26 March 2018
EDM Workshop, CERN/Geneva

Storage ring EDM experiment

Yannis Semertzidis, IBS/CAPP and KAIST

Proton, and deuteron

- Storage ring p,d EDMs @ <10^{-29}e-cm level, 10^3TeV physics reach.
- Priority on the proton EDM
- srEDM axion dark matter sensitivity 1710.05271, Korea

CPEDM collaboration with executive board

- Charged Particle EDM, a new collaboration, part of PBC at CERN

- Storage ring EDM collaboration (srEDM), BNL, Korea, …

- Juelich EDM Investigations (JEDI), COSY/Juelich

- CERN

CPEDM collaboration

What we bring on the table

- Storage ring EDM collaboration (srEDM)
  - First proposal to BNL, 2011
  - SQUID-based beam position monitors
  - High precision beam/spin dynamics simulations
  - Methods to achieve >10^3s polarization lifetime; polarim.; Polariz. dependence cross sections in GEANT4
  - Methods to reduce critical systematic errors (non-planarity of orbits, radial B-fields, …)
  - Additional physics with same ring (axion dark matter)

CPEDM collaboration

What we bring on the table

- Juelich EDM Investigations (JEDI)
  - Polarimeter systematic errors
  - State of the art polarimeter
  - Studies with polarized deuteron beams (stability of tune to better than 10^{-9} per hour, etc…)
  - Beam-based alignment (10um), Rogowski coils, etc.
  - RF-Wien filter for deuteron EDM studies
  - E-field deflectors (under development)

CPEDM collaboration

What we bring on the table

- CERN
  - Critical review of systematic error studies (fresh look at all levels-critically important)
  - Feasibility of polarized beams: creation, transfer, injection and storage into a ring

CPEDM collaboration

The ultimate goal is to design, build, and operate an all-electric ring for protons at their magic momentum (233MeV, 0.7 GeV/c) with CW/CCW injections & a sensitivity of order 10^{-29}*e*-cm. Build 30MeV prototype.

- Design of a realistic lattice
- Spin tracking
- Systematic error budget
- Technical realization

Feasibility study by December 2018

CPEDM work

Work package	Comments	Contributors	Coordination
Science case	• Up to date physics case for EDM • EDM landscape • Motivation for CP-EDM • Critical synthesis of storage ring systematics - can the experiment be done at the required sensivity?	KAIST/FZJ/CERN	Frederic Taubert (CERN) Themis Bowcock (Liverpool) In liason with Joerg Jaeckel (BSM WG lead)
Ring design	• All electric lattice • E/B lattice • Beam and spin dynamics • RF cavities		Yannis Semertzidis (CAPP/IBS & KAIST)
Beam control	• Cooling • Feedbacks		Joerg Pretz (FZJ)
Beam preparation	• Source, acceleration, injection, • Spin manipulation	FZJ/CERN	Beam delivery: Christian Carli (CERN) Spin manipulation NN (FZJ)
Ring components (1)	• RF, • Vacuum...	CERN	NN (CERN)
Ring components (2)	• Shielding, • Electrostatic deflectors, • ExB deflectors • Beam instrumentation (BPMs, SQUIDS...), • Beam and spin manipulators	KAIST/FZJ/CERN	Frank Rathmann
Polarimetry	• Proton • Deutron • Targets • Systematic errors	FZJ	Edward Stephenson (Indiana U.)
Systematics	• Magnetic fields • Alignment • Electric fields • CW/CCW effects	KAIST/FZJ/CERN	Yannis Semertzidis (CAPP/IBS & KAIST)
Siting at CERN	• Site • Civil engineering • Cost	CERN	Mike Lamont (CERN)

CPEDM collaboration, March 9, 2018

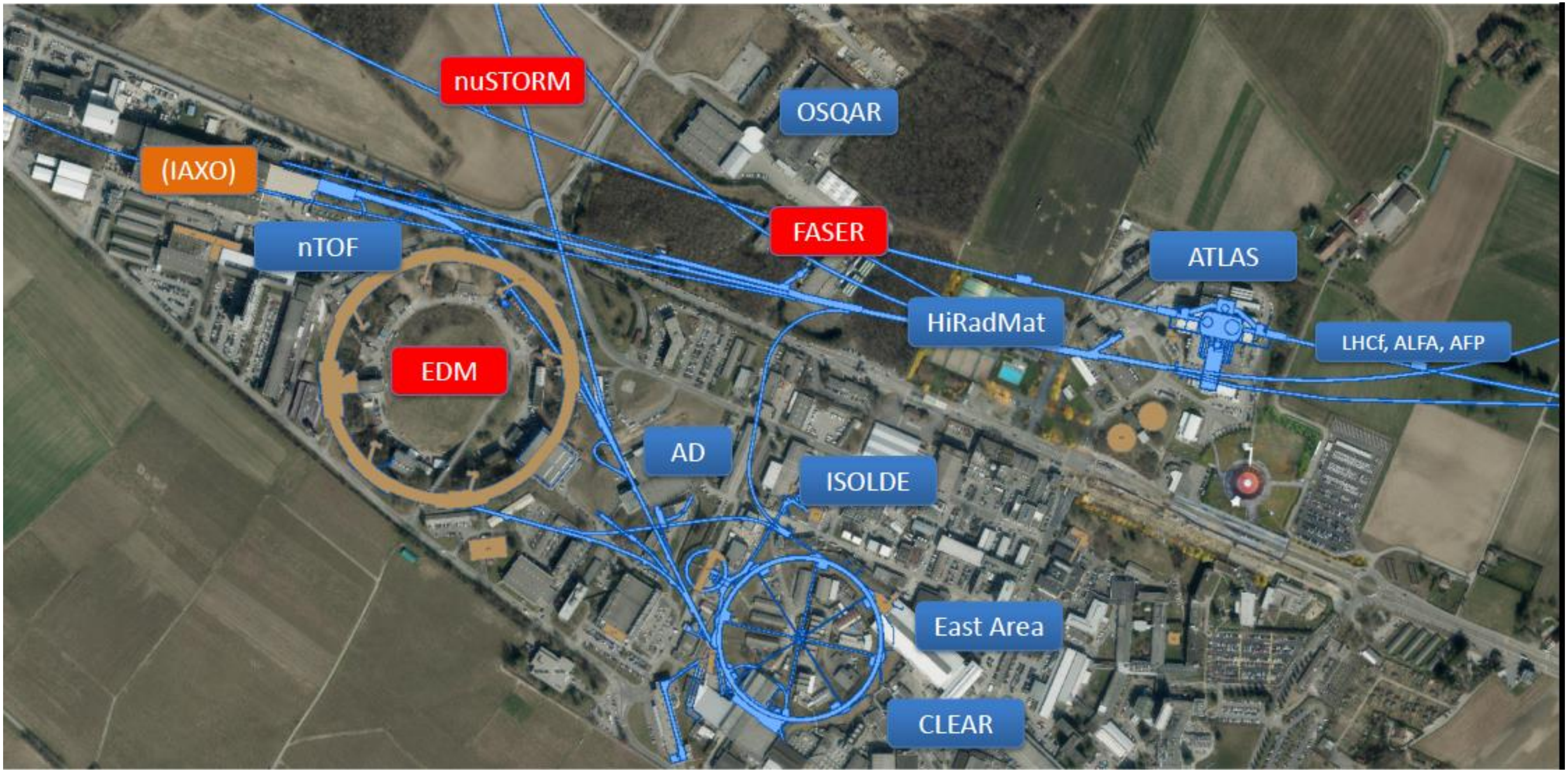
Mike Lamont, CERN

What has CERN got to offer?

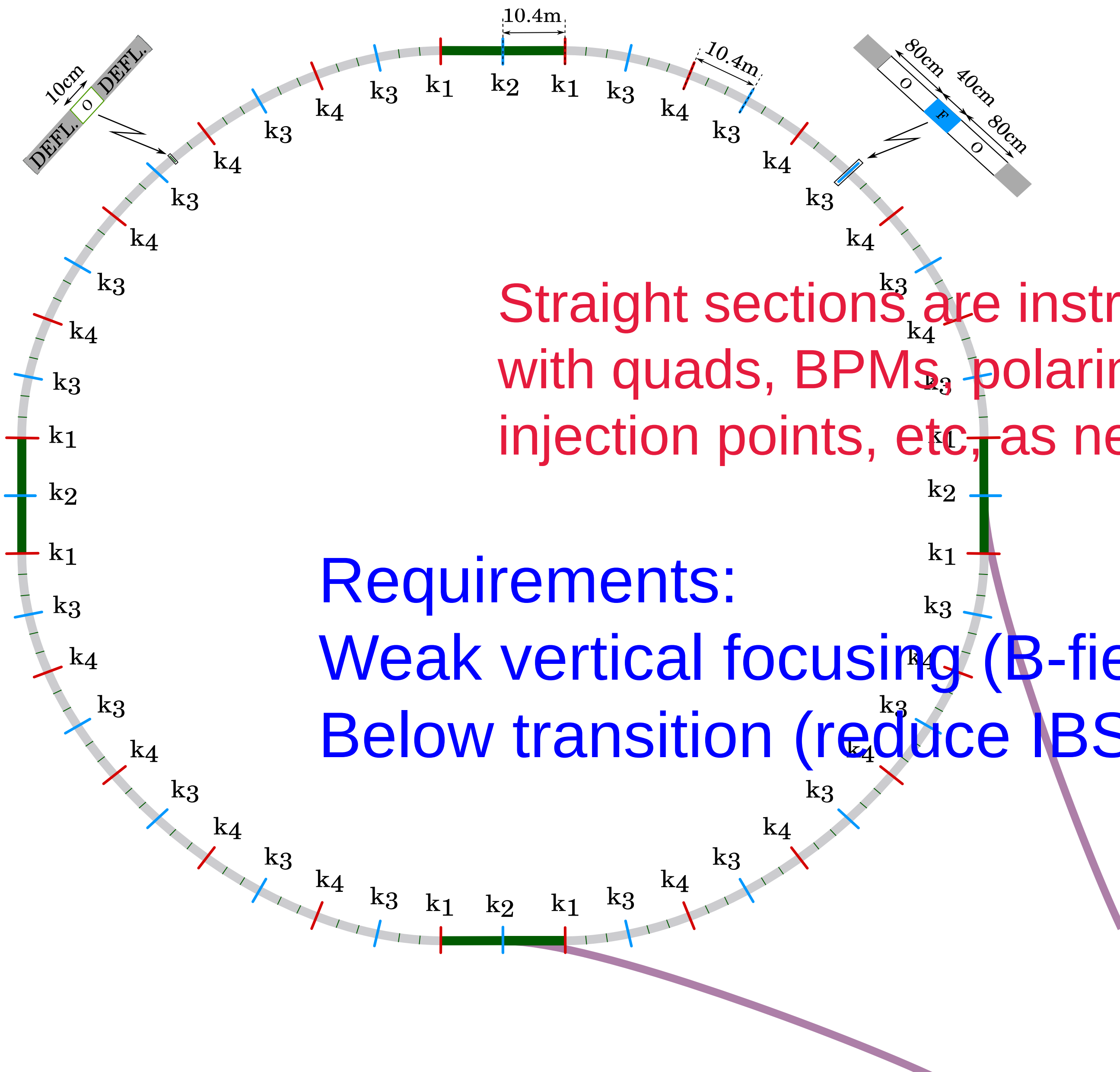
- Existing accelerator complex and associated infrastructure
  - Wide range of beams, intensities, energies
- Technical expertise
  - Vacuum, magnets, power converters, RF, instrumentation, beam transfer, targets, cryogenics, accelerator physics, engineering…
- Experience
- Support
  - workshops, test facilities, engineering…
- Resources, size, and flexibility

- Maximize performance of existing complex
- Harness existing expertise and resources
- New facilities exploiting existing complex
- Novel exploitation of existing facilities

Mike Lamont, CERN



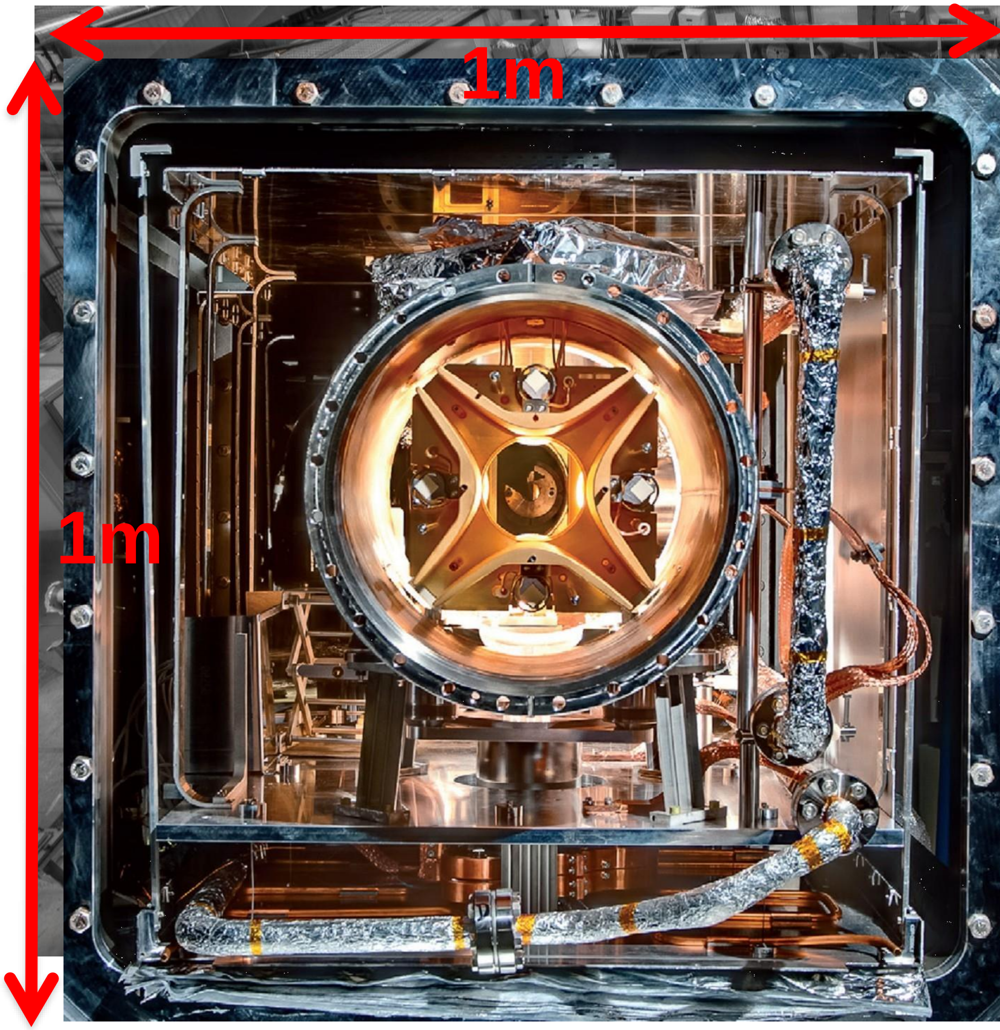
The proton EDM ring (alternate gradient)

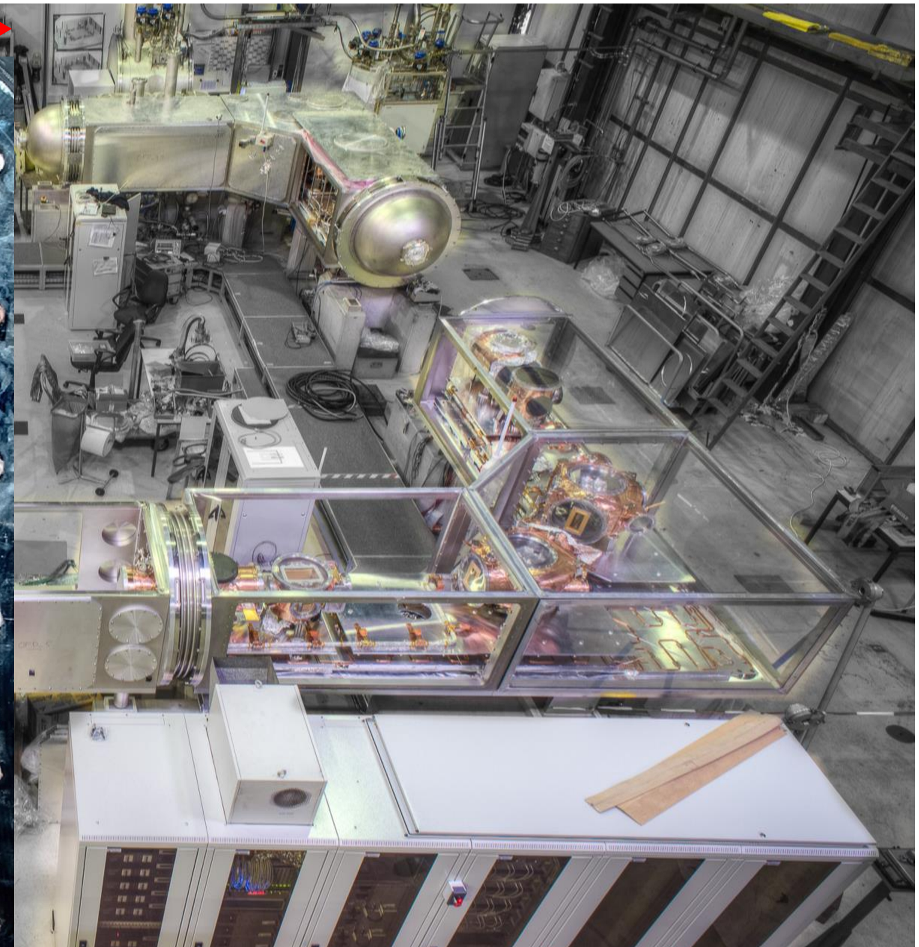


Straight sections are instrumented with quads, BPMs, polarimeters, injection points, etc, as needed.

Requirements:
Weak vertical focusing (B-field sensitivity)
Below transition (reduce IBS)

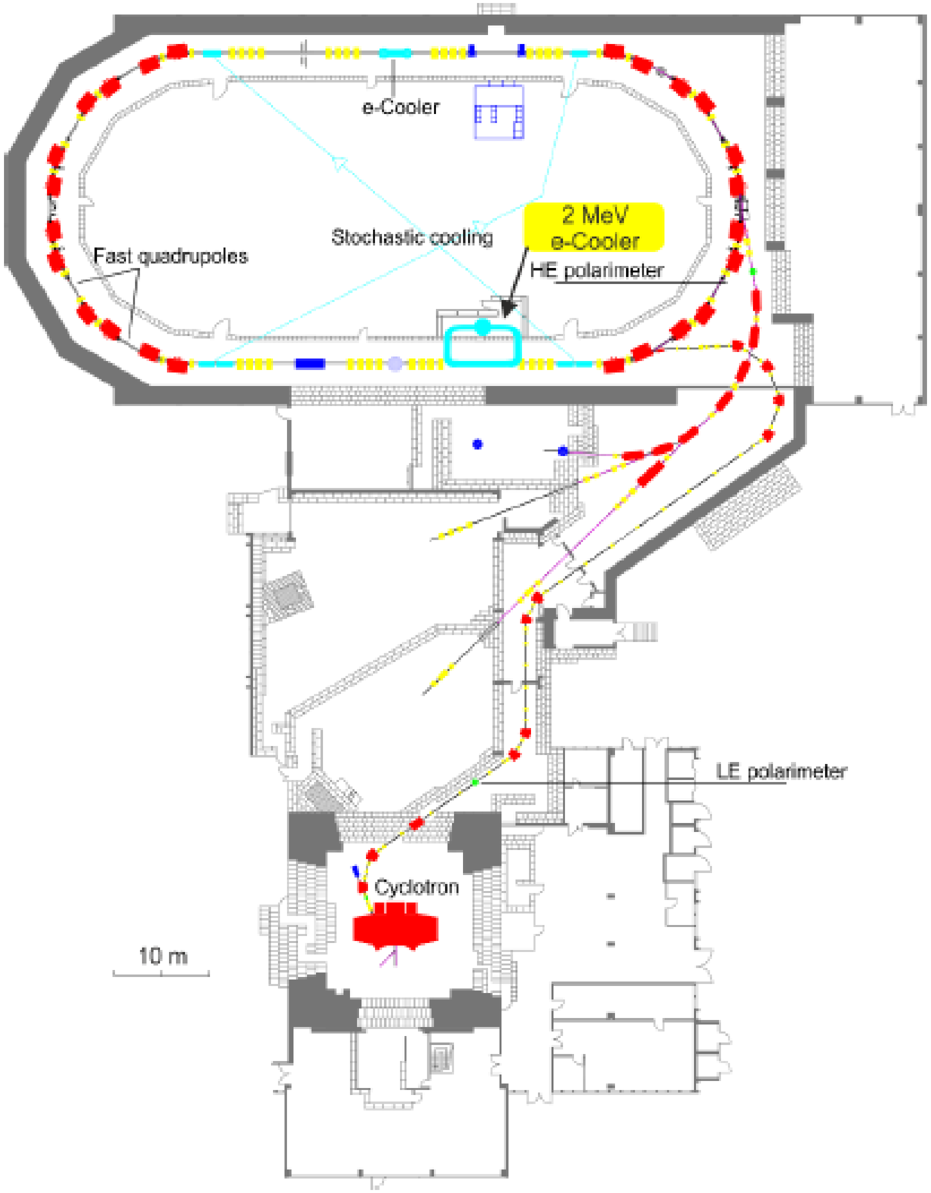
Currently: CSR, Heidelberg, 35 m circ., 10^{-13} Torr





COoler SYnchrotron (COSY)

JÜLICH FORSCHUNGSZENTRUM



- 184 m circumference
- Protons and Deuterons
- Polarized or un-polarized
- p: 295 MeV/c - 3,65 GeV/c
- Stochastic and electron cooling
- 2 e^- cooler: 100 keV and 2 MeV
- Typ. amount of stored particles: 10^{10}
- Internal experiments and 3 external beam lines
- H^- stripping injection

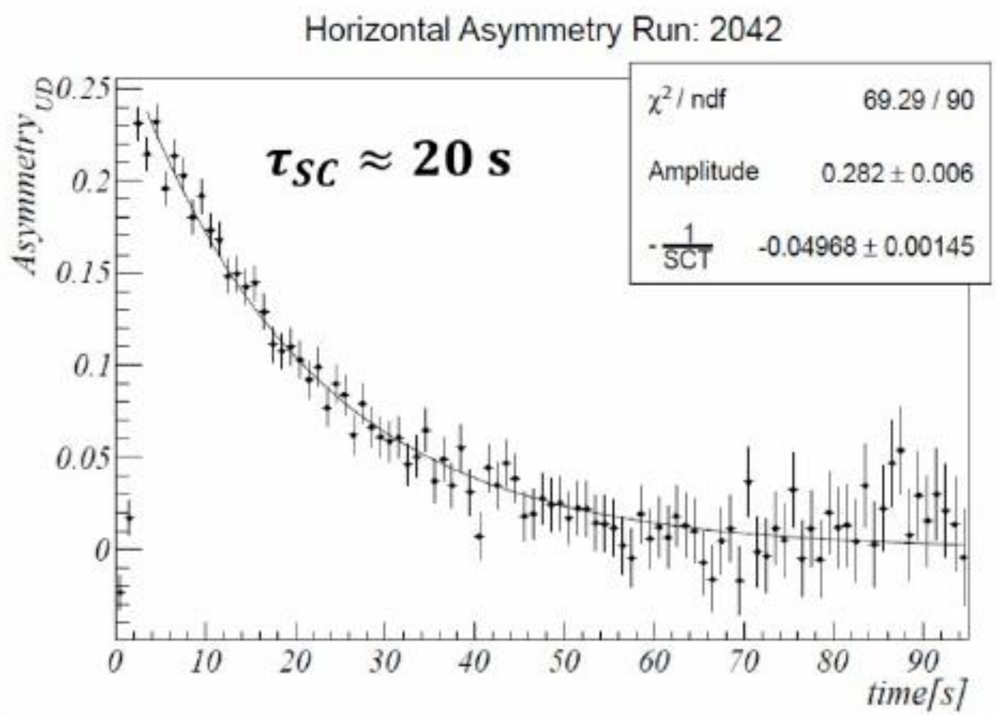
Measurement Principle

Martin Gaisser

Beam Preparation:

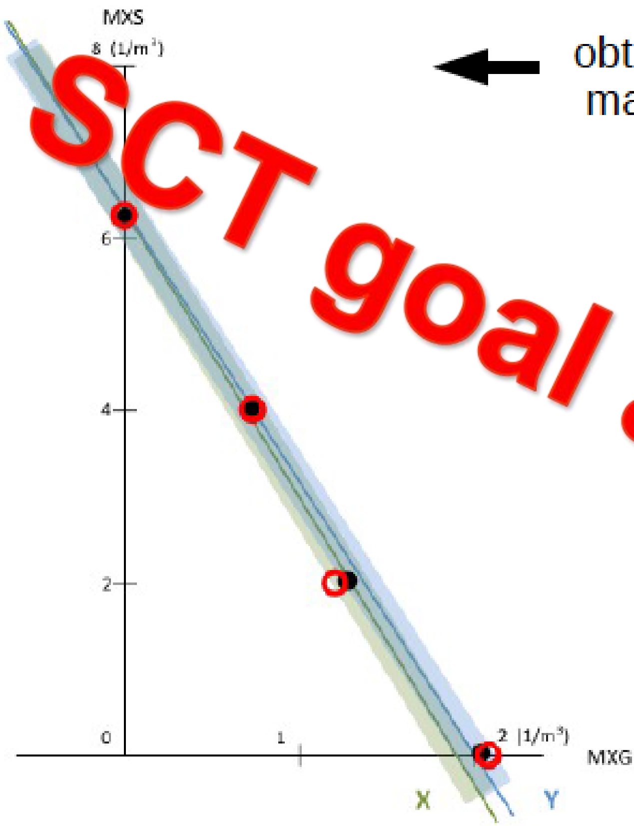
- Inject vertically polarized deuteron beam
- Accelerate
- Cool (with e-cooler) and bunch
- Put spin into horizontal plane (with rf-solenoid on spin tune resonance)

Watch decay of up-down asymmetry (horizontal polarization)



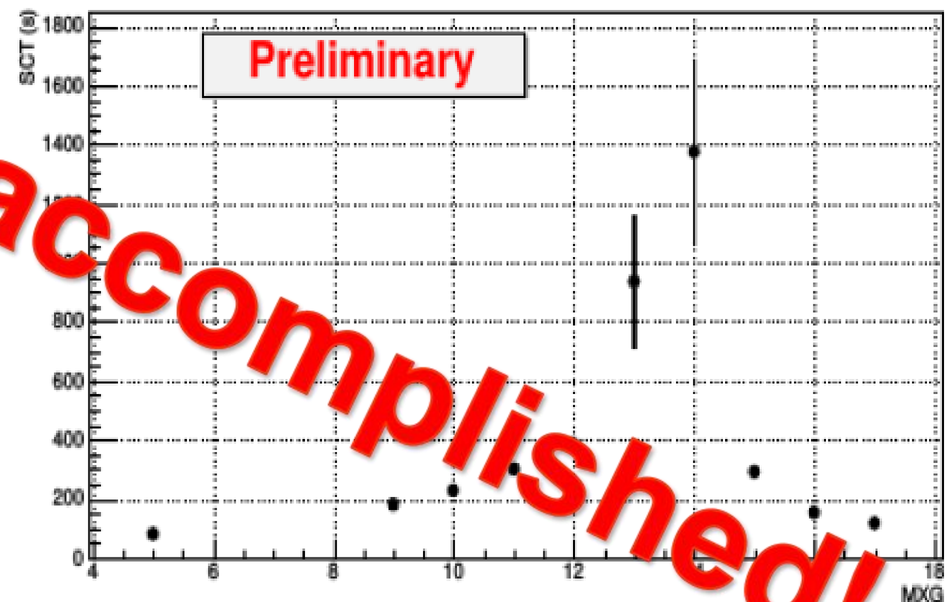
Sextupole Scans

Martin Gaisser



obtain this picture by rastering the MXS-MXG plane, maximum SCT lies on zero chromaticity lines

SCT goal accomplished!



Sextupole strength

Tim Wagner, IKP/Juelich

BEAM BASED ALIGNMENT

Why is it needed?

- For an EDM measurement the orbit has to be as good as possible
- Orbit RMS should be lower than 100 µm
  $\rightarrow$ Orbit Control
- Orbit Control corrects the beam to the BPM zero position
- Goal is to go central through all magnets (i.e. quadrupoles)
- Thus BPM to quadrupole offset has to be known
  $\rightarrow$ Beam Based Alignment

JÜLICH Forschungszentrum

Tim Wagner, IKP/Juelich

BEAM BASED ALIGNMENT

How does it work?

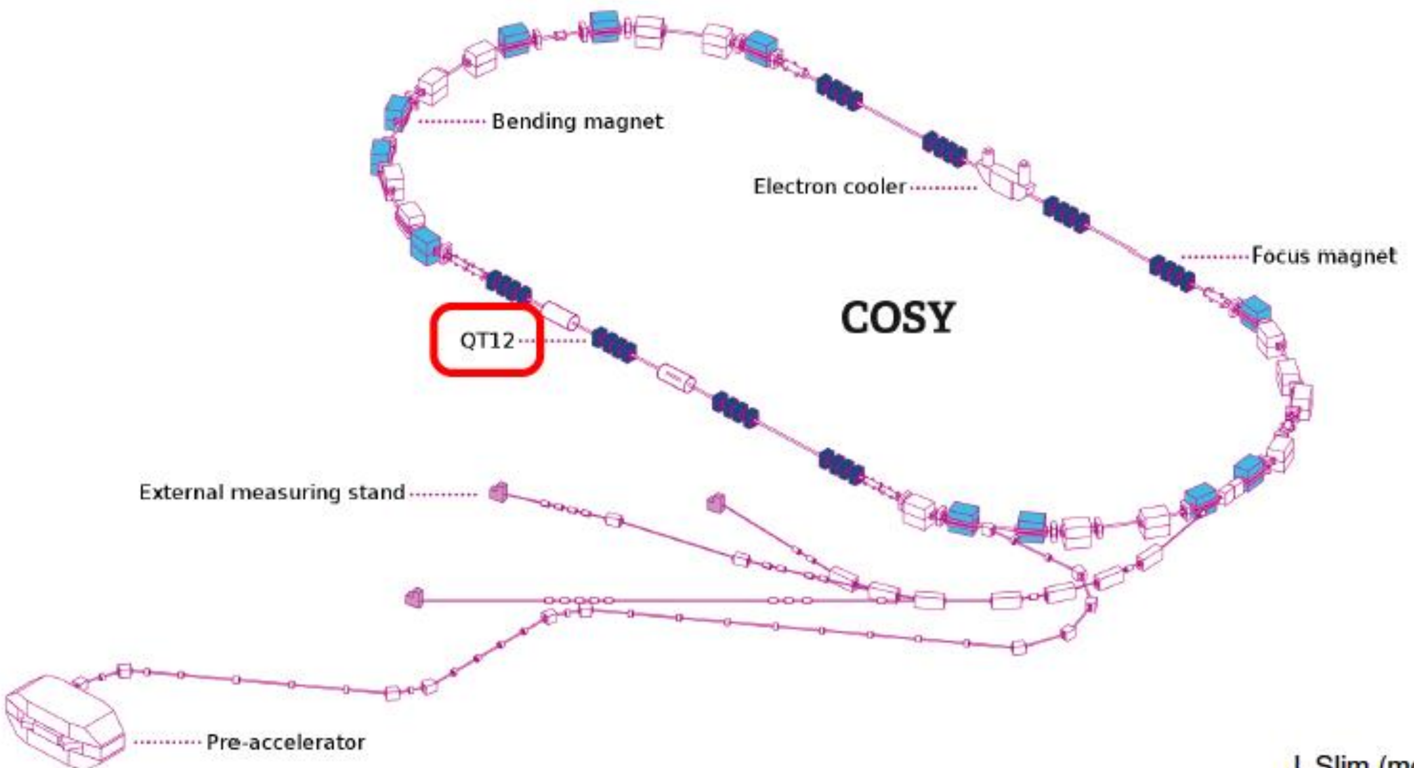
- How does the orbit change when varying the quadrupole strength?

$$\Delta x(s) = \left(\frac{\Delta k x(\bar{s}) l}{B\rho}\right)\left(\frac{1}{1 - k\frac{l\beta(\bar{s})}{2B\rho\tan\pi\nu}}\right) \times \frac{\sqrt{\beta(s)}\sqrt{\beta(\bar{s})}}{2\sin\pi\nu}\cos(\phi(s) - \phi(\bar{s}) - \pi\nu)$$

Tim Wagner, IKP/Juelich

BEAM BASED ALIGNMENT

Measurement



J. Slim (modified)

COSY scetch with position of quadrupole QT12 indicated

BEAM BASED ALIGNMENT

Tim Wagner, IKP/Juelich

Results

	Optimal Position	in mm
Horizontal	-0.255 ± 0.028	-1.98 ± 0.01
Vertical	2.329 ± 0.011	1.15 ± 0.01

- Optimal position given in script setting
- The values in mm are the BPM 6 readings nearby

SUMMARY

- Beam based alignment works
- The change of the magnet strength with additional coils works
- Optimal beam position inside the quadrupole could be determined to be (-1.98 ± 0.01) mm horizontally and (1.15 ± 0.01) mm vertically
- Now additional quadrupole magnets need to be changed to be individually controlled in order to measure this at more positions

Putting together the pEDM experiment

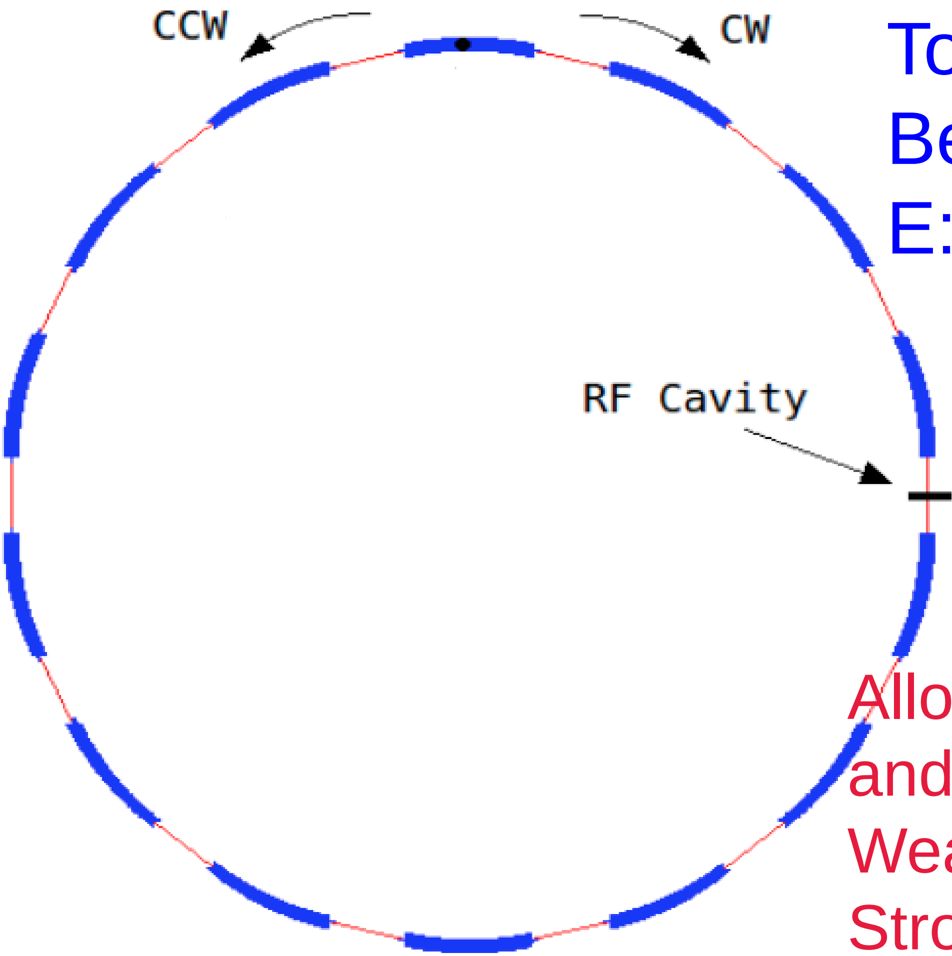
- Mechanically place all elements to 0.1mm local resolution (or as well it is possible)

- Using button BPMs/Rogowski coils to achieve resolution at the 10 micron level.

- Run the experiment with 90 & 180 degrees (radial) spin direction. Use vertical E-field trim plates around the ring to cancel the effect of distortions.

Major systematic error:
Radial B-field

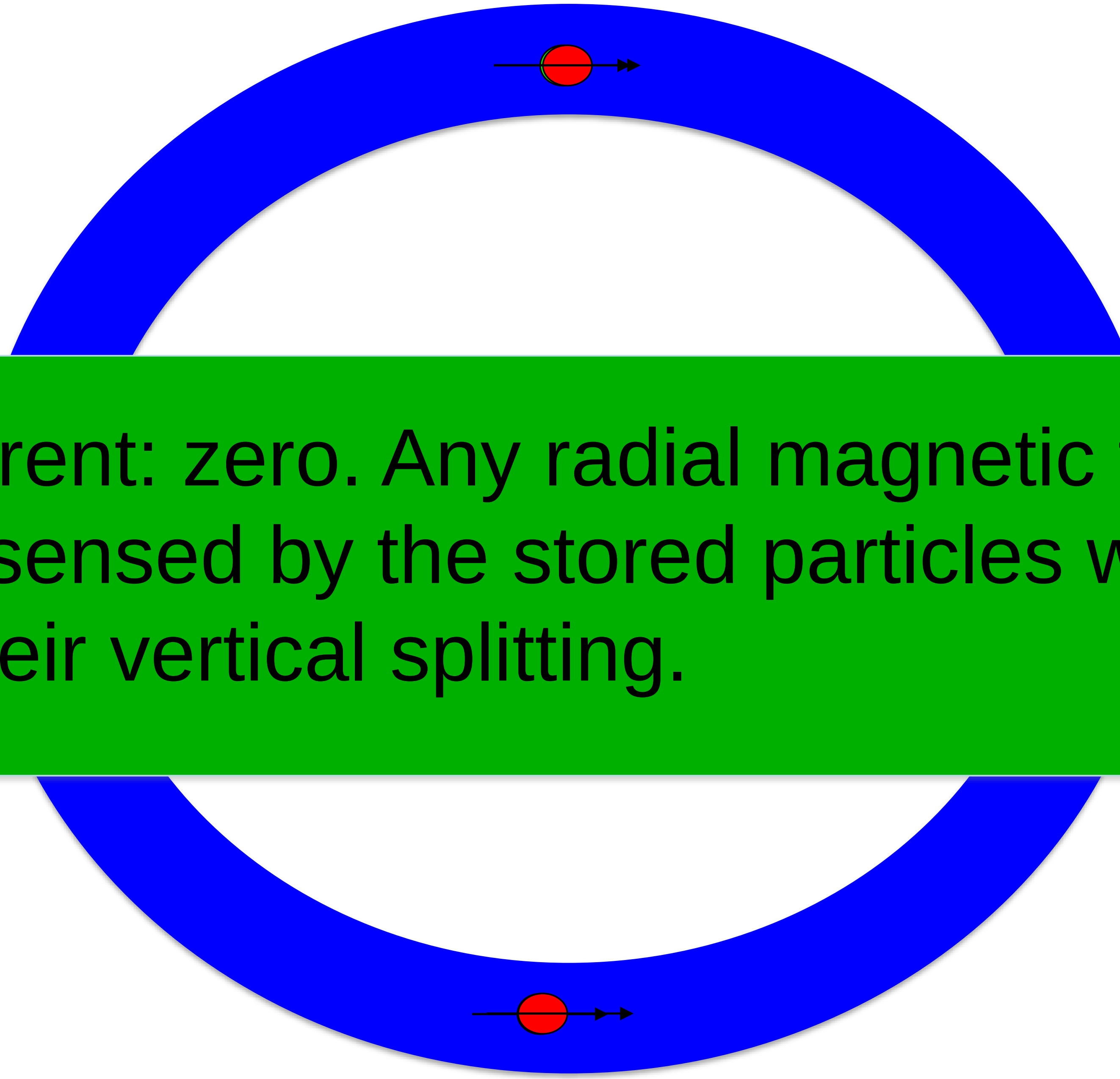
The all-electric proton EDM ring



Total circumference: ~400 m
Bending radius: 40 m
E: 10 MV/m

Allows for simultaneous clock-wise and counter-clock-wise beam storage
Weak vertical focusing
Stronger horizontal focusing

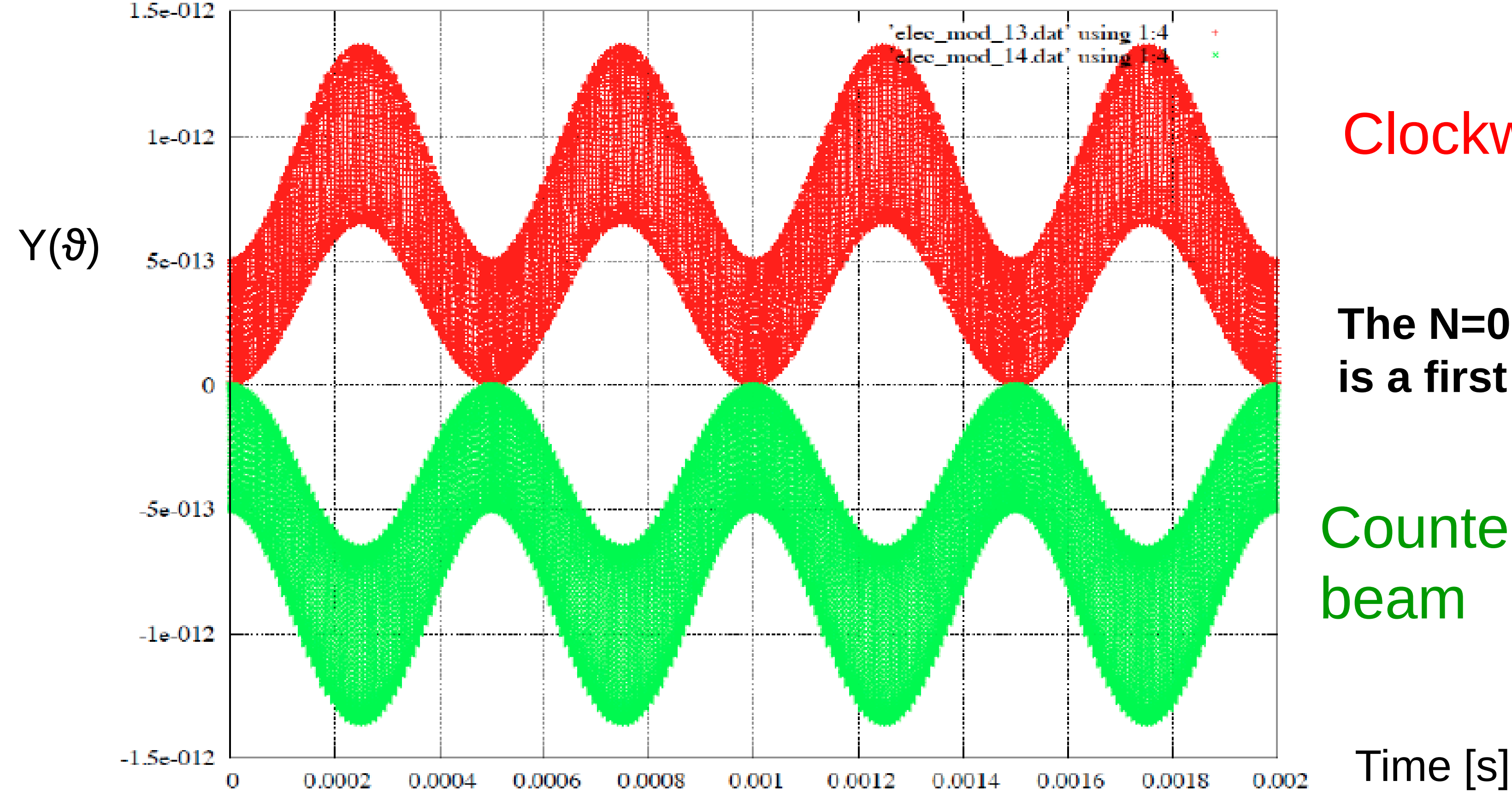
Clock-wise (CW) & Counter-Clock-wise Storage



Total current: zero. Any radial magnetic field in the ring sensed by the stored particles will cause their vertical splitting.

Distortion of the closed orbit due to N^{th}-harmonic of radial B-field

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



The N=0 component is a first order effect!

SQUID BPM to sense the vertical beam splitting at 1-10kHz

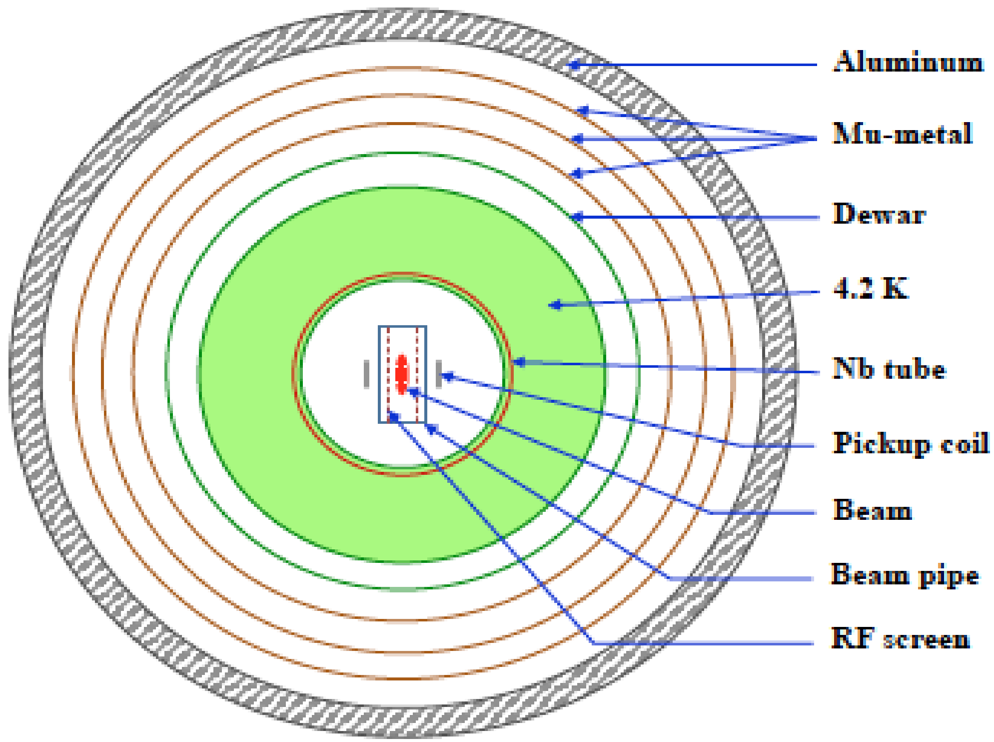
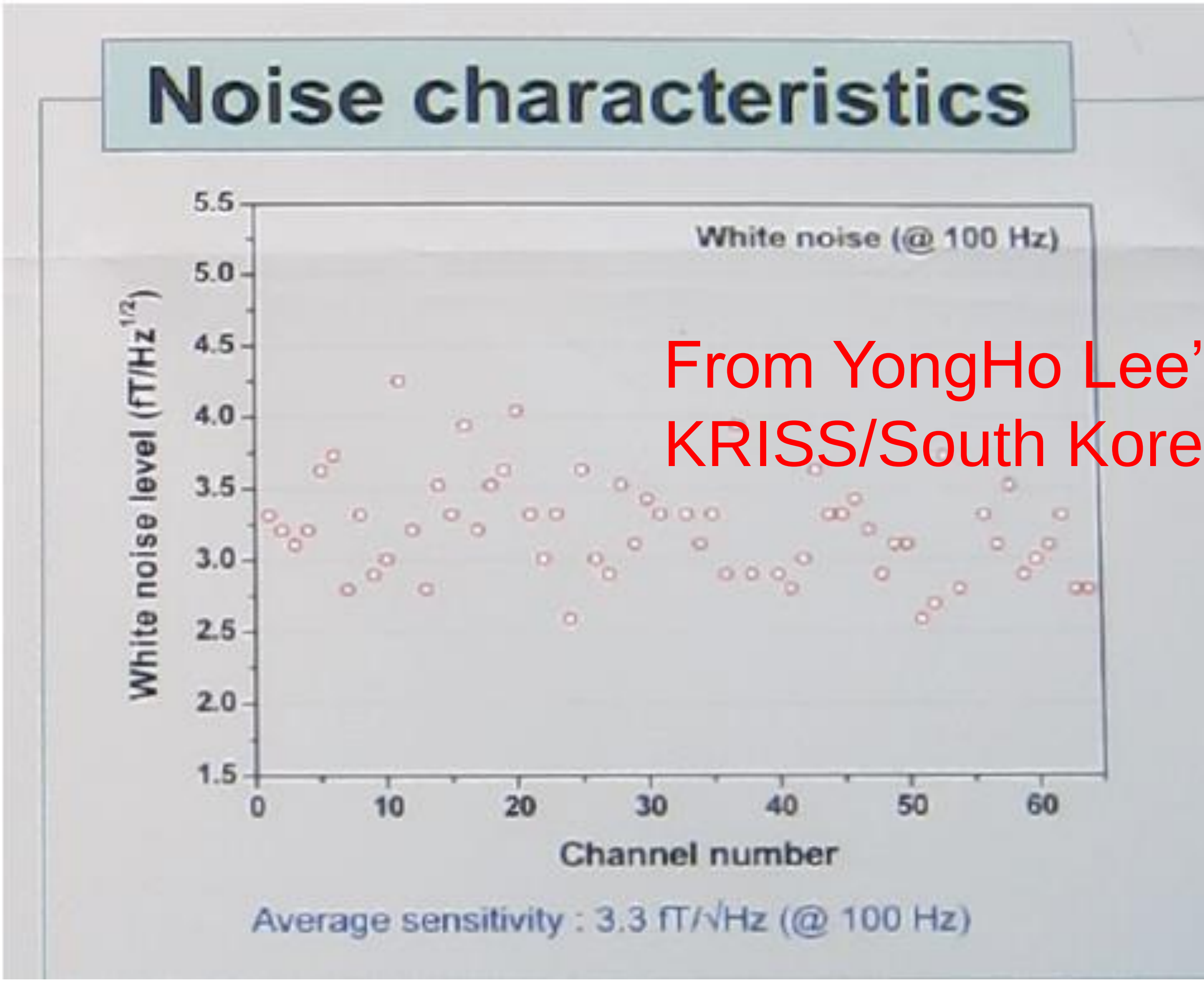


FIG. 3. A schematic of a possible SQUID BPM station. The system is shielded with a superconducting Nb tube, Al tube for RF-shield, and several mu-metal layers.

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



From YongHo Lee's group
KRISS/South Korea

SQUID Hardware - Signal acquisition

Optical receiver

Optical transmitter

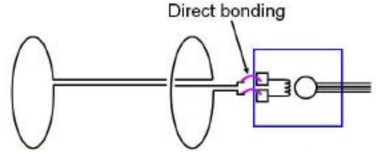
16 channel readout

Signal acquisition PCB

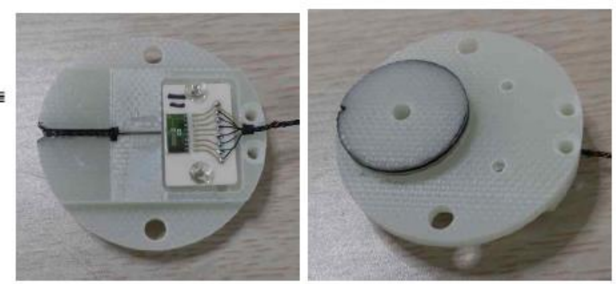
SQUID-based BPMs, Korea

SQUID Hardware - SQUIDs

Axial gradiometer



Planar gradiometer

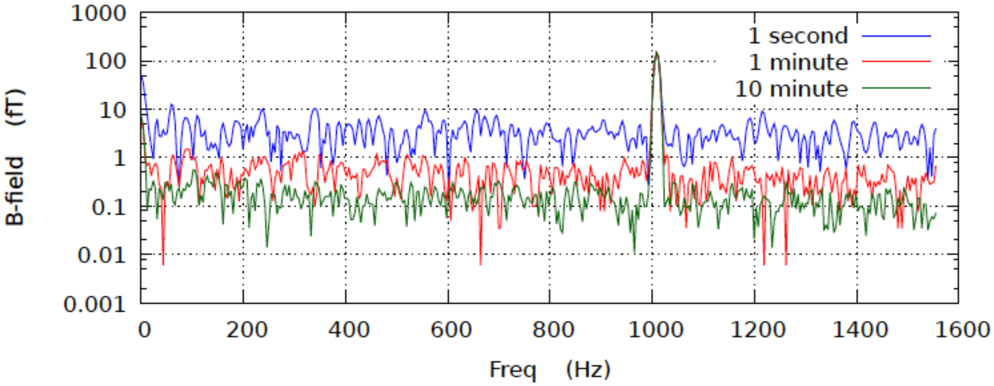


Selcuk Haciomeroglu, IBS/CAPP

SQUID-based BPMs, Korea

Preliminary setup

- We currently have a preliminary setup to play with
- 3 $\mathrm{fT}/\sqrt{\mathrm{Hz}}$ sensitivity
- Currently we are making wire tests.
- We will use the same electronics in the next design



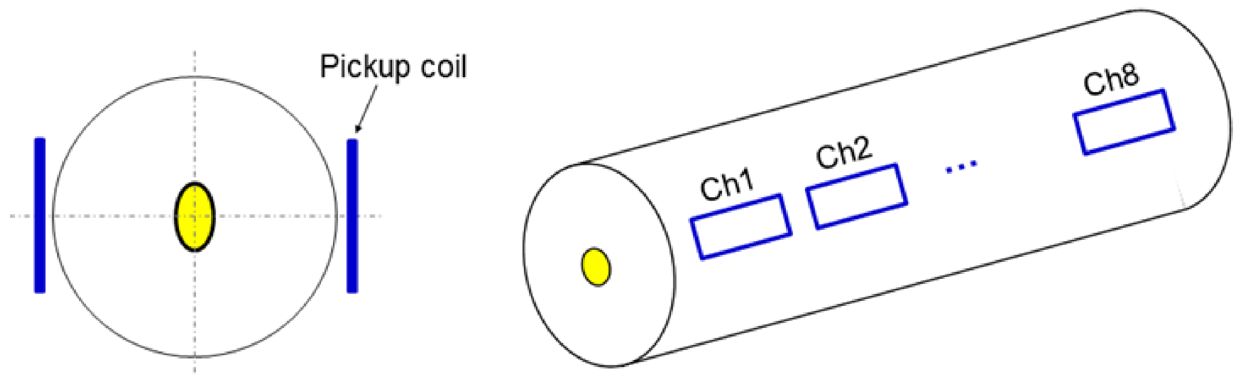
S. Haciomeroglu Status of the B-field studies for the pEDM experiment

Prototype

- The new design is to be delivered by summer
- Will be $2\mathrm{fT}\sqrt{\mathrm{Hz}}$
- We will make wire tests in Korea
- Would be good to test here at COSY

Selcuk Haciomeroglu, IBS/CAPP

16 channel SQUID Magnetometers Array



(a) (b)

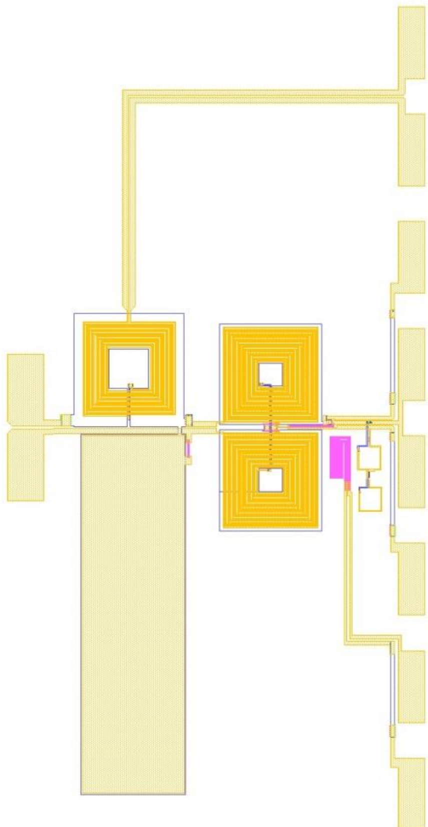
Fig. 21. Arrangement of the pickup coils. Blue lines are pickup coils, and yellow oval is the hypothetical proton beam shape. (a) Two pickup surfaces facing each other to measure two radial field components, and (b) 8 pickup coils are arranged along the beam propagation direction.

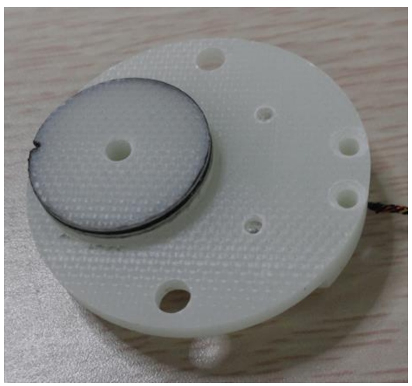
Main configuration of the SQUIDs and dewar are as following:

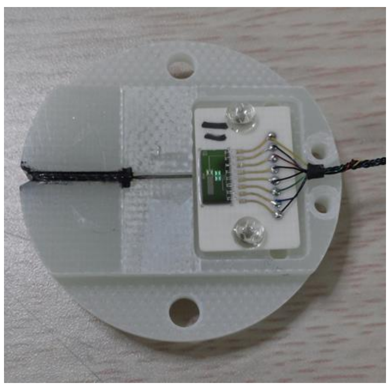
- Inter-coil distance: about 40 mm
- Rectangular coil: 15 mm x 40 mm
- Interval between pickup coils: about 50 mm
- 8 channels/side: 16 channels/dewar
- Either thin film or wire-wound pickup coil

Andrei Matlashov, IBS/CAPP

Magnetometer Parameters



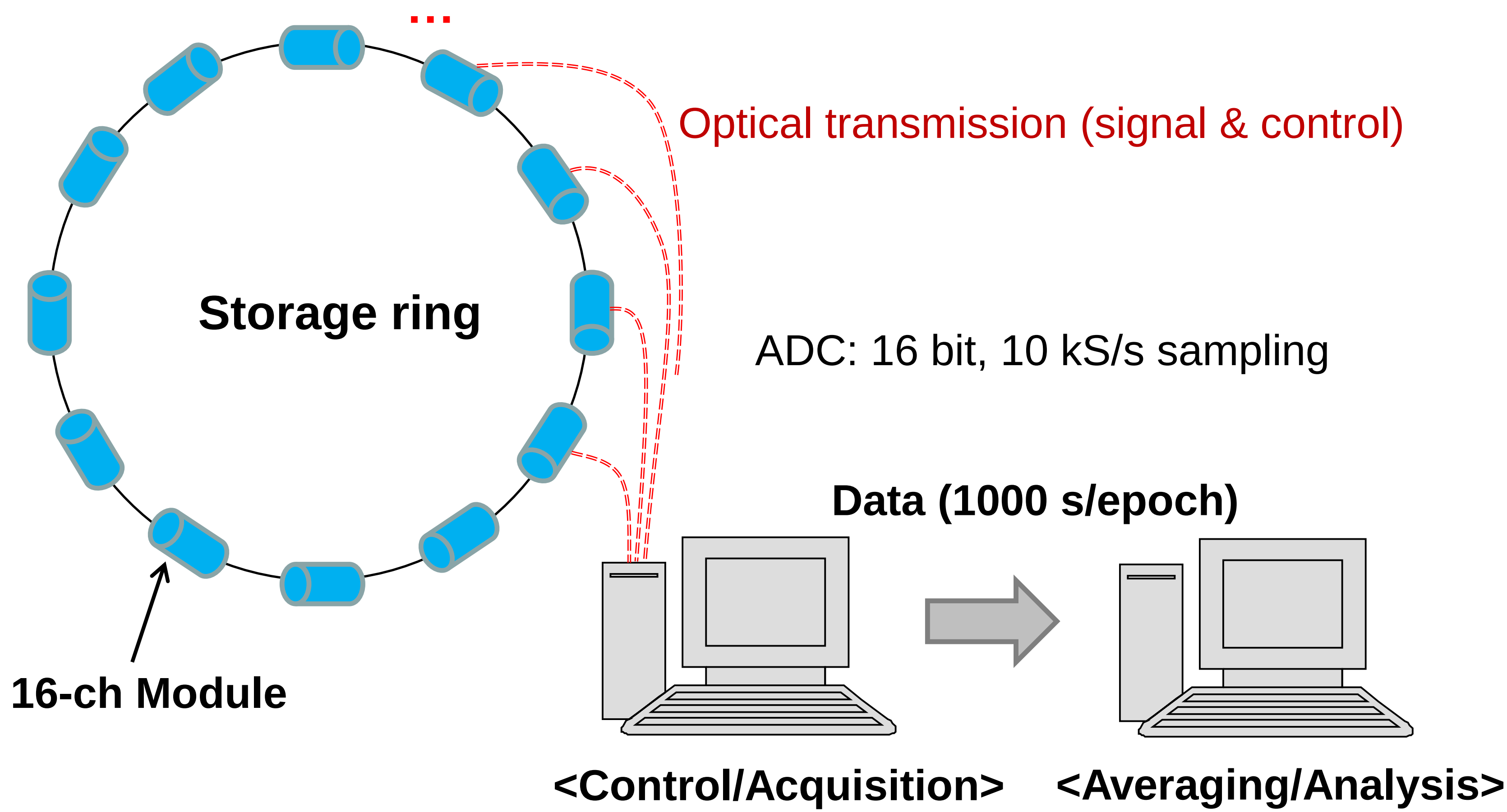




Parameter	Value	Unit
Number of pickup-coil turn	2	Turn
Nb wire diameter	0.13	mm
Pickup coil diameter	**17**	**mm**
Pickup coil inductance L_p	213	nH
Input coil inductance L_i+L_f	202	nH
Mutual inductance Mi (L_s: L_i)	4.78	nH
Pickup area A_p	454	mm^2
Transfer coefficient (B/Φ)	0.4	nT/Φ_0
Flux noise	3.0	$\mu\Phi_0/\sqrt{Hz}$
Field resolution	**1.2**	**fT/√Hz**

Andrei Matlashov, IBS/CAPP

BMP Systems in the Storage Ring



Interference-free control

Noise-free acquisition

No time-delay bet. modules

YongHo Lee, KRISS

- **The First generation (G1) of BMP system: tested at KRISS and moved to CAPP for further tests and research.**

- **The Second generation (G2) of BMP system: designed, all key components manufactured; it will be assembled in May 2018.**

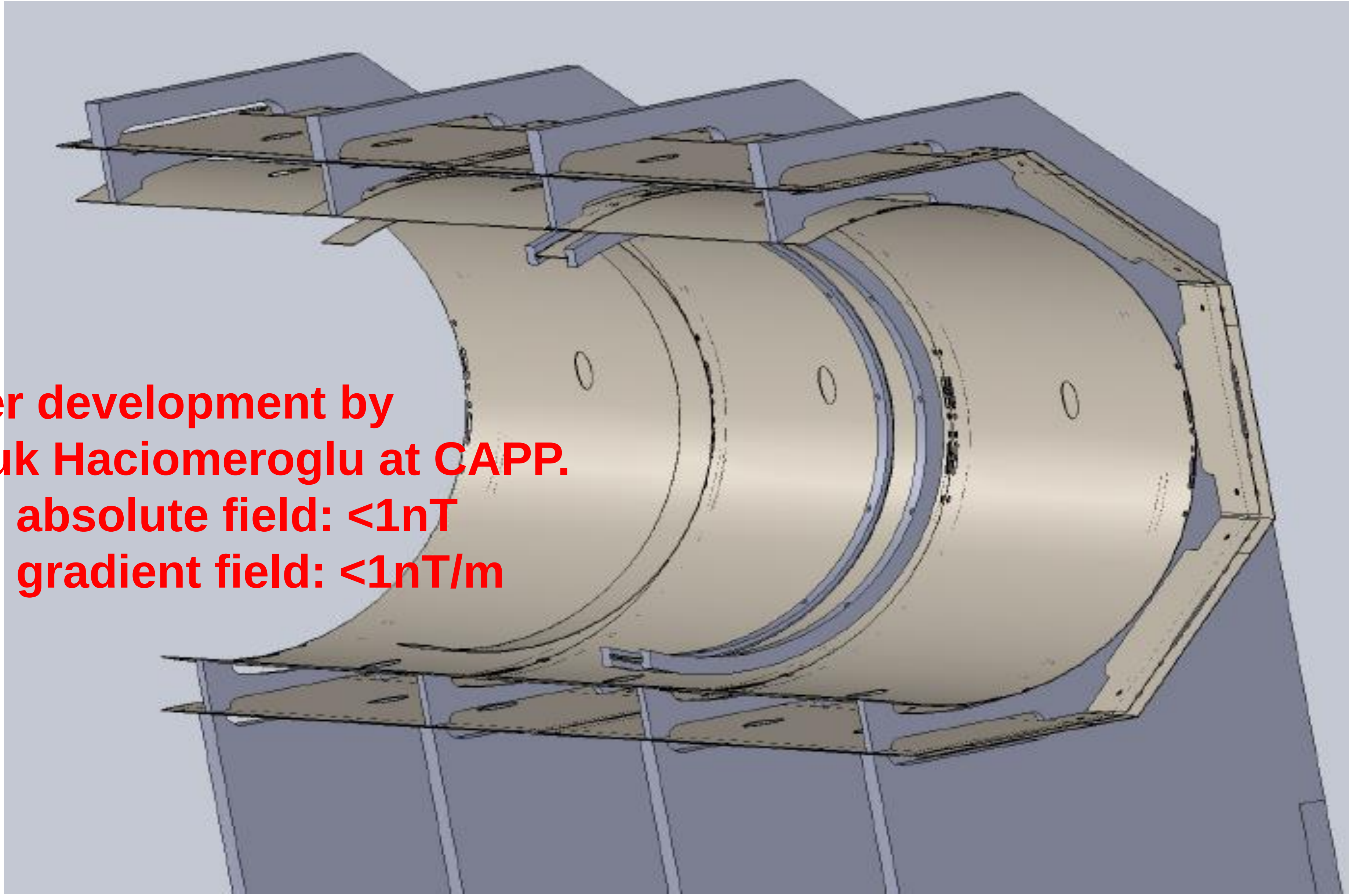
- **Field Resolution: current G1 system → 3.5 fT/√Hz @1 kHz**

- **Field Resolution: under construction G2 system → 1.2 fT/√Hz @1 kHz**

- **Field Resolution: new generation SQUIDs → 0.15 fT/√Hz @1 kHz**

Andrei Matlashov, IBS/CAPP

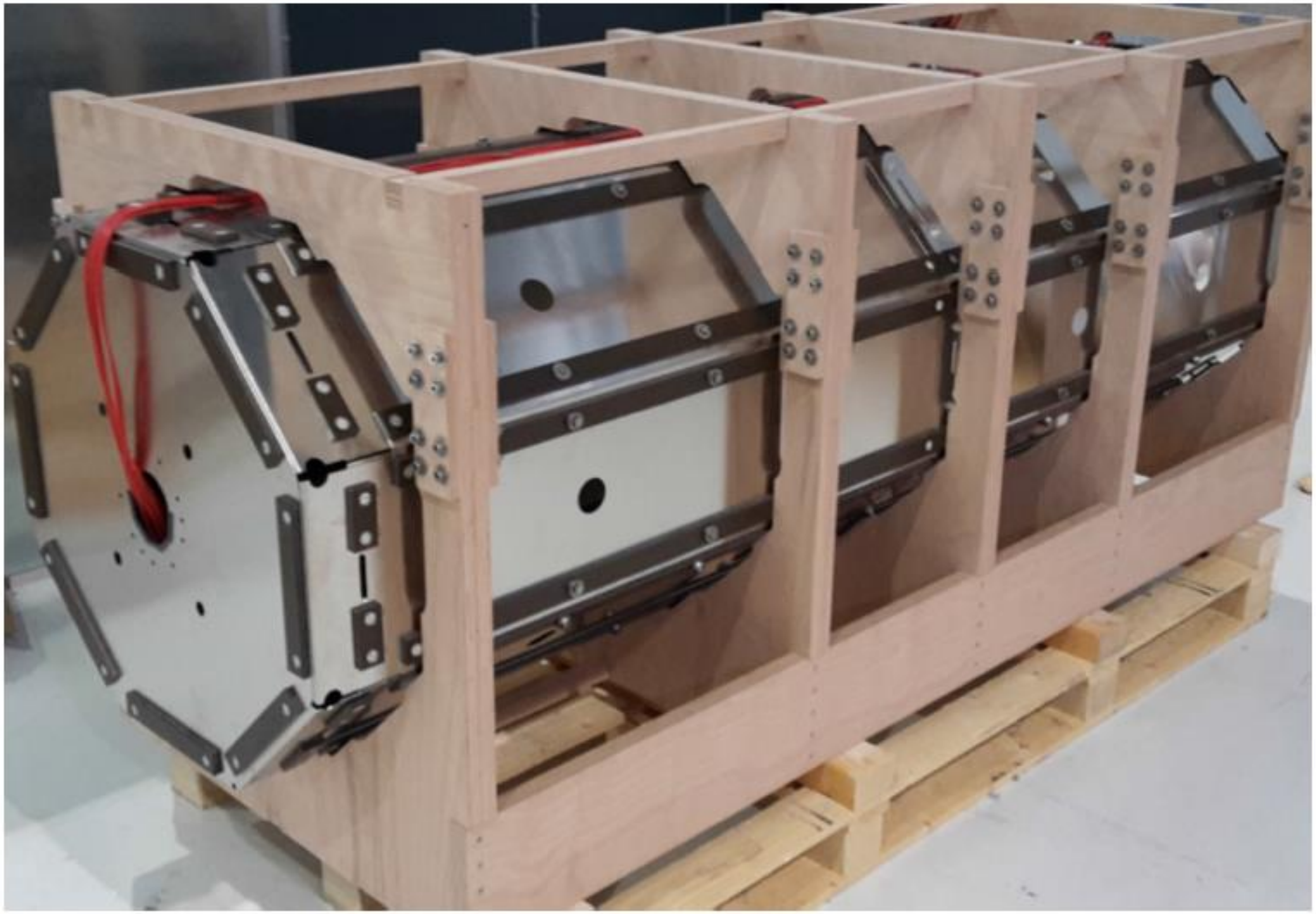
Peter Fierlinger, Garching/Munich



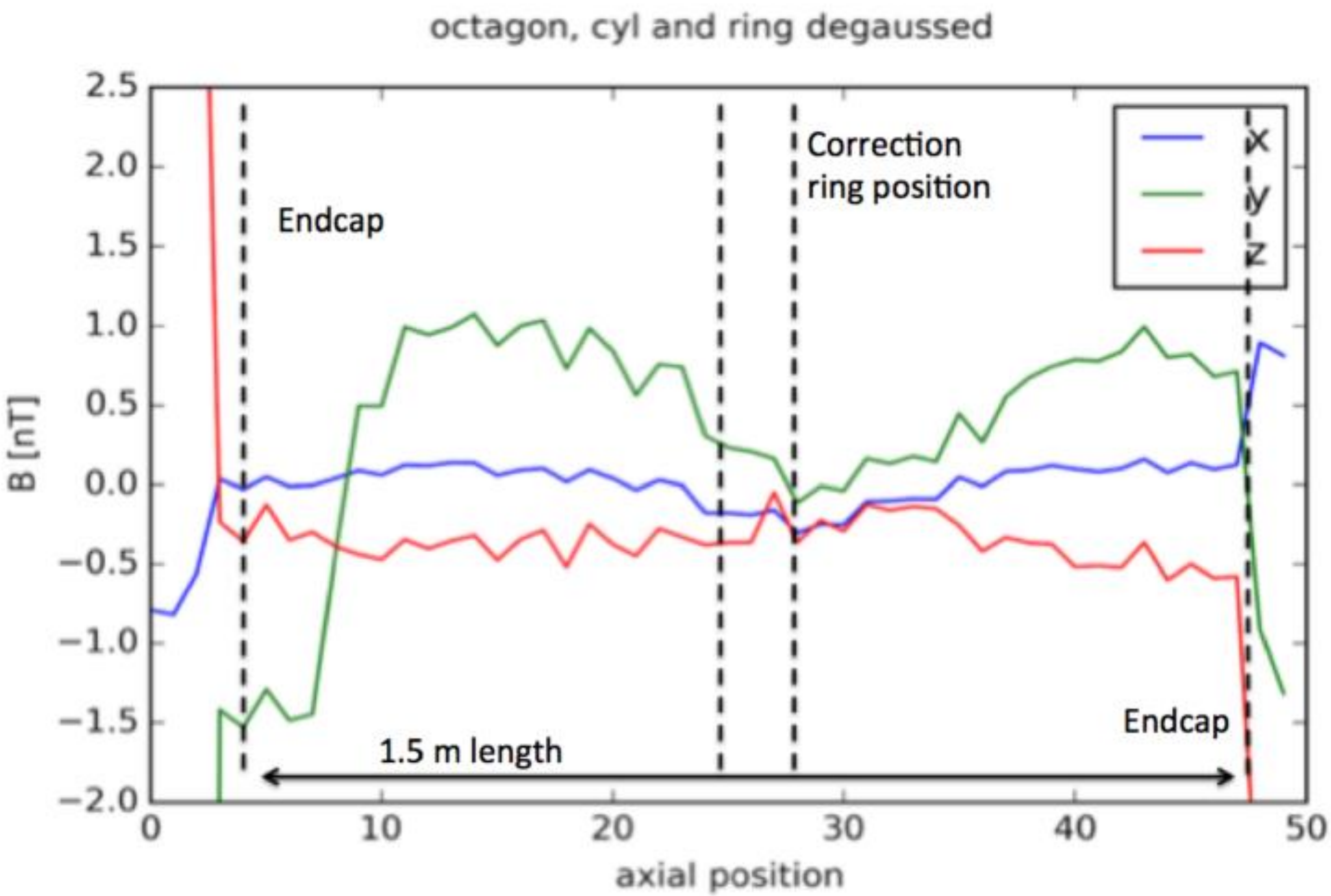
Under development by
Selcuk Haciomeroglu at CAPP.
Need absolute field: <1nT
Need gradient field: <1nT/m

Achieved so far:
Absolute field: <1nT
Gradient field: <1nT/m

Shielding - Prototype



Shielding - Preliminary measurements



Christian Carli, CERN

- <1nT B-field shielding is adequate when lattice beta-functions are uniform
- Much stricter specs when there’s a variation of vertical beta-function.
- Selcuk Haciomeroglu: confirmed specs with high-precision beam/spin simulations

Plan

- Use as uniform vertical beta-function as possible (need <nT shielding)

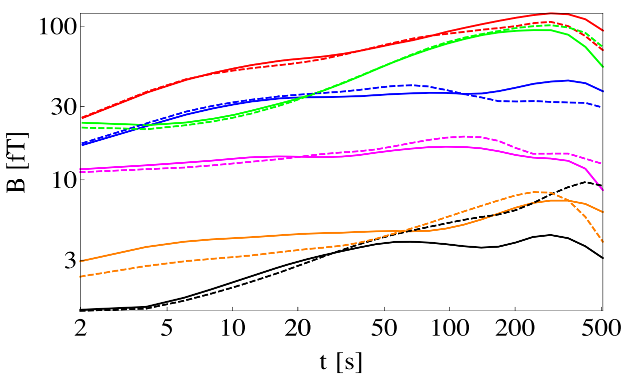
- Investigate on how to reach <pT level B-field shielding with non-uniform vertical beta-function

- …

Most hardware built & tested

E.g.: passive magnetic shielding factor > 6 million @ 1 mHz
(without ext. compensation coils!)

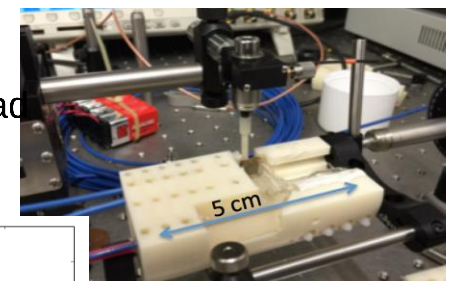
I.Altarev et al., arXiv:1501.07408
I. Altarev et al., , arXiv:1501.07861

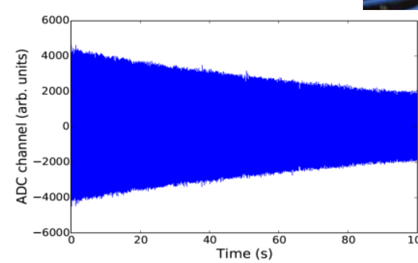


1.5m

- The smallest gradients over an extended volume ever realized: < 50 pT / m stable gradient over EDM cell volume
- Residual field drift < 5 fT in typical Ramsey cycle time
- Hg and Cs magnetometry on < 20 fT level:

Cs sensor head assembly





Raw 199-Hg FPD signal

- Basically all magnetic field related systematics under control

Peter Fierlinger, TUM, magnetic shielding factor > 6M at 1mHz!

I.Altarev et al., arXiv:1501.07408
I. Altarev et al., , arXiv:1501.07861

Physics Today, August 2015

Search for axion dark matter in storage rings

Axion dark matter search with the storage ring EDM method

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[a] *Department of Physics, KAIST, Daejeon 34141, Republic of Korea*
[b] *Center for Axion and Precision Physics Research, IBS, Daejeon 34051, Republic of Korea*

arXiv:1710.05271v1 [hep-ex] 15 Oct 2017

Abstract

We propose using a modified storage ring EDM method to search for the axion dark matter induced EDM oscillation in nucleons. The method uses a combination of B and E-fields to produce a resonance between the $g-2$ precession frequency and the background axion field oscillation to greatly enhance the sensitivity to it. An axion frequency range of 100Hz to 100MHz can be scanned with large sensitivity, corresponding to f_a range of 10^{13} GeV $\leq f_a \leq 10^{19}$ GeV the breakdown scale of the global symmetry generating the axion or axion like particles (ALPs).

Search for axion dark matter in storage rings

- Dark matter axion background field is oscillating
  - ✓ $a = a_0 \cos(\omega_a t)$
  - ✓ $\omega_a \approx m_a c^2/\hbar$, m_a: axion mass
- The oscillating axion field is coupled with
  - ✓ Photon $P_{sig} = \eta^2_{g_{a\gamma\gamma}} \left(\frac{\rho_a}{m_a}\right) B_0^2 V C Q_L$ $a \rightarrow \gamma\gamma$
  - ✓ gluons, fermions, nucleon, etc. → Oscillating EDM

$a(t) = a_0 \cos(m_a t) \Rightarrow$ $d(t) = d_0 \cos(m_a t + \phi_x)$

- Generic feature

$$d_n = 2.4\times10^{-16} \frac{a}{f_a} e\cdot cm \approx 9\times10^{-35} \cos(m_a t)[e\cdot cm]$$

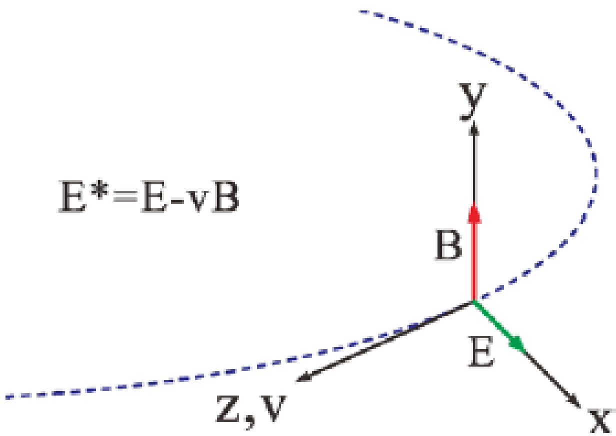
Peter W. Graham and Surjeet Rajendran.
Phys. Rev. D, 84, 055013, (2011)
Phys. Rev. D, 88, 035023, (2013)

Search for axion dark matter in storage rings

In a storage ring

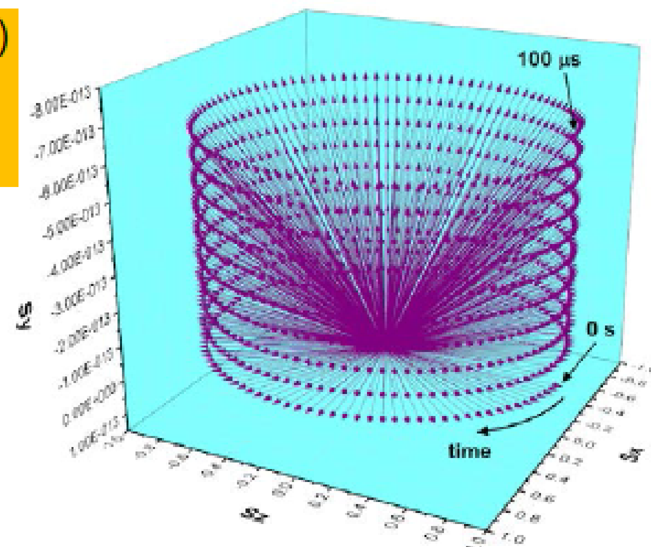
$$\frac{d\vec{\beta}}{dt} = \frac{e}{\gamma m}\left[\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c} - \vec{\beta}\frac{\vec{\beta}\cdot\vec{E}}{c}\right]$$

$$\frac{d\vec{s}}{dt} = \frac{e}{m}\vec{s}\times\left[\left(\frac{g}{2}-\frac{\gamma-1}{\gamma}\right)\vec{B} - \left(\frac{g-2}{2}\frac{\gamma}{\gamma+1}\right)(\vec{\beta}\cdot\vec{B})\vec{\beta} - \left(\frac{g}{2}-\frac{\gamma}{\gamma+1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\frac{\vec{E}}{c} - \frac{\gamma}{\gamma+1}\left(\frac{\vec{\beta}\cdot\vec{E}}{c}\right)\vec{\beta} + \vec{\beta}\times\vec{B}\right)\right]$$



$$d(t) = d_0\cos(\omega_a t + \varphi)$$

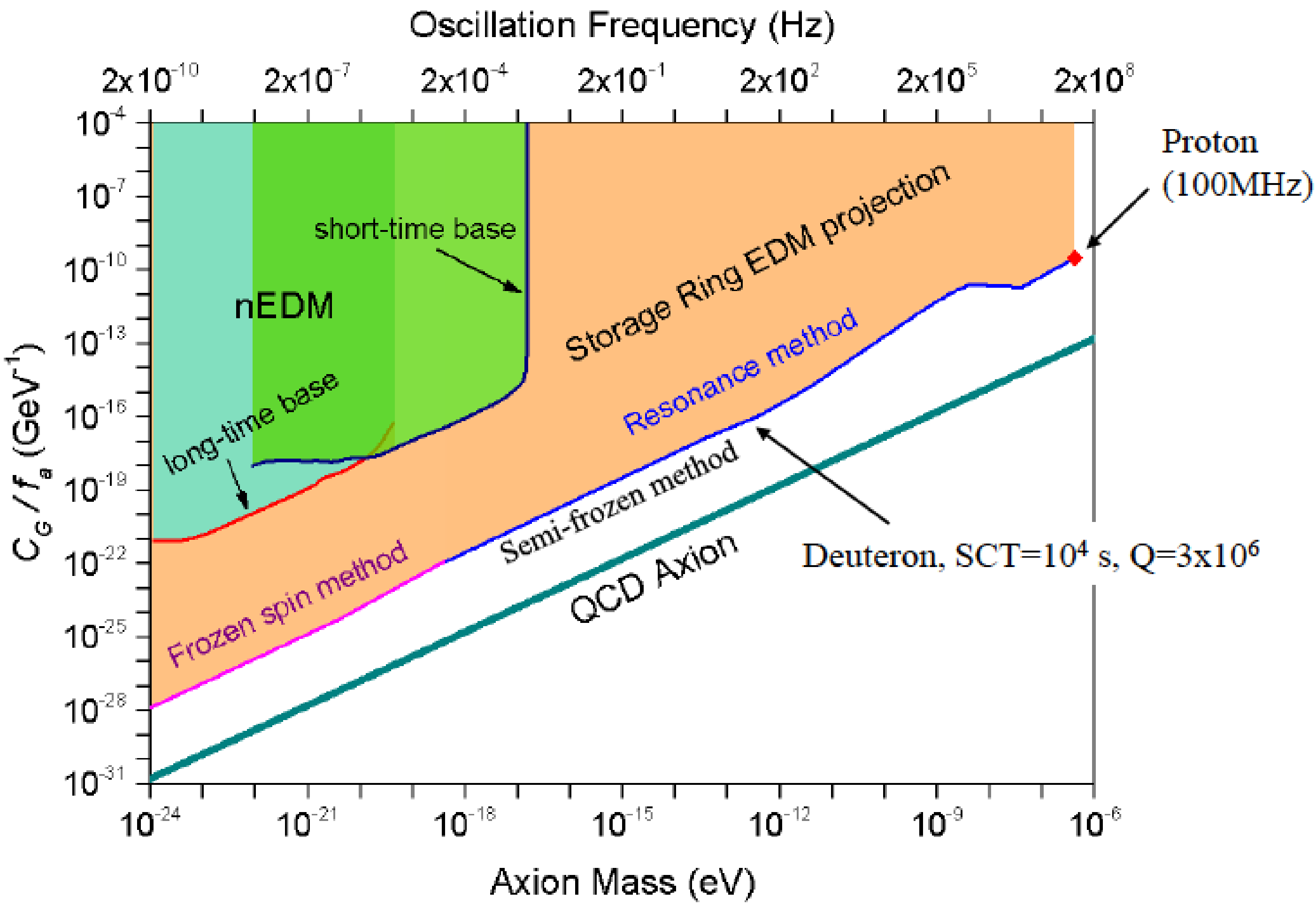
$$\eta(t) = \frac{d(t)4mc}{e\hbar}$$



SeongTae Park, IBS/CAPP

Projected, preliminary

Experiment limit



nEDM: Ultra-cold neutron trap experiment

Summary

- The charged particle EDM collaboration is formed, joining forces between srEDM and JEDI
- Working towards a feasibility study by December 2018
- Prototype of all-electric ring, 30MeV protons to study storage issues, spin coherence time, SQUID-based BPMs, B-field shielding issues, alignment issues, etc.

Extra slides

Physics relevance, comparison with other activities

- The physics reach of a proton and a deuteron experiment at the 10^{-29} *e*-cm is unique:

- Theta_QCD vs. New Physics: help from n, p, and d, ^{199}Hg, electron EDM values.

- Certain systematic errors, e.g., geometrical phases, cancel in clockwise vs. counterclockwise. Unique to storage ring method.

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	$<0.7\times10^{-29}$		10^{-25}-10^{-26}
^{129}Xe atom	$<6\times10^{-27}$	$\sim10^{-30}$-10^{-33}	10^{-26}-10^{-29}
Deuteron nucleus		$\sim10^{-29}$	3×10^{-29}-5×10^{-31}
Proton nucleus	$<5\times10^{-25}$	$\sim10^{-29}$-10^{-30}	10^{-29}-10^{-30}

CP-violation phase from Higgs

EDMs will eventually be discovered: $d_e, d_n, d_p \ldots d_D$

Magnitudes of ≈ -10^{-28} expected for Baryogenesis

Atomic, Molecular, Neutron, ***Storage Ring*** (All important)

Marciano

CP violation phase in***: Hee, H$\gamma\gamma$, Htt,   2HD Model…***

Uniquely explored by 2 loop edms! Barr-Zee effect

May be our only window to Hee, Huu and Hdd couplings

Guided by experiment: *H➔$\gamma\gamma$ (H➔$\tau^+\tau^-$, $\mu^+\mu^-$) etc.*

Updates Anxiously Anticipated!

The Higgs may be central to our existence!

EDM goals (done)

- The EDM experiments are gearing up, getting ready:

- ^{199}Hg EDM <0.7×10^{-29} e-cm sensitivity

- nEDM at PSI 10^{-26} e-cm sensitivity, 1st stage
- nEDM at PSI 10^{-27} e-cm sensitivity, 2nd stage

- nEDM at SNS ~2×10^{-28} e-cm starting data taking 2021

Marciano, CM9/KAIST/Korea, Nov 2014

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

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

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

If ϕ^{NP} is of O(1), Λ_{NP}~<u>3000TeV</u> Probed!

If Λ_{NP}~O(1TeV), ϕ_{NP}~10^{-7} Probed!

<u>Unique Capabilities!</u>

EDM status (cont'd)

- ThO, current limit on eEDM: 10^{-28} *e*-cm, next goal $\times$ 10 improvement.

- TUM nEDM effort, making progress in B-field shielding, met B-field specs, goal: 10^{-28} *e*-cm, staged approach

- ^{225}Ra EDM, $\sim 5 \times 10^{-22}$ e-cm now, $\sim 3 \times 10^{-28}$ *e*-cm w/ FRIB

- Storage ring EDM: p,dEDM goals $\sim 10^{-29}$ - 10^{-30} *e*-cm Strength: statistics, CW-CCW storage.

EDM experiments

- The neutron EDM experiments are making progress. Best goal: ~10^{-28} *e*-cm

- ^{199}Hg limits keep getting better. Currently setting best nEDM limit 1.6×10^{-28}*e*-cm & pEDM 5×10^{-25}*e*-cm

- eEDM limit ~10^{-28}*e*-cm (equivalent to 10^{-27}*e*-cm for nEDM and pEDM: by a factor of m_q/m_e).

Currently, on systematic errors

- The magnetic field shielding work is under control. Simulations, consistent w/ analytical estimations, show Clockwise (CW) and Counter-clockwise (CCW) B-field geometrical phase cancel. Reset the shielding requirements to 10-100nT.

- Hardware dev. achieved specs: <10nT

- The SQUID-based gradiometer to specs is done. Proceeding for 5x better sensitivity system

Currently, on systematic errors

- Electrostatic quadrupole position tolerances by high precision beam/spin dynamics simulations are underway.

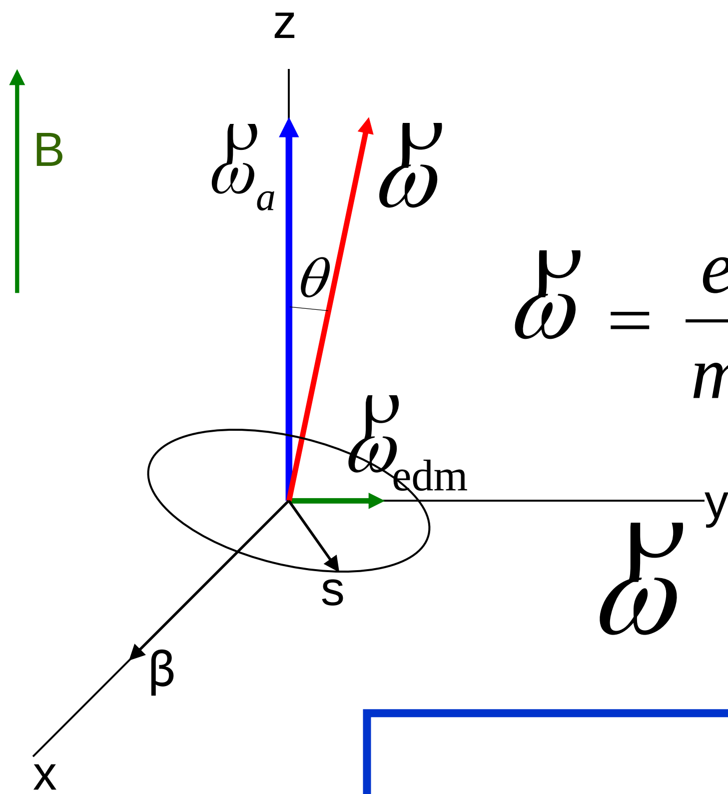
- An independent application is being used to study the same. Teleconferences are used to communicate the results.

- We will have a workshop early (March?) next year to summarize all progress

Currently, on systematic errors

- A consensus is building up to go with the proton EDM first as simpler.
- We are considering various lattices for an all-electric field
- Working on the prototype scale and purpose

Indirect Muon EDM limit from the g-2 Experiment



$$\vec{\omega} = \frac{e}{m}\left\{a\vec{B} + \frac{\eta}{2c}\left(\vec{v}\times\vec{B}\right)\right\}$$

$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_{\text{edm}}$$

$$\tan\theta = \frac{\omega_{edm}}{\omega_a}$$

Ron McNabb's Thesis 2003: $< 2.7\times 10^{-19}\,\mathrm{e\cdot cm}\ 95\%\ \mathrm{C.L.}$

Axion dark matter search in storage rings

- A modified storage ring EDM method can search for the oscillating theta term.

- Oscillating axion field in resonance with the g-2 frequency.

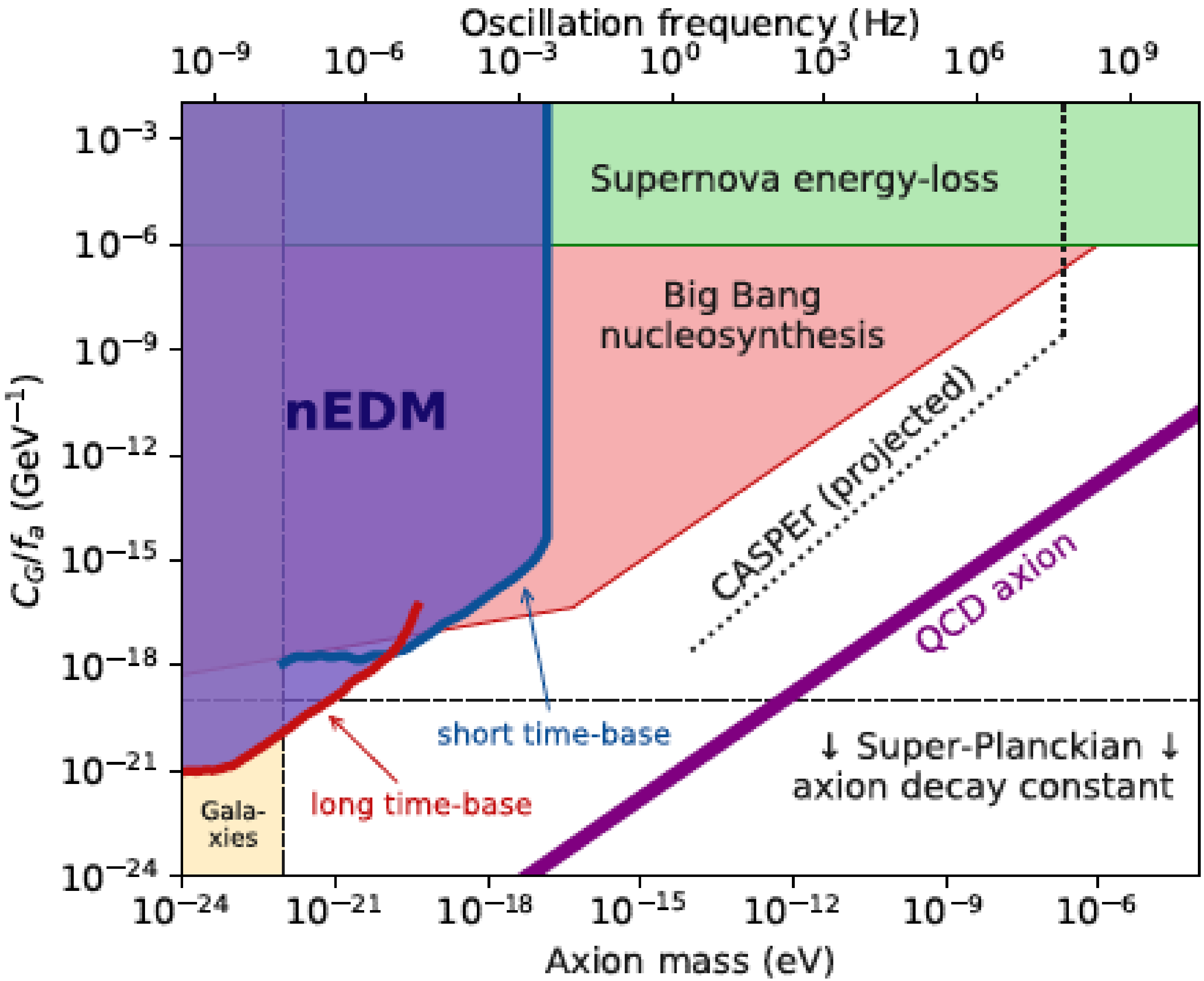
- Frequency range: 100MHz all the way down to sub-micro-Hz.

- Great physics output, simpler systematic errors

Search for axion dark matter in storage rings

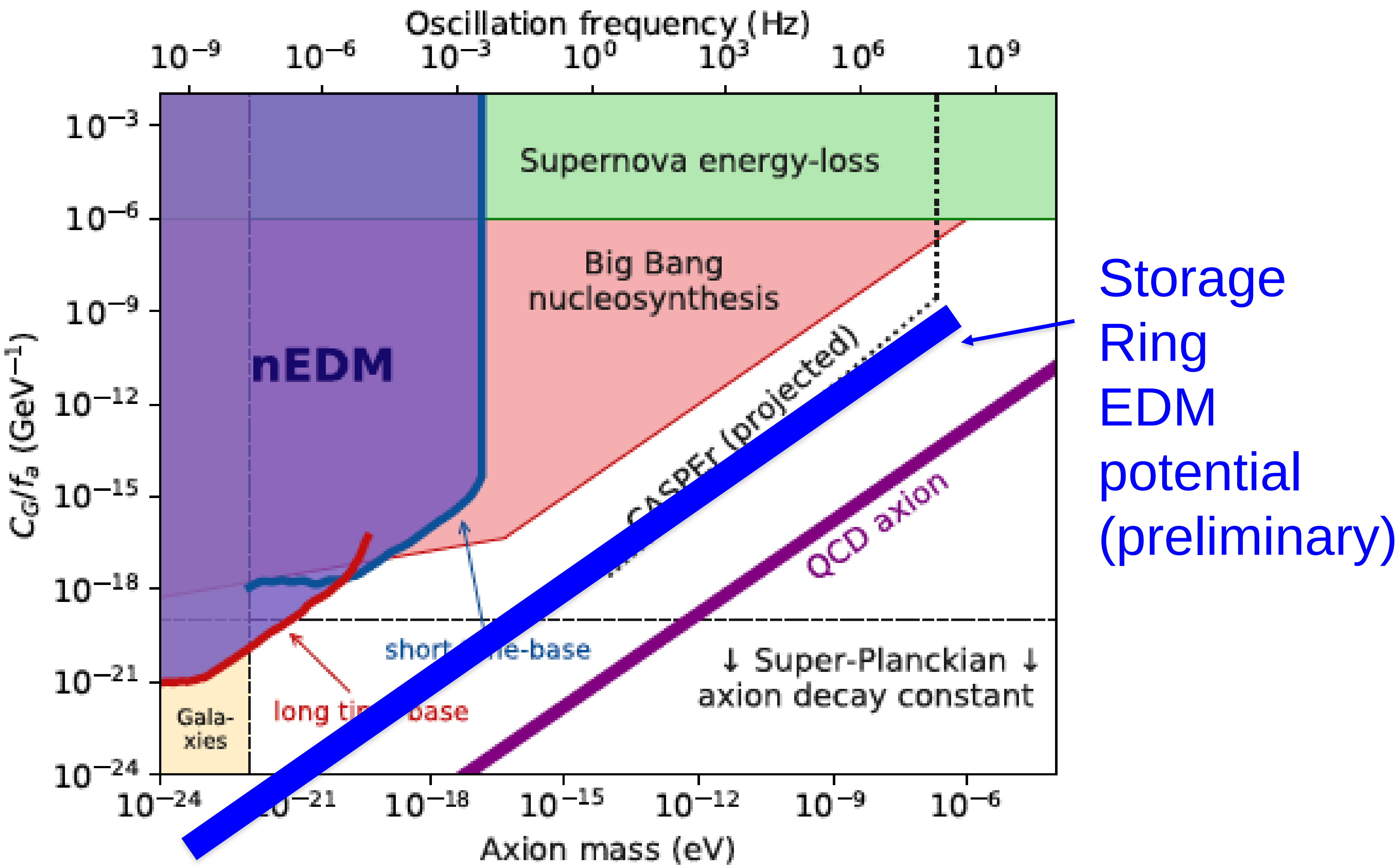
- The axion field (dark matter) induces an oscillating EDM in nucleons P. Graham and S. Rajendran PRD 84, 055013, 2011 and PRD 88, 035023, 2013.

- A combination of the storage ring EDM method plus the g-2 principle we can search for axion dark matter!
- Large effective E-field
- High statistical power
- Large axion frequency coverage
- Can take advantage of large axion coherence time since the stability of the g-2 tune is shown to be at the 10^{-10} level! (Work at COSY)



arXiv:1708.06367v1

PhysRevX.7.041034



arXiv:1708.06367v1

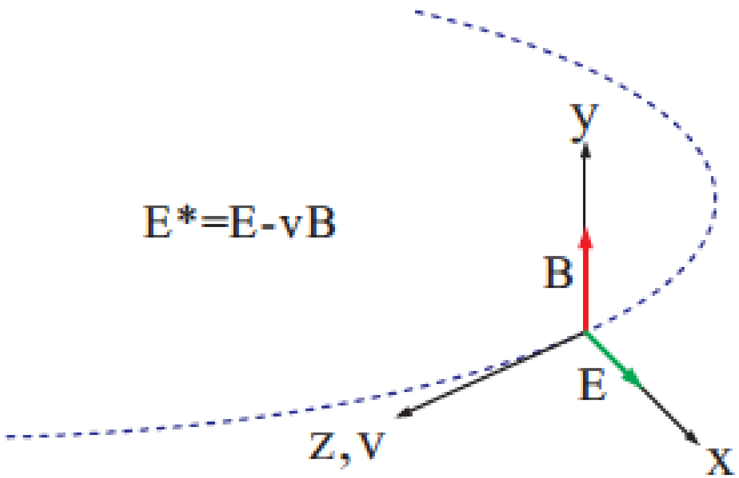
Summary

- Physics reach strong for p,dEDM < 10^{-29} e-cm
- Physics reach enriched with oscillating theta_QCD sensitivity! Probing axion dark matter for axion mass below 0.5 micro-eV.

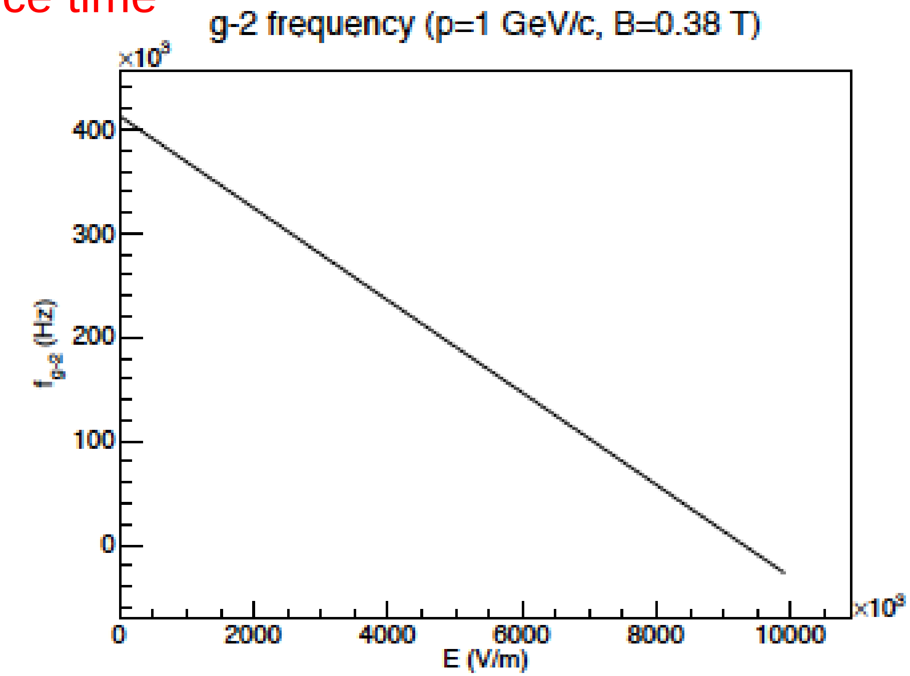
- Systematics: Hardware development is going well.
- High precision software work in parallel. Workshop early next year.

Search for axion dark matter in storage rings (1710.05271)

- Large effective E-field
- Statistics
- Superb tune stability, long spin coherence time



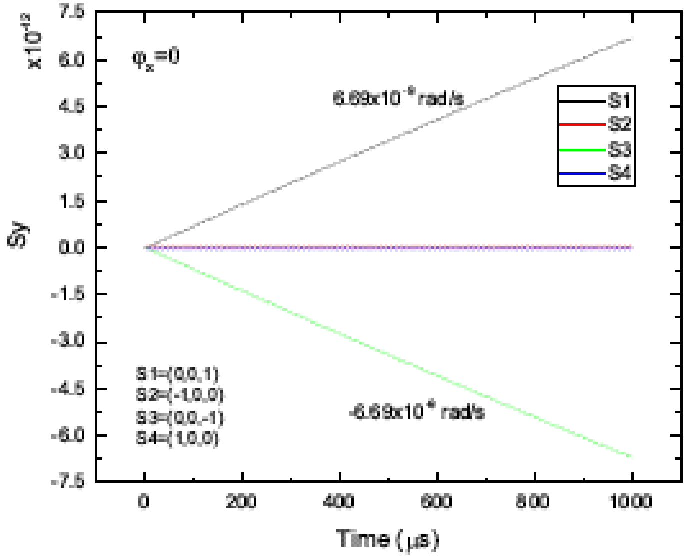
(a) The coordinate of B, E and v



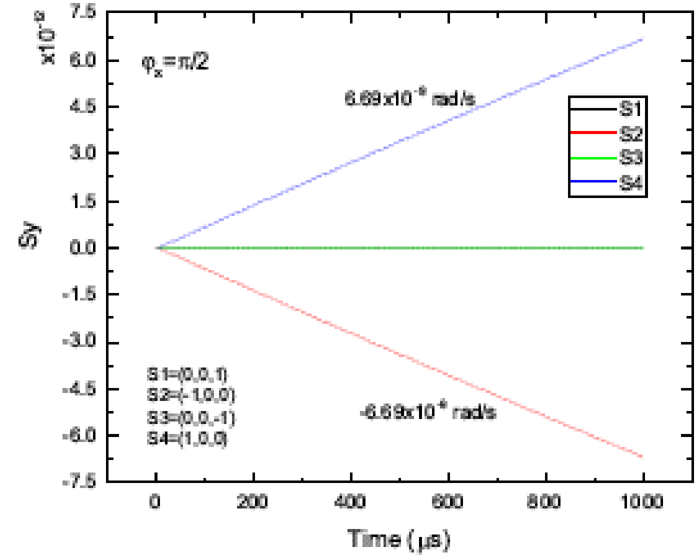
(b) $g-2$ frequency vs E field

Figure 2: E/B combined ring for $g-2$ frequency tunning

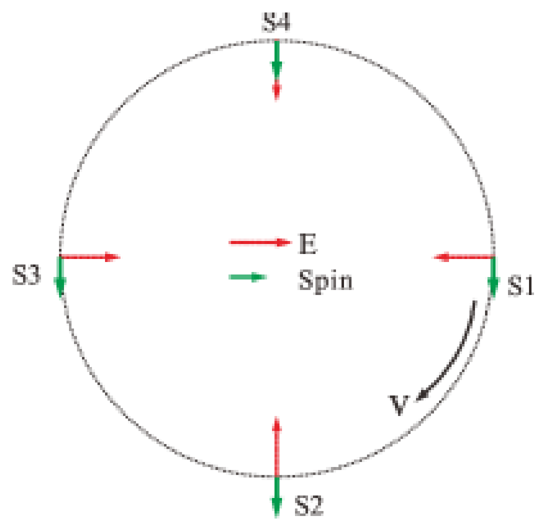
Spin direction



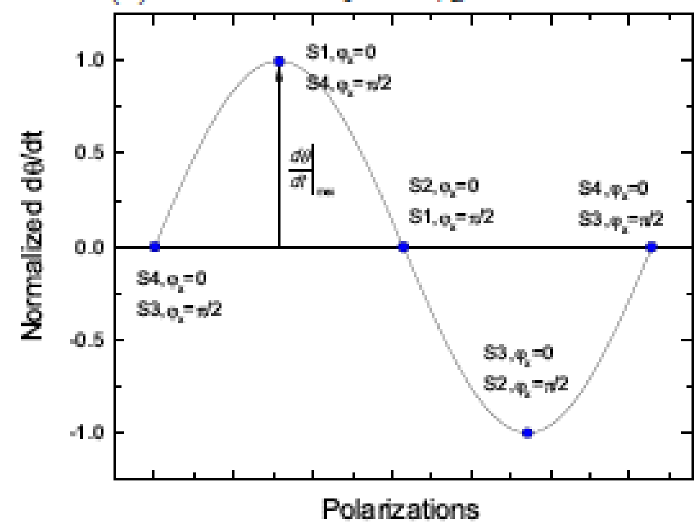
(a) Initial axion phase $\phi_x = 0$



(b) Initial axion phase $\phi_x = 0$



(c) Initial axion phase $\phi_x = \pi/2$



(d) Vertical precession rate vs. initial spin with different axion phase

Figure 4: Vertical spin precession with different initial polarization

Deuteron

Table 1: Examples of experiment parameters for frequency tunning and results of sensitivity calculation (Deuteron). The analyzing power was assumed to be $A = 0.36$ for both B-ring and E/B combined ring.

B (T)	P (GeV/c)	f_{g-2} (Hz)	E_r (V/m)	E^* (V/m)	Sensitivity (e·cm) a	Sensitivity (e·cm) b	Ring
0.38	0.9429	10^2	8.82×10^6	4.23×10^7	1.9×10^{-31}	1.9×10^{-31}	E/B ring ($r = 10$ m)
0.38	0.9433	10^3	8.80×10^6	4.24×10^7	6.0×10^{-31}	1.9×10^{-31}	
0.38	0.9473	10^4	8.65×10^6	4.27×10^7	1.9×10^{-30}	1.9×10^{-31}	
0.38	**0.988**	$\mathbf{10^5}$	$\mathbf{7.05 \times 10^6}$	4.60×10^7	5.5×10^{-30}	$\mathbf{1.8 \times 10^{-31}}$	
0.38	1.035	2×10^5	5.06×10^6	5.00×10^7	7.2×10^{-30}	1.6×10^{-31}	
0.38	1.133	4×10^5	3.47×10^5	5.86×10^7	8.7×10^{-30}	1.4×10^{-31}	
0.38	1.239	6×10^5	-5.47×10^6	6.83×10^7	9.1×10^{-30}	1.2×10^{-31}	
0.38	1.355	8×10^5	-1.26×10^7	7.93×10^7	9.1×10^{-30}	1.0×10^{-31}	
0.38	1.484	10^6	-2.14×10^7	9.21×10^7	8.8×10^{-30}	8.8×10^{-31}	
0.80	2.513	10^6	-9.13×10^6	2.01×10^8	4.0×10^{-30}	4.0×10^{-31}	
0.9198	2.7574	10^6	0	2.28×10^8	3.5×10^{-30}	3.5×10^{-31}	B ring ($r = 10$ m)
9.1977	27.574	10^7	0	2.75×10^9	9.3×10^{-31}	9.3×10^{-31}	

a : Axion $Q = 10^6$, Polarimeter Efficiency = 0.02,
Initial polarization = 0.8, Analyzing power A=0.36, SCT = 10^4 s.

b : Axion $Q = 10^{10}$, Polarimeter Efficiency = 0.02,
Initial polarization = 0.8, Analyzing power A=0.36, SCT = 10^4 s.

Proton

Table 2: Examples of experiment parameters for frequency tunning and results of sensitivity calculation (Proton). The analyzing power used for E/B combined ring was $A = 0.6$ and $A = 0.25$ was used for B field only ring.

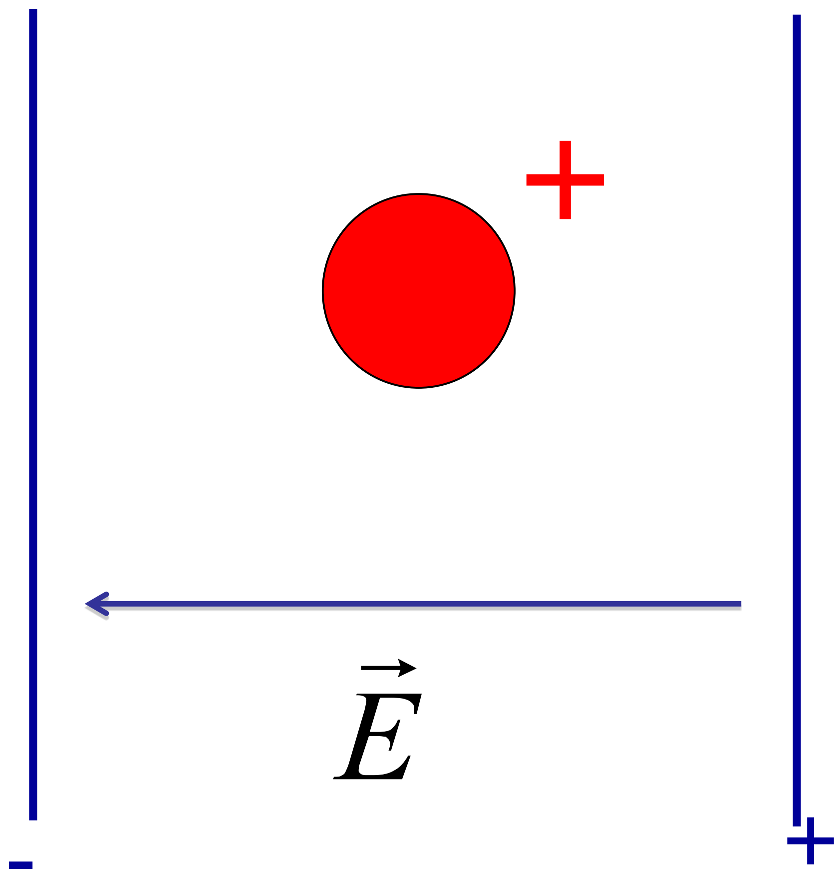
B (T)	P (GeV/c)	f_{g-2} (Hz)	E_r (V/m)	E^* (V/m)	Sensitivity (e·cm) a	Sensitivity (e·cm) b	Ring
0.00010	0.6984	10^2	-8.00×10^6	8.02×10^6	1.0×10^{-30}	1.0×10^{-30}	E/B ring ($r = 52$ m)
0.00008	0.6982	10^3	-8.00×10^6	8.01×10^6	3.2×10^{-30}	1.0×10^{-30}	
-0.00017	0.6964	10^4	-8.00×10^6	7.97×10^6	1.0×10^{-29}	1.0×10^{-30}	
-0.00243	0.6747	10^5	-8.00×10^6	7.57×10^6	3.4×10^{-29}	1.1×10^{-30}	
-0.00495	0.6519	2×10^5	-8.00×10^6	7.15×10^6	5.0×10^{-29}	1.1×10^{-30}	
-0.01523	0.7103	4×10^5	-1.10×10^7	8.24×10^6	6.2×10^{-29}	9.8×10^{-31}	
-0.02002	0.6711	6×10^5	-1.10×10^7	7.51×10^6	8.3×10^{-29}	1.1×10^{-30}	
-0.02666	0.6643	8×10^5	-1.20×10^7	7.38×10^6	9.8×10^{-29}	1.1×10^{-30}	
-0.03327	0.6583	10^6	-1.30×10^7	7.27×10^6	1.1×10^{-28}	1.1×10^{-30}	
0.36587	1.0968	10^7	0	8.33×10^7	3.1×10^{-29}	3.1×10^{-31}	B ring ($r = 10$ m)
3.65868	10.9684	10^8	0	1.09×10^9	7.4×10^{-30}	7.4×10^{-32}	

a : Axion $Q = 10^6$, Polarimeter Efficiency = 0.02, Initial polarization = 0.8, SCT = 10^4 s.
b : Axion $Q = 10^{10}$, Polarimeter Efficiency = 0.02, Initial polarization = 0.8, SCT = 10^4 s.
Analyzing power A : $A = 0.6$ for E/B ring, $A = 0.25$ for B ring

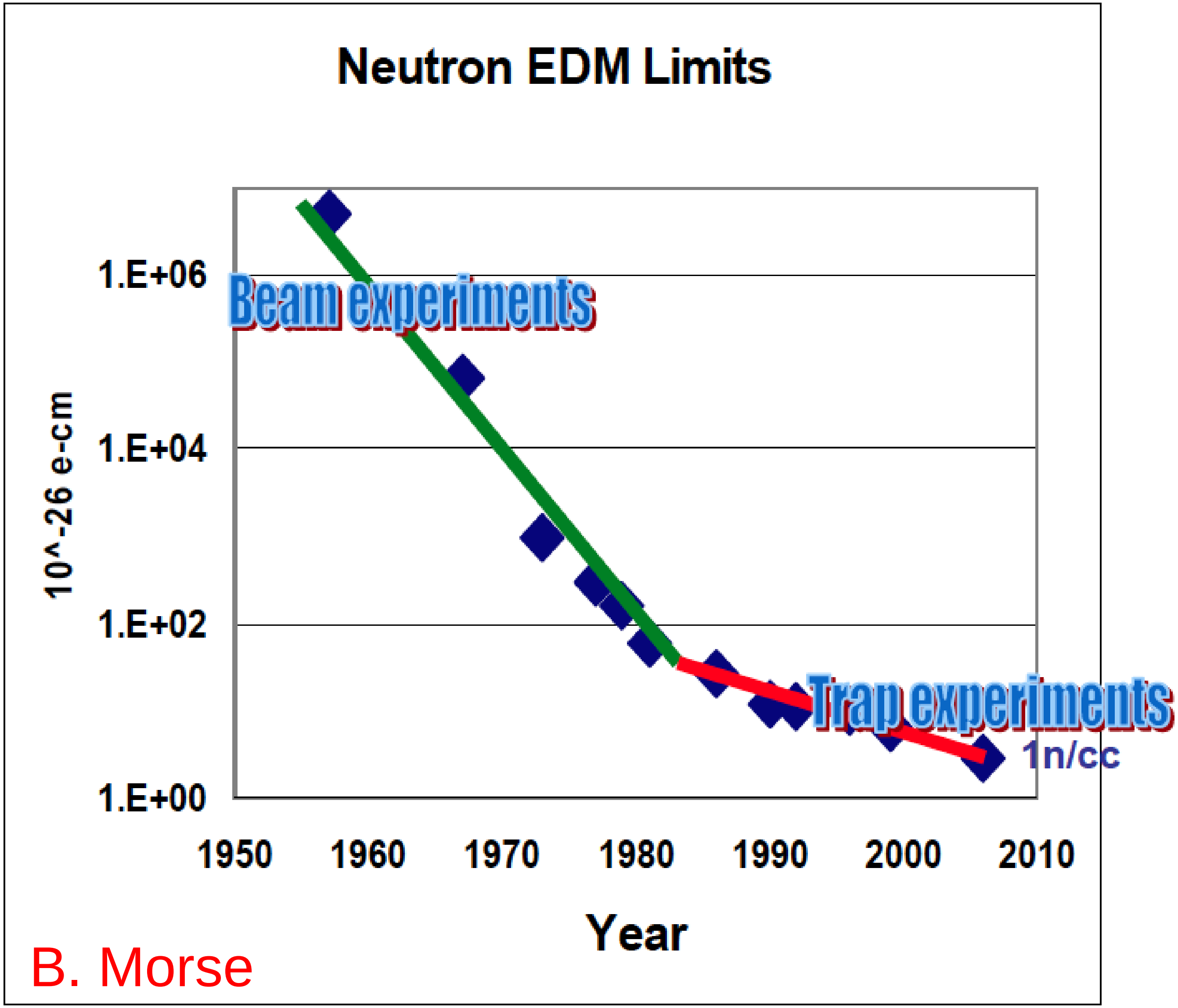
History/Status of nEDM@SNS

- **2011:** NSAC Neutron Subcommittee
- **2013:** Critical R&D successfully demonstrated
- **2014-2017:** Critical Component Demonstration (CCD) phase begun
  - Build working, full-scale, prototypes of technically-challenging subsystems (use these in the full experiment)
  - 4yr NSF proposal for 6.5M$ CCD funded
  - DOE commitment of ≈ 1.8M$/yr for CCD
- **2018-2020:** Large scale Integration and Conventional Component Procurement
- **2021:** Begin Commissioning and Data-taking

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



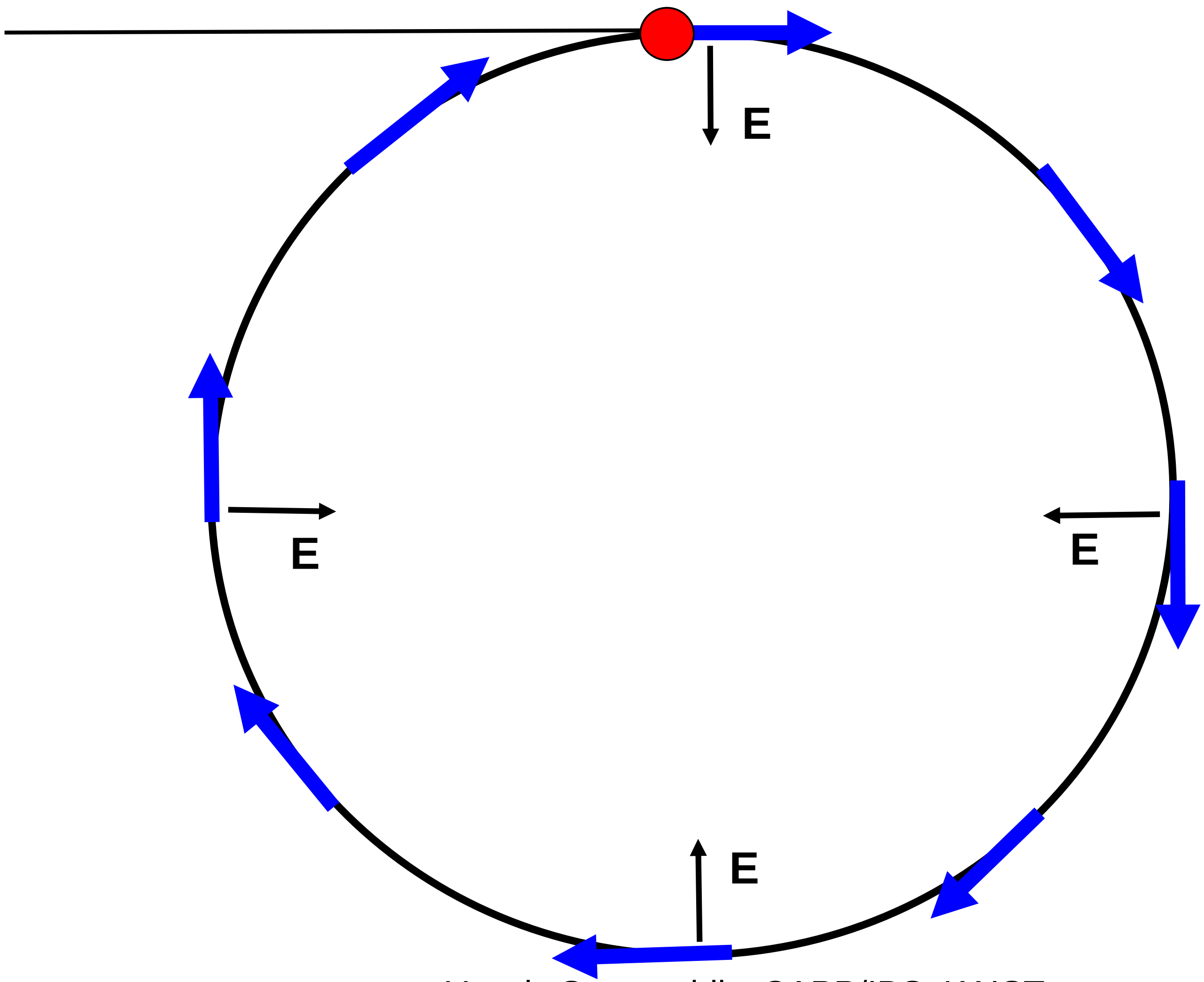
Proton storage ring EDM experiment is combination of beam + a trap



The Electric Dipole Moment precesses in an Electric field

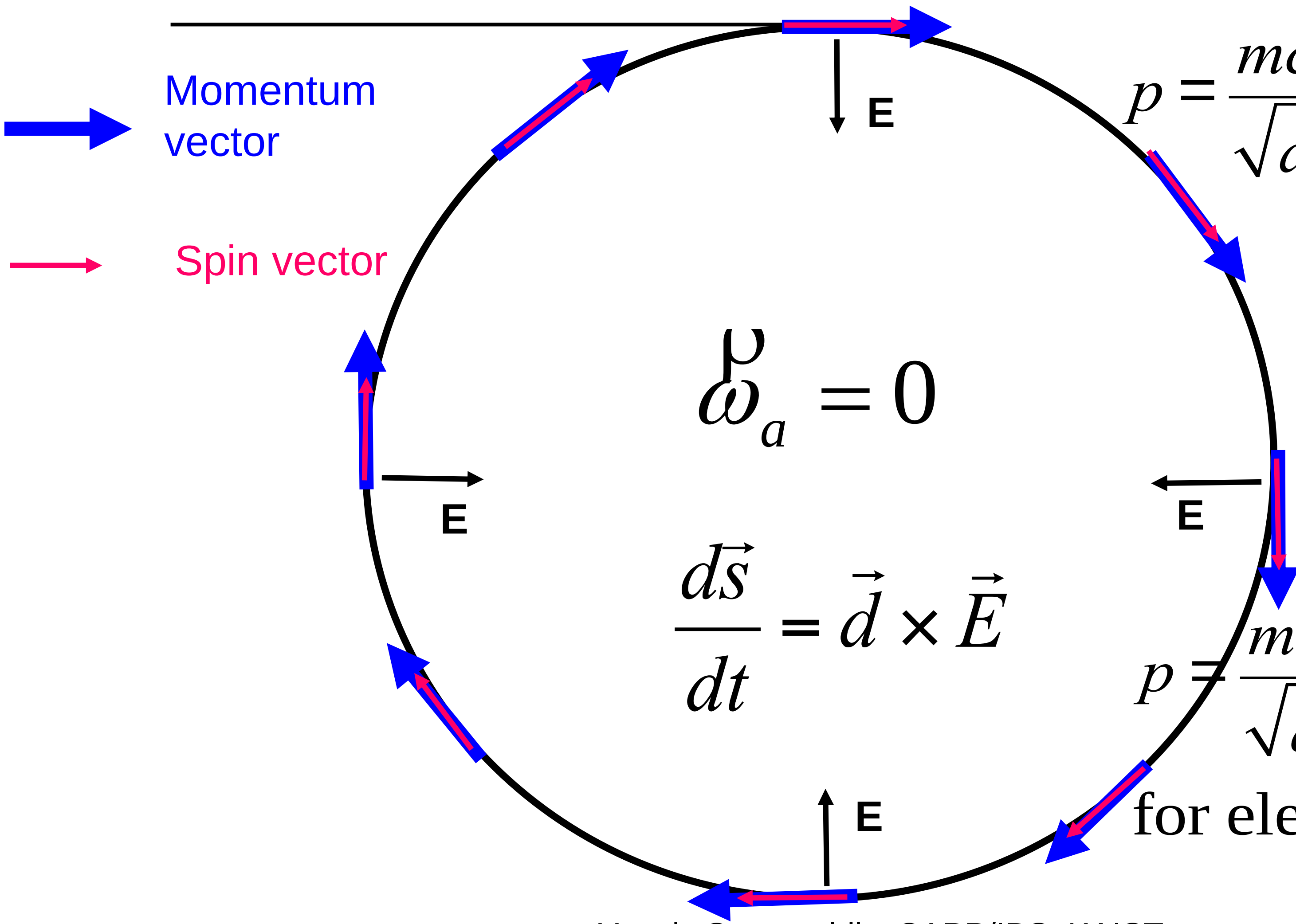
$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$

Stored beam: The radial E-field force is balanced by the centrifugal force.



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

at the magic momentum



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

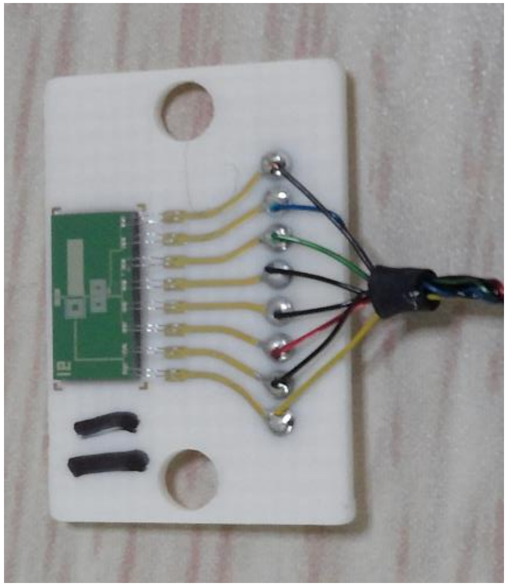
$$\vec{\omega}_a = 0$$

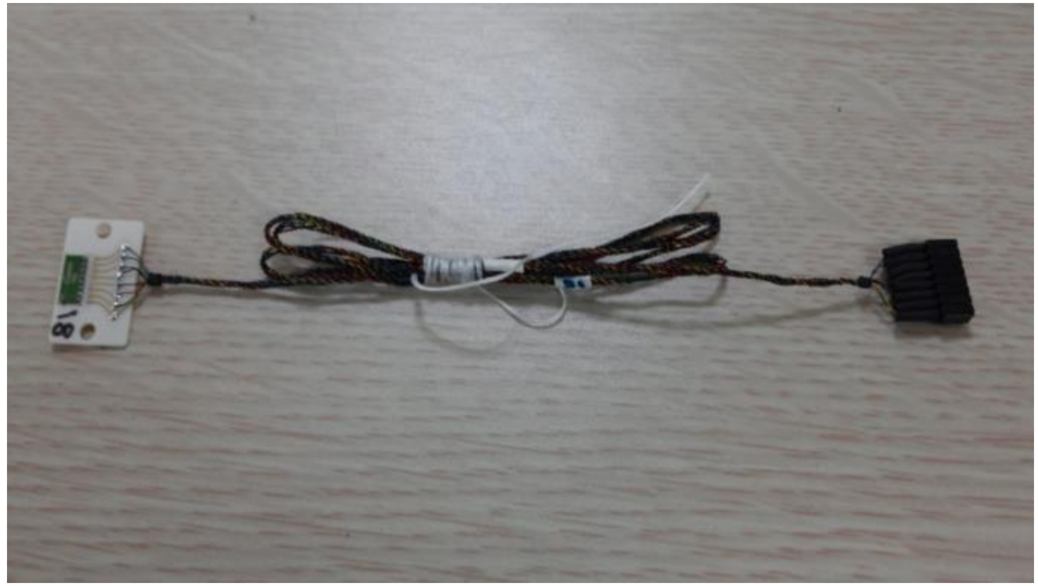
$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$

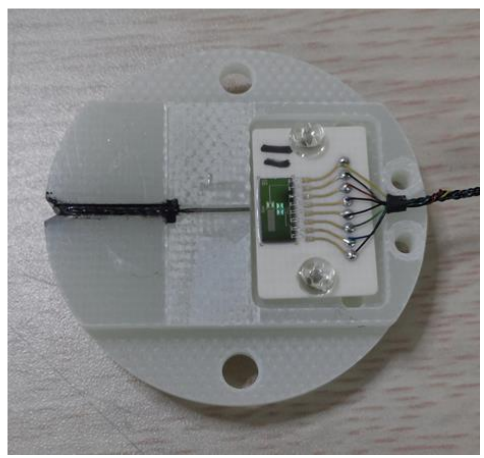
$$p = \frac{mc}{\sqrt{a}} = 15\text{MeV/c}$$

for electrons!

Magnetometer Design







Andrei Matlashov, IBS/CAPP