Part 1

Concept for Storage Ring EDM Search

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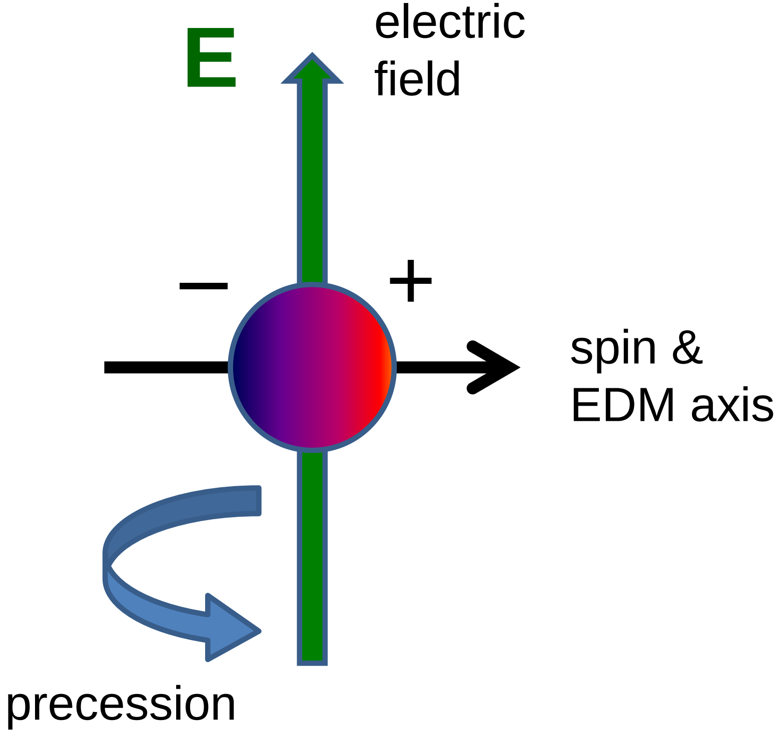
BASIC **EDM** EFFECT:

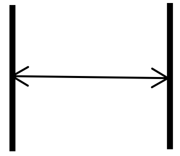
External electric field make torque
on electric dipole (into picture).
But system is already spinning.
Result is precession around
electric field axis.

EXPERIMENT: Detect the spin rotation in response to E-field.

It's possible to add a magnetic field, which makes the precession fast, and look for changes: **B** ± **E**.

Electric fields accelerate charged particles, so searches have been limited to neutral systems.





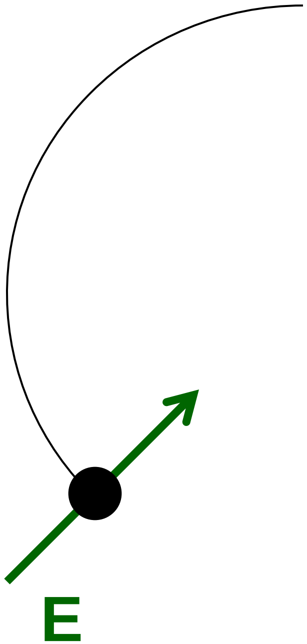
nucleon size
about 1.6 10^{-13} cm

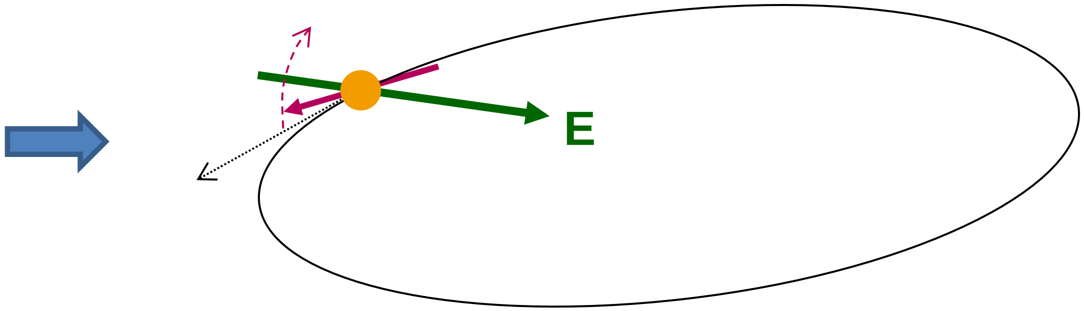
EDM limit for neutron
< 2.9 10^{-26} e·cm.

The precession is slow.

An electric field can capture a *moving, charged* particle into an orbit.

So why not a storage ring rather than a trap?





Polarization starts parallel to velocity, rotates toward vertical due to E-field. Look for the change.

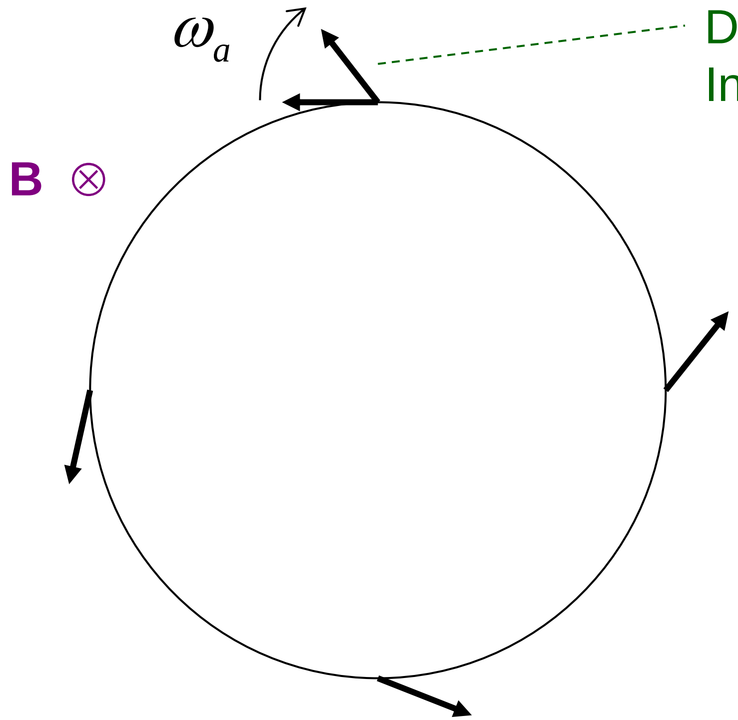
Horizontal position is unstable, vertical is stable.
This preserves the signal.

This works for a magnetic ring, E-field comes from **v** × **B**.

This would open up charged particles for an EDM investigation.

But there is a issue. Whether electric or magnetic, spin rotates at a different rate than the velocity. How do you “freeze” it?

The Deuteron Solution:



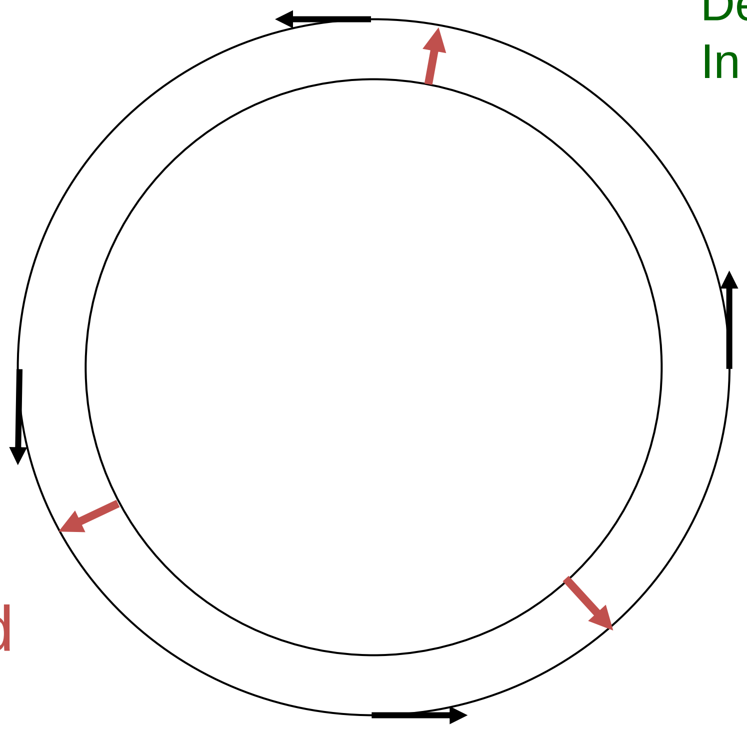
Deuteron anomalous moment = – 0.14.
In one revolution, spin lags momentum.

Idea: Use radial electric field to enlarge orbit and revolution time while keeping B constant.

$$\omega_a = -\frac{q}{m}\left\{ a\vec{B} + \left[a - \left(\frac{m}{p}\right)^2 \right] \frac{\vec{\beta}\times\vec{E}}{c} \right\}$$

anomalous moment (also *G*)

The Deuteron Solution:



E field

(21% diameter increase)

Deuteron anomalous moment = – 0.14.
In one revolution, spin lags momentum.

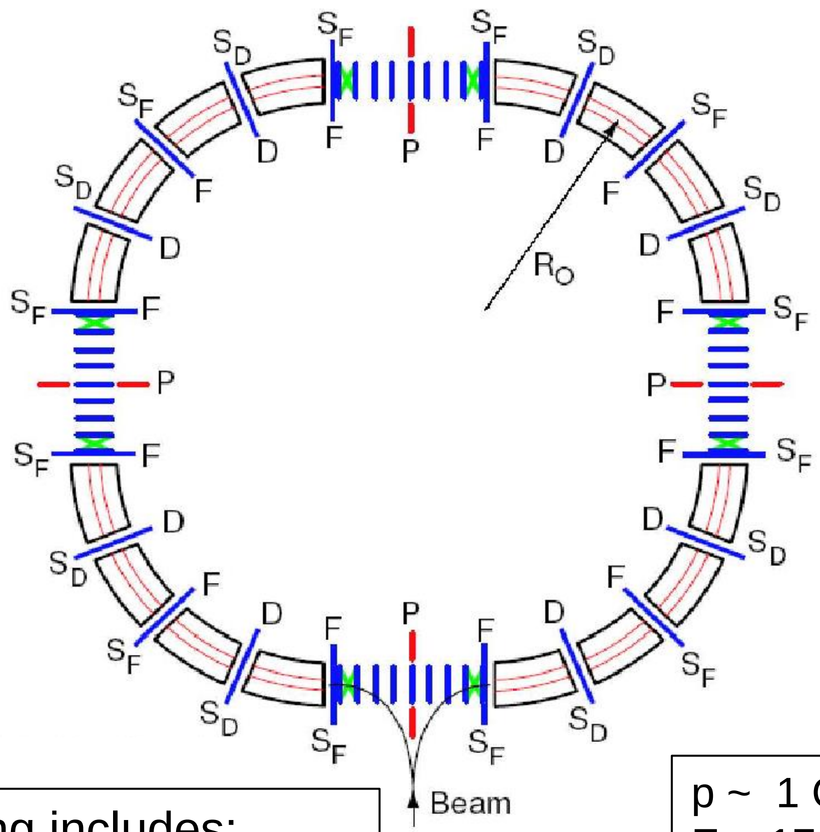
Idea: Use radial electric field to enlarge orbit and revolution time while keeping B constant.

For some ratio of **E** and **B**, the lengthened path will be just right for the spin to track the velocity.

$$E = \frac{aBc\beta\gamma^2}{1 + a\beta^2\gamma^2}$$

(Small precessions will be used for systematic checks.)

The Deuteron Solution:



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Ring includes:
- 2 injection kickers
- RF cavity
- solenoid
- 4 polarimeters

p ~ 1 GeV/c
E ~ 17 MV/m
B ~ 6.8 kG
R0 ~ 5.9 m
Circumference ~ 60 m

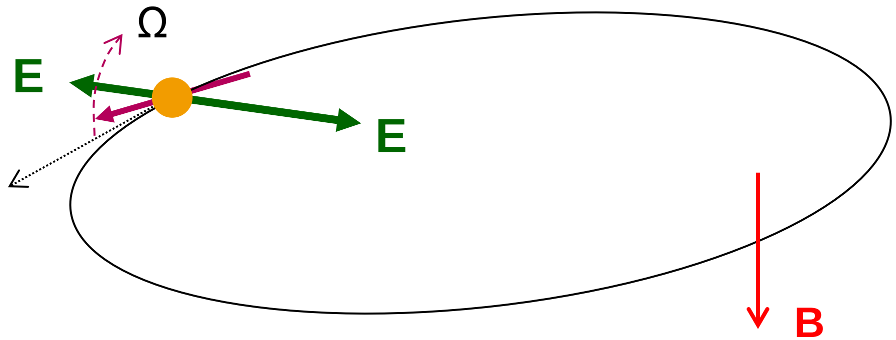
$$E = \frac{aBc\beta\gamma^2}{1 + a\beta^2\gamma^2}$$

For the particle, there are two "electric" fields.

From field plates,
17 MV/m.

From **v** × **B**,
96.3 MV/m.

Sum = 79.3 MV/m.



All ring quantities are either proportional to or inversely proportional to the electric field.

Considerable progress has been made recently on electric field:

- electropolish
- high-pressure water rinse
- new materials (large grain Nb)

Fields up to 60 MV/m may be possible.

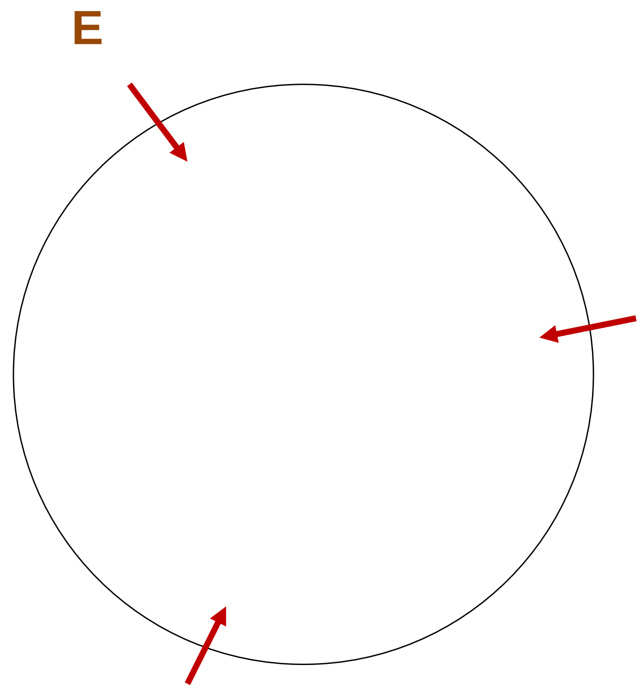
E (MV/m)	r (m)	B (T)	Ω (μrad)
10	10.1	0.40	14.2
17	5.9	0.68	24.1
25	4.0	1.00	35.4
40	2.5	1.60	56.7

Ω: (in 1000 s with d = 10^{-29} e·cm)

B = 1.60: (iron limit)

The Proton Solution:

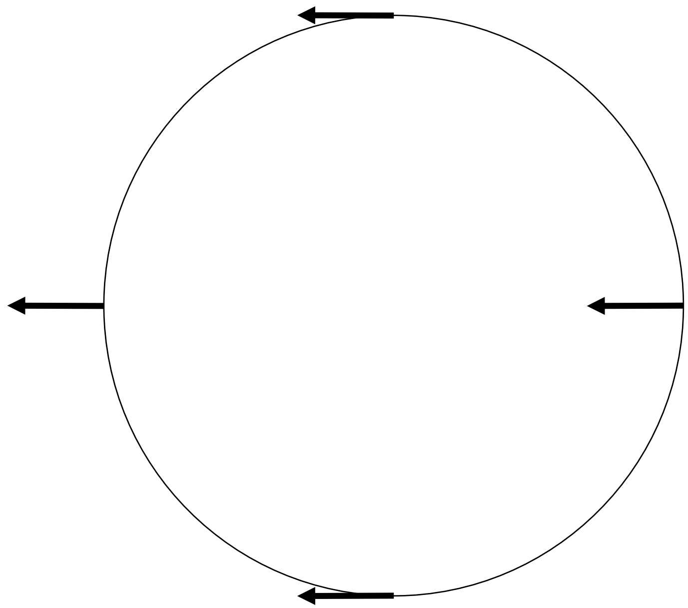
This ring is all electric
(no magnetic bending).



<u>The Proton Solution</u>:

This ring is all electric (no magnetic bending).

At low energy, the spin is stationary.



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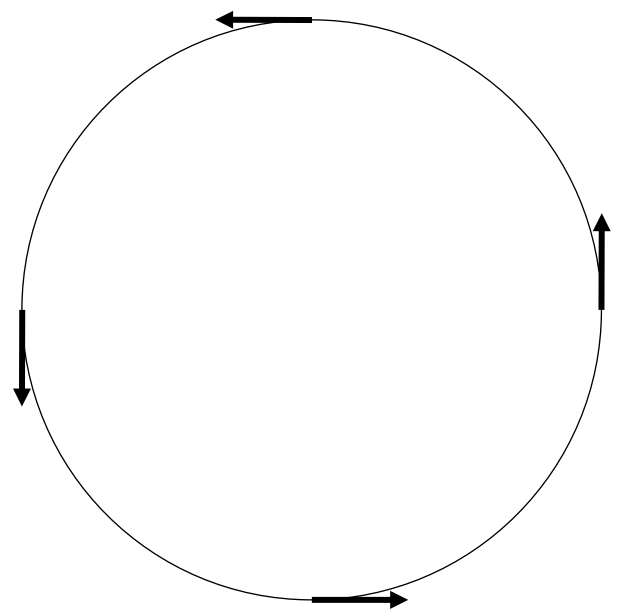


At low energy, the spin is stationary.

At p = 0.701 GeV/c, proton sees **B** = −γ**v**×**E**, and spin tracks velocity.

$$\omega_a = -\frac{q}{m}\left\{ a\vec{B} + \left[a - \left(\frac{m}{p}\right)^2 \right] \frac{\vec{\beta}\times\vec{E}}{c} \right\}$$

set to zero

also cancels

The Proton Solution:

This ring is all electric (no magnetic bending).

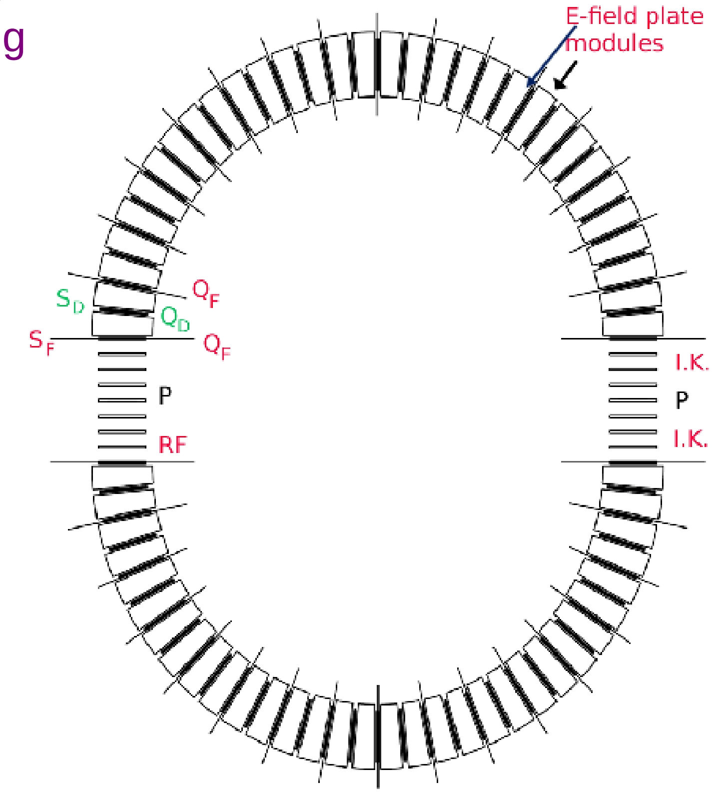
E ~ 17 MV/m
radius ~ 25 m
Circumference ~ 240 m

Electric focusing

At low energy, the spin is stationary.

precession rate = 5.2 μrad in 1000 s.

At p = 0.701 GeV/c, proton sees $\mathbf{B} = -\gamma \mathbf{v} \times \mathbf{E}$, and spin tracks velocity.



$$\omega_a = -\frac{q}{m}\left\{a\vec{B} + \left[a - \left(\frac{m}{p}\right)^2\right]\frac{\vec{\beta}\times\vec{E}}{c}\right\}$$

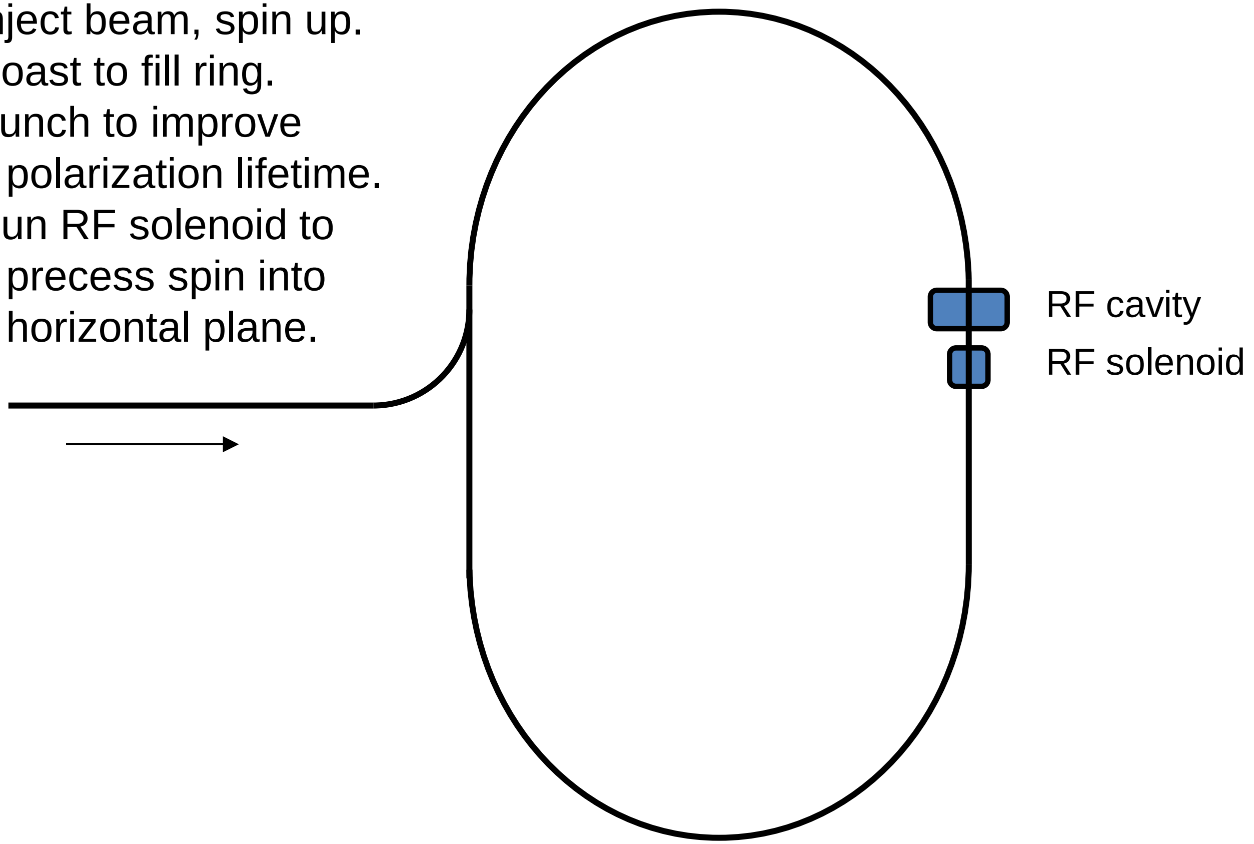
goes to zero

also cancels

How to make a measurement

1

Inject beam, spin up.
Coast to fill ring.
Bunch to improve
polarization lifetime.
Run RF solenoid to
precess spin into
horizontal plane.



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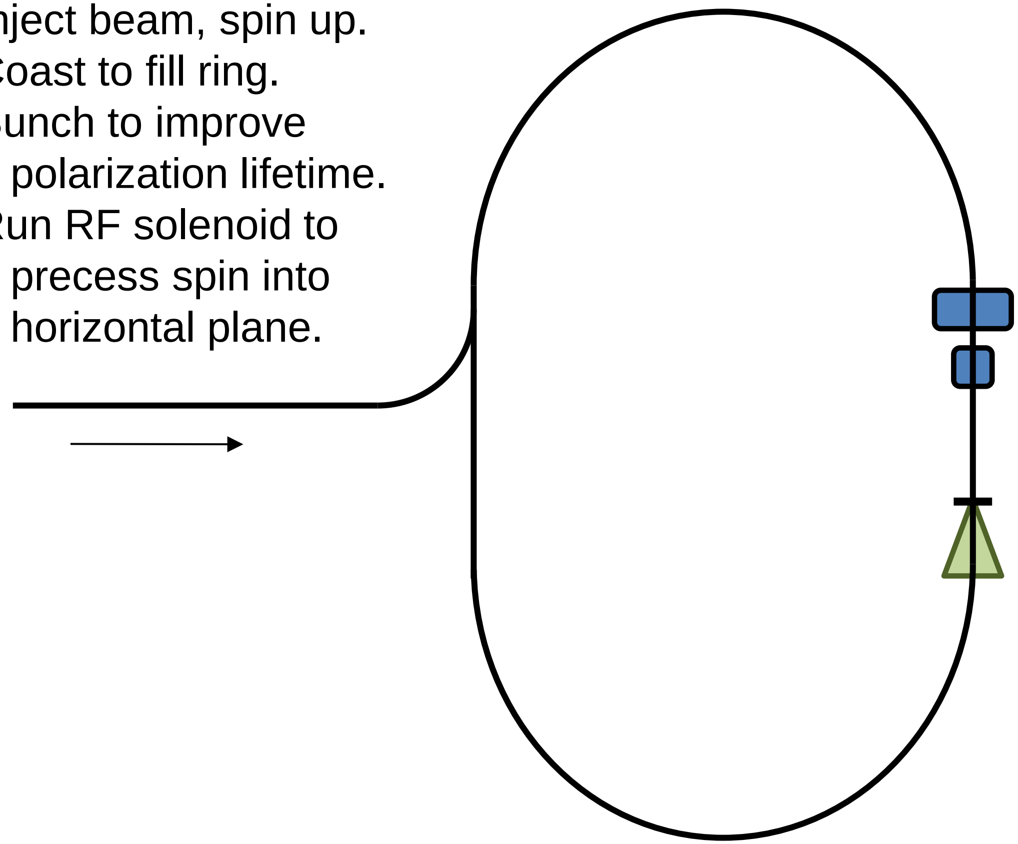

2

Extract beam continuously
onto carbon polarimeter
target.
Watch for small change
in vertical polarization
component in 1000 s
(sensitivity = 10^{-29} e·cm).

$$\varepsilon = pA = \frac{L-R}{L+R}$$

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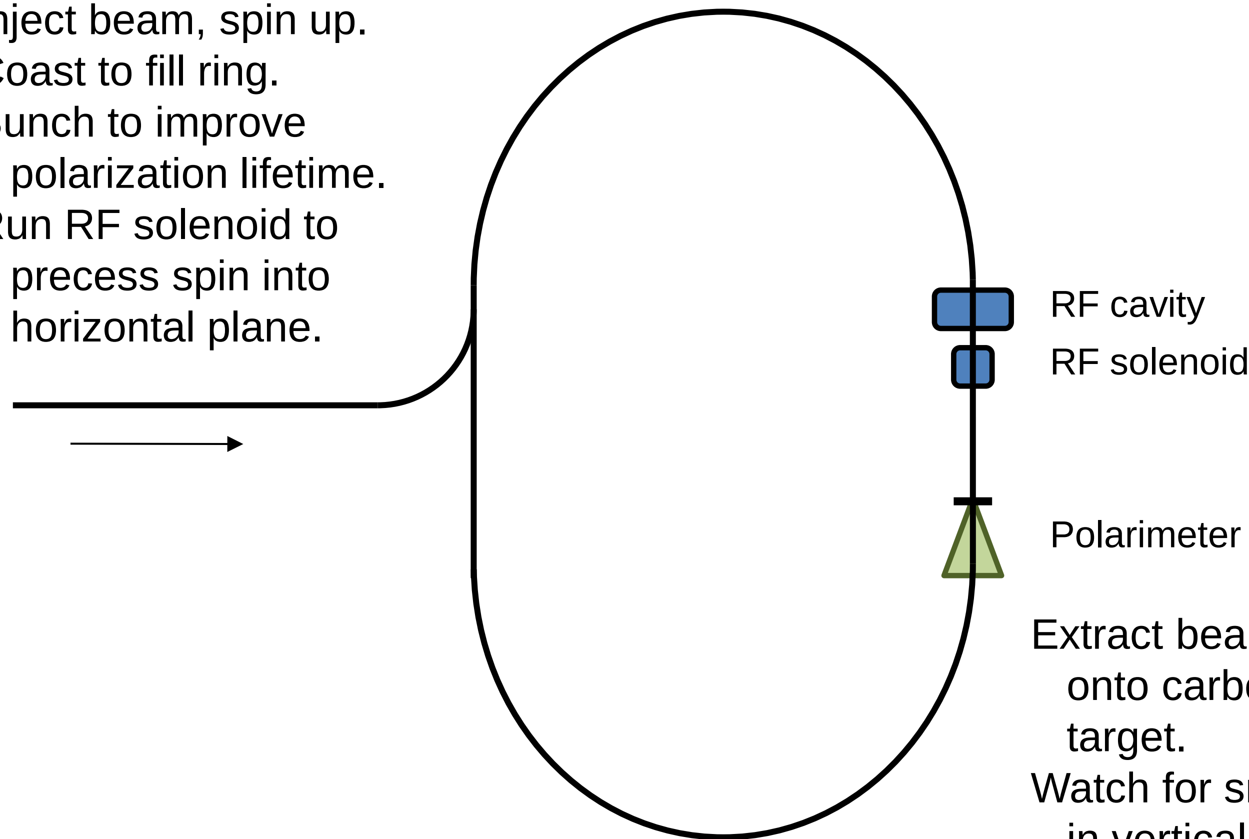

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Extract beam continuously onto carbon polarimeter target.
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$$\varepsilon = pA = \frac{L-R}{L+R}$$

3

Allow polarization to rotate parallel to velocity.
Hold it there with feedback.

Make

$$\varepsilon = \frac{D-U}{D+U} = 0$$

How to make a measurement

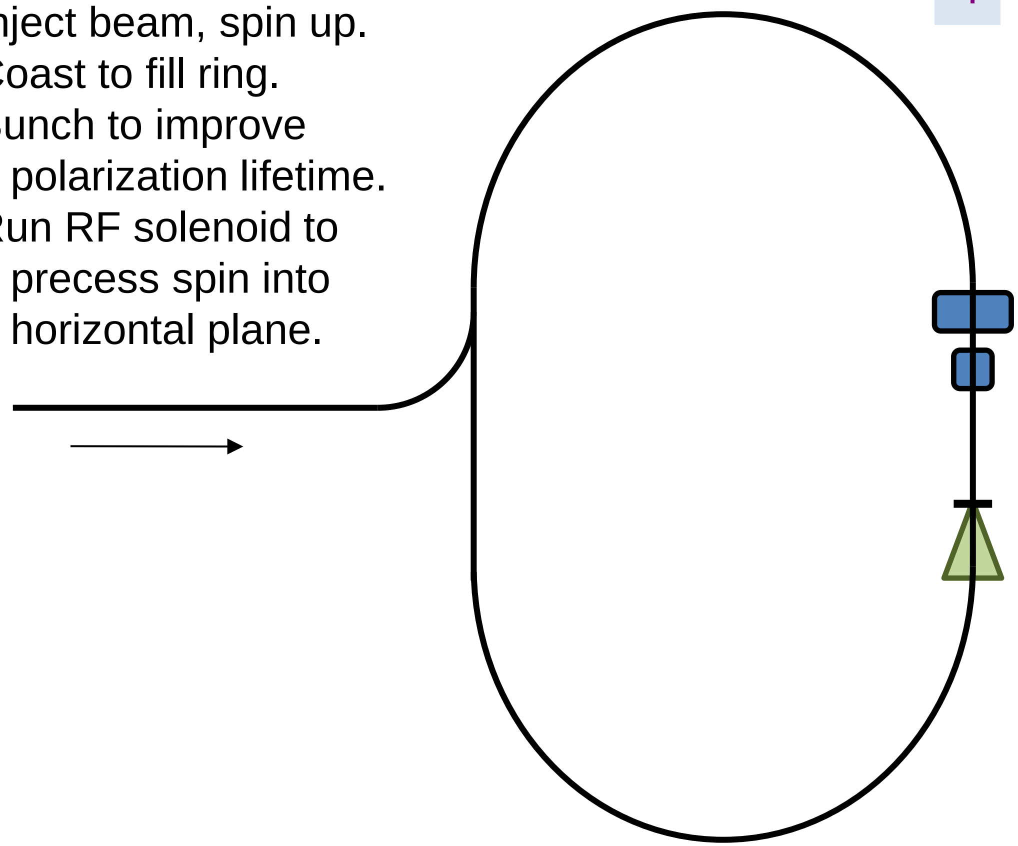
Systematic error management

4

Use +/− polarization,
opposite side detection,
with polarimeter.
(Square wave in RF solenoid.)

1

Inject beam, spin up.
Coast to fill ring.
Bunch to improve polarization lifetime.
Run RF solenoid to precess spin into horizontal plane.



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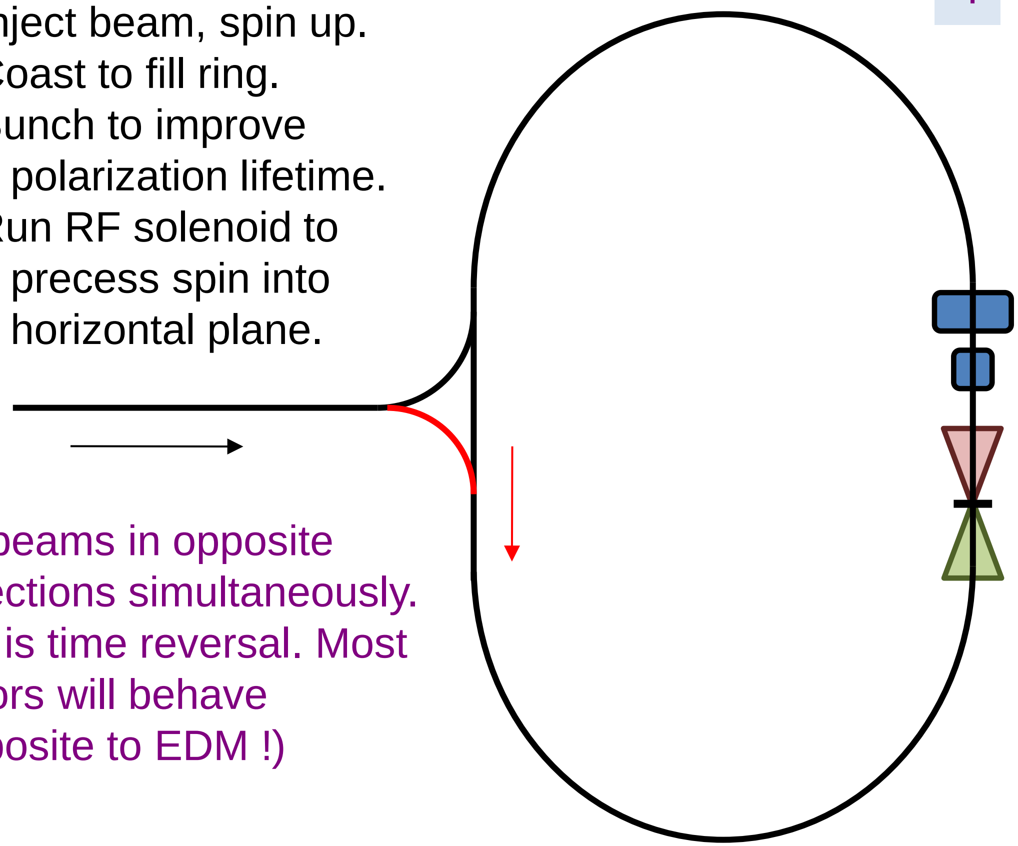

5 Run beams in opposite directions simultaneously.
(This is time reversal. Most errors will behave opposite to EDM !)

3 Allow polarization to rotate parallel to velocity.
Hold it there with feedback.

Make

$$\varepsilon = \frac{D-U}{D+U} = 0$$

Systematic error management

4 Use +/− polarization, opposite side detection, with polarimeter.
(Square wave in RF solenoid.)

2 Extract beam continuously onto carbon polarimeter target.
Watch for small change in vertical polarization component in 1000 s (sensitivity = 10^{-29} e·cm).

$$\varepsilon = pA = \frac{L-R}{L+R}$$

Signal and Statistical Precision

For the proton case: $$\theta_{EDM}(t) = \frac{2dE}{\hbar} t = 5\left(\frac{nrad}{s}\right) t$$

Statistical precision: $$\sigma = \frac{3\hbar}{PAE\sqrt{N_{beam} f T_{tot} \tau_{spin}}}$$

where:

P = 0.8, beam polarization
A = 0.6, analyzing power
E = 17 MV/m, electric field
N_{beam} = 2×10^{10} / fill
f = 0.0055, polarimeter efficiency
T_{tot} = 10^{7} s / year, total run time
τ_{spin} = 10^{3} s, polarization lifetime

$$\sigma = 2.5\times10^{-29}$$ e·cm/yr

The deuteron case is similar, but with much larger θ_{EDM}.