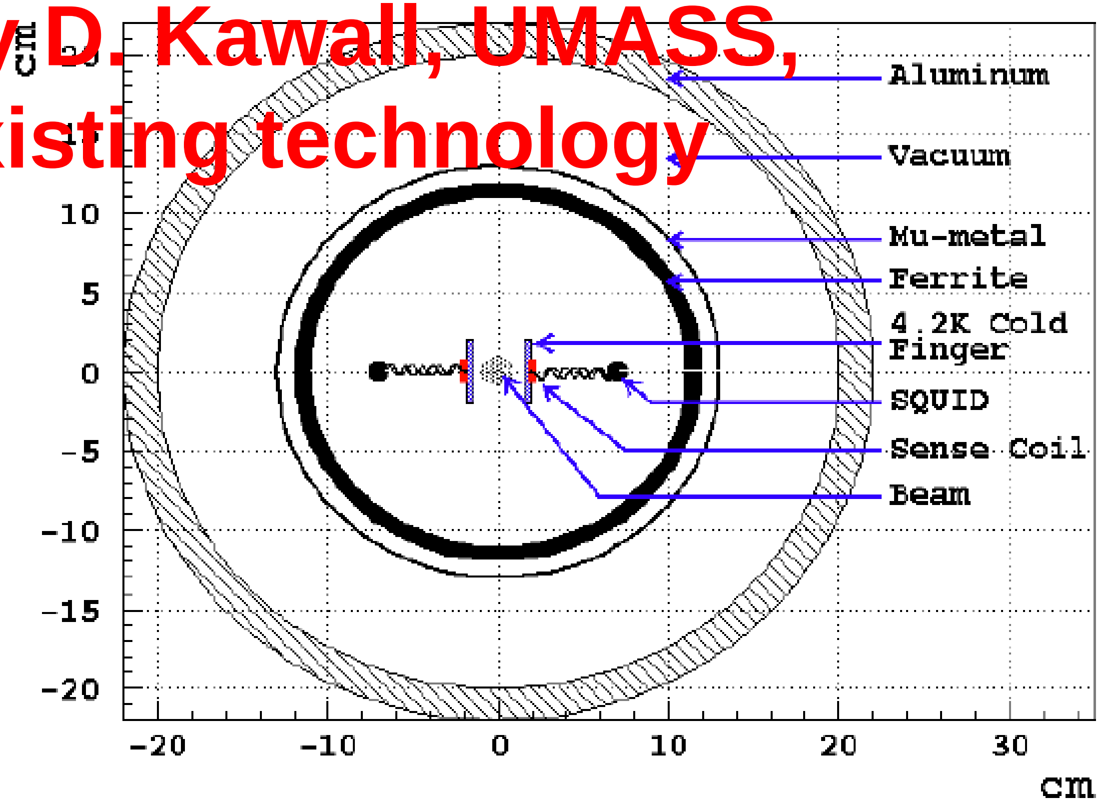
Fourier transforms of the horizontal beam position and betatron tune as measured in the blue ring (RHIC)



Schematic of a SQUID BPM system

Designed by D. Kawall, UMASS, based on existing technology



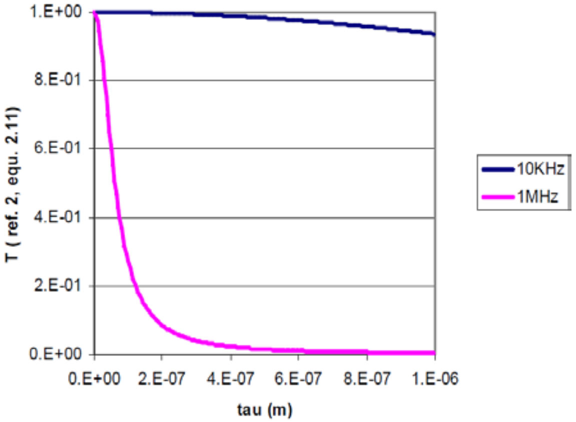


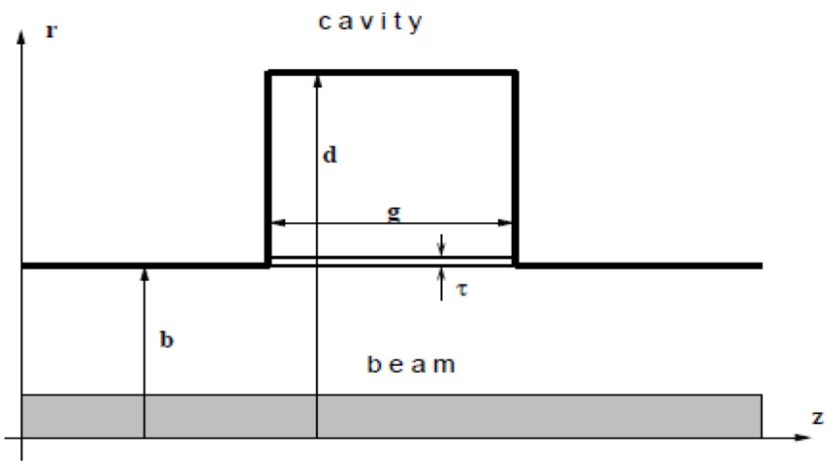
- Tristan Technology LSQ/20 SQUID
- 64 mm long, 12.7 mm diameter
- ≤ 1 fT$/\sqrt{\mathrm{Hz}}$

- Beam's eye view schematic of a SQUID BPM system
- Sense coils, leads, SQUIDs at 4.2K; leads and SQUIDs in superconducting shields
- Ferrite and μ-metal at room temp.
- More magnetic shielding outside Al vacuum chamber

BPM magnetometers

- ✓ Need to be shielded from the beam high frequency EM noise (to avoid SQUID saturation)
- ✓ Need to observe the low frequency B-field coming from the beam
- R. Gluckstern and B. Zotter, *Analysis of Shielding Charged Particle Beams by Thin Conductors*, PRST – Acc. and Beams, 4, 024402 (2001).





2. SCT Development

- We have a SCT working solution (analytically and with precision tracking). Plenty of straight section length.

- Planning tests with polarized deuterons and protons at COSY to benchmark software

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

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:

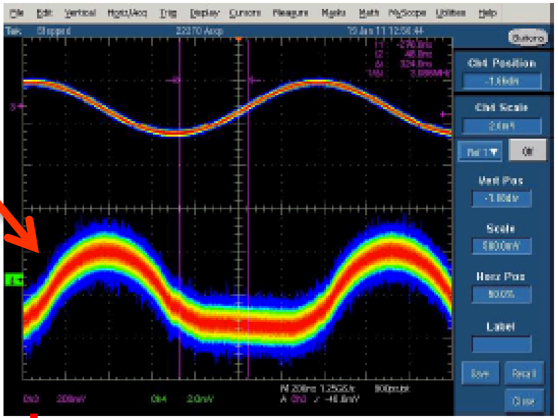
$$d\omega_a = a\vartheta_x^2 + b\vartheta_y^2 + c\left(\frac{dP}{P}\right)^2$$

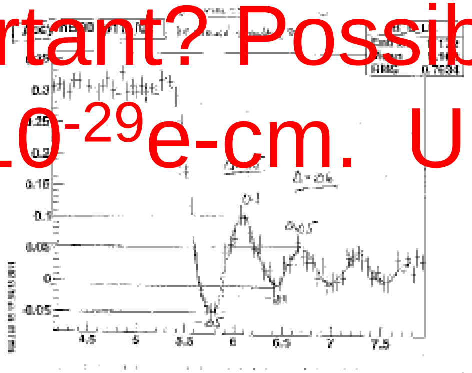
- Correct small effects (as needed) using sextupoles (current plan) and/or cooling (mixing) during storage (under evaluation).

Polarization with cooling holds for a long time

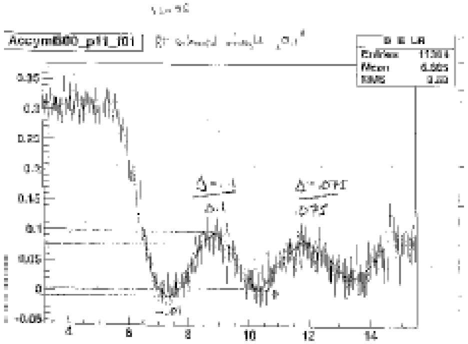
Why is this important? Possibility to get statistics below 10^{-29} e-cm. Upgrade…

Uncooled, and



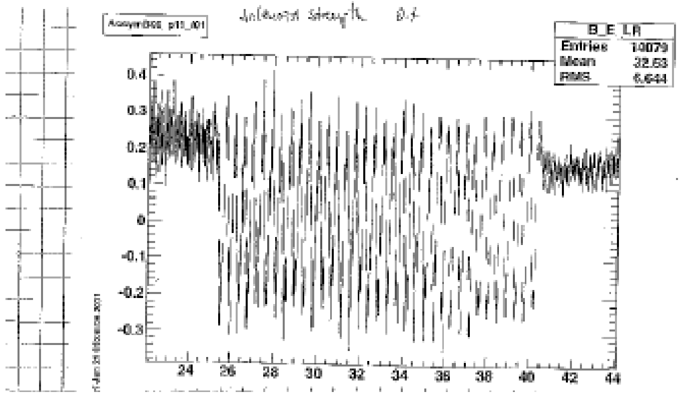


quick drop in oscillation amplitude, then slow decline with oscillation center close to zero



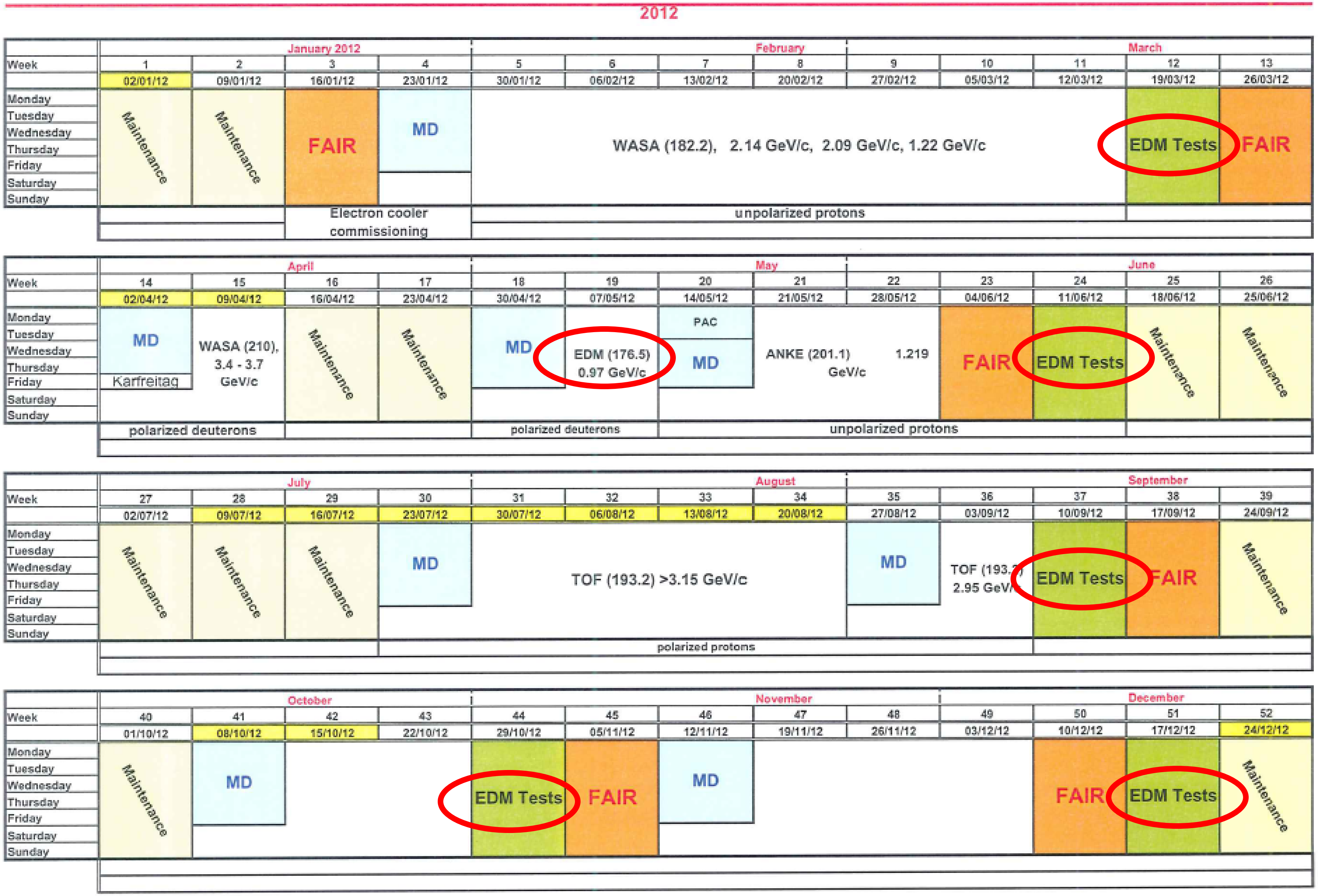
cooled beam profiles

ON



long-lived oscillation pattern, later seen with small decline (1/e time = 520 s)

Our running schedule at COSY/Jülich



Software Development (precise 2^{nd} order description needed)

Describe beam/spin dynamics in electric rings

1. Slow and accurate using 4^{th} order Runge-Kutta integration. At production stage. Already producing results

2. Fast and accurate integrating analytically: Advanced stage.

3. Accurate description of COSY ring near production

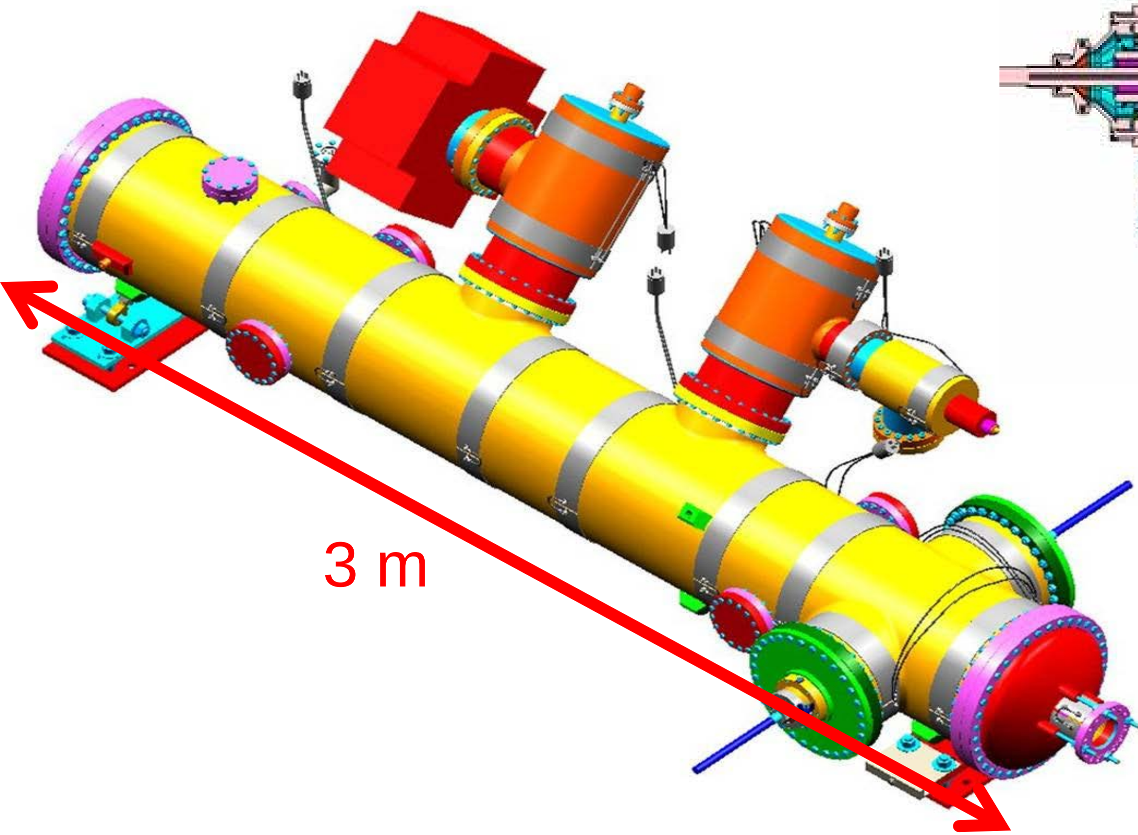
3. Electric Field Development

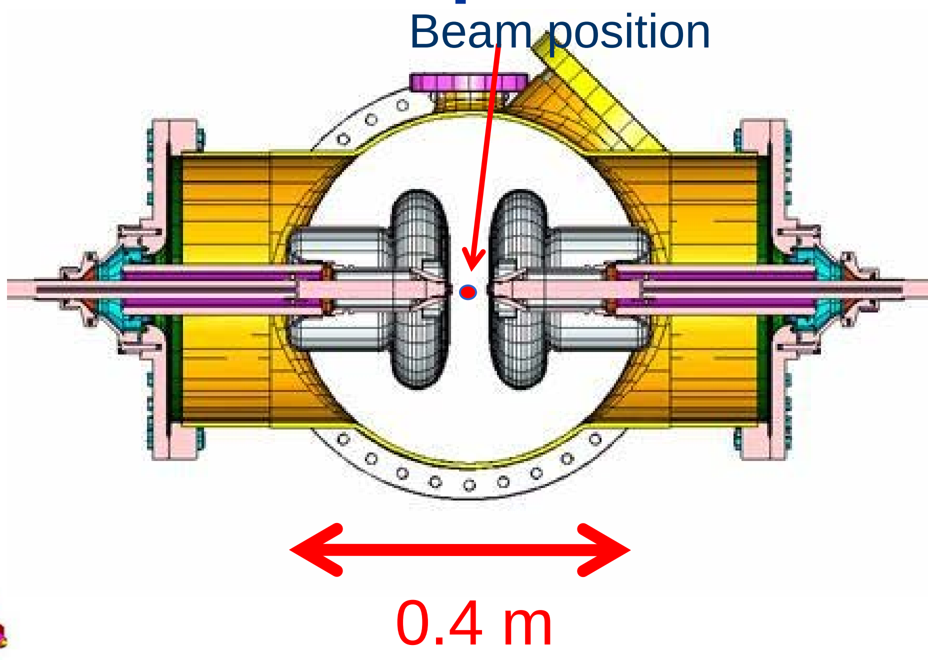
- Reproduce Cornell results with stainless steel plates treated with high pressure water rinsing
- Determine:

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

- Develop and test a large area E-field prototype plate module.

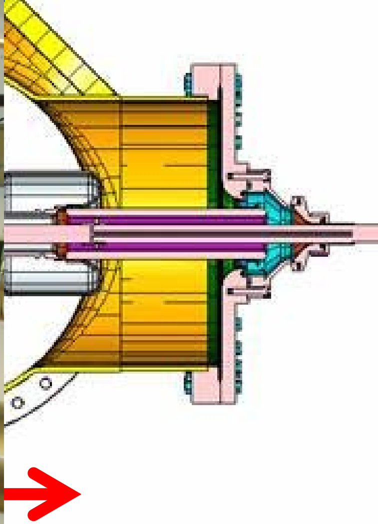
E-field plate module: Similar to the (26) FNAL Tevatron ES-separators





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

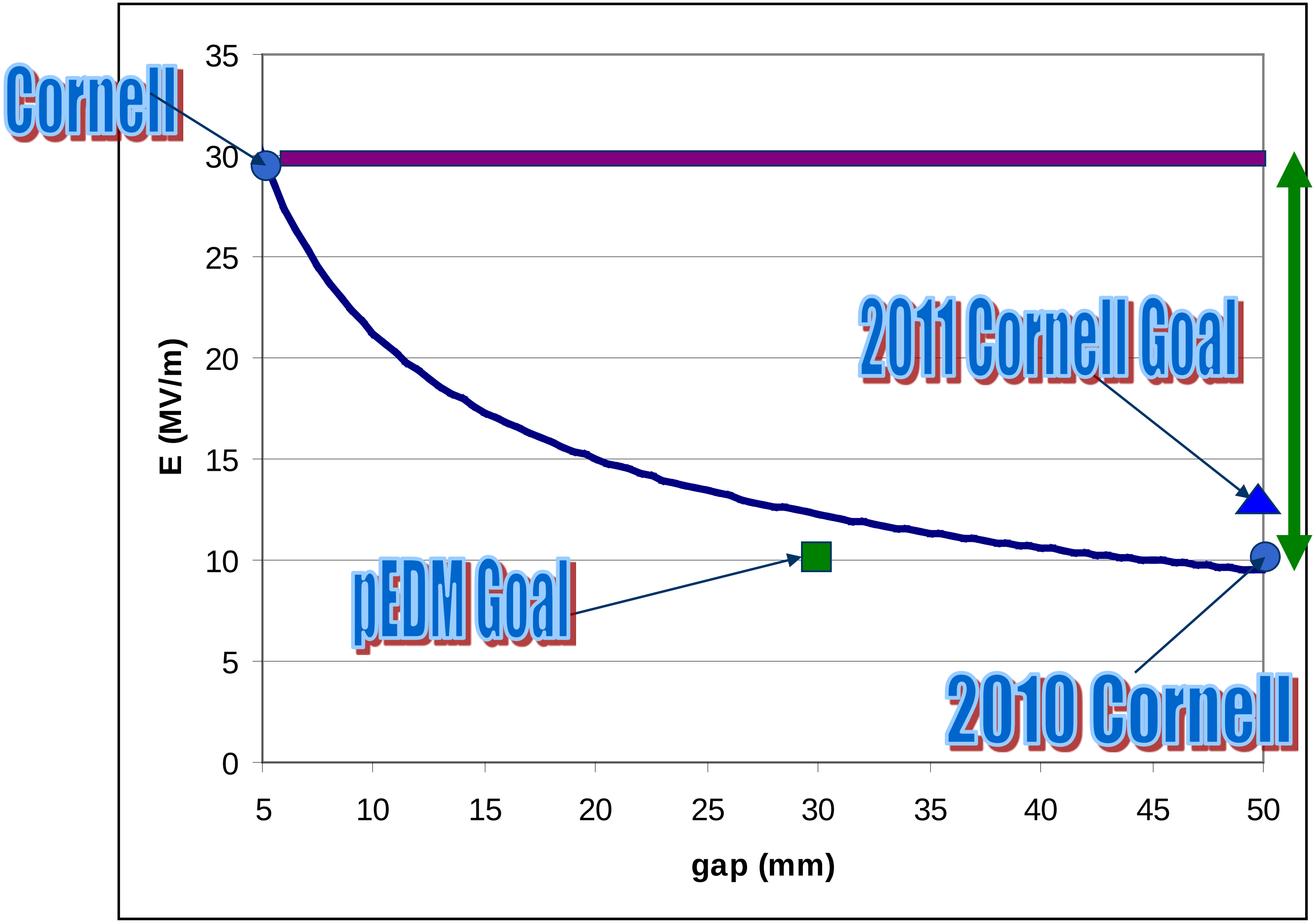
position



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

How to Scale HPWR to 3cm gap?



4. Polarimeter Development

- Polarimeter tests with runs at KVI and COSY demonstrated << 1ppm level systematic errors (long paper has just been submitted)

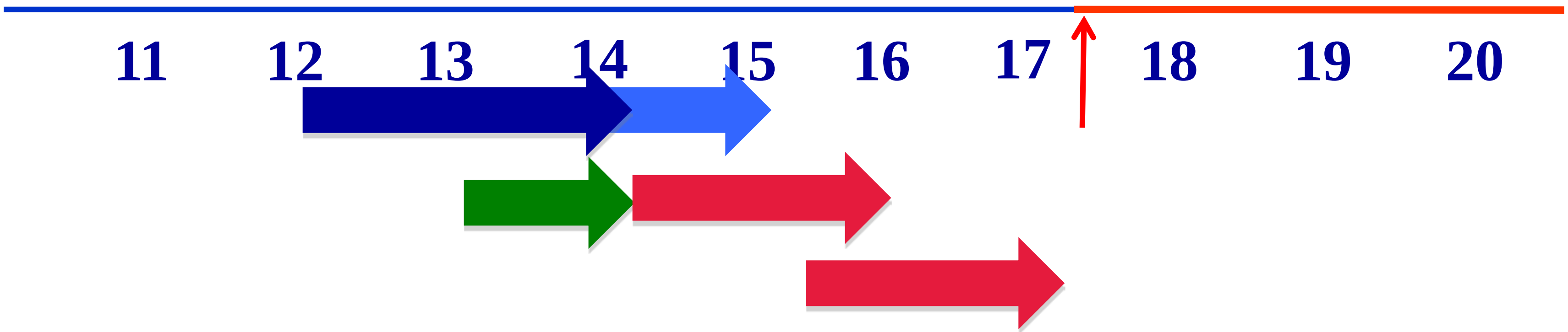
- Technologies under investigation:

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

Proton EDM R&D cost: $2M

- BPM development & testing over two years: $0.6M
- E-field prototype development & testing: 1.8 years: $0.4M
- SCT tests at COSY, 2 years: $0.4M
- Polarimeter prototype, 2 years: $0.6M

Technically driven pEDM timeline



- Two years R&D
- One year final ring design
- Two years ring/beamline 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 need to prove it in an accelerator 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.

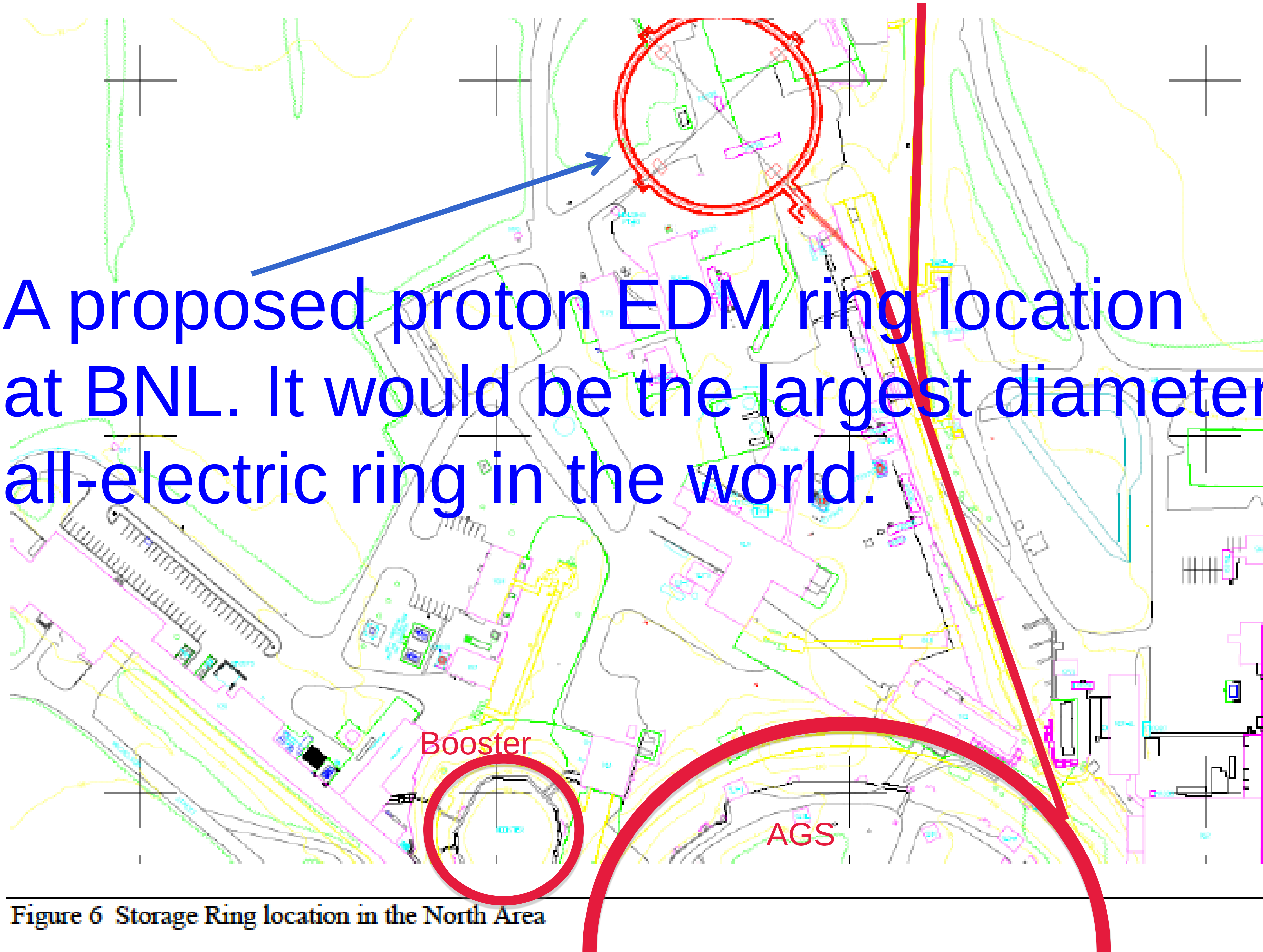


Figure 6 Storage Ring location in the North Area

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

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**

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 ϕ^{NP}~O(1) i.e. beyond LHC or $\phi^{NP}\sim10^{-7}$ at LHC discovery scales!
4. Sets stage for $d_D=d_n+d_p+d(2\text{ body})$, $d(^3He)$…

Summary

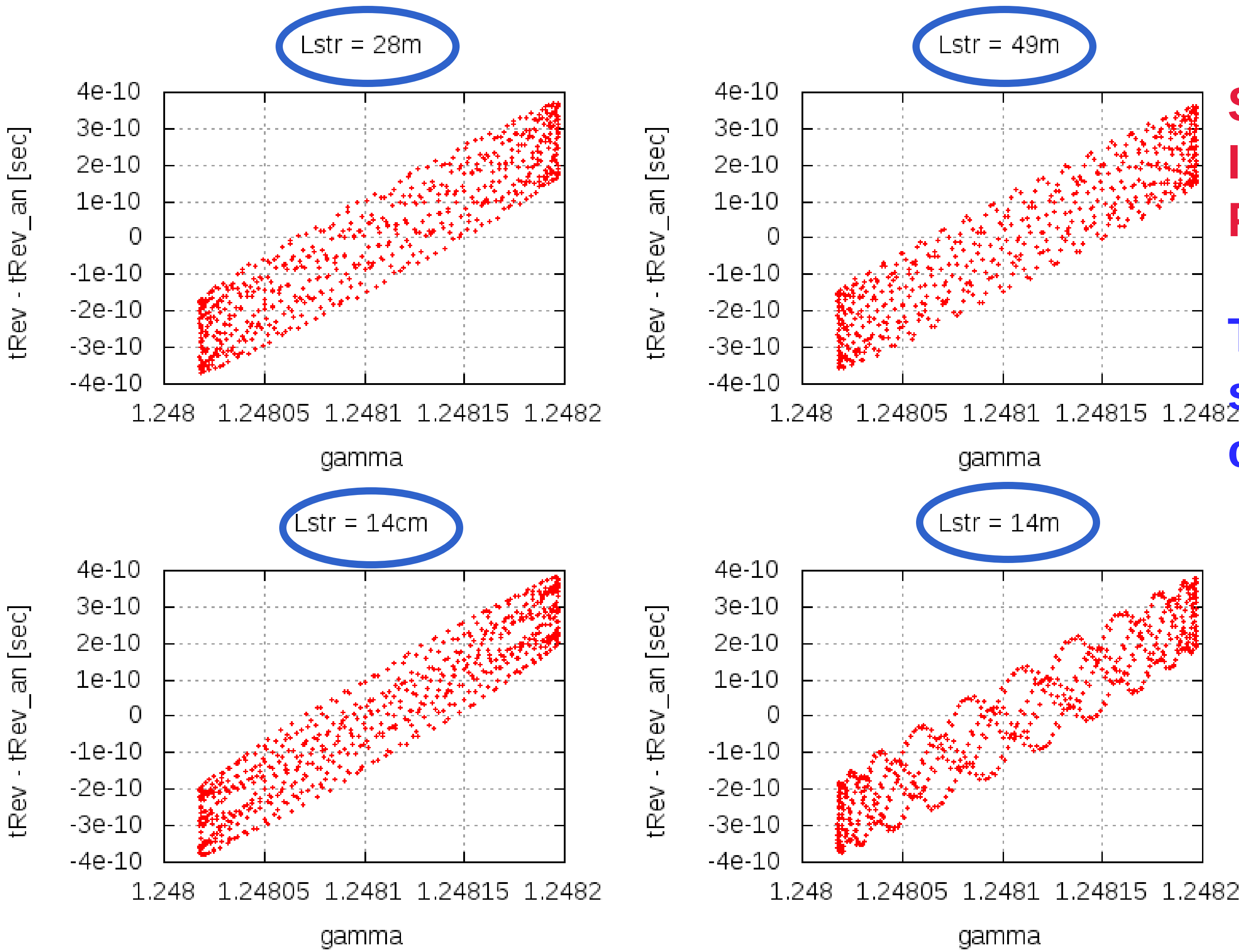
- ✓ Proton EDM physics is a must do, an order of magnitude improvement over the neutron EDM
- ✓ Can leap-frog the competition; complementary
- ✓ E-field issues well understood
- ✓ Working EDM lattice with long SCT and large enough acceptance (1.3×10^{-29} e•cm/year)
- Planning BPM-prototype demonstration including tests at RHIC

- Proposal to DOE: by end of June 2011
- Support it…

Extra slides

Revolution time vs. gamma

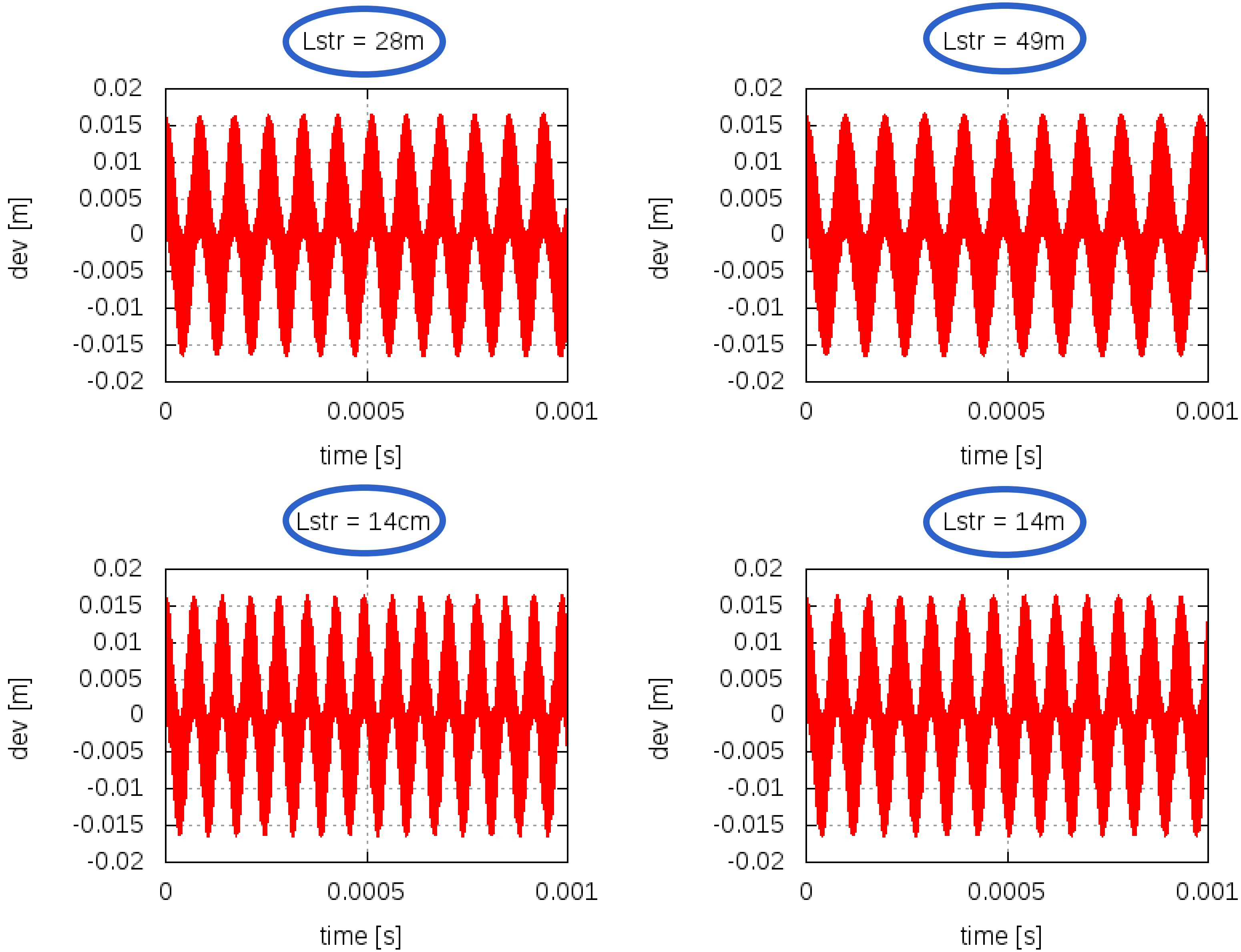
Radial oscillations change the particle energy → a symmetric pattern cancelling non-linearity



S. Haciomeroglu
Istanbul T.U.,
PhD student:

The straight sections do not contribute to SCT.

Radial oscillations vs. time



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.

Filling-in the blanks

System	Cost	W/ Indirects	Contingency	Total	Comments
Electrical		$4.3M	50%	$6.45M	C-AD
V.C. + plates + Vacuum	+HPR	$5.7M	10-50%	$7M	C-AD, S. Nayak
Magnetic shielding	$5.6M	17.55% (up to $0.6M)	50%	$8.56M	Amuneal company
Installation of M.S.	$0.860M	17.55% (up to $0.6M)	50%	$1.45M	Amuneal company
Polarimeter	$0.6M	17.55%	50%	$1.06M	pEDM
Active magn. feed.		$732K	100%	$1.46M	C-AD
Controls		$876.5K	100%	$1.75M	C-AD
Control room		$250K	100%	$0.5M	C-AD
Installation		$3.7M	100%	$7.4M	C-AD
SQUID-BPM	$2.5M	17.55% (up to $0.6M)	50%	$3.91M	pEDM
Total				**$39.54M**	

Conventional, ring at ATR

System	Cost	W/ Indirects	Contingency	Total	Comments
Site Utilities	$165.9K		45%		C-AD
pEDM Ring & services	$7,282.9K		45%		C-AD
Service Buildings & Utilities	$671.3K		45%		C-AD
Beam Transport, Service buildings & Utilities	$810.7K		45%		C-AD
Architectural, Engineering & Construction Services	$2,014.5K		45%		C-AD
Total		12,587.1K	$5,664.2K	**$18,251.3K**	

beamline at ATR

System	Cost w/small project ind. (SPI)	W/ large project Indirects (LPI)	Contingency	Total	Comments
Electrical distribution & tray runs	$502.8K		50%		C-AD
Magnets	$2,215.4K		50%		C-AD
Power supplies	$1,362.5K		50%		C-AD
Vacuum System	$744K		50%		C-AD
Access controls	$152.6K		50%		C-AD
Instr. & controls	$1,594.3K		50%		C-AD
Water cooling	$302.3K		50%		C-AD
Installation labor	$1,103.4K		50%		C-AD
Total		7,302.5K	$3,651.2K	**$10,953.7K**	

Conventional, ring at SEB

System	Cost w/ SPI	W/ LPI	Contingency	Total	Comments
Removals	$5,543.3K	$4773.8K	65%	$7876.8K	C-AD
Utilities	$776.83K		65%		C-AD
Ring shielding & Installation	$2,641.9K		65%		C-AD
Misc.	$1,366.7K		65%		C-AD
Total		8,894.9K	$5,781.7K	**$14,676.6K**	

beamline at SEB

System	Cost w/ SPI	W/ LPI	Contingency	Total	Comments
Extraction	$430.16K		50%		C-AD
Magnets	$748.12K		50%		C-AD
Power supplies	$564.86K		50%		C-AD
Vacuum System	$685.97K		50%		C-AD
Access controls	$800.13K		50%		C-AD
Instr. & controls	$779.76K		50%		C-AD
Water cooling	$295.25K		50%		C-AD
Installation labor	$1,249.9K		50%		C-AD
AC power	$232.33K		50%		C-AD
Removals	$460.55K		50%		C-AD
Total		$5,267.9K	$2,634.0K	**$7,901.9K**	

SCT data from the January 2011 run at COSY

- Beam polarization data with RF and cooling turned-on show a SCT > 500s; more than adequate for the experiment.

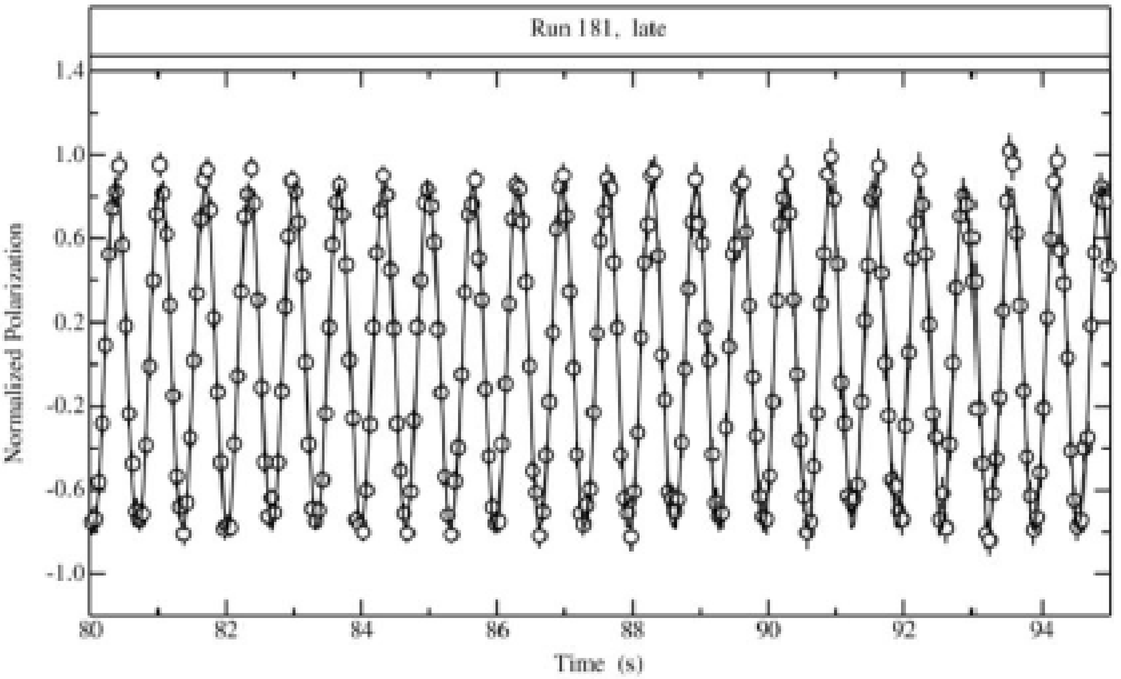


Figure 1: Measurements of the oscillation pattern with both electron cooling and the RF solenoid on as a function of time in the store in seconds. The data is a combination of the vector asymmetry from all four polarization states after subtraction of the unpolarized asymmetry and a normalization to one before the RF solenoid is actuated. The curve is a least squares fit of a sine function whose period is 0.658 ± 0.002 s.

Our running schedule at COSY/Jülich

2011

	January 2011				February				March				
Week	1	2	3	4	5	6	7	8	9	10	11	12	13
	03/01/11	10/01/11	17/01/11	24/01/11	31/01/11	07/02/11	14/02/11	21/02/11	28/02/11	07/03/11	14/03/11	21/03/11	28/03/11
Monday–Sunday	Maintenance	MD	EDM 176.4	FAIR (Nights for RWTH Aachen)	MD	WASA, 208, pd --> He3 X				Karneval FAIR (CBM-ToF)	MD	ANKE 203, pn --> K+ n Λ	
		pol. Deuterons		unpolarized protons									
		970 MeV/c			2196 MeV/c						2425, 2546, 2600 MeV/c		

	April				May					June			
Week	14	15	16	17	18	19	20	21	22	23	24	25	26
	04/04/11	11/04/11	18/04/11	25/04/11	02/05/11	09/05/11	16/05/11	23/05/11	30/05/11	06/06/11	13/06/11	20/06/11	27/06/11
Monday–Sunday	ANKE 203, pn -> K+ n Λ	MD	WASA, 209, ω-decay in pp Karfreitag	Ostern WASA, 184.1, η' in pp 1. Mai	Maintenance	PAC	MD	ANKE, (205), PIT, np --> (pp)Spectator + π-	Himmel-fahrt		Pfingsten	Fronleich-nam	
	unpolarized protons						polarized deuterons						
			2950 MeV/c	3350 MeV/c			1774 MeV/c						

	July				August					September			
Week	27	28	29	30	31	32	33	34	35	36	37	38	39
	04/07/11	11/07/11	18/07/11	25/07/11	01/08/11	08/08/11	15/08/11	22/08/11	29/08/11	05/09/11	12/09/11	19/09/11	26/09/11
Monday–Sunday	ANKE, 205	Maintenance E-Cooler preparations and PAX				FAIR	MD	MD	MD	PAX Filterexperiment			
							PAX						

	October				November					December			
Week	40	41	42	43	44	45	46	47	48	49	50	51	52
	03/10/11	10/10/11	17/10/11	24/10/11	31/10/11	07/11/11	14/11/11	21/11/11	28/11/11	05/12/11	12/12/11	19/12/11	26/12/11
Monday–Sunday	Feiertag FAIR	MD	MD	TOF (193.2), 2.7 GeV/c	Aller-heiligen			FAIR	Maintenance E-Cooler Einbau			Maintenance Weih-nachten	
	pol. protons												

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

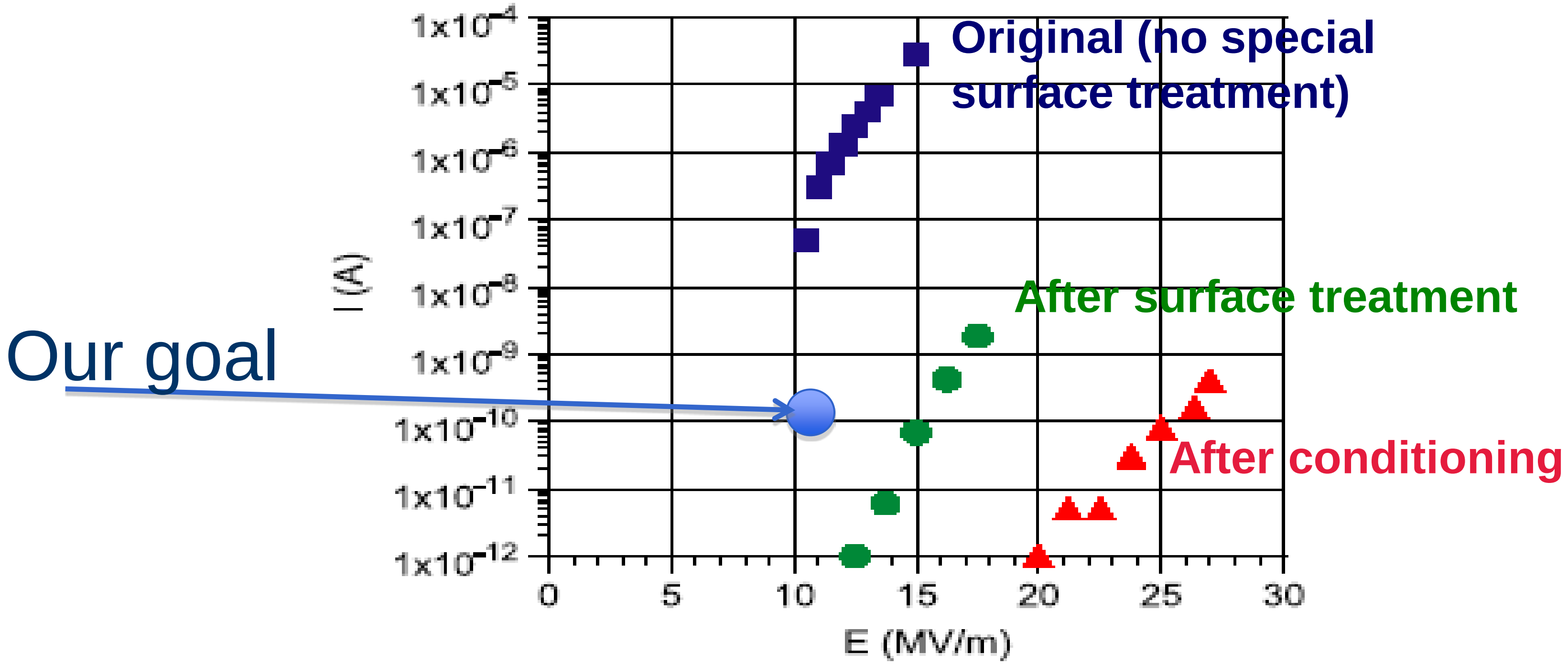


Fig. 4. Field emission current as a function of applied gradient for a 150-mm-diameter stainless steel electrodes: (squares) a typical untreated sample, (circles) first measurement of GCIB treated sample, (triangles) re-measurement of GCIB treated sample after high-voltage conditioning [14].

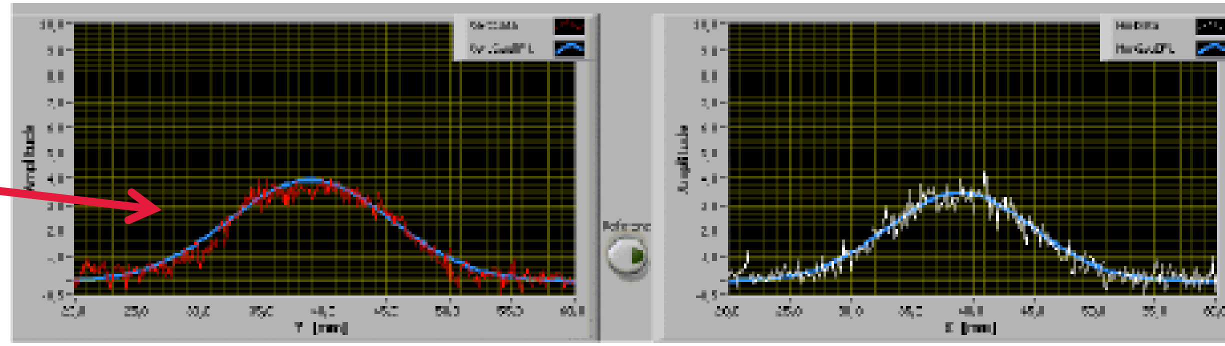
SCT tests at COSY, January 2011

Uncooled

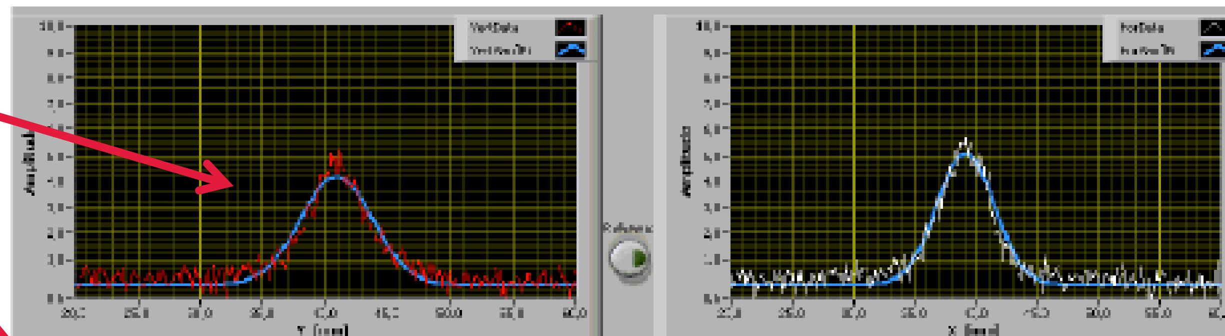
and

cooled beam

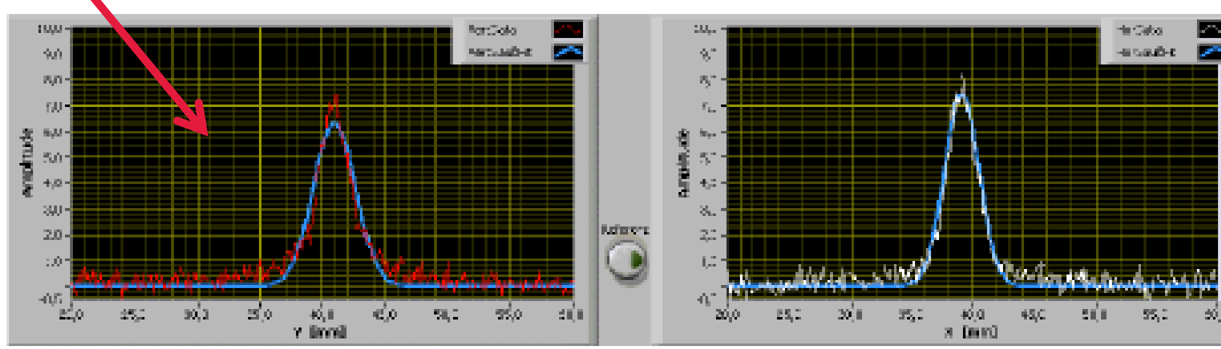
profiles



Vertical (left) and horizontal (right) beam profiles for the uncooled beam and Gaussian fits.



Vertical (left) and horizontal (right) beam profiles for 30 sec cooling and 30 sec cooling off and Gaussian fits.



Vertical (left) and horizontal (right) beam profiles for 60 sec cooling.

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

Risk factors

System	Risk factor at Dec. 2009 rev.	Current Risk factor
Spin coherence time	High	Low-Medium
Beam position monitors	High	High (test in accelerator environment is required)
Polarimeter	Low	Low
E-field strength	Low	Low
E-field plates shape	Low	Low
Software development	Medium	Low

Two different labs to host the S.R. EDM experiments

- BNL, USA: proton "magic" ring
- COSY/IKP, Jülich/Germany deuteron ring: JEDI

From Hans Stroeher's presentation at the March 2011 review

EDM at Storage Rings

JÜLICH
FORSCHUNGSZENTRUM

International srEDM Network

Institutional (MoU) and Personal (Spokespersons …) Cooperation

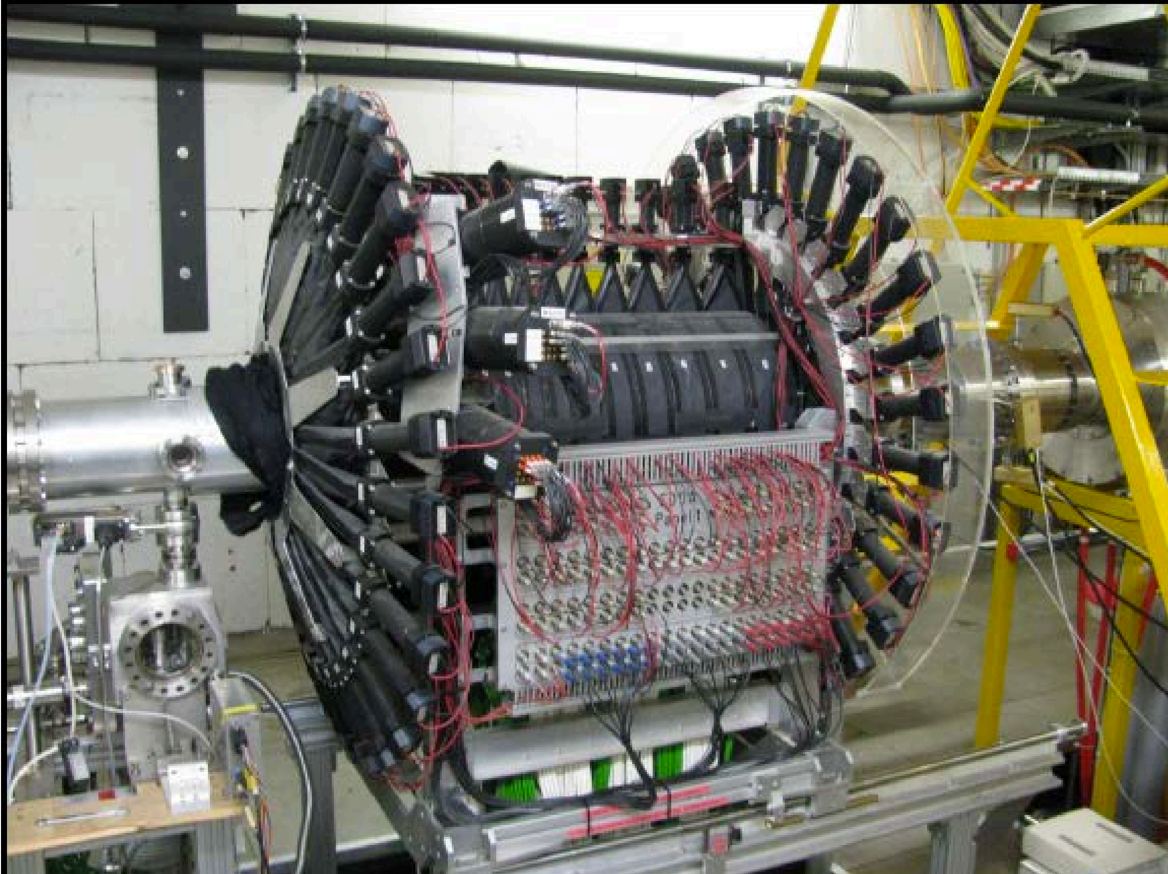
srEDM Collaboration (BNL)	srEDM Collaboration (FZJ)

Common R & D

RHIC	EDM-at-COSY
Beam Position Monitors	Polarimetry
(…)	Spin Coherence Time
	Cooling
	(…)

Spin Tracking

BNL	FZJ
	Study Group
DOE-Proposal	Precursor; Ring Design
CD0, 1, …	HGF Application(s)
pEDM Ring at BNL	**JESS**

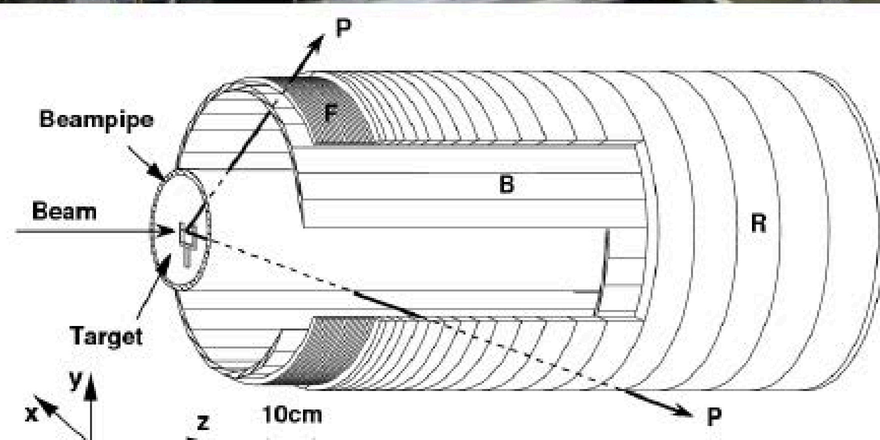


EDDA detector

32 bars measure azimuthal angle

rings measure scattering angle

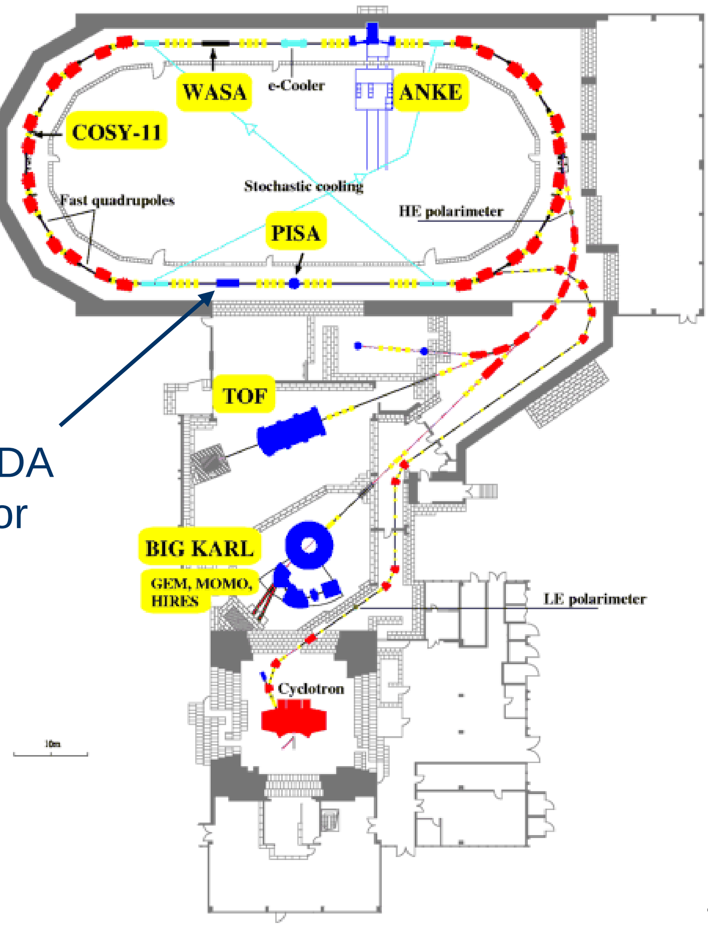
Operate as stopping detector for deuterons, sets beam momentum to be p = 0.97 GeV/c



Thick carbon target used for continuous extraction and high efficiency

Polarimeter Development
COSY tests

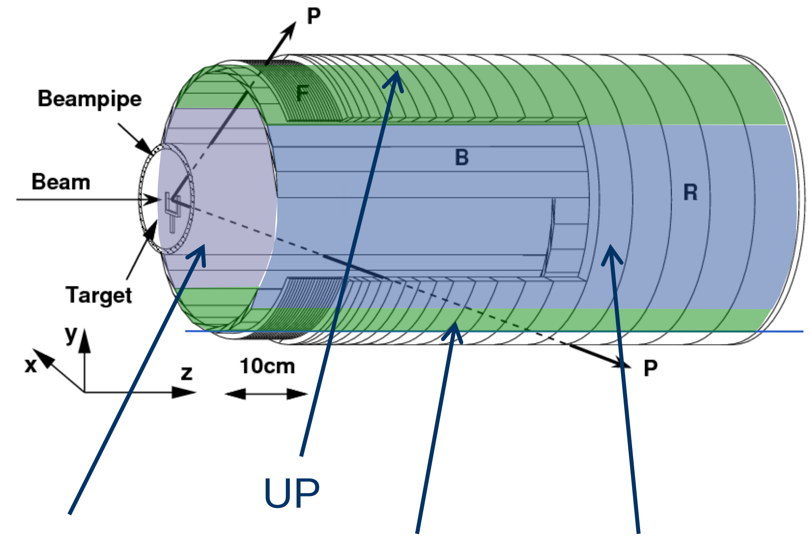
COSY ring:



Use EDDA detector

EDDA detector:

Rings and bars to determine angles.

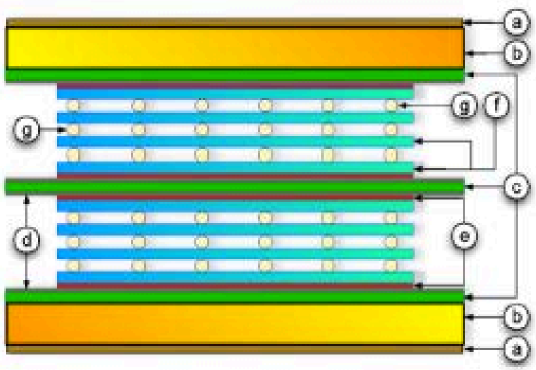


Azimuthal angles yield two asymmetries:

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

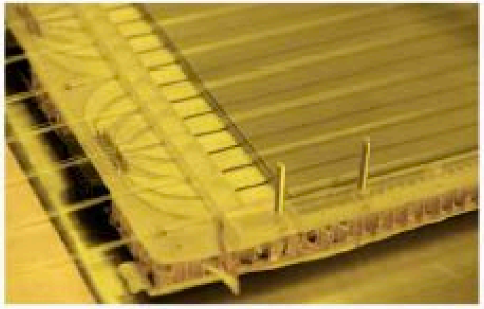
Detector systems: alternatives to scintillators

A Multi-resistive plate chambers(Italy)

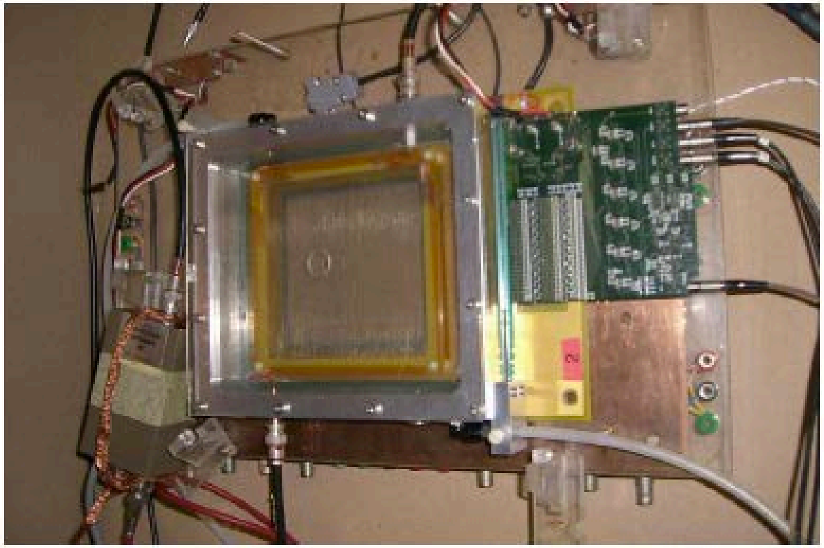


pickup electrodes (green) also shown in photograph

The 20cm x 50cm prototype



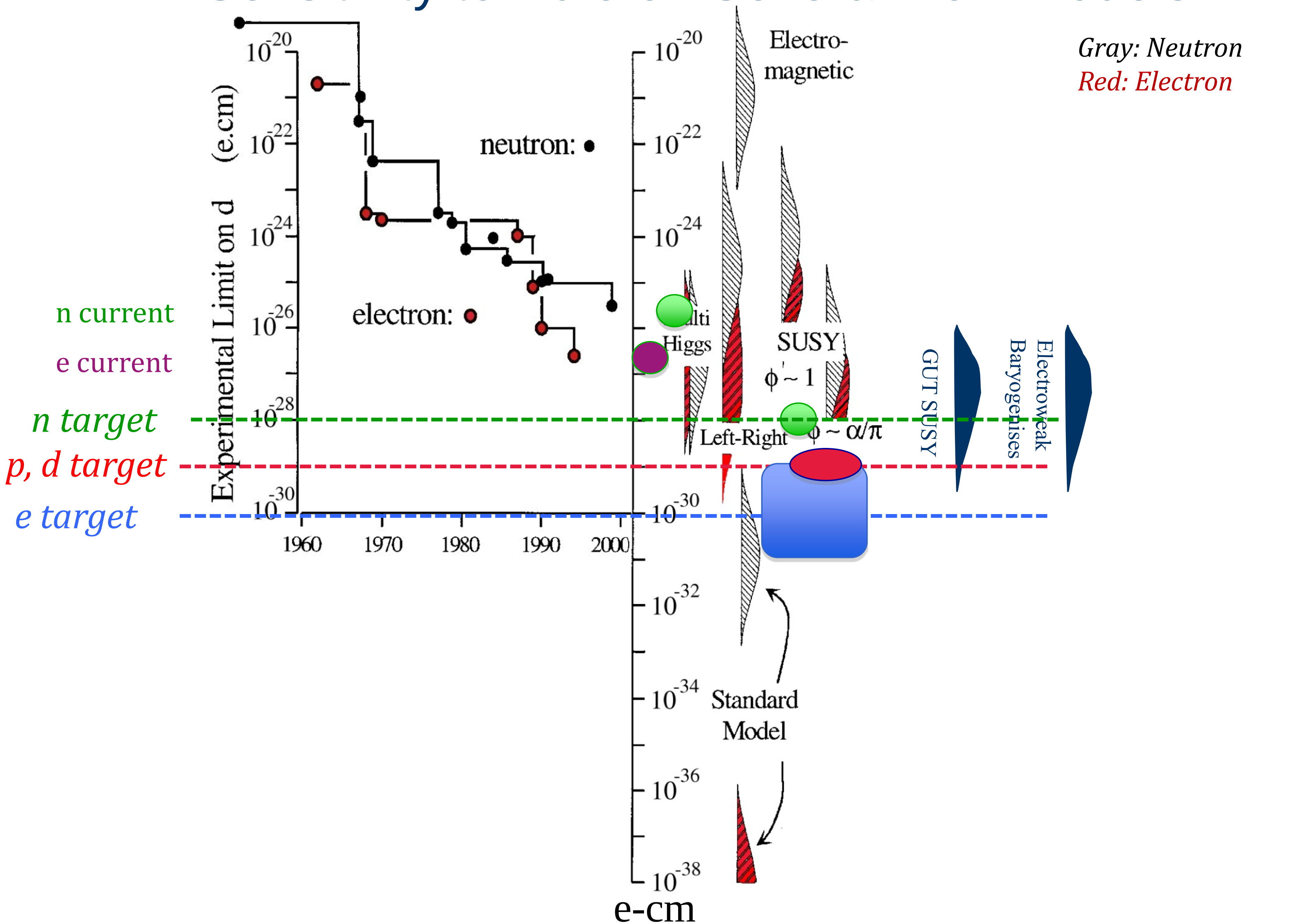
B Micro-megas avalanche detection system Greece)



C Gas electron multiplier (GEM) system

In-beam tests are needed (COSY) to provide sample data sets.

Sensitivity to Rule on Several New Models



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

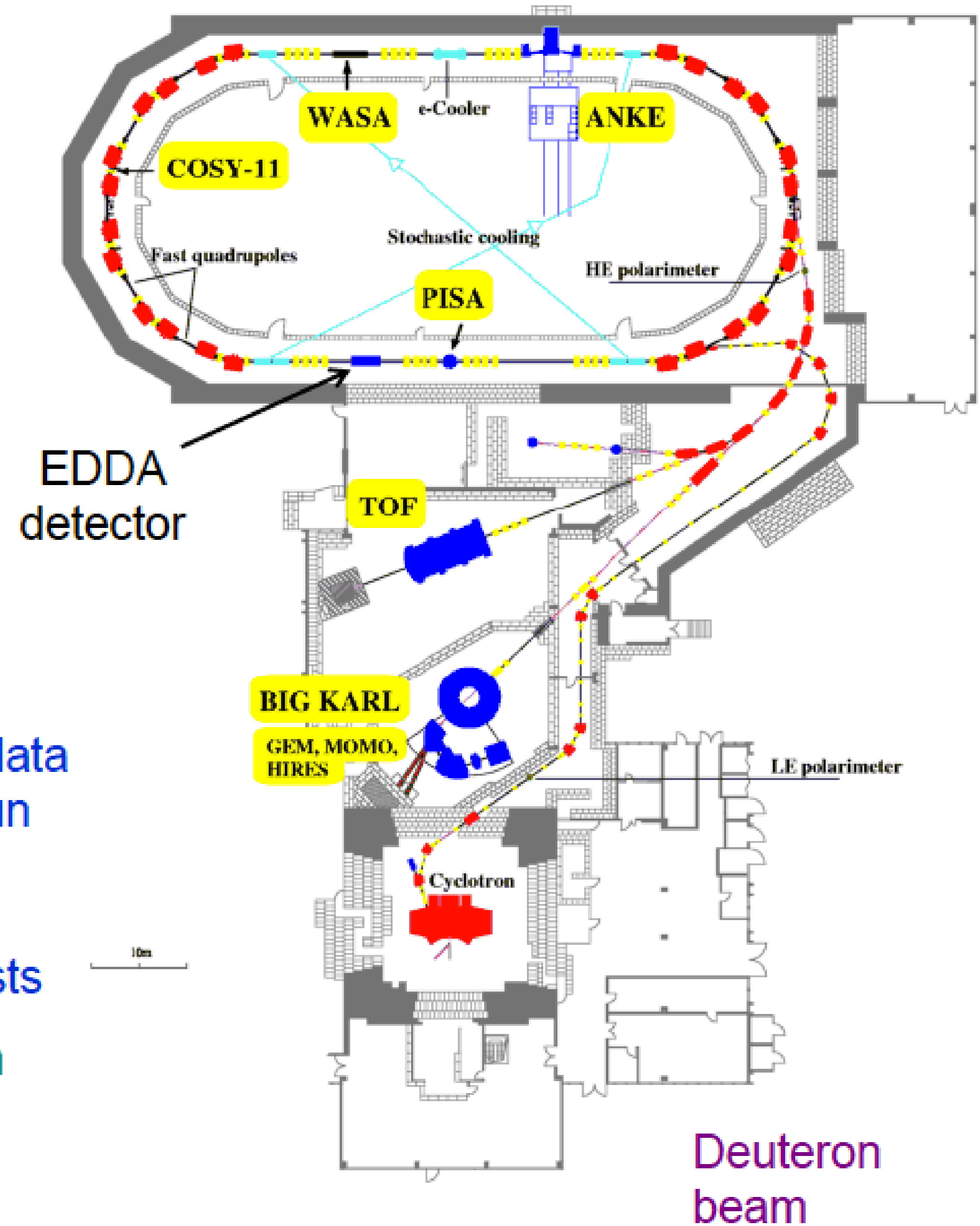
Why COSY?

- Scale like EDM ring
- Polarized P/D beams
- Electron cooling
- Outside user program
- Available equipment

History

- Proposal in 2007
- Visit SPIN@COSY run
- Three polarimeter runs:
  - June 2008 – initial tests
  - September 2008 – trial data
  - June 2009 – final long run (paper in preparation)
- Polarization lifetime runs:
  - January 2011 – initial tests

Prior work at KVI, Groningen
- d=C data, 2004 + 2005
- Systematic errors, 2007



In conclusion

BPMs:

- A combination of passive and active magnetic shielding
- Using proven techniques (Romalis et al.)

- Risk factor: high (even though using existing technology, it needs to be proven in accelerator environment)

cont’d

SCT:

- Lattice: to 1st order SCT is ~10s. Use sextupoles to achieve ~200-500s.
- Tracking studies underway to fine tune the specs

- SCT January run 2011 at COSY a great success. Mixing w/ cooling eliminates the issue. Observed SCT w/ cooling >500s! Studying stochastic cooling for the experiment
- Risk factor: low/medium

cont'd

Software development:

- Accurate beam and spin dynamics tracking based on 4th order RK integration.
- It's slow: 10 h CPU for 10 ms tracking
- It confirmed estimation of tunes, radial B-field effect, tune modulation, etc.
- Studying SCT dependence on lattice parameters, E-field plate shape, etc.
- Fast UAL+SPINK is used for SCT @ COSY
- Plus UAL+ETEAPOT for all-electric; more…
- Risk factor: low

cont'd

E-field strength:

- ~10MV/m for 3 cm plate separation. Stainless steel and high pressure water rinsing (HPWR) is below expected E-field limit
- Challenge: QA is critical for large area plates
- Risk factor: low

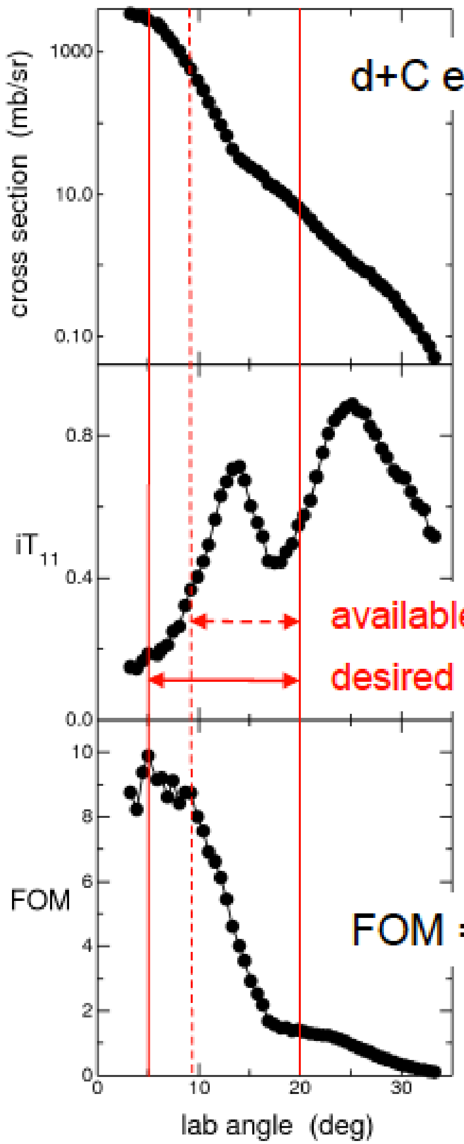
cont'd

Polarimeter:

- Polarimeter data have been analyzed, long paper to be submitted
- Expected systematic error <<1ppm

- Risk factor: low

Deuteron case



d+C elastic, 270 MeV

available at COSY

desired range

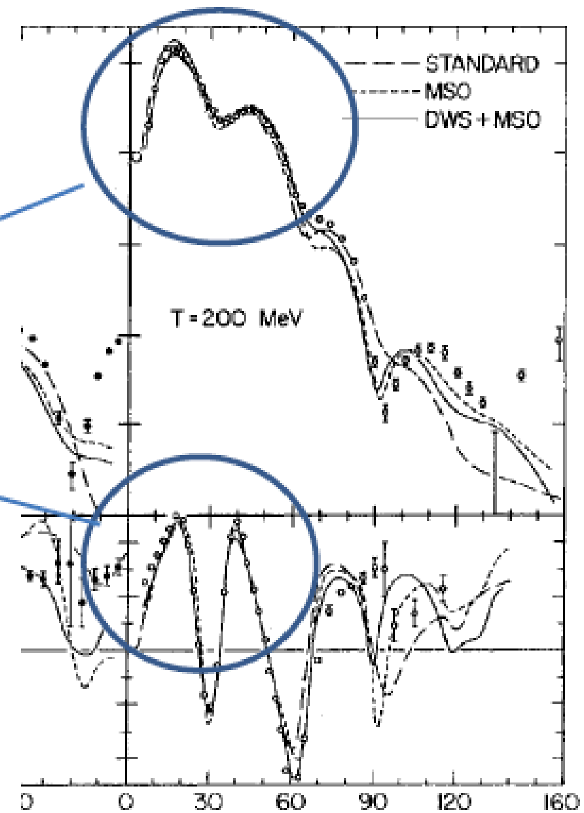
FOM = σA^2

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

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 2π)

analyzing power ~ 0.6

with some selection on elastics

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.)

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

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

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	$<3\times10^{-29}$	$<10^{-29}$	10^{-25}-10^{-26}
^{129}Xe atom	$<6\times10^{-27}$	$\sim10^{-29}$-10^{-31}	10^{-25}-10^{-27}
Deuteron nucleus		$\sim10^{-29}$	3×10^{-29}-5×10^{-31}
Proton nucleus	$<7\times10^{-25}$	$\sim10^{-29}$	10^{-29}

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

Analyzing power can be further optimized

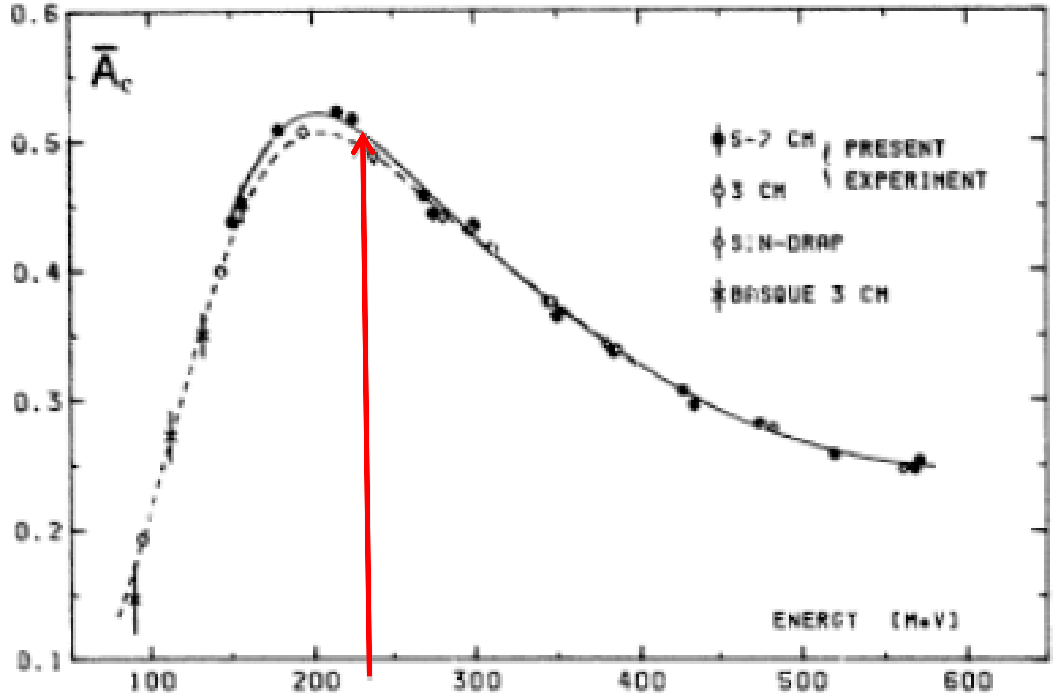


Fig. 4. Angle-averaged effective analyzing power. Curves show our fits. Points are the data included in the fits. Errors are statistical only

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.

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: cancellation level needed for 10^{-28}e-cm is of order 3pG.

EDMs of different systems

Theta_QCD:

$$d_n \simeq -d_p \simeq 3\times 10^{-16}\,\overline{\theta}\ \mathrm{e\cdot cm}$$

$$d_D\left(\overline{\theta}\right)/d_N\left(\overline{\theta}\right) \approx 1/3$$

Super-Symmetry (SUSY) model predictions:

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

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

$$d_D \simeq \left(d_u + d_d\right) - 0.2e\left(d_u^c + d_d^c\right) - 6e\left(d_u^c - d_d^c\right)$$

$$d_N^{I=1} \simeq 0.87\left(d_u - d_d\right) + 0.27e\left(d_u^c - d_d^c\right)$$

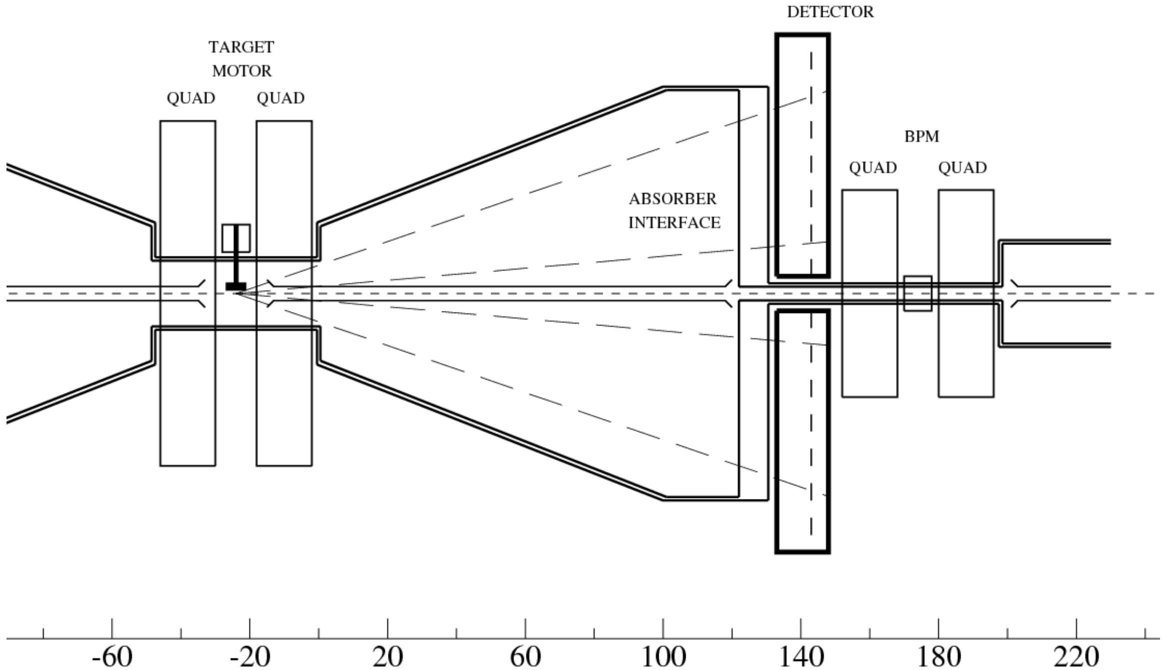
$$d_N^{I=0} \simeq 0.5\left(d_u + d_d\right) + 0.83e\left(d_u^c + d_d^c\right)$$

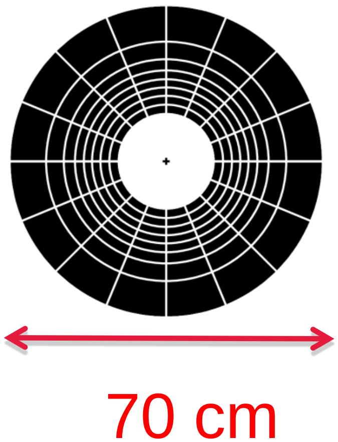
$$d_N^{I=1} = \left(d_p - d_n\right)/2$$

$$d_N^{I=0} = \left(d_p + d_n\right)/2$$

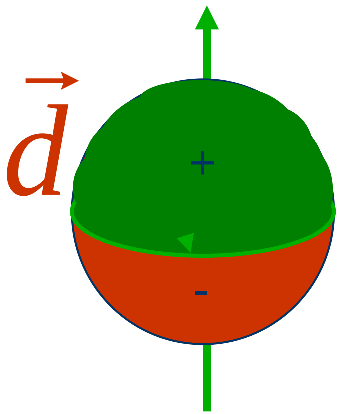
Polarimeter rates:

•Beam intensity with 2×10^{10} pol. protons/ ~10^3s and a detection efficiency of 1% → 200KHz for ~3000cm^2 area, or ~100Hz/cm^2 on average but much higher at small radius. Design: ~1KHz/pad.





The Electric Dipole Moment precesses in an Electric field



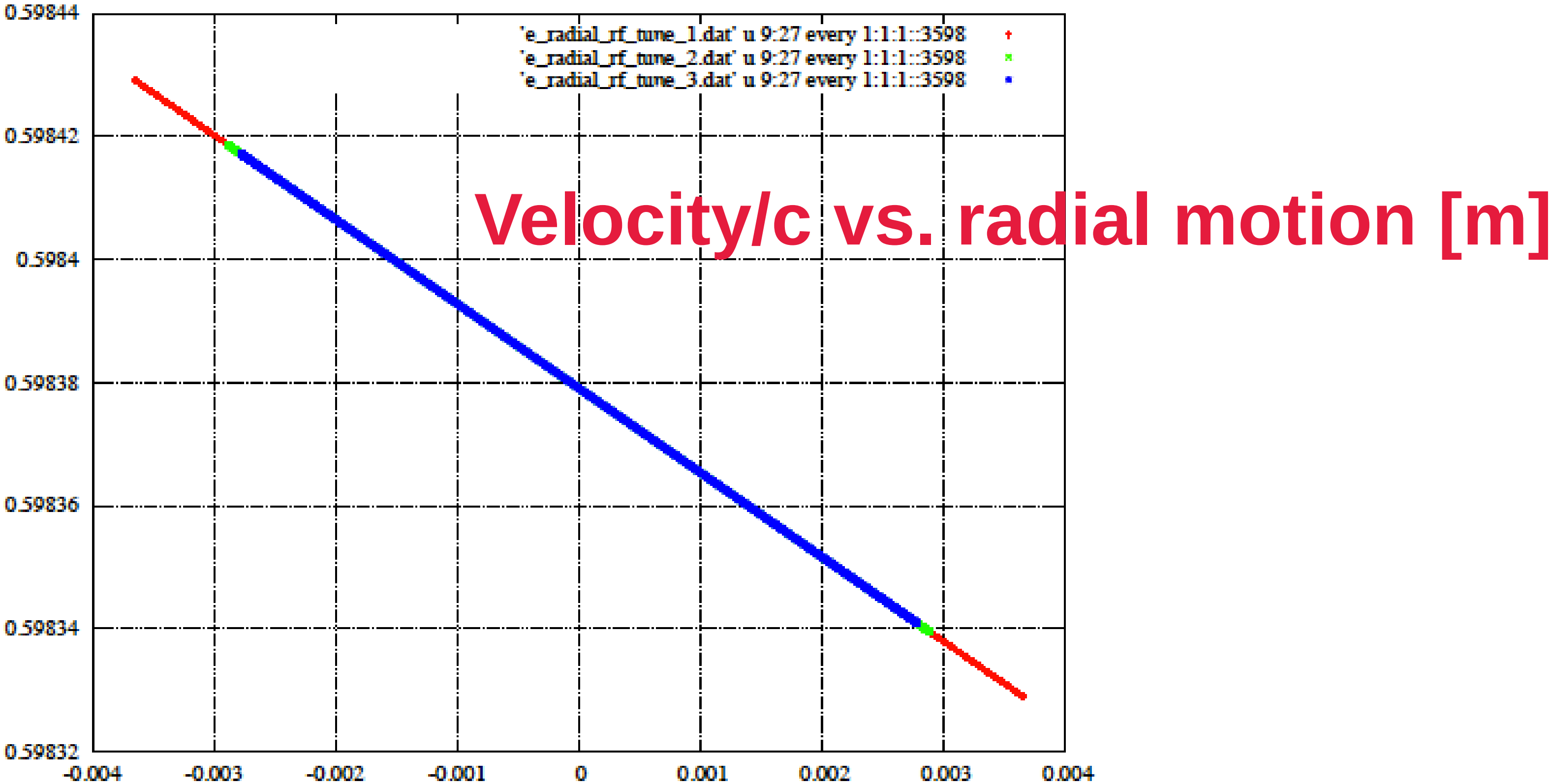
The EDM vector *d* is along the particle spin direction

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

Yannis Semertzidis, BNL

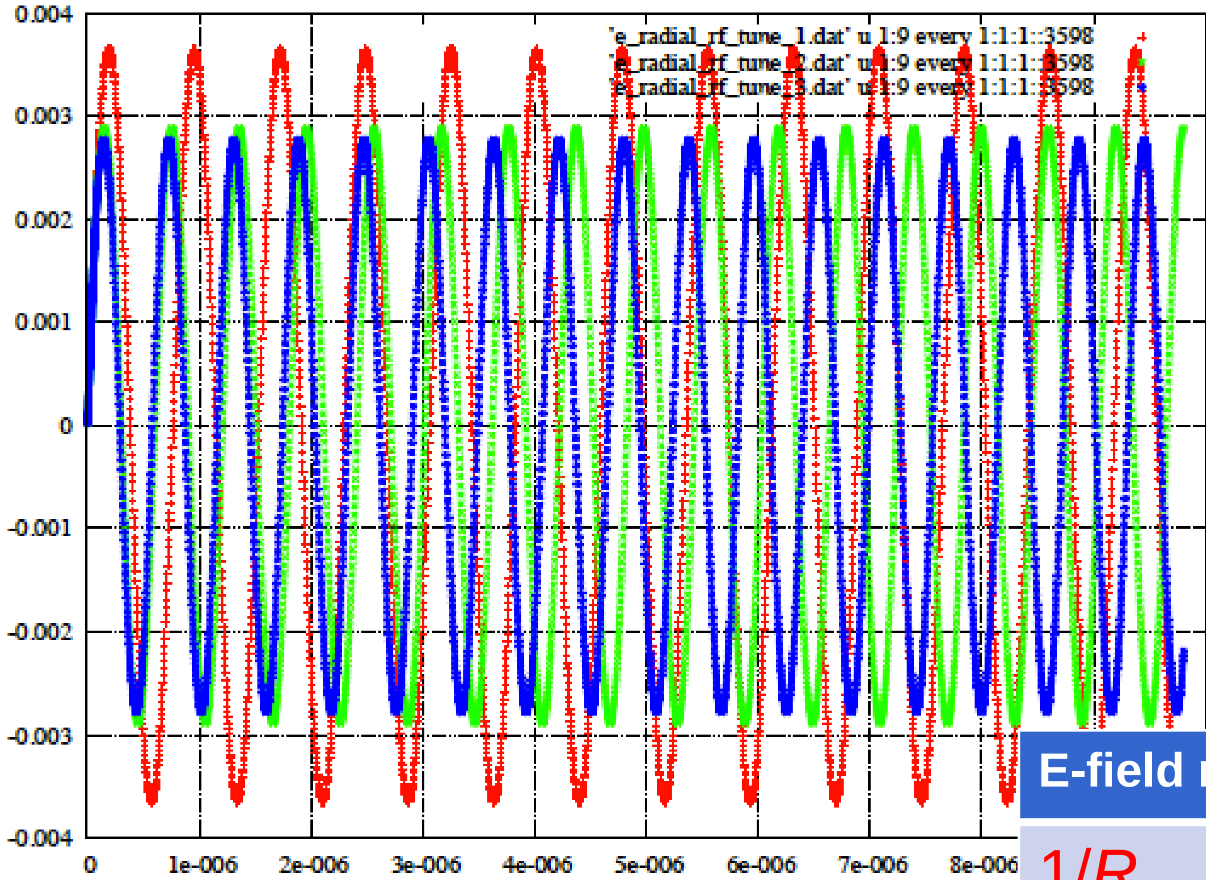
Software development

- Two competing requirements: accuracy, speed
- Total storage ~10^9 revolutions, ~1.5μs/rev.
- E-field complication: Kinetic energy changes with radial oscillations → horizontal focusing



Software development

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



Three different E-field 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

Radial motion [m] vs. time [s]

Software development

- 4^{th} order R.K. integrator (accurate but slow, 10^4 revolutions in ~10 hours CPU)

- Analytic integration with UAL+ ETEAPOT; UAL + SPINK: Fast enough,…

BPMs (high risk item/ must prove before construction approval)

- A radial B-field would cause an EDM-like spin precession AND would split the vertical position of the counter-rotating beams

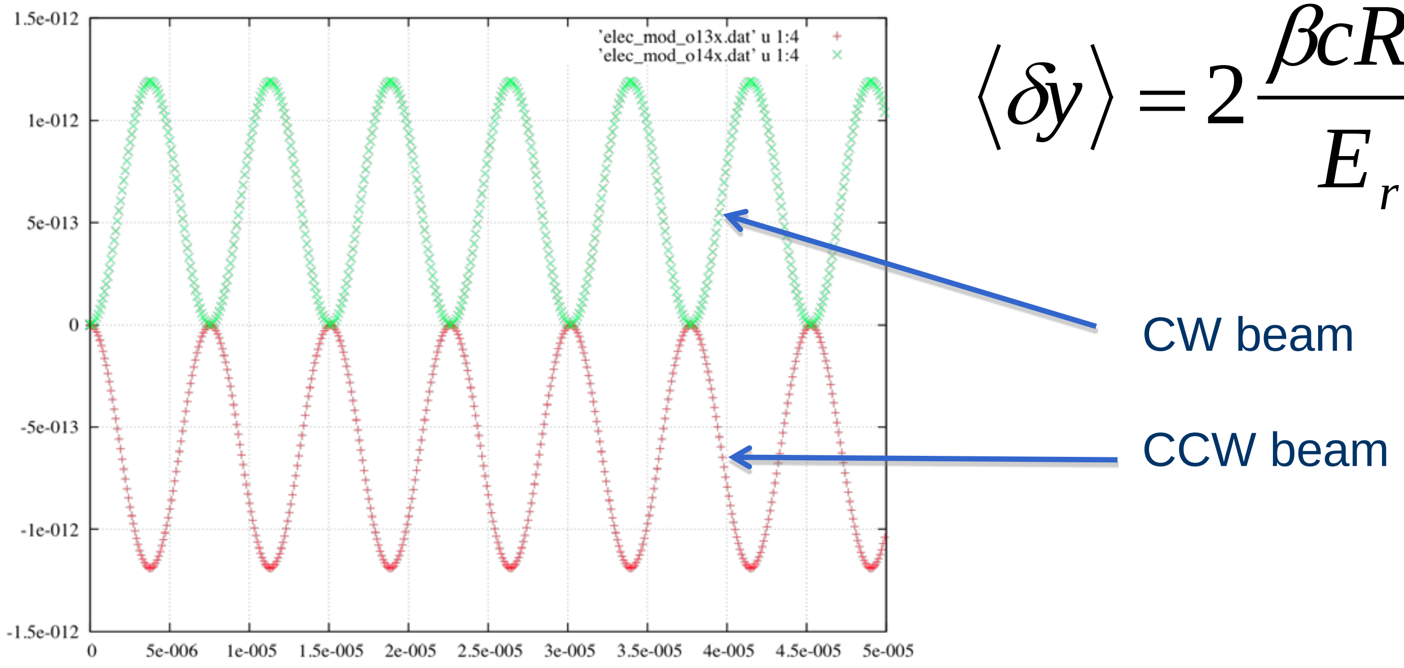
- The splitting depends on the vertical tune Q_y

$$\langle \delta y \rangle = 2\frac{\beta c R_0 B_{r0}}{E_r Q_y^2} \sim 2\,pm$$

BPMs

- The splitting depends on the vertical tune Q_y
- Modulating Q_y would create a frequency dependent separation and a B-field at the same frequency.

Vertical position vs. time



$$\langle \delta y \rangle = 2\frac{\beta c R_0 B_{r0}}{E_r Q_y^2} \sim 2\,pm$$

BPMs

- Developed and installed a resonant BPM in IP10 of RHIC; resonance ~100MHz
- Statistics adequate for S/N=1 per day
- Estimated systematics large (BPM alignment, bunch parameters,…). Will still take data for diagnostics…

- We took a conservative approach instead: use near-DC effect → B-field generated by the beam itself (position modulated only when $\langle B_{r0} \rangle \neq 0$).

Low T_c SQUIDS as BPMs

- Place them behind a shield (protect from the high frequency beam noise)
- Look at the vertical tune modulation frequency
- Minimize B-field noise from shields (important)
- Direction sensitive

- Commercially available SQUIDS have enough sensitivity. Expect S/N>6, for 10^{-29}e•cm
- Plan to develop it and install it in RHIC ($0.6M)

So what are the BPM issues?

- B-field noise: addressed by shielding + feedback

- Vibrations: Commercial SQUID system with vibration damping has noise figure plenty good enough

What are NOT BPM issues?

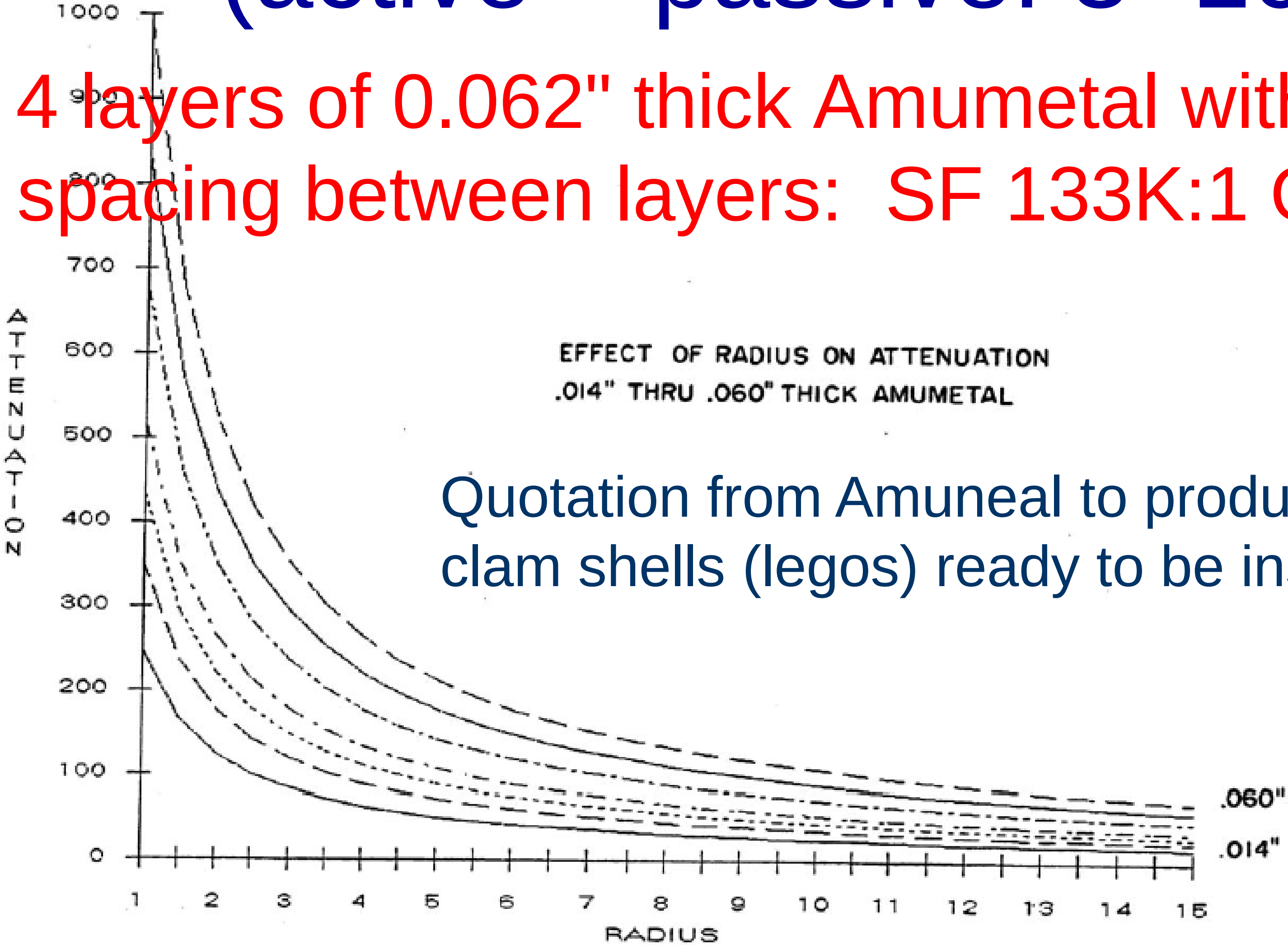
- Electronics rack temperature stability. NSLS II: two BPMs sense the absolute position of beam. They require 0.1C stability for 200nm resolution

- EDM ring: One BPM senses the difference between two C.R. beams at the modulation frequency. (Kurt Vettel responsible for NSLS II BPMs just joined the collaboration.)

- Ring temperature stability: just as any other accelerator

Magnetic shielding (active + passive: 3×10^8)

4 layers of 0.062" thick Amumetal with 3" spacing between layers: SF 133K:1 OD 35”



Quotation from Amuneal to produce 4 layers of clam shells (legos) ready to be installed.

Magnetic shielding options (active + passive: 3×10^8)

4 layers of 0.062" thick Amumetal with 3" spacing between layers: SF 133K:1 OD 35”

Item	Part	Rev	Description	Lead Time
3	17014-03	A	SREDM Magnetic Shielding - 4 Layers of .062" Thick Amumetal	

1. This is a budgetary quote for a three layer clamshell magnetic shield to shield an approx 277 foot diameter ring.

2. Shield to be fabricated using .062" thick Amumetal, which conforms to MIL-N-14411C, Comp. 1 and ASTM A753-02, Alloy Type 4.

3. 3.00" spacing between shield layers.

4. Shields will be supplied as half cylinders with a 2.00" overlap in 60.00 long segments (two 30" segments assembled with joiner band).

5. Quoting spacers between layers to be fabricated from High Density Polyethylene (HDPE) plastic.

6. Price includes a one time engineering/programming charge, plus commercial truck freight to Brookhaven National Laboratory, Upton, NY 11973.

Quantity	Unit Price	Extended Price
1.00	$5,560,858.00 EA	$5,560,858.00

Parameters of current lattice

Table 2. The table of parameters for the proton EDM ring is shown here. The lattice has been estimated using the exact electric field and not an effective dipole magnetic field.

Parameter	**Value**	**Comment**
Proton Momentum	0.7007405 GeV/c	Kinetic energy: 232.8 MeV, $\beta = 0.59838$, $\gamma = 1.2481$
Ring bending radius	40 m	
Total length of straight sections	11.6 m	If more straight section length is needed the ring bending radius has to increase proportionally.
Radial E-field strength	10.5 MV/m	For plate separation of 3 cm the voltage on the plates is about ±160 KV.
Number of sections	16	The E-field plates within a section are ~16m long each. They can be segmented into 5 pieces, 3.14 m long each.
Radial E-field dependence at y=0	$R^{0.2}$	The E-field is slightly increased at larger radius.
Total length of orbit	263 m	
Horizontal tune	1.3	
Vertical tune	0.2-0.1	To be modulated by ~10% around 0.1
$\beta_{x,max}$	28 m	Horizontal aperture: 3 cm
$\beta_{y,max}$	240 m	Vertical aperture: 8 cm
Cyclotron frequency	0.6839 MHz	
$f_{rf} = 135 \times 0.6839$ MHz	90 MHz	Total RF voltage: 5 KV for synchrotron tune of 0.01
Slip factor	0.45	Sign is – (TBC)

Why does the world need a Storage Ring EDM experiment at the 10^{-29} e-cm level ?

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

Magnetic field shielding issues

- Reduce the N=0 Fourier component of the radial magnetic field around the ring to below 0.02nG level, when its frequency dependence is below mHz. Higher frequency (f_2) B-fields need to be below (f_2/f_1)*0.02nG level.

- For N>0, the field needs to be reduced below $(N/0.1)^2 \times (f_2/f_1) \times$0.02nG level

- A combination of a passive shield (10^4-10^5) and an active feedback (~10^4) will be used.

Radial B field splits CW and CCW beam in vertical direction

- Lorentz force from B_r of opposite sign for CW and CCW beams $\Rightarrow$ they split vertically
- Expanding $\boldsymbol{B}_r$ in multipoles, write the equation of motion in vertical y :

$$\frac{d^2y}{d\theta^2} + Q_y^2 y = \frac{\beta c R_0}{E_r} \sum_{N=0}^{\infty} B_{rN} \cos\left(N\theta + \phi_N\right)$$

- This has solutions :

$$\delta y(\theta) = \pm \sum_{N=0}^{\infty} \frac{\beta c R_0 B_{rN}}{E_r} \left[\frac{1}{Q_y^2 - N^2}\right] \cos(N\theta + \phi_N) + y_0 \cos(Q_y\theta + \phi_Q),$$

- Q_y is vertical betatron tune, last term is vertical betatron oscillation
- Distortion of equilibrium orbit of opposite sign for the CW and CCW beams
- Only N=0 term, B_{r0}, leads to $\langle \delta y_{CW} - \delta y_{CCW} \rangle \neq 0$
- With vertical tune $Q_y \approx 0.1$, average vertical displacement of each beam :

$$\delta y = \pm \frac{\beta c R_0 B_r}{E_r Q_y^2} = \pm \frac{0.6 \times 3 \times 10^8 \text{ m/s} \times 40 \text{ m} \times 2.2 \times 10^{-17} \text{ T}}{10.5 \times 10^6 \text{ V/m} \times 0.1^2} = \pm 1.5 \times 10^{-12} \text{ m}.$$

$\Rightarrow$ Net radial magnetic field B_r of 2.2×10^{-17} T splits the CW and CCW beams vertically by $\approx$ 3.0 pm

High sensitivity magnetometry of small magnetic fields

- At least two approaches have demonstrated ability to detect such fields
- (i) K SERF magnetometer developed by M. Romalis' group at Princeton
  (J.C. Allred, R.N. Lyman, T.W. Kornack, and M.V. Romalis, Phys. Rev. Lett. 89, 130801 (2002))
  - Have demonstrated sensitivity of ≈ 1 fT/$\sqrt{\mathrm{Hz}}$ at $\omega \approx 2\pi\times$ 50 Hz
    (T.W. Kornack, S.J. Smullin, S.-K. Lee, and M.V. Romalis, Appl. Phys. Lett. 90, 223501 (2007))
- (ii) Commercially available low temperature superconductor DC SQUIDs (LTS dc SQUIDs)
  - Systems from Tristan Technologies have demonstrated $\delta B \leq 1$ fT/$\sqrt{\mathrm{Hz}}$
  - http://www.tristantech.com
  - Many examples in literature of non-commercial devices with similar sensitivity
    (0.7 fT/$\sqrt{\mathrm{Hz}}$ by W. Vodel and K. Mäkiniemi, Meas. Sci. Technol. 3, 1155 (1992))
  - Systems primarily developed for study of heart and brain biomagnetic fields
- Will focus on solution using SQUIDs
  - Commercially available
  - Implementation and operation might be simpler than SERF magnetometers

$\Rightarrow$ System performance often limited by magnetic field noise - not the magnetometer

$\Rightarrow$ Need to reduce magnetic field noise at ω_m below sensitivity of magnetometer

Parameters of a SQUID BPM system

- $\boldsymbol{B}$ field sensitivity depends on input current noise of SQUID and coil inductance
- For maximum sensitivity, need to match inductance of sense coil to input coil of SQUID
- For LSQ/20 LTS dc SQUID of Tristan Tech., input coil inductance $L \approx 1.8\mu$H
- A 4 turn coil, 4 cm long × 1.5 cm high (area of 6 cm^2) has $L \approx 1.6\mu$H
- LSQ/20 + flux locked loop and iMAG SQUID controller has $\delta I_{\rm noise} \leq 0.7$ pA/$\sqrt{\rm Hz}$
- Magnetic field sensitivity extracted from flux sensitivity :

$$\begin{aligned}
\delta\Phi_{\rm noise} = NA\delta\boldsymbol{B}_{\rm noise} &= \delta I_{\rm noise} \times (L_{\rm input} + L_{\rm sense}) \\
\delta\boldsymbol{B}_{\rm noise} &= \frac{(0.7 \times 10^{-12}\ {\rm A}/\sqrt{\rm Hz}) \times (3.54 \times 10^{-6}\ {\rm H})}{(4\ {\rm turns}) \times (6 \times 10^{-4}\ {\rm m^2/turn})} \\
&= 1.0\ {\rm fT}/\sqrt{\rm Hz}.
\end{aligned}$$

⇒ If ambient field noise at ω_m is ≤ 1 fT/$\sqrt{\rm Hz}$, combined noise ≤ 2 fT/$\sqrt{\rm Hz}$
⇒ A single system is sensitive enough to measure $\boldsymbol{B}_r$ to the required level

- Of course, would never rely on a single system
- Also want to improve $S/N \gg 1$

Summary and Conclusions

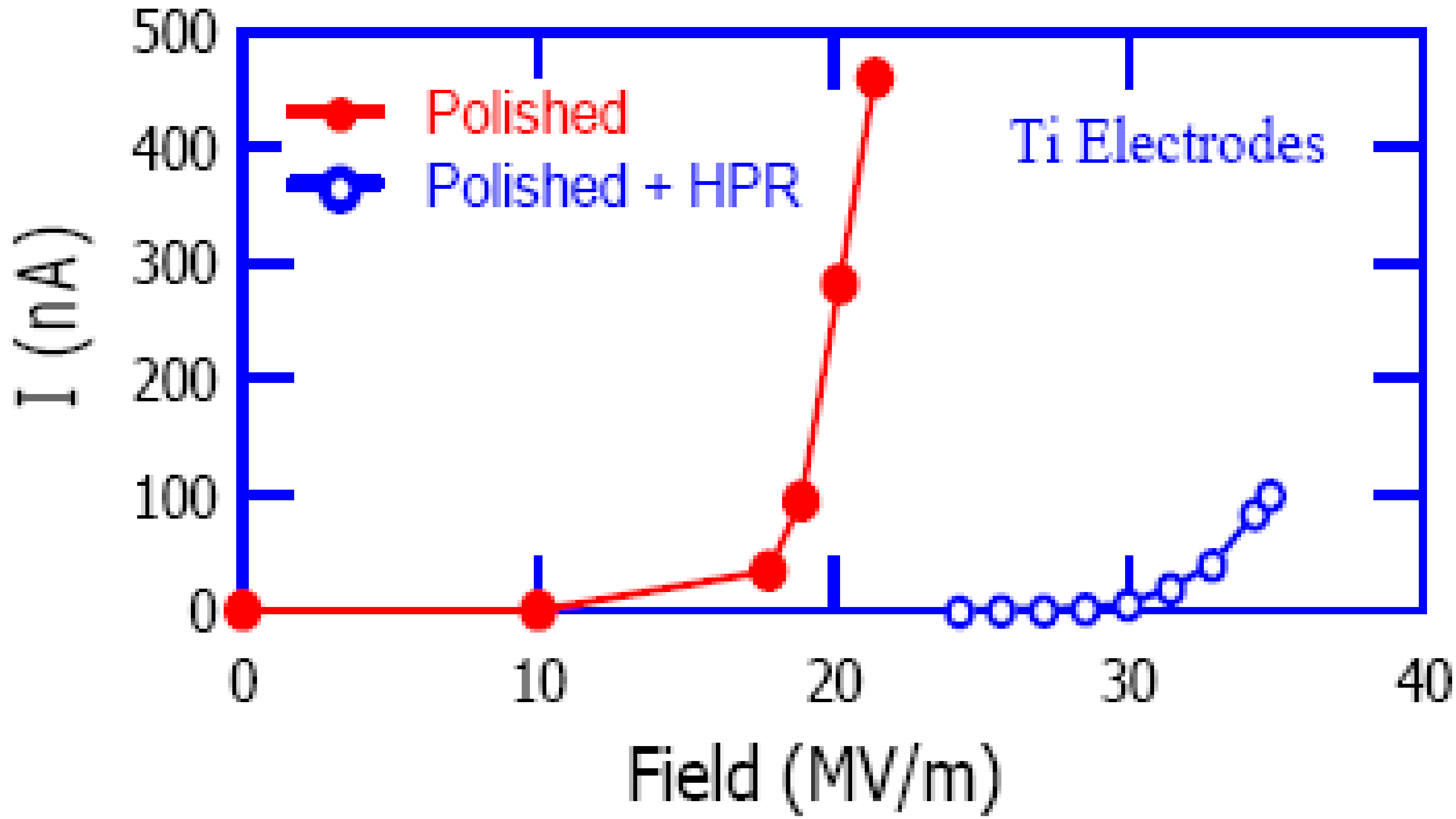
- Net radial magnetic field of 0.22 pG would causes precession equivalent to pEDM of $d_p = 10^{-29}$ e·cm
- This field would split the CW and CCW beams by 3 pm
- Magnetic field from beams split in vertical has radial component
- By modulating vertical tune, can look for this field using SQUIDs and lock-in amplifier
- Require sensitivity $\leq$ 1 fT/$\sqrt{\mathrm{Hz}}$ at ω_m
- A single SQUID magnetometer has this sensitivity
- Magnetic shielding with noise $<$ 1 fT/$\sqrt{\mathrm{Hz}}$ above 35 Hz has been demonstrated
- Large effort required :
  - Design cold finger/cryostat, integrate with other elements of experiment
  - Integration of SQUID controller output with lock in, DAQ, many parameters to be determined

$\Rightarrow$ Demonstrating that this works in storage ring environment will be necessary

$\Rightarrow$ Systematics : thermal, dimensional stability, ground motion, slow changes in B, ...

$\Rightarrow$ Great challenge and a great opportunity

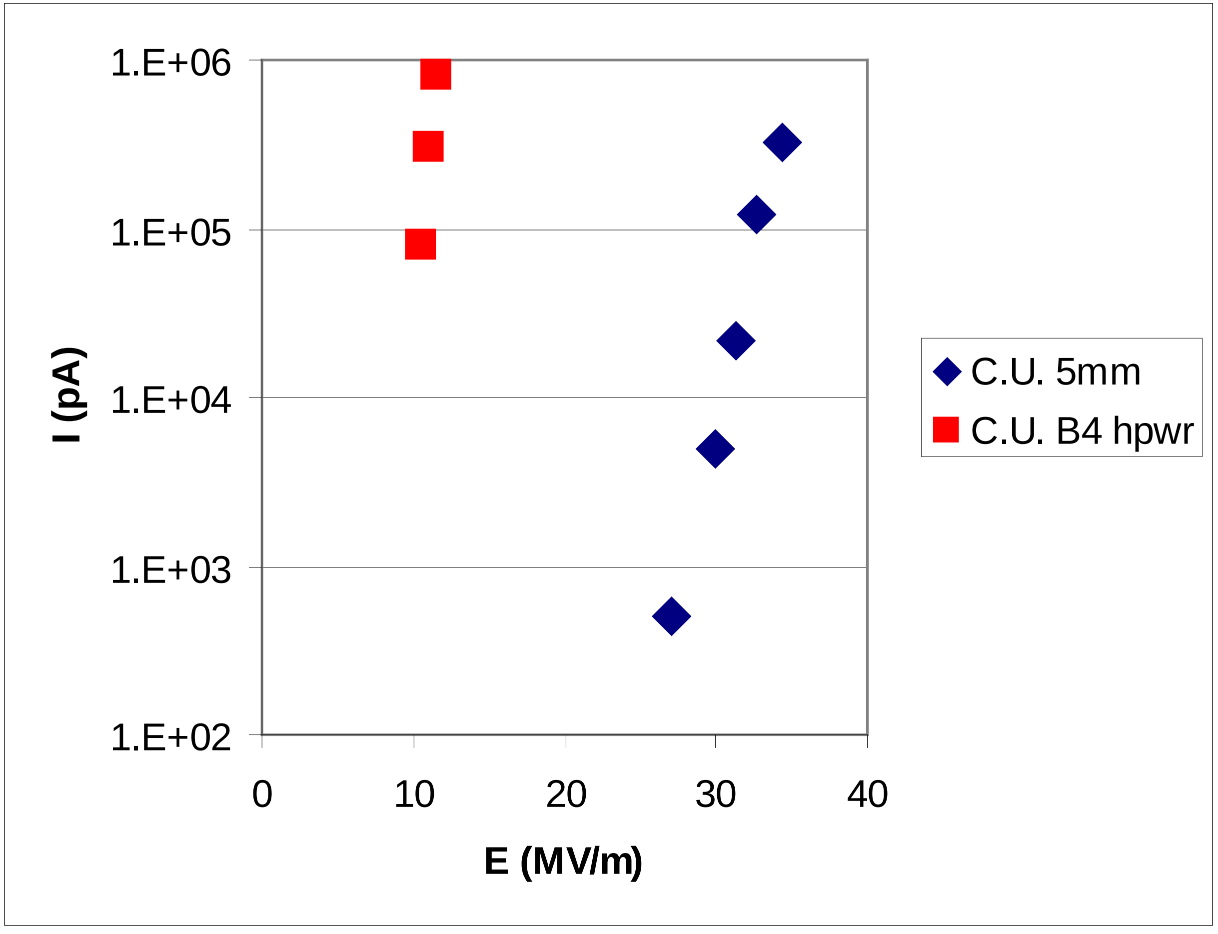
E-field strength



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)

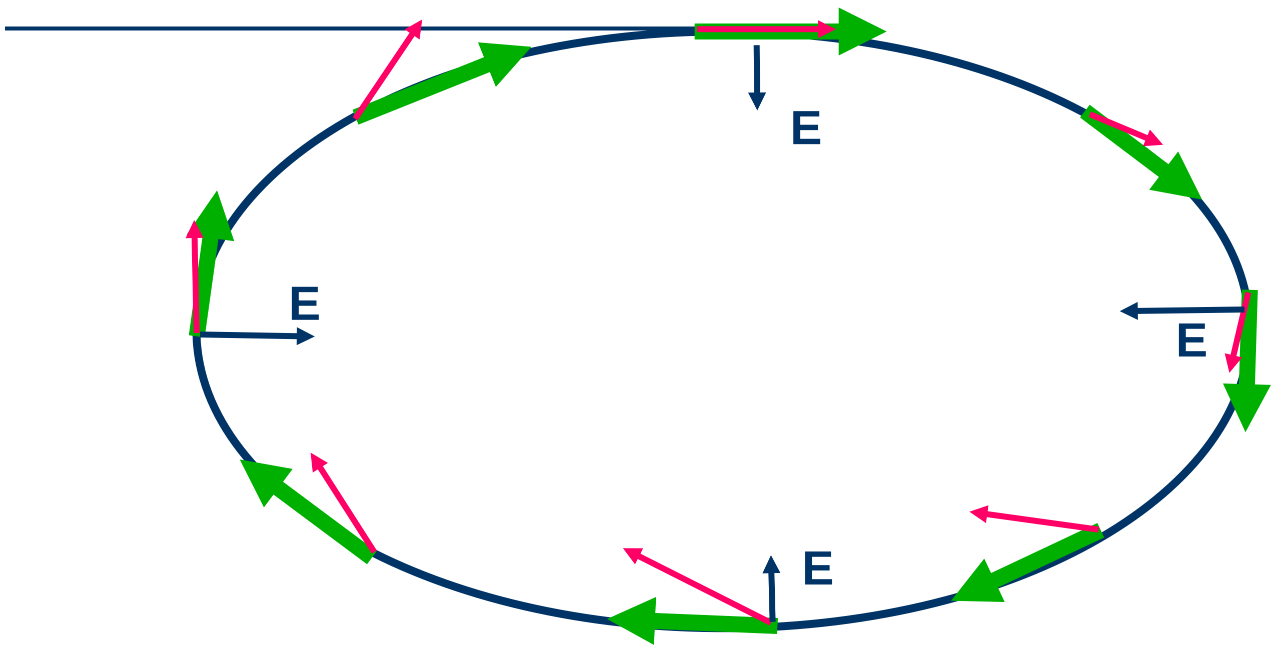
High Pressure Water Rinsing



Why Storage Ring EDMs?

- Storage rings offer a unique setting for a sensitive electric dipole moment (EDM) probe of charged particles. A number of simple systems can be probed with high accuracy: p, d, ^{3}He,…
- The mechanical (centrifugal) force balances the strong radial E-fields.
- Pencil-like, high intensity/high polarization beams of protons and deuterons have been around for decades.
- Ready for prime time.

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.



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

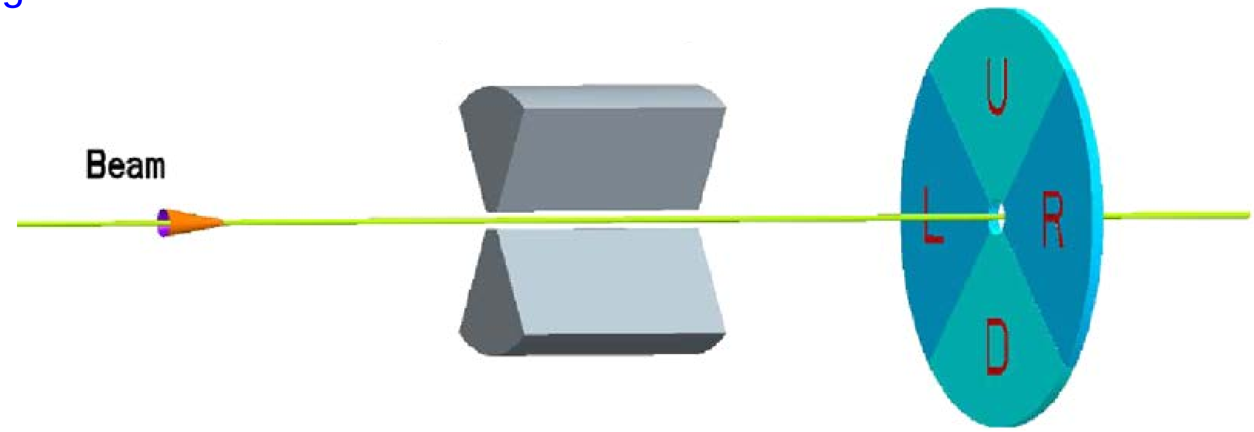
$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$

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 TPC detector and/or MRPC

Extraction: lowering the vertical focusing



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

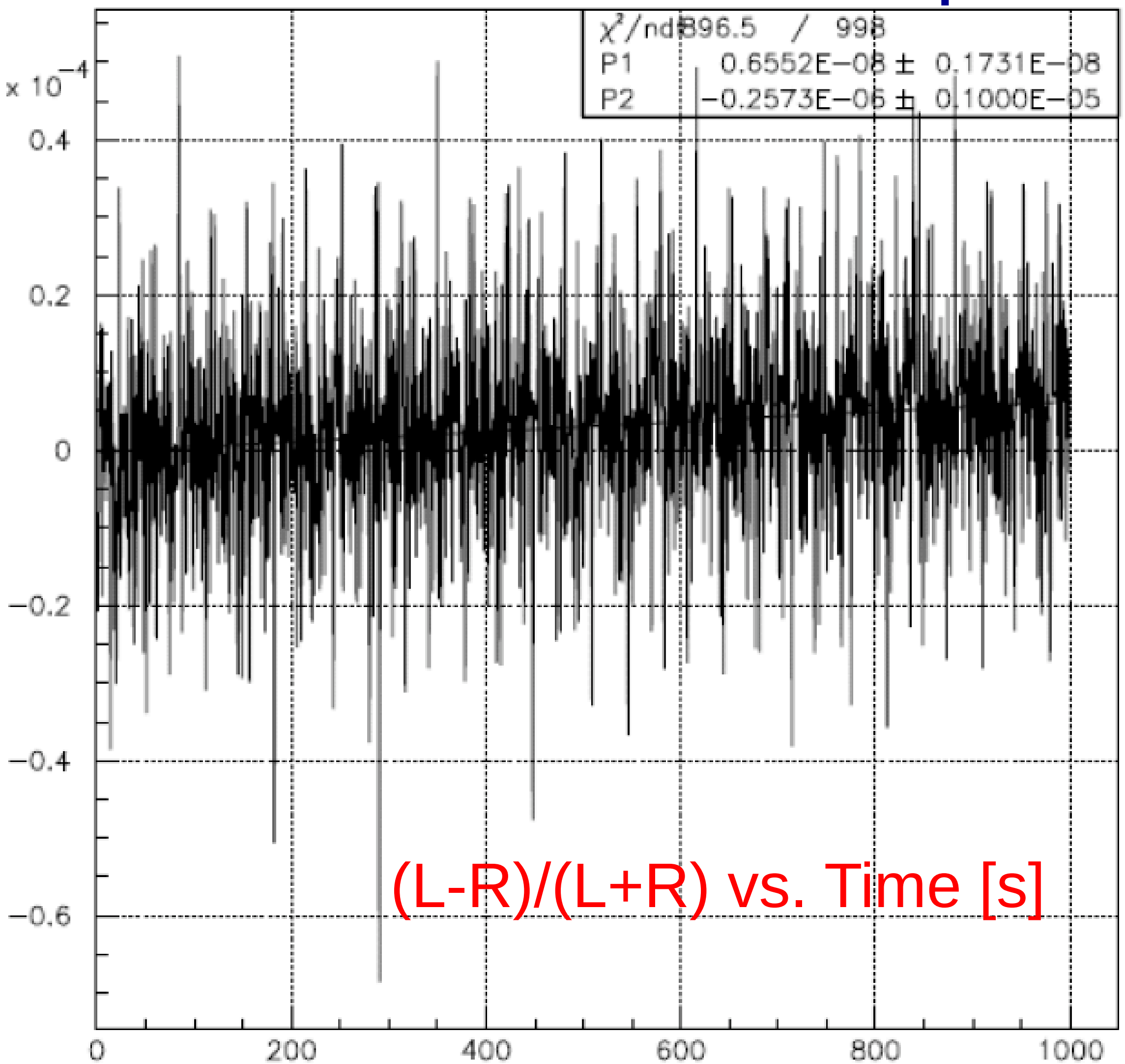
carries EDM signal
increases slowly with time

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

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

Freezing the horizontal spin precession

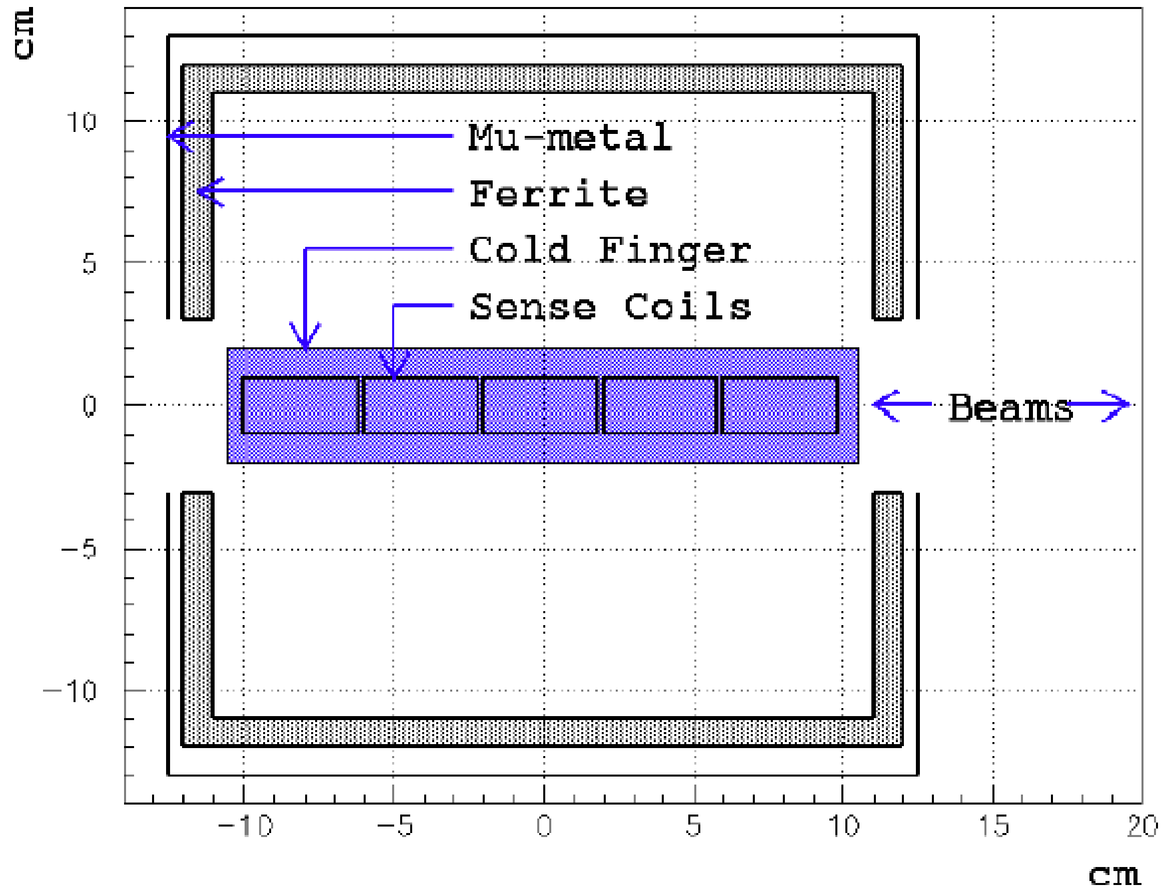
$$\vec{\omega}_a = \frac{e}{m}\left(a - \left(\frac{m}{p}\right)^2\right)\vec{\beta}\times\vec{E}$$

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

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

- The “magic” momentum concept was first used in the last muon g-2 experiment at CERN and BNL.

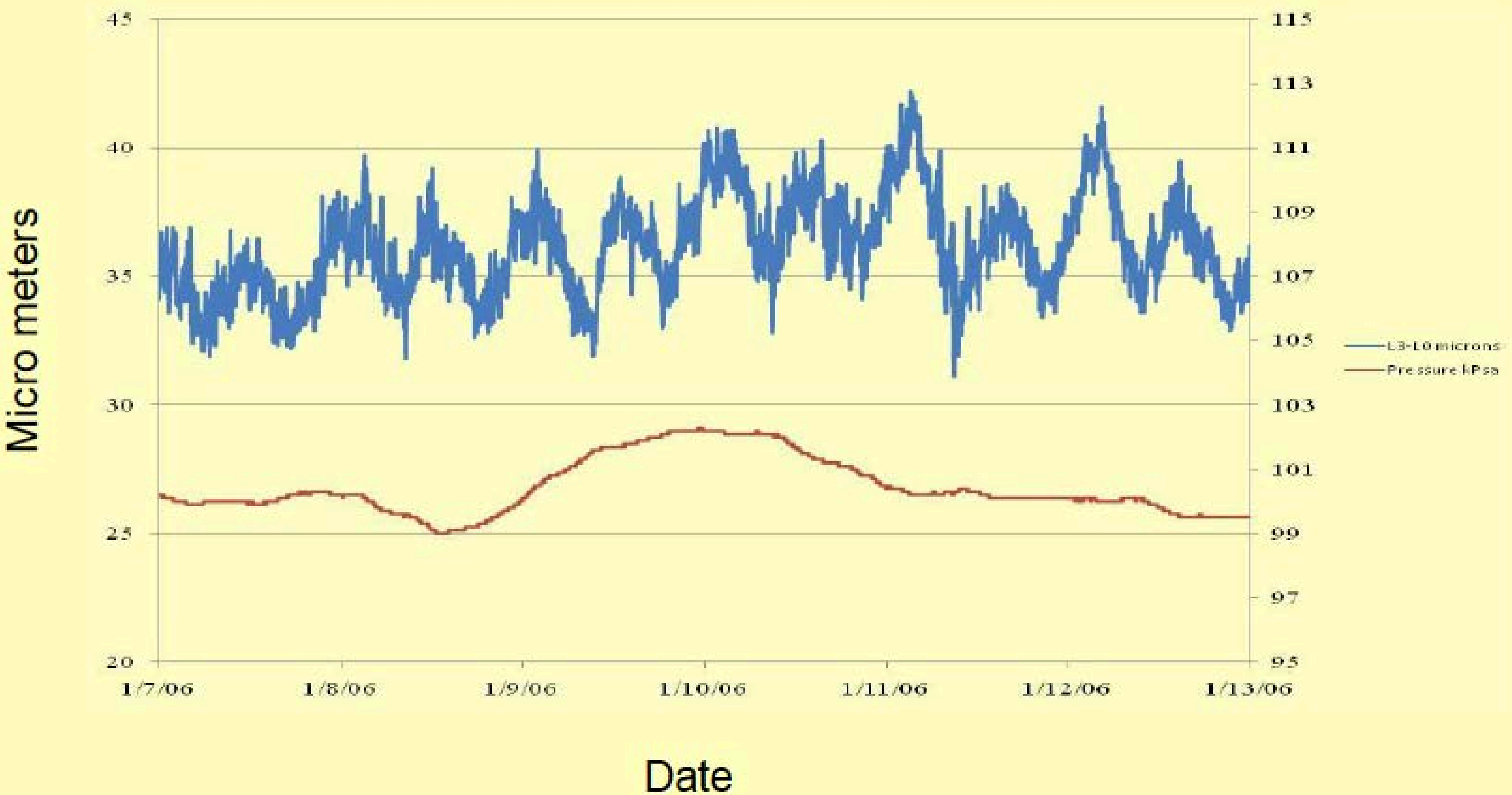
Schematic of a SQUID BPM system



- Side view schematic of a SQUID BPM system
- Sense coils, leads, SQUIDs at 4.2K; leads and SQUIDs in superconducting shields
- Ferrite and μ-metal at room temp, more magnetic shielding outside vacuum chamber

MINOS Tidal Data

Difference in two sensors 90 meters apart



J T Volk Fermilab Dec 2008

Expected stability of B-field

- 10μG at 1Hz (mainly due to solar activity)
- 0.1μG/m gradient (earth's dipole field)
- Human heart: 0.1μG (near chest wall)
- Shield factors of 10^4-10^5 for large systems are achieved with commercially available systems

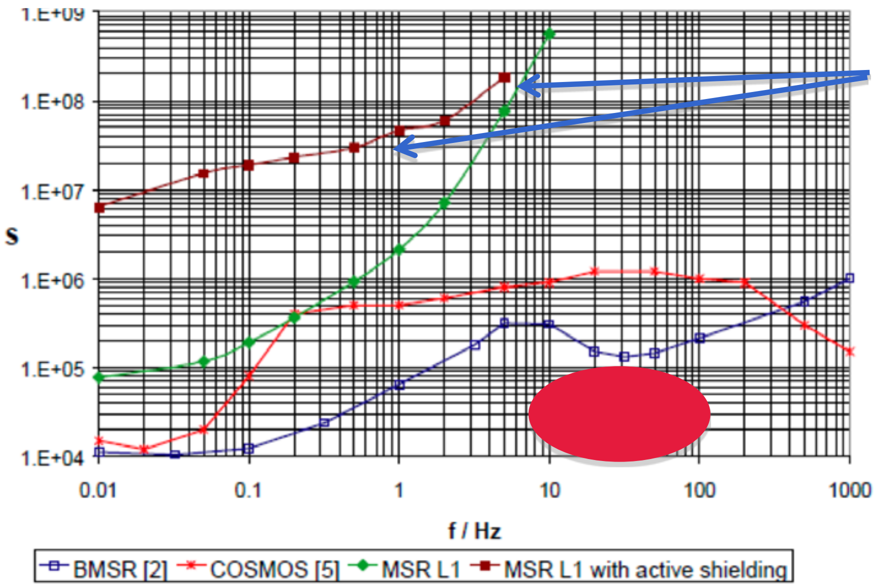


Figure 6: *Shielding factor over frequency for MSR L1 and other shielded rooms.*

Measured by applying 1μT oscillating field in the Berlin shielded room: 7 mu-metal layers and one thick Al-RF shield.

We would need a shielding factor of 10^4-10^5 at 10-100Hz for the modulation method to work.