PAC meeting
BNL, 12 September 2006

LOI: deuteron ion EDM (dEDM) to 10^{-29} e·cm

Y. K. Semertzidis, BNL
for the Storage Ring EDM Collaboration

- Resonance EDM method using 1.5GeV/c deuterons in a 5m×10m storage ring

- Using well established accelerator techniques

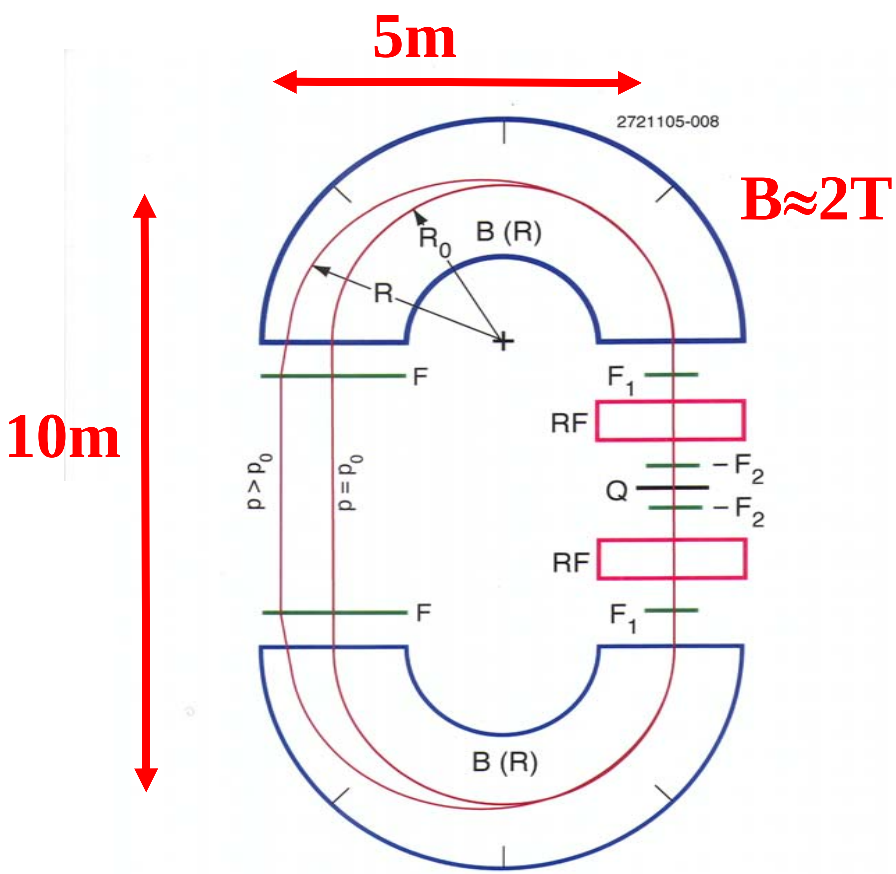
- EDM Study of d, P, ^{3}He, … is possible with same method

$$\frac{d\vec{S}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

Elements of a successful EDM experiment

- High intensity, highly Polarized source with well defined initial state
- Interact with a strong E-field for a long time
- Analyze as a function of time, with high efficiency, high analyzing power (asymmetry)

Resonance Electric Dipole Moment Method



Y. Orlov et al., PRL 96, 214802 (2006)

- High intensity (~10^{12}/cycle), horizontally polarized deuteron beam
- Coherent synchrotron tune equals the g-2 tune → Rabi resonance: Effective rest frame E-field is oscillating at the g-2 frequency
- EDM signal: Change of vertical component of spin in time

Motivation

Applying accelerator techniques established for ~50 years

- High intensity (~10^{12}/cycle), highly polarized, low emittance deuteron beams are available

- Interact in a strong E-field (ala Rabi resonance technique)

- deuteron polarimeters are available, with high analyzing power for ~1.5 GeV/c d-momentum

Storage
Ring
EDM
Collaboration

Letter of Intent: Development of a Resonance Method to Search for a Deuteron Electric Dipole Moment using a Charged Particle Storage Ring

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Deuteron Statistical Error:

$$\sigma_d \approx \frac{13\hbar}{\delta\beta_0 c \langle B \rangle AP\sqrt{N_c f \tau_p T_{Tot}}}$$

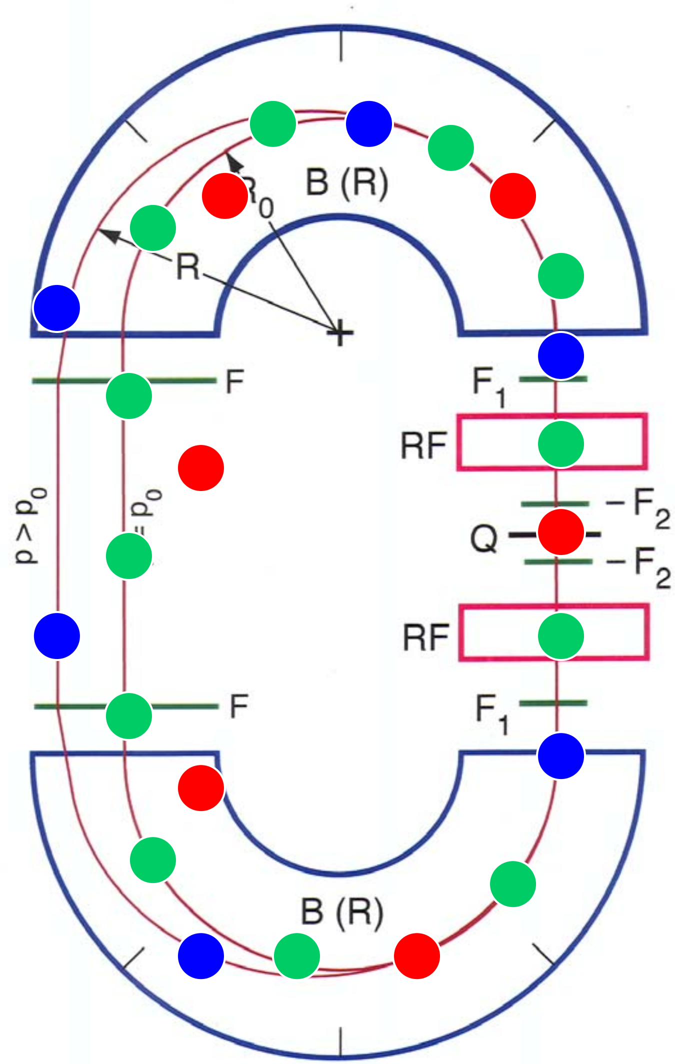
τ_p	: 1000s	**Polarization Lifetime (Coherence Time)**
A	: 0.36	**The left/right asymmetry observed by the polarimeter**
P	: 0.95	**The beam polarization**
N_c	: 10^{12}d/cycle	**The total number of stored particles per cycle**
T_{Tot}	: 5000h/yr.	**Total running time per year**
f	: 0.042	**Useful event rate fraction**
$\delta\beta_0/\beta_0$	: 0.01	**Velocity modulation**
$\langle B \rangle$	: 1.2T	**The average magnetic field around the ring**

$$\sigma_d \approx 2\times10^{-29}\,\mathrm{e}\cdot\mathrm{cm}\,/\,\mathrm{year}$$

Major Concepts in Place:

- Polarized source, spin manipulation, high efficiency injection
- Analyzing method
- Spin Dynamics
- Systematics

Simultaneously Controlled Experiments



Bunches:

- EDM: Spin Up
- EDM: Spin Down
- No EDM effect

Three classes of systematic errors

Source	Examples	Remedy
Beam dynamics	Losses	Red minus Blue
Beam dynamics	Motion	Red minus Blue
Polarimetry	Gain effects	Red minus Blue
Spin dynamics	Oscillating B_r	Tune1 minus Tune2
Spin dynamics	Comb. B_v with B_l or B_r (geom. phase)	Tune1 minus Tune2

Our Request:

- PAC Physics Endorsement
- Support for full proposal (2007) and Technical Review

Support for a FY2007 proposal:

- Beam and spin dynamics studies
- Engineering support for a cost estimate
- Support for visitors/consultants

Beam and Spin Dynamics Studies

- To optimize the lattice design
- To maximize the number of tools to deal with the (many) unanticipated systematic errors

Storage Ring Electric Dipole Moments

- d @ 10^{-29}e·cm would be the best EDM sensitivity over *present* or *planned* experiments for θ_{QCD}, quark, and quark-color (T-odd Nuclear Forces) EDMs.
- This LOI is for d. P, ^{3}He, etc., are natural extensions i.e. a facility to pin down the CP-violation source.
- Well defined initial state to study EDM

Extra Slides

The other EDM efforts

7 Appendix I: EDM Efforts Reported at Lepton Moments Symposium

A White Paper summarizing all EDM efforts is being prepared and will be finished before we submit a proposal. Here, we give a brief summary of the experimental talks on EDMs from the recent Third International Symposium on Lepton Moments. All the presentations are now available on the Symposium web site http://g2pc1.bu.edu/lept06/.

Table 3: **Talks on EDMs of Molecules.**

Ed Hinds - Imperial College	Measurement of the electron EDM using cold YbF molecules	~10 year old efforts
David DeMille - Yale	The PbO experiments at Yale	
Eric Cornell - JILA/Colorado	Searching for an electron EDM in trapped molecular ions	New efforts
Neil Shafer-Ray - Oklahoma	Possible measurement of the electron EDM with g=0 paramagnetic molecules	

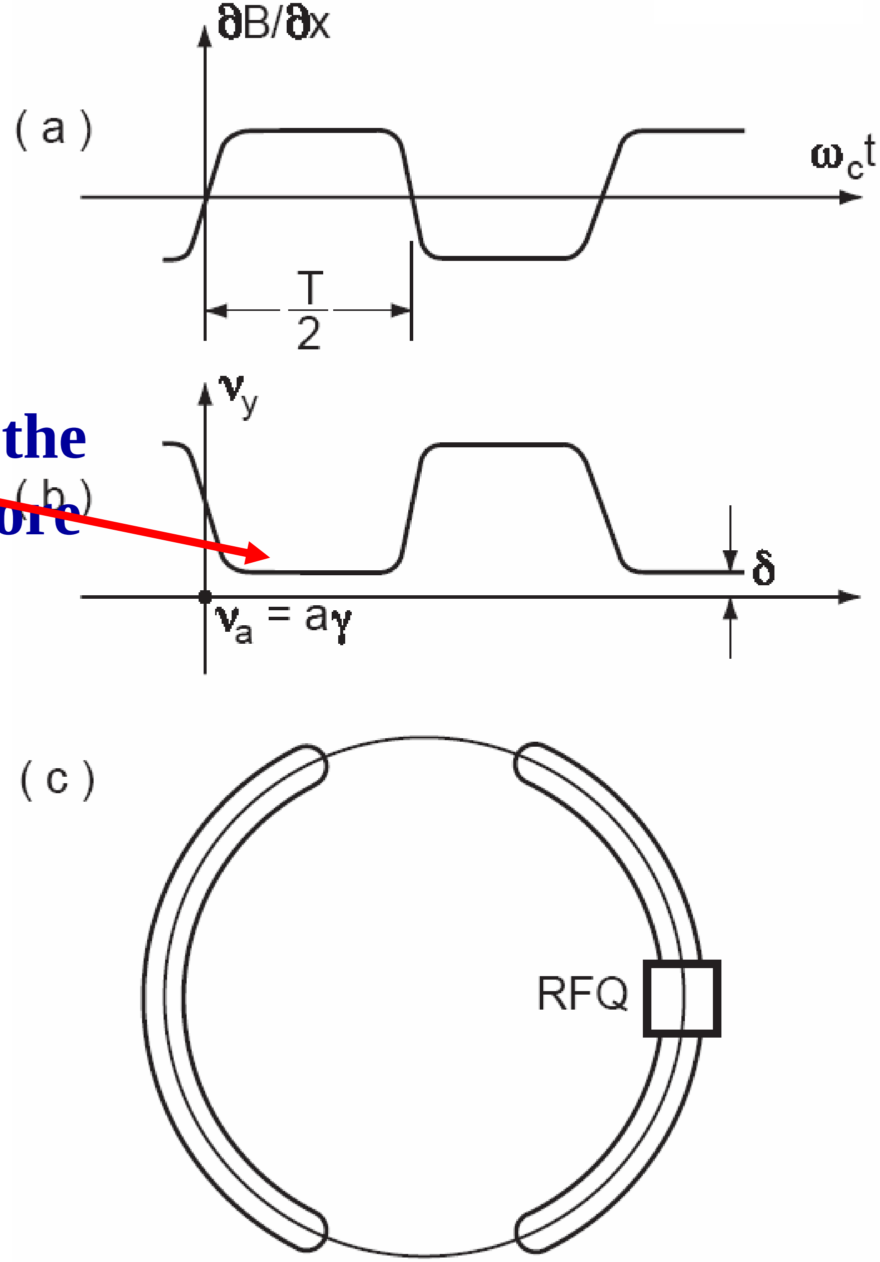
Support for a FY2007 proposal:

- Beam and spin dynamics studies (1 month FTE each):
  1. Injection and RF-Capture scheme
  2. Spin coherence time
  3. Spin tracking, detailed systematic studies

- Engineering support for a cost estimate (1 month FTE)

- Support for visitors, consultants ($25K for Yuri Orlov for FY2007)

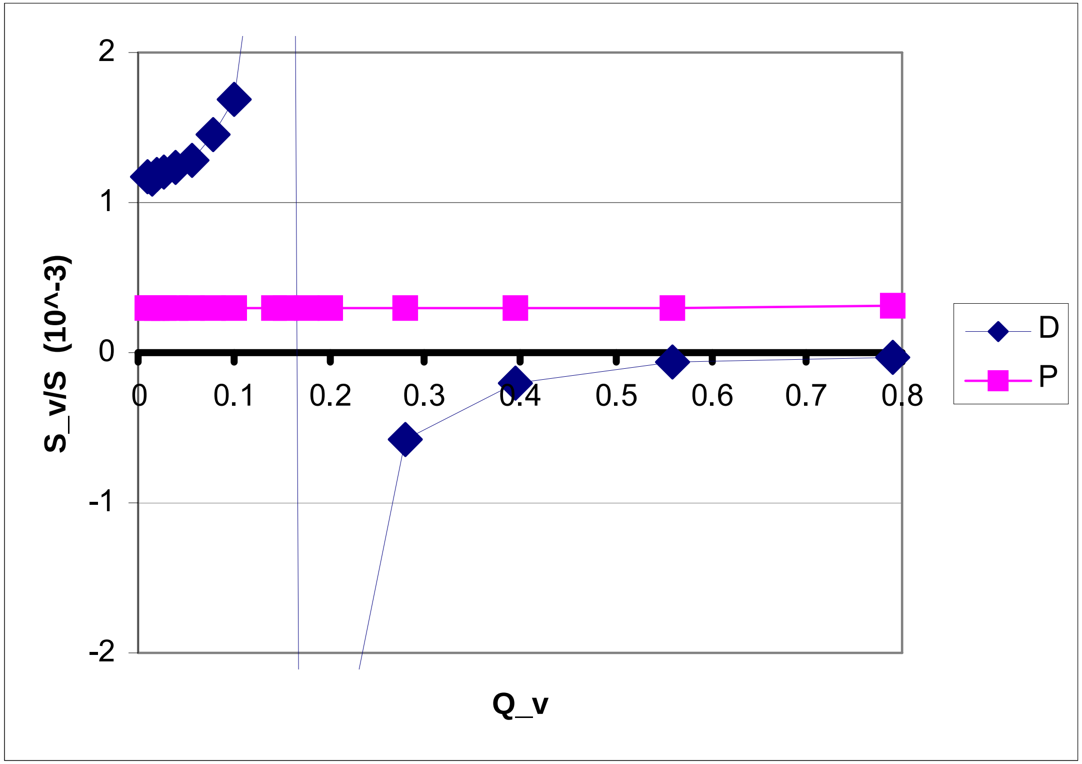
Two half beam technique (RF-Quadrupole)



This tune makes the Deuteron spin more Sensitive to background

Backgrounds are vertical tune dependent; EDM signal is not!

$$\frac{ds_v}{dt} \propto \frac{1}{Q_v^2 - Q_s^2}$$



Resonance EDM systematic errors

Examples: 1) Skew quadrupole where $D \neq 0$,

2) RF-cavity (vertical offset or misalignment), …

3) …

Remedy: They depend on the vertical tune… They all do!

Deuteron EDM at BNL

- Great physics opportunity; it will not be done at LHC
- The Infrastructure is there (polarized source, spin manipulating devices, …).
- The human factor: Hadron and spin expertise, the best in the world.
- Compatible with the lab mission: The nuclear physics lab of US, QCD Lab, θ_{QCD}

Deuteron EDM at BNL

- Home of the successful (and sophisticated) muon g-2 experiment.
- Moderate cost to build a 5m by 10m ring
- Moderate Intensity, compatible with current conditions
- Moderate power cost for running it: ~1.5GeV/c. One pulse every ≈1000s.

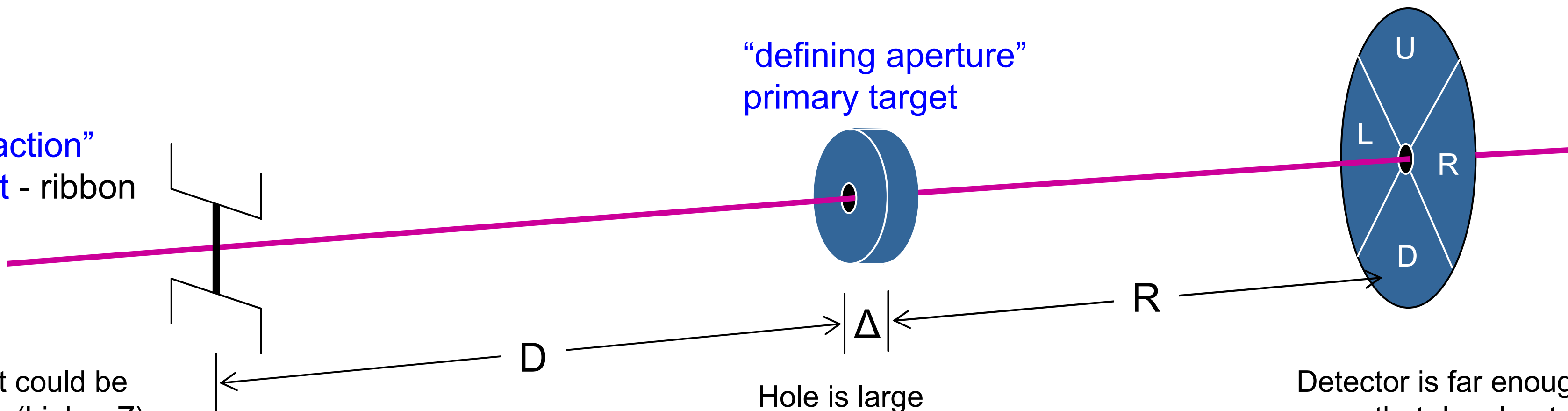
CERN?

- The Infrastructure for ions is there (no polarized source or spin manipulating devices). LEIR is going to be sitting idle for >10 months per year!
- The human factor: Hadron expertise
- Enthusiastic invitation (John Ellis, Jos Engelen,…)

LEIR as a possible location for the Orlov ring

Nuclear Scattering as Deuteron EDM polarimeter

IDEA:
- make thick target defining aperture
- scatter into it with thin target



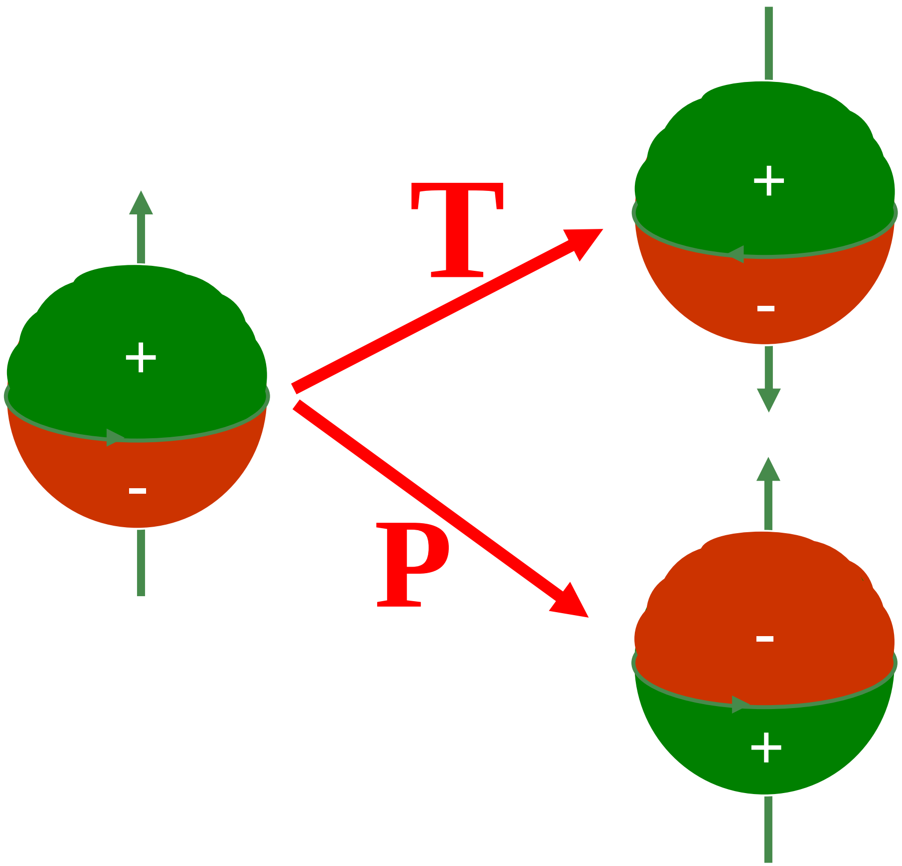
Target could be Ar gas (higher Z).

Target "extracts" by Coulomb scattering deuterons onto thick main target. There's not enough good events here to warrant detectors.

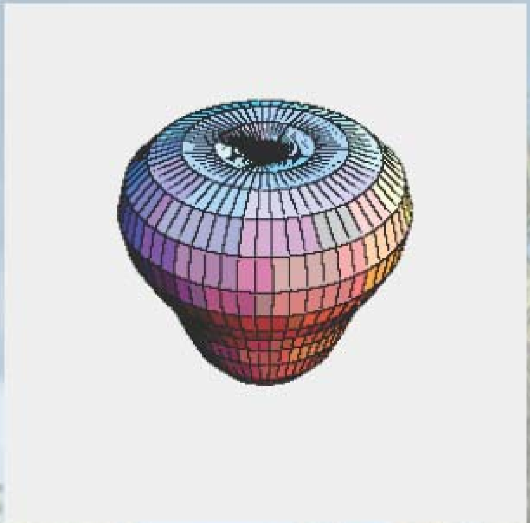
Hole is large compared to beam. Every-thing that goes through hole stays in the ring.

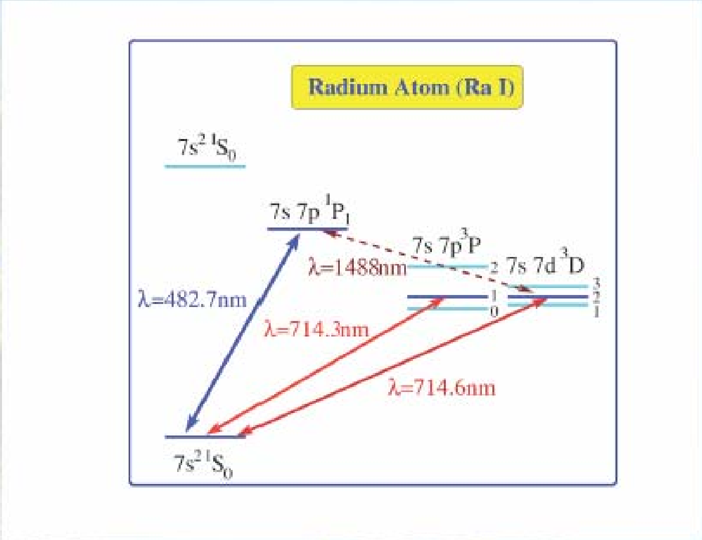
Detector is far enough away that doughnut illumination is not an acceptance issue: Δ < R.

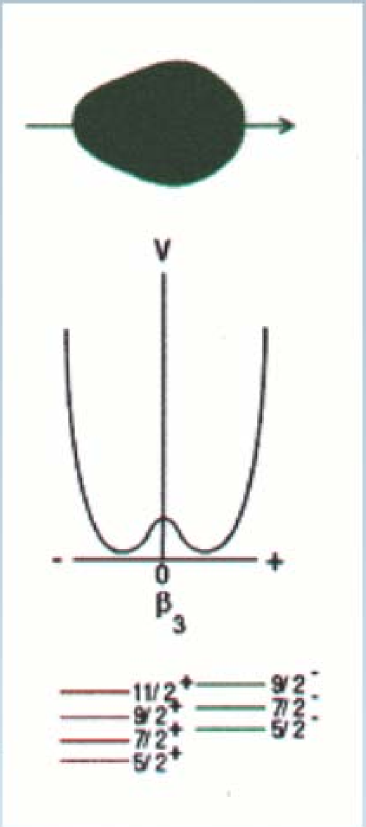
A Permanent EDM Violates both T & P Symmetries:



Amplification in deformed radium atoms







- Big enhancement ~10^4 from atomic degeneracy.
- Additional factor from octupole deformation?

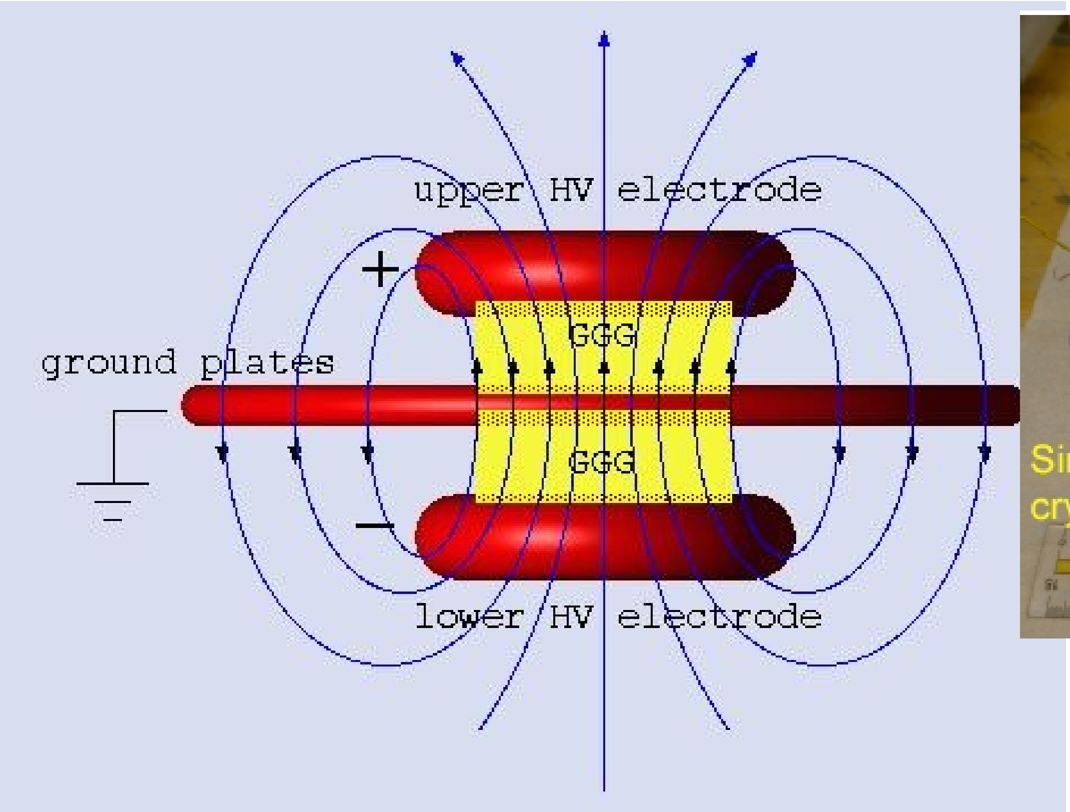
1. $\langle S_z \rangle_{Hg} = 0.00 g_\pi g_0 + 0.06 g_\pi g_1 - 0.01 g_\pi g_2$ e.fm^3
2. $\langle S_z \rangle_{Ra} = -1.5\, g_\pi g_0 + 6.0\, g_\pi g_1 + 4.0\, g_\pi g_2$ e.fm^3

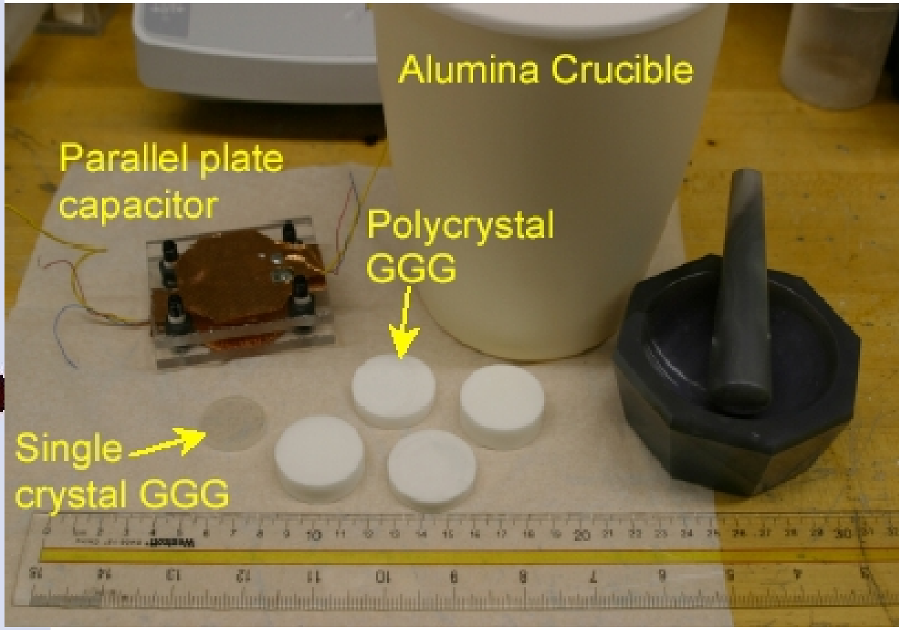
J. Dobaczewski, J. Engel, PRL **94**, 232502 (2005).

Caveat: all these calculations employ an incomplete Schiff operator, cf.

C.-P. Liu, W.C. Haxton, M.J. Ramsey-Musolf, RT, A.E.L. Dieperink, nucl-th/0601025.

Solid State Electron EDM Search at 50mK





Estimated sensitivity 10^{-30}e·cm, no sensitivity to θ_{qcd}

Limit on the Electron Electric Dipole Moment in Gadolinium-Iron Garnet

B. J. Heidenreich, O. T. Elliott, N. D. Charney, K. A. Virgien, A. W. Bridges, M. A. McKeon, S. K. Peck, D. Krause, Jr., J. E. Gordon, and L. R. Hunter

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(Received 14 September 2005; published 15 December 2005)

A new method for the detection of the electron electric dipole moment (EDM) using a solid is described. The method involves the measurement of a voltage induced across the solid by the alignment of the sample's magnetic dipoles in an applied magnetic field, H. A first application of the method to GdIG has resulted in a limit on the electron EDM of $5 \times 10^{-24} e$ cm, which is a factor of 40 below the limit obtained from the only previous solid-state EDM experiment. The result is limited by the imperfect discrimination of an unexpectedly large voltage that is even upon the reversal of the sample magnetization.

DOI: 10.1103/PhysRevLett.95.253004 PACS numbers: 32.10.Dk, 11.30.Er, 14.60.Cd, 75.80.+q

Table 1: **Features of the resonance EDM search method**

Velocity modulation	at the $g-2$ frequency
$g-2$ precession	in the ring plane
EDM precession	perpendicular to the ring plane
Polarization monitor	continuous, scattering from thick C target
Signal size	$\sim 1\mu$rad/1000s in dS_y/dt at $d = 10^{-29}$ e·cm
leading to an asymmetry sens.	3×10^{-7} per 1000 s beam store
Similar asymmetry experiments	Parity violation, with $< 10^{-7}$ asymmetry [12, 13]

Systematic problem	**Remedy**
(1) Oscillating B_r	alternating vertical tune bunches
(2) Polarimeter alignment	alternate bunches with reversed EDM signal
(3) High $g-2$ precession harmonics	momentum compaction factor $\alpha_p = (\Delta L/L)/(\Delta_p/p) = 1$

Resonance Electric Dipole Moment Method

PRL **96,** 214802 (2006) PHYSICAL REVIEW LETTERS week ending 2 JUNE 2006

Resonance Method of Electric-Dipole-Moment Measurements in Storage Rings

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(Received 12 December 2005; published 1 June 2006)

A "resonance method" of measuring the electric dipole moment (EDM) of nuclei in storage rings is described, based on two new ideas: (1) Oscillating particles' velocities in resonance with spin precession, and (2) alternately producing two sub-beams with different betatron tunes—one sub-beam to amplify and thus make it easier to correct ring imperfections that produce false signals imitating EDM signals, and the other to make the EDM measurement.

DOI: 10.1103/PhysRevLett.96.214802 PACS numbers: 29.20.Dh, 13.40.Em

In search of new physics through precision Electric Dipole Moment Experiments

Main competition: Neutron EDM

Year	Exp begin data taking	Exp goal
2005		
2007		
2008	UCN-PSI	10^{-27}e·cm
2009	UCN-ILL	2×10^{-28}e·cm/yr
2011	UCN-LANL/SNS	1×10^{-28}e·cm

Ideas to work (together)

- Synchrotron tune ~0.18, dv/v~1-3%, RF-cavity 10-20 MV
- Coherence time
- Polarimeter Integration
- Systematics

RF-Cavity issues

- Synchrotron tune ~0.18, dv/v~1-3%, RF-cavity 10-20 MV

Mei Bai, M. Blaskiewicz, Ilan Ben-Zvi, A. Facco, Alfredo Luccio, Y.Orlov, V. Shemelin, …

Triple Spoke at β=0.62

Frequency	345 MHz
β_0	0.63
L($3\beta\lambda/2$)	82 cm
QR_S (G)	93 Ω
R/Q	549 Ω
below for E_{ACC} = 1.0 MV/m	
RF Energy	0.565 J

- 4 cm diameter beam aperture
- Transverse diameter 45.8 cm,
- Interior length of 85 cm.
- Can be scaled to 239 MHz with corresponding 18% increase in all dimensions and voltage.
- 20 MV possible with 2 cavities.
- Refrigeration: 10.6 MV/m with 270 W

Coherence time issues

- Goal of 1000 s
- Use sextupoles, and possibly decapoles
- Needs to work at two different n-values (systematics)

G. Onderwater, Y.Orlov, V. Ptitsyn, Y. Shatunov

Polarimeter issues

- Asymmetry
- Efficiency
- Integration with rest of the experiment

E. Stephenson, G. Onderwater, A. Ferrari (M.C.).

Systematics, collective effects

- Tune dependence of B_r, systematic error
- Functional form of image charges interference
- Wake fields
- Beam tube wall resistance
- Tune shifts and other collective effects

M. Blaskiewicz, A. Fedotov, B. Morse, Y.Orlov, YkS, A. Sidorin,…

Other EDM efforts

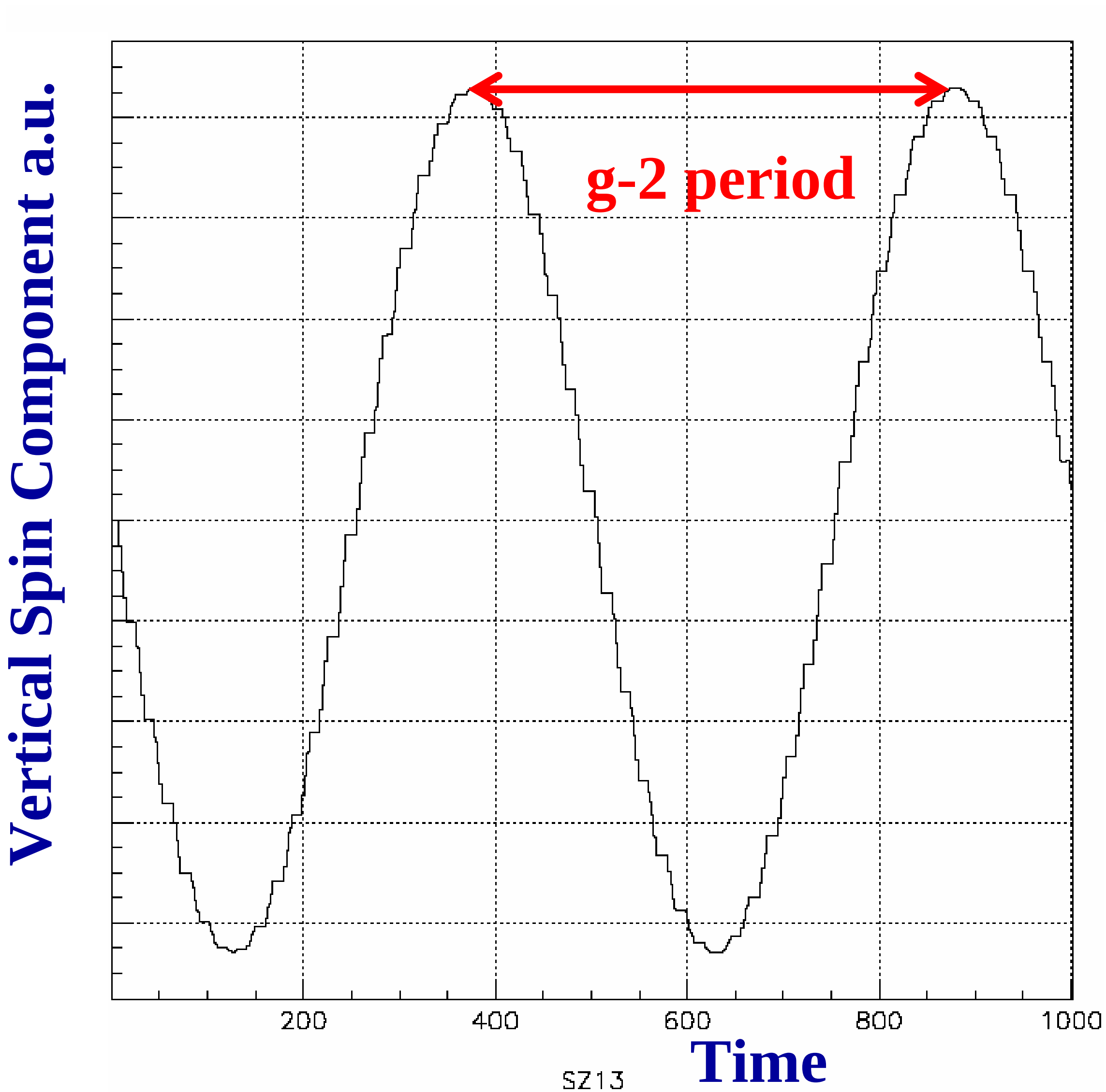
- Appendix I: Efforts reported at Third International Symposium “Lepton Moments”. http://g2pc1.bu.edu/lept06
- I am the coordinator for EDM/g-2 part of WG3 of “Flavour in the era of LHC” at CERN and a yellow report is due early next year. http://cern.ch/flavlhc

Electric Dipole Moments in Storage Rings

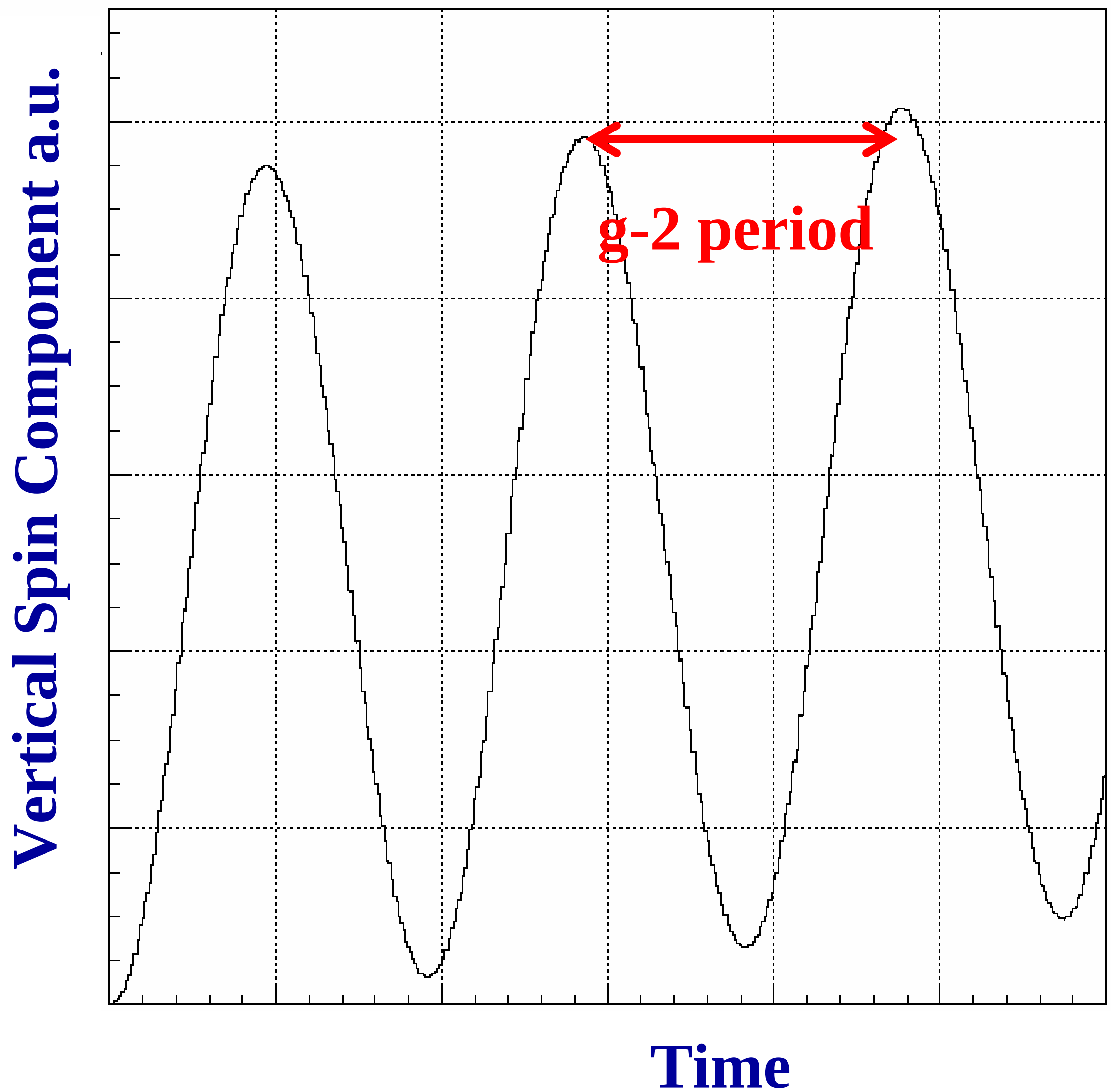
$$\frac{d\vec{s}}{dt} = \vec{d} \times \left(\vec{v} \times \vec{B} \right)$$

e.g. 1T corresponds to 300 MV/m for relativistic particles

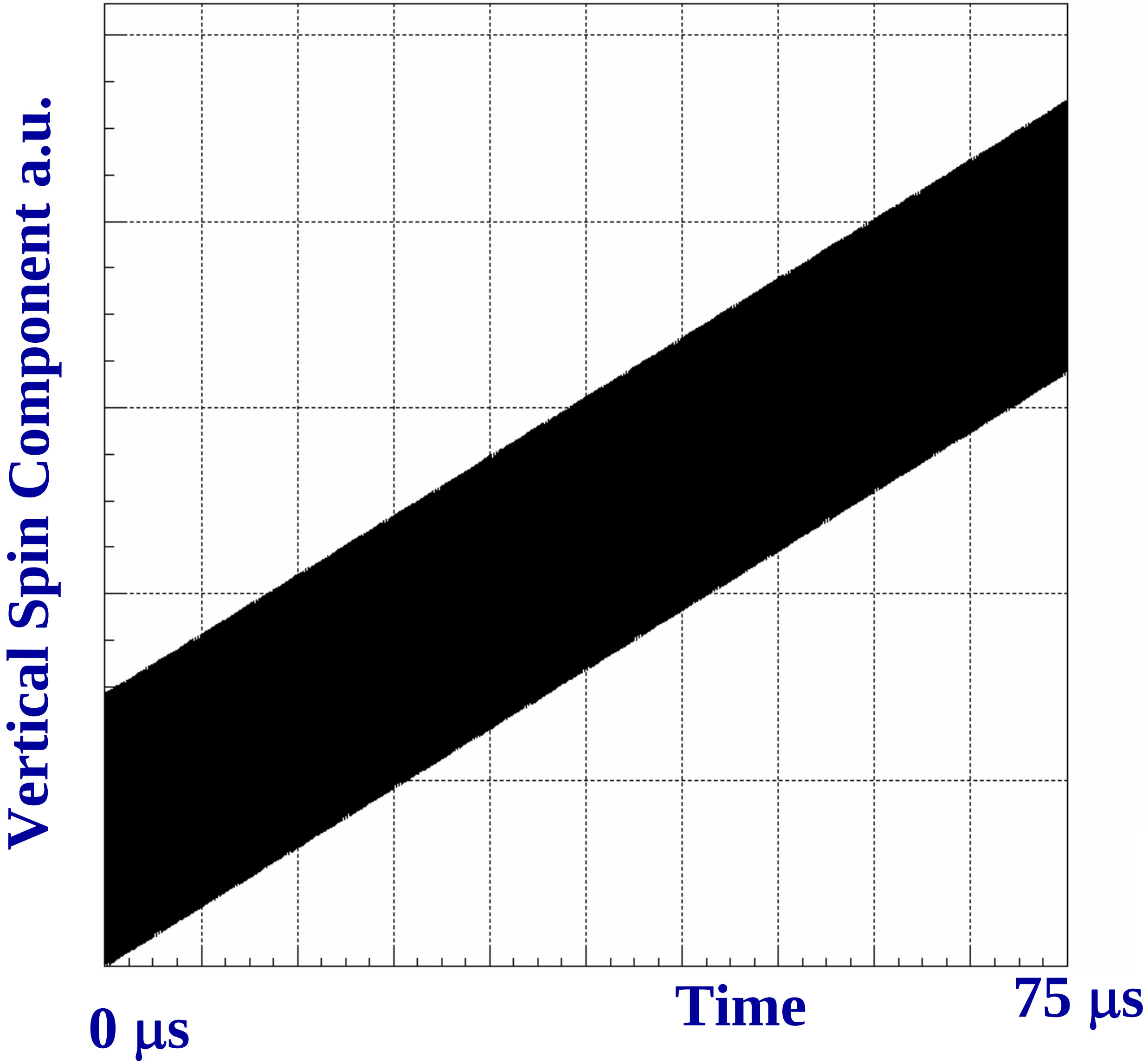
Vertical Spin Component without Velocity Modulation



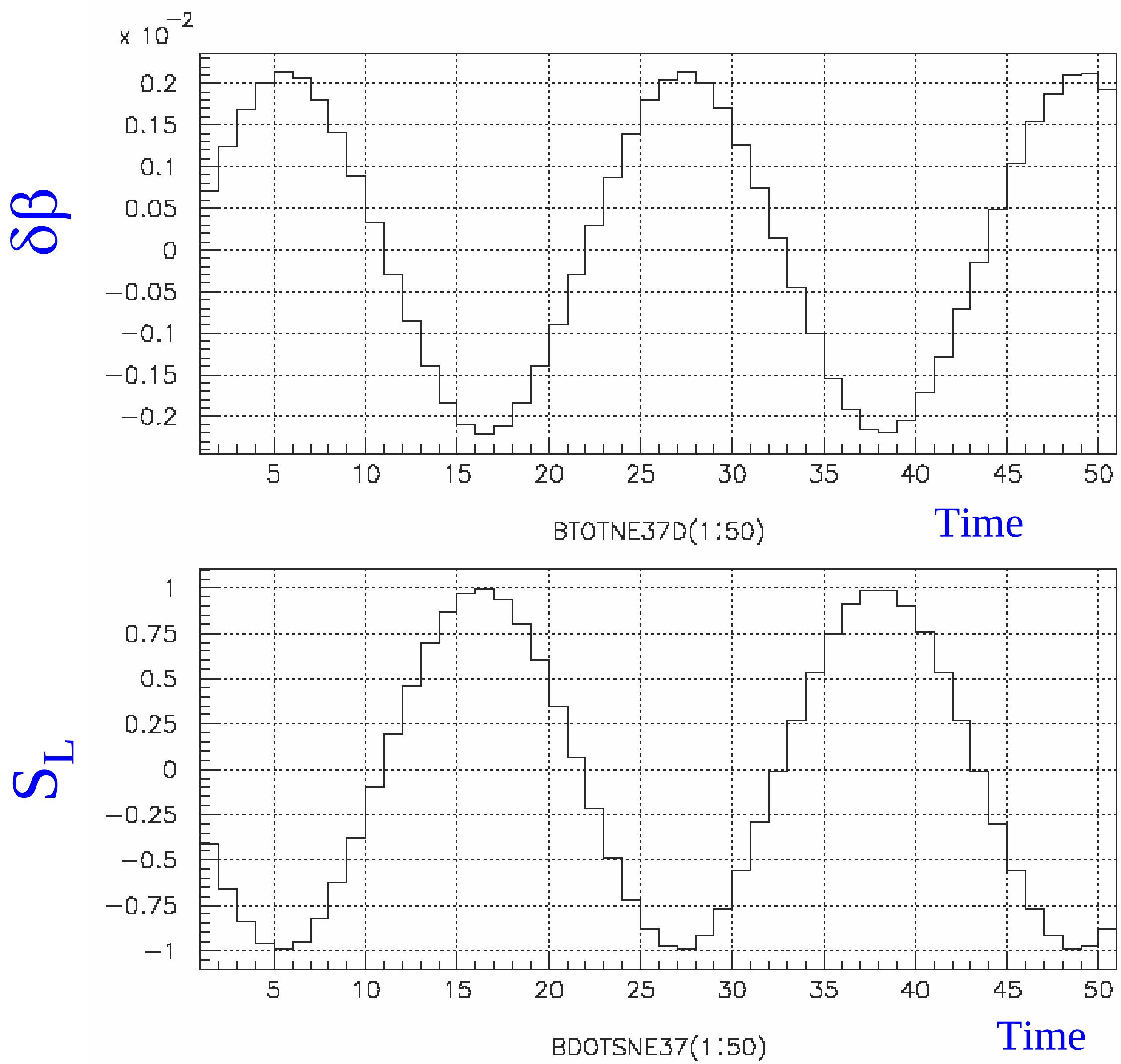
Vertical Spin Component with Velocity Modulation at ω_a



Vertical Spin Component with Velocity Modulation (longer Time)



Velocity (top) and g-2 oscillations



Yuri Orlov's new idea

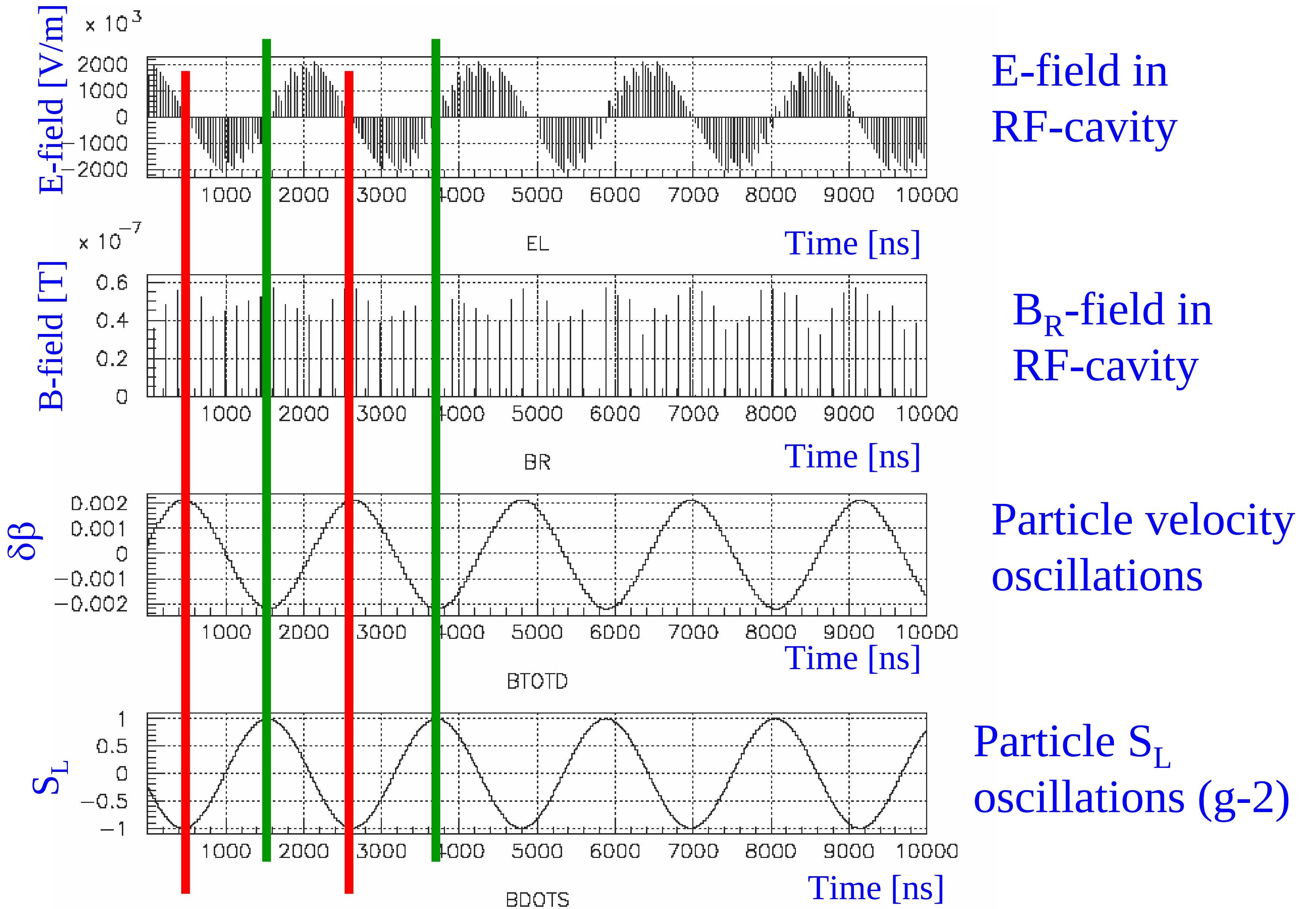
Particle velocity oscillations

Particle S_L oscillations

(i.e. g-2 oscillations)

The synchrotron oscillation phase (top) compared to g-2 phase (bottom). ~5us total horizontal scale

RF-fields and oscillation phases



Effect of the vertical offset, YkS note #85

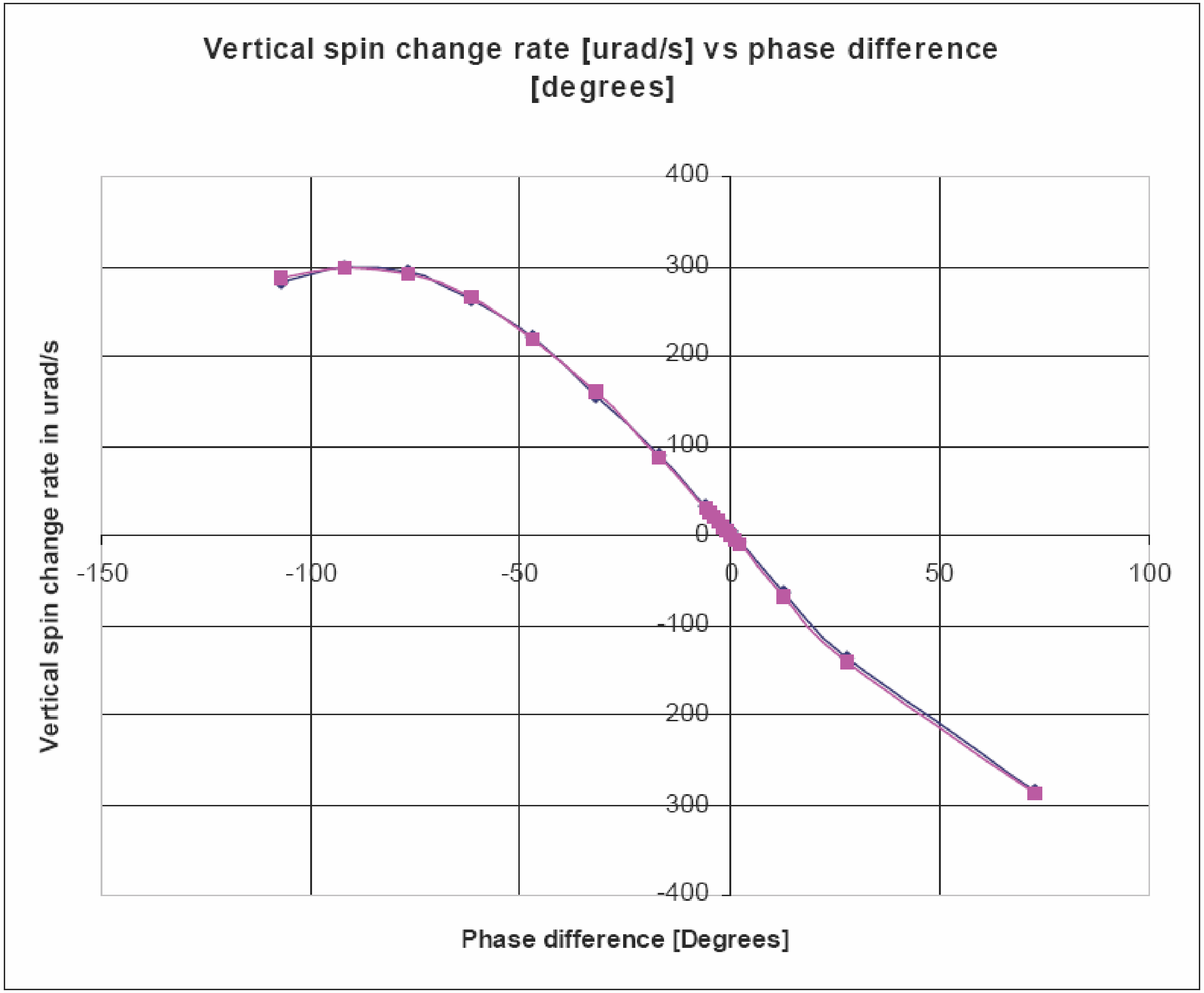


Figure 1. The vertical spin precession rate in μrad/s versus the phase difference (ϕ) between the synchrotron oscillations and the g-2 precession in degrees (modulo 180°) for an RF-cavity offset of 10μm is shown. An overlay of the function 300 μrad/s * sin(ϕ) is also shown.

Effect of the angular offset, YkS note #92

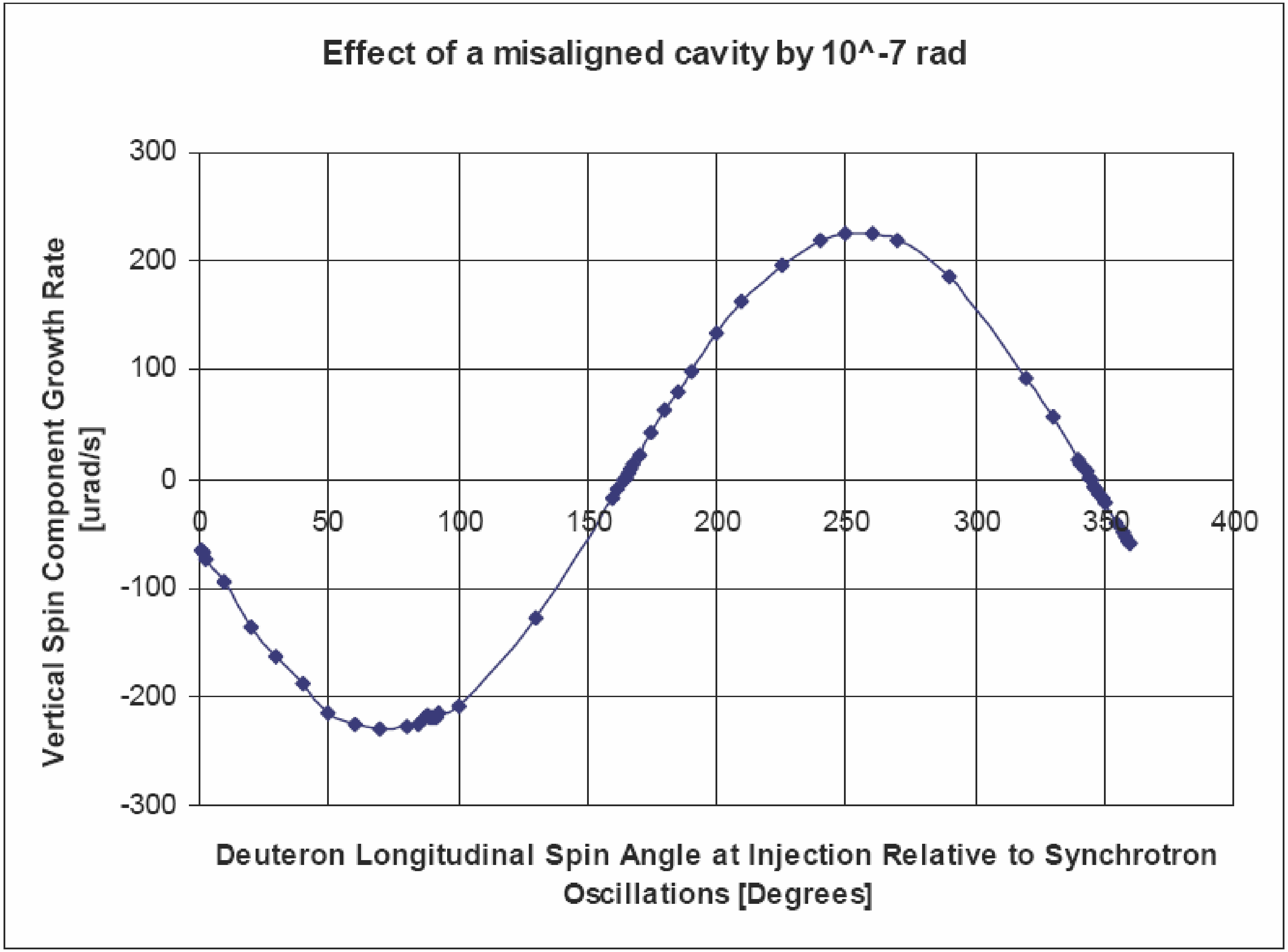


Figure 1. The effect of a misaligned cavity depends on the relative phase between the synchrotron and g-2 oscillations. This dependence is very different from the EDM effect dependence.

Two classes of systematic errors

- Beam and polarimeter related (e.g. beam losses, beam displacement, detector gain effects,…)

- Spin dynamics related (second order spin resonances, e.g. B_r correlated with momentum oscillations, or an unfortunate combination of B_v and B_l (geometrical effect))

- Consecutive stored bunches have different EDM effects.
- Background effects depend on the vertical tune, the EDM does not.