The status of the storage ring Proton EDM

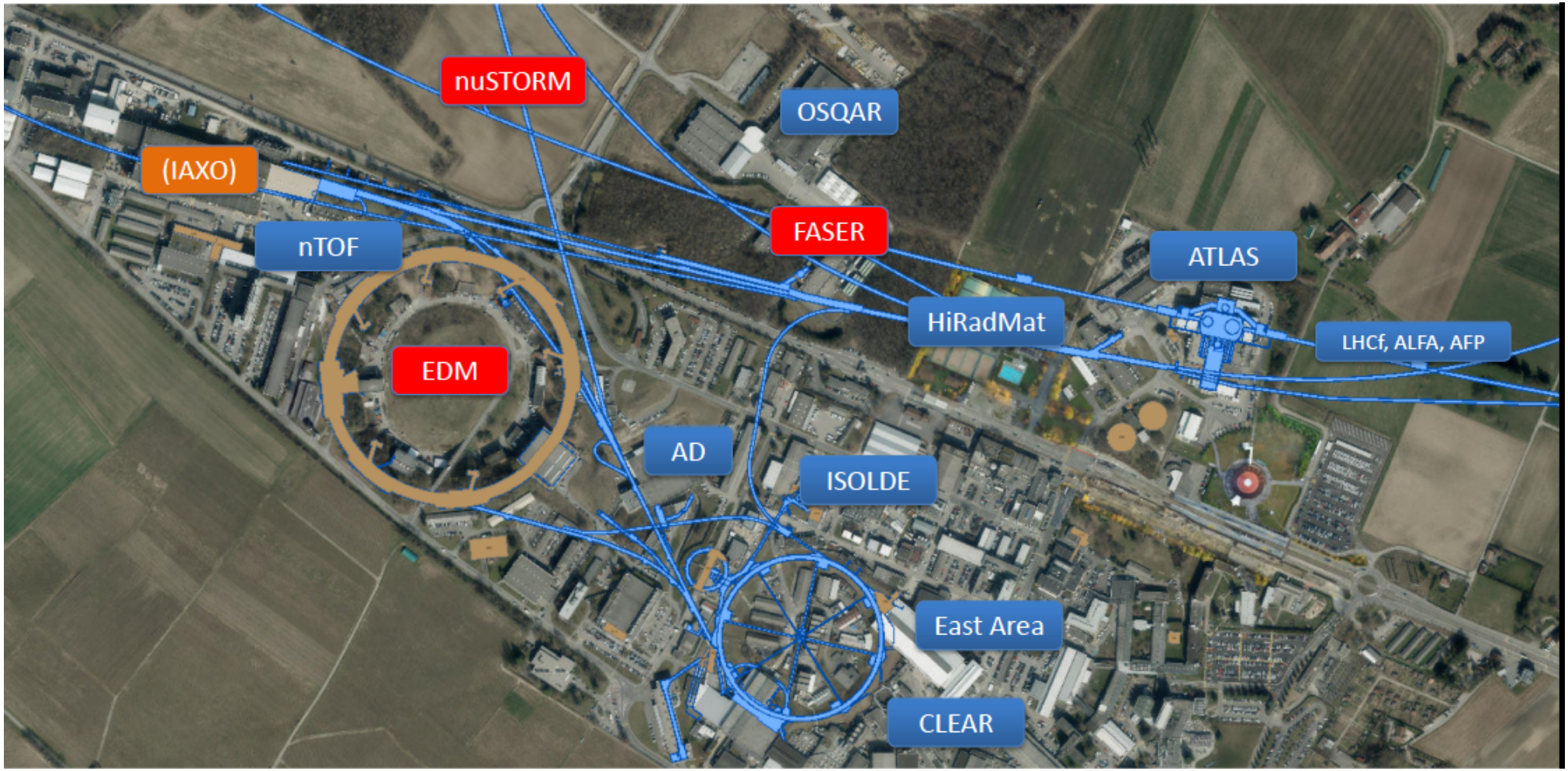
Yannis K. Semertzidis, IBS/CAPP & KAIST

- At 10^{-29} *e*-cm, it improves theta_QCD sensitivity by three orders of magnitude
- It probes SUSY-like New Physics at the 10^3 TeV level
- **Hybrid ring: electric bending, magnetic focusing, major progress in combating systematic errors**

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

Mike Lamont, CERN



CPEDM collaboration, Juelich, March 9, 2018

Spin and EDM: Proton and Deuteron

- Spin generates a magnetic dipole moment
- If it also generates an electric dipole moment: it violates both P&T, through CPT cons.→CP violation

Spin and EDM: Proton and Deuteron

- The QCD Lagrangian contains a P&T-violating term! A potential resolution of which could result to axions and the axion-dark matter: theta_QCD

$$L_{\not{CP}} = \bar{\theta}\,\frac{\alpha_s}{8\pi}\,G\tilde{G}$$

M. Pospelov, A. Ritz, Ann. Phys. 318 (2005) 119.

$$d_n\left(\bar{\theta}\right) \approx -d_p\left(\bar{\theta}\right) \approx 3.6\times 10^{-16}\,\bar{\theta}\ \mathrm{e}\cdot\mathrm{cm}$$

$$\text{Exp.:}\ \ d_n < 3\times 10^{-26} e\cdot\ \mathrm{cm} \rightarrow \bar{\theta} < 10^{-10}$$

Axion and EDM: Proton and Deuteron

- Storage ring p,d EDMs @ $<10^{-29}$ *e*-cm level, SUSY-like New Physics ~10^3TeV reach.

- Probing DC (permanent) EDM

EDMs of hadronic systems are mainly sensitive to

- Theta-QCD (part of the SM)

- CP-violating sources beyond the SM

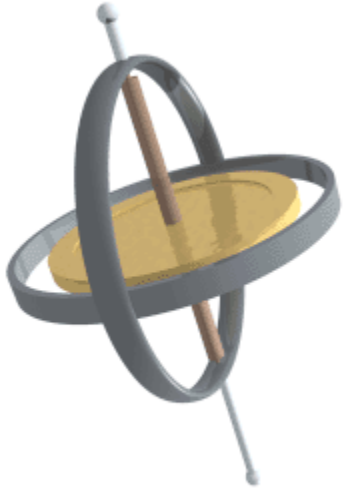
Alternative simple systems are needed to be able to differentiate the CP-violating source (e.g. neutron, proton, deuteron,…).

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

The Electric Dipole Moment precesses in an Electric field

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

Spin equations: at rest



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

$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_d, \qquad (4)$$

$$\vec{\omega}_a = -\frac{e}{m}\left[a\vec{B} - \left(a - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}}{c}\right], \qquad (5)$$

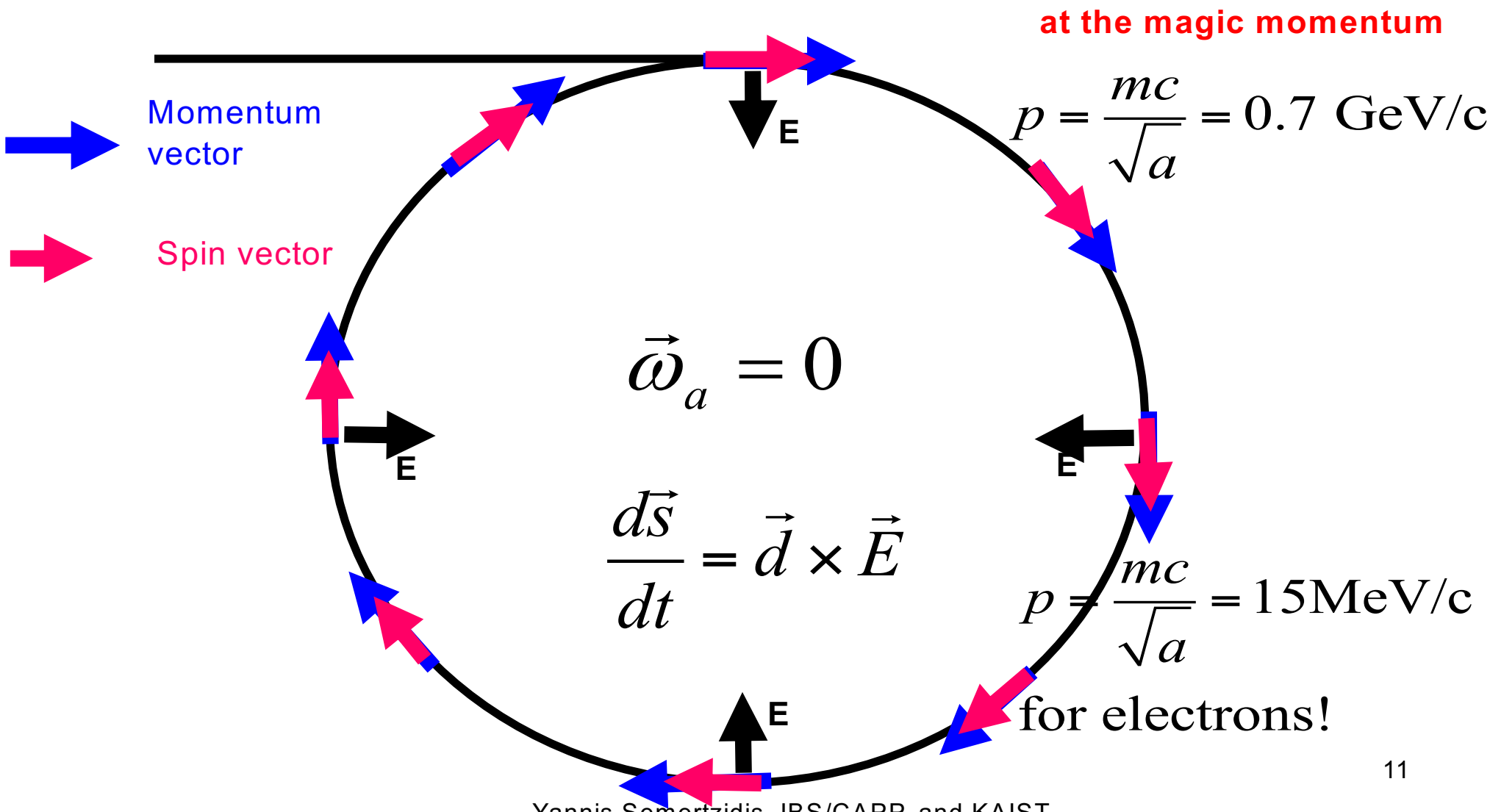
$$\vec{\omega}_d = -\frac{e}{m}\left[\frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta} \times \vec{B}\right)\right], \qquad (6)$$

where $a = (g-2)/2$ is the magnetic anomaly with $a = -0.14$ for deuterons. Here, other terms are omitted by assuming the conditions $\vec{\beta}\cdot\vec{E} = \vec{\beta}\cdot\vec{B} = 0$.

Storage rings

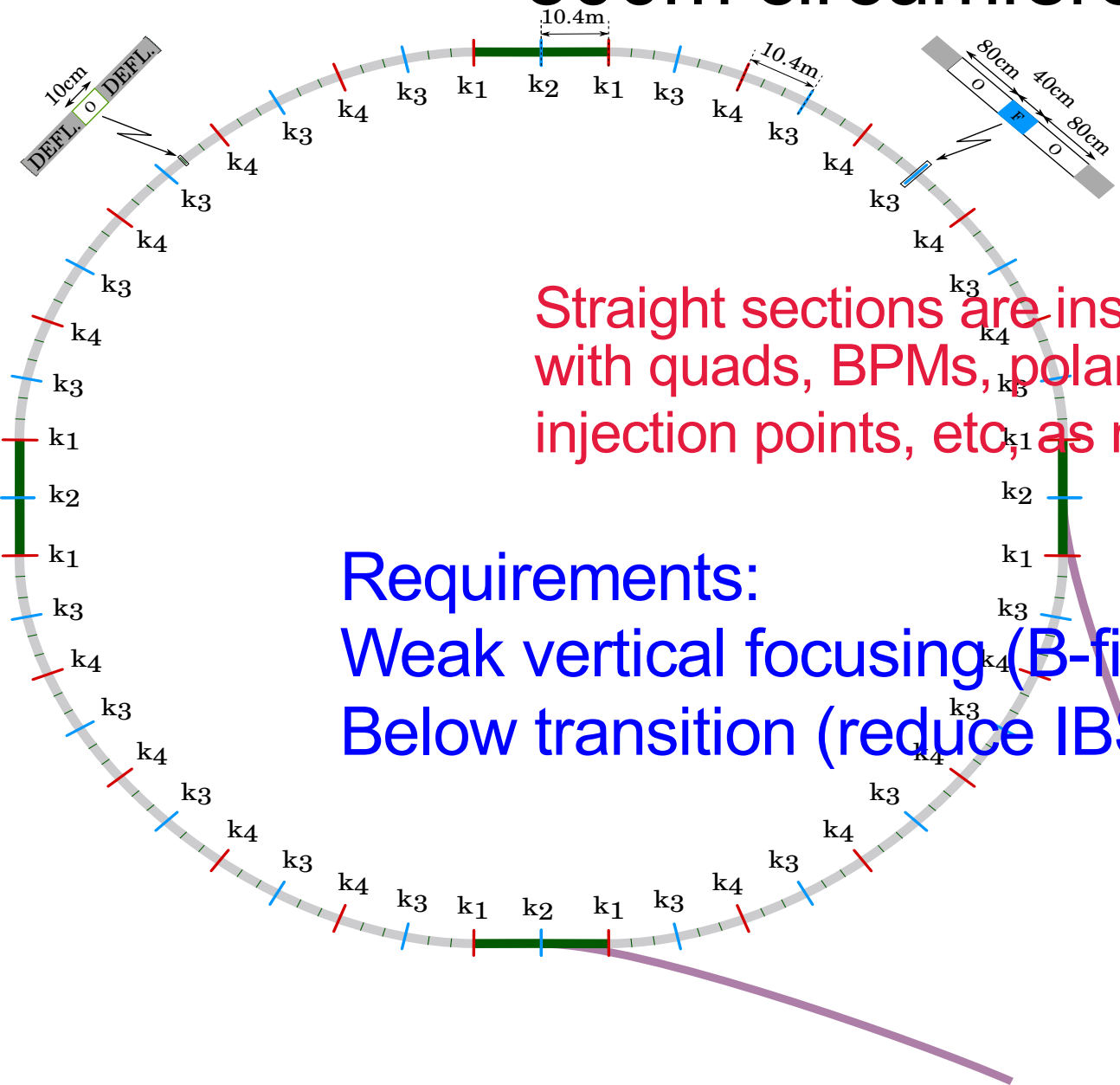
In the muon g-2 ring, for gamma=29.3

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



All-electric storage ring lattice

The proton EDM ring (alternate gradient), 500m circumference



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

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

Systematic errors

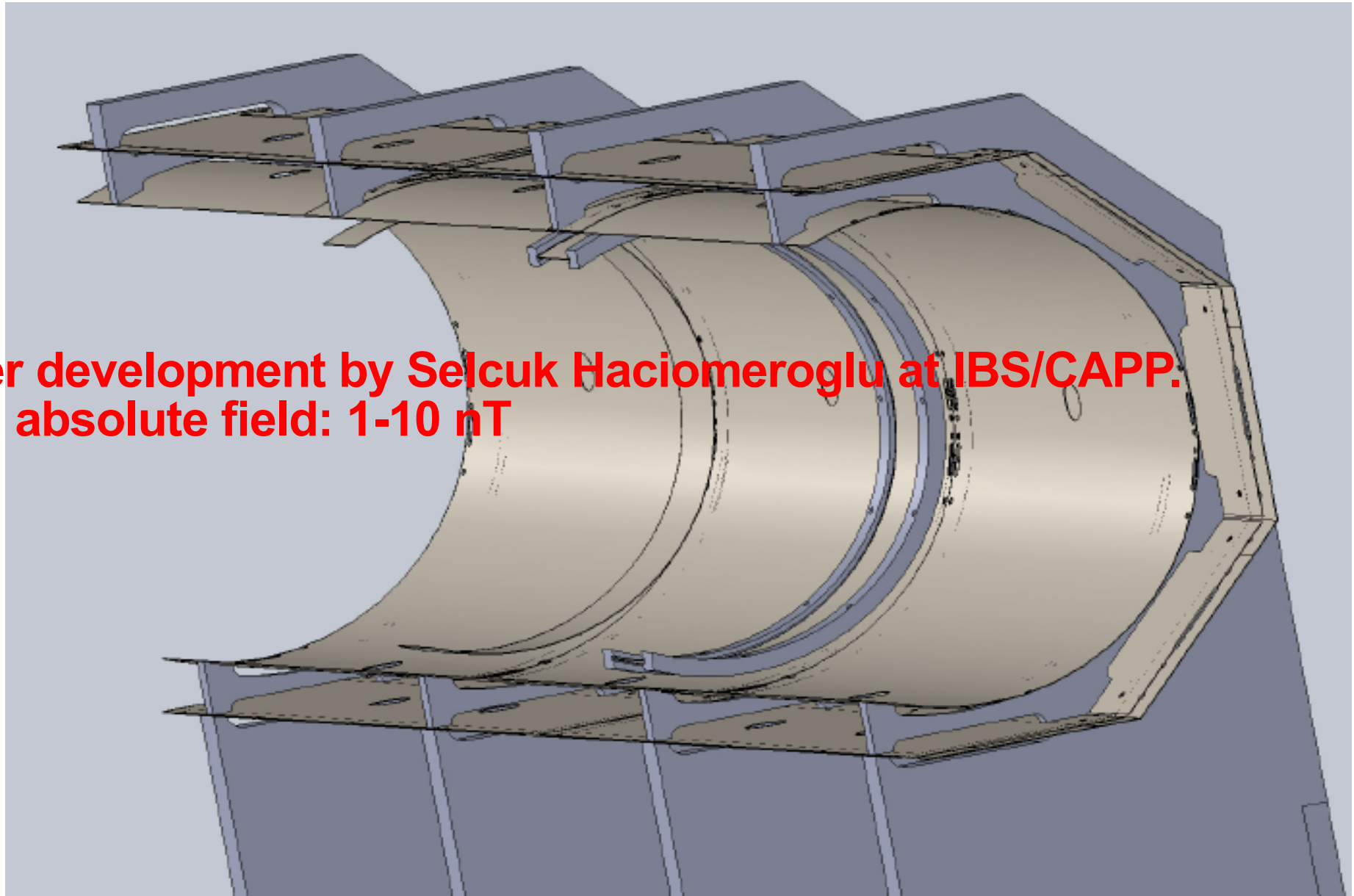
TABLE III. Main systematic errors of the experiment and their remediation.

Effect	Remediation
Radial B-field	SQUID BPMs with 1 fT/$\sqrt{\text{Hz}}$ sensitivity eliminate it.
Geometric phase	Plate alignment to better than 100 μm, plus CW and CCW storage. Reducing B-field everywhere to below 10-100 nT. BPM to 100 μm to control the effect.
Non-Radial E-field	CW and CCW beams cancel the effect.
Vert. Quad misalignment	BPM measurement sensitive to vertical beam oscillation common to CW and CCW beams.
Polarimetry	Using positive and negative helicity protons in both the CW and CCW directions cancels the errors.
Image charges	Using vertical metallic plates except in the quad region. Quad plates' aspect ratio reduces the effect.
RF cavity misalignment	Limiting longitudinal impedance to 10kΩ to control the effect of a vertical angular misalignment. CW and CCW beams cancel the effect of a vertically misplaced cavity.

Major systematic error source

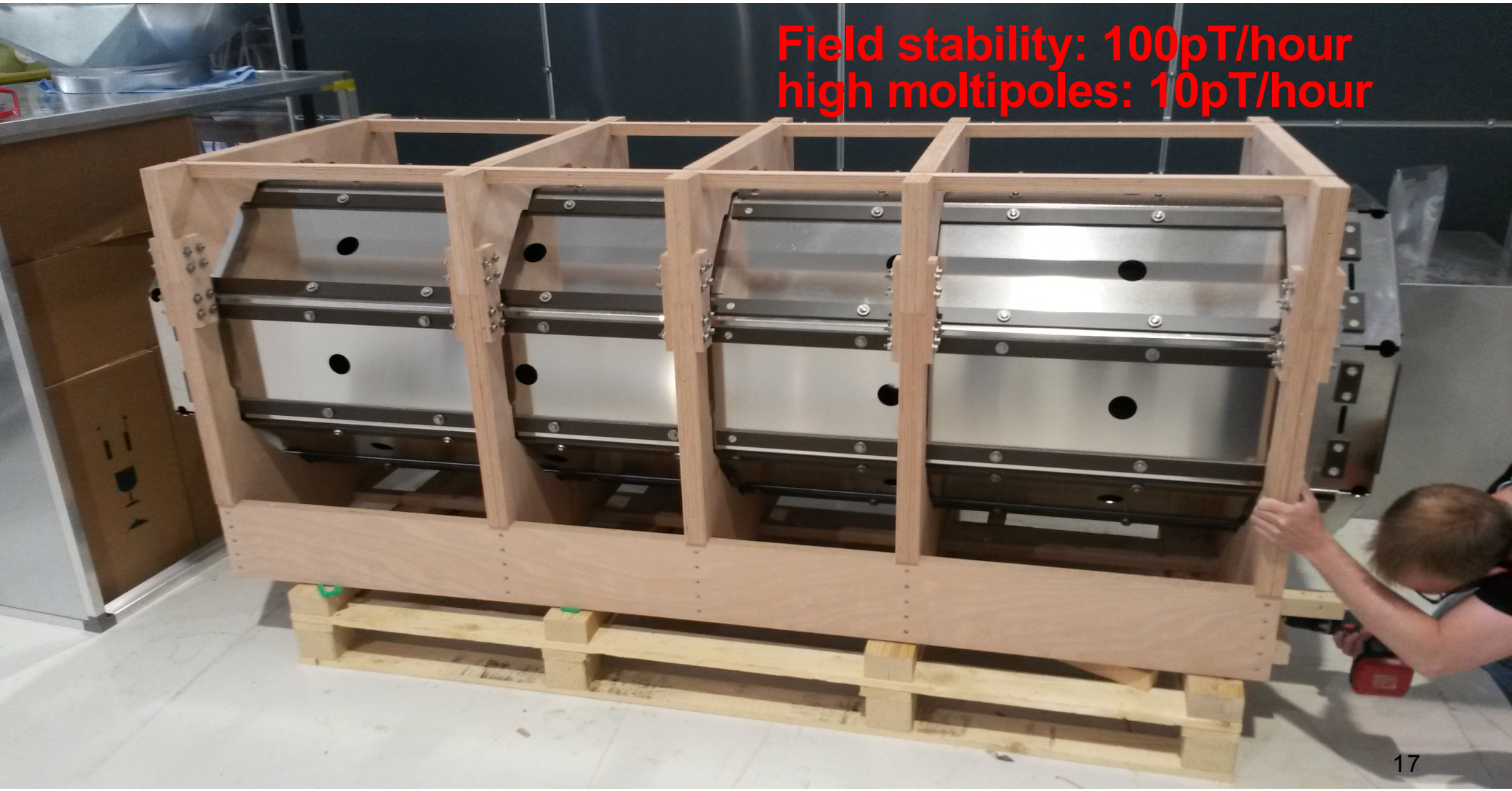
- Radial magnetic field:
  - Magnetic shielding <1nT
  - Detect it using SQUID-based Beam-Position-Monitors (BPM), See morning talk by Selcuk Haciomeroglu
  - Previous understanding: only the DC component (N=0) is important, the higher harmonics ($N>0$) *cancel out*

In collaboration with Peter Fierlinger, Garching/Munich

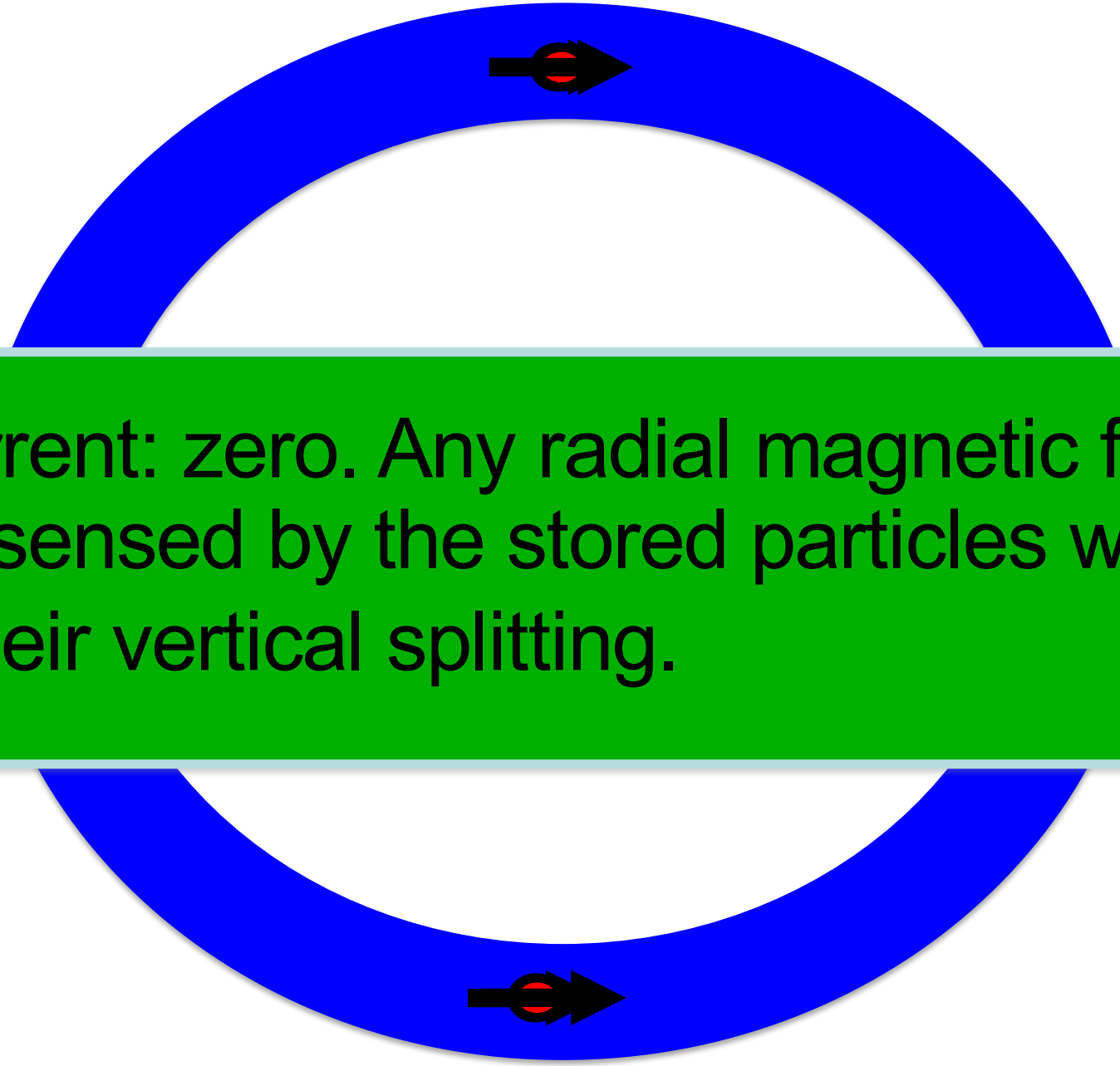


Under development by Selcuk Haciomeroglu at IBS/CAPP.
Need absolute field: 1-10 nT

In collaboration with Peter Fierlinger, Garching/Munich



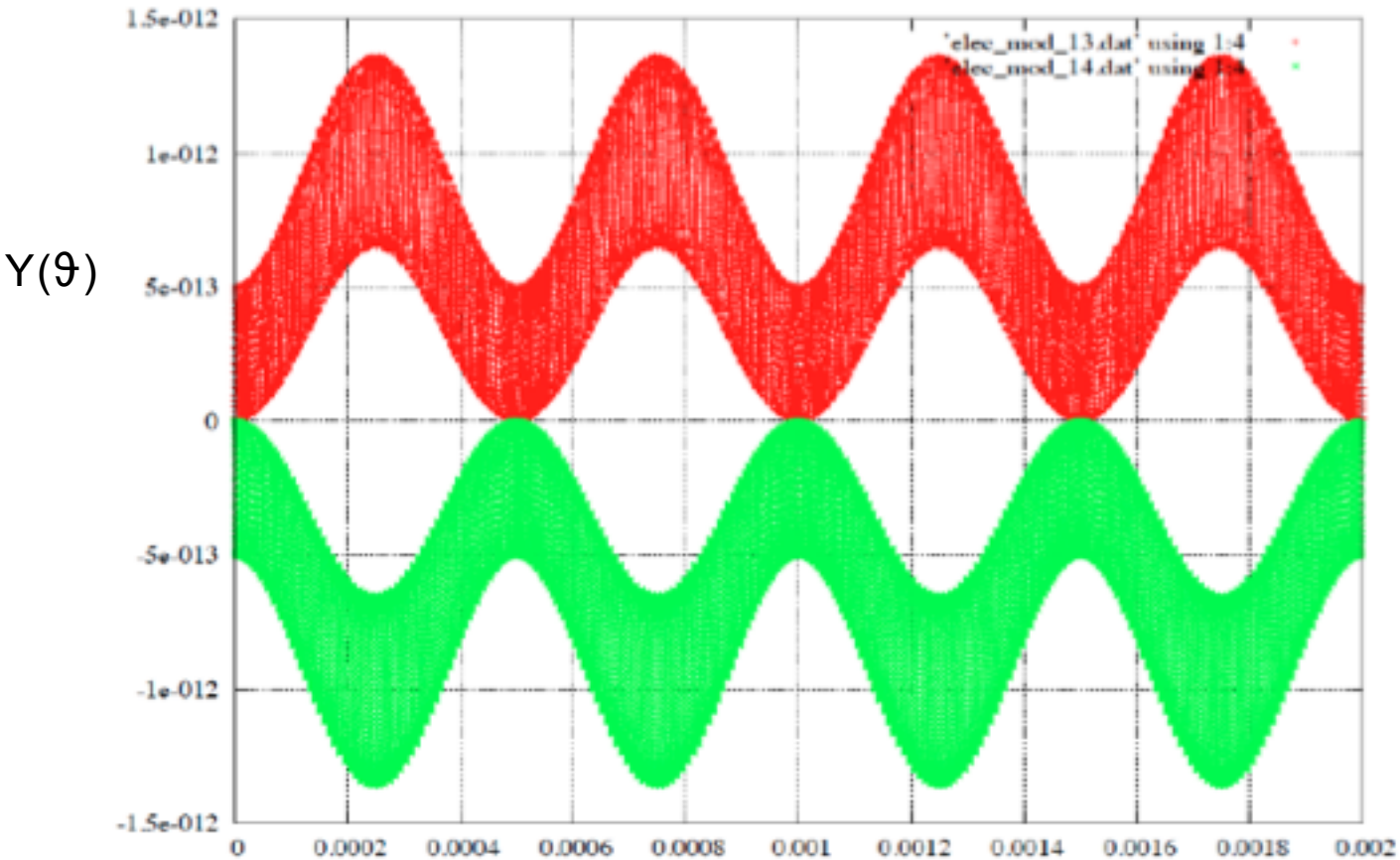
Clock-wise (CW) & Counter-Clock-wise Storage



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

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

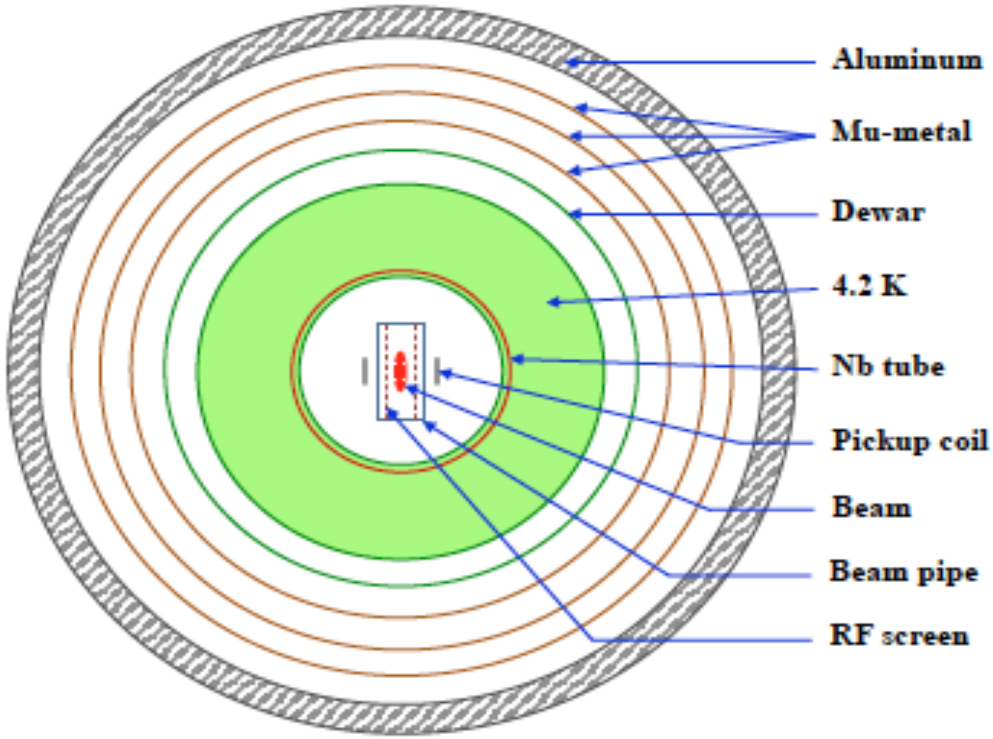


Clockwise beam

The N=0 component is a first order effect!

Counter-clockwise beam

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



See Selcuk Haciomeroglou's talk, this morning

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.

- Christian Carli (CERN):

  The effect of high-harmonics of radial B-field is significant when the lattice beta-function is not constant!

  INDEED!

- New plan:
  - Hybrid storage ring lattice
  - Electric bending with alternate magnetic focusing
  - Allows simultaneous CW and CCW storage

arXiv:1806.09319v2 [physics.acc-ph] 26 Jun 2018

A hybrid ring design in the storage-ring proton electric dipole moment experiment

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(Dated: 27 June 2018)

A new hybrid design is proposed for the frozen spin, storage-ring electric dipole moment method, which can essentially eliminate the impact of the main systematic errors. We are proposing using electric bending plates to steer the particles, and use alternate magnetic focusing instead of electric focusing. The magnetic focusing should permit simultaneous clock-wise and counter-clock-wise storage to cancel systematic errors related to out of plane dipole electric fields. The quadrupole electric fields can be eliminated by successive storage using alternate magnetic focusing each time with different strength. The beta-functions, related to the beam envelops of the counter-rotating beams, are going to be somewhat varying depending on the sign of the magnetic quadrupole currents. However, even this small effect can be eliminated since alternate runs with flipped currents in the magnetic quadrupoles will allow the counter-rotating beams to trace, on average, the same paths everywhere.

Lattice: replace E-quads with B-quads

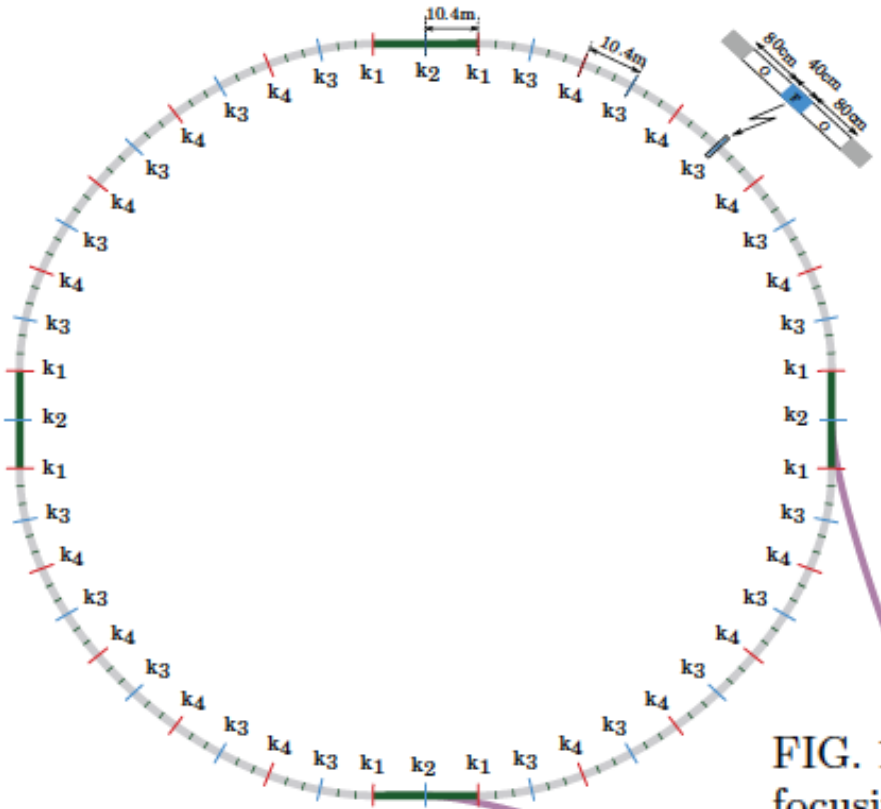


FIG. 1. A detail of the storage ring lattice is shown here with focusing and defocusing quadrupoles (shown as k_3 and k_4). The bending sections, including the short straight sections, have a length of 10.417 m, three sections assembled as one unit. The long straight sections are 20.834 m long with a quadrupole (shown as k_2) in the middle and two half-length quads (shown as k_1) at both ends. The values of the magnetic quadrupole strength are: $k_1 = 0.1\mathrm{T/m}$, $k_2 = -0.1\mathrm{T/m}$, $k_3 = -0.1\mathrm{T/m}$, $k_4 = 0.1\mathrm{T/m}$. The vertical tune, when running with these quadrupole strengths, is $Q_y = 0.67$, while the horizontal tune is $Q_x = 1.73$.

Beta-functions for clock-wise (CW) and counter-clock-wise (CCW)

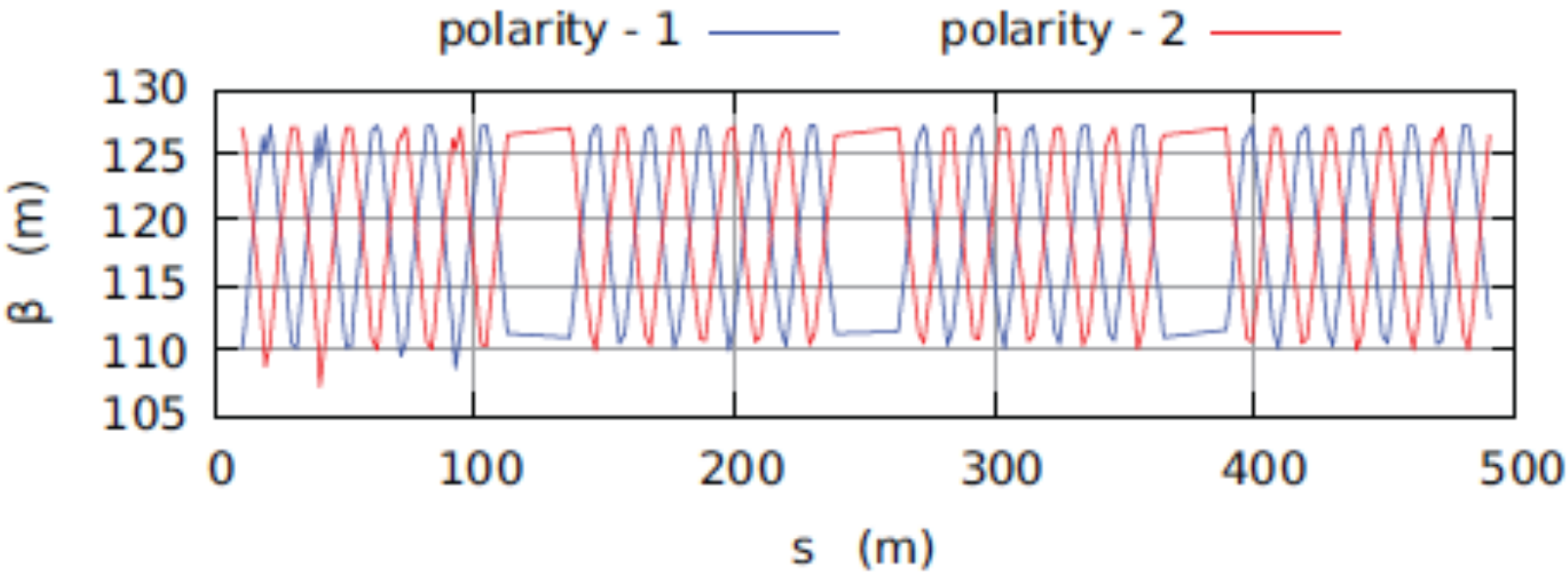


FIG. 2. The beta-function values around the ring for CW and CCW operations. They flip sign when the magnetic quadrupoles are running with opposite sign and therefore the counter-rotating particles on average trace the same paths.

Background: radial B-field with B-quads is not a problem

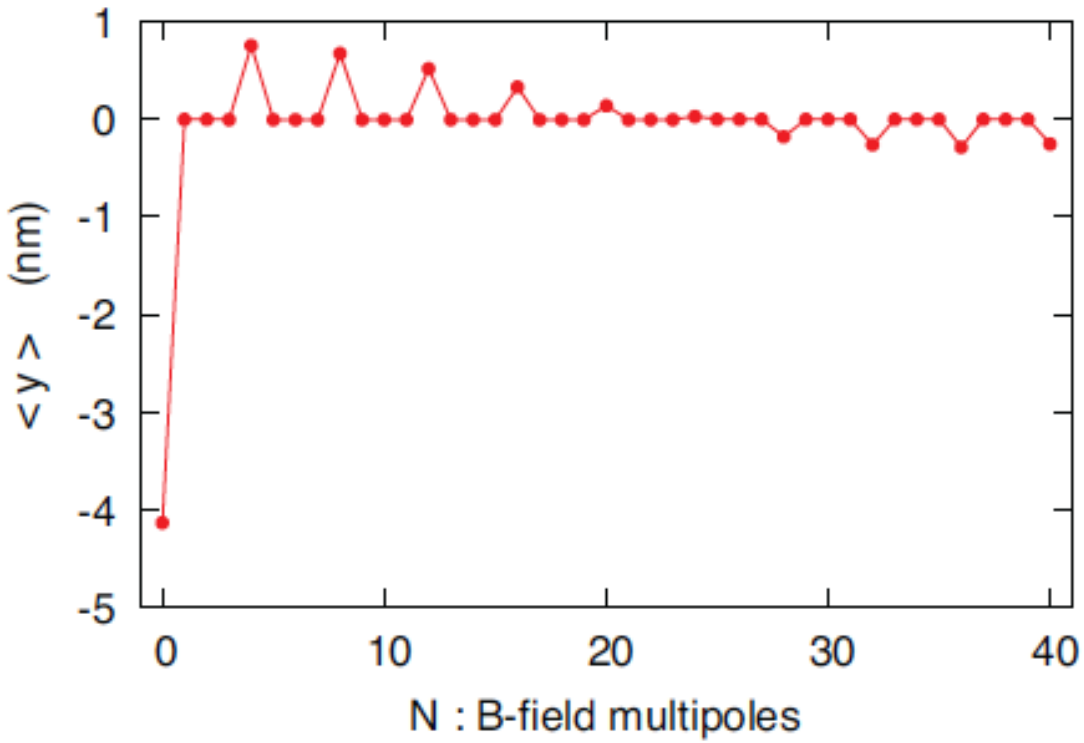


FIG. 3. The average vertical beam offset when only magnetic focusing is used, as a function of the radial B-field multipoles (N-values). The amplitude of the background radial B-field is always kept at 1pT, while the quadrupole strength is kept at ± 0.1T/m.

Background: radial B-field with B-quads is not a problem

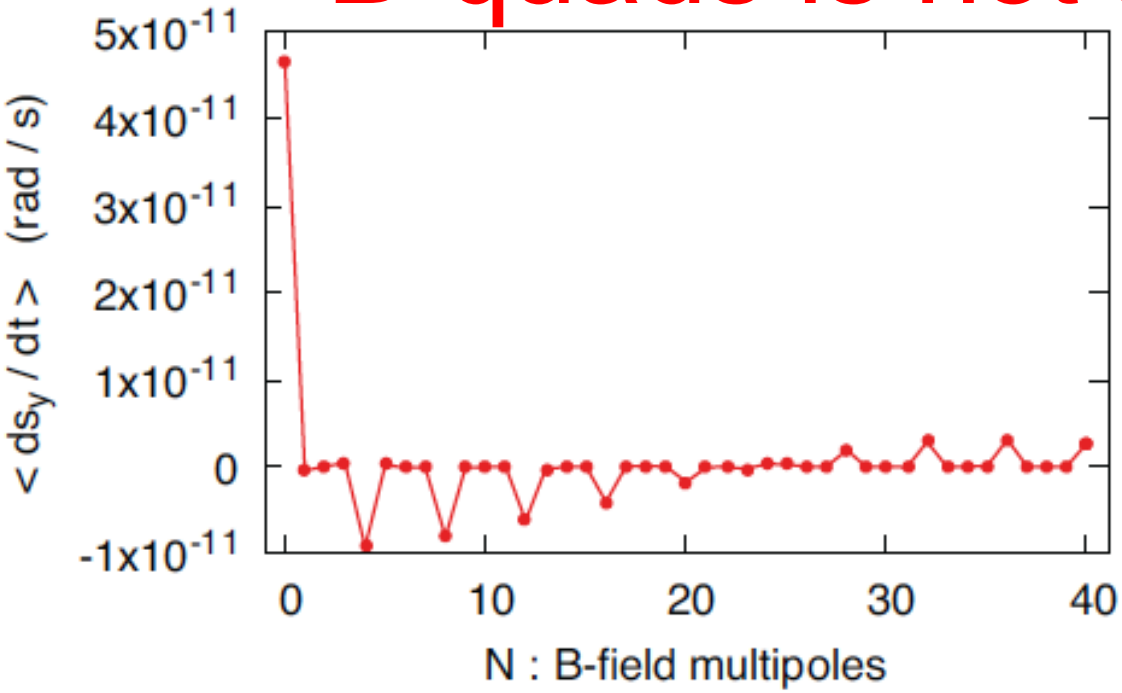


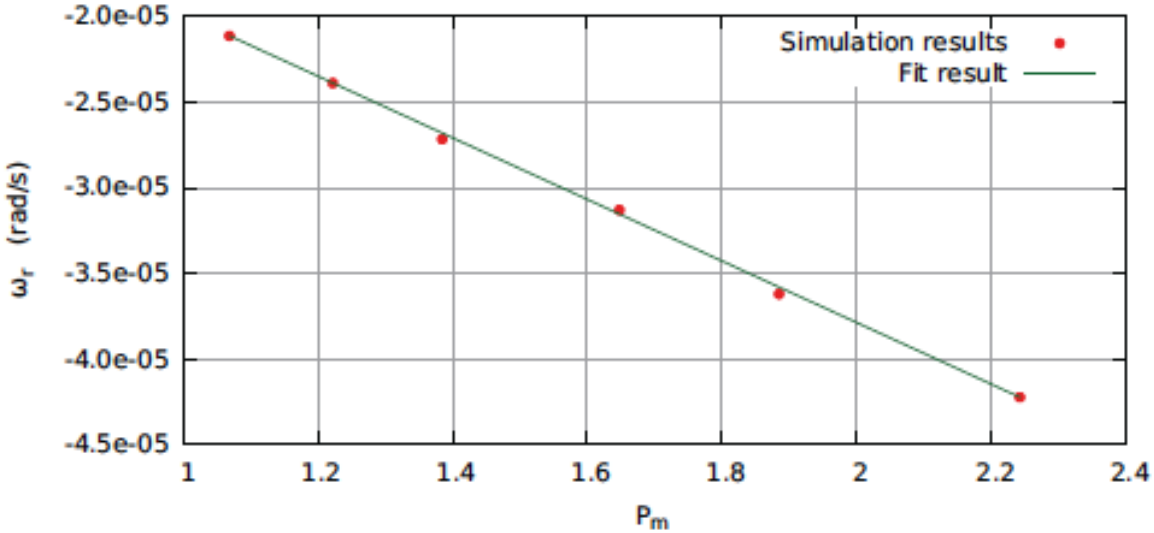
FIG. 4. The vertical spin precession of the counter-rotating beams when only magnetic focusing is used, for different radial B-field multipoles (N-values). The amplitude of the radial B-field is always kept at 1pT, while the quadrupole strength is kept at ± 0.1T/m. A genuine EDM signal for 10^{-29} $e \cdot$cm is larger than 1nrad/s, and therefore much larger than the background signal.

Background: E-fields

- Vertical dipole E-field: Cancels CW vs. CCW

- Some E-field focusing: Vertical quadrupole E-field. Probed by using several strong magnetic field focusing values

$$R_V = R_{\mathrm{EDM}} + R_{\mathrm{B_r}} \times \frac{Q^2_{\mathrm{Backgr}} + \ldots}{\zeta \times Q^2_{\mathrm{Magnetic}} + Q^2_{\mathrm{Backgr}} + \ldots}$$



Inverse of magnetic focusing strength

Background: Some E-field focusing

FIG. 7. The vertical spin precession rate as a function of the $P_m = 1/Q_y^2$ when the background effect is due to a combination of a DC ($N = 0$) radial magnetic field around the ring with strength of 1pT and a large electric focusing effect of the bending plates. The bending plate focusing corresponds to an (electric) vertical focusing field index of $m = 0.1$. The fit result is from a first order polynomial. The DC-offset corresponds to the EDM precession rate, which in this case it is -1.9×10^{-6}rad/s, consistent within errors to the input EDM value corresponding to -1.6×10^{-6}rad/s.

Axion and EDM: Proton and Deuteron

P. Graham, S. Rajendran:

The axion dark matter as an oscillating field of theta_QCD induces an oscillating EDM

$$d_n = 2.4\times10^{-16}\frac{a}{f_a} \sim (9\times10^{-35})\cos(m_a t) \quad [e\cdot\mathrm{cm}]\,, \tag{1}$$

$$a(t) = a_0\cos(m_a t), \tag{2}$$

arXiv:1710.05271v2 [hep-ex] 14 Jun 2018

Axion dark matter search using the storage ring EDM method

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

(Dated: June 15, 2018)

We propose using the 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 $g-2$ spin precession frequency and the background axion field oscillation to greatly enhance sensitivity to it. An axion frequency range from 10^{-9} Hz to 100 MHz can in principle be scanned with high sensitivity, corresponding to an f_a range of 10^{13} GeV $\leq f_a \leq 10^{30}$ GeV, the breakdown scale of the global symmetry generating the axion or axion like particles (ALPs).

I. INTRODUCTION

Peccei and Quinn proposed a dynamic oscillating field to solve the strong CP problem [1] and that oscillating field is called an axion [2–8]. An axion in internal atomic field. By combining Eq. (1) and Eq. (2) with a possible static EDM, one can write the total EDM as,

$$d(t) = d_{DC} + d_{AC}\cos(m_a t + \varphi_{ax}), \tag{3}$$

Electric Dipole Moments in Magnetic Storage Rings

$$\frac{d\vec{s}}{dt} = \vec{d} \times \left(\vec{v} \times \vec{B} \right)$$

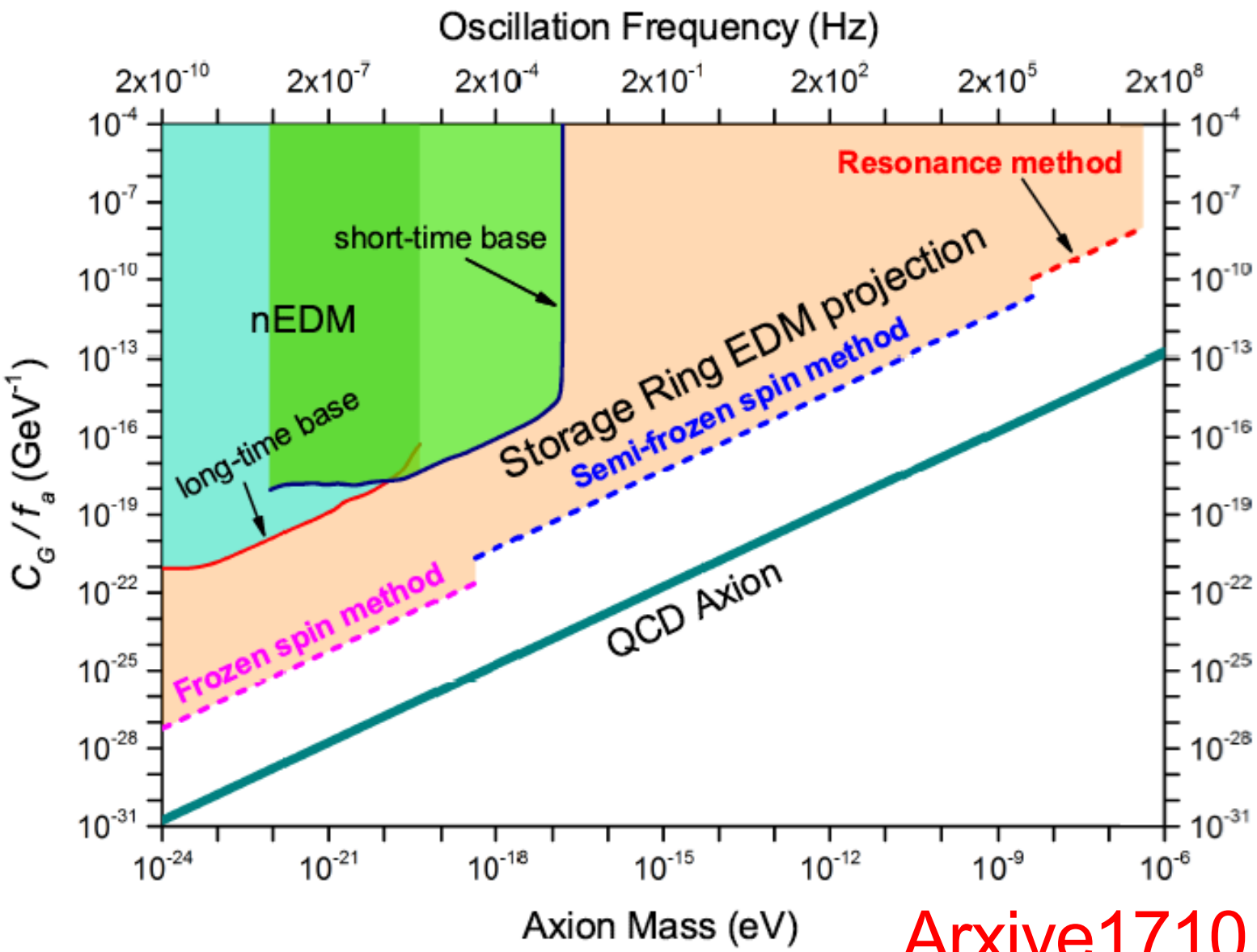
e.g. 1 T corresponds to 0.3 GV/m for relativistic particles

Why oscillating, when DC is hard enough!

- Easier for resonance with nuclei (CASPEr, …)
-
- Resonance with g-2 precession, more sensitive!

- Parasitic to frozen spin EDM method

Projected, preliminary



Arxive1710.05271

De Broglie wavelength >1km, whole ring within axion-field coherence

COSY ring and detection signal

Feasibility study at COSY/Juelich using existing facilities and equipment.

PI: SeongTae Park, IBS/CAPP

Executive summary for "Axion-EDM: An Axion Search with COSY"

For Lab. use

Exp. No.:	Session No.

Collaboration JEDI

Spokesperson for test beam time: Name: Seongtae Park
Local: Volker Hejny (COSY), Edward Stephenson (Indian

Address:
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Summary

- CPEDM: a combined collaboration srEDM and JEDI

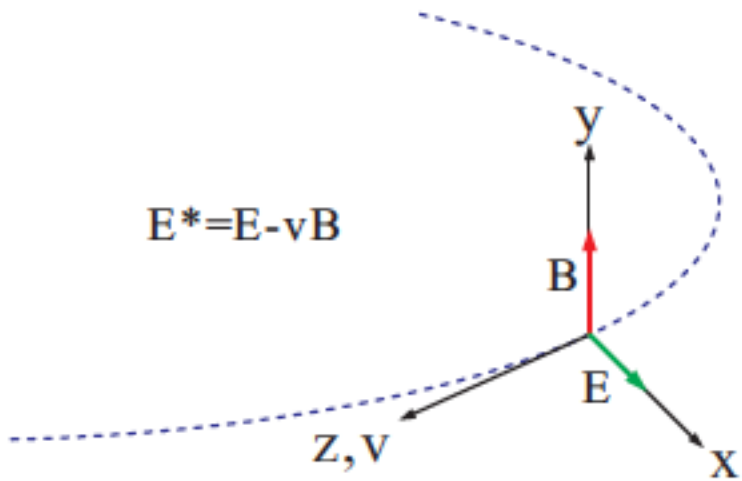
- Systematic error studies, feasibility studies as part of Physics Beyond Colliders (PBC) at CERN. The hybrid ring lattice method is a major breakthrough and under intense scrutiny

- Physics reach enriched with oscillating theta_QCD sensitivity! Probing axion dark matter for axion mass below 0.5 micro-eV (~100MHz). Using existing equipment/facilities, leveraging EDM effort.

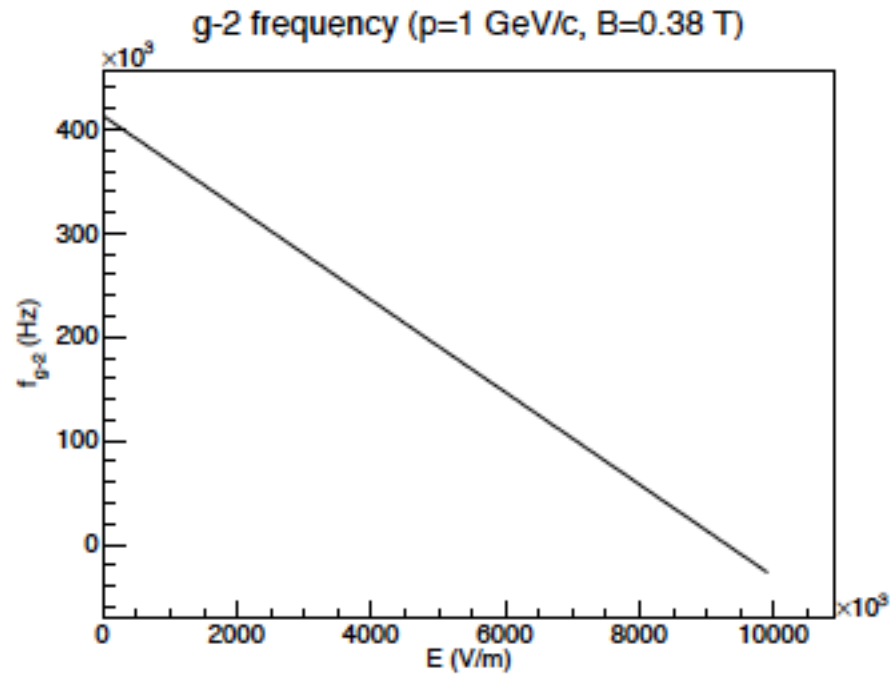
Extra slides

Search for axion dark matter in storage rings (1710.05271)

- Large effective E-field
- Superb tune stability, long spin coherence time: (COSY/Juelich)
- Statistics



(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

Search for axion dark matter in storage rings

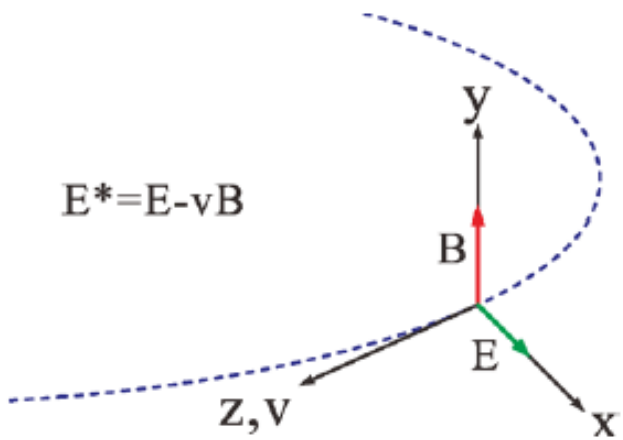
In a storage ring

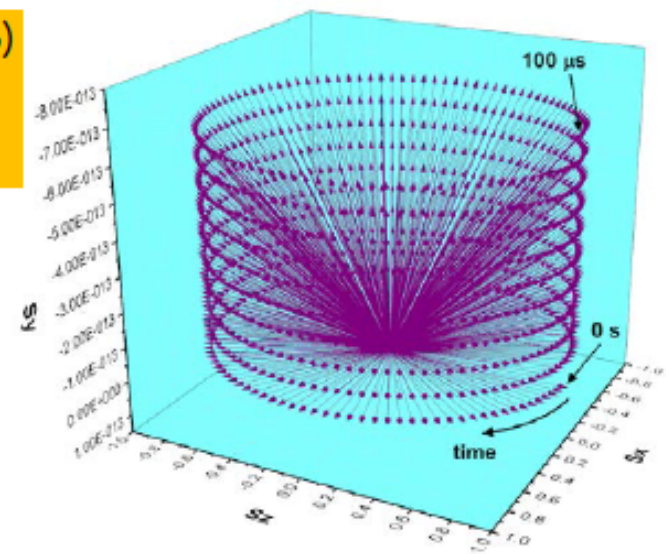
$$\frac{d\vec{\beta}}{dt} = \frac{e}{\gamma m}\left[\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c} - \vec{\beta}\frac{\vec{\beta}\cdot\vec{E}}{c}\right]$$

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

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

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

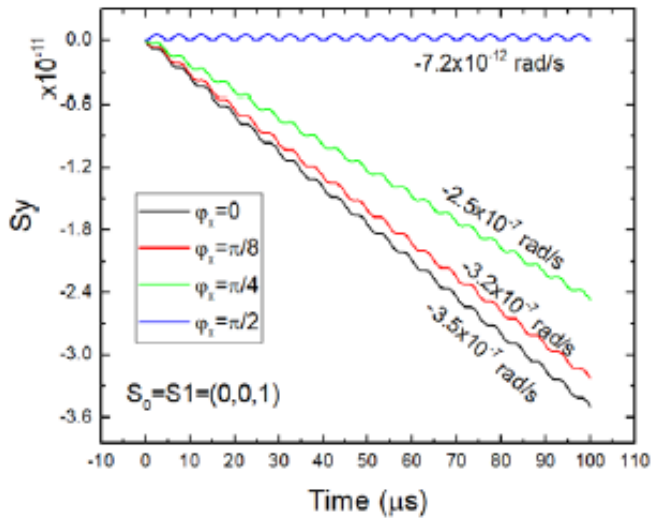


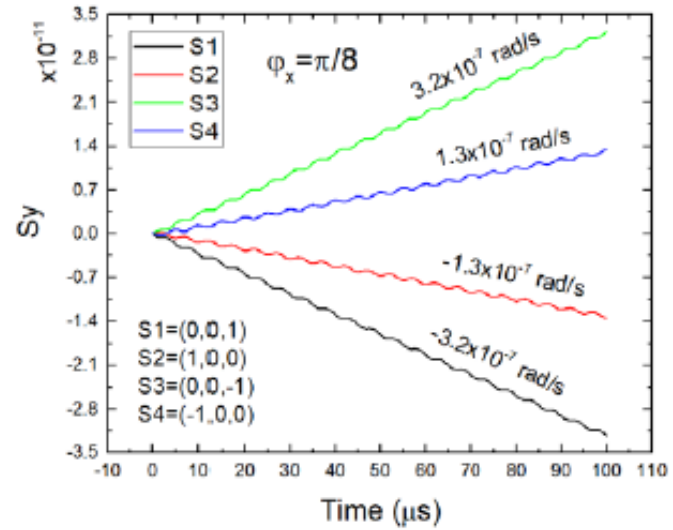


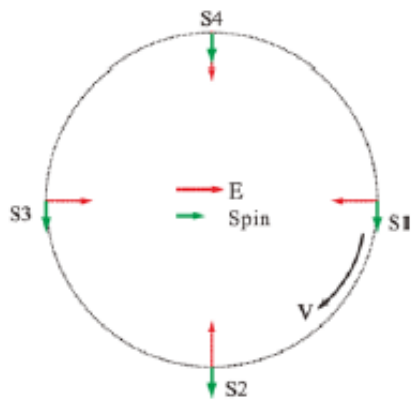
Axion phase effect

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

→ φ_x=0 means d is parallel to s, positive and max.







ω_{EDM} depends on the initial axion phase (φ_x). However actual ω_{EDM} can be obtained from the measurement of two orthogonal initial spin settings.

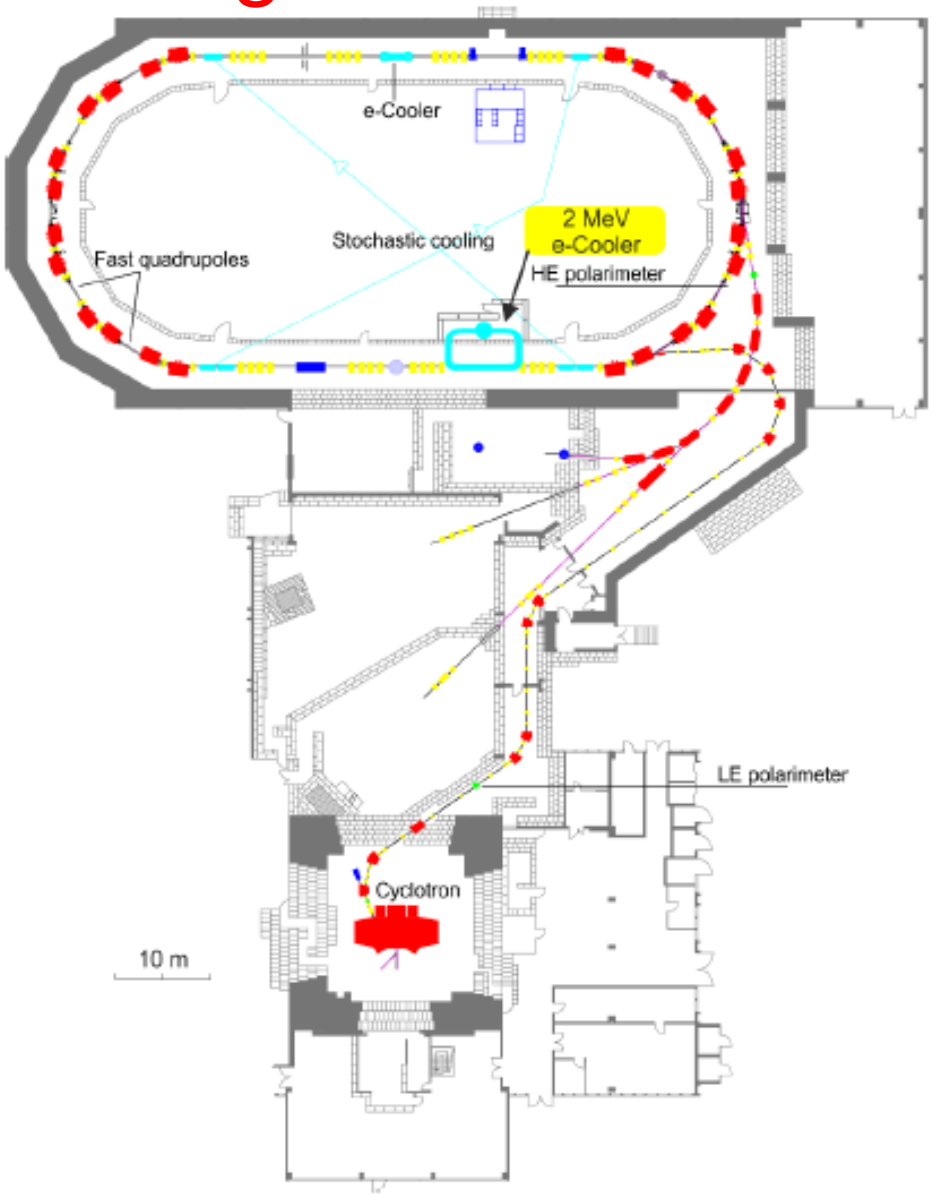
$$\omega_{EDM} = \sqrt{\omega_{EDM,S1}^2 + \omega_{EDM,S2}^2}$$

❖ Axion phase is not an experimentally controllable parameter

COoler SYnchrotron (COSY)

JÜLICH FORSCHUNGSZENTRUM

The right machine for the resonance method!



- 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

COSY ring and detection signal

Feasibility study at COSY/Juelich

Scanning for a day: 10^{-24} *e*-cm

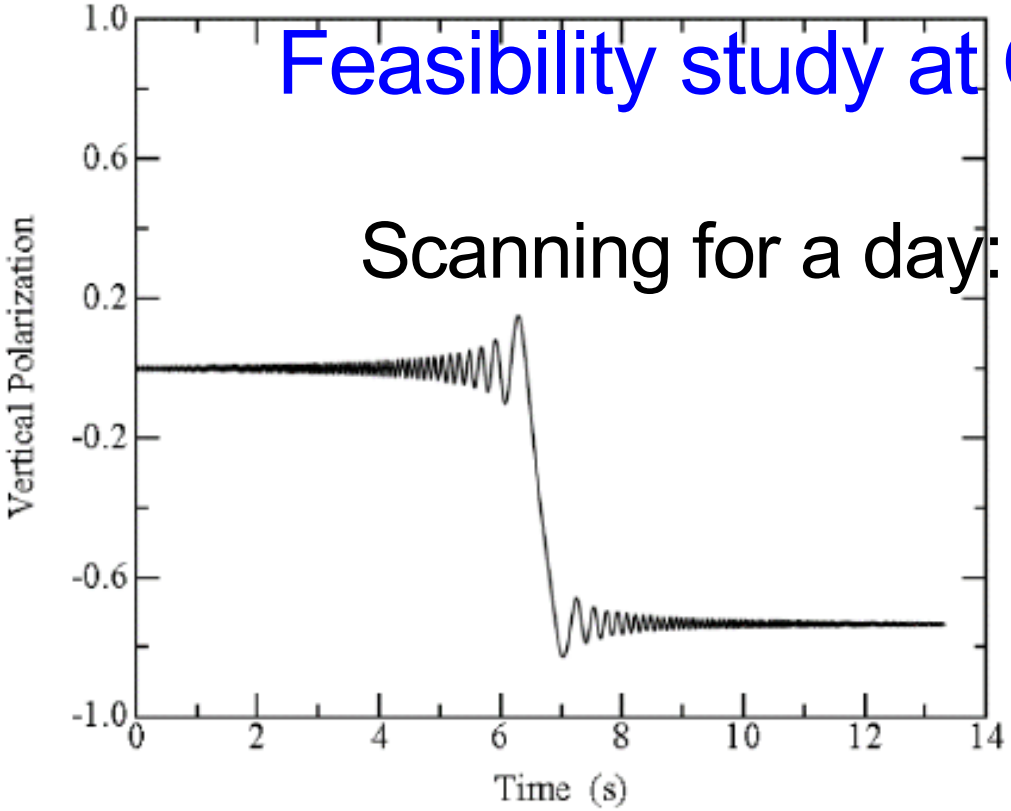


Figure 1: A "no-lattice" [14] calculation of the resonance crossing with a scan rate of 0.5 Hz/s. The strength of the oscillating EDM is 1.6×10^{-21} e·cm. Within the span of less than one second, this causes a jump of −0.75 in the p[Y] component of the beam polarization (assumed to initially be completely polarized in the ring plane).

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
  - Theoret. analysis to achieve >10^3s polarization lifetime; GEM Pol.; Polariz. depend. 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
  - Experimental achievement of long spin coherence time
  - 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

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**

Measurement Principle

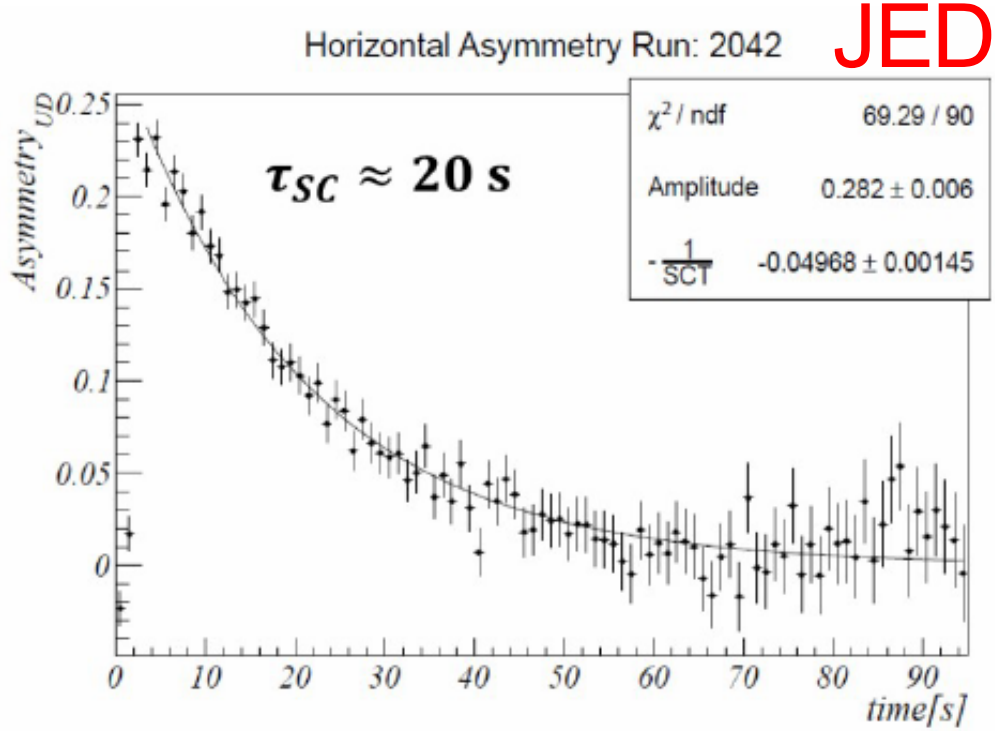
Martin Gaisser, COSY/Juelich

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)

JEDI Collaboration

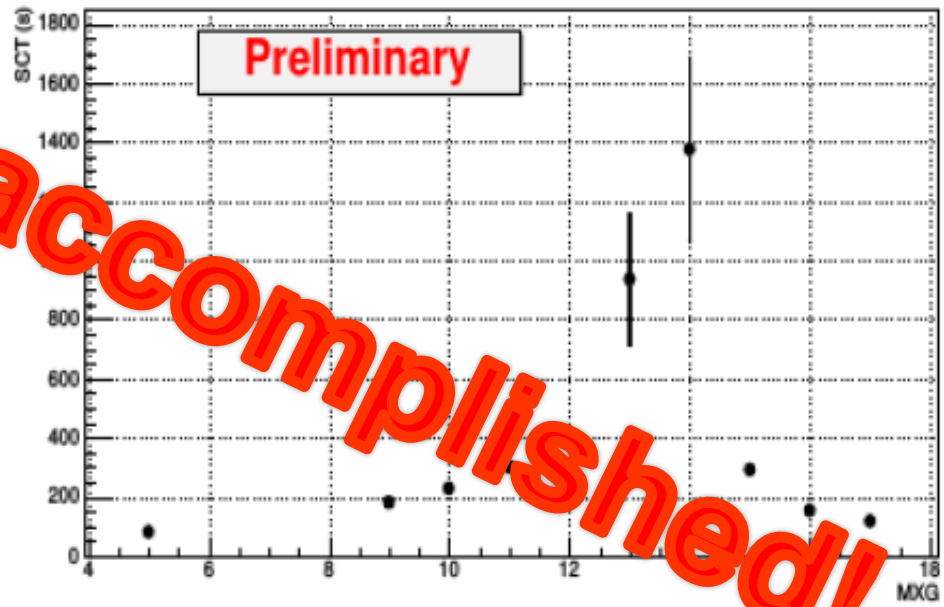


Sextupole Scans

Martin Gaisser, COSY/Juelich

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

JEDI Collaboration



SCT goal accomplished!

Sextupole strength