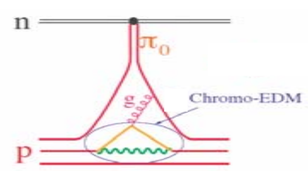
Flavour in the era of the LHC
dEDM, CERN, 16 May 2006

Update on the EDMs in Storage Rings

Yannis K. Semertzidis

Brookhaven National Lab

- Experimental Technique
- Systematic errors
- Schedule
- Summary



hep-ex/0605022 **Accepted for publication by PRL**

Resonance method of electric-dipole-moment measurements in storage rings

Yuri F. Orlov[1,2], William M. Morse[1], Yannis K. Semertzidis[1]

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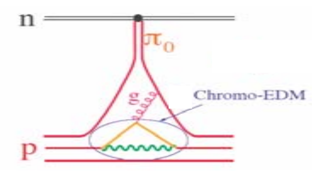
Abstract

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.

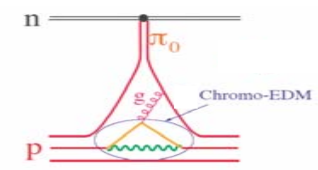
PACS numbers: 29.20Dh, 21.20.Ky.



Resonance Electric Dipole Moment

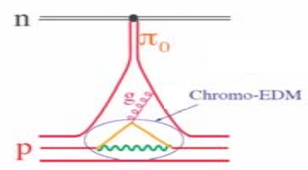
- D @ 10^{-29}e·cm would be the best EDM sensitivity over *present* or *planned* experiments for θ_{QCD}, quark, and quark-chromo (T-odd Nuclear Forces) EDMs.

- D, P, ^{3}He, etc., i.e. a facility to pin down the CP-violation source.



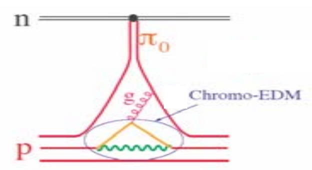
Neutron/deuteron EDM Timeline

Year	Exp begin data taking	Exp goal
2006		
2007		
2008	UCN-PSI	10^{-27}e·cm
2009	UCN-ILL	2×10^{-28}e·cm/yr
2010		
2011	UCN-LANL/SNS	10^{-28}e·cm

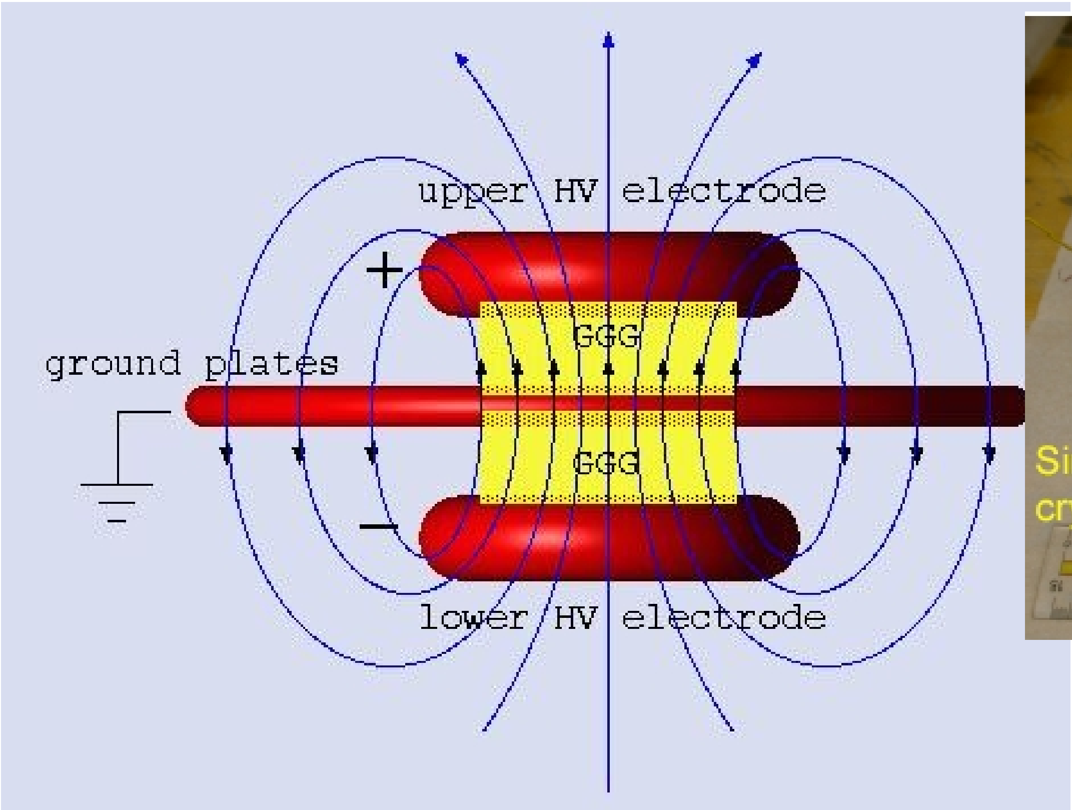


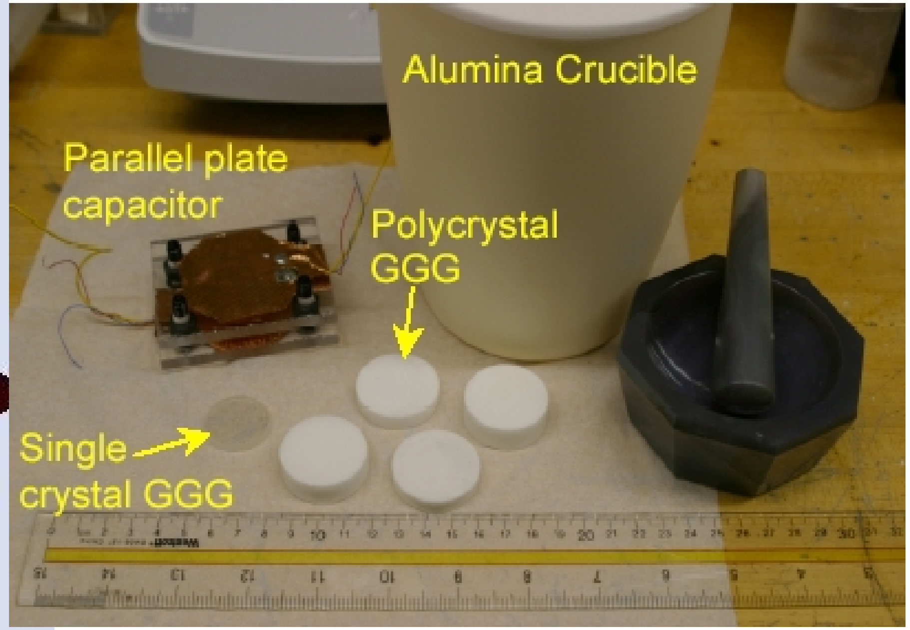
Future Prospects in electron EDM:

- Electron: YbF Ultra-cold molecules. Goal ~1000, B.E. Sauer *et al.*
- Electron: PbO*, goal ~1000, D. DeMille *et al.*
- E. Commins: "It takes 15 years for the electron EDM Exps from idea to end of exp…"

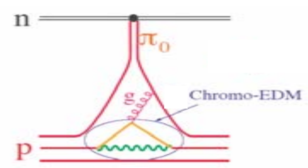


Solid State Electron EDM Search at 50mK





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



PRL 95, 253004 (2005) PHYSICAL REVIEW LETTERS week ending 16 DECEMBER 2005

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

Physics Department, Amherst College, Amherst, Massachusetts 01002, USA

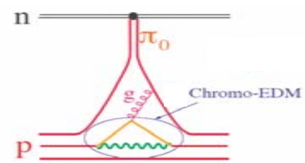
S. K. Lamoreaux

Physics Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

(Received 14 September 2005; published 15 December 2005)

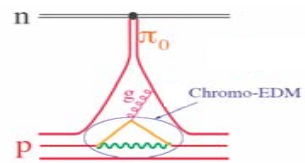
A new method for the detection of the electron electric dipole moment (EDM) using a solid is described. The method involves the measurement of a voltage induced across the solid by the alignment of the sample's magnetic dipoles in an applied magnetic field, H. A first application of the method to GdIG 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



Experimental Principle of dEDM

- Polarize
- Interact with an E-field
- Analyze as a function of time

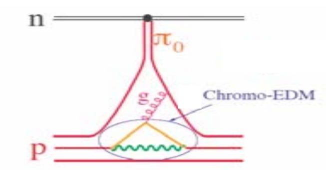


The deuteron is a winner

- High intensity, polarized deuteron beams with high polarization are currently available

- Interact with a very strong E-field

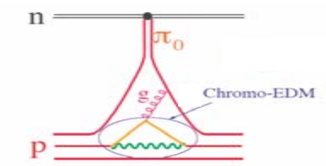
- deuteron polarimeters are available, with high analyzing power for ~1.5 GeV/c d-momentum



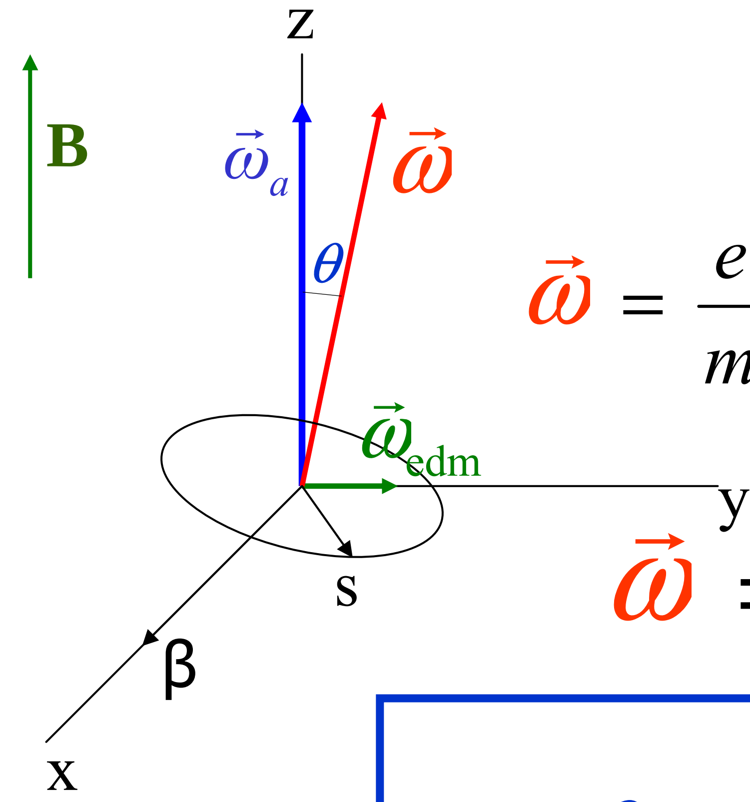
Electric Dipole Moments in Storage Rings

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

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



Indirect Muon EDM limit from the g-2 Experiment

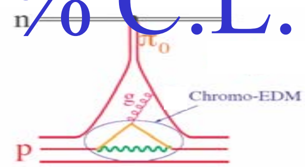


$$\vec{\omega} = \frac{e}{m}\left\{a\vec{B} + \frac{\eta}{2c}\left(\vec{u}\times\vec{B}\right)\right\}$$

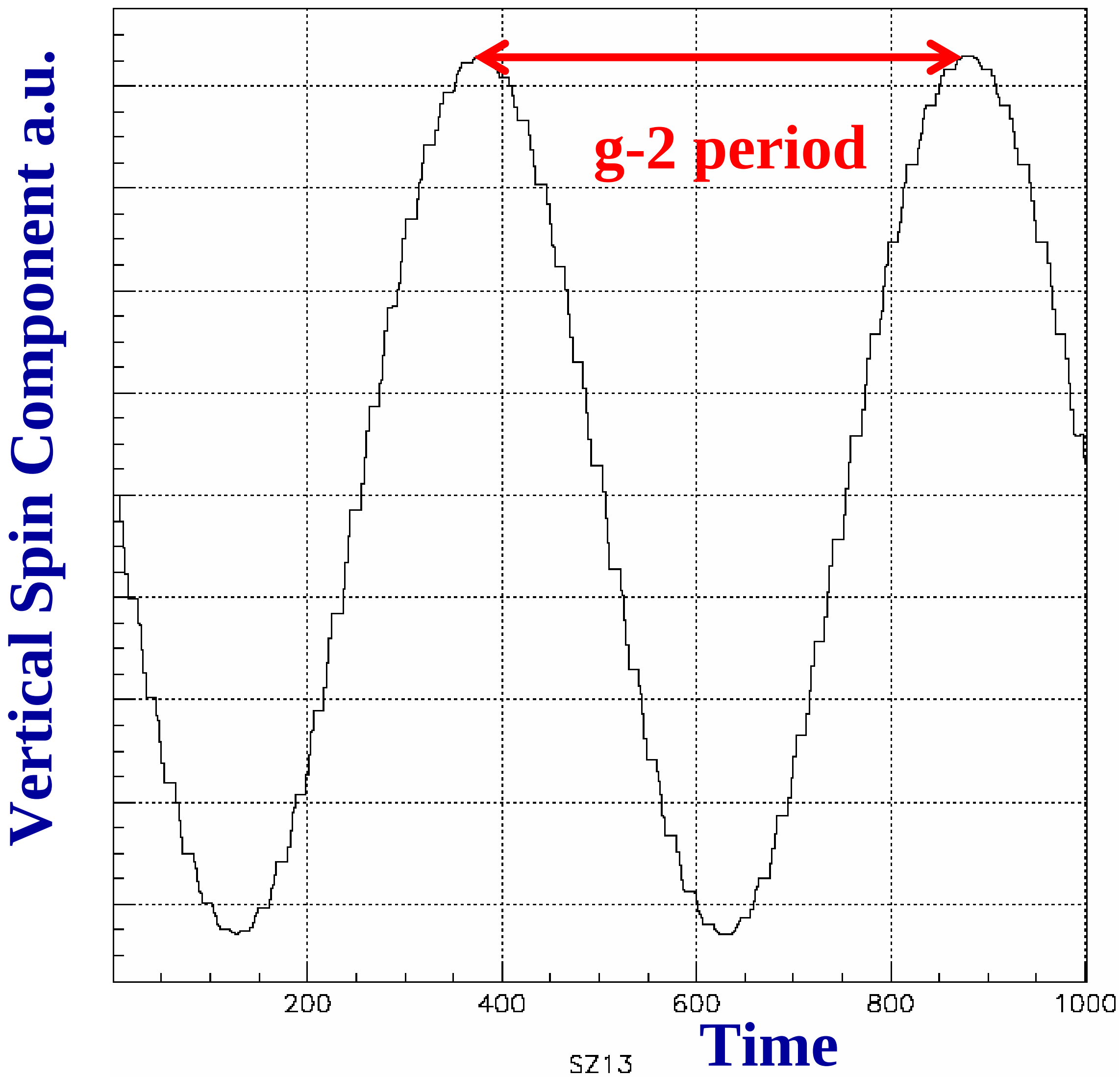
$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_{\mathrm{edm}}$$

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

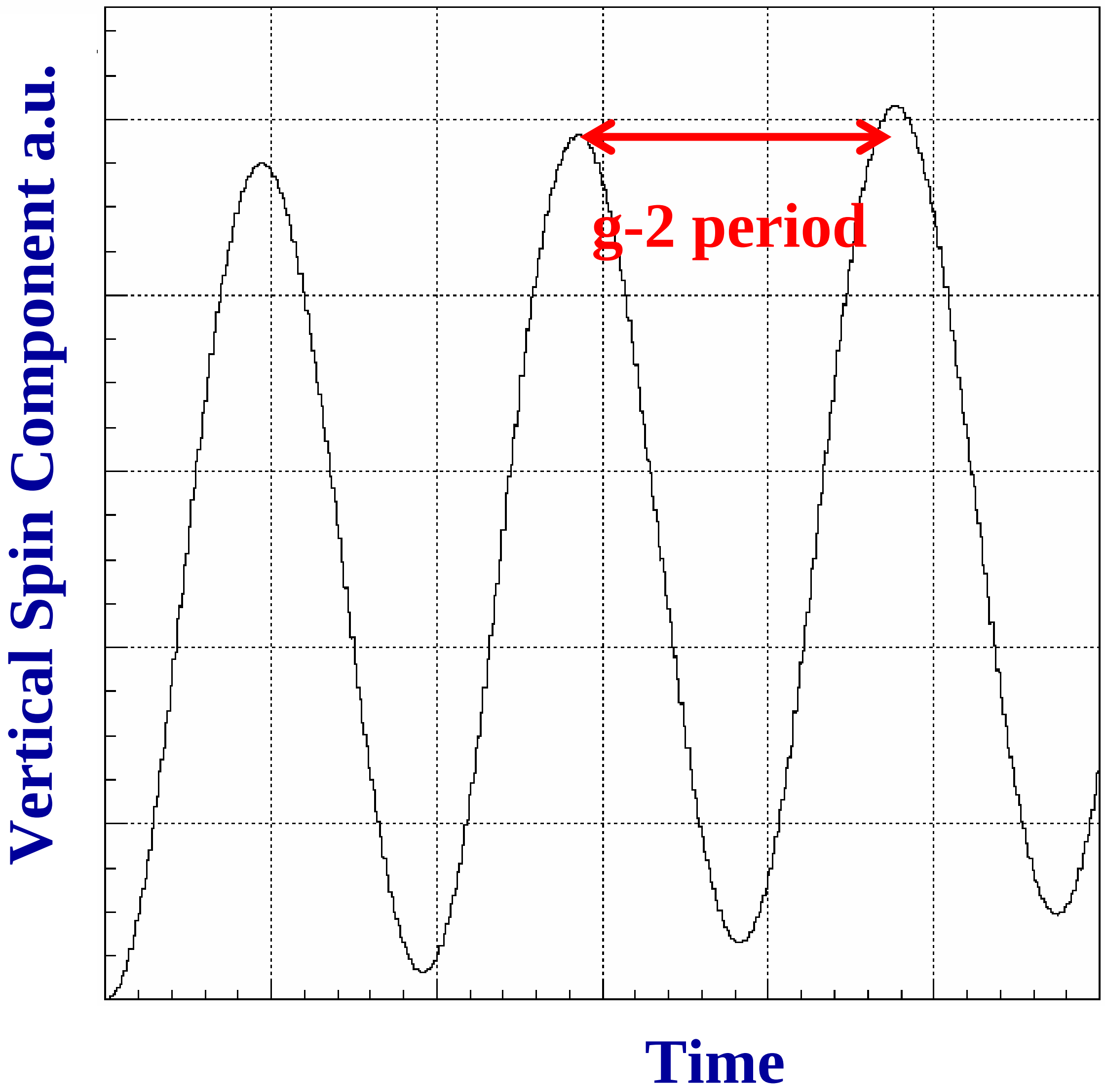
Ron McNabb's Thesis 2003: $< 2.7\times 10^{-19}\,\mathrm{e}\cdot\mathrm{cm}$ 95% C.L.



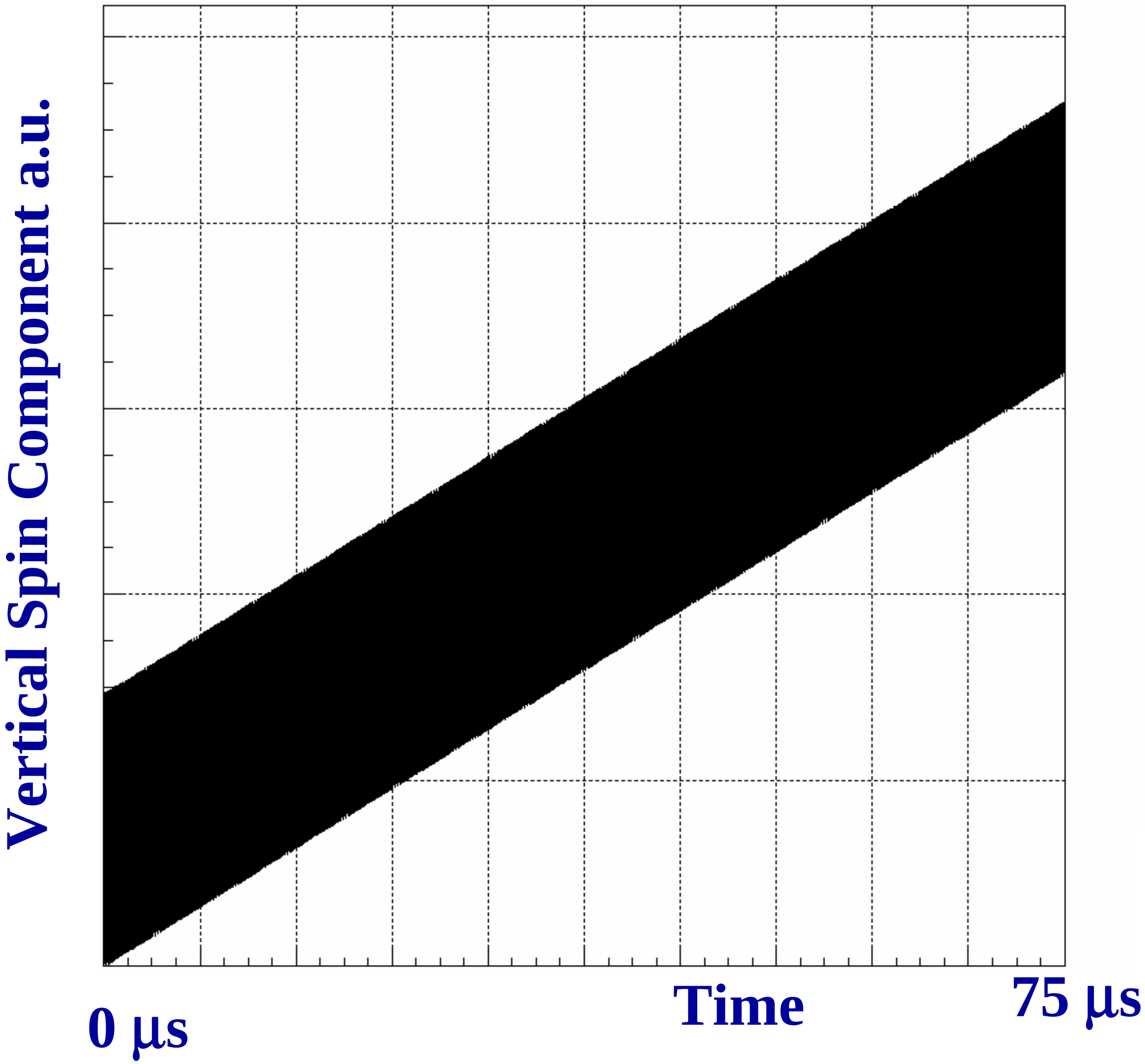
Vertical Spin Component without Velocity Modulation



Vertical Spin Component <u>with</u> Velocity Modulation at ω_a

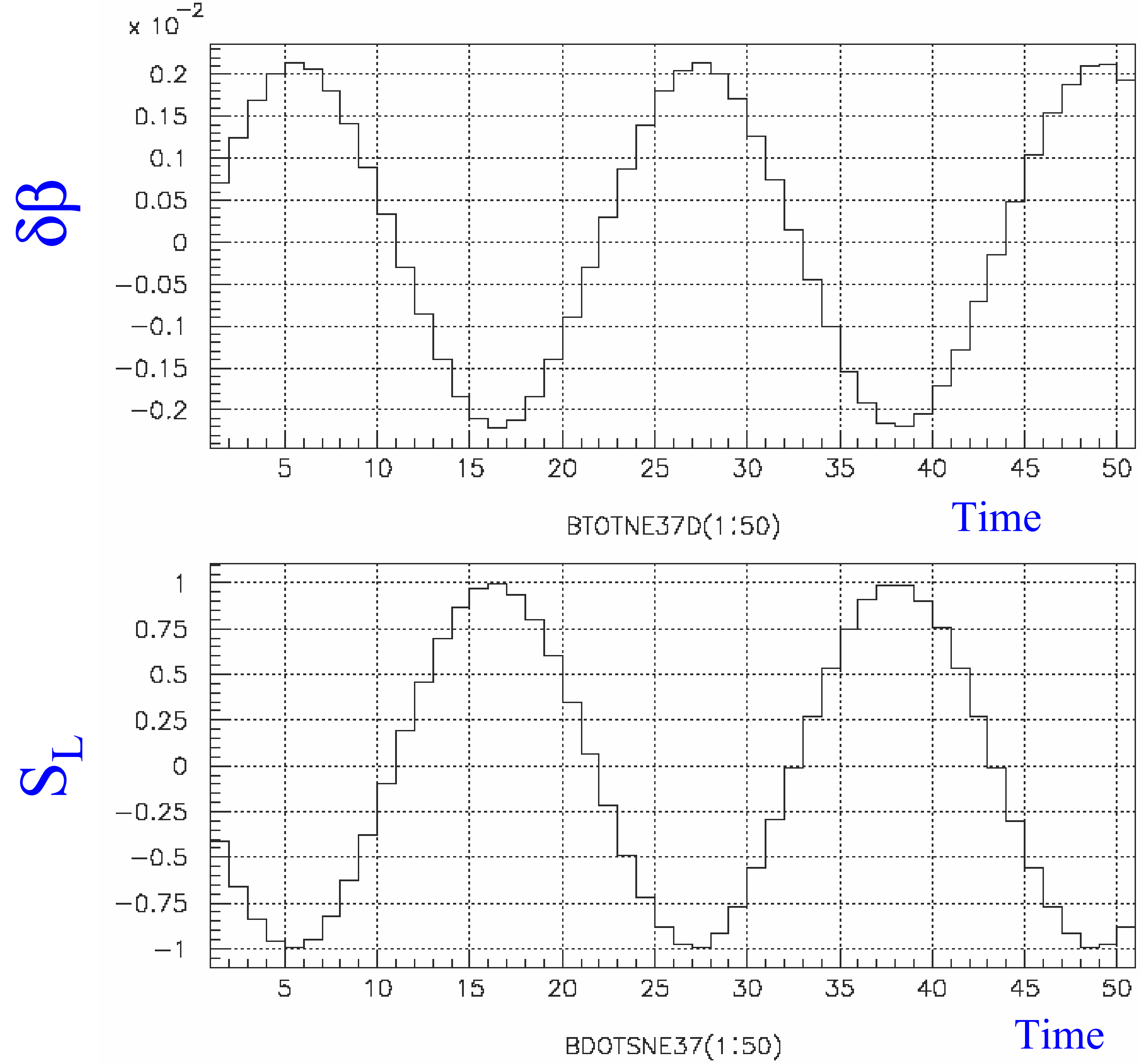


Vertical Spin Component <u>with</u> Velocity Modulation (longer Time)



Velocity (top) and g-2 oscillations

Yuri Orlov's idea

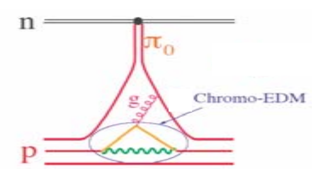


Particle velocity oscillations

Particle S_L oscillations

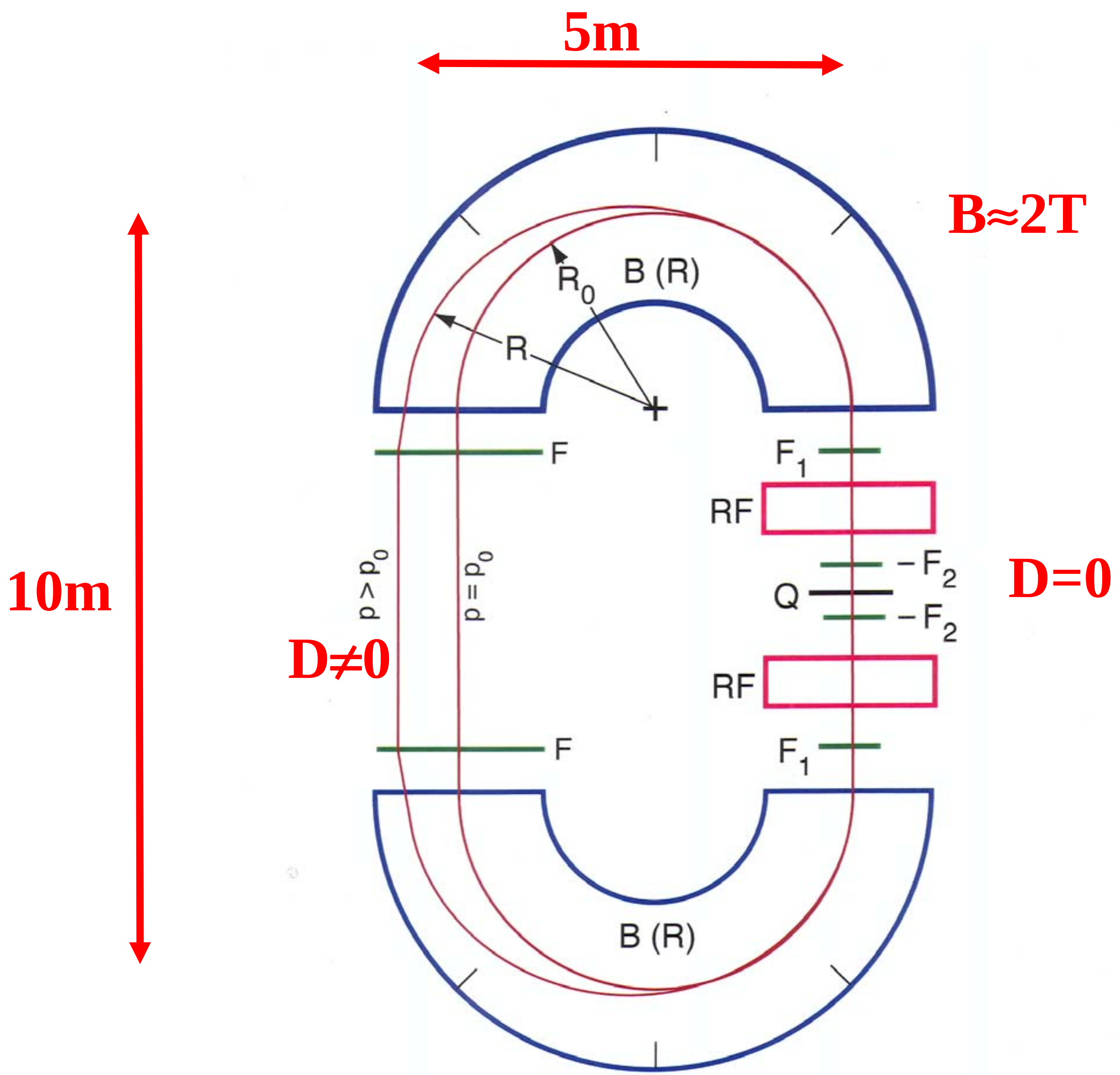
(i.e. g-2 oscillations)

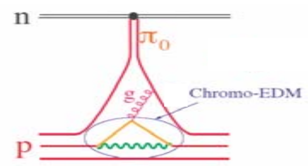
The synchrotron oscillation phase (top) compared to g-2 phase (bottom). ~5us total horizontal scale



The Orlov ring

$P_0 \approx 1.5$GeV/c

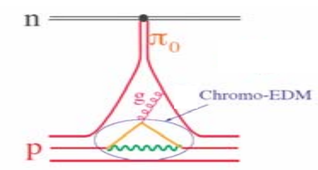




Deuteron Coherence Time

- Multipoles of B-fields
- Vertical (Pitch) and Horizontal Oscillations
- Finite Momentum Acceptance ΔP/P

I.B. Vasserman *et al.*, Phys. Lett. **B198**, 302 (1987); A.P. Lysenko, A.A. Polunin, and Yu.M. Shatunov, Particle Accelerators **18**, 215 (1986).



Deuteron Statistical Error:

$$\sigma_d \approx \frac{16\hbar}{\delta\beta_0 c \langle B \rangle AP\sqrt{N_c f \tau_p T_{Tot}}}$$

τ_p : 1000s **Polarization Lifetime (Coherence Time)**

A : 0.4 **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**

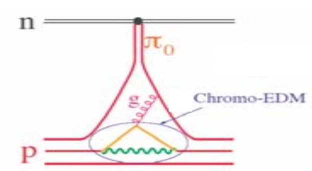
T_{Tot}: 5000h/yr. **Total running time per year**

f : 0.016 **Useful event rate fraction**

$\delta\beta_0$: 0.01-0.03 **Velocity modulation amplitude**

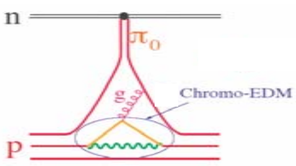
$<B>$: 1.2 T **The average magnetic field around the ring**

$$\sigma_d \approx 1-3\times10^{-29}\,\mathrm{e\cdot cm\,/\,year}$$



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 10-20MV
  Mei Bai (BNL), M. Blaskiewicz(BNL), Ilan Ben-Zvi (BNL), A. Facco (Padua), A. Luccio (BNL), Y.Orlov (Cornell, BNL), V. Shemelin (Cornell),…

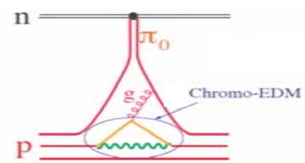
Triple Spoke at β=0.62

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

By Ilan Ben-Zvi

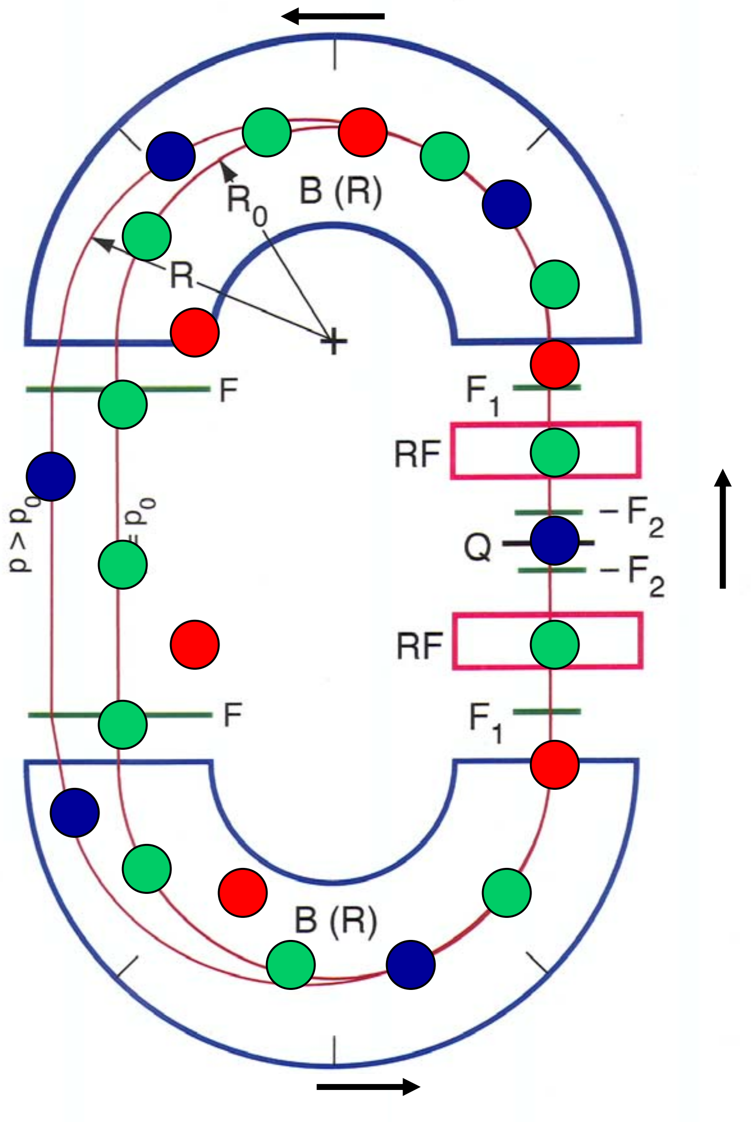
2006



Alternate bunches can have different velocities (for controlling systematic errors)

Spin direction ↓

Velocity direction ↓



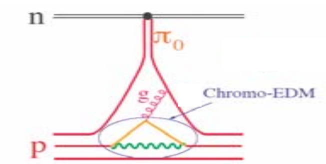
● Deuteron bunch

EDM effect:

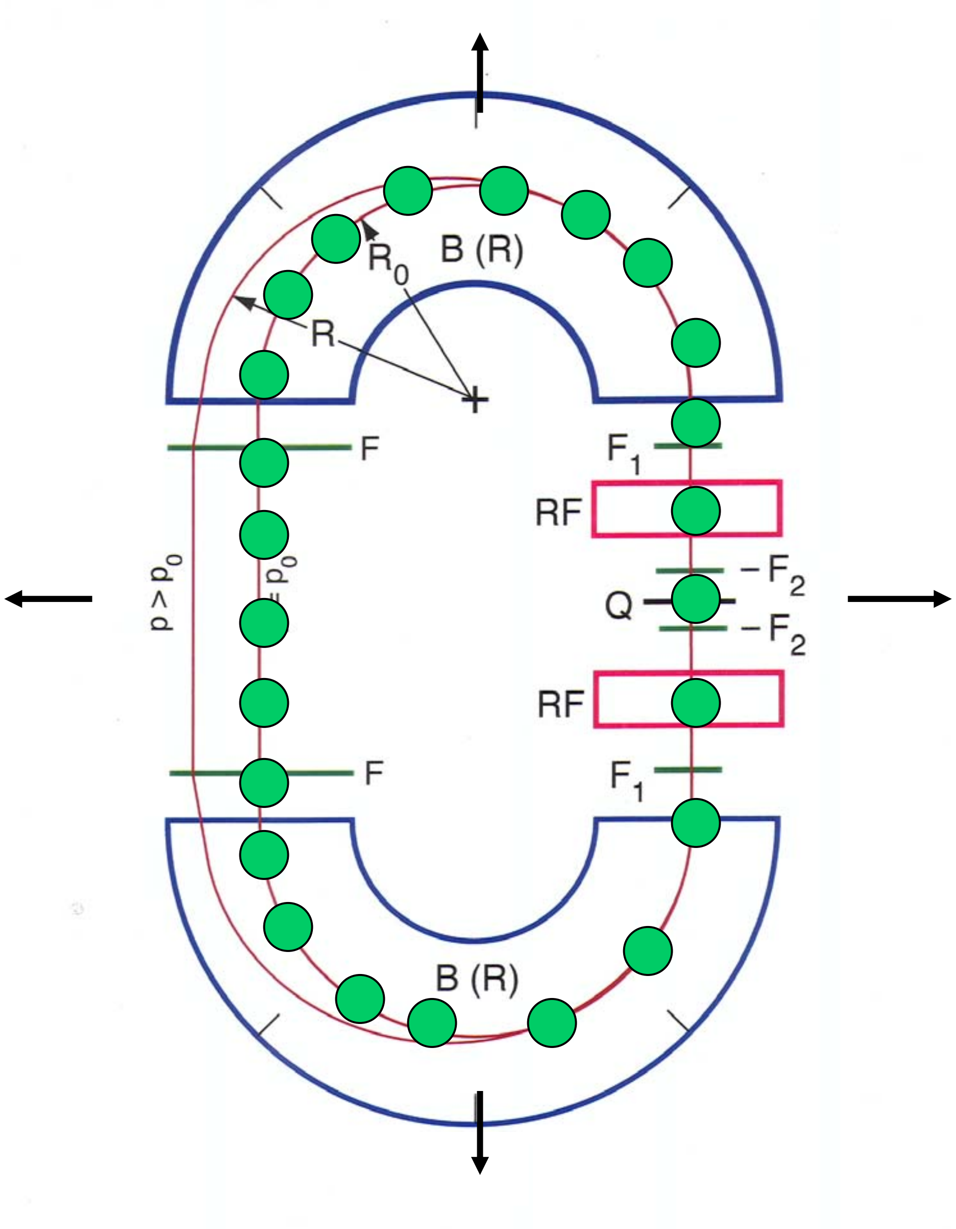
● Spin Up

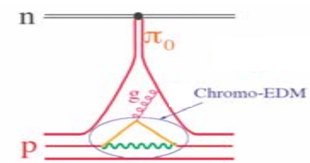
● Spin Down

● No EDM effect

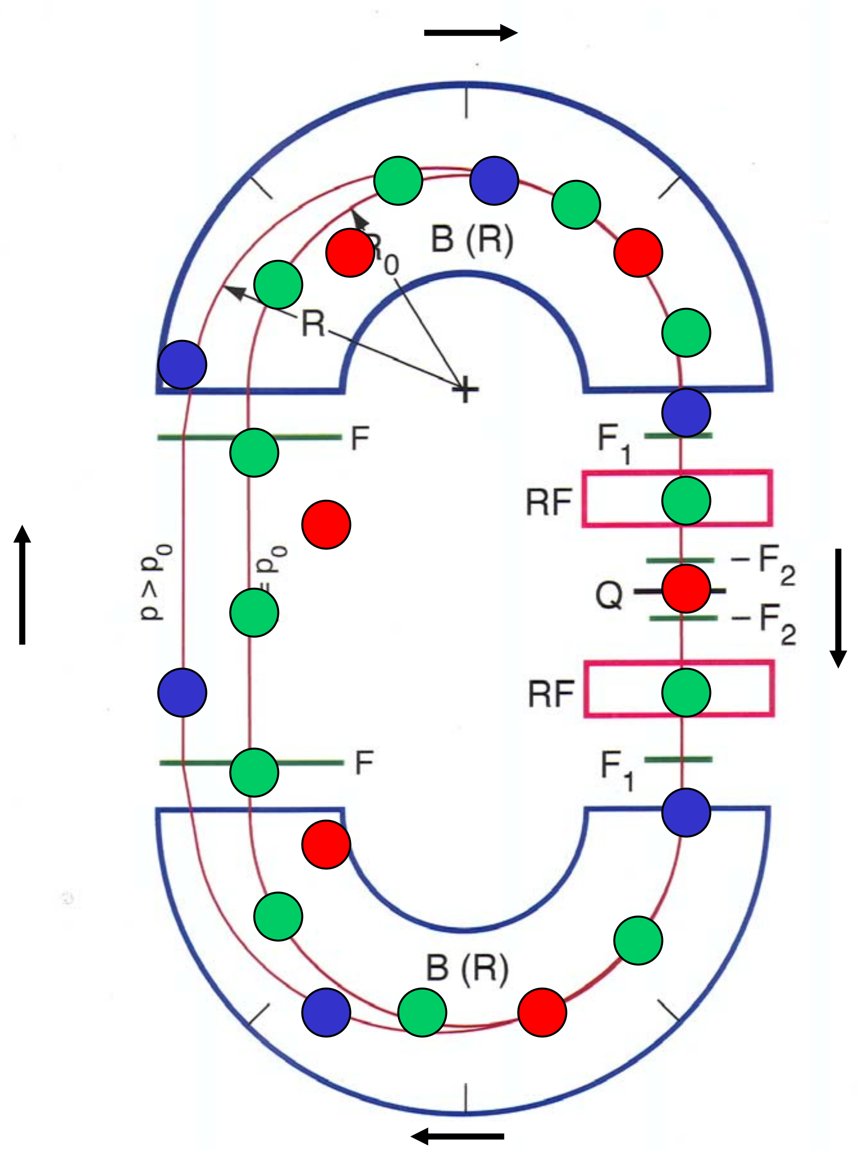


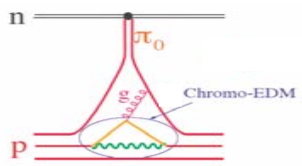
1/4 a cycle (~0.25 μs) later



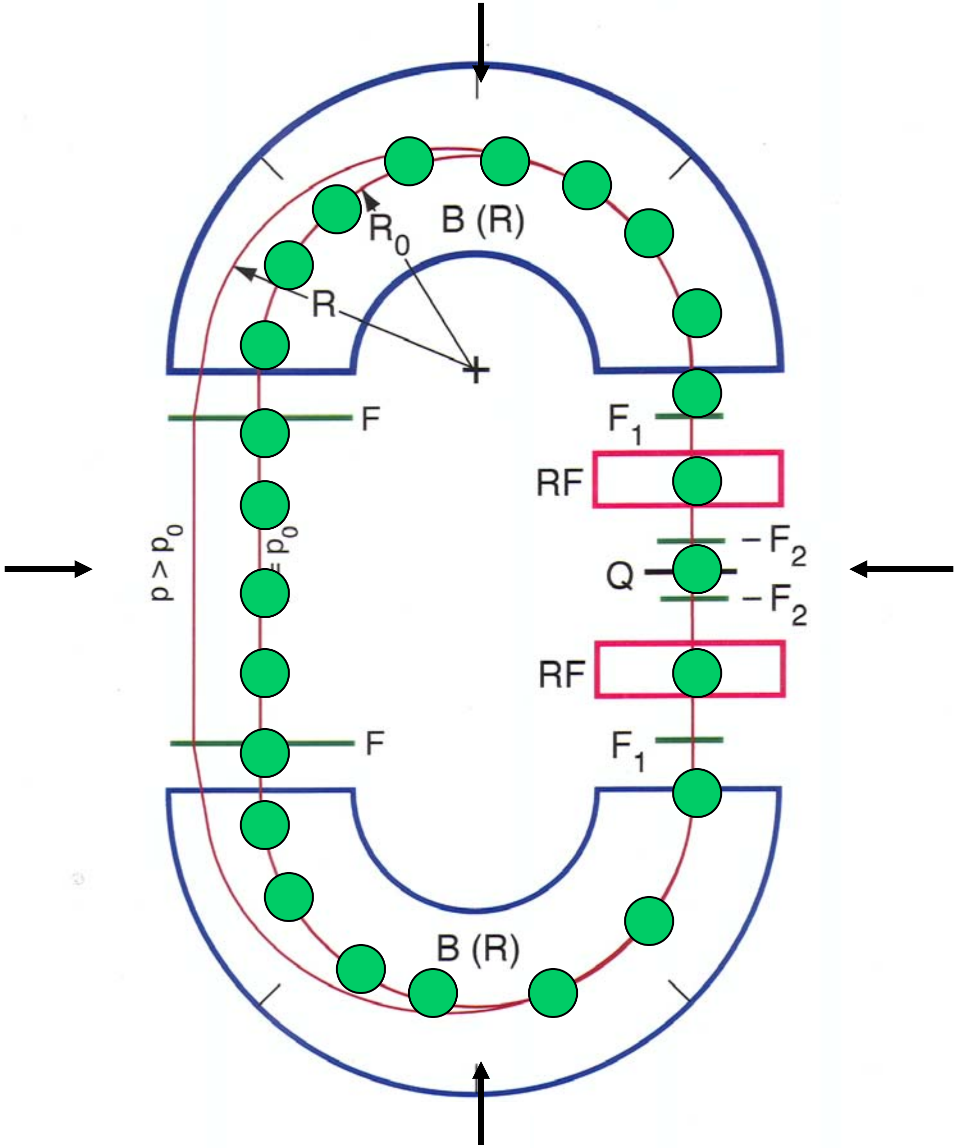


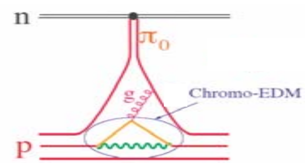
Half a cycle (~0.5 μs) later



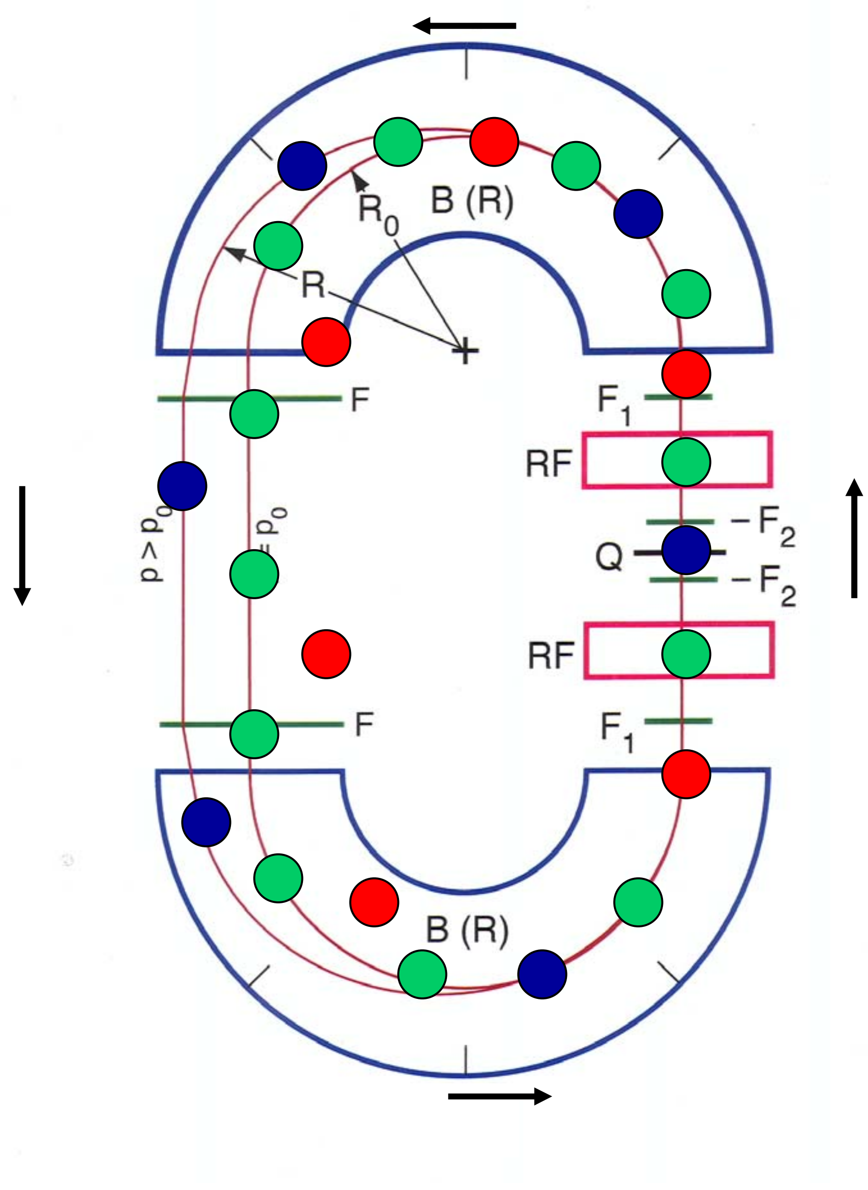


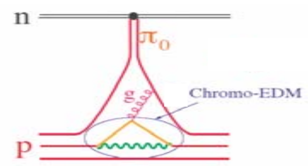
3/4 a cycle (~0.75 μs) later





One full cycle (~1 μs) later

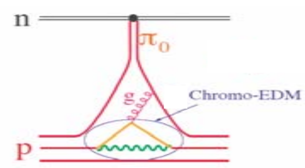




Coherence time issues

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

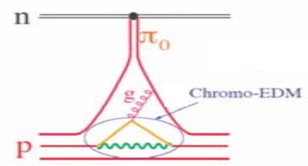
G. Onderwater (KVI), Y. Orlov (Cornell, BNL), V. Ptitsyn (BNL), Y. Shatunov (BINP)



Polarimeter issues

- Asymmetry
- Efficiency
- Integration with rest of the experiment

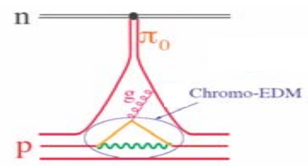
<u>E. Stephenson</u> (IUCF), G. Onderwater (KVI), A. Ferrari (Frascati).



<u>Systematics, collective effects</u>

- 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 (BNL), <u>A. Fedotov</u> (BNL), B. Morse (BNL), Y.Orlov (Cornell, BNL), YkS (BNL), <u>A. Sidorin</u> (DUBNA),…



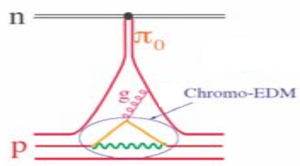
Resonance EDM systematic errors

Examples: 1) Skew quadrupole where D≠0,

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

3) …

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

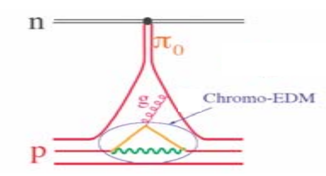


Systematics studies, tracking

- Particle and spin tracking

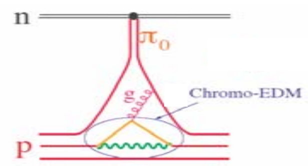
- Lattice parameter optimization

Johan Bengtsson (BNL), Alfredo Luccio (BNL), Gerco Onderwater (KVI), YkS (BNL)



Possible labs for 0.7-2GeV/c EDM Exps

Lab	D, P, ^{3}He (Polarized)	Equipment needed	Comment
BNL	Y, Y, Y	OK!	EBIS
CERN	N, N, N	Polarized Source, Spin manipulating devices	LHC +
COSY	Y, Y, N	Spin manipulating devices	Intensity, commitment to GSI, Funding
Frascati	N, N, N	IUCF's front end, Spin manipulating devices	New direction, Intensity
KVI	Y, Y, ?	Accumulator, Spin manipulating Dev.	Funding?



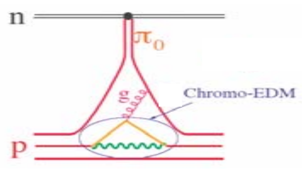
Deuteron EDM at BNL

- Great physics opportunity; it will not be done at LHC

- The Infrastructure is there (polarized source, spin manipulating devices, …).

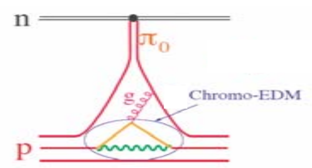
- The human factor: Hadron and spin expertise, one of the best in the world.

- 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 capabilities
- Moderate power cost for running it: ~1.5GeV/c. One pulse every ≈1000s.

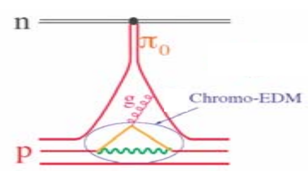


CERN?

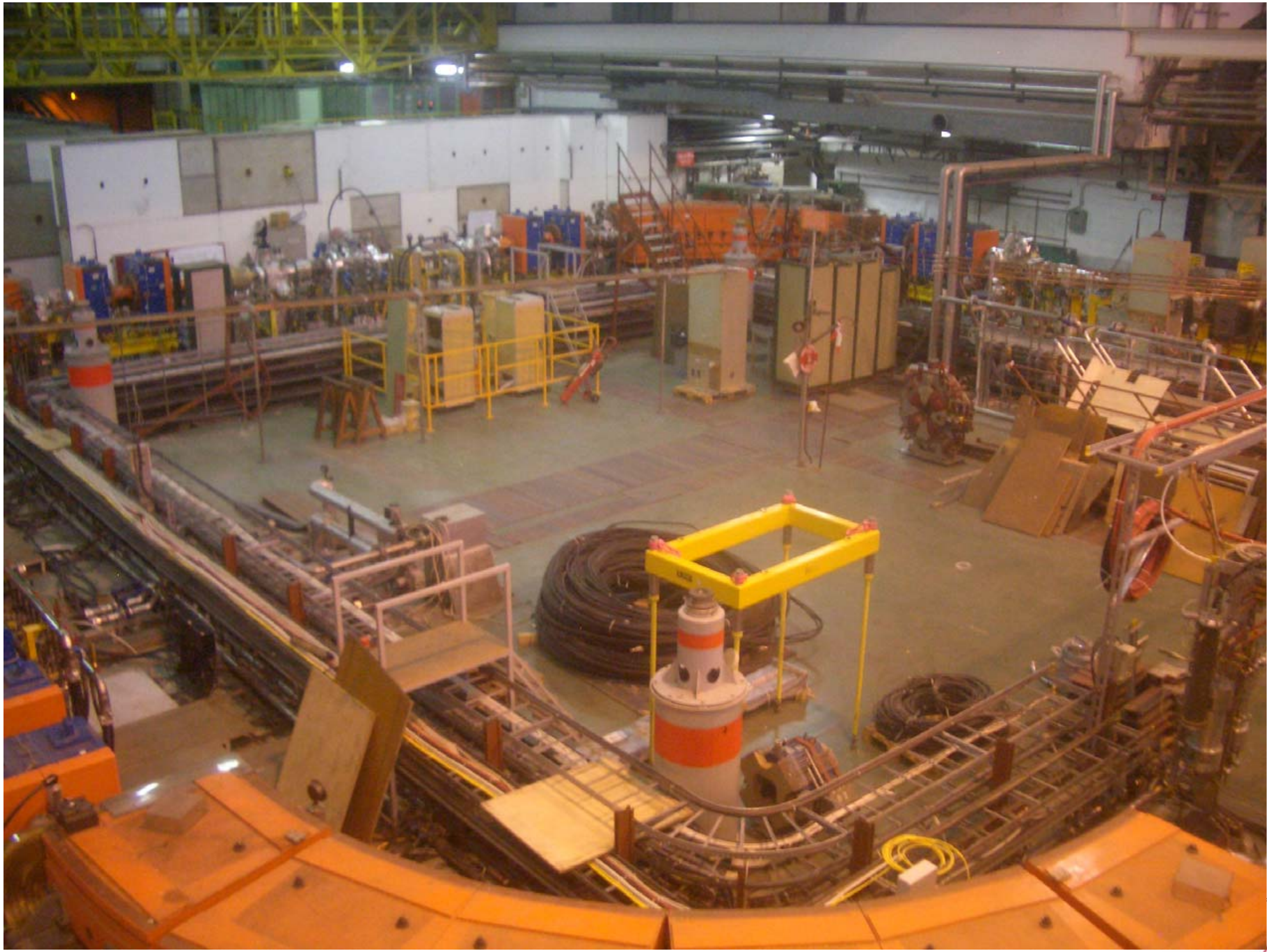
- The Infrastructure for ions is there (no polarized source or spin manipulating devices). LEIR is going to be sitting idle for >10 months per year!

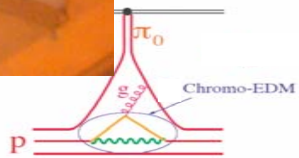
- The human factor: Hadron expertise one of the best in the world

- Enthusiastic endorsement (John Ellis, Jos Engelen,…)



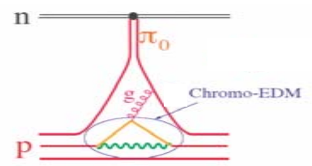
LEIR as a possible location for the Orlov ring





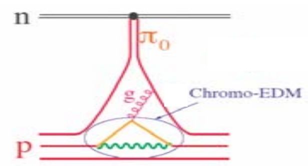
EDM Collaboration Meetings

- January 2006: We decided to send the LOI to BNL to ask for support to finish the proposal.
- June 2006: finalize the ring parameters for the LOI.



Deuteron EDM Timeline

- June 2006 Letter of Intent
- We need to develop the final ring lattice and tolerances on parameters
- Goal for a proposal within a year from June 2006



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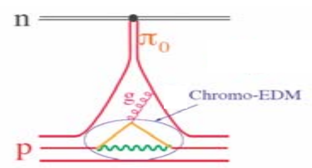
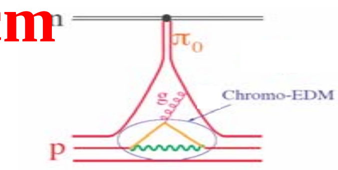
2010		
2011	← UCN-LANL/SNS	10^{-28}e·cm



Neutron/deuteron EDM Timeline

	Exp begin data taking	Exp goal
2006		
2007		
2008 ←	UCN-PSI	10^{-27}e·cm
2009 ←	UCN-ILL	2×10^{-28}e·cm/yr
2010		
2011 ←	UCN-LANL/SNS	10^{-28}e·cm
2012 ←	Deuteron in Storage Ring	10^{-29}e·cm



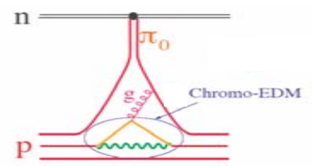
Overview

1) First rate physics

2) It will not be done at LHC

3) Compatible with the mission and present infrastructure and expertise of BNL

4) Moderate cost to build the 5m by 10m orlov ring; and a moderate power cost to run it (~1.5 GeV/c deuterons)



Summary

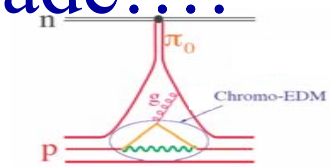
- Neutron, and deuteron EDM experiments are sensitive probes of physics beyond the SM and of CP-violation in particular.

Unique sensitivity to

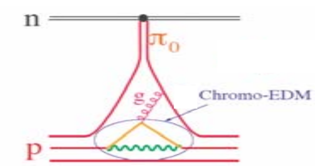
- θ_{QCD}
- Quark EDM
- Quark-color EDM

with the deuteron at 10^{-29}e·cm holding the best EDM sensitivity over *present* or *planned* experiments.

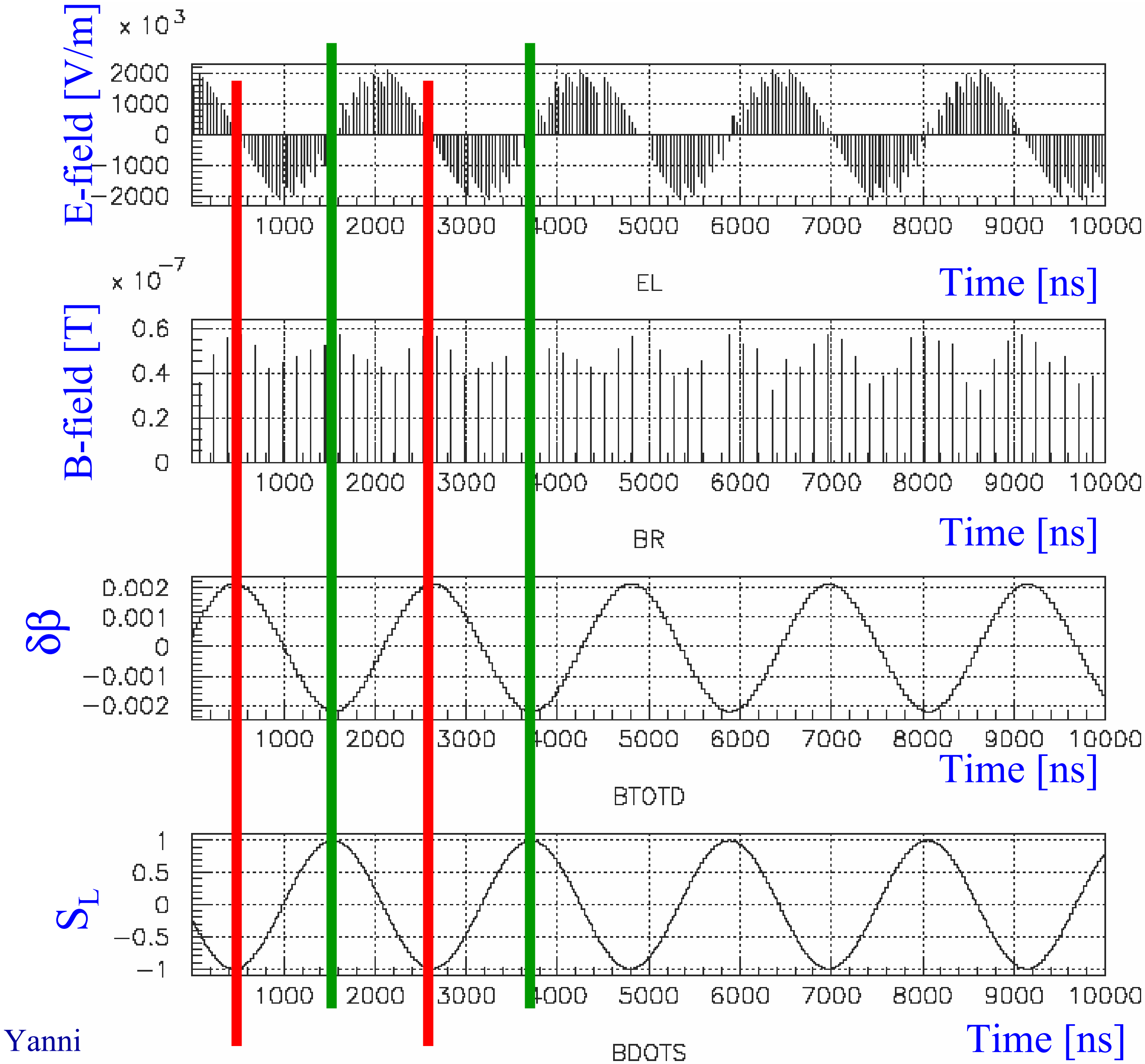
Together n (p) and deuteron EDM exp: pinpoint EDM source, promising a very exciting decade…!



Extra Slides



RF-fields and oscillation phases

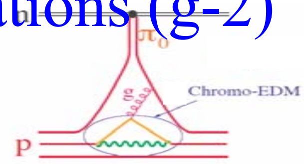


E-field in RF-cavity

B_R-field in RF-cavity

Particle velocity oscillations

Particle S_L oscillations (g-2)



Yanni

Effect of the vertical offset, YkS note #85

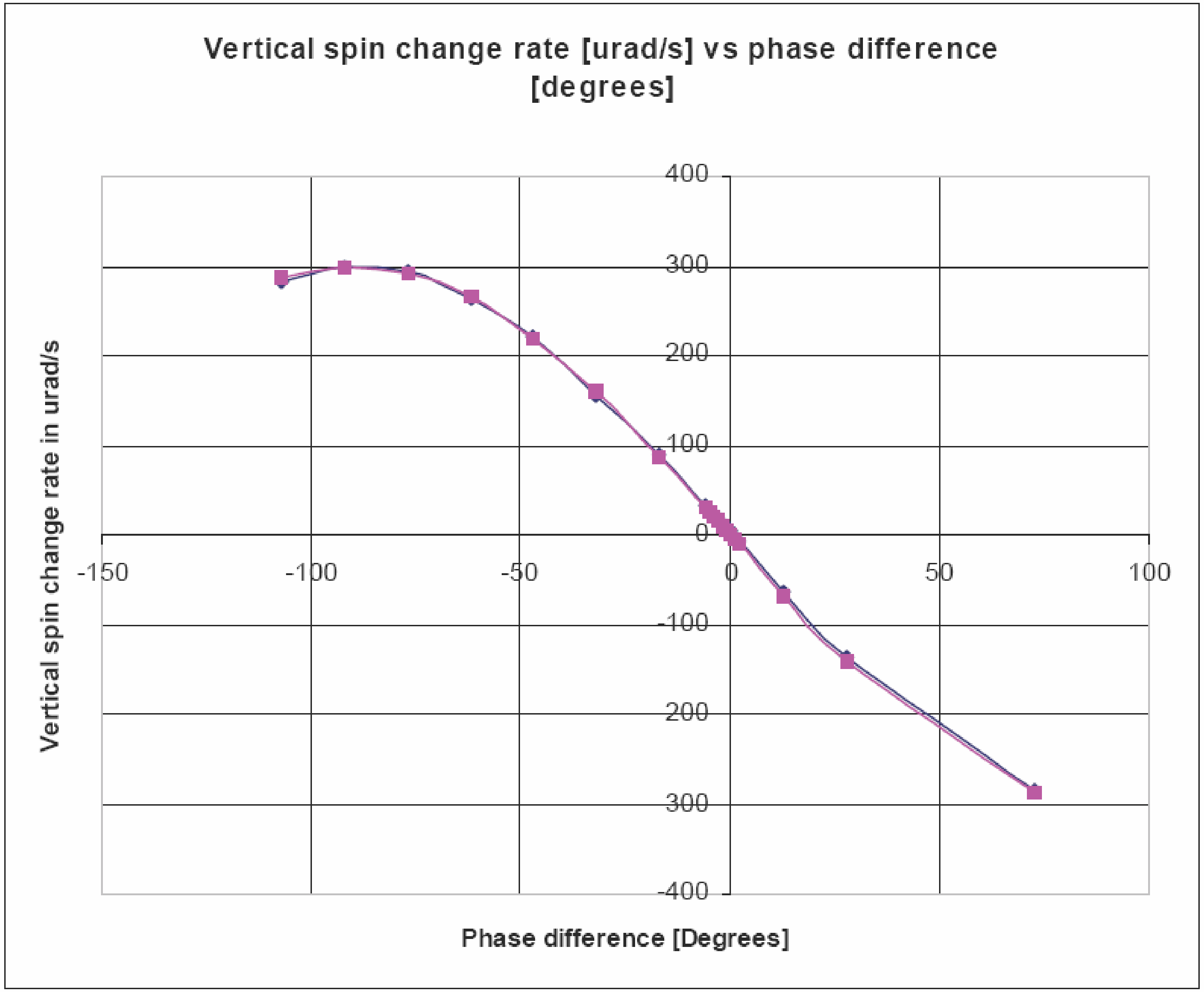
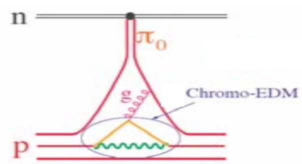


Figure 1. The vertical spin precession rate in μrad/s versus the phase difference (ϕ) between the synchrotron oscillations and the g-2 precession in degrees (modulo 180°) for an RF-cavity offset of 10μm is shown. An overlay of the function 300 μrad/s * sin(ϕ) is also shown.



Effect of the angular offset, YkS note #92

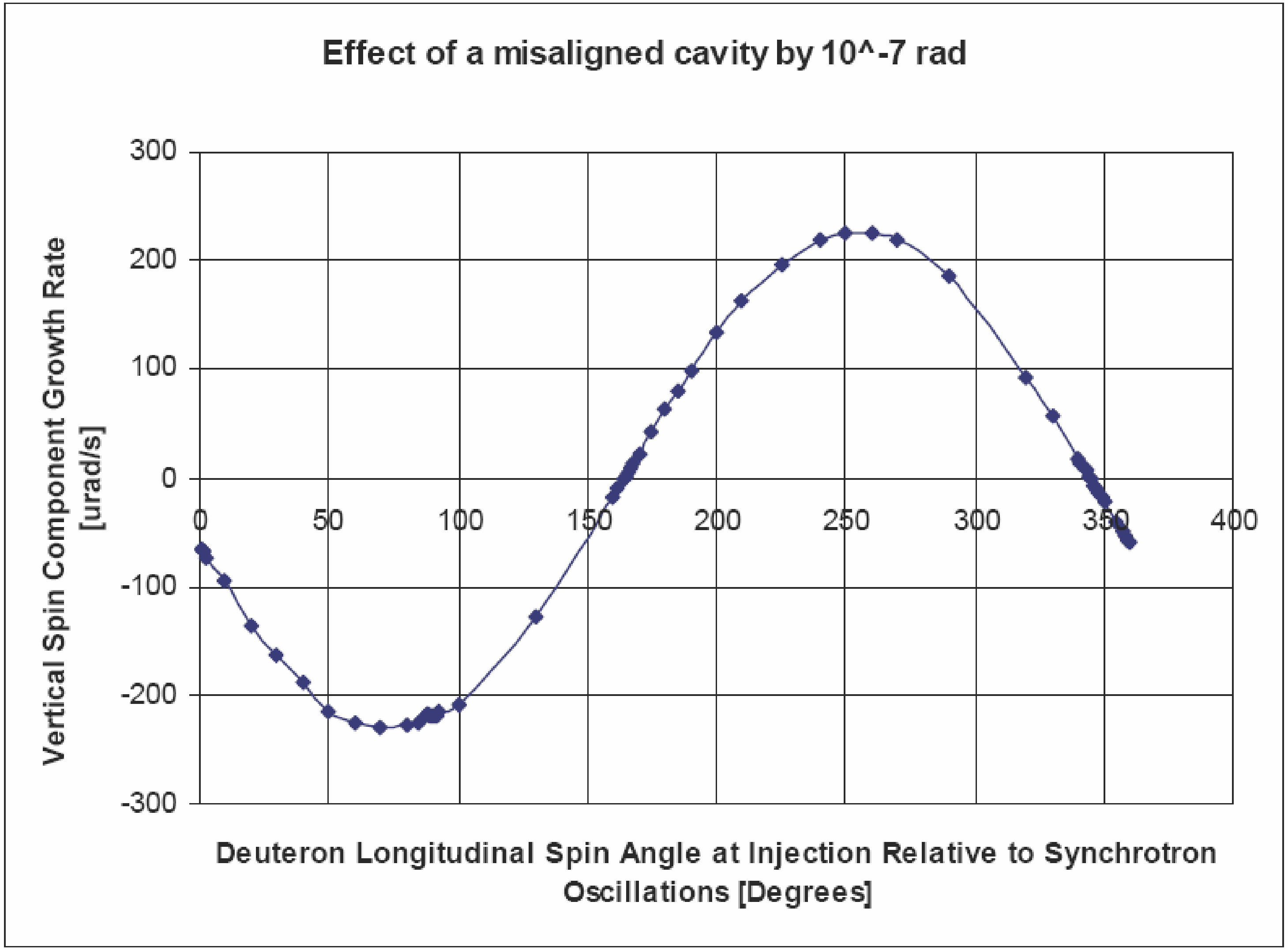
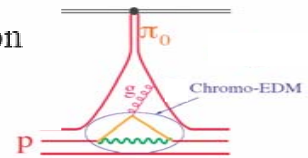
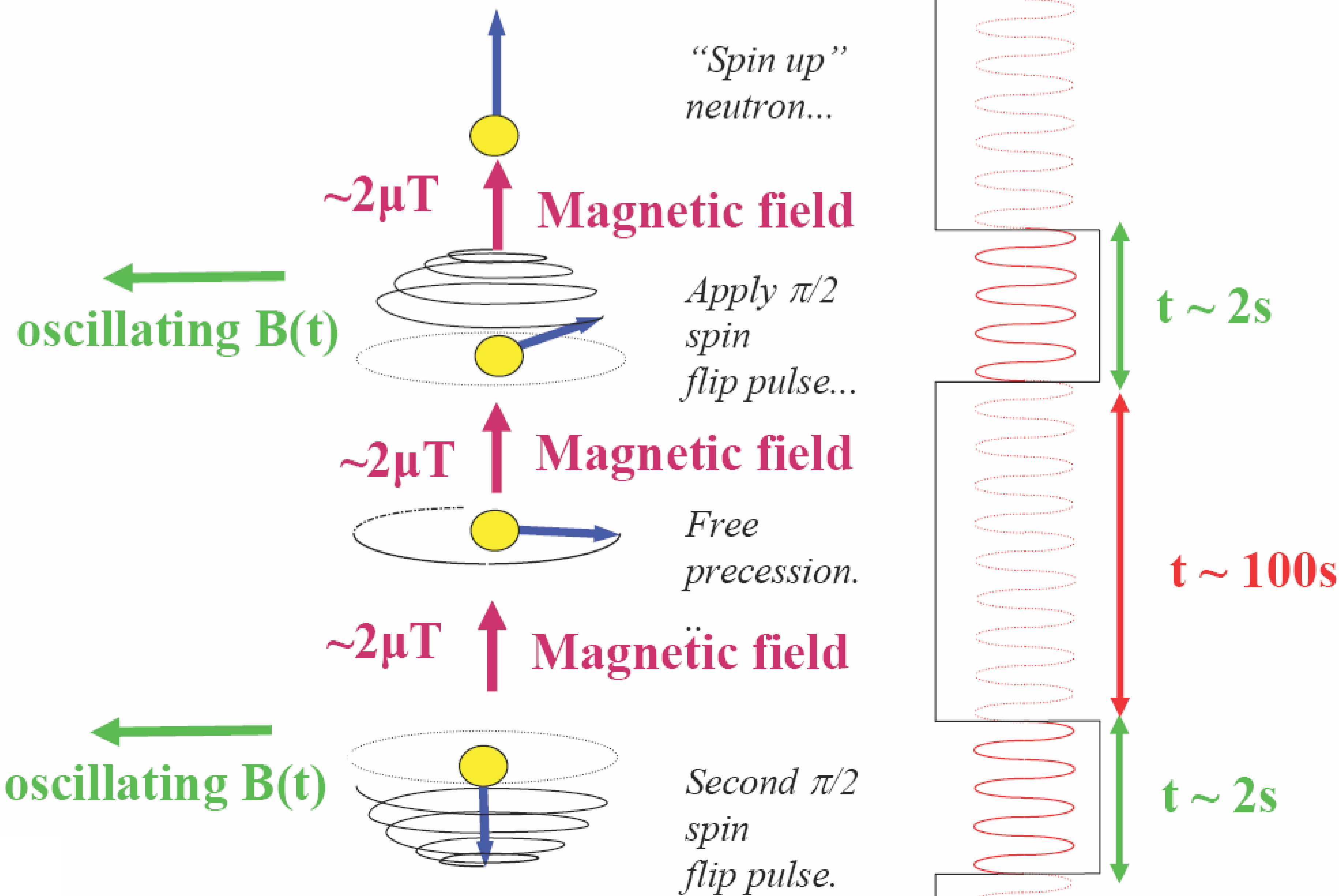


Figure 1. The effect of a misaligned cavity depends on the relative phase between the synchrotron and g-2 oscillations. This dependence is very different from the EDM effect dependence.



Ramsey's method

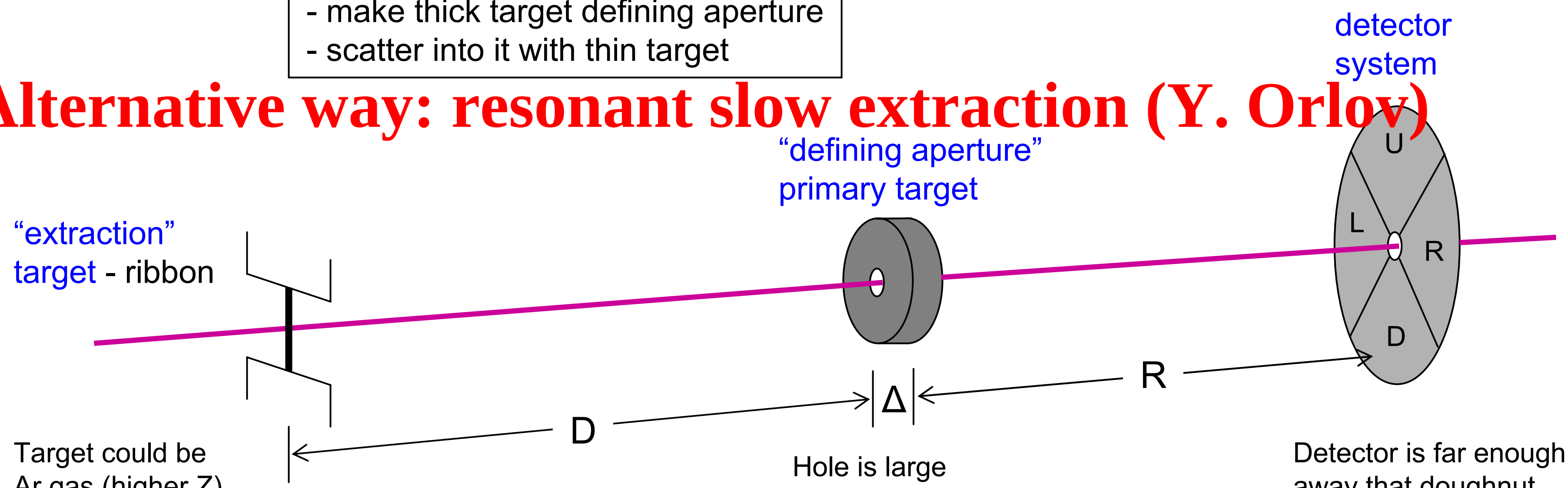


Nuclear Scattering as Deuteron EDM polarimeter

Ed Stephenson's

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

Alternative way: resonant slow extraction (Y. Orlov)



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.

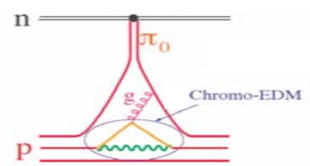
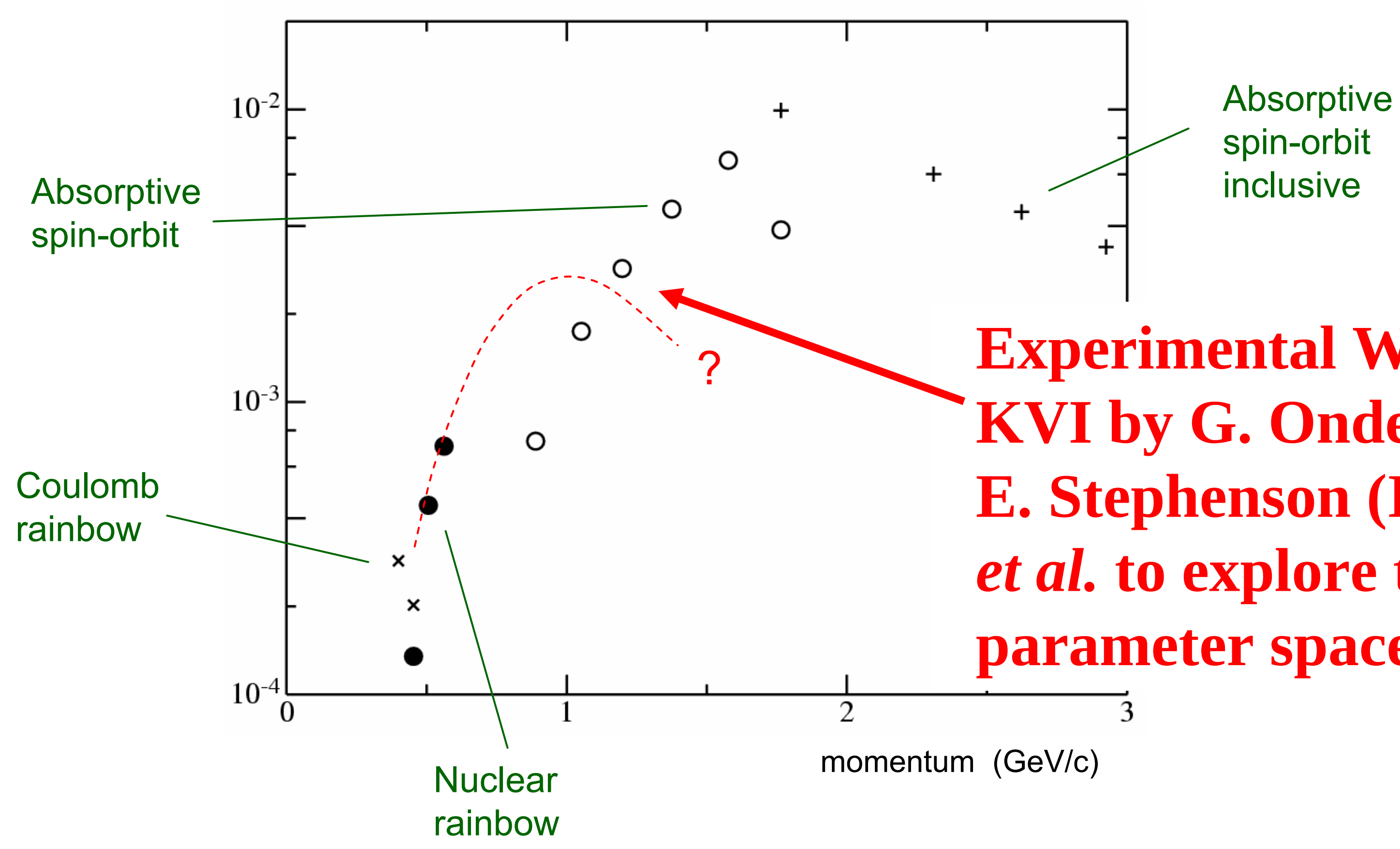
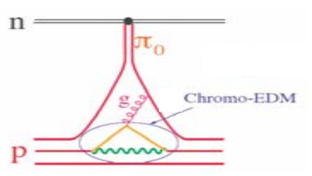


Figure of merit = effiency $\times \langle iT_{11} \rangle^2$



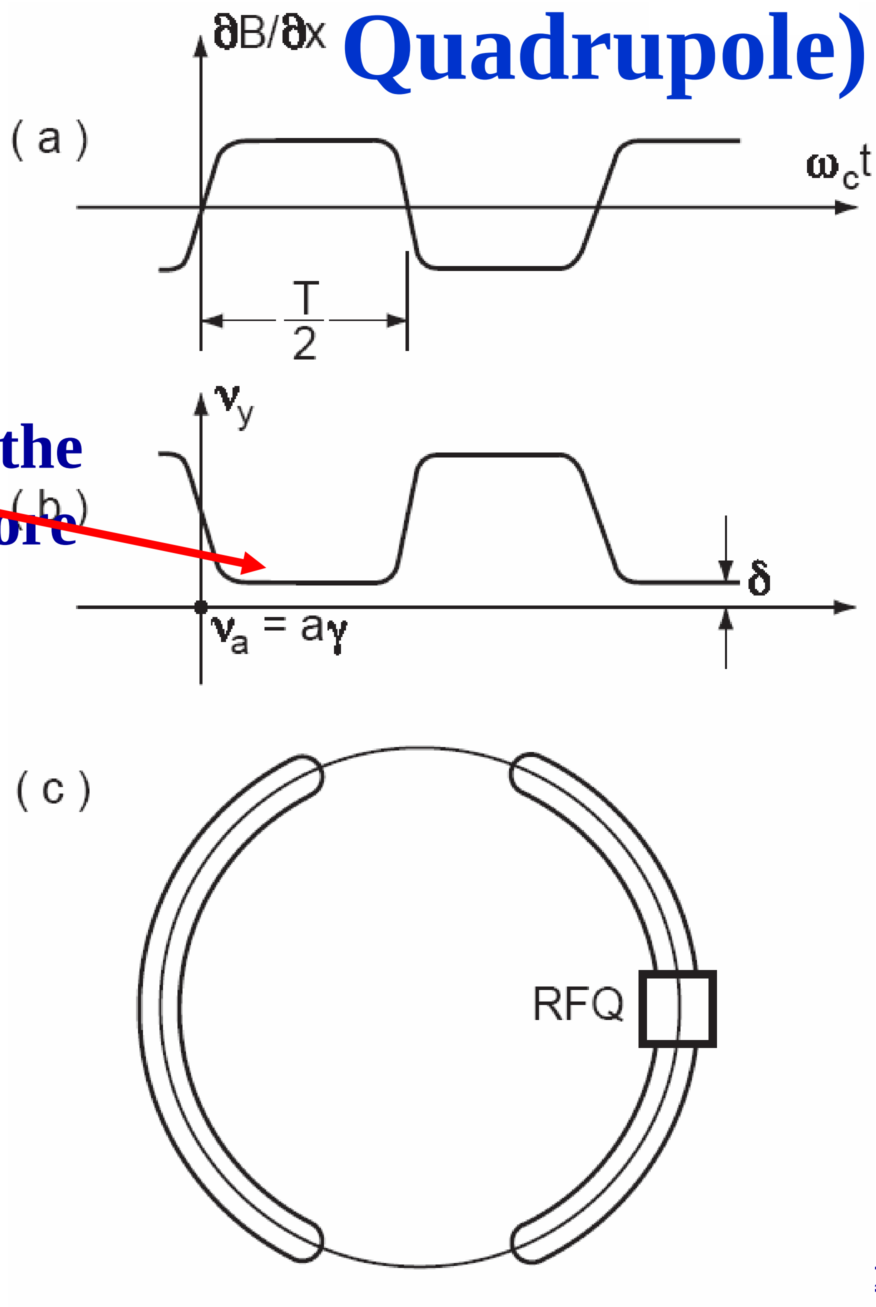
Experimental Work at KVI by G. Onderwater, E. Stephenson (IUCF), *et al.* to explore this parameter space.

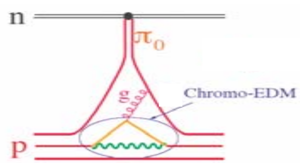
Extrapolation of nuclear rainbow effect is not known.



Two half beam technique (RF-Quadrupole)

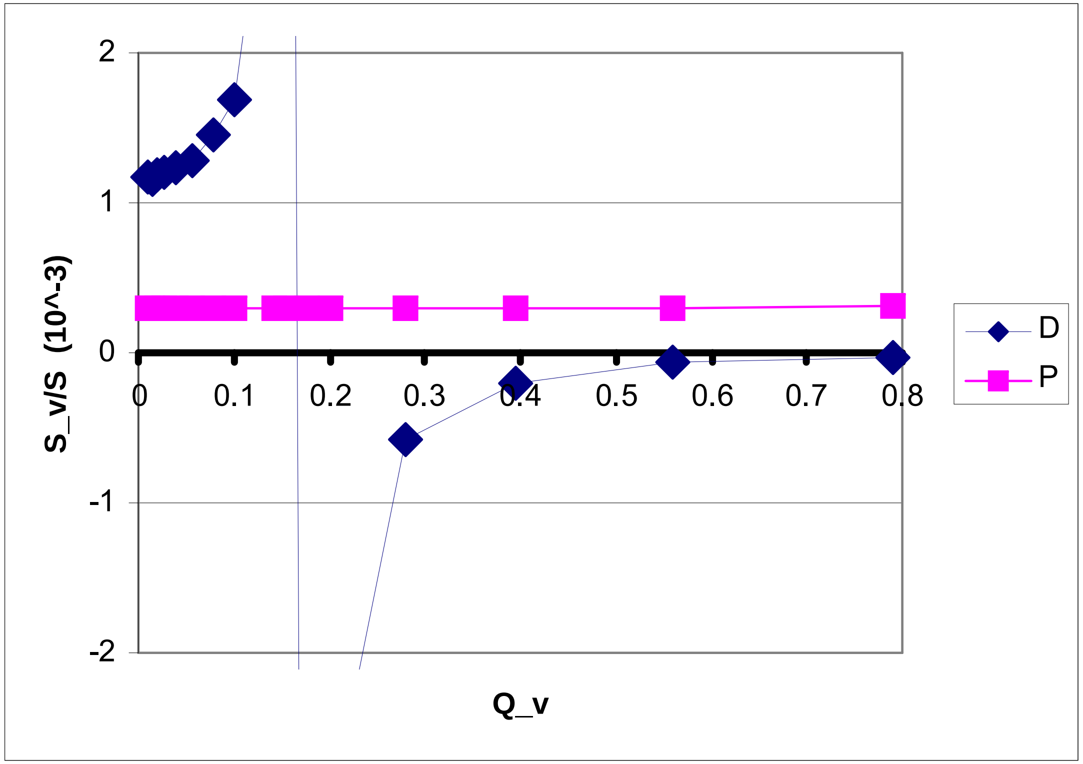
This tune makes the Deuteron spin more Sensitive to background

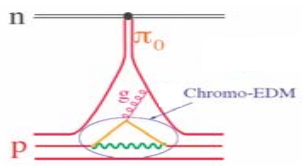




Backgrounds are vertical tune dependent; EDM signal is not!

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



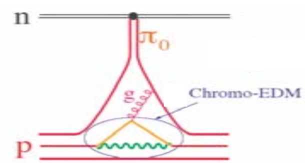


neutron EDM exps in preparation

- UCN at PSI: Ramsey's method of separated oscillatory fields. First goal 1×10^{-27}e·cm, begin data taking ~2008.

- UCN at ILL (Sussex, RAL,…): Ramsey's method of separated oscillatory fields. Goal 2×10^{-28}e·cm/year, begin data taking 2009.

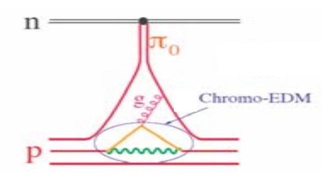
- Ultra-Cold Neutrons (UCN), at SNS (LANL,…): Polarized ^{3}He stored together in a superfluid ^{4}He. Goal 1×10^{-28} e·cm, begin data taking ~2011.



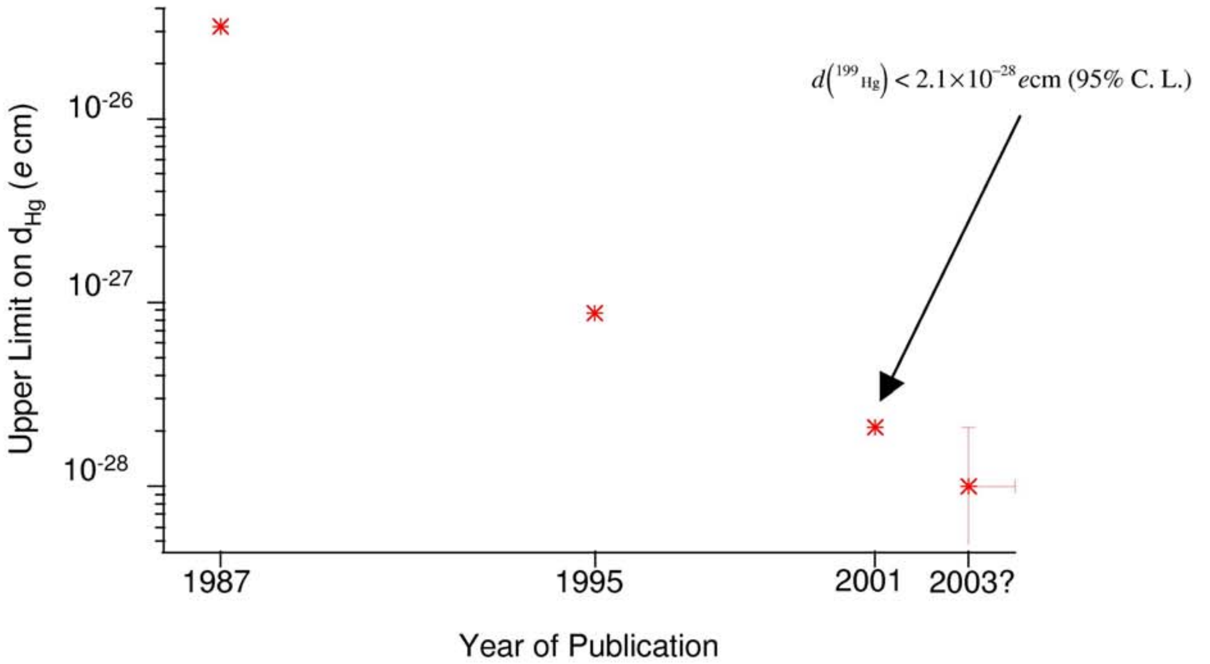
Current Atomic EDM Limits

- **Paramagnetic Atoms, ^{205}Tl: electron $|d_e| < 1.6\times10^{-27}$e·cm (90%CL)**
  PRL 88, 071805 (2002)

- **Diamagnetic Atoms, ^{199}Hg Nucleus: $|d(^{199}Hg)| < 2.1\times10^{-28}$e·cm (95%CL)**
  PRL 86, 2505 (2001)



UW ^{199}Hg EDM Limit —Historical Perspective



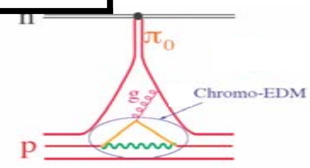
1987: S.K. Lamoreaux, J.P. Jacobs, B.R. Heckel, F.J. Raab, and E.N. Fortson, Phys. Rev. Lett. **59**, 2275 (1987).

1995: J.P. Jacobs, W.M. Klipstein, S.K. Lamoreaux, B.R. Heckel, and E.N. Fortson, Phys. Rev. A **52**, 3521 (1995)

2001: M.V. Romalis, W.C. Griffith, J.P. Jacobs, and E.N. Fortson, Phys. Rev. Lett. **86**, 2505 (2001).

EDM Status

Particle	**System**	**Limit [e·cm]**
Electron	^{205}Tl (~10^{-24} e·cm)	1.5×10^{-27}
Mercury	^{199}Hg atom	2×10^{-28}
Proton	^{199}Hg atom	5×10^{-24}
Neutron	Ultra-Cold n	3×10^{-26}



A value of θ_{QCD} =10^{-13} would create an EDM of

System	**EDM value**
Proton	$\approx -3\times10^{-29}$ e·cm
Neutron	$\approx 3\times10^{-29}$ e·cm
Deuteron	$\approx -1\times10^{-29}$ e·cm
Tl atom	$\approx 5\times10^{-31}$ e·cm
Hg atom	$\approx 1\times10^{-32}$ e·cm