Поиск электрических дипольных моментов частиц и ядер в накопительных кольцах

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OUTLINE

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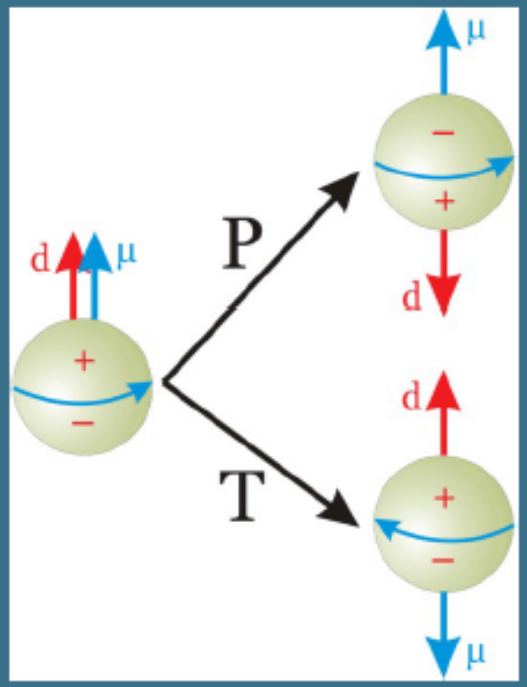
Motivation for a search for the electric dipole moments at storage rings

Electric Dipole Moments (EDMs)



Permanent EDMs violate parity **P** and time reversal symmetry **T**

Assuming **CPT** to hold, combined symmetry **CP violated** as well.

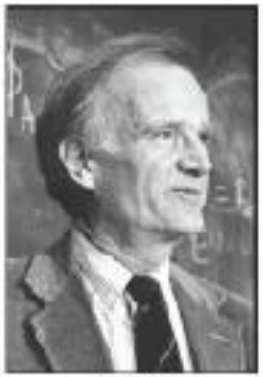
EDMs are candidates to solve mystery of matter-antimatter asymmetry
- may explain why we are here!

CP-violation was discovered at BNL in 1964

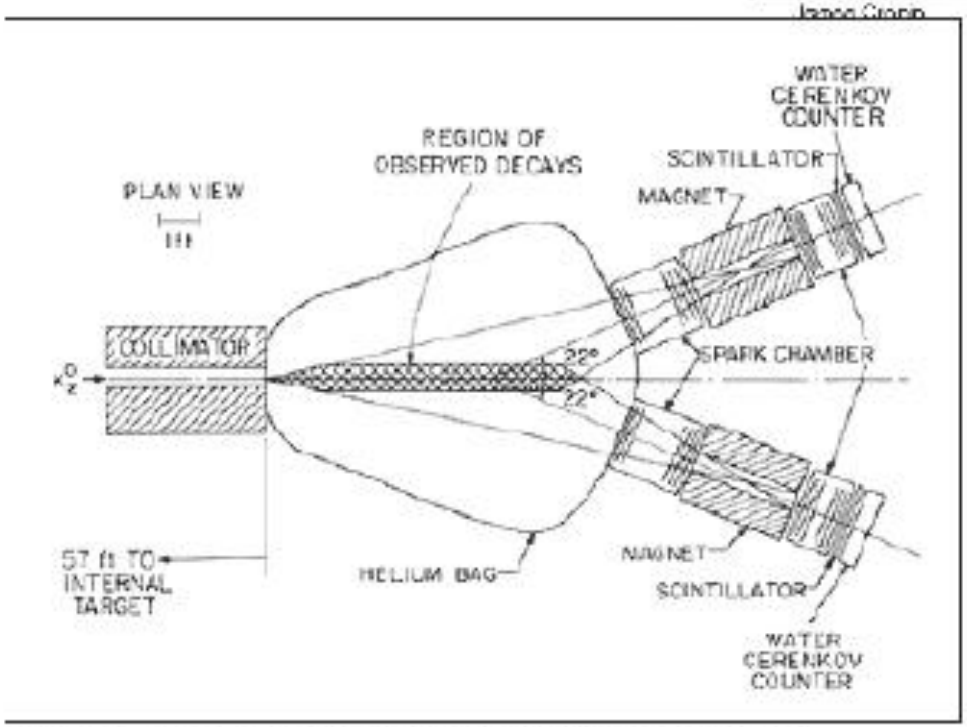
James W. Cronin and Val L. Fitch, both then of Princeton University, proposed using Brookhaven's AGS to verify a fundamental tenet of physics, known as CP symmetry, by showing that two different particles did not decay into the same products. They picked as their example neutral K mesons, which are routinely produced in collisions between a proton beam and a stationary metal target.

The experiment set out to show that in millions of collisions, the short-lived variety of K meson always decayed into two pi mesons, while the long-lived variety never did. But to their surprise, a "suspicious-looking hump" in the data showed an unexpected result that years of subsequent experimentation and theory have been unable to explain: occasionally, the long-lived neutral K meson does decay into two pi mesons. Cronin and Fitch had found an example of CP violation.

James Cronin



Val Fitch



Schematic of the experimental apparatus used by Cronin and Fitch.

Physics strength comparison

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^{-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	$<7\times10^{-25}$	$\sim10^{-29}$	4×10^{-29}-2.5×10^{-30}
Electron	$<8.7\times10^{-29}$		

Origin of EDMs

- **Standard Model EDMs are due to CP violation in the quark weak mixing matrix – CKM (e.g. the K^0/B^0-system) but…**
  - e^- and quark EDM's are zero at first order
  - Need at least two "loops" to get EDM's (electron actually requires 4 loops!)
    - Thus EDM's are VERY small in standard model

Neutron EDM in Standard Model is ~ 10^{-32} e-cm (=10^{-19} e-fm)

Electron EDM in Standard Model is < 10^{-40} e-cm

Physics Beyond the Standard Model

- **New physics (e.g. SuperSymmety = SUSY) has additional CP violating phases in added couplings**
  - New phases: (ϕ_{CP}) should be ~ 1 (why not?)
- **Contributions to EDMs depends on masses of new particles** $d_n \propto \frac{\sin\phi_{CP}}{M_{SUSY}^2}$
  - In MSSM (Minimal Supersymmetric Standard Model)

$$d_n \sim \left(\frac{200\ \mathrm{GeV}}{M_{SUSY}}\right)^2 \times 10^{-25}\ \mathrm{e-cm}$$

Search for the muon EDM in framework of *g*-2 experiments

BNL experiment

$$\Omega = \sqrt{\Omega_{MDM}^2 + \Omega_{EDM}^2}$$

$$t = \frac{\pi}{2\Omega}$$

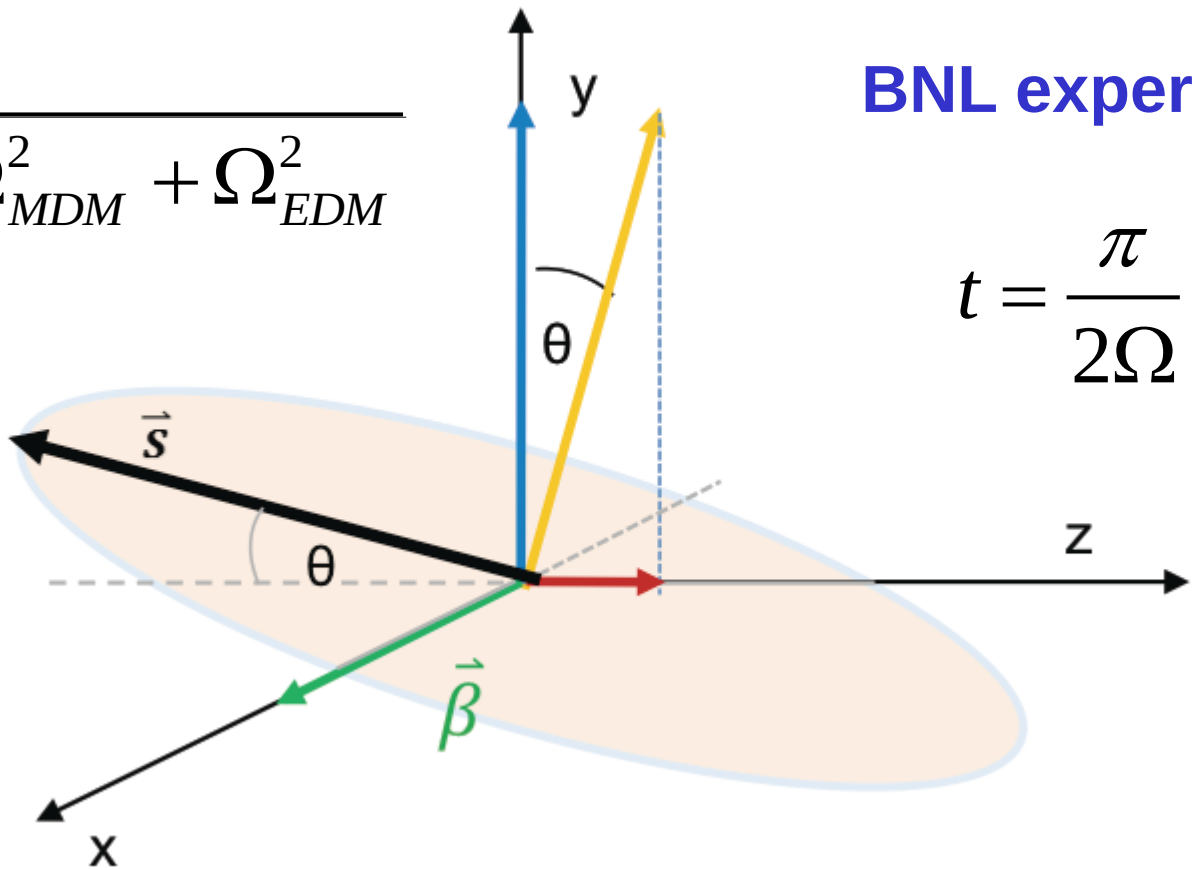


Figure 1. The contributions to the precession frequency Ω from the magnetic dipole moment and the electric dipole moment. The resulting spin precession plane.

Muon d <1.8×10^{-19} e·cm

Next plans for the muon EDM experiments (Fermilab and J-PARC):

Muon d $<10^{-21}$ $e\cdot$cm

Resonance methods of the storage ring EDM experiments

Resonance synchrotron oscillations

Generalized Thomas-Bargmann-Mishel-Telegdi equation of spin motion in storage rings in the cylindrical coordinate system:

$$\boldsymbol{\Omega}^{(cyl)} = -\frac{e}{m}\left\{G\boldsymbol{B} - \frac{G\gamma}{\gamma+1}\boldsymbol{\beta}(\boldsymbol{\beta}\cancel{\cdot}\boldsymbol{B})\right.$$

$$+\left(\frac{1}{\gamma^2-1} - G\right)(\boldsymbol{\beta}\times\cancel{\boldsymbol{E}}) + \frac{1}{\gamma}\left[\boldsymbol{B}_{\parallel} - \frac{1}{\beta^2}(\boldsymbol{\beta}\times\cancel{\boldsymbol{E}})_{\parallel}\right]$$

$$\left.+\frac{\eta}{2}\left(\cancel{\boldsymbol{E}} - \frac{\gamma}{\gamma+1}\boldsymbol{\beta}(\boldsymbol{\beta}\cdot\cancel{\boldsymbol{E}}) + \boldsymbol{\beta}\times\boldsymbol{B}\right)\right\}.$$

The sign $\parallel$ means a horizontal projection for any vector.

$$\mathbf{E} = 0, \quad \beta = \beta_0 \cos\left(\Omega t + \phi\right).$$

Y. F. Orlov, W. M. Morse, and Y. K. Semertzidis, Resonance Method of Electric-Dipole-Moment Measurements in Storage Rings, Phys. Rev. Lett. **96**, 214802 (2006).

However, a nonlinearity of beam oscillations brings radial oscillations which result in an oscillating radial magnetic field acting on the *magnetic dipole moment*. Thus, this experiment cannot be successful due to large systematic errors.

Resonance spin flippers. RF Wien filter

One can also use a resonance radial electric field

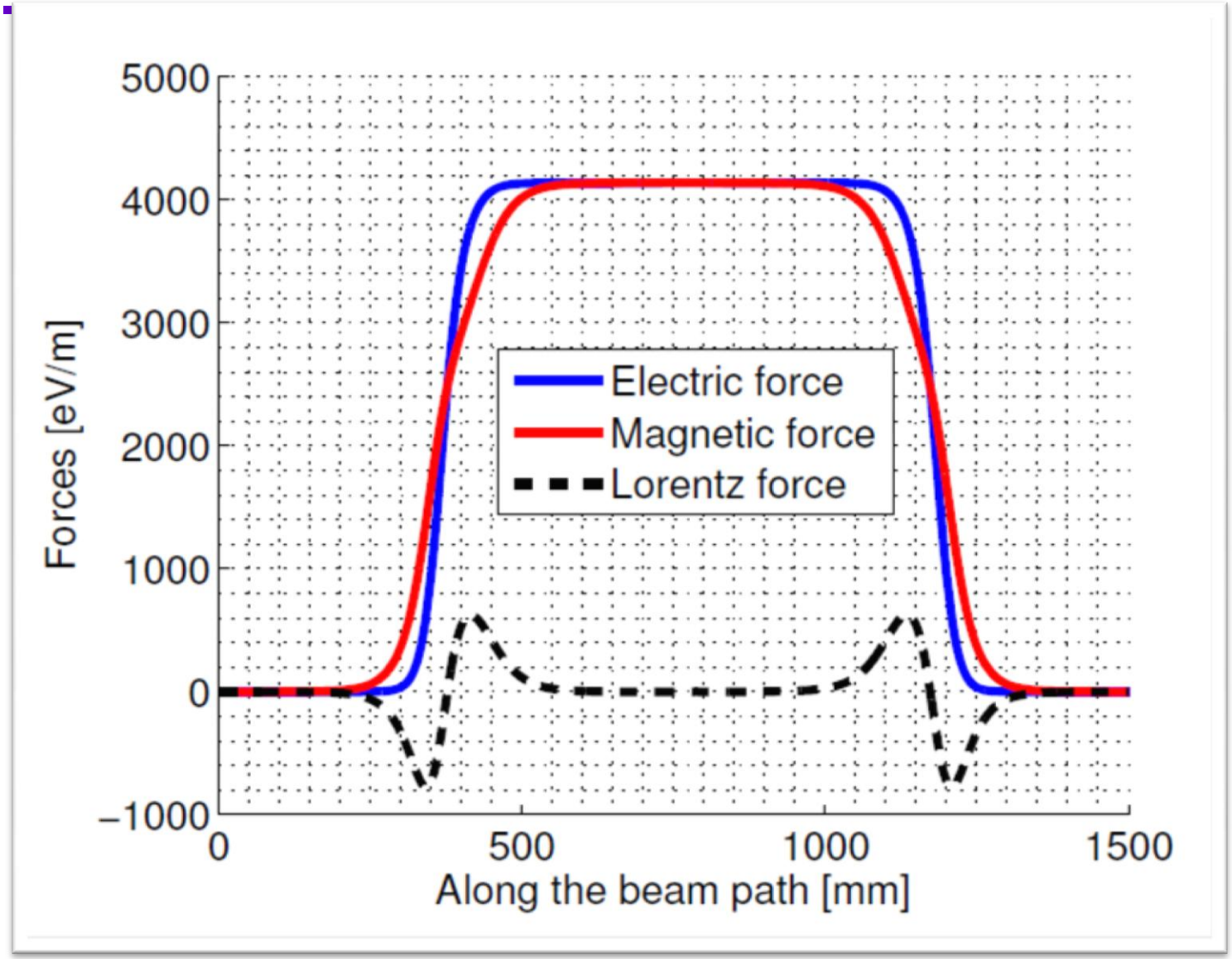
$$\mathbf{E} = \mathbf{E}_0 \cos\left(\Omega t + \phi\right),$$

because the vector *β×E* is vertical and does not create any resonance effect:

$$\boldsymbol{\Omega}^{(cyl)} = -\frac{e}{m}\left\{ G\boldsymbol{B} - \frac{G\gamma}{\gamma+1}\boldsymbol{\beta}(\boldsymbol{\beta}\cdot\boldsymbol{B}) + \left(\frac{1}{\gamma^2-1} - G\right)(\boldsymbol{\beta}\times\boldsymbol{E}) + \frac{1}{\gamma}\left[\boldsymbol{B}_{\parallel} - \frac{1}{\beta^2}(\boldsymbol{\beta}\times\boldsymbol{E})_{\parallel}\right] + \frac{\eta}{2}\left(\boldsymbol{E} - \frac{\gamma}{\gamma+1}\boldsymbol{\beta}(\boldsymbol{\beta}\cdot\boldsymbol{E}) + \boldsymbol{\beta}\times\boldsymbol{B}\right)\right\}.$$

However, this field negatively influences beam dynamics.

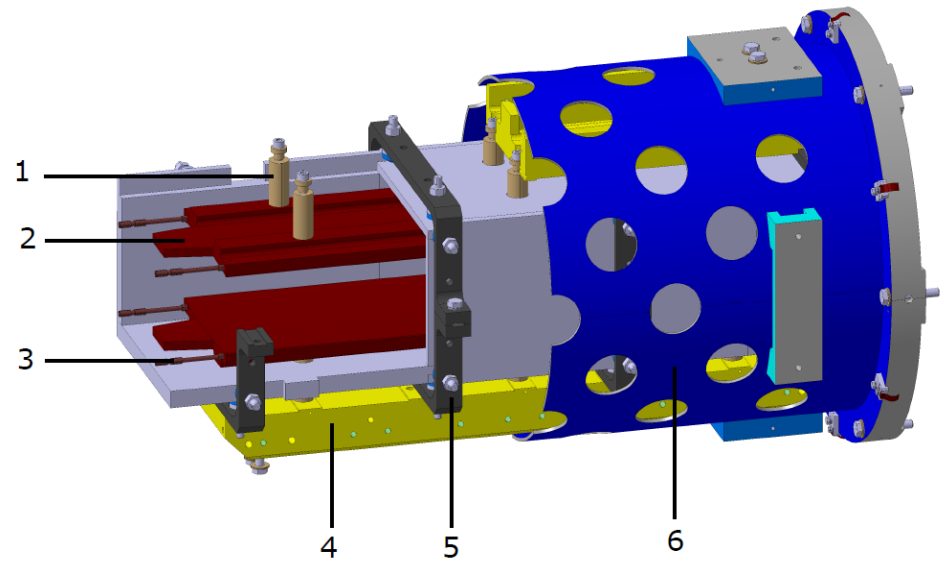
The better possibility is the use of the radio-frequency Wien filter.



Lorentz force compensation

Providing minimal integral Lorentz force requires careful shaping of electrodes and all other components.

RF Wien filter



$$\vec{F}_L = q(\vec{E} + \vec{v} \times \vec{B})$$

Lorentz force integral with $\vec{v}$ along Wien filter axis

$$\frac{q}{\ell}\int_{-\ell/2}^{\ell/2} \begin{pmatrix} E_x - c\beta B_y \\ E_y + c\beta B_x \\ E_z \end{pmatrix} dz = \begin{pmatrix} 5.97 \times 10^{-3} \\ 7.97 \times 10^{-3} \\ 1.27 \times 10^{-21} \end{pmatrix} \mathrm{eV/m}$$

$$\int_{-\ell/2}^{\ell/2} \vec{B} dz = \begin{pmatrix} 2.73 \times 10^{-9} \\ 0.047 \\ 6.96 \times 10^{-7} \end{pmatrix} \mathrm{T\,mm}$$

Continued work on RF driving circuit → to reach $\int Bdl \sim 0.2$ Tmm seems possible.

Important distinguishing features of storage ring EDM experiments are also a simultaneous influence of external fields on the electric and magnetic dipole moments and the existence of a resonance effect even when the stimulating torque acting *on the EDM* is equal to zero.

$$\boldsymbol{\Omega}^{(cyl)} = -\frac{e}{m}\left\{ G\boldsymbol{B} - \frac{G\gamma}{\gamma+1}\boldsymbol{\beta}(\boldsymbol{\beta}\cdot\boldsymbol{B}) + \left(\frac{1}{\gamma^2-1} - G\right)(\boldsymbol{\beta}\times\boldsymbol{E}) + \frac{1}{\gamma}\left[\boldsymbol{B}_{\parallel} - \frac{1}{\beta^2}(\boldsymbol{\beta}\times\boldsymbol{E})_{\parallel}\right] + \frac{\eta}{2}\left(\cancel{\boldsymbol{E} - \frac{\gamma}{\gamma+1}\boldsymbol{\beta}(\boldsymbol{\beta}\cdot\boldsymbol{E}) + \boldsymbol{\beta}\times\boldsymbol{B}}\right)\right\}.$$

There is not a resonance field acting on the EDM!

1. ``Resonance'' stimulated by the oscillating vertical magnetic field in the storage ring with the main magnetic field B_0

$$\boldsymbol{\mathcal{B}}(\Phi)\cos(\omega' t+\chi) = B_0^{(osc)} \sum_{n=-\infty}^{\infty} a_n \cos\left[(\omega' + n\omega_c)t + \chi\right]$$

The angular velocity of the spin rotation in the cylindrical coordinates is given by ($\boldsymbol{\beta}=\beta \boldsymbol{e}_\phi$)

$$\boldsymbol{\Omega}^{(cyl)} = \omega_0\left[1 + b_z\cos(\omega t+\chi)\right]\boldsymbol{e}_z - \frac{e\eta}{2m}\beta B_0\left[1 + b_r\cos(\omega t+\chi)\right]\boldsymbol{e}_r,$$

$$\omega_0 = -\frac{eG}{m}B_0.$$

In the considered case,

$$b_r = b_r^{(m)} = b_z = b_z^{(m)} = \frac{a_n B_0^{(osc)}}{B_0}.$$

Evidently, the constant and oscillating parts of the vector $\mathbf{\Omega}^{(cyl)}$ are collinear. This vector forms the small angle with the z axis

$$\vartheta = \sin\vartheta = -\frac{e\eta}{2m\omega_0}\beta B_0 = \frac{\eta\beta}{2G}$$

Any resonance effect does not exist:

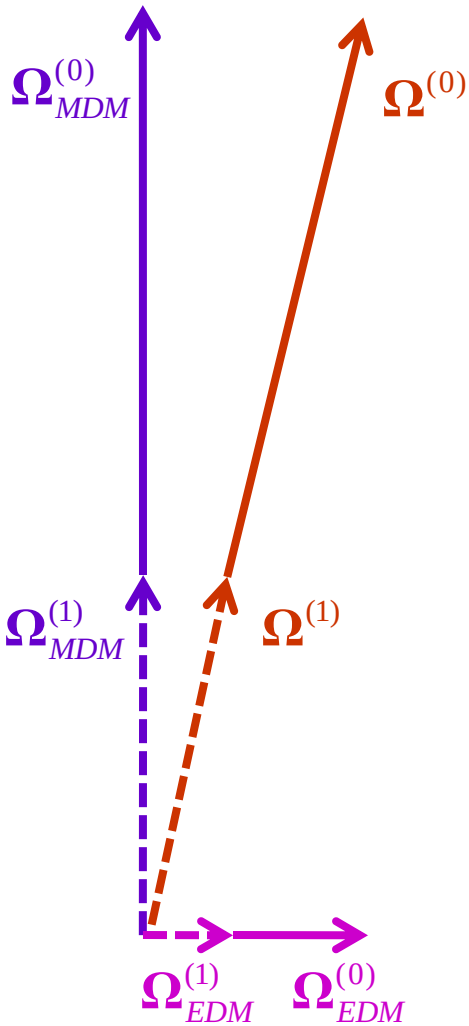
$$\mathbf{\Omega}^{(cyl)} = \omega_0\left[1 + b_z\cos\left(\omega t + \chi\right)\right]\mathbf{e}_\vartheta, \qquad \mathbf{e}_\vartheta = \mathbf{e}_z + \vartheta\mathbf{e}_r.$$

$$\mathbf{\Omega}^{(cyl)} = \mathbf{\Omega}^{(0)} + \mathbf{\Omega}^{(1)}$$

constant part **oscillating part**

$$\mathbf{\Omega}^{(0)} = \omega_0\mathbf{e}_\vartheta, \qquad \mathbf{\Omega}^{(1)} = \omega_0 b_z\cos\left(\omega t + \chi\right)\mathbf{e}_\vartheta.$$

Figure 1. Magnetic-field ``flipper”.



$$\mathbf{\Omega}^{(cyl)} = \mathbf{\Omega}^{(0)} + \mathbf{\Omega}^{(1)}$$

constant part **oscillating part**

$$\mathbf{\Omega}^{(0)} = \omega_0 \mathbf{e}_{\vartheta},$$

$$\mathbf{\Omega}^{(1)} = \omega_0 b_z \cos\left(\omega t + \chi\right) \mathbf{e}_{\vartheta}.$$

2. Resonance stimulated by the oscillating radial electric field in the storage ring with the main magnetic field B_0

$$\boldsymbol{E}_0 = E_0 \boldsymbol{e}_r, \qquad b_r = b_r^{(e)} = \frac{a_n E_0}{\beta B_0}, \qquad b_z = b_z^{(e)} = -\frac{\beta a_n E_0}{G B_0}\left(\frac{1}{\gamma^2 - 1} - G\right)$$

It is very convenient to switch to the new axes, $\boldsymbol{e}_\zeta = \boldsymbol{e}_r - \vartheta \boldsymbol{e}_z$, $\boldsymbol{e}_\phi$ and $\boldsymbol{e}_\vartheta$

$$\boldsymbol{\Omega}^{(cyl)} = \omega_0 \left[1 + b_z \cos(\omega t + \chi)\right] \boldsymbol{e}_\vartheta + \omega_0 \vartheta \left(b_r - b_z\right) \cos(\omega t + \chi) \boldsymbol{e}_\zeta.$$

$$b_r^{(e)} - b_z^{(e)} = \frac{a_n E_0}{\beta B_0} \cdot \frac{G+1}{G\gamma^2} = -\frac{e g a_n E_0}{2 m \beta \gamma^2 \omega_0}.$$

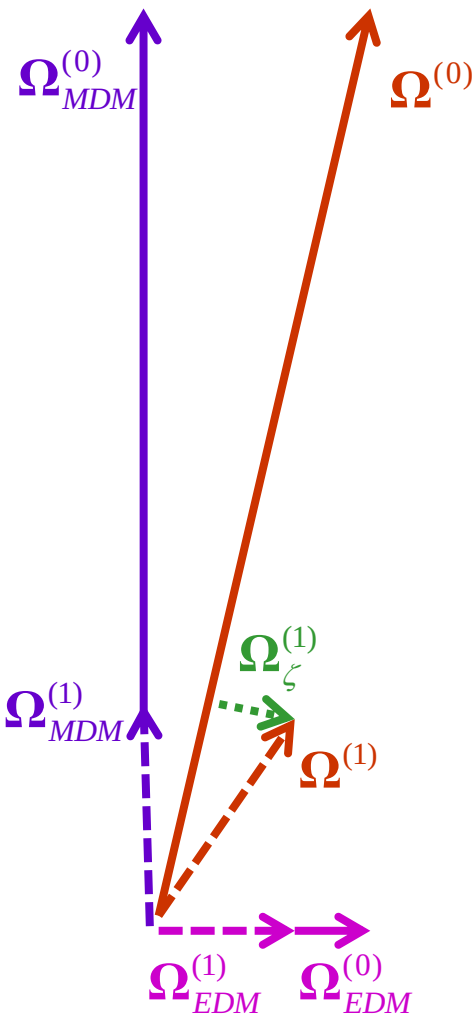
The horizontal spin polarization at the initial vertical spin direction is given by

$$P_x(t) = \mathfrak{E} t \sin(\omega t + \chi),$$

$$P_y(t) = -\mathfrak{E} t \cos(\omega t + \chi)$$

$$\mathfrak{E} = \frac{1}{2}\omega_0 \vartheta \left(b_r^{(e)} - b_z^{(e)}\right) = -\frac{e\eta}{4m} \cdot \frac{G+1}{G\gamma^2} a_n E_0.$$

Figure 2. Electric-field flipper.



For the E-field flipper,

$$\mathbf{\Omega}^{(cyl)} = \mathbf{\Omega}^{(0)} + \mathbf{\Omega}^{(1)},$$

$$\mathbf{\Omega}^{(0)} = \omega_0 \mathbf{e}_{\vartheta},$$

$$\mathbf{\Omega}^{(1)} = \omega_0 b_z^{(e)} \cos\left(\omega t + \chi\right)\mathbf{e}_{\vartheta}$$

$$+\omega_0 \vartheta \left(b_r^{(e)} - b_z^{(e)}\right)\cos\left(\omega t + \chi\right)\mathbf{e}_{\zeta}.$$

$$\| \quad \mathbf{\Omega}^{(1)}_{\zeta}$$

3. Resonance stimulated by the rf Wien filter in the storage ring with the main magnetic field B_0

There is not any oscillating force acting on a particle:

$$B_0^{(osc)} + \beta E_0 = 0.$$

Oscillating fields should be synchronized:

$$\mathbf{E} = \mathbf{E}_0 \cos\left(\omega t + \chi\right), \qquad \mathbf{B}^{(osc)} = \mathbf{B}_0^{(osc)} \cos\left(\omega t + \chi\right).$$

The angular velocity of the spin rotation takes the form

$$\Omega^{(cyl)} = \omega_0 \left[1 + \left(b_z^{(e)} + b_z^{(m)}\right) \cos\left(\omega t + \chi\right)\right] \mathbf{e}_z + \underline{\omega_0 \vartheta \mathbf{e}_r}.$$

There is not a resonance field acting on the EDM!

However, $\boldsymbol{e}_\vartheta$ and $\boldsymbol{e}_z$ are not collinear

To determine the resonance effect, it is convenient to pass to the axes $\mathbf{e}_\vartheta$ and $\mathbf{e}_\zeta$:

$$\mathbf{e}_\vartheta = \mathbf{e}_z + \vartheta \mathbf{e}_r, \qquad \mathbf{e}_\zeta = \mathbf{e}_r - \vartheta \mathbf{e}_z.$$

In this case,

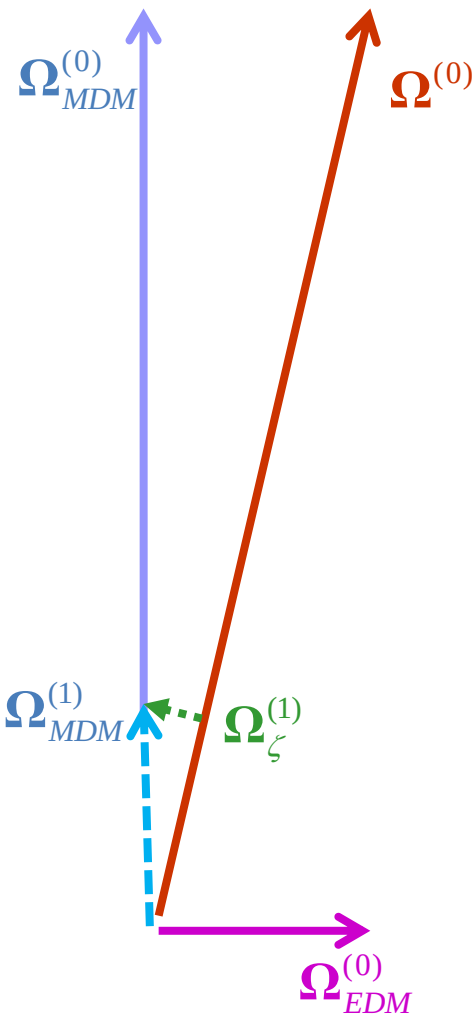
$$\Omega^{(cyl)} = \omega_0 \left[1 + \delta \cos(\omega t + \chi)\right] \mathbf{e}_\vartheta - \omega_0 \vartheta \delta \cos(\omega t + \chi) \mathbf{e}_\zeta,$$

where

$$\delta = b_z^{(e)} + b_z^{(m)} = -b_r^{(e)} + b_z^{(e)} = -\frac{a_n E_0}{\beta B_0} \cdot \frac{G+1}{G\gamma^2}.$$

The resonance EDM effect is provided by the oscillating torque acting on the MDM

Figure 3. rf Wien filter.



For the rf Wien filter,

$$\mathbf{\Omega}^{(cyl)} = \mathbf{\Omega}^{(0)} + \mathbf{\Omega}^{(1)},$$

$$\mathbf{\Omega}^{(0)} = \omega_0 \mathbf{e}_{\vartheta},$$

$$\mathbf{\Omega}^{(1)} = -\omega_0 \left(b_r^{(e)} - b_z^{(e)} \right) \cos\left(\omega t + \chi \right) \mathbf{e}_{\vartheta}$$

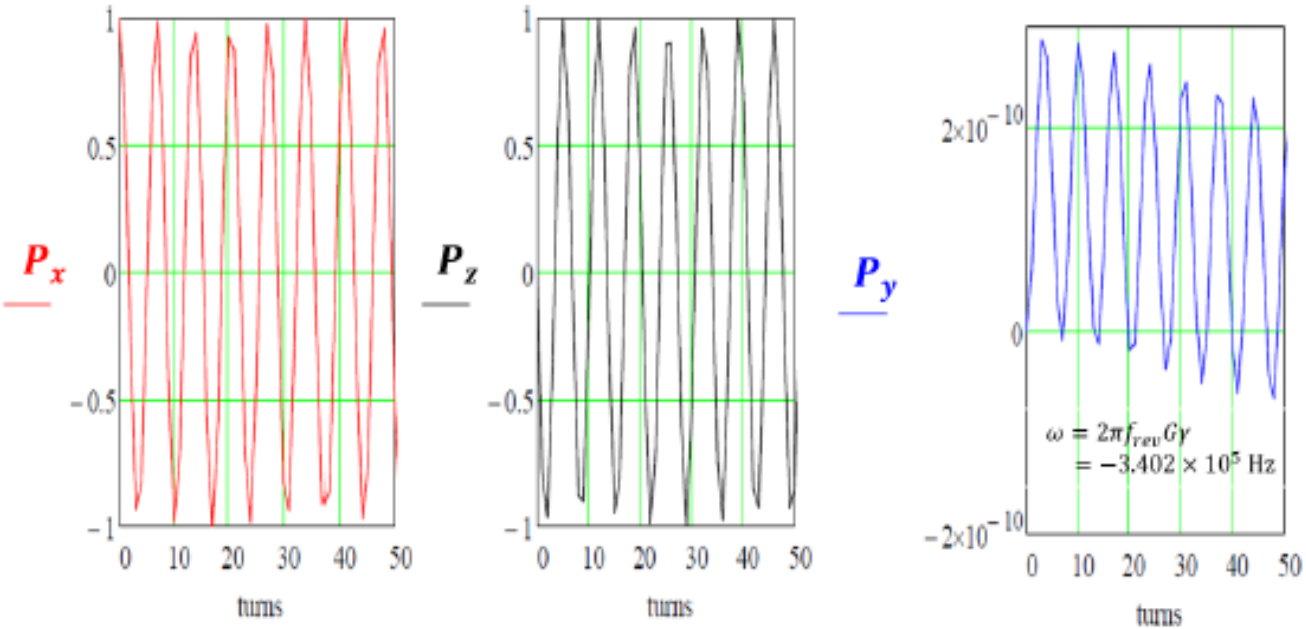
$$+\omega_0 \vartheta \left(b_r^{(e)} - b_z^{(e)} \right) \cos\left(\omega t + \chi \right) \mathbf{e}_{\zeta}.$$

$$\| \quad \mathbf{\Omega}_{\zeta}^{(1)}$$

Buildup of $P_y(t)$ using RF Wien filter for deuterons

A simple model calculation with parameters:

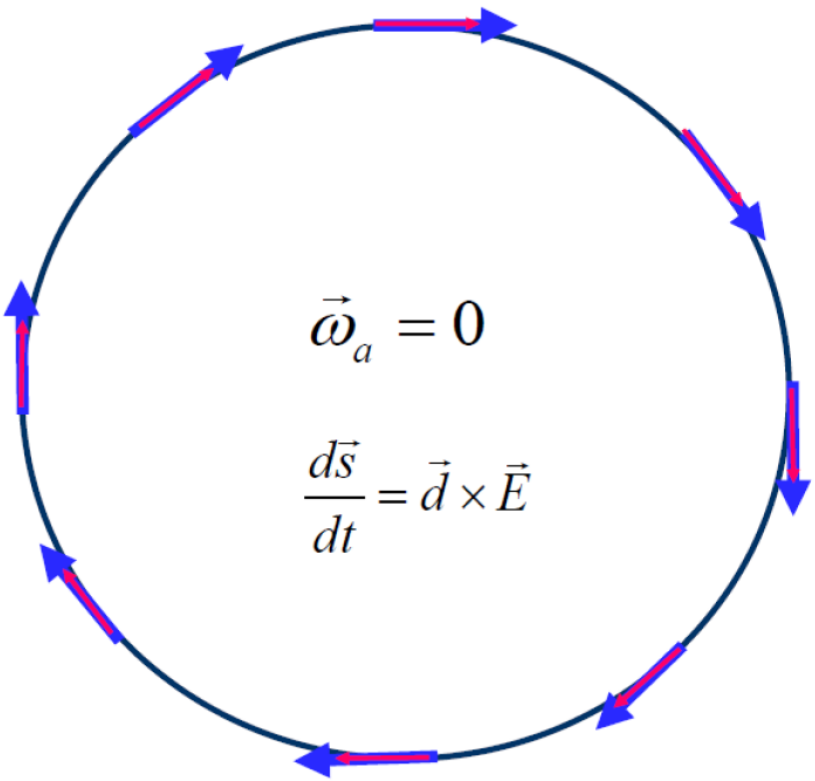
- Beam energy: $T_d = 50\,\mathrm{MeV}$,
- Length of device: $L_{\mathrm{RF}} = 1\,\mathrm{m}$.
- Assumed deuteron EDM: $d = 10^{-24}\,\mathrm{e\,cm}$.
- Electric RF field: $30\,\mathrm{kV\,cm^{-1}}$.



EDM effect accumulates in $P_y \propto d$ [1, 2].

Frozen spin method of the storage ring EDM experiments

A Proposal to Measure the Proton Electric Dipole Moment with 10^{-29} $e\cdot$cm Sensitivity by the Storage Ring EDM Collaboration



October 2011

frozen spin method

Storage Ring EDM Collaboration

V. Anastassopoulos[18], D. Babusci[10], M. Bai[3], S. Baessler[23], M. Berz[17], M. Blaskiewicz[3], K. Brown[3], P. Cameron[3], G. Daskalakis[6], N. D' Imperio[3], M.E. Emirhan[13], F. Esser[24], G. Fanourakis[6], A. Fedotov[3], A. Ferrari[25], W. Fischer[3], T. Geralis[6], Y. Giomataris[21], F. Gonnella[20], M. Gross Perdekamp[11], R. Gupta[3], G. Guidoboni[8], S. Haciomeroglu[13,3], Y. Haritantis[18], G. Hoffstaetter[5], H. Huang[3], M. Incagli[19], D. Kawall[16], B. Khazin[4], I.B. Khriplovich[4], I.A. Koop[4], T. Laopoulos[1], R. Larsen[3], D.M. Lazarus[3], A. Lehrach[9], P. Lenisa[8], P. Levi Sandri[10], F. Lin[3], A.U. Luccio[3], A. Lyapin[15], W.W. MacKay[3], R. Maier[9], K. Makino[17], N. Malitsky[3], W. Marciano[3], S. Martin[26], W. Meng[3], F. Meot[3], R. Messi[20], D. Moricciani[20], W.M. Morse[3], S.K. Nayak[3], Y.F. Orlov[5], C.S. Ozben[13], A. Pesce[8], V. Ptitsyn[3], B. Parker[3], P. Pile[3], V. Polychronakos[3], B. Podobedov[3], D. Raparia[3], F. Rathmann[9], S. Redin[4], S. Rescia[3], G. Ruoso[14], T. Russo[3], N. Saito[22], J. Seele[28], Y.K. Semertzidis[3,*], Yu. Shatunov[4], V. Shemelin[5], A. Sidorin[7], A. Silenko[2], N. Simos[3], S. Siskos[1], A. Stahl[27], E.J. Stephenson[12], H. Stroeher[9], J. Talman[3], R.M. Talman[5], P. Thieberger[3], N. Tsoupas[3], Y. Valdau[9], G. Venanzoni[10], K. Vetter[3], S. Vlassis[18], G. Zavattini[8], A. Zelenski[3], K. Zioutas[18]

Combined electric and magnetic fields

Frozen spin method:

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

Use a radial E_r-field to cancel the g-2 precession

VOLUME 93, NUMBER 5 PHYSICAL REVIEW LETTERS week ending 30 JULY 2004

New Method of Measuring Electric Dipole Moments in Storage Rings

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A new highly sensitive method of looking for electric dipole moments of charged particles in storage rings is described. The major systematic errors inherent in the method are addressed and ways to minimize them are suggested. It seems possible to measure the muon EDM to levels that test speculative theories beyond the standard model.

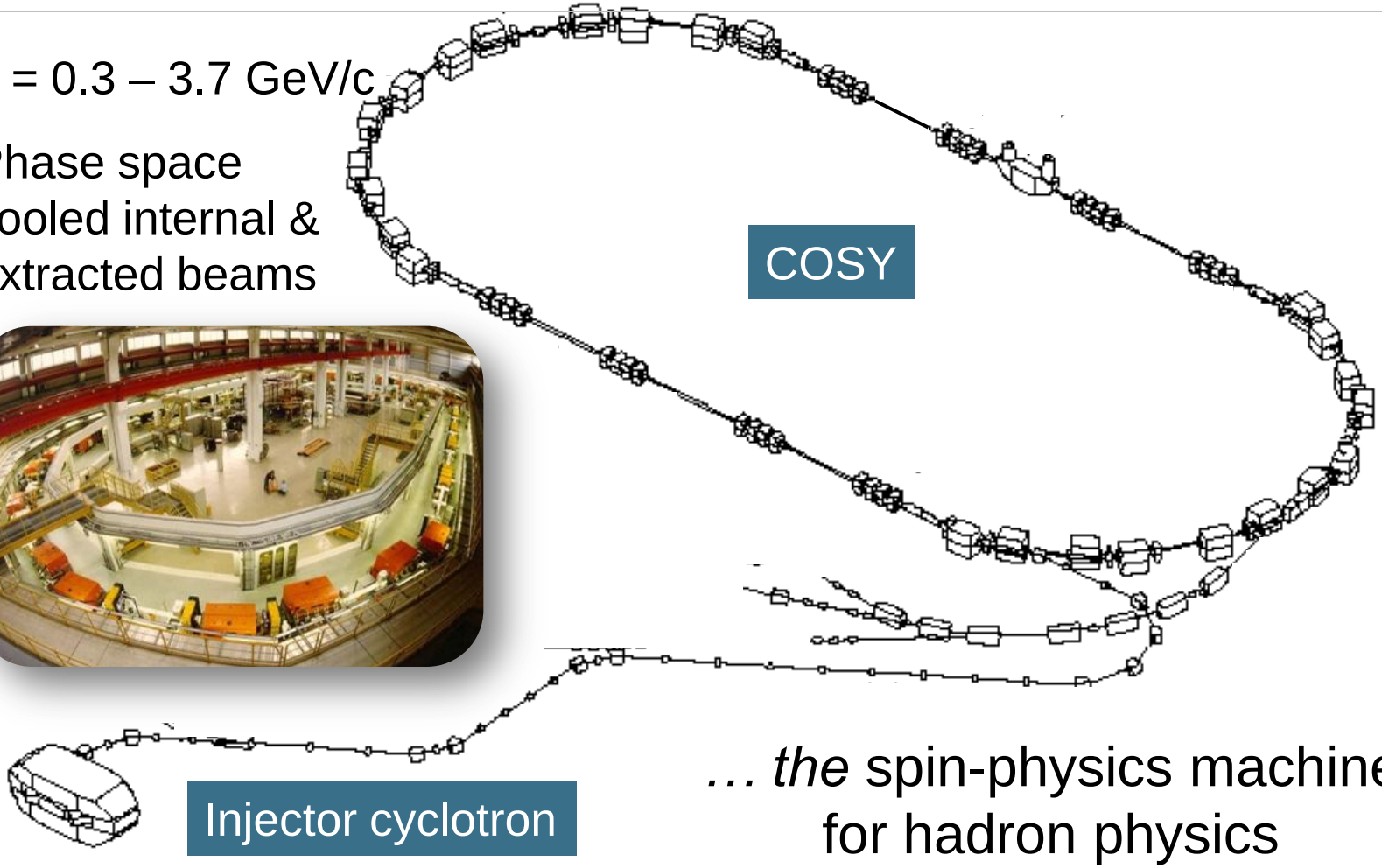
Muon d $<10^{-24}$ $e\cdot$cm

EDM at COSY – COoler SYnchrotron

Cooler and storage ring for (polarized) protons and deuterons

p = 0.3 – 3.7 GeV/c

Phase space cooled internal & extracted beams

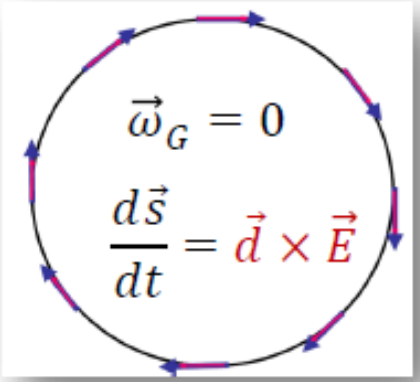


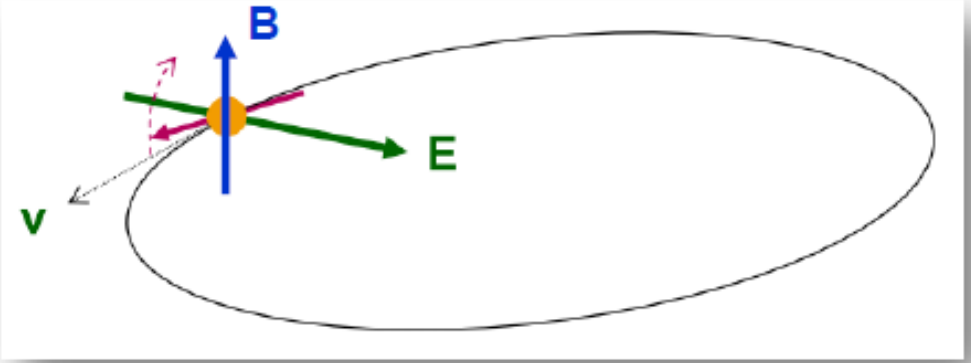
… *the* spin-physics machine for hadron physics

When the radial electric and vertical magnetic fields are combined, the connection between them is given by

$$E = \frac{GBc\beta\gamma^2}{1 - G\beta^2\gamma^2} \approx GBc\beta\gamma^2 .$$

A *magic* storage ring for protons (electrostatic), deuterons, …





particle	p (MeV/c)	T (MeV)	E (MV/m)	B (T)
proton	701	232.8	16.789	0.000
deuteron	1000	249.9	−3.983	0.160
^{3}He	1285	280.0	17.158	−0.051

Possible to measure p, d, ^{3}He using **one** machine with $r \sim 25$ m

All-electric storage ring for the proton EDM experiment

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,…)

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

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

Analyzing power can be further optimized (E. Stephenson)

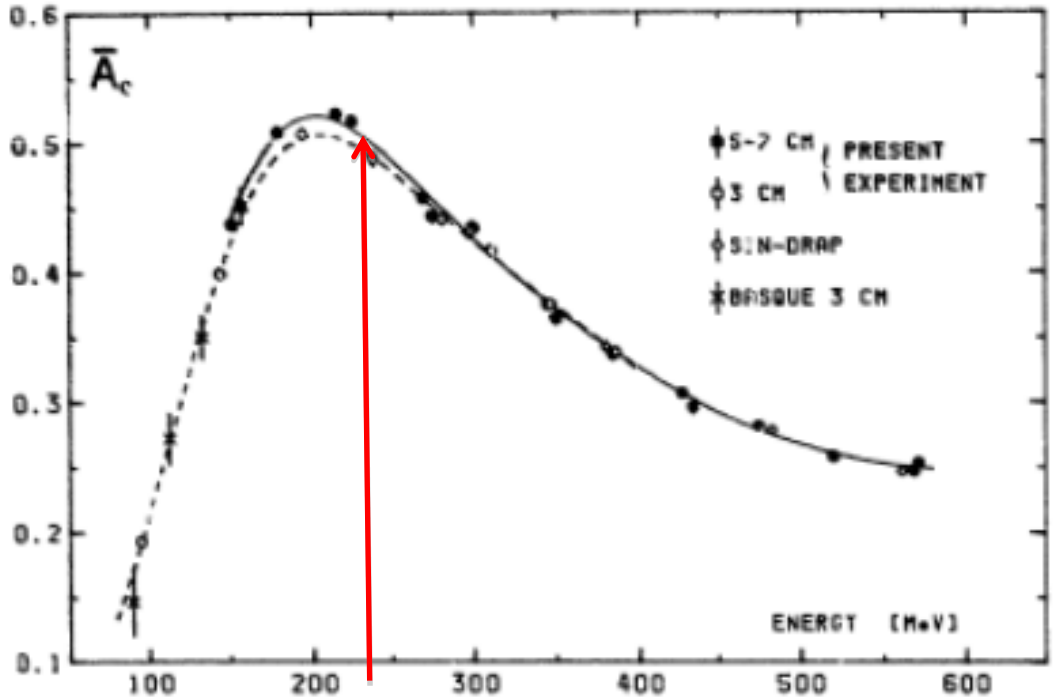


Fig. 4. Angle-averaged effective analyzing power. Curves show our fits. Points are the data included in the fits. Errors are statistical only

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.

Simulations team

Spin Coherence Time

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

$$d\omega_a \approx \left(\frac{dP}{P}\right)^2 \times 10^7 \,\mathrm{rad/s}$$

- Due to beam momentum spread dP/P there is spread in the horizontal spin precession.
- The linear part of the spread is canceled by using RF-cavity. The quadratic part is canceled by using compensating sextupole magnets.

Cancelling the 2nd order effects with sextupoles

$$\Delta\omega_a \approx a_x A_x^2 + a_y A_y^2 + a_p \left(\frac{dP}{P}\right)^2_{\max}$$

- Strategically placed <u>sextupoles</u> around the ring will cancel the effect from <u>dp/p, horizontal and vertical betatron oscillations</u>. Method applied at Novosibirsk. Our case is analyzed by Y. Orlov who estimated SCT of 10^3s should be possible.

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 : 2×10^{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 : 17 MV/m Radial electric field strength (65% azim. cov.)

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

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

Summary

- Large EDMs can demonstrate an existence of new physics.
- Search for the muon EDM will be performed in framework of the *g*-2 experiments. The expected sensitivity is of the order of 10^{-21} *e*·cm.
- Search for the EDMs of the proton, deuteron, and helion (^{3}He nucleus) will be carried out at COSY, Jülich by the resonance method. The expected sensitivity is of the order of 10^{-24} *e*·cm.
- Stimulation of resonance synchrotron oscillations is not appropriate due to large systematic errors.
- The highest sensitivity of the order of 10^{-29} *e*·cm can be reached with the frozen spin method. The experiments can be performed in storage rings with combined electric and magnetic fields (proton, deuteron, and helion) and in an all-electric storage ring (proton).

Thank you for your attention

Magnetic focusing

The magnetic field components are given by

$$B_x = gy \tag{1}$$

for the radial B-field dependence and

$$B_y = B_0 + gx - g\frac{y^2}{2R_0} \tag{2}$$

For the vertical field component, with

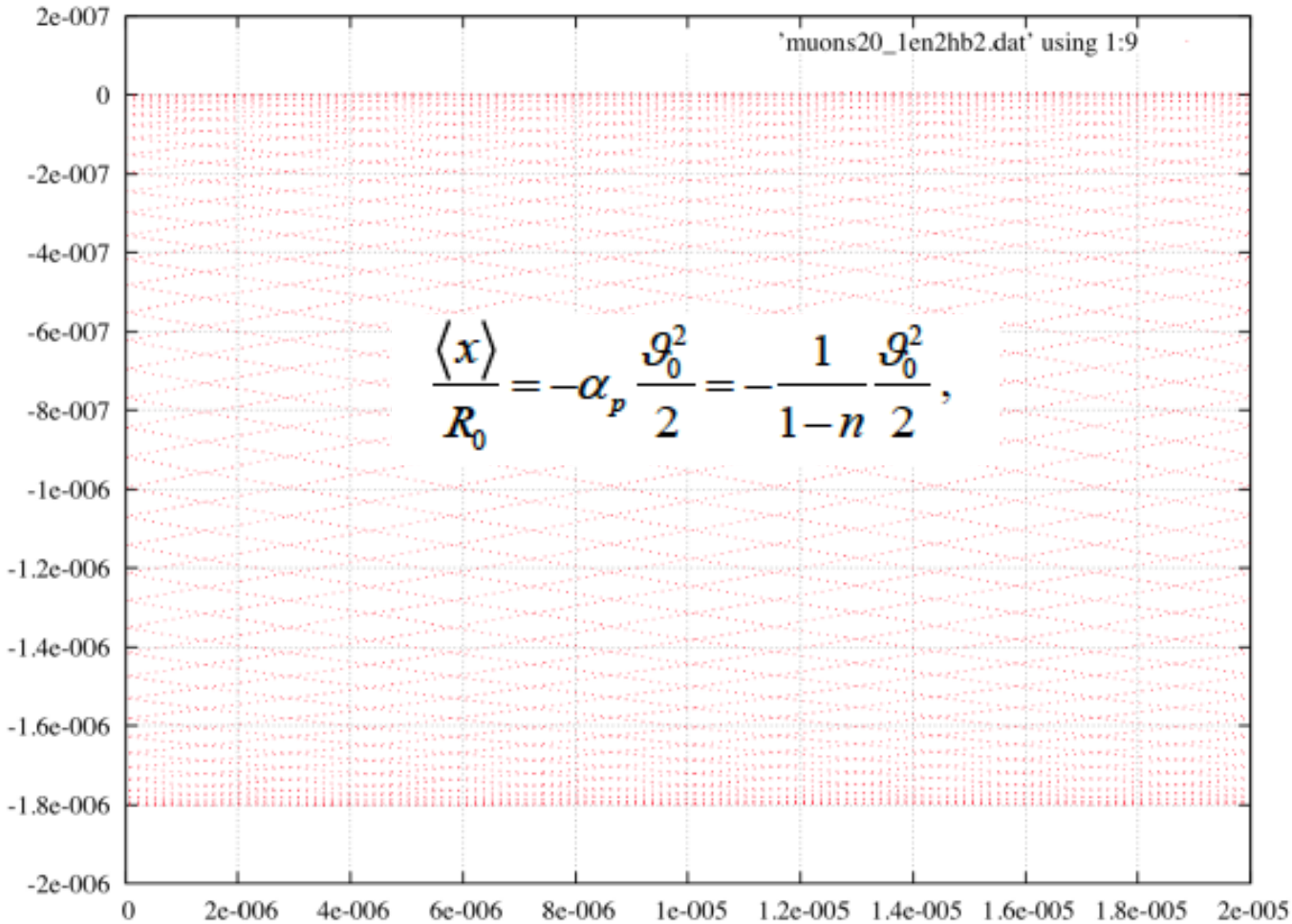
$$g = -n\frac{B_0}{R_0} \tag{3}$$

and n the field focusing index, a positive number less than 1. The non-linear term comes in from the application of Maxwell's equations in cylindrical coordinates [7] (without this term the vertical betatron oscillations are not linear).

The time averaged, relative B-field change is then

$$\left\langle \frac{B_y}{B_0} - 1 \right\rangle = -\frac{n}{R_0}\langle x \rangle + n\frac{y_0^2}{4R_0^2} = \frac{n}{1-n}\frac{\vartheta_0^2}{2} + \frac{\vartheta_0^2}{4}, \tag{4}$$

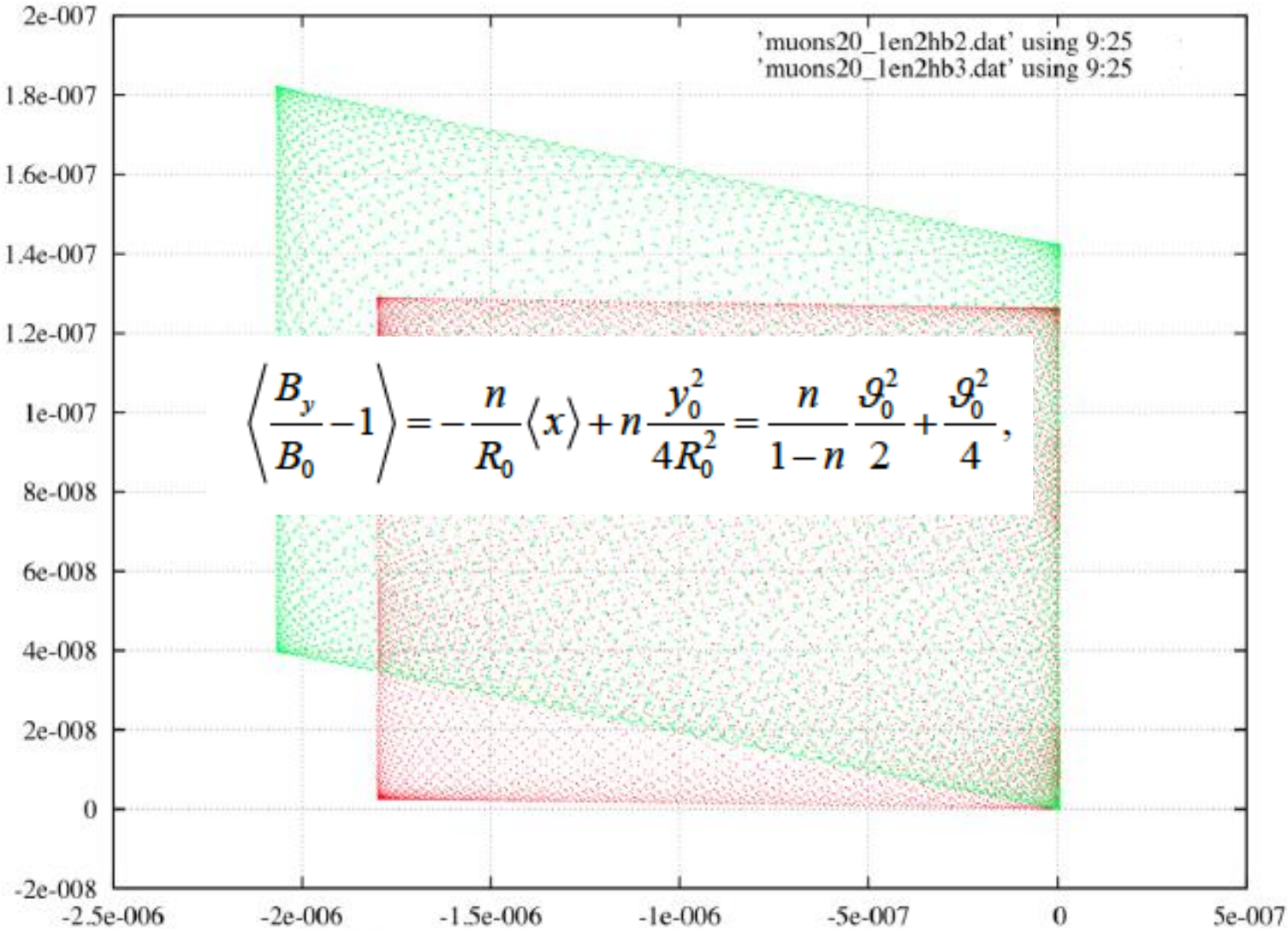
Radial oscillations



$$\frac{\langle x \rangle}{R_0} = -\alpha_p \frac{\vartheta_0^2}{2} = -\frac{1}{1-n}\frac{\vartheta_0^2}{2},$$

Figure 2. The particle deviation [m] from the ideal radial position vs. time [s]. Eq. (5) predicts a maximum of -1.8×10^{-6}m, consistent with the tracking results shown here. The maximum angle is 0.5mrad and n=0.01.

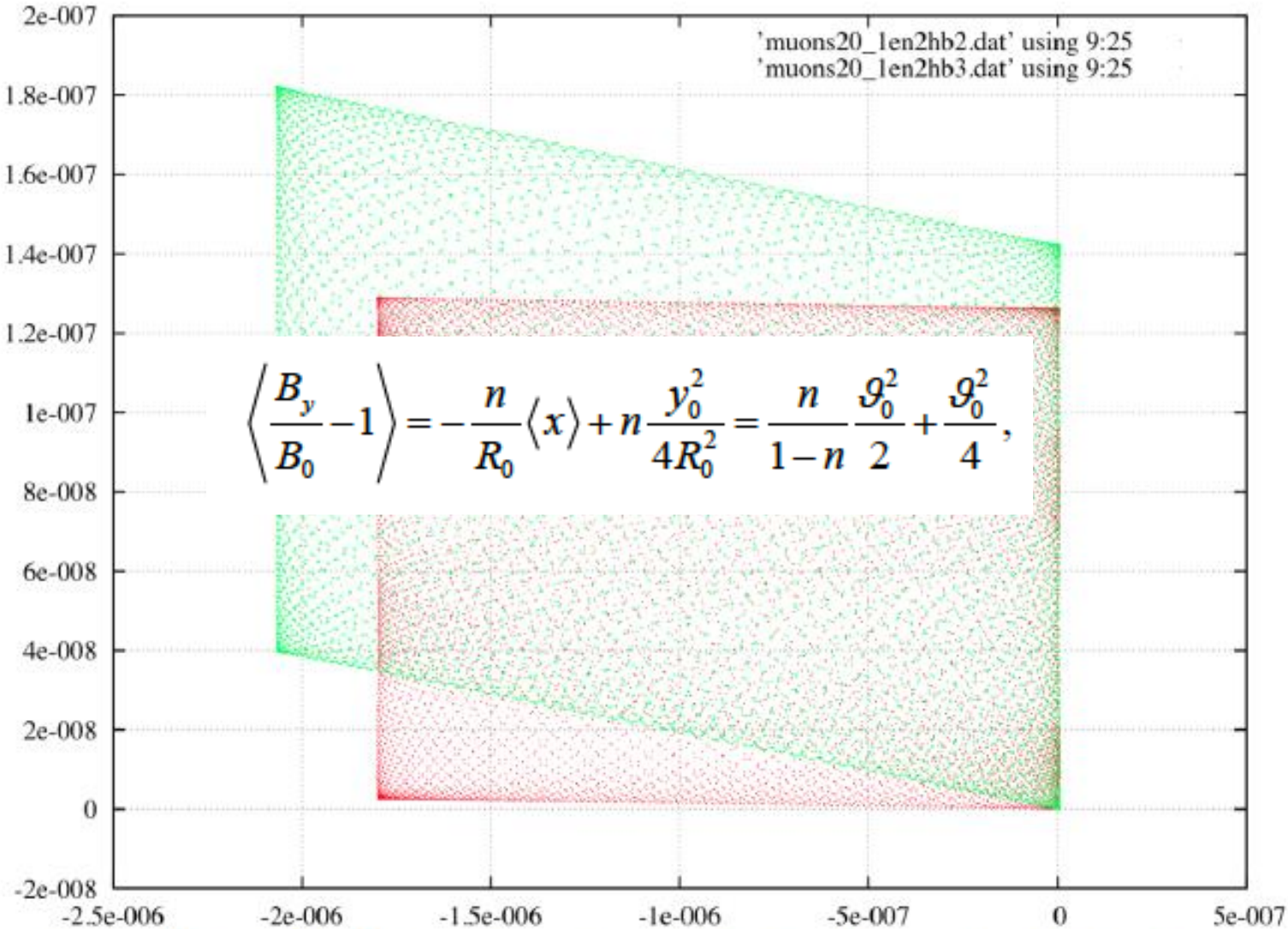
B-field vs. vertical position



$$\left\langle \frac{B_y}{B_0} - 1 \right\rangle = -\frac{n}{R_0}\langle x \rangle + n\frac{y_0^2}{4R_0^2} = \frac{n}{1-n}\frac{\vartheta_0^2}{2} + \frac{\vartheta_0^2}{4},$$

Figure 7. The relative B-field change as a function of the radial position [m] for two *n*-values: 0.01 (red) and 0.137 (green).

B-field vs. vertical position



$$\left\langle \frac{B_y}{B_0} - 1 \right\rangle = -\frac{n}{R_0}\langle x \rangle + n\frac{y_0^2}{4R_0^2} = \frac{n}{1-n}\frac{\vartheta_0^2}{2} + \frac{\vartheta_0^2}{4},$$

Figure 7. The relative B-field change as a function of the radial position [m] for two *n*-values: 0.01 (red) and 0.137 (green).