Future use of muon g-2 ring at Fermilab

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- Some really exciting possibilities for the muon g-2 ring:
  - Frozen spin deuteron EDM experiment at $\sim 10^{-26}e$-cm, equivalent to $\sim 10^{-27}e$-cm for the neutron EDM
  - Requires consecutive clockwise (CW) and counterclockwise (CCW) injections
  - Other possibilities include a) negative muon storage with magnetic focusing, b) frozen spin muon and proton EDM (they require CW and CCW injections).

A Permanent EDM Violates both T & P Symmetries:

$$\vec{\mu} = g\left(\frac{q}{2m}\right)\vec{s}, \quad \mathcal{H} = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$$

$$\vec{d} = \eta\left(\frac{q}{2mc}\right)\vec{s}$$
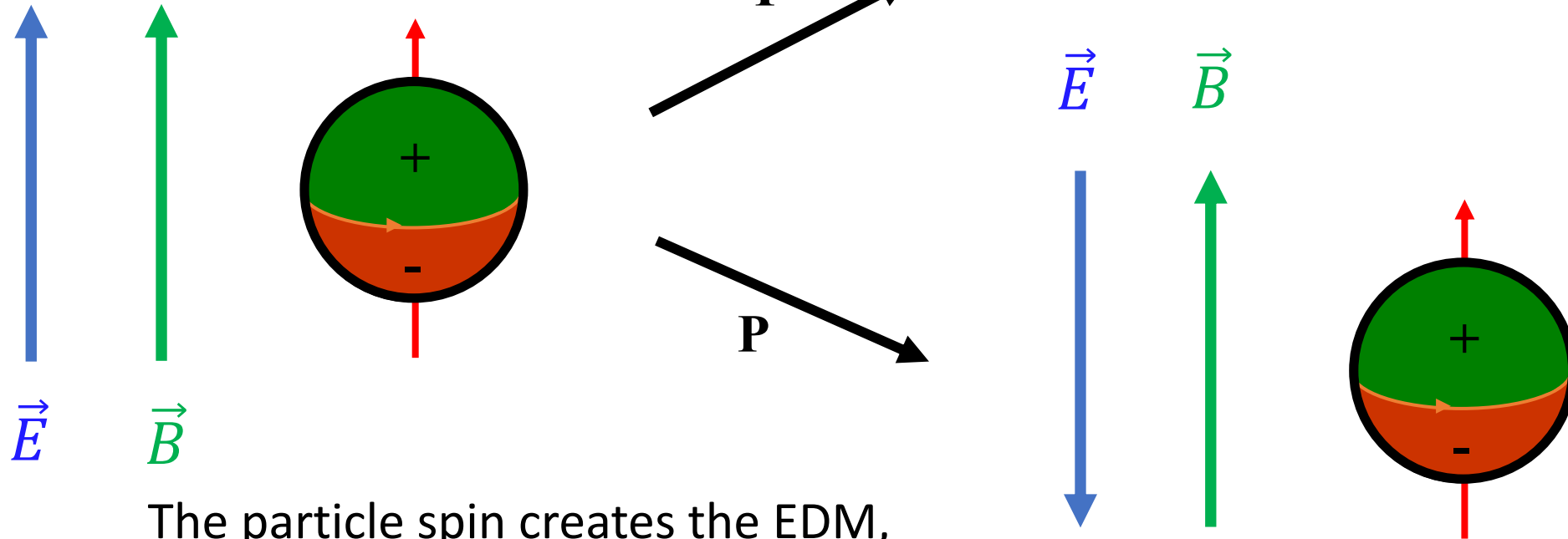
The particle spin creates the EDM,
EDM is "locked" to the spin

Hadronic EDMs: Physics strength comparison (Marciano)

System	Current limit [e·cm]	Future goal	Neutron equivalent
Neutron	$<1.6 \times 10^{-26}$	$\sim 10^{-28}$	10^{-28}
^{199}Hg atom	$<7 \times 10^{-30}$	$<10^{-30}$	10^{-26}
^{129}Xe atom	$<6 \times 10^{-27}$	$\sim 10^{-29}\text{-}10^{-31}$	$10^{-25}\text{-}10^{-27}$
Deuteron nucleus		$\sim 10^{-29}$	$3 \times 10^{-29}\text{-}$ 5×10^{-31}
Proton nucleus	$<2 \times 10^{-25}$	$\sim 10^{-29}$	10^{-29}

From theta-QCD

From SUSY-like CPV

Why can we do deuteron EDM with high sensitivity?

- Several breakthrough developments in our understanding of the storage ring EDM experiments:
  - Symmetries in the ring lattice, substantially reduce the level of systematic errors.
  - CW and CCW injections are a must. Simultaneous is much better (proton EDM with electric bending only), second best is consecutive (deuteron EDM-negative magnetic anomaly).

- Related work:
  - Omarov *et al.,* 2007.10332 (symmetric lattice, radial pol. systematic error reduction)
  - Haciomeroglu *et al.,* DOI (pEDM with hybrid lattice, Vertical E-field cancellation)
  - Anastassopoulos *et al.,* DOI (all-electric pEDM, challenging systematics, still OK)
  - 2008 Deuteron EDM proposal to AGS, https://www.bnl.gov/edm/
  - Graham *et al.,* DOI (DM/DE in storage rings)
  - On Kim *et al., https://arxiv.org/pdf/2105.06655.pdf* (axion search using RF-Wien filter)

Main systematic error sources and remediation

- Vertical electric field.

- Requires CW and CCW injections. For combined fields lattice (vertical B-field and radial E-field) the CW and CCW injections are consecutive. The final EDM sensitivity will be determined by the stability of the (unwanted, vertical) E-field when we flip the B-field. Bill Morse is describing the only lattice where CW and CCW is simultaneous and this systematic error drops: requires much larger ring.

- Vertical velocity imbalance inside the radial E-field regions (coupled with a small radial spin component).

- Make the ring lattice as symmetric as possible to reduce it by orders of magnitude.

- Use radially polarized bunches as a reference to completely eliminate it.

Main systematic error source: Vertical E-field

- Expected to limit the deuteron EDM exp. sensitivity

- The problem: Requires CW and CCW injections. For combined fields lattice (vertical B-field and radial E-field) the CW and CCW injections are consecutive.

- Requirement: The electric field plane should not change direction when we flip the vertical B-field. This is a major assumption/uncertainty in the method.

- Assuming ~1nrad stability (random change, easily measurable with Fabry-Perot, see deuteron EDM proposal at https://www.bnl.gov/edm/) of average E-field direction between B-field direction flipping could give ~$10^{-26}e$-cm limitation. (Simultaneous storage highly suppresses this systematic error source.)

What is the new idea in storage ring EDMs?

- Omarov *et al.*, 2007.10332, the lattice symmetry reduces the systematic errors. Showing the level of systematic errors for low and highly symmetric lattices:
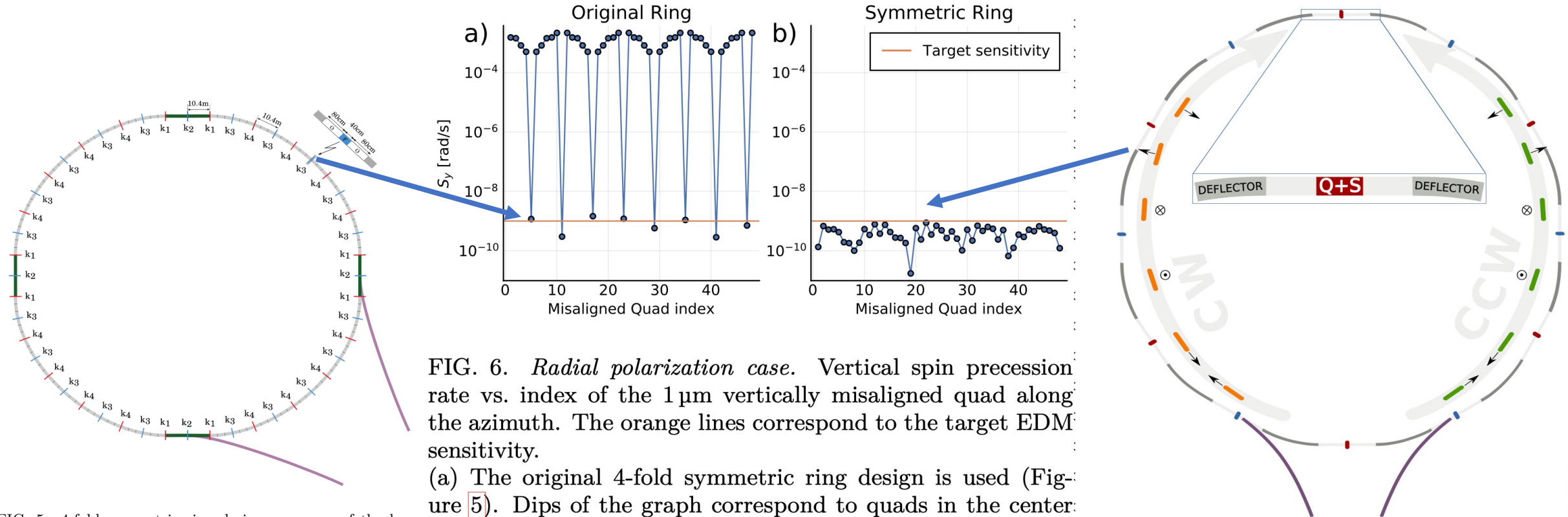

FIG. 5. 4-fold symmetric ring design, presence of the long straight sections reduce the number of symmetric points (adapted from [28])

FIG. 6. *Radial polarization case.* Vertical spin precession rate vs. index of the $1\,\mu m$ vertically misaligned quad along the azimuth. The orange lines correspond to the target EDM sensitivity.
(a) The original 4-fold symmetric ring design is used (Figure 5). Dips of the graph correspond to quads in the center of the four long straight sections, and middle points between them shown in Figure 5. Quad numbering starts after the long straight section on the right in the CCW direction.
(b) The symmetric ring design is used (Figure 2). Notably the performance is many orders of magnitude better than 4-fold ring (a).

FIG. 2. Schematic top view of the symmetric ring. Both CR beams have longitudinally, radially, and vertically polarized bunches with different helicities (arrows in dark color). Blue and red correspond to focusing and defocusing quads. Naturally, CR beams see opposite focusing effect from magnetic quads. The actual number of FODO sections is 24.

Why choose deuteron EDM in the g-2 ring?

- Technical reasons:
- The muon g-2 ring with magnetic focusing, offers a highly symmetric ring lattice.
- Polarized deuteron sources can provide statistics for much better than $10^{-27}e$-cm level.
- The required RF-system and polarimeters are well within our present ability.
- The required radial E-field strength is well within present ability.
- The beam storage time is ~20s, with <10^{-9} Torr the required vacuum level, the main expensive system (TBC).

- Potential science reach:
- Due to the shape of deuteron-nuclei, parity violating effects are enhanced by more than an order of magnitude. (EDM due to θ_{QCD} almost cancels out…!)
- $10^{-26}e$-cm deuteron EDM is equivalent to $10^{-27}e$-cm for the neutron for SUSY-like new CP-violation. This is a great opportunity. (Present nEDM limit is $1.6\times10^{-26}e$-cm.)

Insert vertically polarized deuterons into the ring

- Use an RF cavity to bunch the beam

- Use an RF-solenoid to create longitudinally and radially polarization bunches (cross check the vertical velocity issue and search for DM/DE).

- Magnetic focusing for a first frozen spin deuteron EDM measurement at P=0.5 GeV/c, E_{kin}=65 MeV, β=0.26, γ=1.035

- Radial E-field: -3.2MV/m

- Magnetic field B: 0.28T, EDM Spin Prec. Rate = 5.5 nrad/s

- CW and CCW injection (flipping of B-field is required)

Above or below transition depending on focusing

- Simulation plot by Zhanibek Omarov, KAIST PhD student
- Below transition requires $n < 0.24$
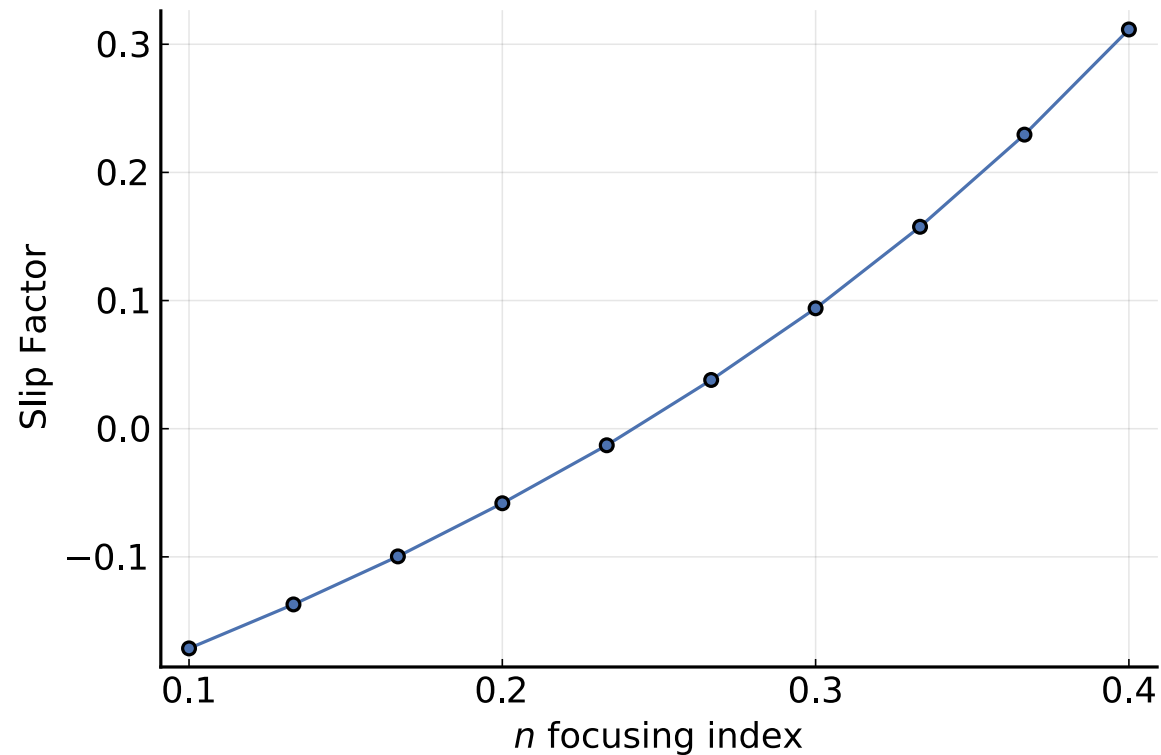
Statistical sensitivity? Issues to consider

- Intra-Beam-Scattering lifetime, best at below transition (TBC)

- Coulomb scattering off gas molecules

- Spin coherence time (should be OK for 20s with RF-cavity even without sextupole fields)

- $10^{-26}e$-cm is a reasonable first step to establish systematic error source, i.e., stability of vertical E-field.

Additional possibilities

- Proton and muon EDM using frozen spin method with combined E and B-fields

- Search for axion dark matter (DM), search for dark energy (DE)

- Muon g-2 using magnetic focusing? It's possible.

Frozen spin method for protons

- Use RF cavity to bunch the beam

- Use an RF-solenoid to create longitudinal and radial polarization bunches

- Magnetic focusing, for a first frozen-spin proton EDM exp. at P=0.250GeV/c (0.240 GeV/c), E_{kin} = 33 MeV (30 MeV), β=0.26 (0.25), γ=1.035 (1.032) and low sensitivity

- Radial E-field of about 6.2 MV/m (5.7MV/m)

- Magnetic field ~0.037T (0.036T), EDM Spin Prec. Rate = 2.5 nrad/s

- CW and CCW injections (flipping of B-field is needed)

Frozen spin method for muons

- Magnetic focusing

- Radial E-field

- CW and CCW injections (requires opening a new injection point for CCW)

- The particle gamma factor is around 5, an easy experiment over present one when only CW injection is used.

- P=0.6GeV/c, γ=5.8, 3.2MV/m, 0.27T, R=7.112m

- P=0.5GeV/c, γ=4.8, 1.9MV/m, 0.23T, R=7.112m

Storage Ring Electric Dipole Moments exp. options

Fields	Example	EDM signal term	Comments
Dipole magnetic field **(B)** **(Parasitic)**	Muon g-2	Tilt of the spin precession plane. **(Limited statistical sensitivity due to spin precession)**	Eventually limited by geometrical alignment. **Requires consecutive CW and CCW injection to eliminate systematic errors**
Combination of electric & and magnetic fields **(E, B)** **(Combined lattice)**	Deuteron, ^{3}He, proton, etc.	Mainly: $$\frac{d\vec{s}}{dt} = \vec{d} \times \left(\vec{v} \times \vec{B} \right)$$	High statistical sensitivity. **Requires consecutive CW and CCW injection with main fields flipping sign to eliminate systematic errors**
Radial Electric field **(E)** & Electric focusing **(E)** **(All electric lattice)**	Proton, etc.	$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$	Large ring, CW & CCW storage. **Requires demonstration of adequate sensitivity to radial B-field syst. error**
Radial Electric field **(E)** & Magnetic focusing **(B)** **(Hybrid, symmetric lattice)**	Proton, etc.	$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$	Large ring, CW & CCW storage. **Only lattice to achieve direct cancellation of main systematic error sources (its own "co-magnetometer").**

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Issues to study for the deuteron EDM:

- Intra-beam-scattering (IBS) lifetime plus required vacuum

- Spin coherence time

- Systematic errors
  - Spin
  - Polarimeter

- Overall sensitivity

- Cost: $5-10M plus polarized source (TBC)

Axion Dark Matter (small sensitivity)

- Magnetic focusing
- Let the spin precess at different g-2 frequencies
- With and without radial E-field (different sensitivity)
- Easy experiment over present muon g-2 setting

Axionlike dark matter search using the storage ring EDM method

Seung Pyo Chang,[1,2] Selçuk Hacıömeroğlu,[2] On Kim,[1,2] Soohyung Lee,[2] Seongtae Park,[2,*] and Yannis K. Semertzidis[1,2]

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Dark Matter/Dark Energy

- Magnetic focusing

- Radial E-field for frozen spin

- CW and CCW injections. Main error source (vertical velocity) is suppressed with symmetric lattice.

Storage ring probes of dark matter and dark energy

Peter W. Graham[1], Selcuk Hacıömeroğlu[2], David E. Kaplan[3], Zhanibek Omarov[4,2], Surjeet Rajendran[3], and Yannis K. Semertzidis[2,4]

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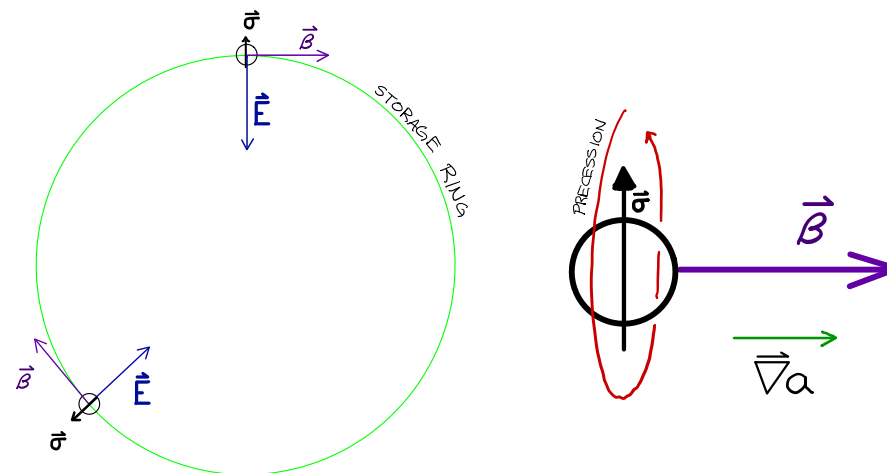
FIG. 1. A sketch of the geometry for this storage ring proposal (left figure) and the directions of the proton's spin $\vec{\sigma}$, velocity $\vec{\beta}$ and precession, as well as the axion field gradient seen by the proton (right figure). The proton's spin must be oriented radially and will then precess around its velocity (out of the plane of the ring).

Alternative focusing options for g-2 (doc-db 194)

- Before CERN went with the "magic" momentum they were considering magnetic focusing.

- Yuri Orlov, in the sixties wrote to E. Picasso that an RF-system could solve the issue related to the muon position resolution.

- When I asked Francis Farley what was the reason for the rejection, he said: we didn't know what is the effect of the RF-fields on the spin.

- Today we have high confidence in the simulation results, agreements with analytical estimations down to 1ppb

- An RF-cavity with low Q is required (to be designed)

- B-field focusing and RF-cavity, E. Metodiev et al., NIM A 797 (2015) 311.

- Pitch effect with quadrupole component in cylindrical coordinates:

focusing, i.e. $\omega_m = \omega_a(1 - C^*)$

$$C^* = \left(a - \frac{n}{1-n}\right)\frac{\theta_0^2}{2}.$$

Alternative focusing options for g-2 (doc-db 194)

Table 3. The different parameter values and requirements for various n-values in the FNAL muon g-2 experiment. We have always assumed 1mrad maximum vertical oscillation angle. The vertical admittance estimation assumes 70 mm half aperture.

- RF-cavity will reduce B-field uncertainty

- Inject polarized protons to map the magnetic field

- Meeting with B-field team for best choice

n-value	Vertical oscillation effect on g-2 frequency [ppb]	Vertical beta function [m]	Vertical oscillation amplitude [mm]	Vertical ring admittance [mm-mrad]	Maximum radial deviation due to 1mrad vertical oscillations	B-field change over full hor. aperture [ppm]	Absolute ave. muon position requirement for 50ppb B-field accuracy
0.01	5	70	70	70	7.1 μm	140	35 μm
0.02	10	50	50	100	7.1 μm	280	18 μm
0.05	26	32	32	150	7.5 μm	700	7.1 μm
0.1	56	22.5	22.5	220	8 μm	1400	3.5 μm

Obviously, without the electro-static quads present we can have a larger vertical aperture, and the ring admittance becomes similar to the one used in E821 when we use a field index between 0.01 and 0.02. The beam line admittance in E821 was ~50 mm mrad. Therefore running with n=0.01 and 70mm half (vertical) aperture should be carefully considered. The horizontal CBO frequency is about 33kHz, and the vertical at ~0.5MHz, both very far away from the g-2 frequency of ~200kHz.

Weak magnetic focusing, Precision tracking

Yannis K. Semertzidis, BNL

Reasons to consider weak magnetic focusing:
1) Develop the beam/spin dynamics tools (tracking) and compare with theoretical expectations.
2) At the end of the experiment we can run with magnetic focusing. Some syst. errors are different.
3) Possibly cross-check with polarized protons (needs proton polarimetry- as per FJM Farley).
4) J-PARC muon g-2 plans to use ultra-weak magnetic focusing.

Summary

- Muon g-2 announcement put strong wind into the storage ring g-2/EDM sails

- The most promising of the possibilities is the frozen-spin EDM method. First estimations show that 10^{-26} e-cm may be possible for the deuteron and proton due to the vertical E-field temporal stability (see Bill Morse's talk on the hybrid/symmetric ring lattice evading this systematic error). Study further the systematic error sources, IBS and vacuum requirements. Better sensitivity may be possible.

- Possibly 10^{-22} e-cm for the muon (current exp. target is 10^{-21} e-cm), statistics limited.

- The cost is ~$5-10M, FNAL would need a polarized proton/deuteron source. Combined with the hybrid/symmetric ring for the proton EDM (see Bill Morse's talk aiming for 10^{-29} e-cm), it will provide a very powerful physics program.

Extra slides

Is the polarimeter analyzing power good at P_{magic}? YES!
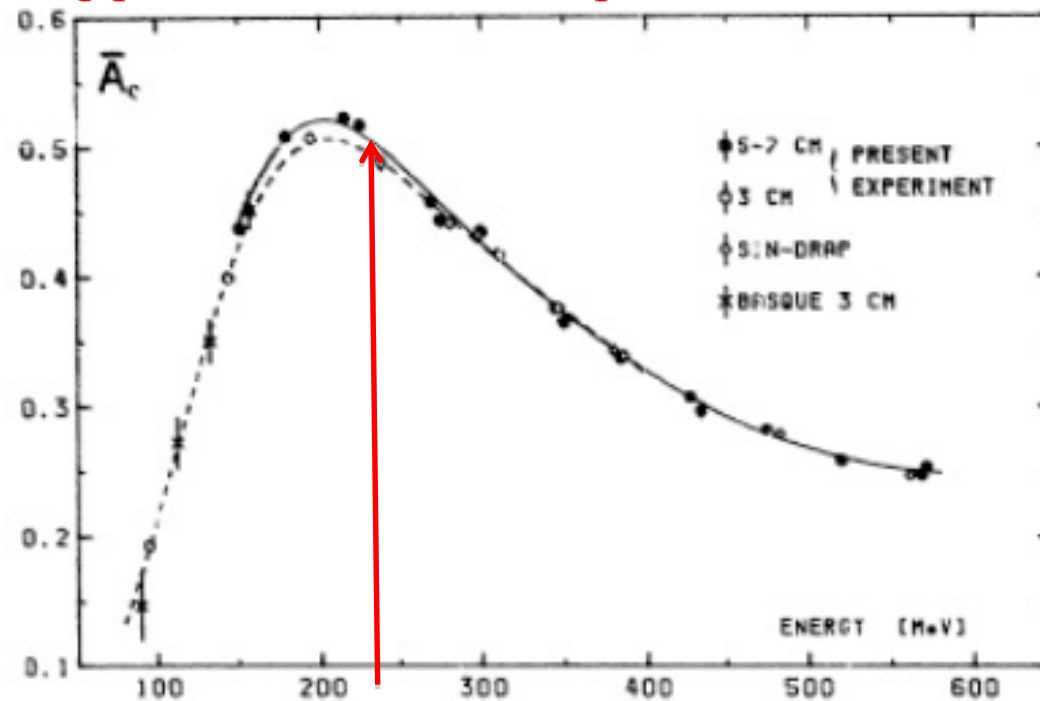
Analyzing power can be further optimized

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.

Proton Statistical Error (230MeV): 10^{-29} e-cm

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

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 (10^3s)

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

f   : 1%   Useful event rate fraction (efficiency for EDM)

E_R : 4.5 MV/m   Radial electric field strength