deuteron EDM (dEDM) Plan

Yannis K. Semertzidis, BNL

for the Storage Ring EDM Collaboration

- **Physics recognition by the community**
- **Nuclear Physics (and in the European) Long Range Plan**
- **Plan and status of dEDM systematic error studies:**

a) **Polarimeter related systematic errors**

b) **Spin related systematic errors**

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

Physics Recognition, dEDM prominent role

- CERN series of workshops: “Flavour in the era of LHC” with a Yellow report due spring 2007
- NP Long range planning: Fundamental Symmetries
- TOWARDS THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS: THE BRIEFING BOOK (See **http://www.arxiv.org/abs/hep-ph/0609216**)
- CIPANP’06
- Cape Cod: Lepton Moments 6/2006
- EDMs and CP-violation: INT-UoW 3/2007

- Storage Ring EDM: Complementary to neutron; Direct method on charged particles

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

Why deuteron EDM?

$$d_D \simeq 10^{-24}\, e \cdot cm\ \sin\delta_{SUSY} \left(\frac{1TeV}{M}\right)^2$$

At 10^{-29} e·cm, the mass probed is $M = 10^2$ TeV. If there is new physics at the LHC energy scale, it can probe δ_{SUSY} to 10^{-5} rad. Both are well beyond the LHC design sensitivity.

May provide a new CP-violation source to explain BAU

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

Nuclear Physics Long Range Plan (10 year)

- “Fundamental Symmetries”: EDMs made it high in the priority list and dEDM is included by name as an important experiment.
- We asked for $2 M for dEDM R&D in the Chicago meeting. The negotiations for the plan include $2 M for R&D and the cost of the experiment. …exp. is fundable…

Deuteron Statistical Error:

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

τ_p **Spin Coherence Time (SCT)**

A **The left/right asymmetry observed by the polarimeter**

P **The beam polarization**

N_c **The total number of stored particles per cycle**

T_{Tot} **Total running time per year**

f **Useful event rate fraction (polarimeter efficiency)**

$\delta\beta_0$ **Velocity modulation**

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

- **Ring design**
- **Polarimeter/source**
- **DOE**

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

Storage Ring EDM Collaboration

Presented to the BNL PAC, September 2006.

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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PAC recommendation

Collaboration response

Please find below the recommendation of the NPP PAC from September.

LoI: Search for a Deuteron Electric Dipole Moment Using a Charged Particle Storage Ring

This letter proposes a search for a deuteron electric dipole moment using a stored beam. The goal is a statistical precision of about 10^{-29} e·cm; an appropriate level for an experiment we expect would take a number of years to develop. In this experiment, a longitudinally polarized beam develops a vertical spin component due to the torque of the motional electric field in the ring bending magnets acting on the electric dipole moment. The PAC is enthusiastic about this ingenious new approach to electric dipole moment searches. Because it is a new technique, however, there will be a daunting new set of false edm effects and associated systematic errors to consider. We believe it is very important to identify the most important of these difficulties and address them with a combination of simulation and measurement. We strongly encourage the collaboration to investigate the options for measurements in existing rings with polarized deuteron beams. Development of a program of simulations and tests should include, but not be limited to, complete characterization (intensity, size, energy, polarization) of the tails of the beam and their effects on the measurement, investigations of resonant extraction, considerations of correlations between energy and position in the 'extraction' region, and characterization of the effects of common lattice imperfections. Indeed, short of implementing the resonant enhancement of vertical polarization described in the proposal, measurements of zero left-right asymmetries at the requisite level must be demonstrated. A clear plan for near-term milestones including consideration of these issues (over perhaps a two-year period) should accompany any request to the laboratory for continued support.

Clearly there is enthusiasm for your continuing development of this experiment and I look forward to a plan as suggested in the last sentence of the recommendation.

Study potential errors: Demonstrate that we can identify and quantify them. Find those that impose significant constraints on EDM ring design.

Make tests in a storage ring (COSY) with setup as close as possible to dEDM conditions.

Polarimeter Plan Questions

- Can we make a systematic catalog of polarimeter false asymmetries using a conceptual scheme of "drivers" and "sensitivities" such that the information is a reliable predictor of polarimeter issues? Is it good enough to get us down to 10^{-7}?
- What are the requirements we need to meet at COSY in order to precess the polarization into the horizontal plane and have it survive?
- How do we take a ring such as COSY and extend the polarization coherence time?
- Is it possible to measure the phase of a fast g-2 precession with enough precision to be useful as a feedback mechanism in the dEDM study?

Nuclear Scattering as Deuteron EDM polarimeter

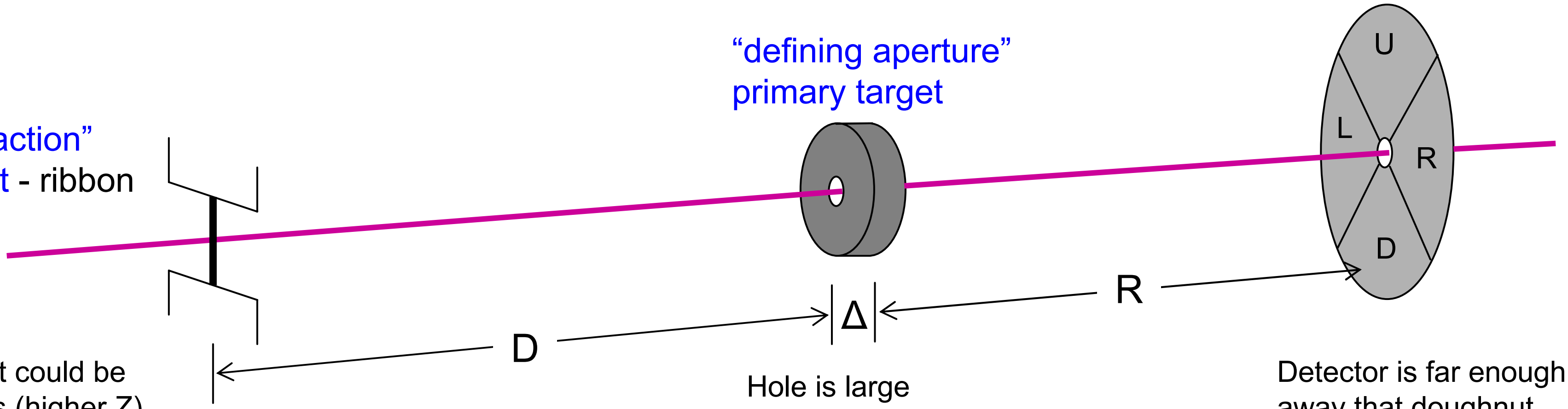
“Dual target” technique

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

detector system

“defining aperture” primary target

“extraction” target - ribbon



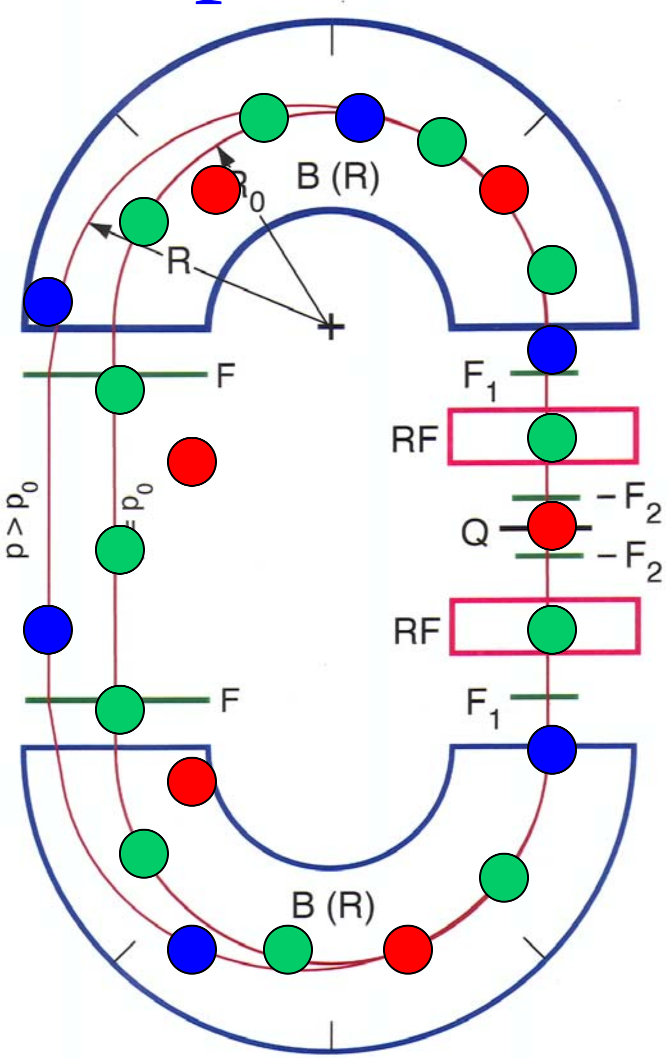
Target could be Ar gas (higher Z).

Target “extracts” by Coulomb scattering deuterons onto thick main target.

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: $\Delta < R$.

Simultaneously Controlled Experiments



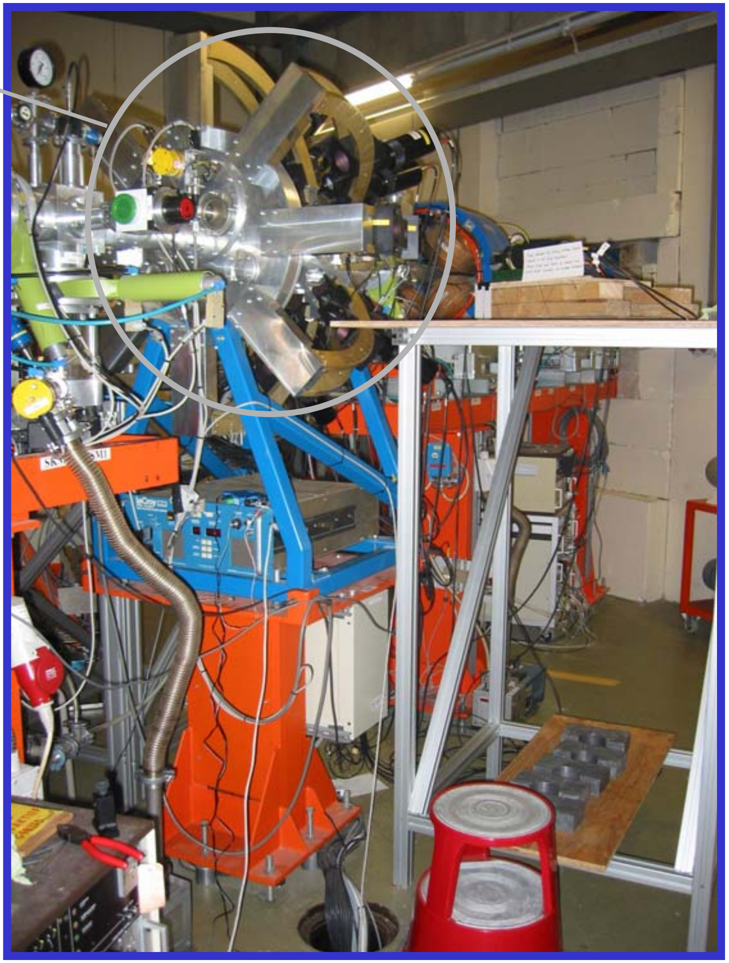
EDM: Spin Up

EDM: Spin Down

No EDM effect

Plan for the KVI cyclotron, Groningen/The Netherlands

Use KVI polarimeter (with modifications) to explore systematic polarimeter errors.



Deuteron beam time approved!
Runs in 2007

1 Identify error driving terms (position, angle, spot size, tails, incomplete spin flip, etc.) and produce these in controlled beam manipulations.

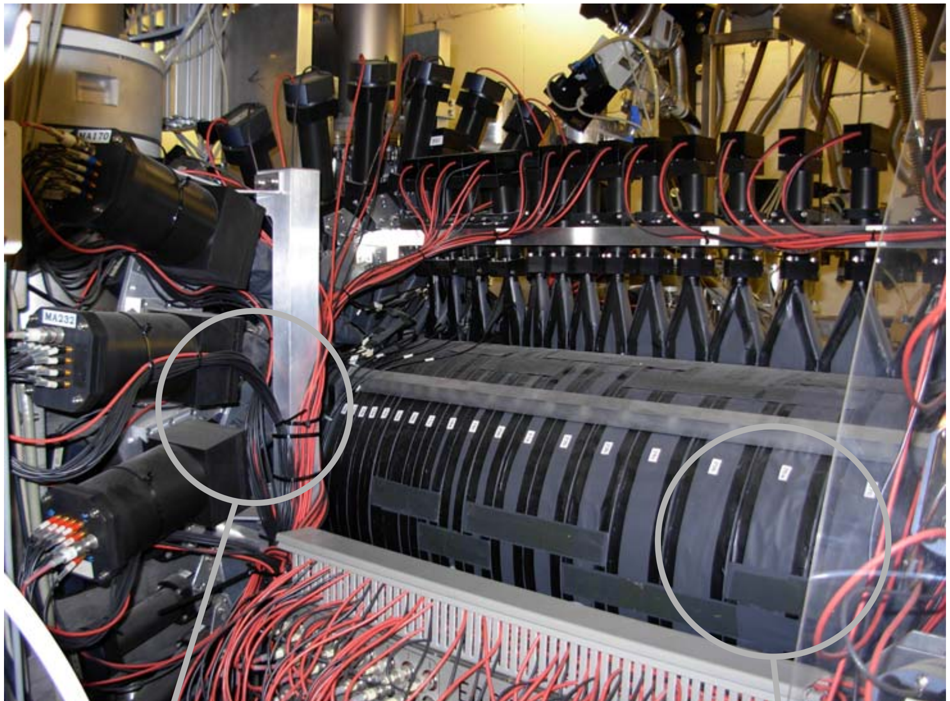
2 Predict, then measure, size of effect on polarization value from polarimeter (depending on analysis method).

This establishes confidence in a procedure that quantifies systematic effects on polarimeter measurements and identifies those that pose serious constraints on the EDM ring design.

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

Plan for COSY cooled storage ring, Jülich/Germany

Proposal submitted March 12, 2007



Thick annular carbon target will go at the front of the detector. Upstream gas target illuminates carbon.

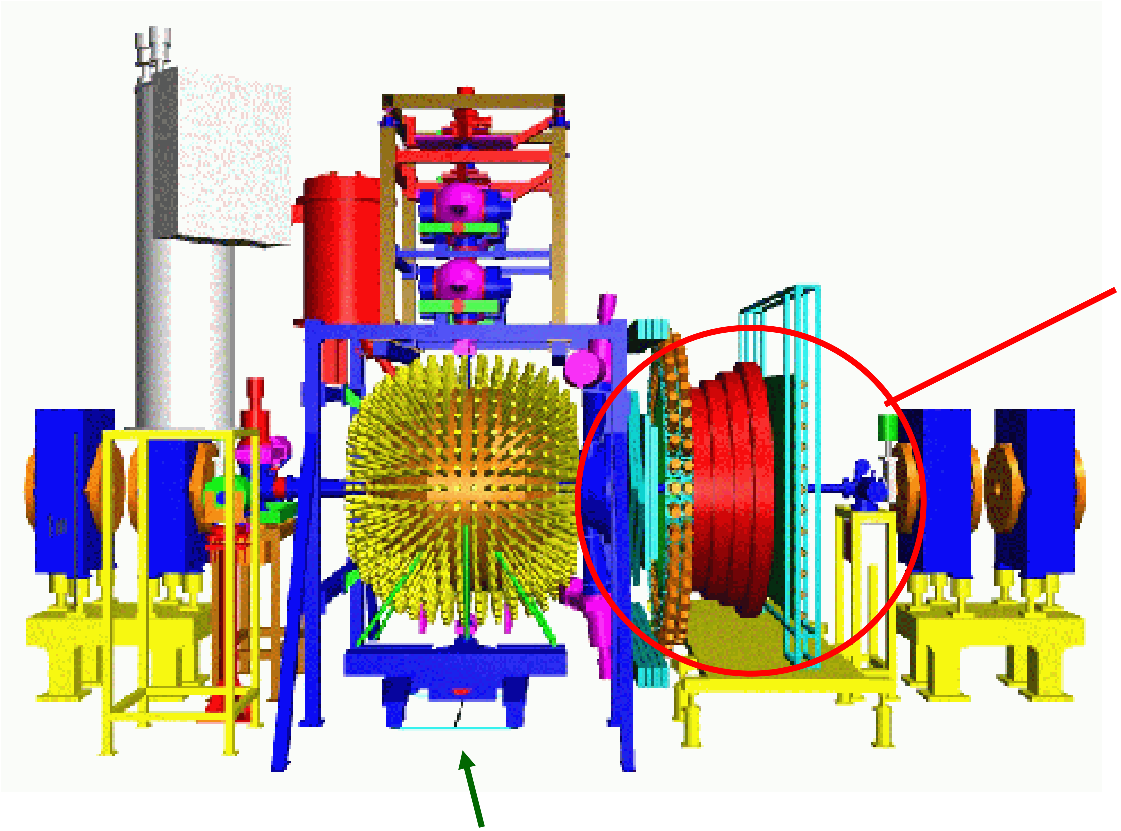
Left-right scintillator array measures effects of beam polarization.

Part I: Use EDDA detector as mock polarimeter for "realistic" testing

1. Install and test double target for high efficiency (>1%) operation.
2. Use RF solenoid to rotate deuteron polarization into horizontal plane, measure g-2 precession in bunched beam.
3. Induce synchrotron oscillations and measure effect on polarization measurement.

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

Part II: Gather data for polarimeter design



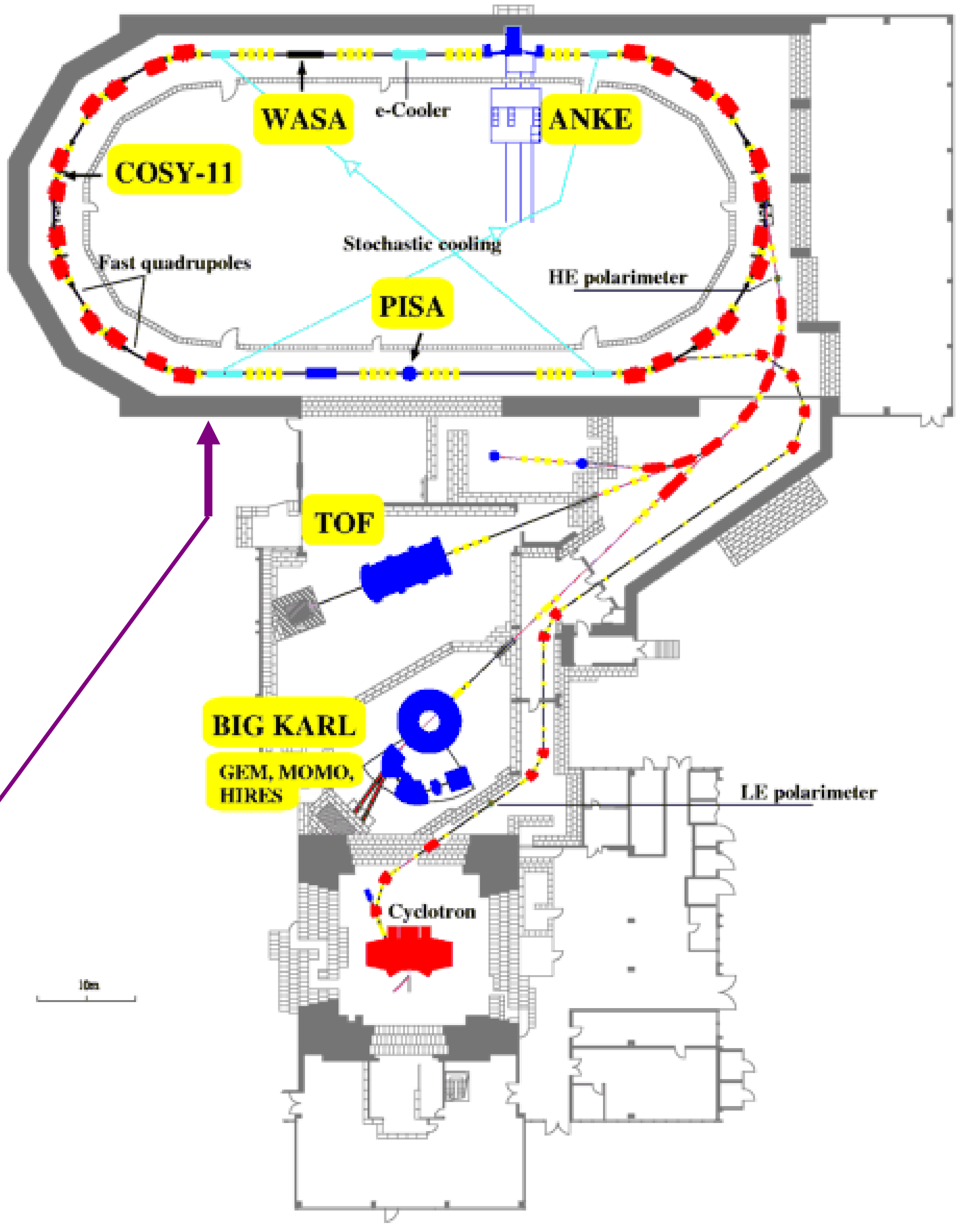
WASA detector will
need new holder
for solid fiber targets.

Measure cross section and analyzing power angular distributions for deuteron-induced reactions between 1.0 and 1.5 GeV/c using the WASA forward tracking detector.

The EDM polarimeter must separate elastic scattering and low Q-value reactions (useful for polarization measurement) from breakup protons (no spin dependence). Data will go into polarimeter Monte Carlo simulation.

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

Part III: Construct prototype dEDM polarimeter. Install in COSY ring for commissioning, calibration, and testing for sensitivity to EDM polarization signal and systematic errors.



Most likely location behind present EDDA detector.

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

Proposal to COSY/Germany

Proposal:

Polarimeter Development for a Search for
a Permanent Electric Dipole Moment on the Deuteron

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We propose to perform an R&D program in the COSY storage ring at IKP/FZJ aimed at the design of a highly sensitive and efficient deuteron polarimeter. This polarimeter is intended for use on a storage ring set up to measure (or limit) a permanent electric dipole moment of the deuteron at the level of 10^{-29} e·cm. The polarimeter would be designed for

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

Timeline and Goals

2007: [COSY proposal submitted]
Run polarimeter tests at the KVI.
Run double target tests at COSY.

2008: Run beam precession tests.
Run synchrotron oscillation tests.
Collect polarimeter design data.

2009: Construct dEDM polarimeter prototype.
Install at COSY and commission.

↓

Results go into publications and **T**echnical **D**esign **R**eport.

Support needed for:

exp. design
equipment
travel
data analysis

Spin related systematic errors

- Main issue: radial → vertical oscillations coupling.

  Solution for a single source: We have identified several alternative solutions.

- Multiple sources pause a challenge since they come in with their own phases (beta function not constant…)

- Collective effects

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

Spin Plan Questions

- Is it possible to amplify the spin systematic errors in a controlled way for a fraction of the stored bunches? What are the issues? How the different sources interfere with each other?
- Is it possible to modulate the ring parameters in such a way that one understands and cancels the driving terms that produce a resonance between the spin precession and an oscillating B_r from some skew field-error in the ring?
- What scheme is needed to extend the polarization coherence time? How is the SCT affected by the rest of the ring requirements?
- What collective effects are important? How do we study them?
- Is it possible to develop a reliable and efficient spin tracking program capable of providing the required accuracy of calculation?

Spin related systematic errors Plan of attack

- Develop & evaluate various ring lattices. Optimize for minimum systematic & statistical errors
- Evaluate effect of Electromagnetic quads: no effect on beam dynamics, tuned to cancel spin errors originating from specific elements. Confirmed by simulations
- Modulate beta-function values around the ring to identify the systematic error sources.
- Change coherent vertical oscillation frequency to ½ of g-2 using non-linearities. If successful it eliminates the main spin systematic error in one shot.

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

Other progress

- Identified EDM teams, potential conflicts
- Identified several potential systematic error sources
- Meeting on polarized sources and injection schemes
- One injection scheme under consideration needs electron cooling (exploring alternative injection schemes…)

Timeline and Goals

2007:

- Study various Ring Lattice versions
- Determine the accuracy level of the spin tracking programs
- Determine systematic errors with multiple error sources around the ring
- Study collective effects

2008:

- Feasibility studies of EM-quads
- Beta function modulation
- Non-linearities to convert vert. osc. freq. to ½ the g-2 frequency
- Study spin coherence time

Support needed for:

Experts' time,
Visitors/consultants

↓

Results go into **T**echnical **D**esign **R**eport

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

dEDM Plan Budget

- **help requested from C-AD ~$150K**
  - 1 month of Mike Blaskiewicz to develop schemes for RF injection
  - 0.5 month of Anatoli Zelenski for polarized deuteron source to match dEDM requirements
  - 1 month of Vadim Ptitsyn to work on the spin coherence time issues
  - 2.5 months of Alfredo Luccio to do spin tracking for systematics
  - 0.5 month of Nicholas D'Imperio for EM field simulations that include collective effects
  - 0.5 month of Al Pendzick to do the costing of the experiment to be included in the proposal
- **Other Laboratory Help**
  - Visitors/Consultants $120K
  - Polarimeter study @ KVI & COSY $240K
  - Travel support to KVI & COSY $60K
  - LDRD (approved) for Limited Travel and Post-Doc $115K

- **The Collaboration needs $570K to produce a proposal**

Summary

- dEDM figures prominently in the "Fundamental Symmetries" section of the LRP and the ELRP. The experiment is fundable
- We have identified the major systematic errors and came up with a comprehensive plan to address them.
- Our plan allows for identifying not yet determined systematic error sources by measurements and simulations
- Work at KVI will start ASAP; proposal to COSY has been already submitted
- In two years from start of support we can have the proposal for the dEDM ready
- We need the support for R&D to make progress towards understanding the viability of the method, not before

Extra Slides

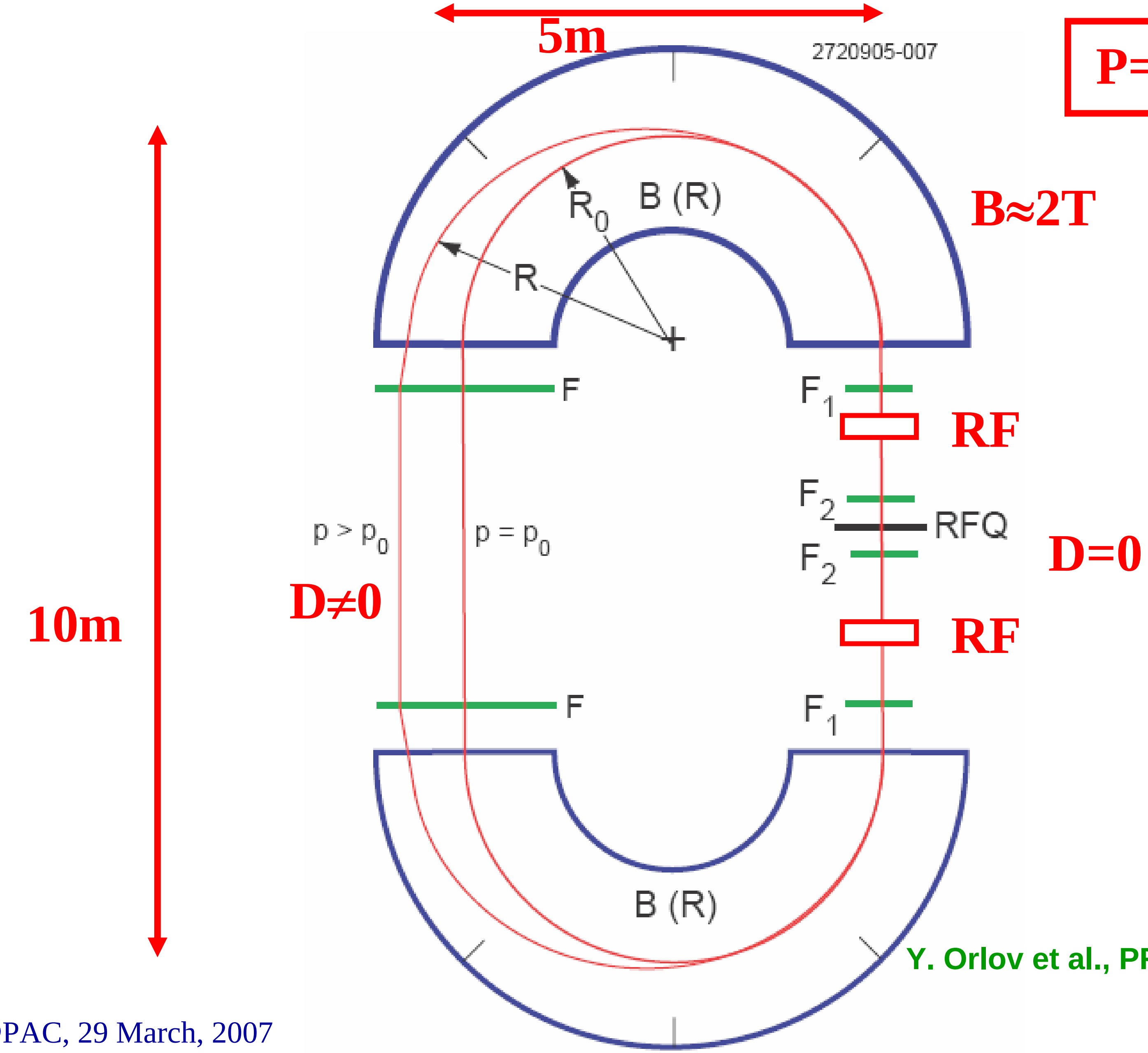
dEDM Team Structure

Number	System	Team Leader
1	Slow Extraction	D. Lazarus
2	Spin Dynamics	Y. Orlov
3	Polarimetry	E. Stephenson
4	Lattice/beam dynamics	A. Luccio
5	Spin Coherence Time	V. Ptitsyn
6	Collective effects	A. Fedotov
7	Injection/capture system	M. Blaskiewicz
8	Mechanical alignment of ring	Y. Semertzidis
9	Source and beam preparation	A. Zelenski
10	Deuteron/Proton issues	B. Morse
11	DAQ	J. Miller
12	Low beta RF-cavities	I. Ben-Zvi

Table 2. The major systems and the corresponding team leaders are shown.

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

The Orlov lattice



P=1-1.5GeV/c

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

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

Why resonance EDM?

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

•Using well established accelerator techniques

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

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

Why resonance deuteron EDM?

- High intensity (~10^{12}/cycle), highly polarized, low emittance deuteron beams are available
- Interact in a strong E-field (Coherent synchrotron tune equals the g-2 tune → Rabi resonance: Effective rest frame E-field is oscillating at the g-2 frequency)
- deuteron polarimeters are available, with high analyzing power for ~1.5 GeV/c d-momentum

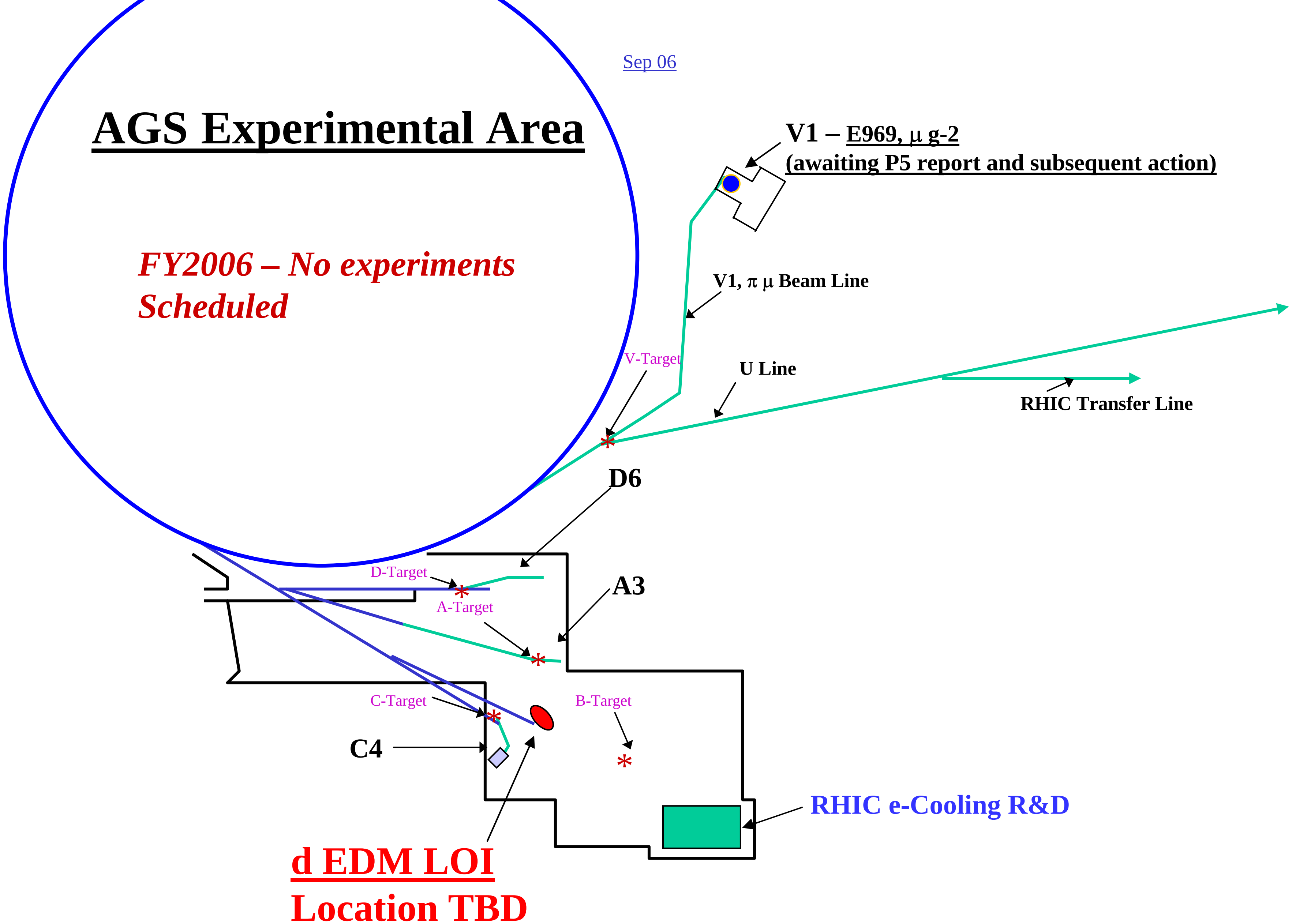
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

Major Concepts in Place:

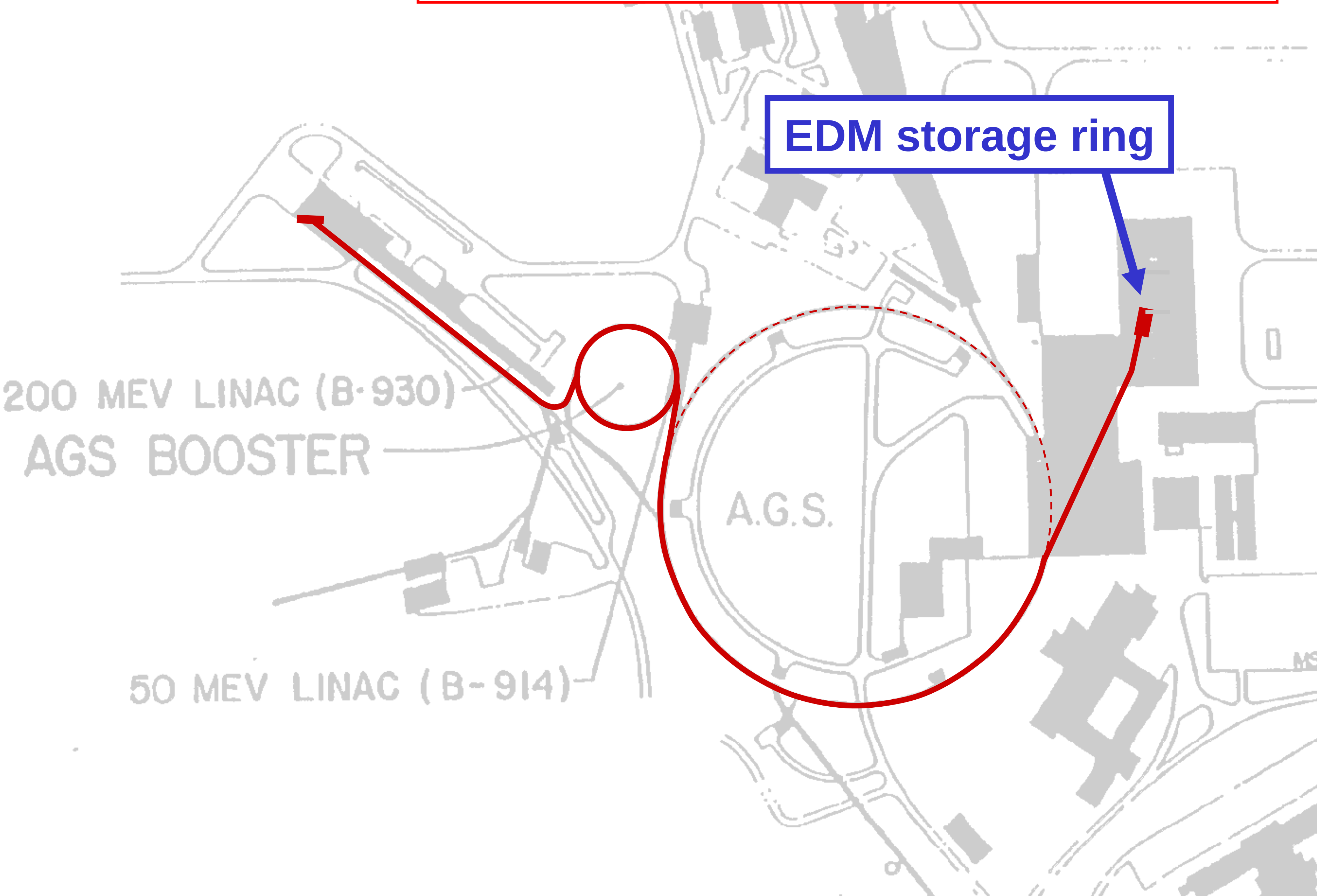
- Polarized source, spin manipulation, high efficiency injection
- Analyzing method
- Spin Dynamics
- Systematics

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

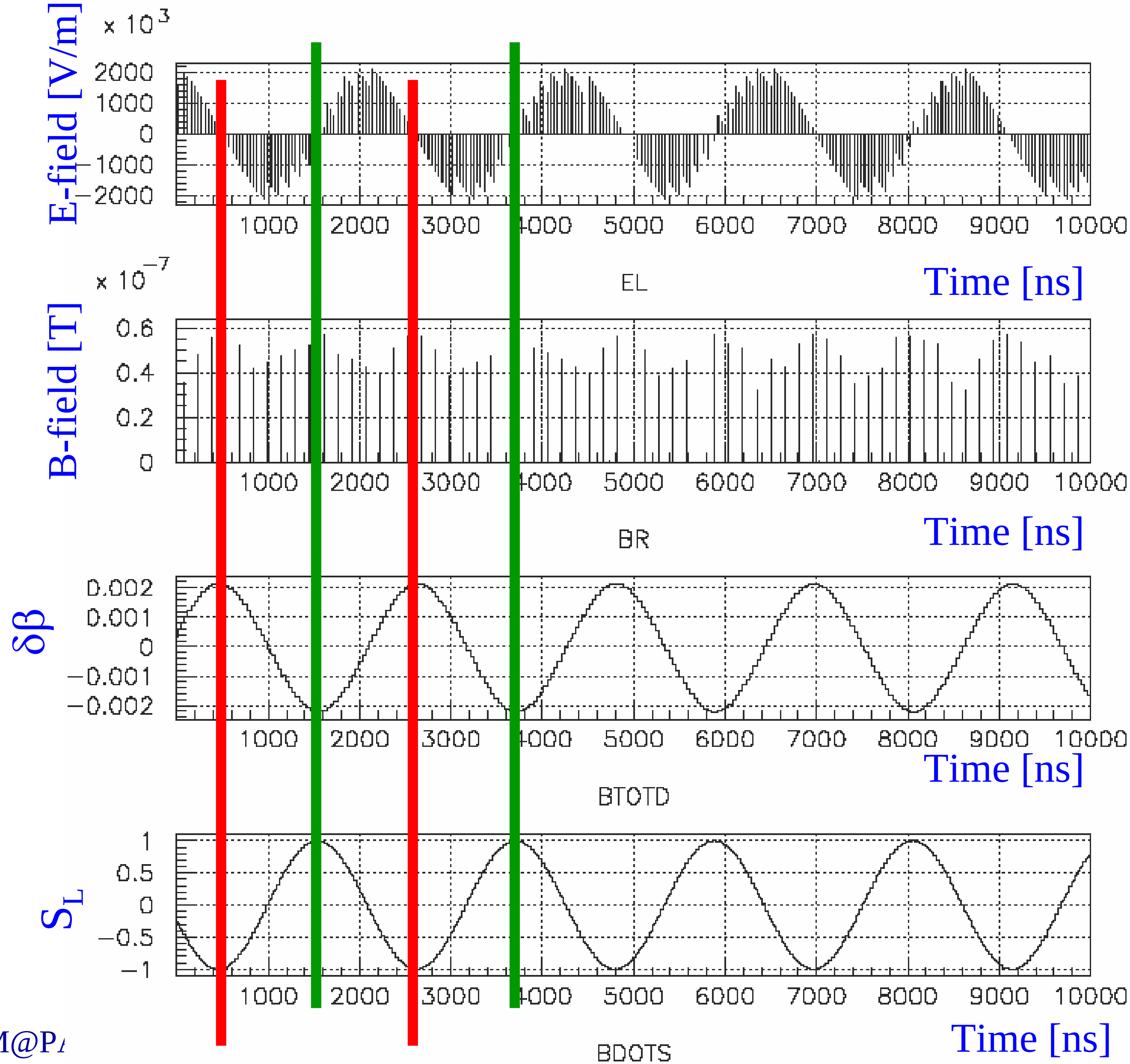
AGS Experimental Area



The deuteron EDM search at BNL



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)

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

Effect of the vertical offset, YkS note #85

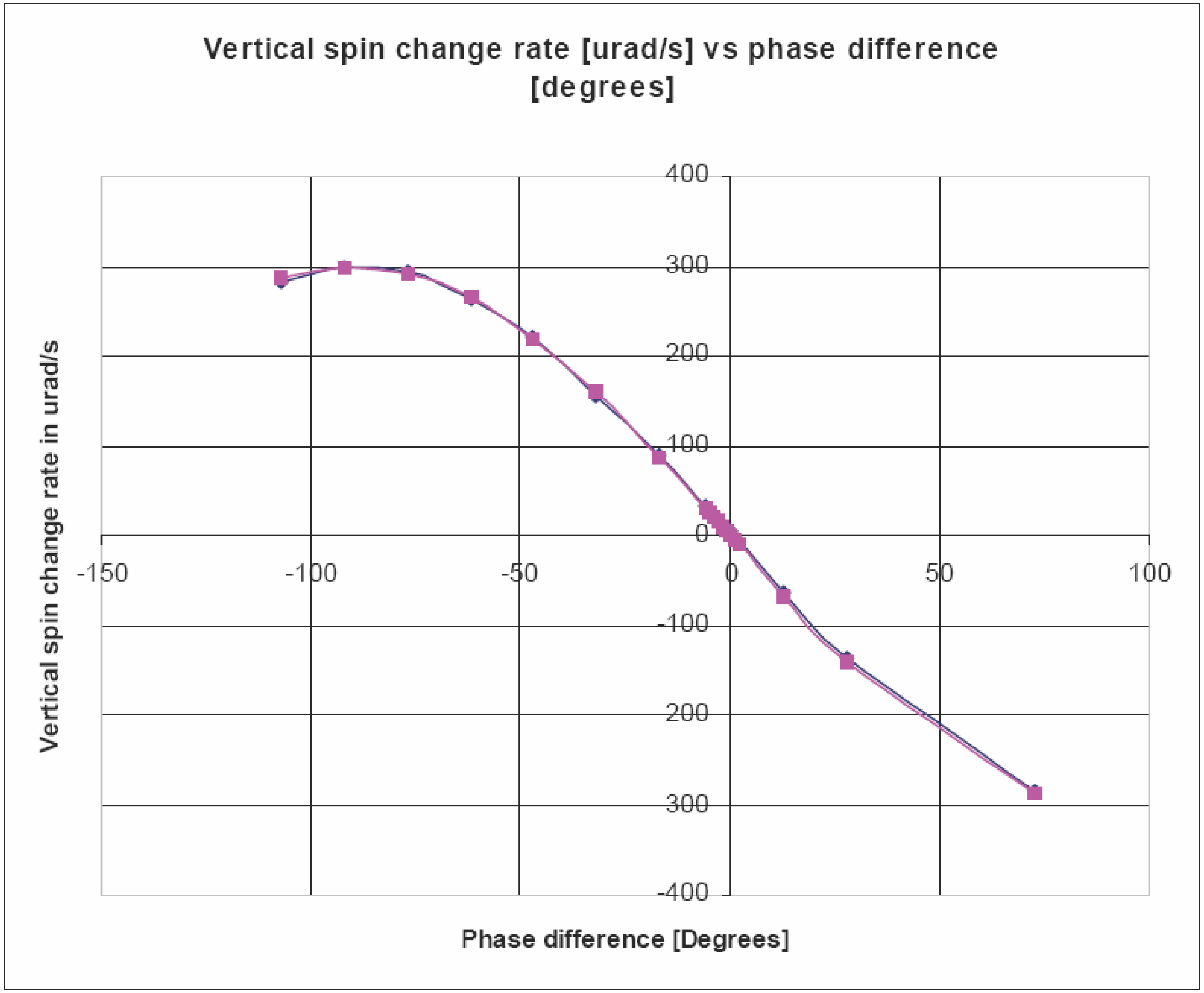


Figure 1. The vertical spin precession rate in μrad/s versus the phase difference (ϕ) between the synchrotron oscillations and the g-2 precession in degrees (modulo 180°) for an RF-cavity offset of 10μm is shown. An overlay of the function 300 μrad/s * sin(ϕ) is also shown.

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

Effect of the angular offset, YkS note #92

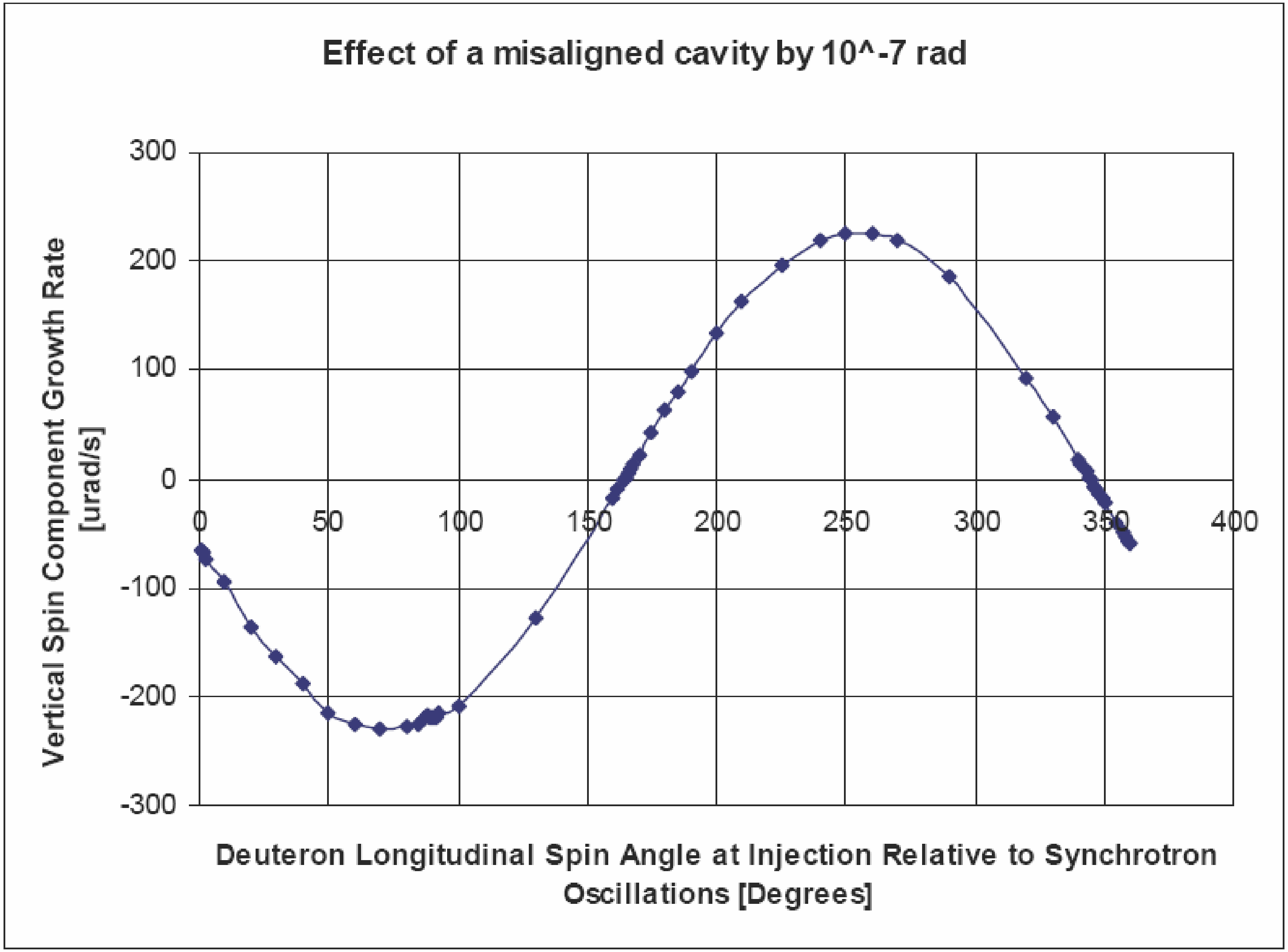


Figure 1. The effect of a misaligned cavity depends on the relative phase between the synchrotron and g-2 oscillations. This dependence is very different from the EDM effect dependence.

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

From the Systematic Errors Plan…

Our general strategy for studying systematic errors is to identify and exploit the specific symmetries of the method. Those are:

1) Our stored beam will be undergoing synchrotron oscillations in resonance with the g-2 frequency. Consecutive beam bunches will have 180° phase difference in their synchrotron oscillations while the polarization directions remain the same, meaning that their respective EDM signals will also have the opposite sign. A large range of systematic errors will have the same sign and will therefore be eliminated by properly subtracting the signals from consecutive bunches. Most of the polarimetry errors fall in this category.
2) Many systematic errors, including those from spin dynamics, have opposite symmetry to the EDM signal when the direction of the beam in the storage ring goes from clock-wise (CW) to counter-clock-wise (CCW).
3) Changing the ring lattice parameters in specific ways to make the systematic errors time dependent while keeping the EDM effect constant can effect a separation. This will provide a tool to identify many of the spin systematic error sources and eliminate them.
4) Eliminating the source of the main spin related systematic errors by modifying the ring response function with the help of nonlinearities is an important tool.

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

A value of $\theta_{QCD} = 10^{-13}$ 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

BNL budget issues

- LDRD "frozen" until last week
- Dropped Y.O. support as of end of 9/06
- "Day" jobs other than EDM
- People from C-AD need an account number…

Systematic errors

The current list of potential spin related systematic errors includes:

1) Radial-vertical coupled oscillations
2) Collective effects
3) Instrumental alignment tolerances
4) Polarimeter instrumental errors

Schedule and Budget

- Use a plausible dEDM ring lattice to study the effect of multiple systematic error sources located randomly around the ring. Test the accuracy of the software used to simulate the effects, its simulation speed and techniques to improve it.

  Determine the sensitivity level of the two tune technique with and without the presence of many error sources around the ring. The estimated required calendar time is three months - summer, 2007.
  - Add fields generated due to collective effects, in a dynamic fashion, i.e. add time dependence (collective effects depend on the beam intensity and therefore they will be changing from early to late times after beam injection). Estimated calendar time to achieve a reliable simulation of the collective effects is two months - fall, 2007.
  - Study the case of varying the amplitude of the ring beta-function around the ring. Do this without changing the vertical betatron tune in the dispersive part of the ring. Study the Fourier analyzed signals and the statistical sensitivity of fitting for the systematic errors in the final data set. The estimated time to calculate the parameters of such a ring and understanding its errors is four calendar months-winter 2007/2008.
  - Study the ring where the horizontal forced oscillation frequency is modified to half of the g-2 frequency in the presence of synchrotron oscillation at the g-2 frequency. The estimated calendar time for completing this study is six calendar months-spring/summer 2008.

Schedule and Budget

The schedule for the polarimeter tests as presented in more detail section can be summarized as follows:

- Use EDDA polarimeter with annular carbon target to measure efficiency – 10-day run in fall, 2007.
- Make carbon fiber target for WASA, measure d+C cross sections and analyzing powers – 17-day run in winter, 2008.
- Install new RF dipole (if we need it), improve EDDA electronics – 2 times 10-day runs in spring, 2008.
- Modify COSY RF (if needed) and add forced synchrotron oscillations to study – 10-day run in fall, 2008.

It is expected that we will start making significant progress as soon as BNL support materializes. Overall we need support for two person-years for the next two years, by which time we expect to have the proposal ready. Specifically we need $195 K to support visitors and (mostly) locals to work on the spin related systematic errors. We also need $75 K to support (mostly) visitors and locals to work on the beam capture, collective effects, and interface with the polarimeter.

The polarimeter hardware requirements are estimated at the $240 K level, which include incremental investment in electronics and mechanical equipment to fully utilize the presently available detectors at COSY and KVI. In addition we need $60 K in travel support for running the tests at COSY and KVI for the next two years. The total required sum to support the dEDM R&D is $570 K for the next two years.

Hadronic EDMs

- Theta bar QCD
- Quark EDM
- Quark-color EDM

Hadronic EDMs

$$L_{\not{CP}} = \bar{\vartheta}\,\frac{\alpha_s}{8\pi} G\tilde{G}$$

$$d_n(\bar{\vartheta}) \simeq -d_p(\bar{\vartheta}) \simeq 3.6\times 10^{-16}\,\bar{\vartheta}\ \mathrm{e\cdot cm} \rightarrow \bar{\vartheta} \leq 2\times 10^{-10}$$

$$d_D(\bar{\vartheta}) \simeq -10^{-16}\,\bar{\vartheta}\ \mathrm{e\cdot cm}$$

So far no models produce BAU with this term!

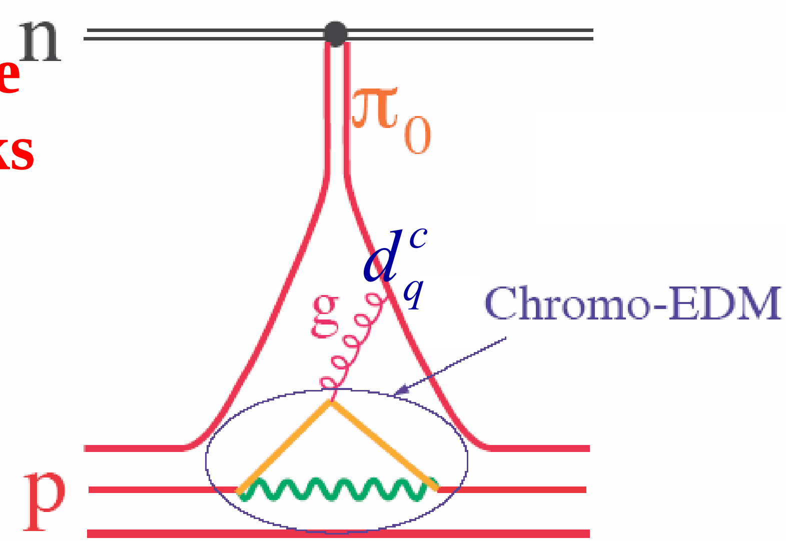
Quark EM and Color EDMs

$$L_{CP} = -\frac{i}{2}\sum_{q}\bar{q}\left(d_q \sigma_{\mu\nu}F^{\mu\nu} + d_q^c \sigma_{\mu\nu}G^{\mu\nu}\right)\gamma_5 q$$

$$d_D\left(d_q, d_q^c\right) \simeq \left(d_d + d_u\right) - 0.2e\left(d_d^c + d_u^c\right) + 6e\left(d_d^c - d_u^c\right)$$

$$d_n\left(d_q, d_q^c\right) \simeq 1.4\left(d_d - 0.25 d_u\right) + 0.83e\left(d_d^c + d_u^c\right) + 0.27e\left(d_d^c - d_u^c\right)$$

i.e. Deuterons and neutrons are sensitive to different linear combination of quarks and chromo-EDMs…



Several models produce BAU!

Comparison With Other EDM Efforts

	Current Bound	Future Goal	$\sim d_n$ Equivalent
Neutron	$d_n < 3\times10^{-26}$ e-cm	$\sim 10^{-28}$ e-cm	10^{-28} e-cm
^{199}Hg atom	$d_{Hg} < 2\times10^{-28}$ e-cm	$\sim 2\times10^{-29}$ e-cm	$10^{-25} - 10^{-26}$ e-cm
^{129}Xe atom	$d_{Xe} < 6\times10^{-27}$ e-cm	$\sim 10^{-30} - 10^{-33}$ e-cm	$10^{-26} \sim 10^{-29}$ e-cm
Deuteron	–	10^{-29} e-cm	$3\times10^{-29} - 5\times10^{-31}$ e-cm

Deuteron Competitive – Better!

Marciano 9/2006

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

Deuteron Statistical Error:

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

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

$$\sigma_d \approx 2\times 10^{-29}\,\mathrm{e}\cdot\mathrm{cm}\,/\,\mathrm{year}$$