Storage Ring Search

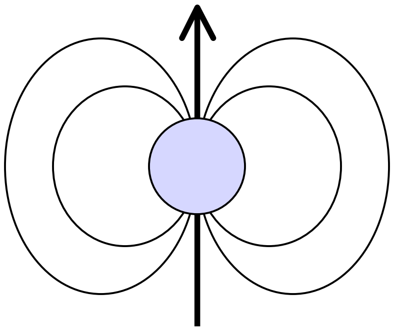
for an

Electric Dipole Moment

Proposed Searches for Electric Dipole Moments of the Muon, Deuteron, and Proton in Storage Rings

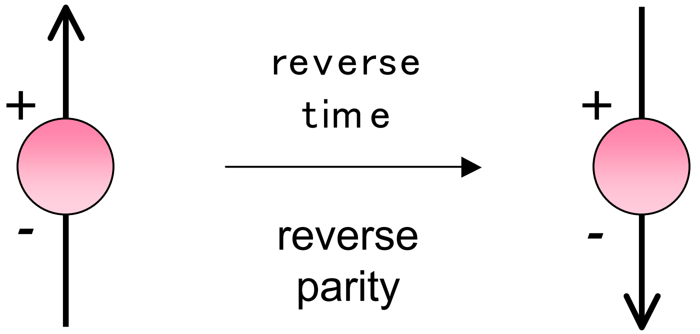
Ed Stephenson
Indiana University Cyclotron Facility

DIPOLES:



$\mu \cdot B$

commonplace



$d \cdot E$

T violating
CP violating

These symmetry violations arise from the connection of an EDM with spin. EDMs oriented along spatial axes are also commonplace.

Searches begin with neutron in 1950s.

Smith, Purcell, and Ramsey, PR **108**, 120 (1957)

Present limits (neutral particles):

neutron $< 6.3 \times 10^{-26}$ e·cm

Harris *et al.,* PRL **82**, 904 (1999)

paramagnetic atoms (Tl) for electron $< 1.6 \times 10^{-27}$ e·cm

relativistic effects enhance sensitivity

Regan *et al.,* PRL **88**, 071805 (2002)

diamagnetic atom (^{199}Hg) $< 2.1 \times 10^{-28}$ e·cm

Romalis *et al.,* PRL **86**, 2505 (2001)

screening reduces to 4×10^{-25} e·cm on neutron

Dmitriev and Sen'kov, PRL **91**, 212303 (2003)

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diamagnetic atom (^{199}Hg) < 2.1 × 10^{-28} e·cm

Active planning underway to improve limits by 10-100 or more:

store neutrons in ^{4}He bath with trace polarized ^{3}He
Golub, Lamereaux, *et al. LANSCE and SNS*

diamagetic atoms with octupole nuclear deformations (Ra, Rn)
Yungman, *KVI Groningen*
Holt, *ANL* etc.

paramagnetic molecules with greater enhancements (YbF, PbO)
Hudson *et al.*
deMille etc.

bulk magnetization of garnet in electric field
C.-Y. Liu and Lamoreaux *at IUCF*

storage ring is new technique for charged particles at 10^{-29} e·cm

Standard Model expectations require three-loop diagrams and fall into the range 10^{-31} e·cm (deuteron) to 10^{-39} e·cm.

Searches presently planned are unlikely to reach these limits.

Any EDM found by a planned or proposed search would be a signal of physics beyond the Standard Model !

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So why look?

An EDM would help with fundamental puzzles…

Additional sources of CP-violation are needed to explain matter-anti-matter asymmetry of the universe (why are we here).

Extensions to the Standard Model (SUSY) suggest that EDMs will appear within next 1-2 orders of magnitude improvement in sensitivity.

If no EDM is found by any planned or proposed search. then our ability to explain open Standard Model issues will be in serious trouble !

What does a storage ring bring to present spectrum of searches?

Discovery Phase

- a larger effective electric field from $\boldsymbol{v} \times \boldsymbol{B}$ in particle frame
  - increase is 10 to 100 times typical laboratory field
- the ability to extend searches to charged particles
  - muon, deuteron, proton, (^{3}He)
  - need a source of polarized particles, method to measure
    - small spin components to qualify

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Development Phase

different systematic effects from trap or box searches

not subject to leakage currents in high voltage searches

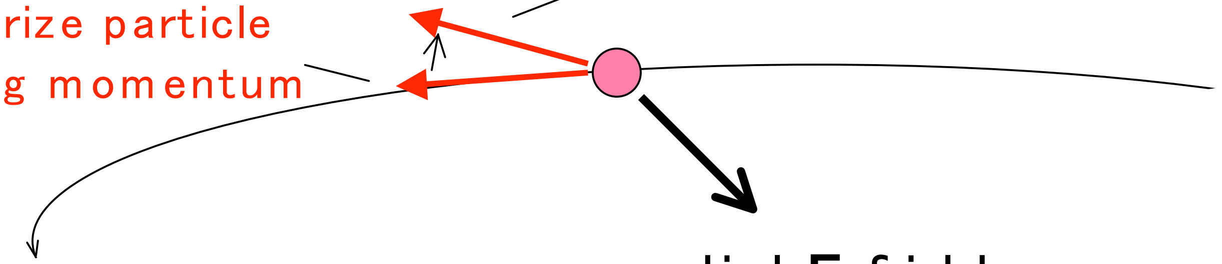
comparison of related systems (proton, neutron, deuteron)

allow initial exploration of source of CP-violation
(EDM on quark or in N-N interaction)

permit special sensitivity to quark EDMs in deuteron case

Liu and Timmermans, PRC
Lebedev *et al.,* PRD **70**, 016003 (2004)

What is the signal?

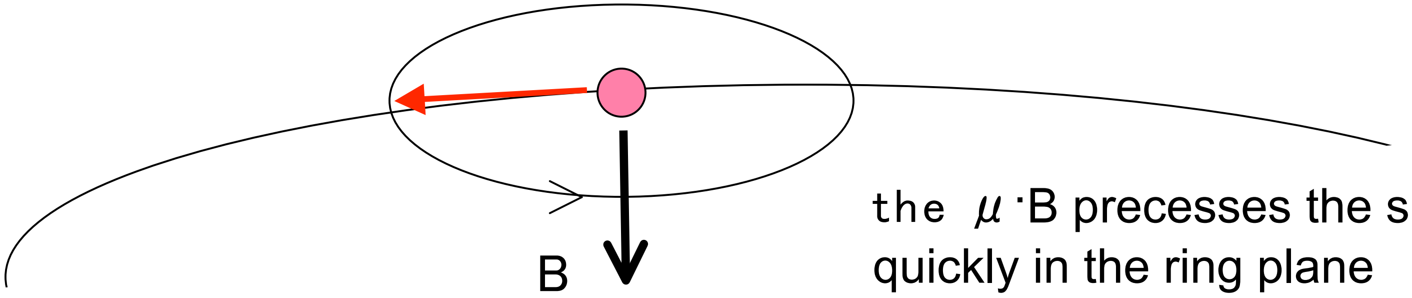


first
polarize particle
along momentum

an EDM will cause spin to
precess out of ring plane -
vertical polarization rises with time

radial **E** field
in particle frame

but there is a problem:



the $\mu \cdot$B precesses the spin
quickly in the ring plane

（together the precession plane tilts, but this is hard to observe）

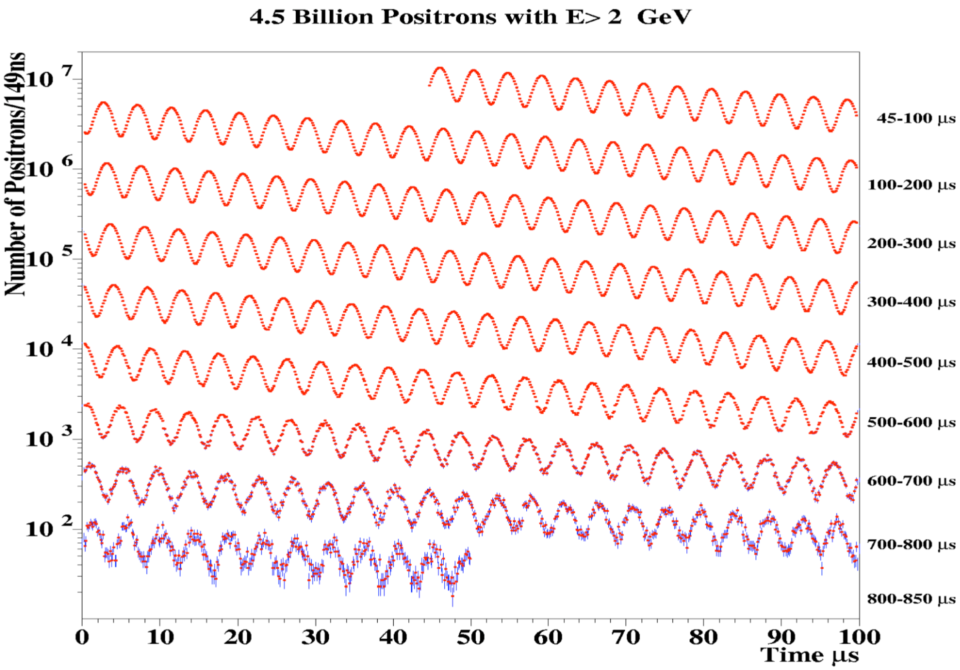
Nevertheless, this was used for muon EDM limit from *g-2* experiment.

Brookhaven *g-2* experiment:

- polarized muons from pion decay
- observe precession in 1.45 T field
  - using forward electron from decay

$$\omega_a = \textcircled{a}\frac{eB}{m}$$

unknown



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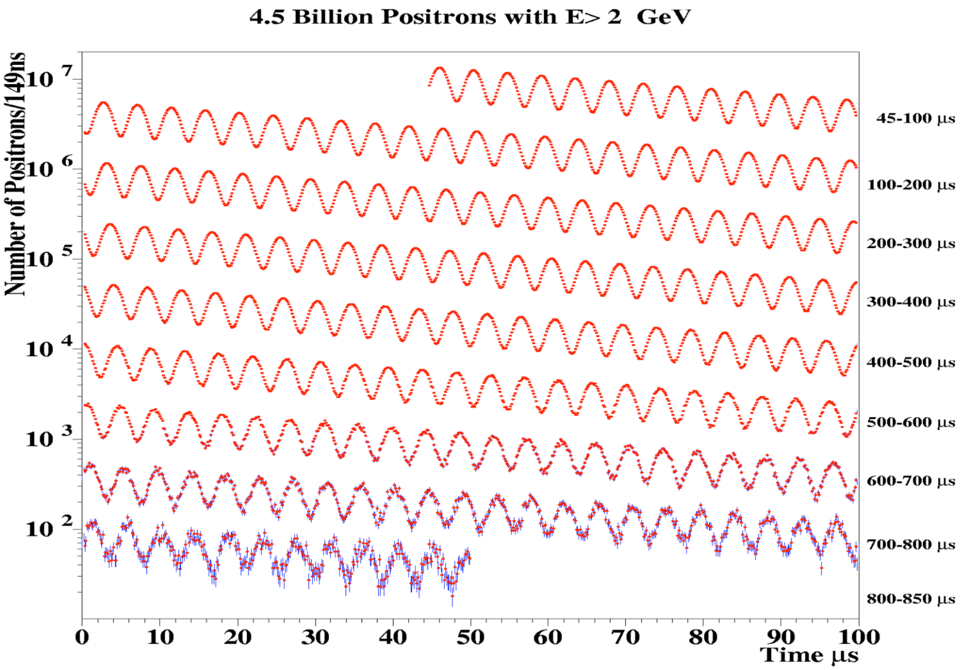

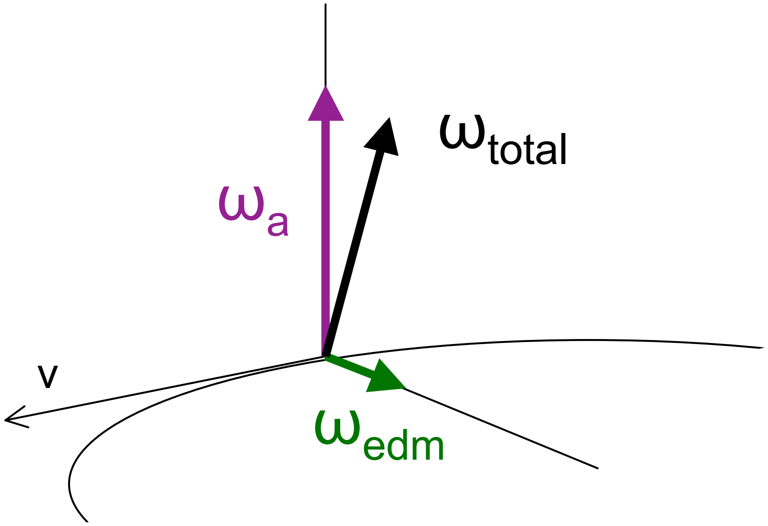

If the muon has an EDM,
the spin will oscillate vertically.

Upper limit on muon EDM is:
  2.7×10^{-19} e·cm

thesis of Ron McNabb

Two methods to deal with the *g-2* spin precession problem:

"Frozen spin" method

uses radial electric field to "slow" the anomalous spin precession

most "developed" of the two methods

restricted to particles with small anomalous moment (muon, deuteron),
  thus less flexible

larger ring, more expensive

sensitivity ~ 10^{-27} e·cm, limited by vertical E-field systematics

will discuss in detail to give sense of what is required

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“Resonant” method

uses spin-synchrotron resonance to build EDM signal

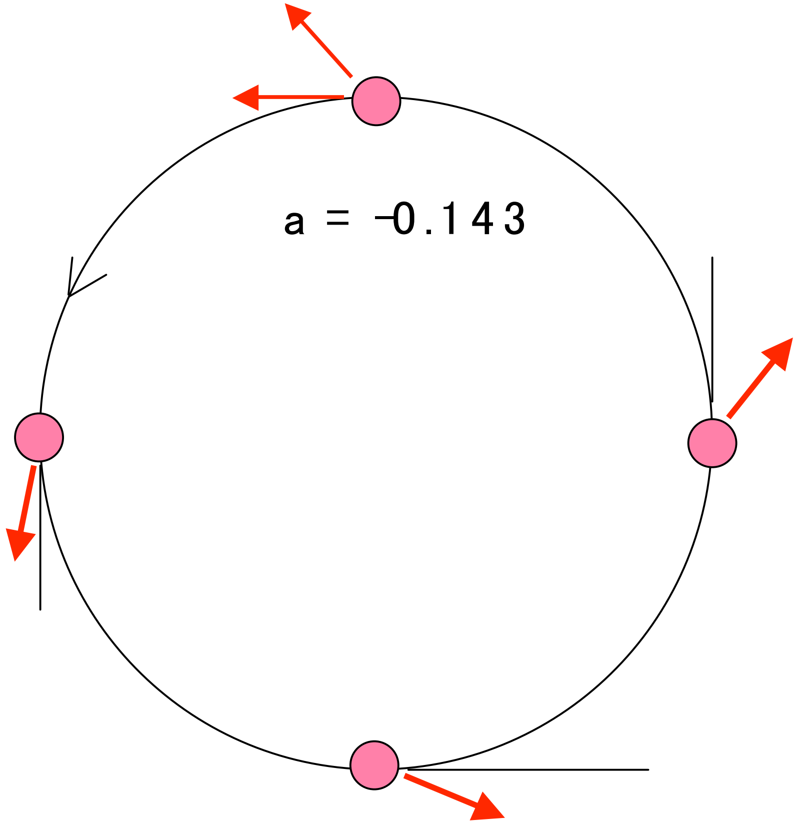
- study of this option began only recently
- can be used (in harmonic mode) for any anomalous moment, thus more flexible
- smaller ring, less expensive

sensitivity ~ 10^{-29} e·cm (4 months data collection)

Frozen Spin

good when anomalous moment is small (μ , d)

For the deuteron, $\omega_a < \omega_{cyc}$ and spin lags behind revolution around the ring.



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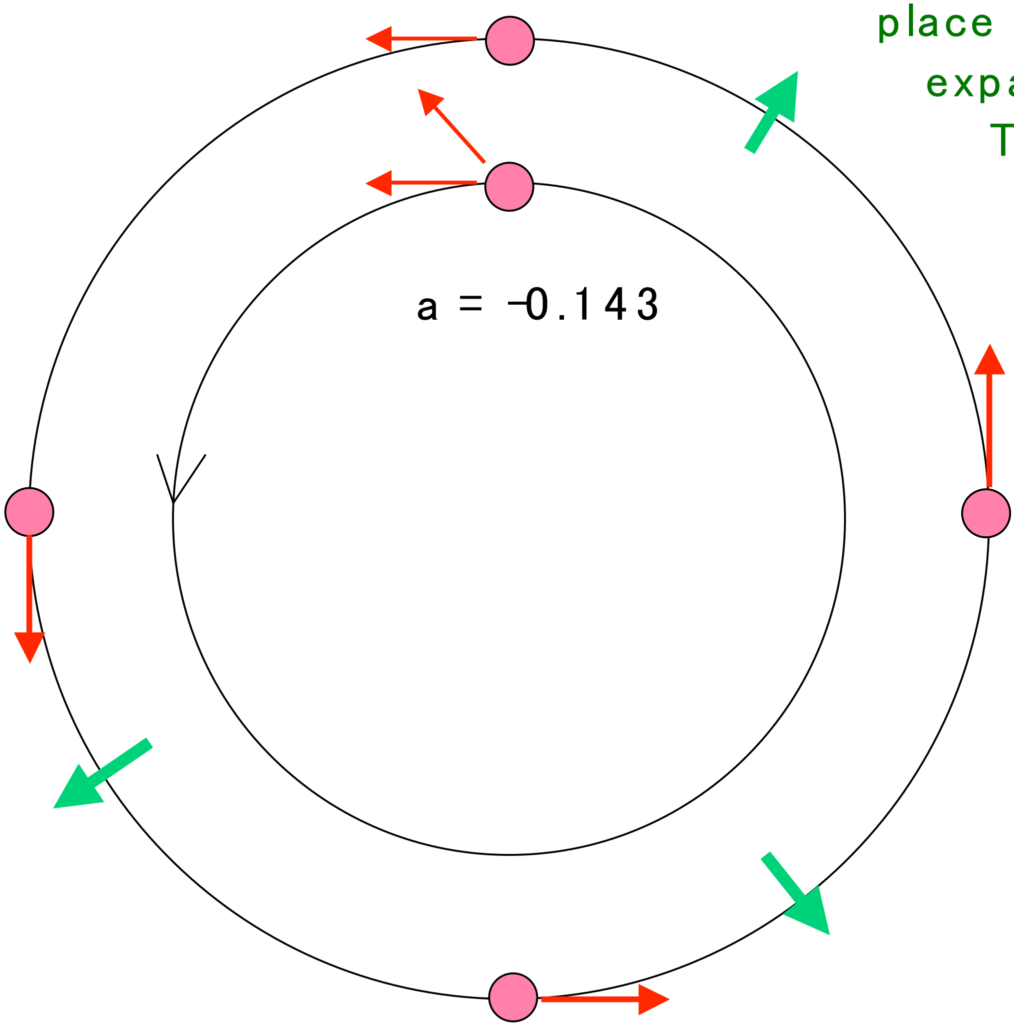


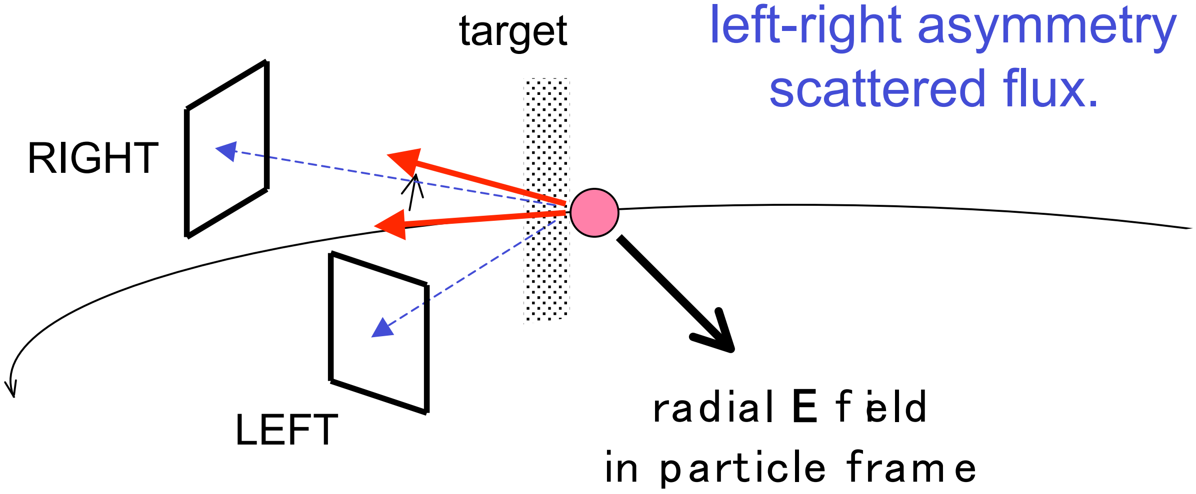
In all the bending magnets,
place an outward E field to
expand the size of the orbit.
This lengthens the time for
the particle to complete
a revolution while keeping
the B field the same.

The right ratio of B and
E makes $\omega_a = \omega_{cyc}$.

p = 0.7 GeV/c (126 MeV)
E = 3.5 MV/m
B = 0.21 T
radius = 13.3 m

What is the signal?

For stable particles, a measurement of the vertical polarization component requires a target and yields a left-right asymmetry in the scattered flux.



How frozen is "frozen"?

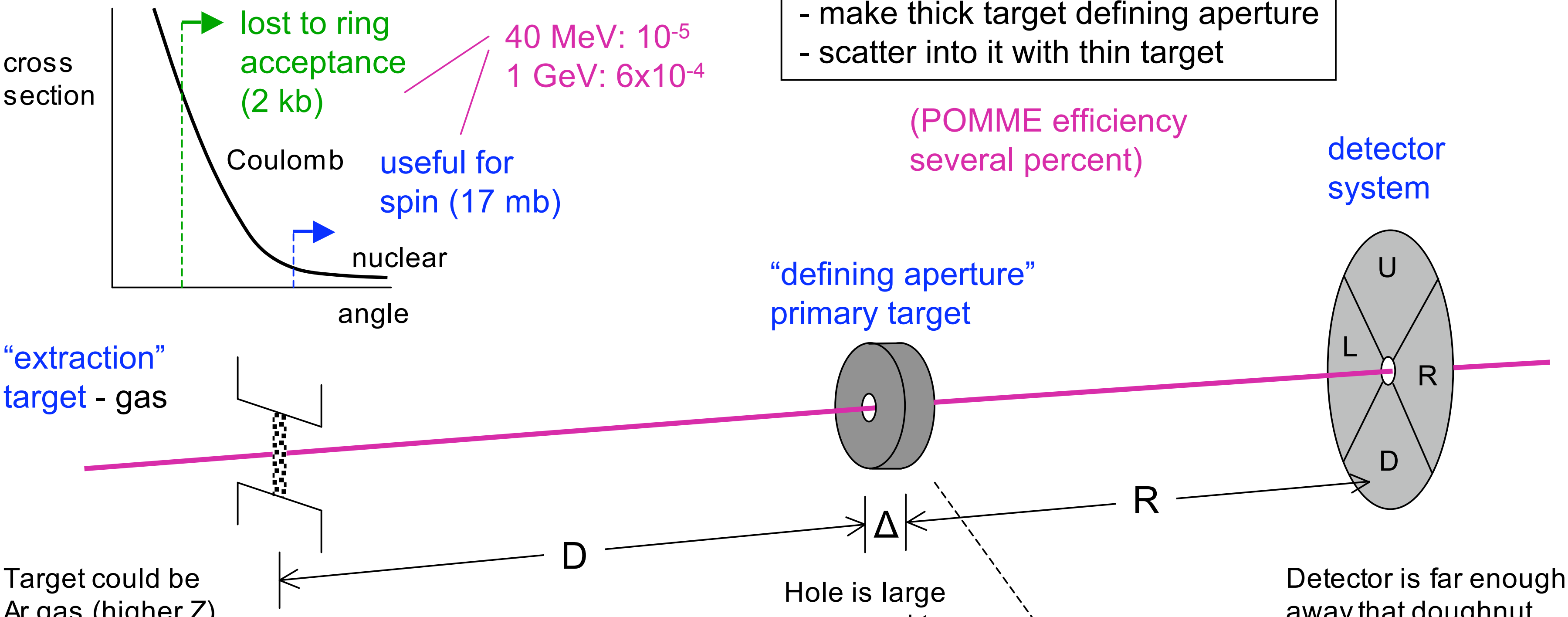
The limit is set by the asymmetry being > 10^{-5} for tensor polarization of 2% and a related analyzing power of 6%. It is 1/20° . That requires a control over the E/B ratio of 1 part in 5 × 10^{10}. This is *impossible*.

Alternative

Allow spin to precess slowly in the ring plane. Measure polarizations continuously. Extract EDM signal from precession curves.

EDM polarimeter

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



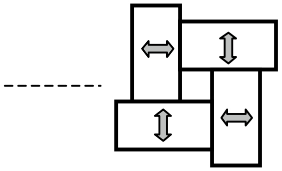
Target could be Ar gas (higher Z).

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

Events must imbed far enough from hole to not multiple scatter out of primary target, thus Δ << D. Δ, which is a large fraction of the deuteron range, sets scale for polarimeter.

Hole is large compared to beam. Everything that goes through hole stays in the ring. (It may take several orbits to stop scattered particle.)

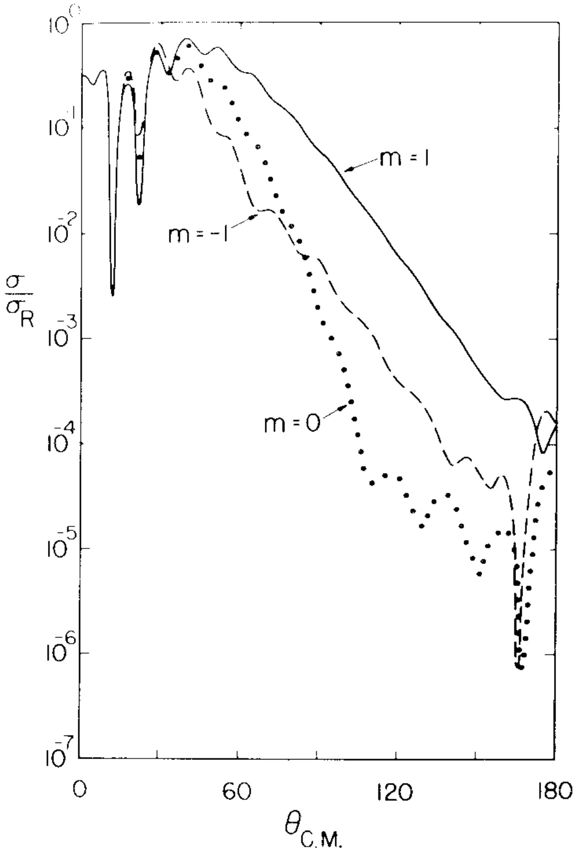
Primary target may need to be iris to allow adjustment of position and inner radius. It may also need to be removed during injection.



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

Rainbow elastic scattering

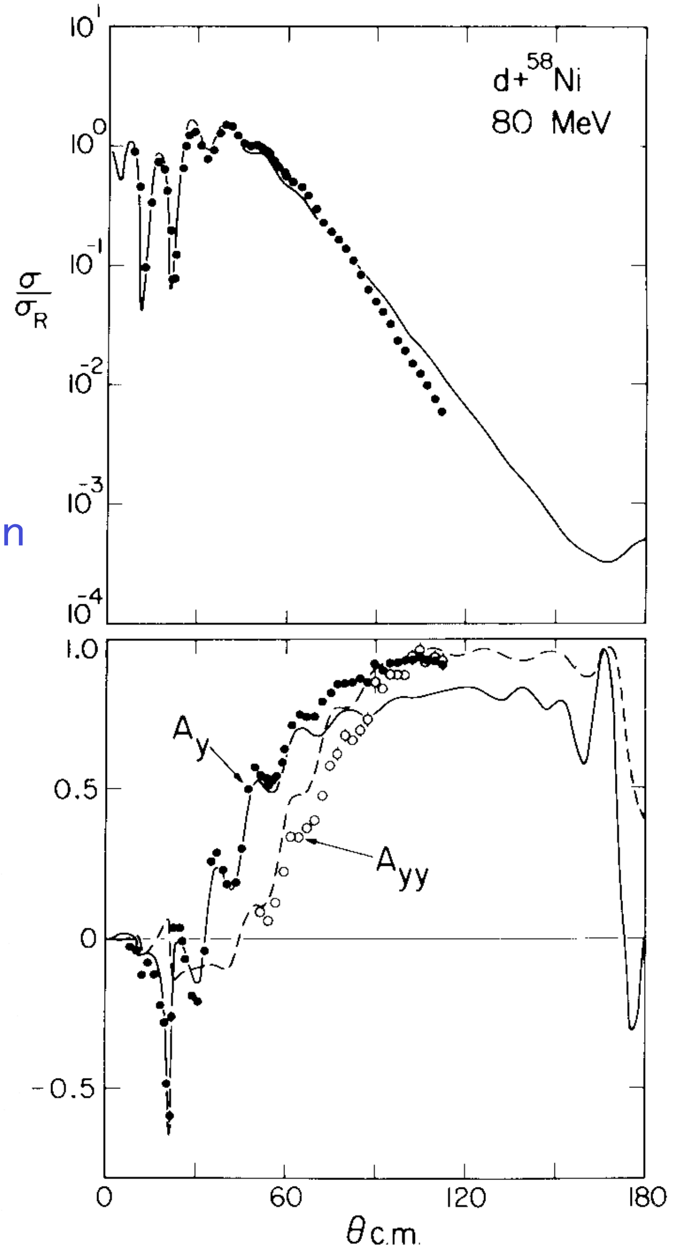
A strong spin-orbit force separates
the deuteron spin projections
(perpendicular to scattering plane)
into three very different cross sections.



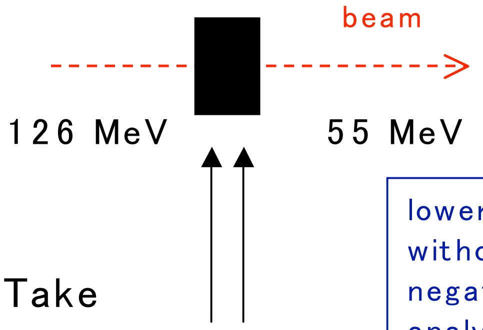
In this scheme, the
analyzing powers can
be calculated as:

$$A_y = \frac{\sigma_1 - \sigma_{-1}}{\sigma_1 + \sigma_0 + \sigma_{-1}}$$

$$A_{yy} = \frac{\sigma_1 + \sigma_{-1} - 2\sigma_0}{\sigma_1 + \sigma_0 + \sigma_{-1}}$$



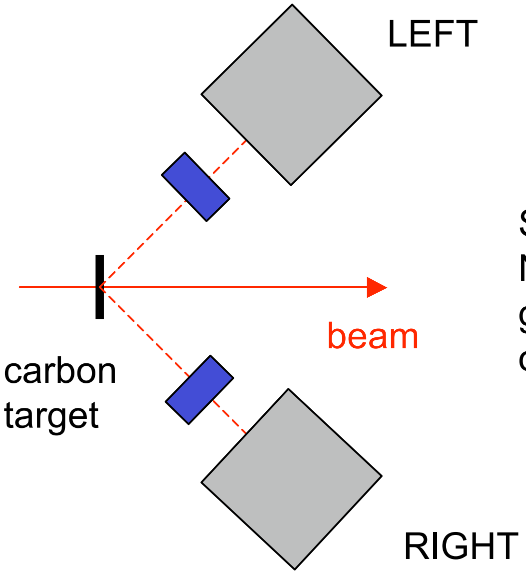
Basic Plan



Take
data at
two energies:
80 and 110 MeV.

lower limit without hitting negative analyzing powers

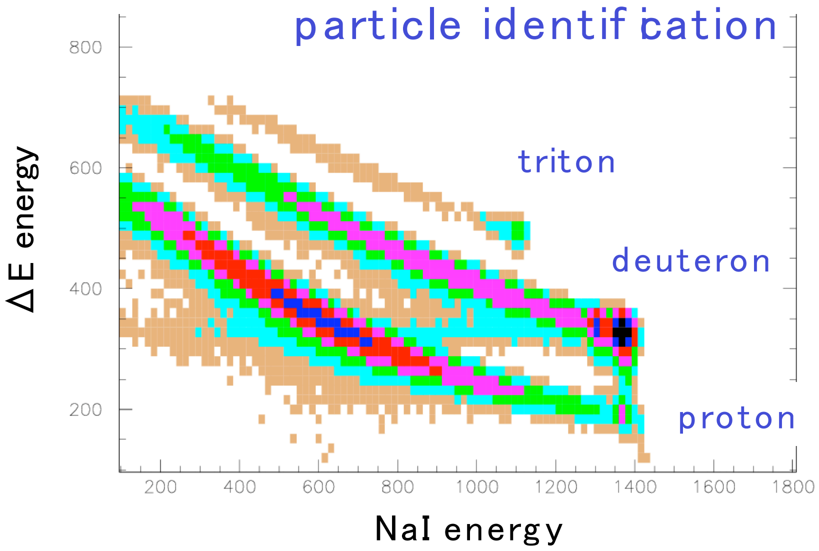
CH$_2$ or C target

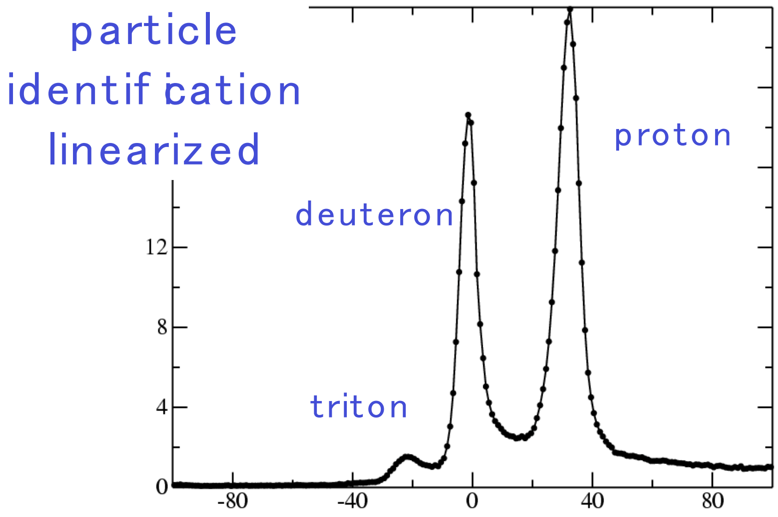


Set up plastic and NaI scintillators to gather broad range of particle data.

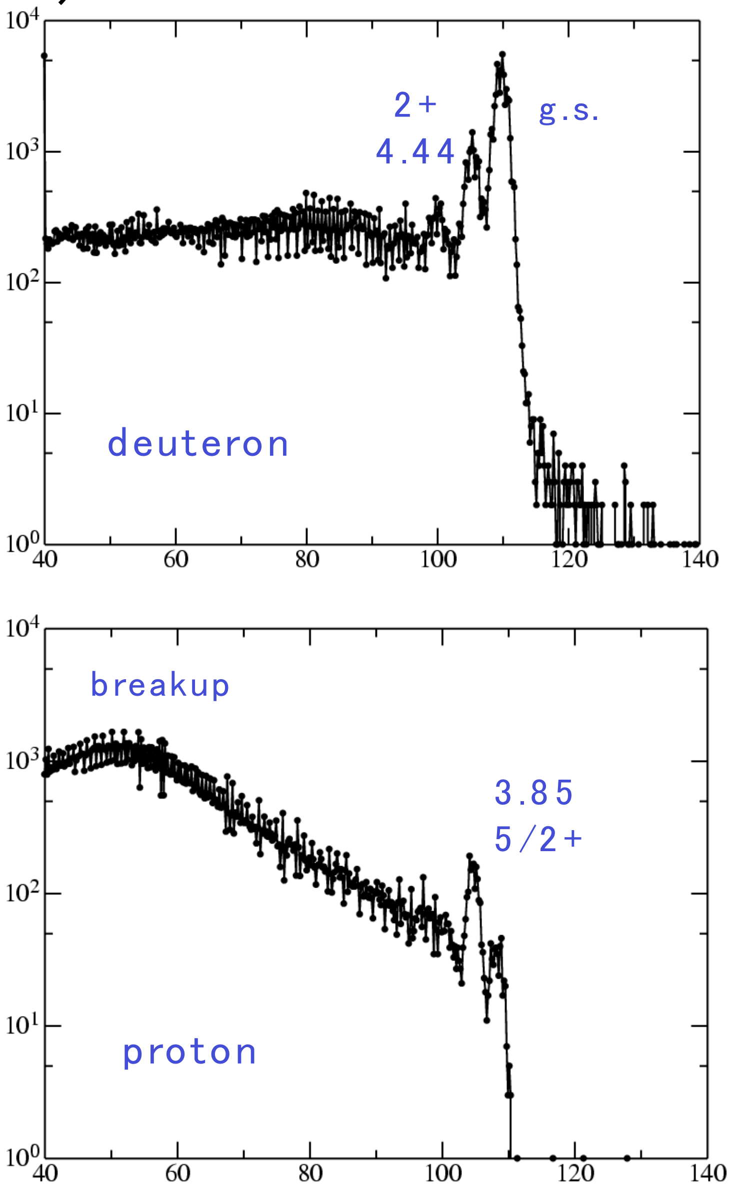
KVI in-beam polarimeter with 8 detector arm

Sample spectra (110 MeV, 27°)



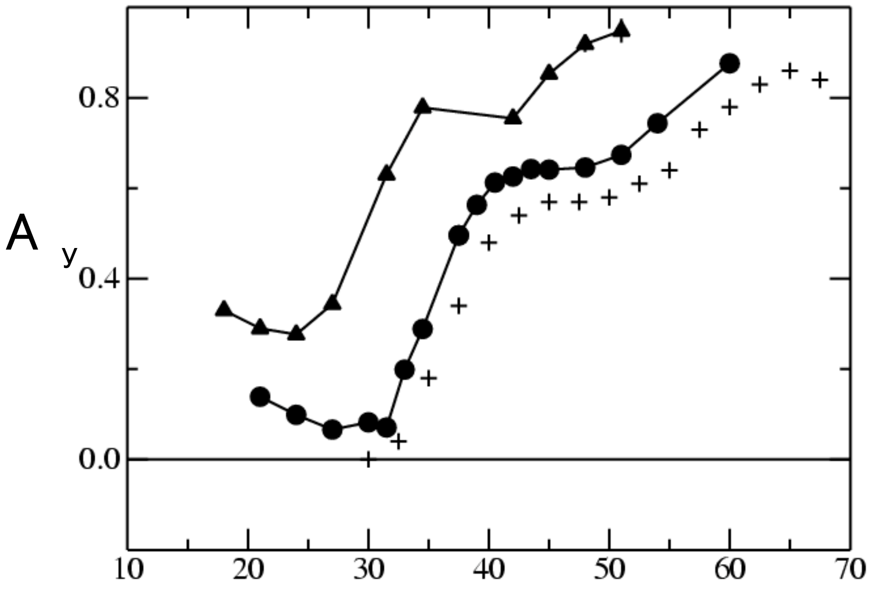

particle identification linearized

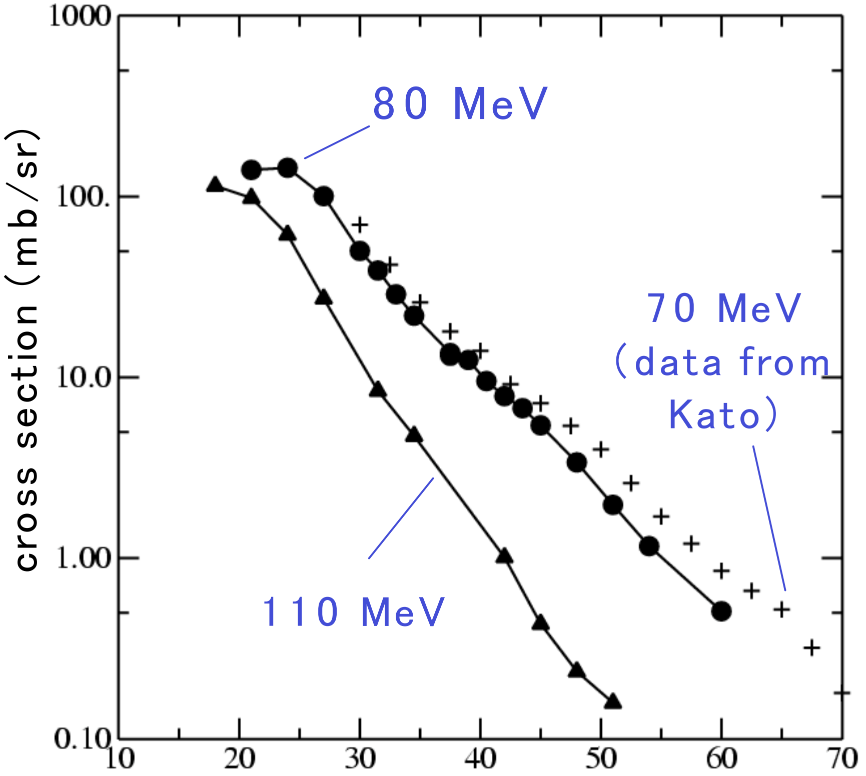
selected particle spectra



energy of particle emitted from target (MeV

Deuteron elastic scattering angular distributions

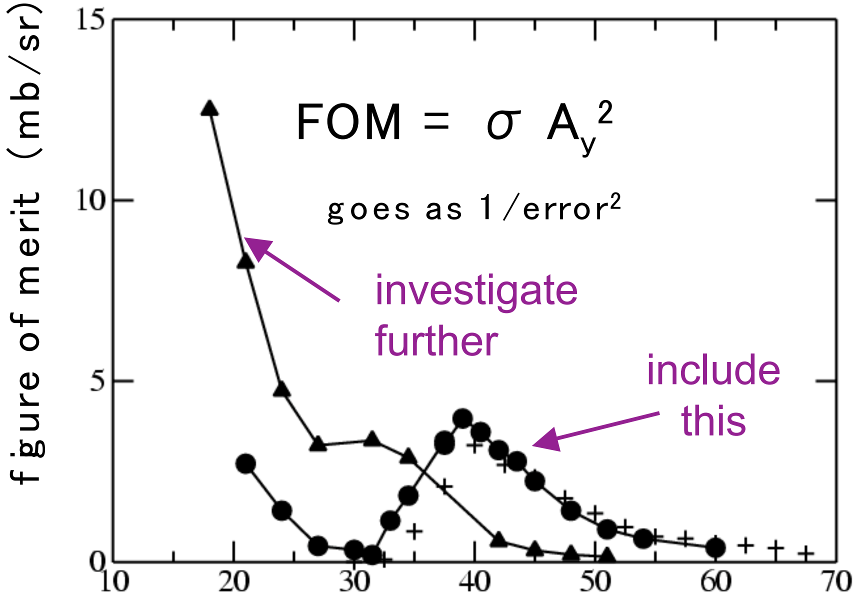




80 MeV

70 MeV (data from Kato)

110 MeV



$\mathrm{FOM} = \sigma A_y^2$

goes as $1/\mathrm{error}^2$

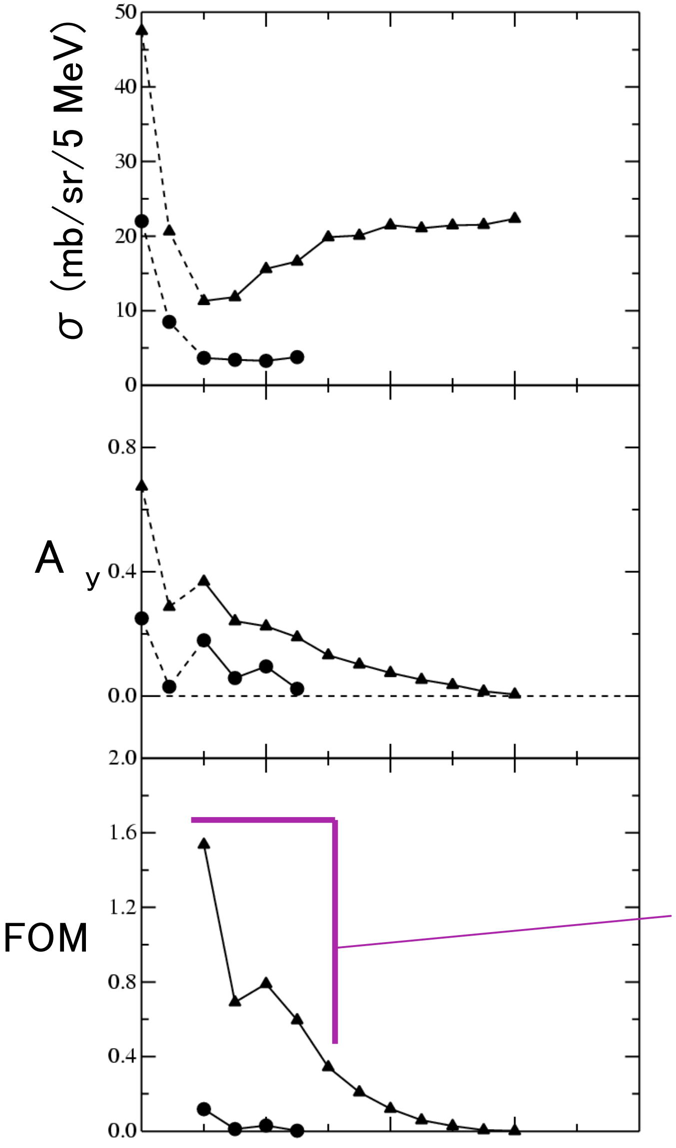
investigate further

include this

laboratory scattering angle (deg)

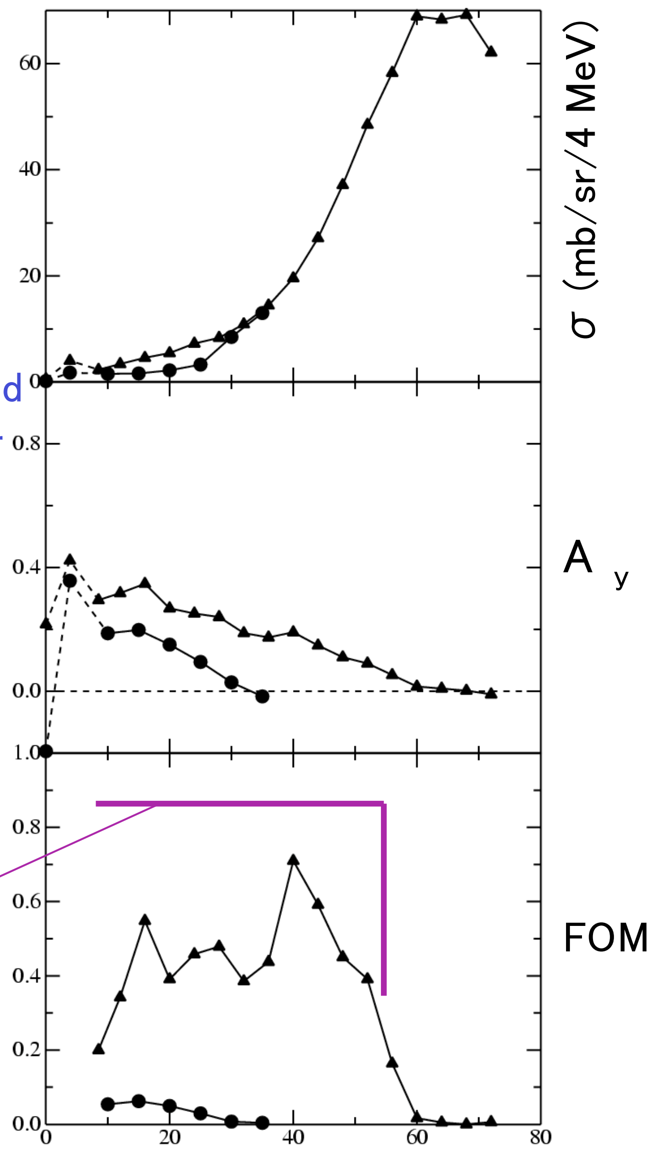
Deuterons and protons from the continuum

34.5°

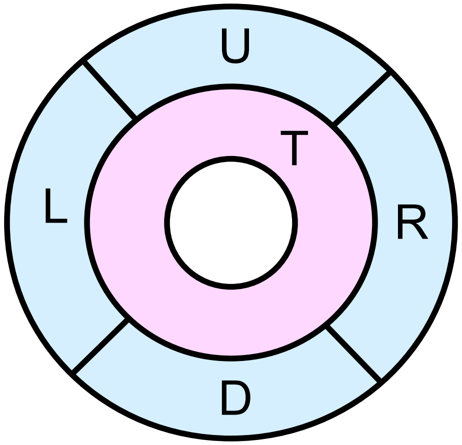


The positive analyzing powers from the spin-orbit interaction extend into the continuum for both deuterons and protons (neutron transfer or breakup).

The design should include some of these regions.



Polarimeter “mock-up”



The deuteron beam from a polarized ion source is specified by the fractions of the beam in each magnetic substate:

$$\tau_{10} = \sqrt{\tfrac{3}{2}}\,(f_+ - f_-)$$

$$\tau_{20} = \sqrt{\tfrac{1}{2}}\,(1 - 3f_0)$$

At any time the beam is specified with four parameters:

- τ_{10}: vector polarization
- τ_{20}: tensor polarization
- β: polar angle of spin axis
- φ: azimuthal angle of spin axis

Each polarimeter data time slice can be used to obtain:

$$S = L + R + D + U + 4T$$

$$\Delta_{LR} = (L - R)/S$$

EDM term appears here

$$\Delta_{DU} = (D - U)/S$$

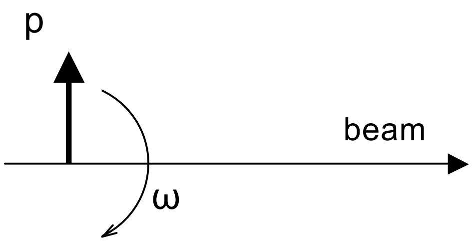
$$\Delta_{20} = (L + R + D + U - 4T)/S$$

$$\Delta_{22} = (L + R - D - U)/S$$

These can all be obtained for a single spin state.

Differences between opposite spin states can cancel some systematic errors.

Data Generator



Inject P sideways (in ring plane)
Allow to precess at ω for 1 second
EDM precession is added by
  integrating longitudinal component (p_z)
Take polarization shapshot at regular
  intervals (say every 10 ms)
Compute count rate in each detector
Change count rate randomly based on
  statistics for that rate

$$it_{11} = \tau_{10} \tfrac{1}{\sqrt{2}} \sin\beta \cos\phi$$

$$t_{20} = \tau_{20} \tfrac{1}{2} (3\cos^2\beta - 1)$$

$$t_{21} = \tau_{20} \sqrt{\tfrac{3}{2}} \sin\beta \cos\beta \sin\phi$$

$$t_{22} = \tau_{20} \sqrt{\tfrac{3}{8}} \sin^2\beta \cos 2\phi$$

where

$$\tau_{10} = \sqrt{\tfrac{3}{2}} (f_+ - f_-)$$

$$\tau_{20} = \sqrt{\tfrac{1}{2}} (1 - 3 f_0)$$

Count rates:

$$C_L = C_0 \, (1 + 2\, it_{11}\, iT_{11} + t_{20}\, T_{20} + 2\, t_{21}\, T_{21} + 2\, t_{22}\, T_{22})$$

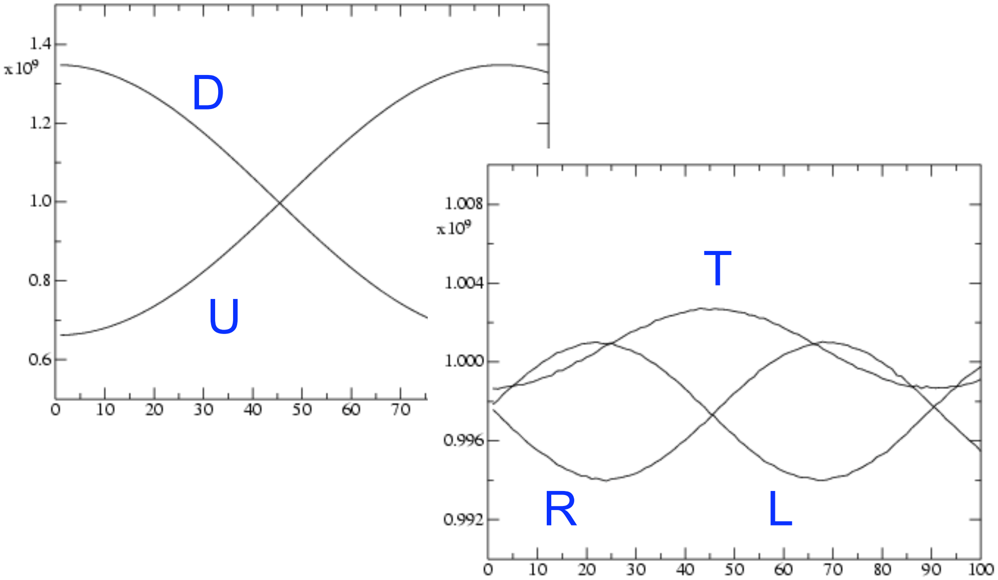
$C_R =$

$C_D =$

$C_U =$

$C_T =$

etc. with angles rotated as
  needed for each detector



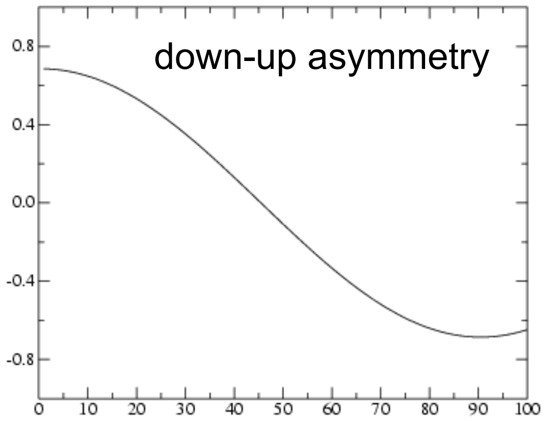
Typical Output

function of time

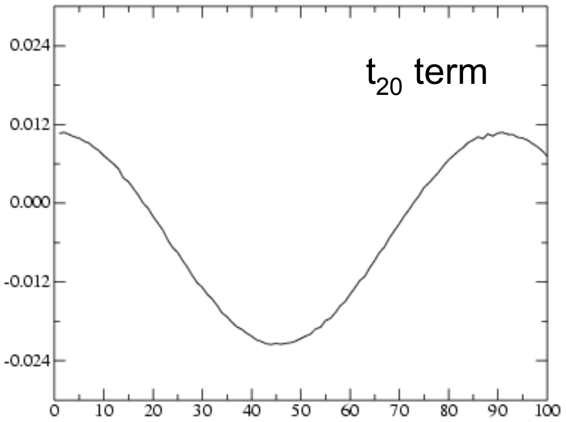
$$\vartheta = \theta_0 + \bar{\theta} t$$

spin injection angle

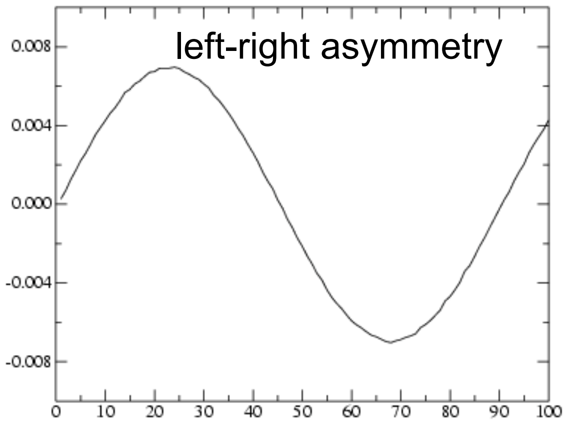
spin precession rate



$$\Delta_{DU} = A_1 \cos\vartheta + A_2 + A_3 \sin 2\vartheta$$



$$\Delta_{20} = A_7 (3\sin^2\vartheta - 1)/2$$



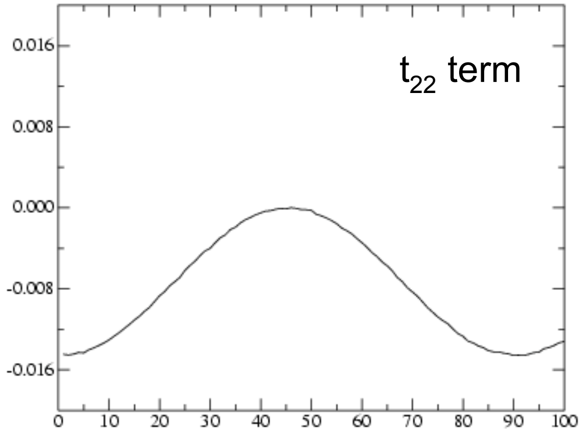
$$\Delta_{LR} = A_4 10^{-4} \cos\vartheta + A_5 10^{-4}$$

$$+ A_6 \sin 2\vartheta$$

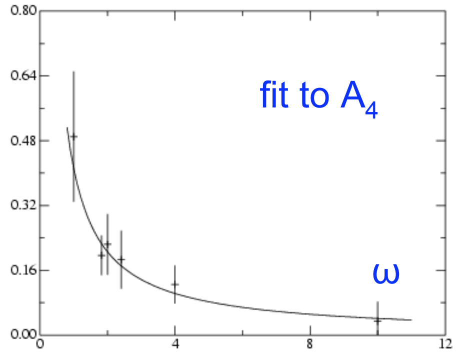
EDM term

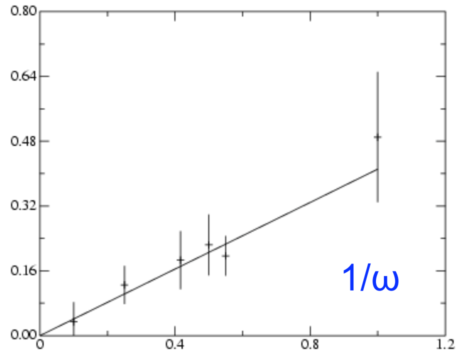
t_{21} term

constant term needed because EDM grows from zero



$$\Delta_{22} = A_8 \cos^2\vartheta$$





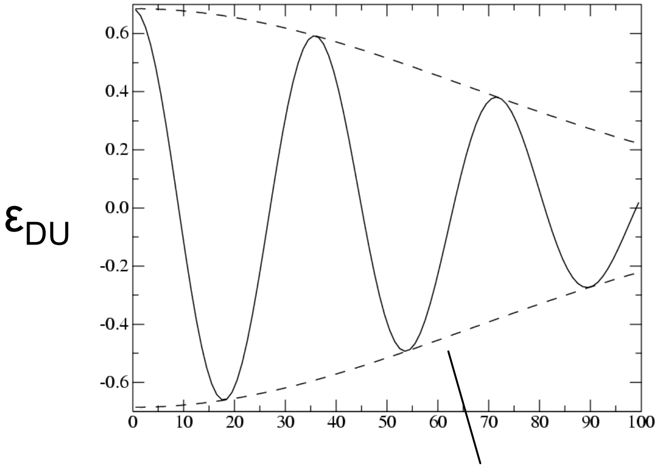
A_4 at several precession rates

Depolarization

Reduction is convolution of cosine with Gaussian of width σ

$$atten: \quad \exp\left(-\sigma^2/2\right)$$

When depolarization comes from finite-width binning, σ ∝ *Dt*.



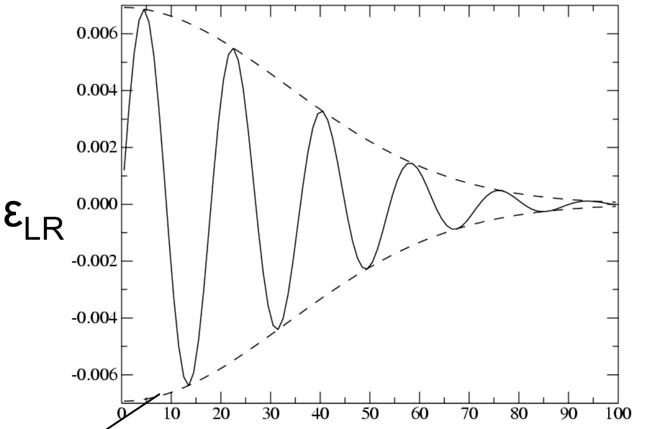
envelope is:

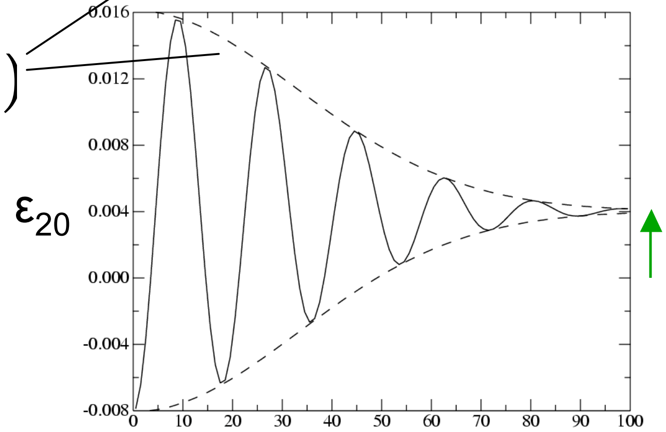
$$\exp\left(-\frac{D^2t^2}{2}\right)$$

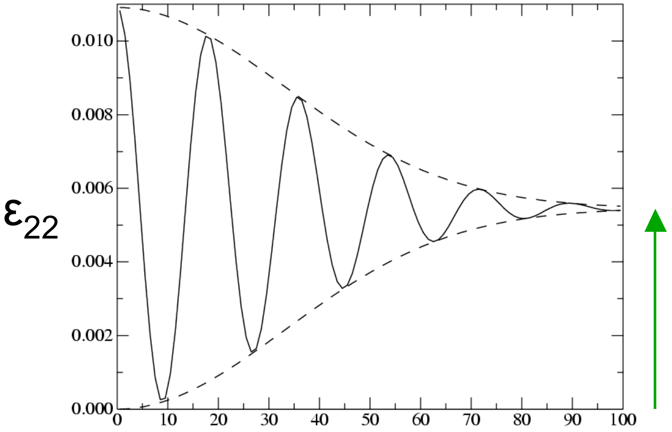
D is added to the list of fitting parameters.

Tensor asymmetries vary twice as quickly (for this case) and attenuate twice as quickly

$$\exp\left(-2D^2t^2\right)$$







Beam moments t_{20} and t_{22} go to non-zero value (note arrows).

Deuteron Statistical Error (126MeV):

$$\boxed{\sigma_d \approx 8 \frac{\hbar a \gamma^2}{\sqrt{\tau_p} E_R (1+a) A P \sqrt{N_c f T_{Tot}}}}$$

τ_p	: 10s.	**Polarization Lifetime (Coherence Time)**
A	: 0.5	**Polarimeter left/right asymmetry**
P	: 0.55.	**The beam polarization**
N_c	: 4×10^{11}d/cycle.	**The number of stored particles per cycle**
T_{Tot}:		**Total experiment running time**
f	: 0.01	**Useful event rate fraction**
E_R	: 3.5MV/m.	**Radial electric field**
σ_d	: 10^{-27} e·cm.	**Statistical error**

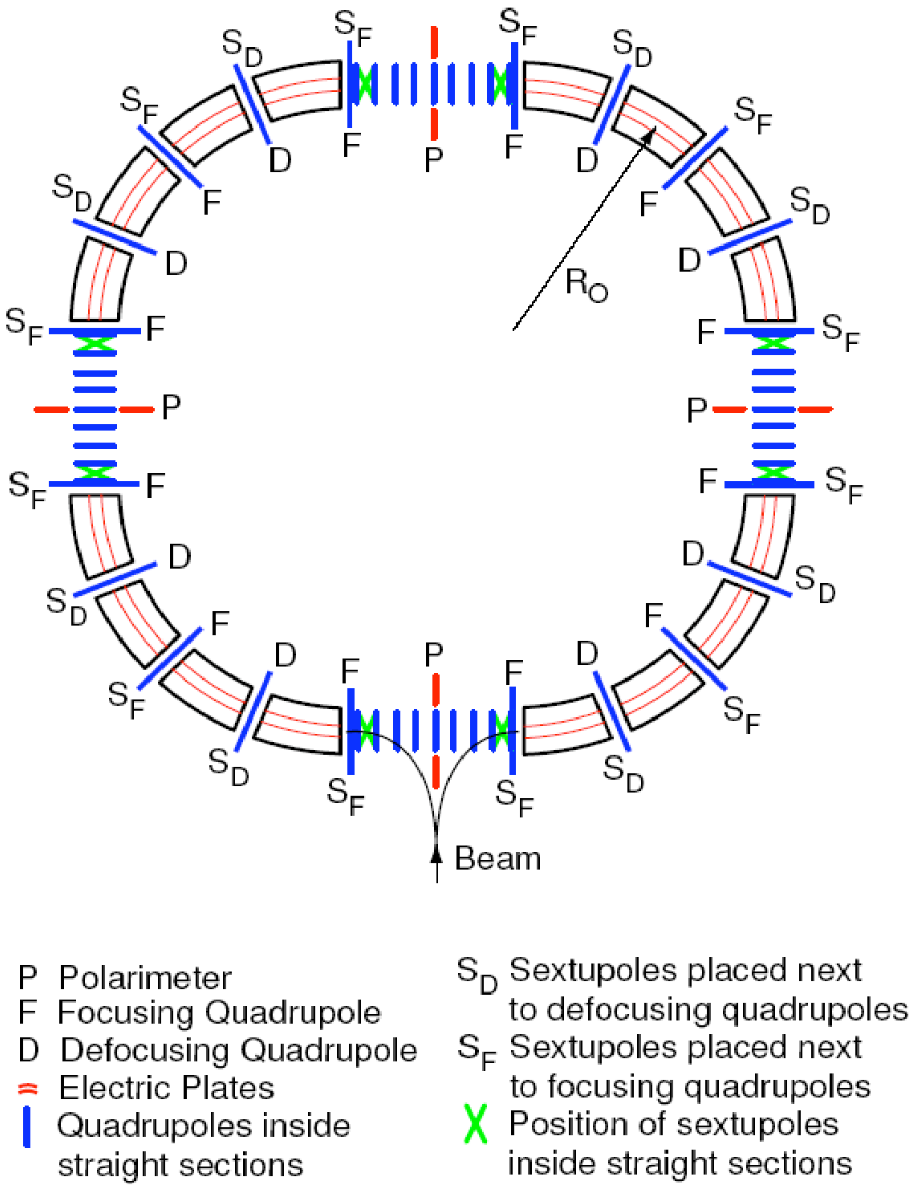
T_{tot} is approximately three days of continuous running

Polarization coherence time:

In-plane polarization is inherently unstable, so depolarizing effects must be minimized.

Spread in ω_a from $\Delta p/p$ is removed by locking all orbits to RF cavity.

Betatron oscillations cause spread because particles with different orbit length have different p in RF system and different ω_a. Cancel this with sextupole fields that move the average orbit position depending on betatron amplitude. This must be done in three dimensions.

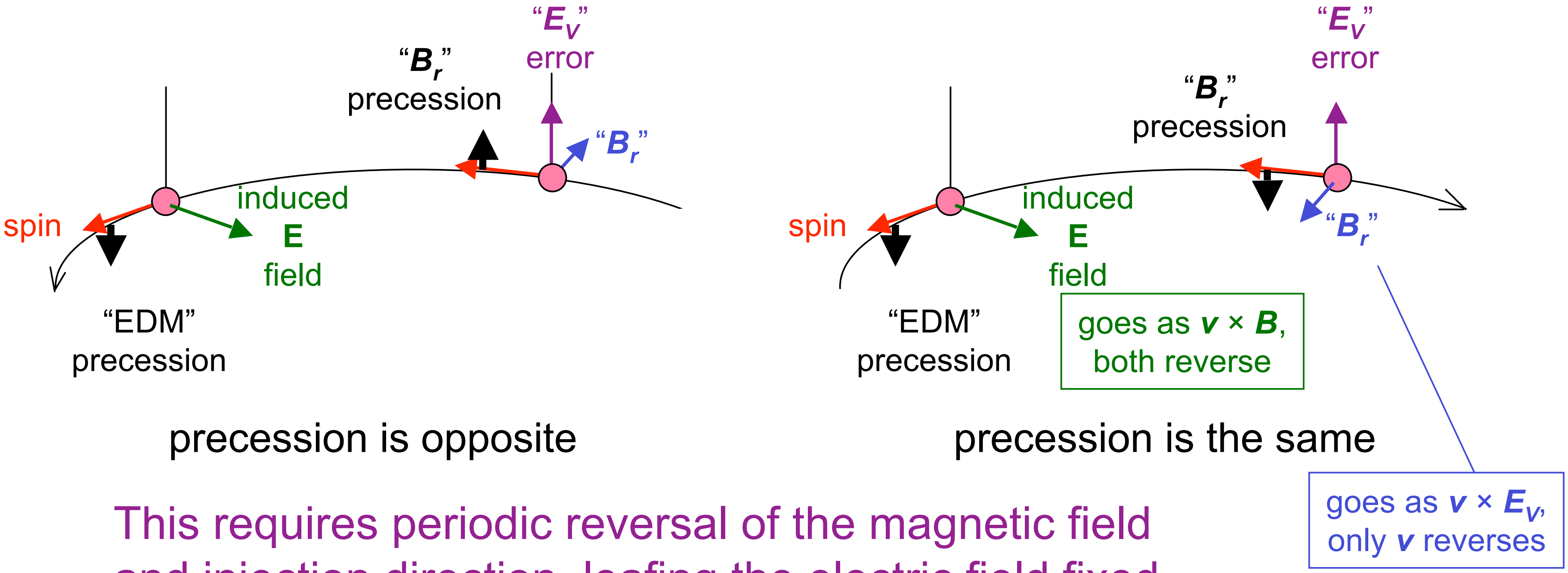


mock ring lattice shows sextupole placement

The leading systematic effect comes from $\boldsymbol{B}_r$.
In the "frozen spin" ring this arises from E-field alignment.
$\boldsymbol{v} \times \boldsymbol{E}_v$ generates $\boldsymbol{B}_r$ in particle frame.

One solution is to operate the ring in both directions.

counter-clockwise (CCW) clockwise (CW)



goes as $\boldsymbol{v} \times \boldsymbol{B}$, both reverse

goes as $\boldsymbol{v} \times \boldsymbol{E}_v$, only $\boldsymbol{v}$ reverses

precession is opposite precession is the same

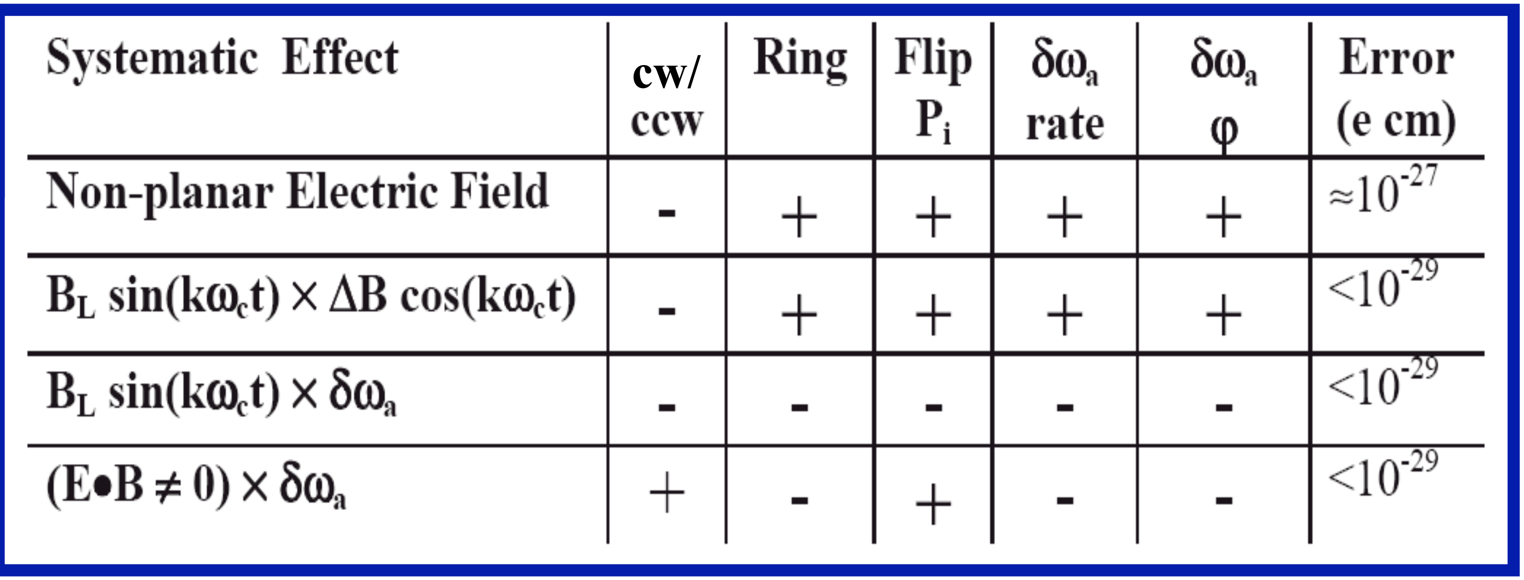
This requires periodic reversal of the magnetic field and injection direction, leafing the electric field fixed.

We estimate errors in this procedure limit sensitivity to 10^{-27} e·cm.

Systematic Error Symmetries (+) Same as EDM; (-) is opposite

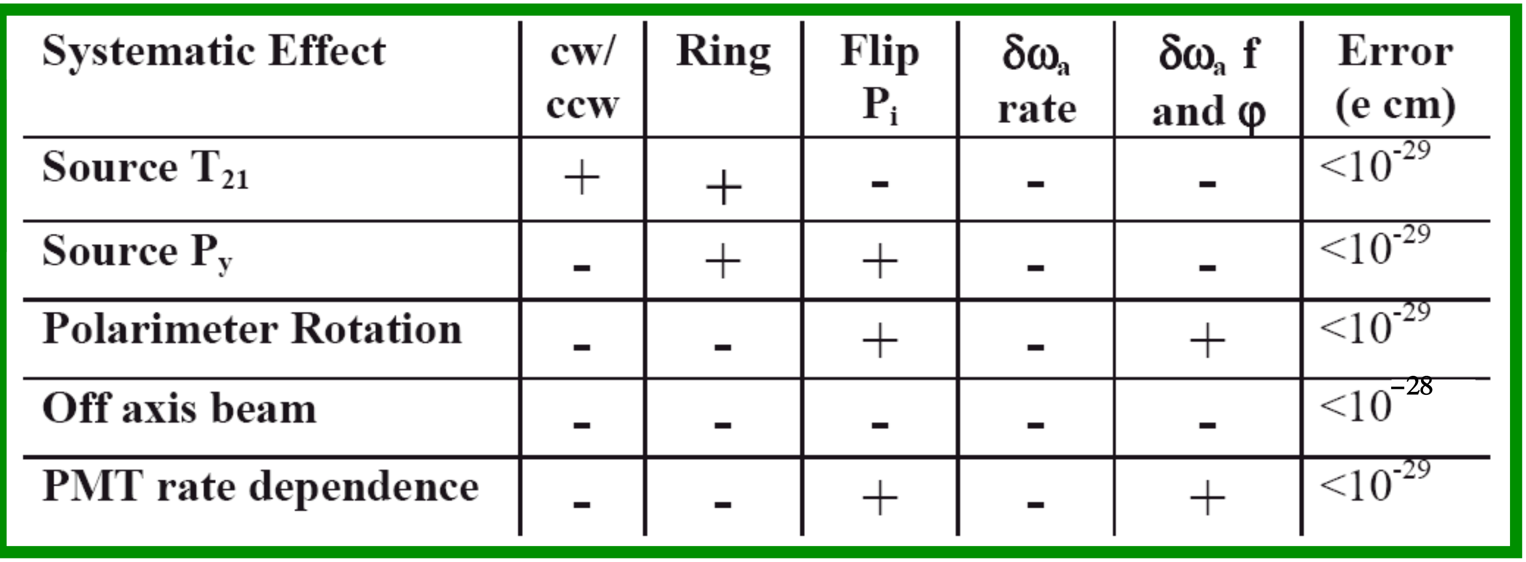
Spin Related

Non-Commutativity Effects



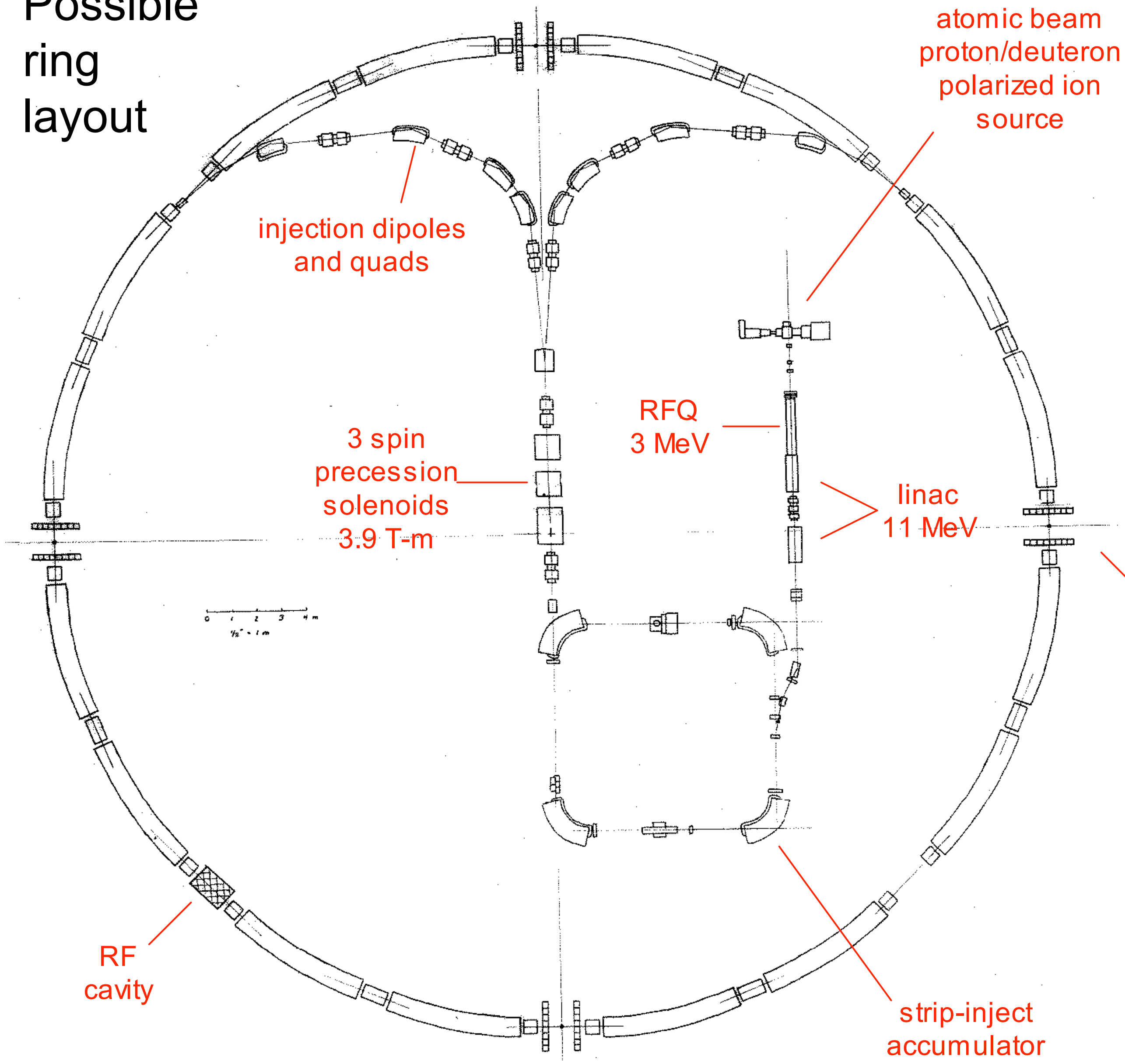
Systematic Effect	cw/ ccw	Ring	Flip P_i	$\delta\omega_a$ rate	$\delta\omega_a$ φ	Error (e cm)
Non-planar Electric Field	-	+	+	+	+	$\approx 10^{-27}$
$B_L \sin(k\omega_c t) \times \Delta B \cos(k\omega_c t)$	-	+	+	+	+	$<10^{-29}$
$B_L \sin(k\omega_c t) \times \delta\omega_a$	-	-	-	-	-	$<10^{-29}$
$(E \bullet B \neq 0) \times \delta\omega_a$	+	-	+	-	-	$<10^{-29}$

Polarimeter Related



Systematic Effect	cw/ ccw	Ring	Flip P_i	$\delta\omega_a$ rate	$\delta\omega_a$ f and φ	Error (e cm)
Source T_{21}	+	+	-	-	-	$<10^{-29}$
Source P_y	-	+	+	-	-	$<10^{-29}$
Polarimeter Rotation	-	-	+	-	+	$<10^{-29}$
Off axis beam	-	-	-	-	-	$<10^{-28}$
PMT rate dependence	-	-	+	-	+	$<10^{-29}$

Possible ring layout



atomic beam proton/deuteron polarized ion source

injection dipoles and quads

RFQ 3 MeV

3 spin precession solenoids 3.9 T-m

linac 11 MeV

polarimeter (4)

RF cavity

strip-inject accumulator and synchrotron

Example for ring:

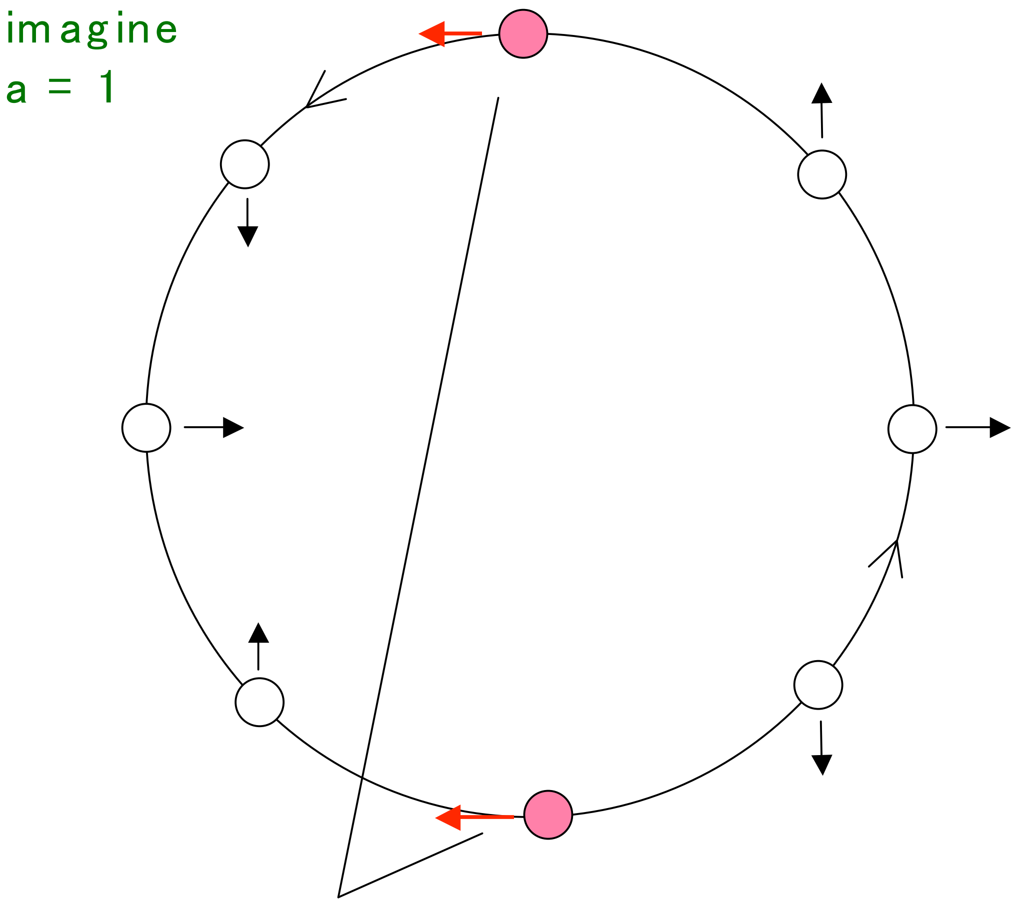
1. polarized ion source
2. pre-accelerator
3. accumulator
4. accelerator
5. spin preparation
6. injection
7. EDM ring

Ring Properties:

$E = 3.5$ MV/m
$B = 2.1$ kG
$T(d) = 126$ MeV
$p = 0.7$ GeV/c
$\beta = 0.35$
$\gamma = 1.07$
dipole radius $= 13.3$ m

Resonance

good for a broad class of charged particles

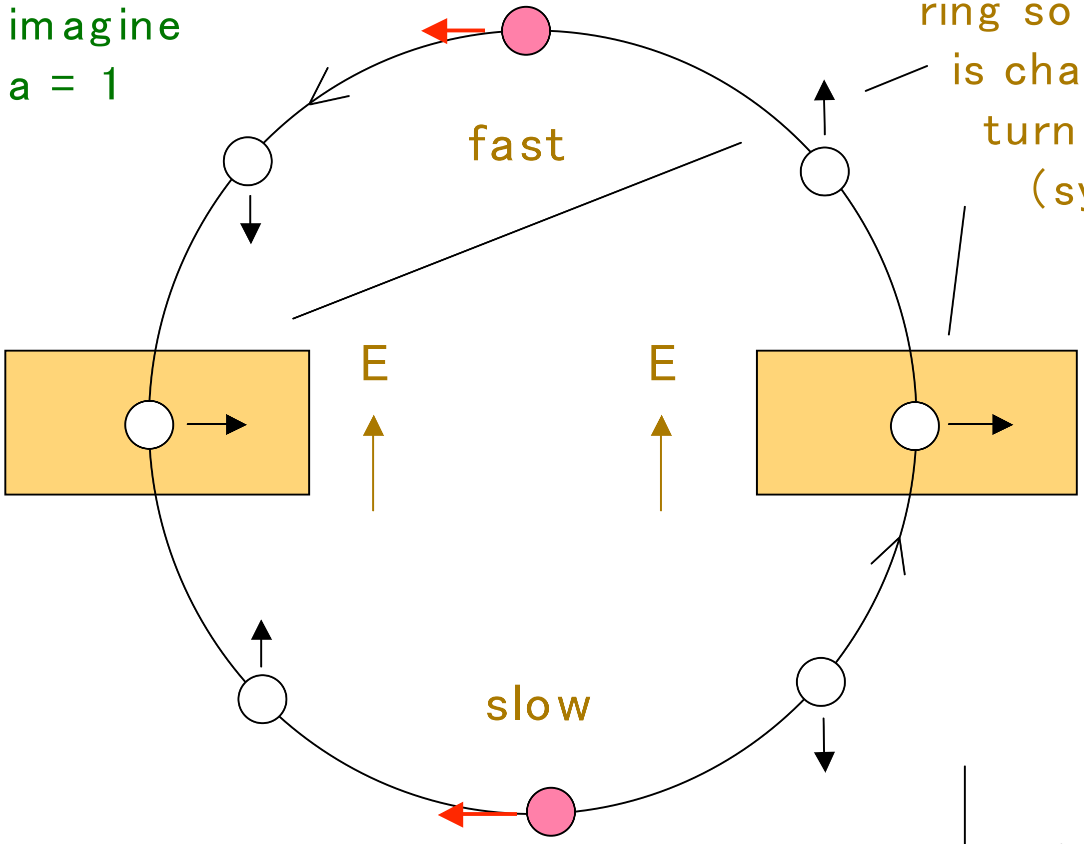


Since spin reverses, contributions to EDM precession cancel.

Resonance

good for a broad class of charged particles

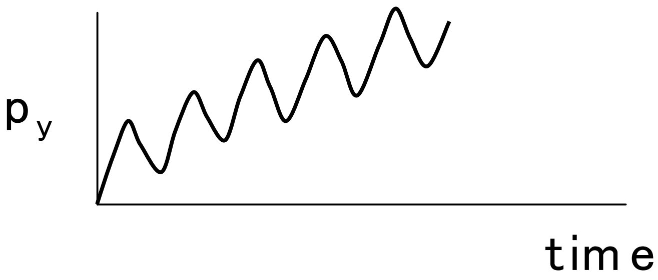
imagine
$a = 1$



Put 2 RF cavities in the ring so that the velocity is changed twice on each turn around the ring (synchrotron oscillation).

$\boxed{\omega_{sync} = \omega_a}$

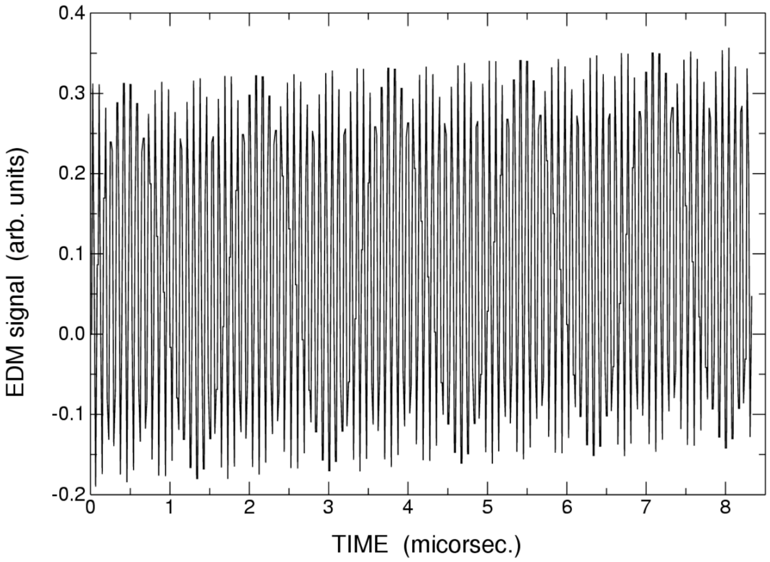
Vertical polarization accumulates in opposite ways on opposite sides of the ring. But speed change means it does not cancel.



for protons, operate at $\omega_{sync} = \omega_a - 2$

No radial electric field required.
Ring operates at $\omega_a = \omega_{sync}$; oscillations are forced.

Accumulation of vertical polarization happens along with much larger vertical oscillation (as in *"g-2"*).



(Simulation for proton ring.)

Bending magnet field not restricted by E-field,
so larger fields (× 8) and smaller ring.
In principle, any particle can run with any magnetic moment.

For particles such as protons ($a = 1.79$), $\omega_{sync} > \omega_{cyc}$.
Such high frequencies are hard to achieve, so operate at an
with this relationship to the cyclotron frequency.

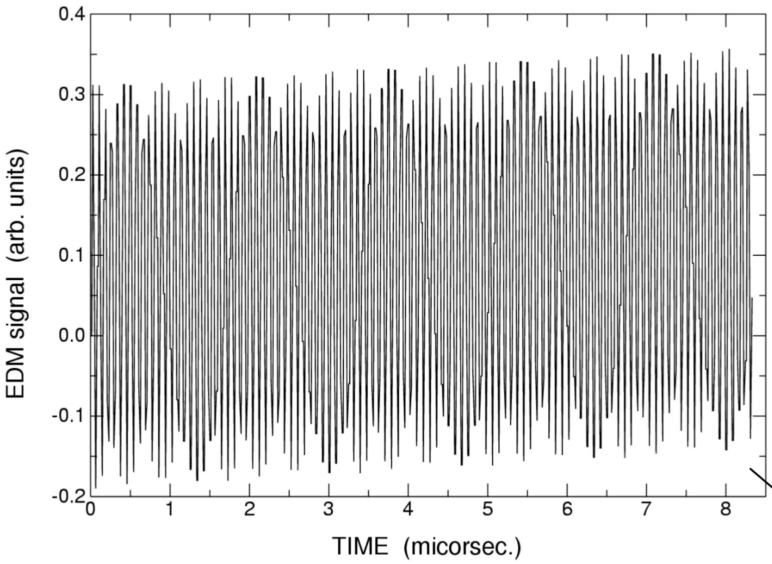
$$\omega_a - \omega_{sync} = n\ \omega_{cyc}$$

integer

Since $\omega_a = a\ \gamma\ \omega_{cyc}$, choose γ
so that $\omega_{sync} << \omega_{cyc}$.

For proton, one choice is $n = 2$ and $T = 160$ MeV,
which gives $\omega_{sync} = \omega_{cyc} / 10$.

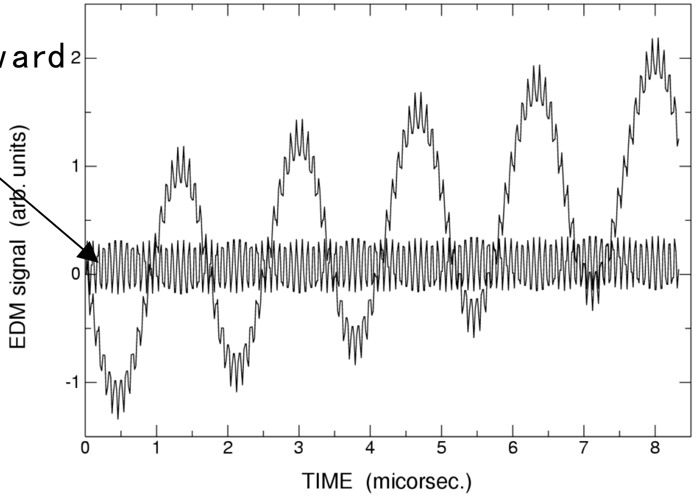
In this case, the rate of EDM accumulation can be enhanced
by modulating the strength of the magnetic field around the ring.
The number of field oscillations around the ring is “n”.



"EDM" signal when all magnets have the same field.

50 turns
EDM rise about 0.49

carry
signal
forward



Add "EDM" signal with half of magnets reduced to 40% of original field (0.64 T).

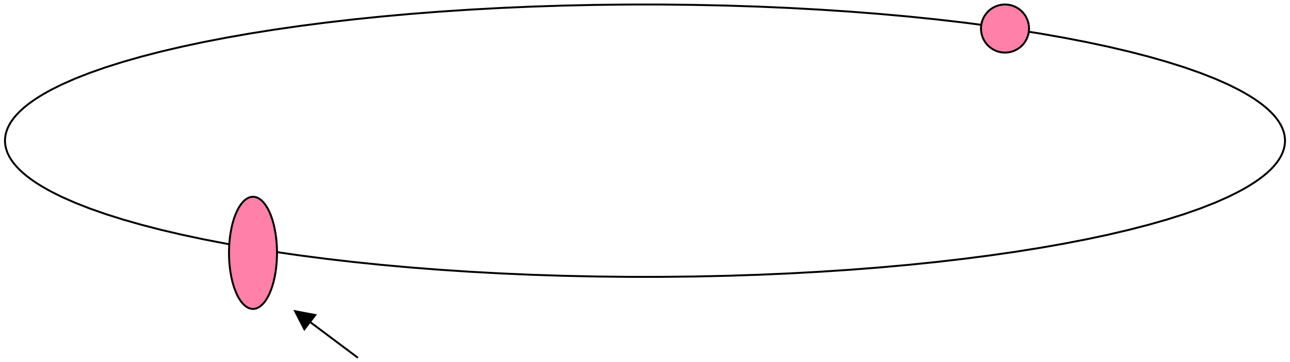
Average accumulate rate up 26 times.

ω_a is divided into two components, one of which is in resonance with ω_{sync}, and the other with the magnetic field.

Accumulate rate is
proportional to
1 - magnetic field fraction.

RF fields are large for this design.
B_r along with vertical displacement may mimic EDM.

Use more than one bunch to monitor systematic effect; use RF dipole to change vertical tune for each bunch.



larger vertical oscillations
sample systematic errors
from radial fields.

Summary

Special storage rings offer the opportunity to search for an EDM on a charged particle at sensitivities extending to 10^{-29} e·cm. (This limit is statistical for ~ 4 months of data accumulation time.)

The observation of an EDM with this sensitivity would be an indication of physics beyond the Standard Model. An upper limit at this level would severely constrain SUSY models.

If an EDM were found, the storage ring provides an opportunity to search on more cases, allowing an investigation of the source for *CP*-violation.

The storage ring search is challenging, but within the reach of present technological methods.

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