Flavour in the era of LHC, WG3
CERN, 8 November 2005

The Deuteron EDM experiment at the 10^{-29}e·cm level with the resonant storage ring method

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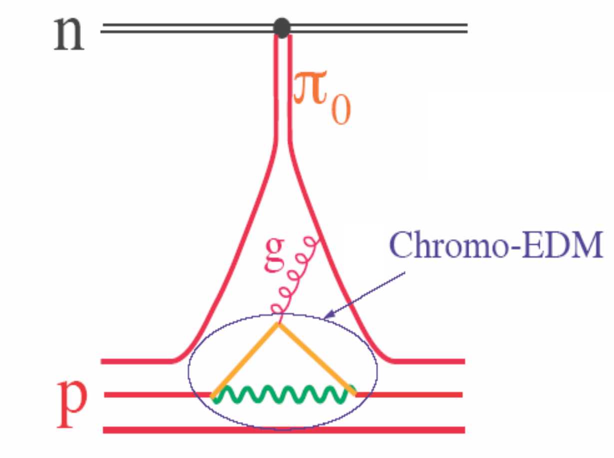
- The resonant EDM method
- Systematic errors
- Things to do



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

Experimental Principle of EDM

- Polarize (e.g. deuteron polarized source, ~100%)
- Interact in an E-field
- Analyze as a function of time (e.g. deuteron polarimeter, analyzing power up to 100%)

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

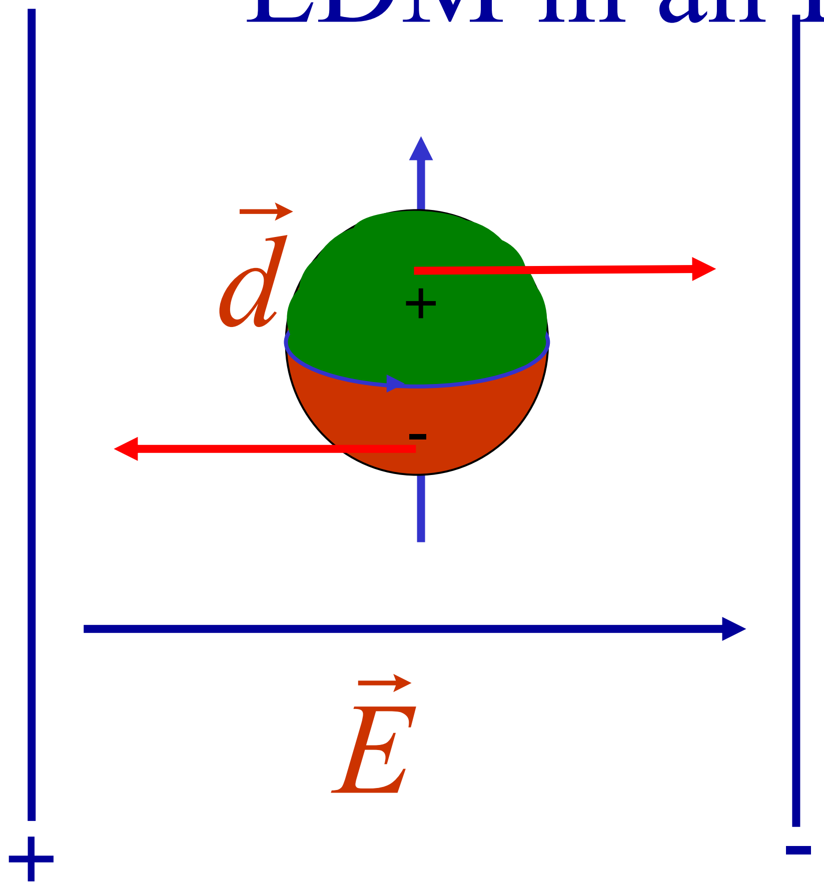
Electric Dipole Moments in Storage Rings

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

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

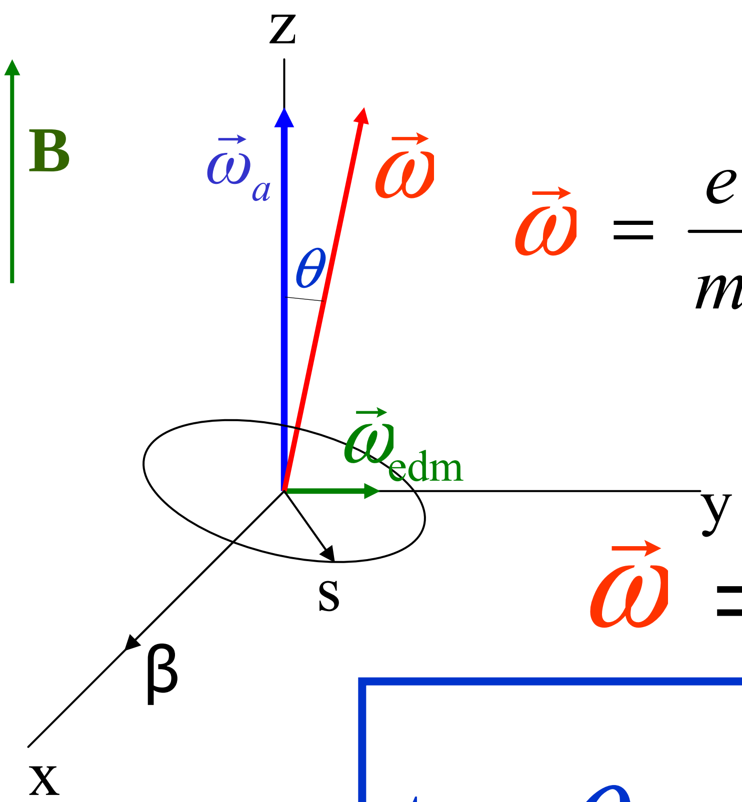
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

EDM in an Electric Field…



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

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



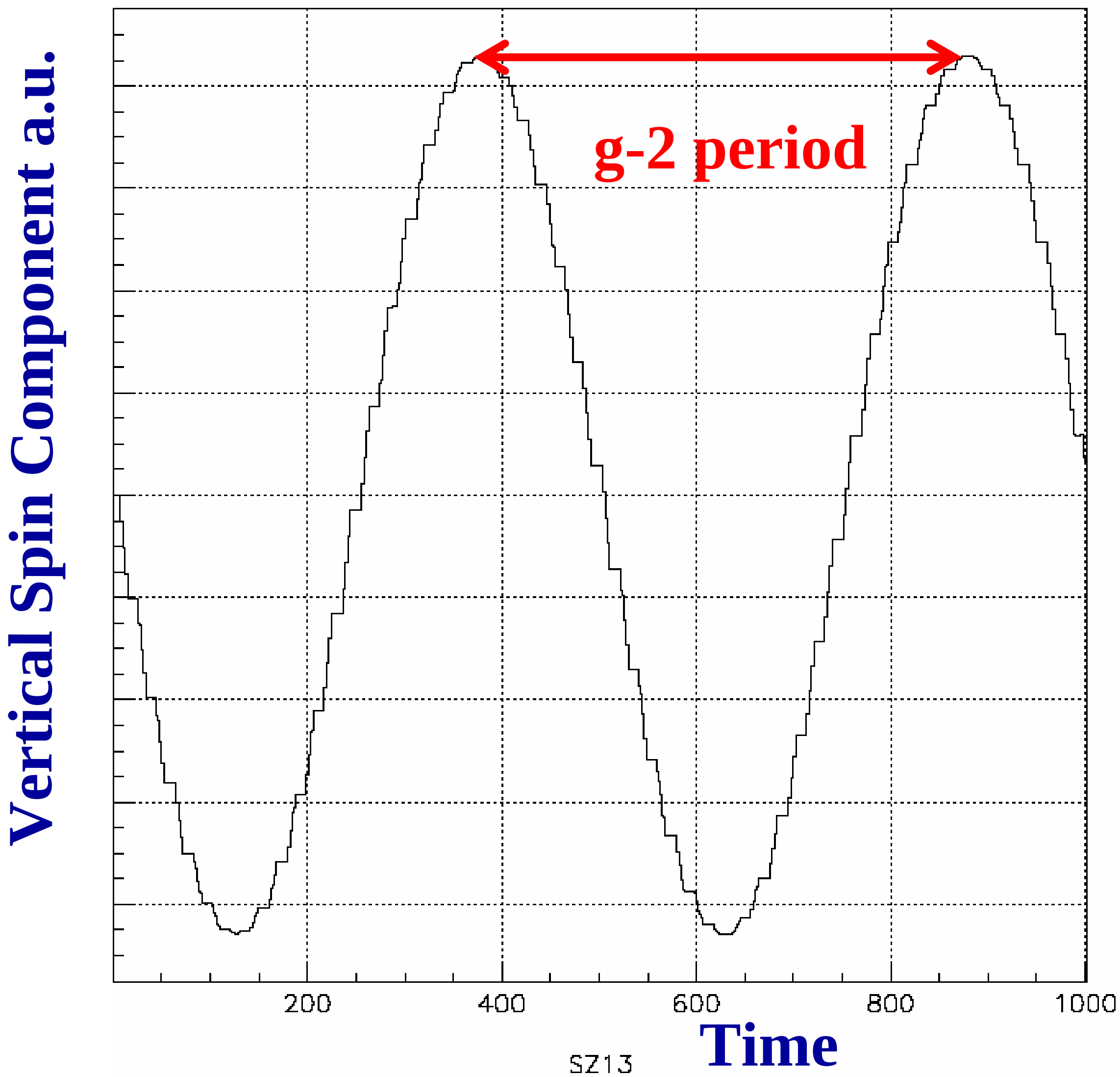
$$\vec{\omega} = \frac{e}{m}\left\{a\vec{B} + \frac{\eta}{2c}\left(\vec{u}\times\vec{B}\right)\right\}$$

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

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

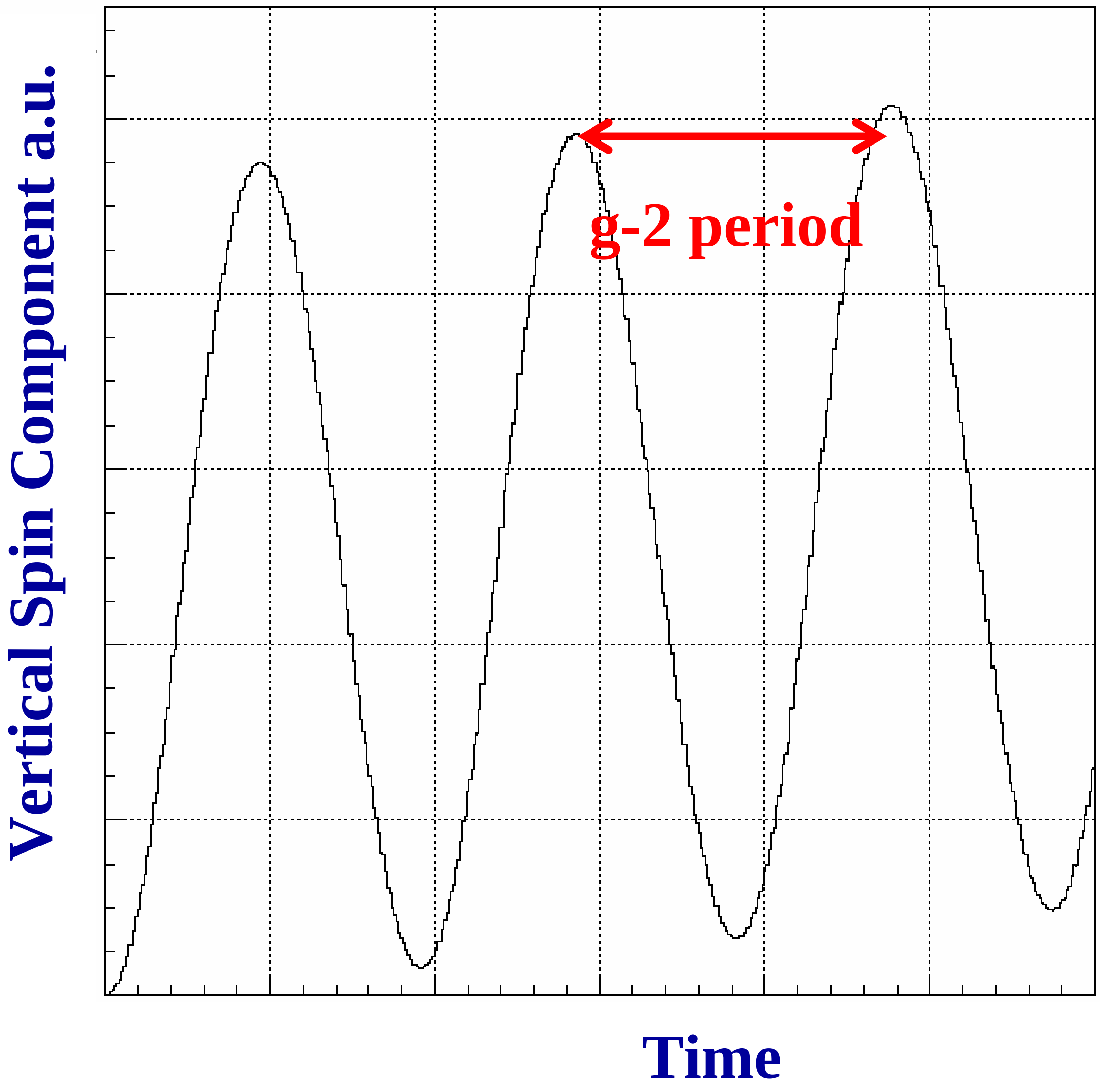
$$\frac{d\vec{s}}{dt} = \vec{\mu}\times\vec{B} + \vec{d}\times\vec{E}$$

Vertical Spin Component <u>without</u> Velocity Modulation (deuterons)



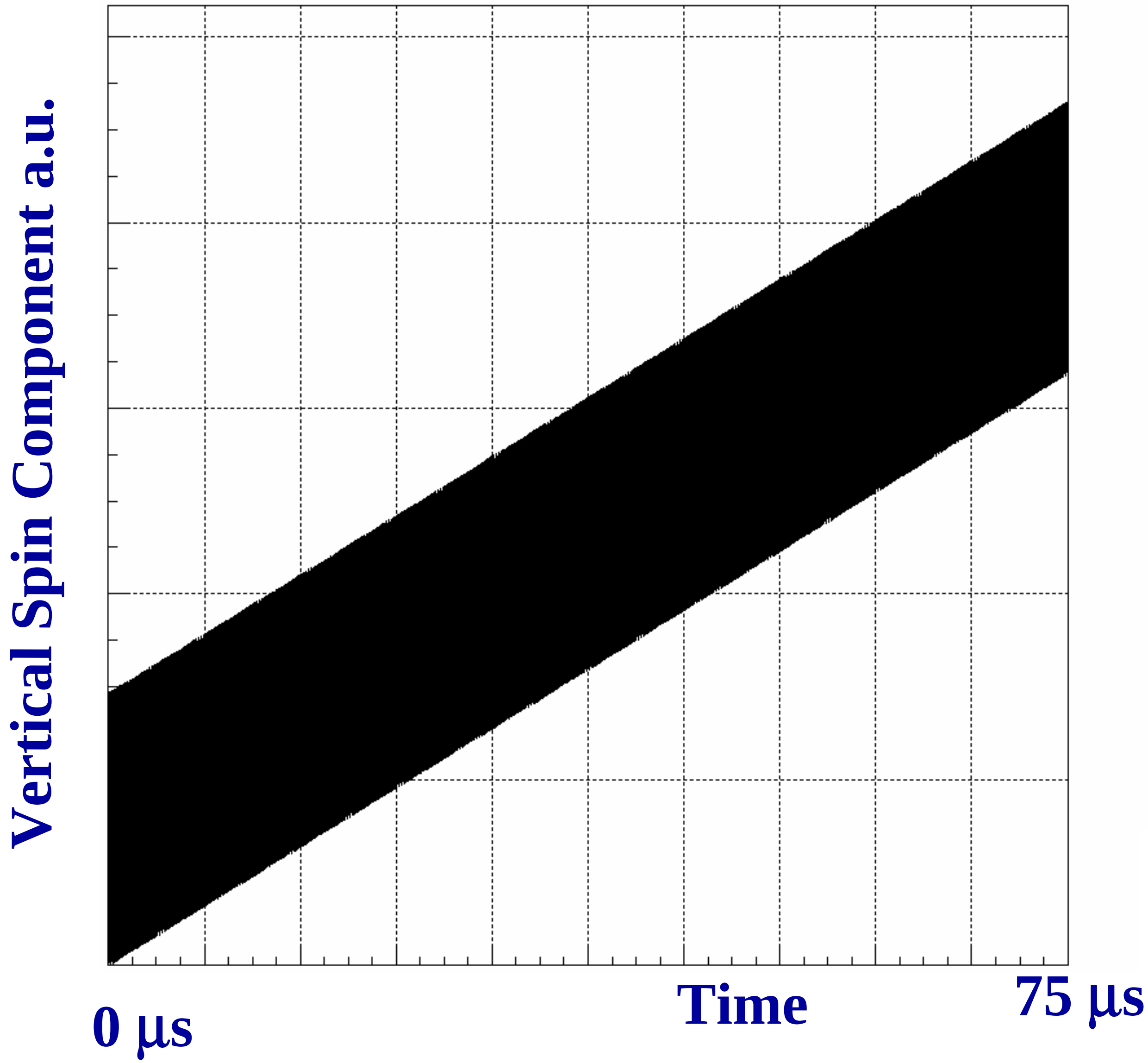
$\vec{E}$

Vertical Spin Component with Velocity Modulation at ω_a



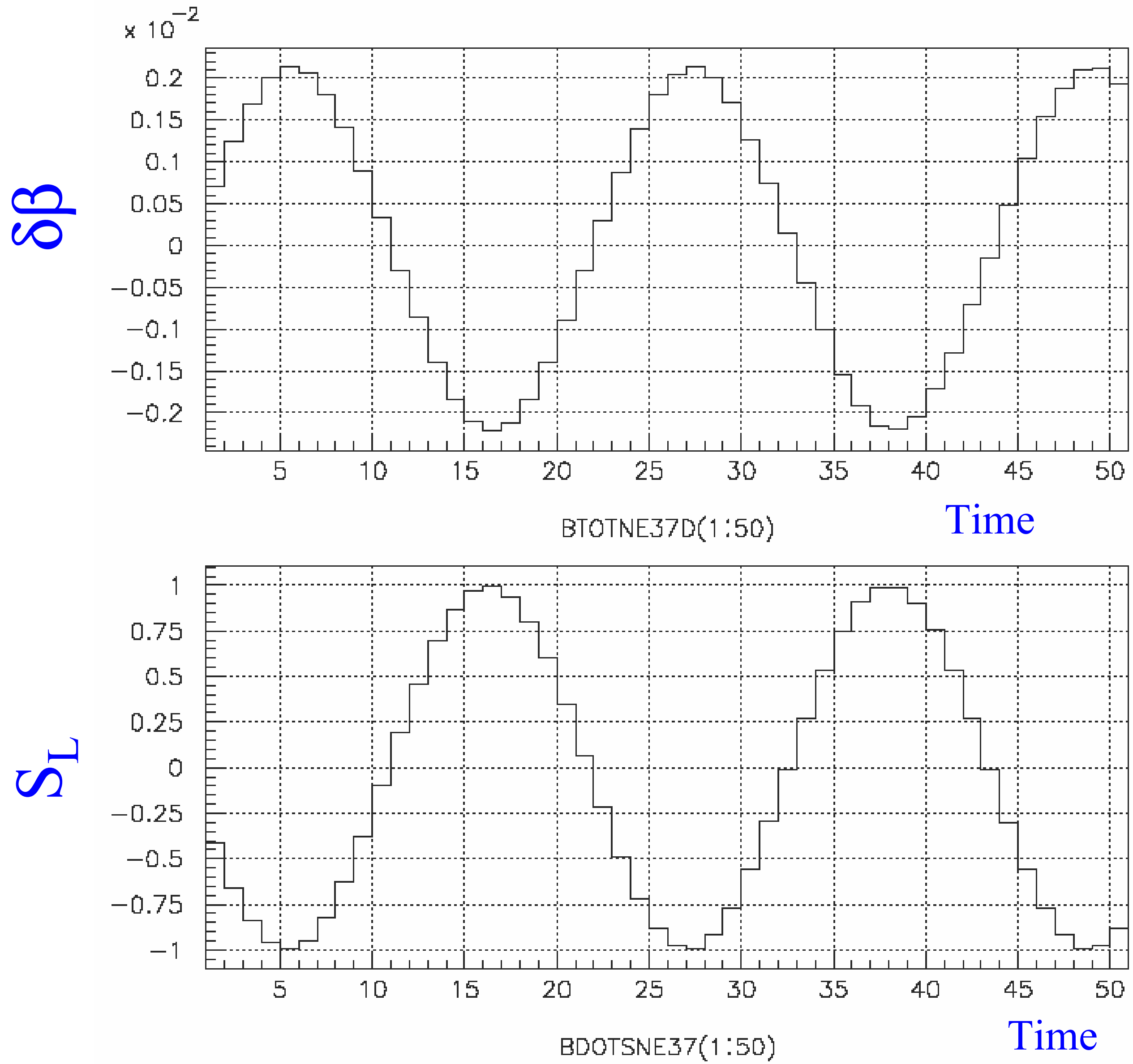
$\vec{E}$

Vertical Spin Component with Velocity Modulation (longer Time)



$+ \vec{d} \times \vec{E}$

Velocity (top) and g-2 oscillations



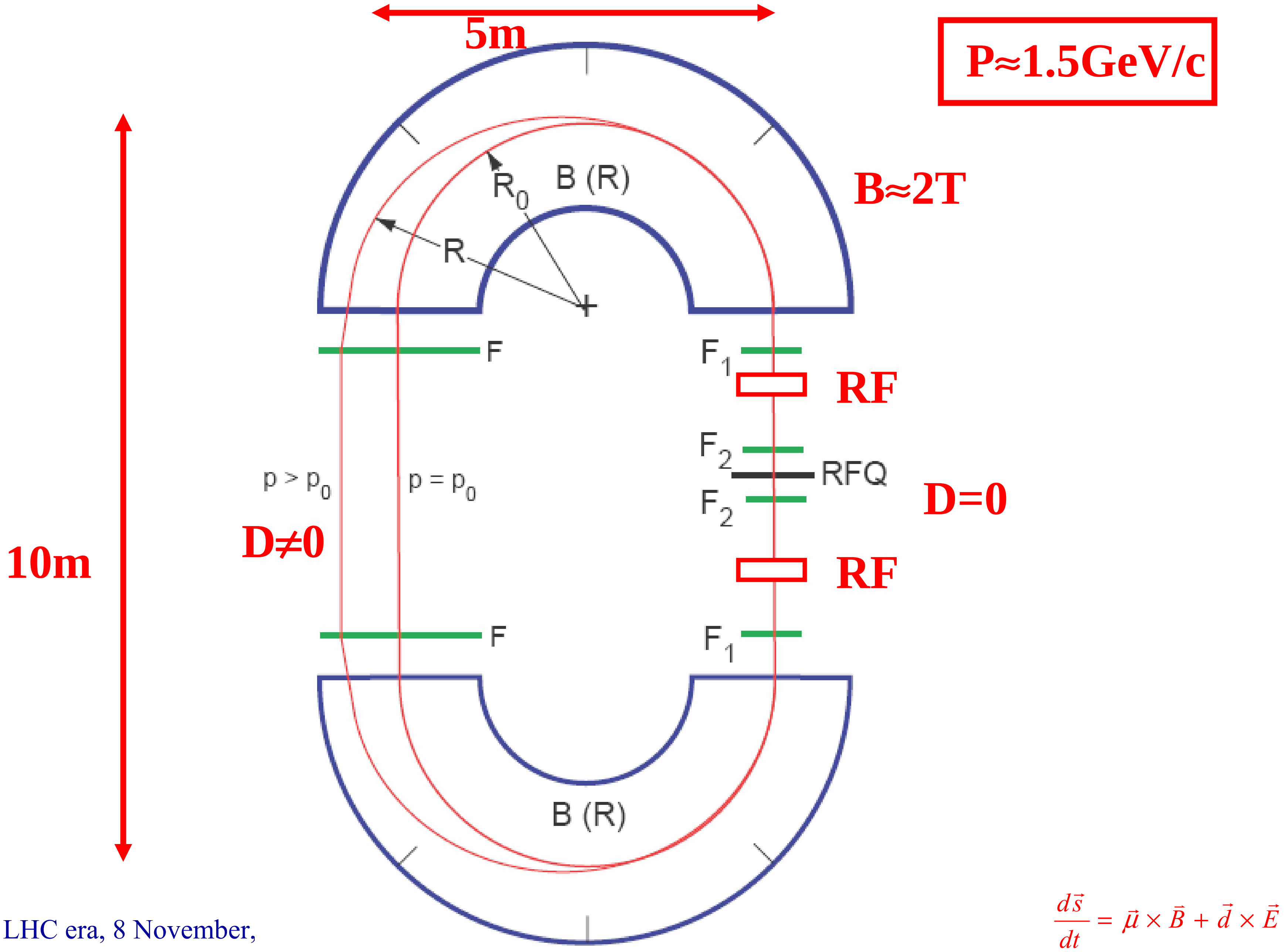
Particle velocity oscillations

Particle S_L oscillations
(i.e. g-2 oscillations)

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

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

Yuri Orlov's new lattice

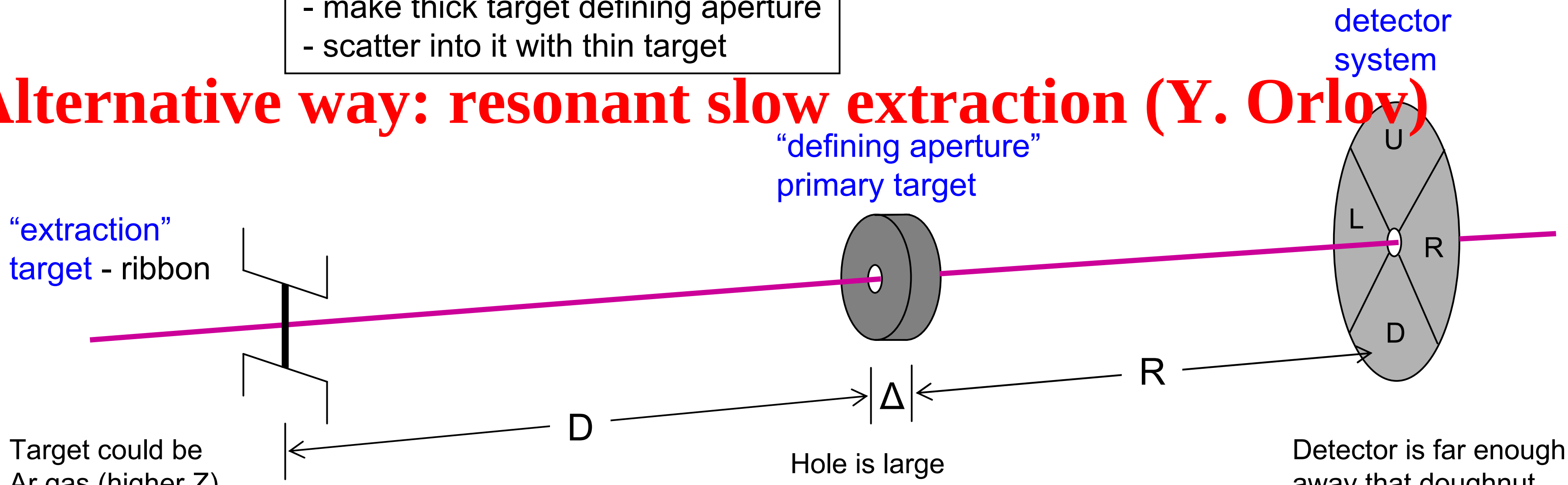


Nuclear Scattering as Deuteron EDM polarimeter

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).

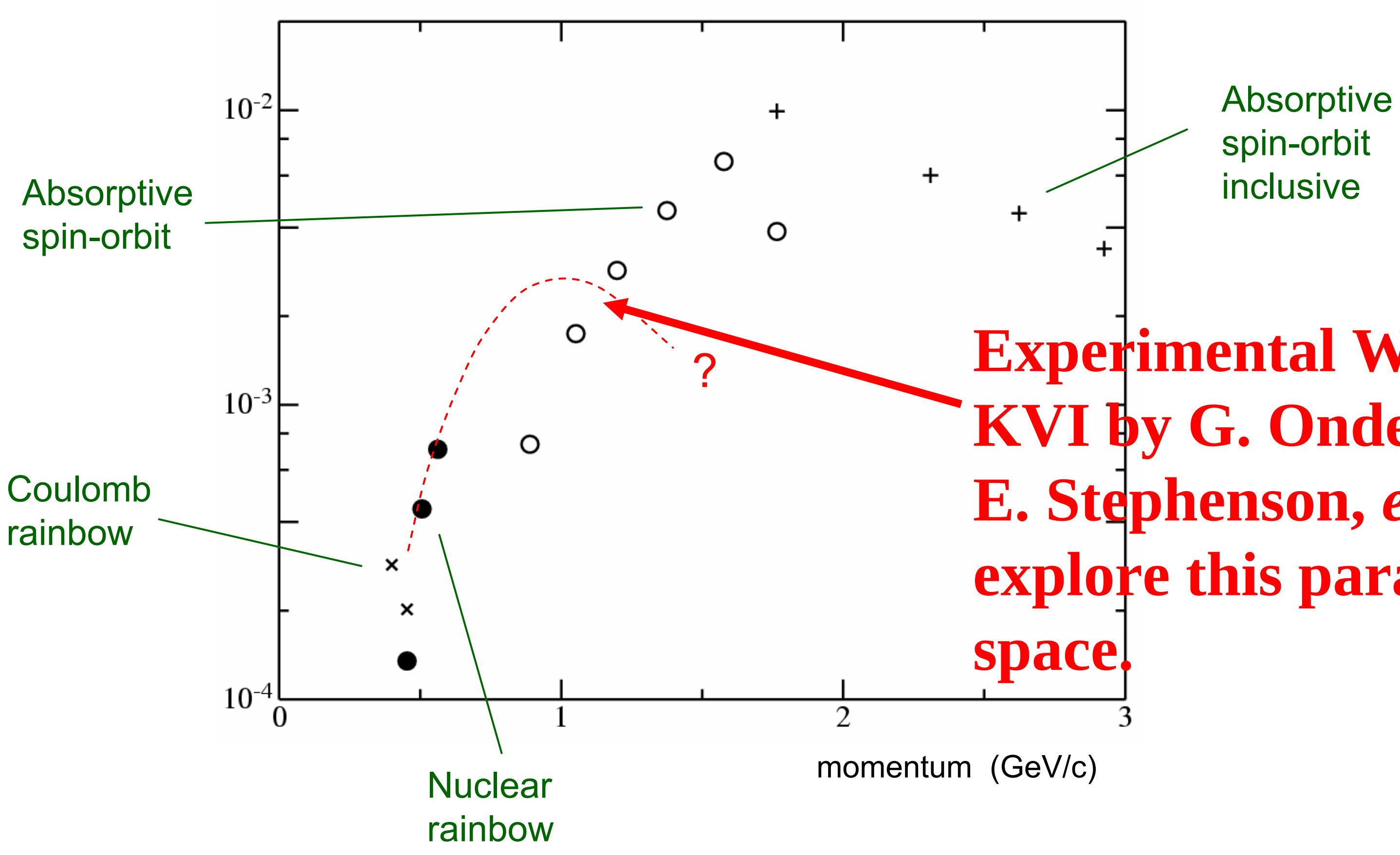
Target "extracts" by Coulomb scattering deuterons onto thick main target. There's not enough good events here to warrant detectors.

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: $\Delta < R$.

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

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



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

Extrapolation of nuclear rainbow effect is not known.

Deuteron Coherence Time

- E, B field stability
- Multipoles of E, B fields
- Vertical (Pitch) and Horizontal Oscillations
- Finite Momentum Acceptance $\Delta P/P$

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 : 0.6 **The left/right asymmetry observed by the polarimeter**

P : 0.95 **The beam polarization**

N_c : 4×10^{11} d/cycle **The total number of stored particles per cycle**

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

f : 0.05 **Useful event rate fraction**

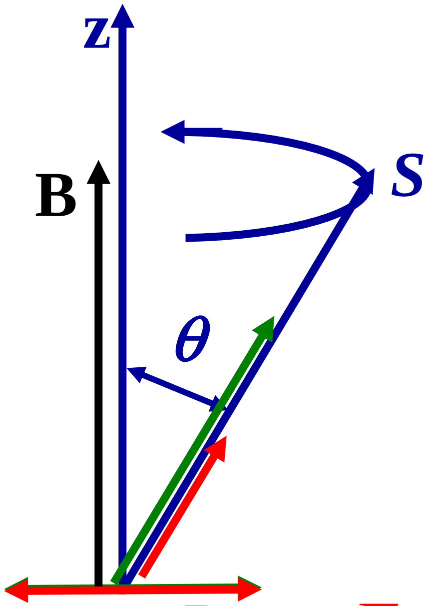
$\delta\beta_0$: 0.01 **Velocity modulation**

$\langle B\rangle$: 1T **The average magnetic field around the ring**

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

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

Resonance spin-flip



B_R or E_R

$$\cos\theta = \frac{s_z}{\sqrt{s(s+1)}}$$

$$B_R = B_0 \sin(\omega_a t)$$

$$\vec{E}_R = \gamma(\vec{v}\times\vec{B}) = \gamma v B = \gamma B v_0 \sin(\omega_a t), \quad \omega_a = a\gamma\omega_c$$

- E_R works on the EDM (signal)
- B_R works on the magnetic moment (background)

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

Resonance EDM Systematic Errors

- Two classes of systematic errors: DC, or frequency dependent (AC)
- Vertically offset cavity
- Misaligned in angle cavity

Systematic errors due to ~0Hz forces

- DC, or almost DC forces (other than magnetic)

$$\vec{F}_{\mathrm{v}} = 0 \Rightarrow \vec{F}_{\mathrm{ext}}(\mathrm{DC}) + q\left\langle \vec{\mathrm{v}} \times \vec{B}_R \right\rangle = 0$$

i.e. modulating v at ω_a modulates B_R at the same frequency.

- Examples: 1) Gravity,
  2) Charging up the beam pipe…

Remedy

- Clock-Wise (CW) injection and Counter-Clock-Wise (CCW) injection (Imitates $T \to -T$):

$$B \to -B$$

$$v \to -v$$

$$v \times B \to v \times B$$

Systematic errors due to AC forces

- AC forces, due to modulating v at ω_a.

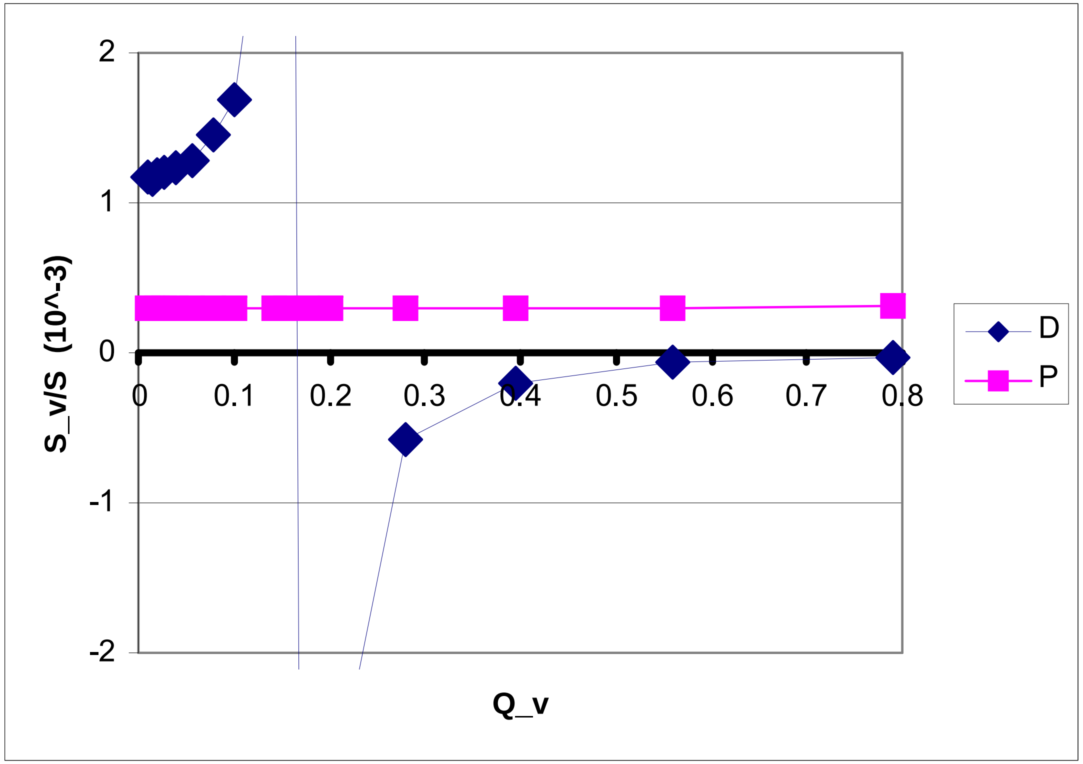
Examples: 1) Radial B-field or skew quadrupole where $D \neq 0$,
2) RF-cavity (vertical offset or misalignment), …

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

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

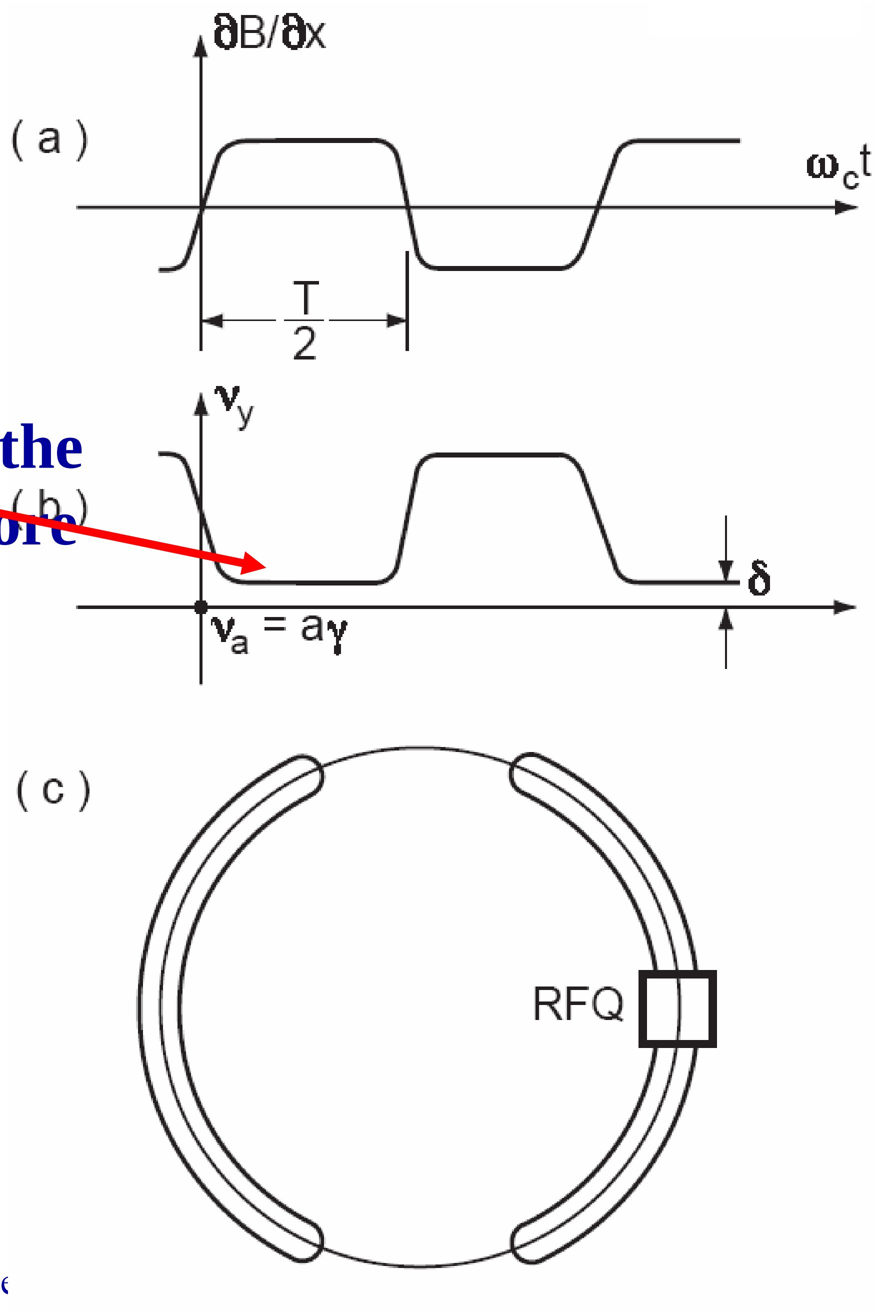
AC Backgrounds are vertical tune dependent; EDM signal is not!

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



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

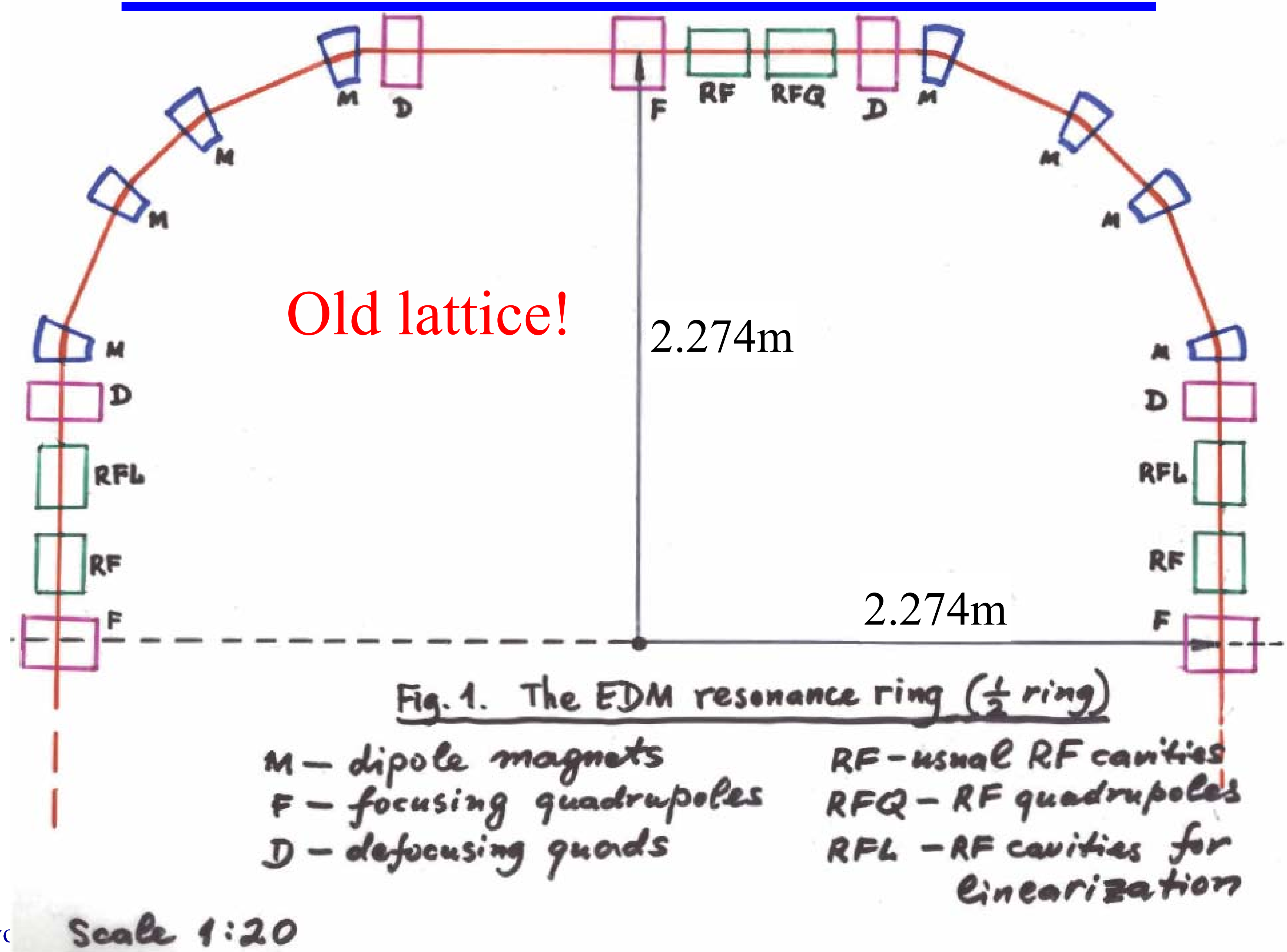
Two half beam technique



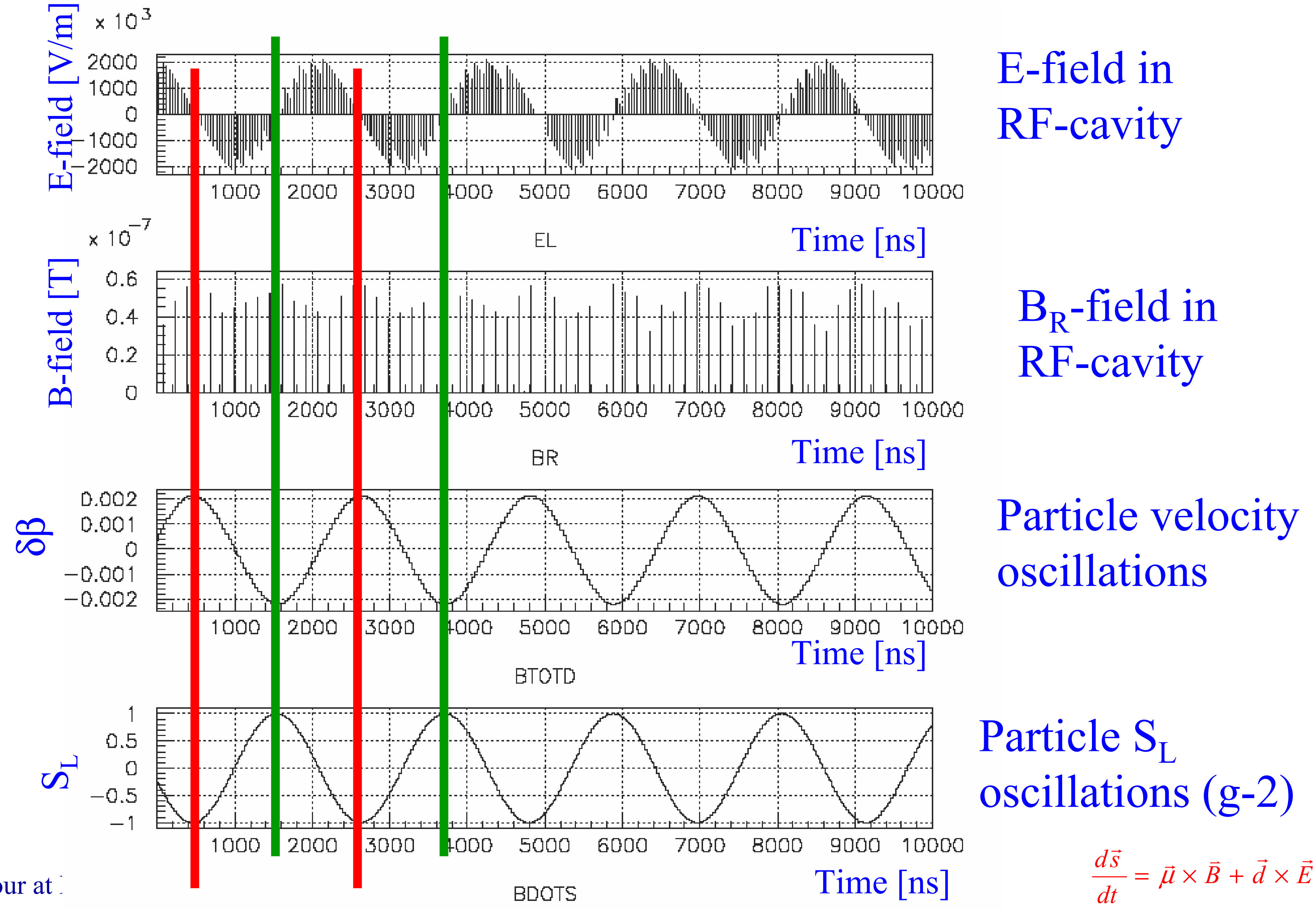
This tune makes the Deuteron spin more Sensitive to background

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

Yuri Orlov's EDM note #70



RF-fields and oscillation phases



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

Effect of the vertical offset, YkS note #85

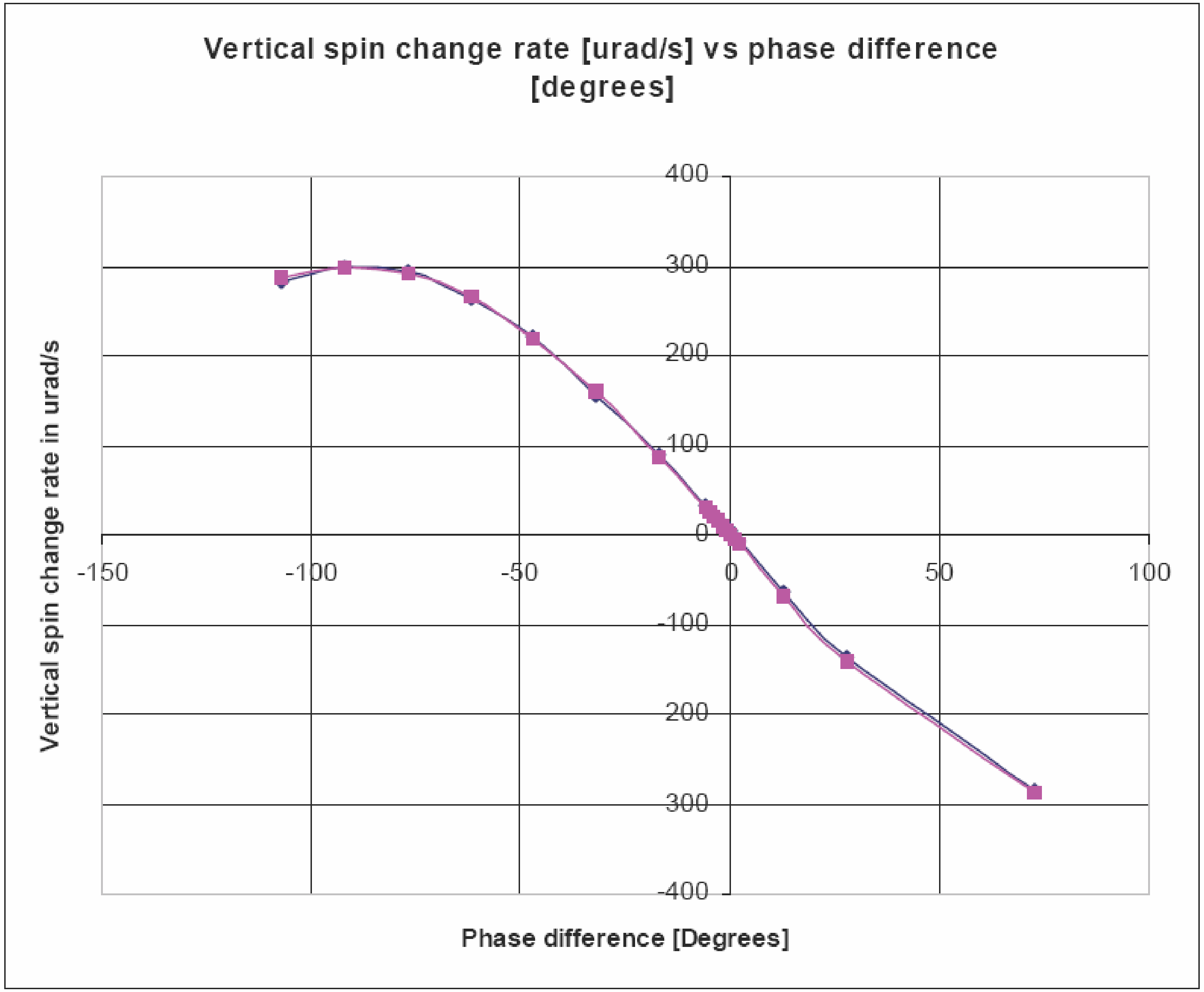


Figure 1. The vertical spin precession rate in μrad/s versus the phase difference (ϕ) between the synchrotron oscillations and the g-2 precession in degrees (modulo 180°) for an RF-cavity offset of 10μm is shown. An overlay of the function 300 μrad/s * sin(ϕ) is also shown.

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

Effect of the angular offset, YkS note #92

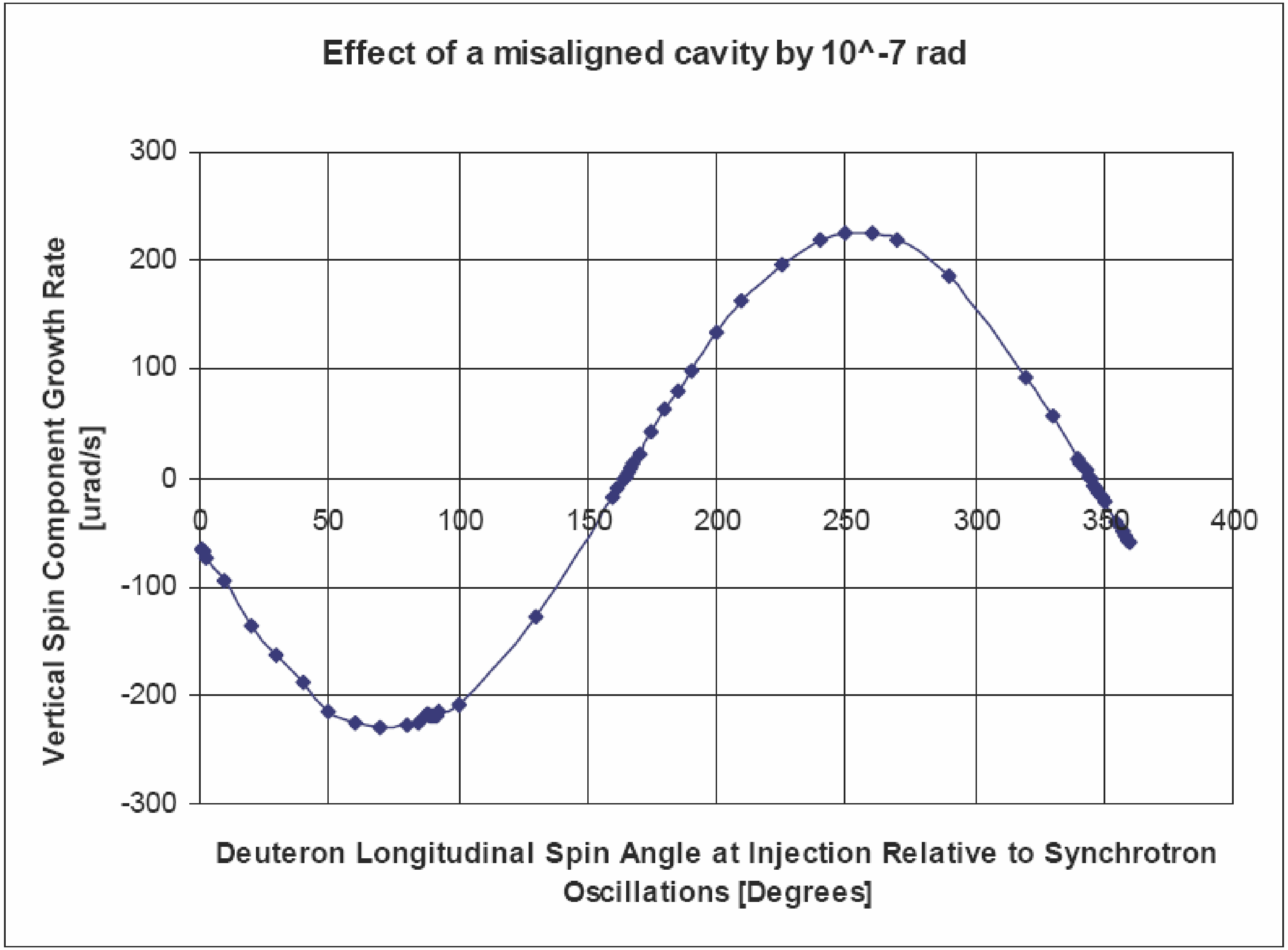


Figure 1. The effect of a misaligned cavity depends on the relative phase between the synchrotron and g-2 oscillations. This dependence is very different from the EDM effect dependence.

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

EDM Spin Resonance Method

Some of Y. Orlov's main ideas:

- Synchrotron tune = ($a\gamma$-N), a=(g-2)/2, N=0,1,2,…
- Cancel systematics by the two half beam storage at different vertical tunes
- Use n=1 in the dipole magnets, and α_p=1 mainly to keep the phase of the g-2 rotation linear with t.
- D-function≈0 at straight section…

Deuteron EDM Timeline

- ~end of this year/January 2006 Letter of Intent
- We need to develop the final ring lattice and tolerances on parameters
- Goal for a proposal by the end of next year

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

List of things to do…

1. Compaction factor: $\alpha_p=1$ or $\alpha_p\neq1$ Graziano Venanzoni, and Yuri Orlov
2. Low beta (=0.6) Super-Conducting Cavities with one mode having $\omega=3\omega_{RF}$ Alberto Facco, …
3. Space Charge, Impedance, etc. Mikhail Zobov
4. RFQ
5. Polarimetry M.C. Anna Ferrari, Ed Stephenson
6. Slow Extraction together with polarimetry
7. Spin Coherence Time Yuri Orlov
8. Polarimetry measurements G. Onderwater, E.S.