A Search for Axion-like Particles with a Horizontally Polarized Beam in a Storage Ring

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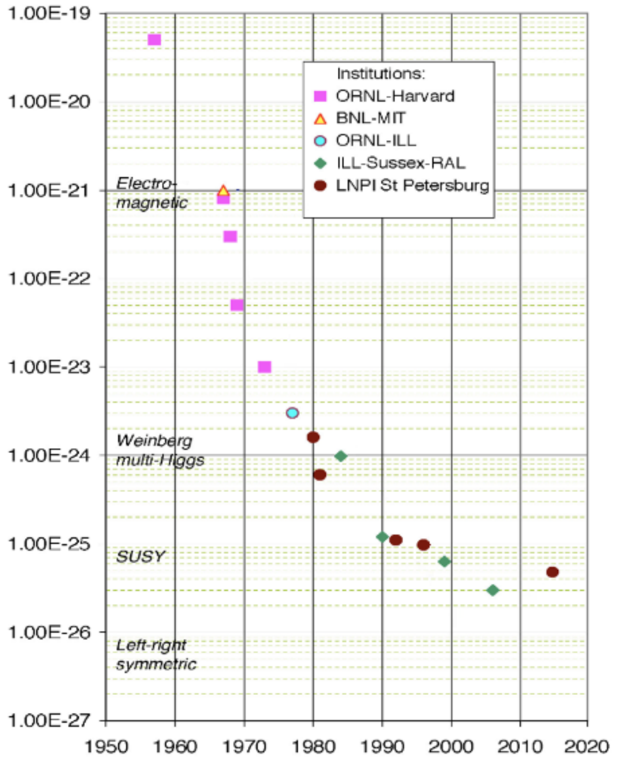
Axions proposed to explain the lack of CP violation. Electric dipole moments (EDMs) did not appear.



Axions are a candidate for interstellar dark matter.

One characteristic is the ability to induce oscillating EDM.

$$d = d_0 + d_1 \cos(\omega t + \varphi)$$

Oscillation frequency connected to axion mass.

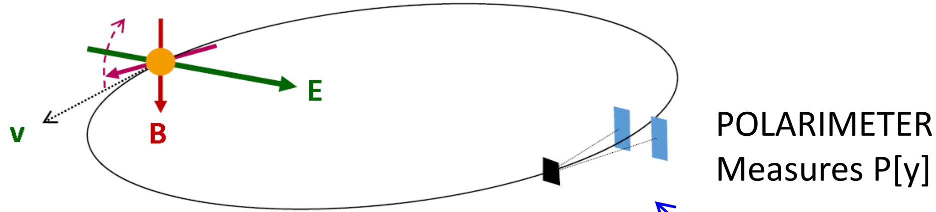
At the time of observation, the phase is unknown.

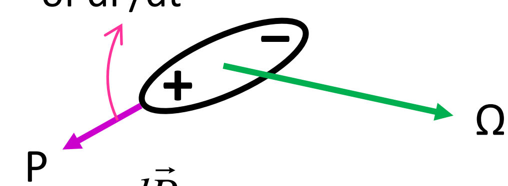
Idea: create an oscillating polarization, look for resonance at ω.

Description of the axion search (demonstration)

We start from a known COSY setup: polarized deuterons at 0.97 GeV/c
Beam is electron (pre-)cooled with long, in-plane polarization lifetime.

Standard picture of frozen spin EDM experiment:



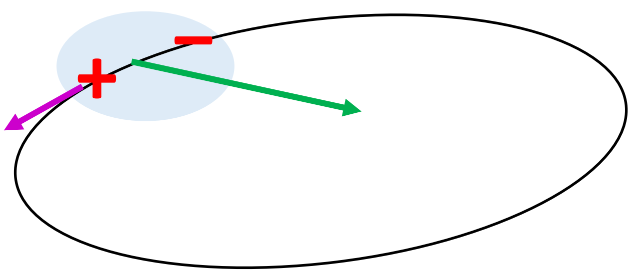


$$\frac{d\vec{P}}{dt} = \vec{P} \times \vec{\Omega}$$

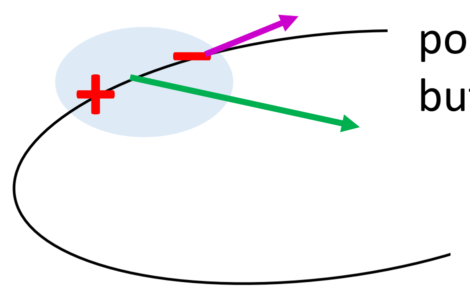
$$\vec{\Omega} = \frac{\eta q}{2mc}\left(\vec{E} + c\vec{\beta} \times \vec{B}\right)$$

In the axion search:
(spin is not frozen)

For deuteron in COSY



after ~3 revolutions



polarization reversed
but EDM has flipped

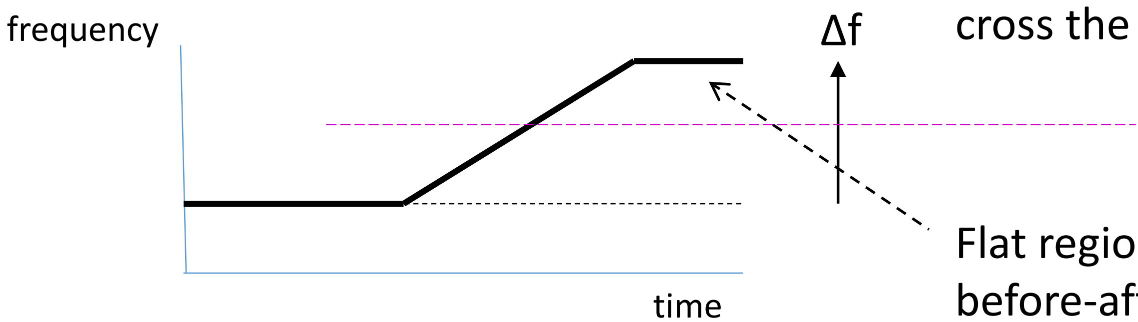
combination allows
signal accumulation

EDM accumulation
depends on v ll p.

Axion accumulation
is automatic if the
frequency is right.

But phase is unknown.

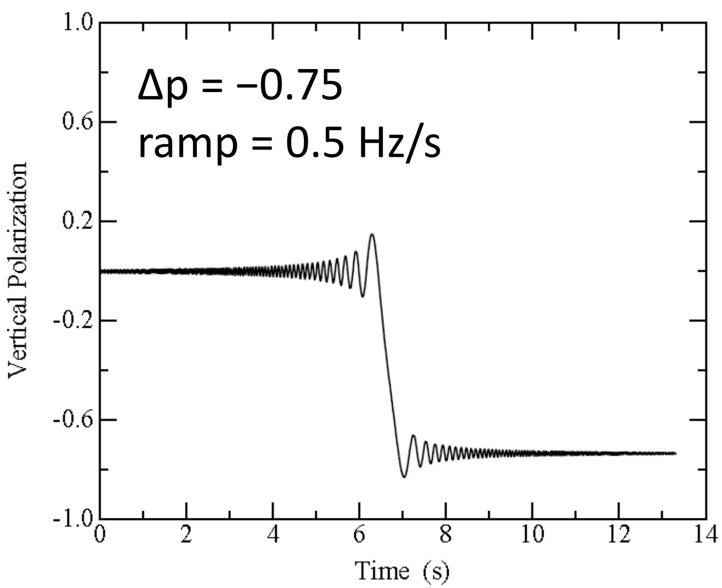
The frequency is unknown.
So scan for it.



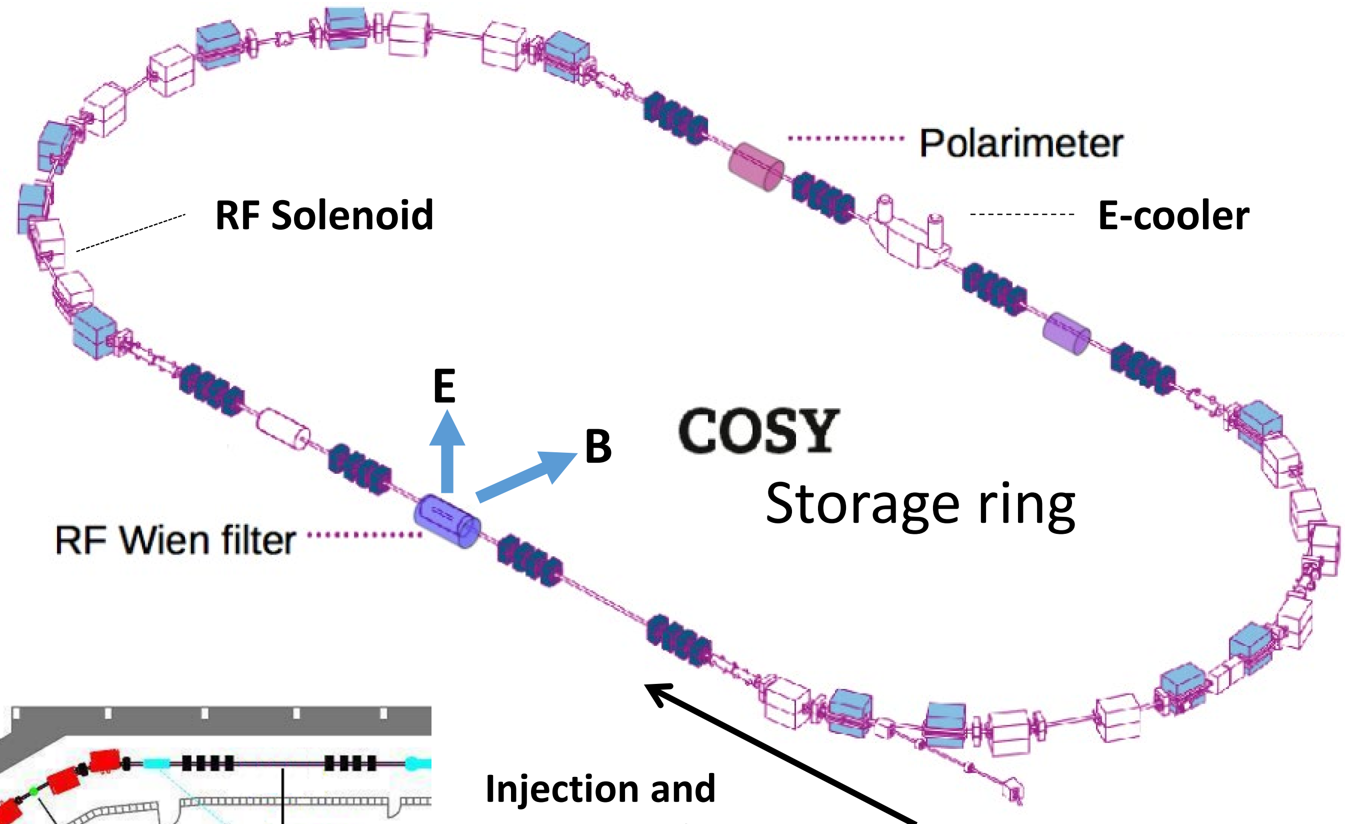
You may be lucky enough to cross the axion frequency.

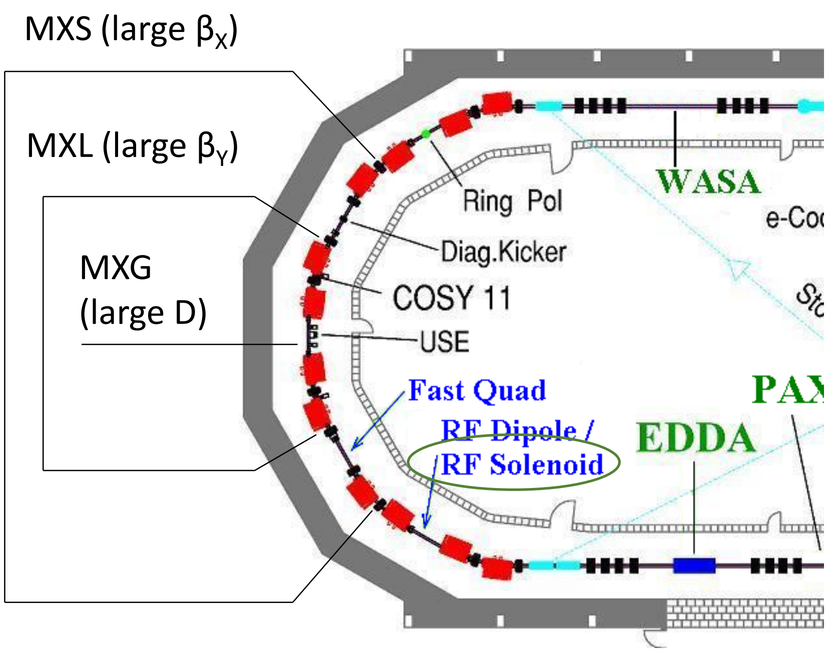
Flat regions allow for a precise before-after comparison.

Then you will measure:

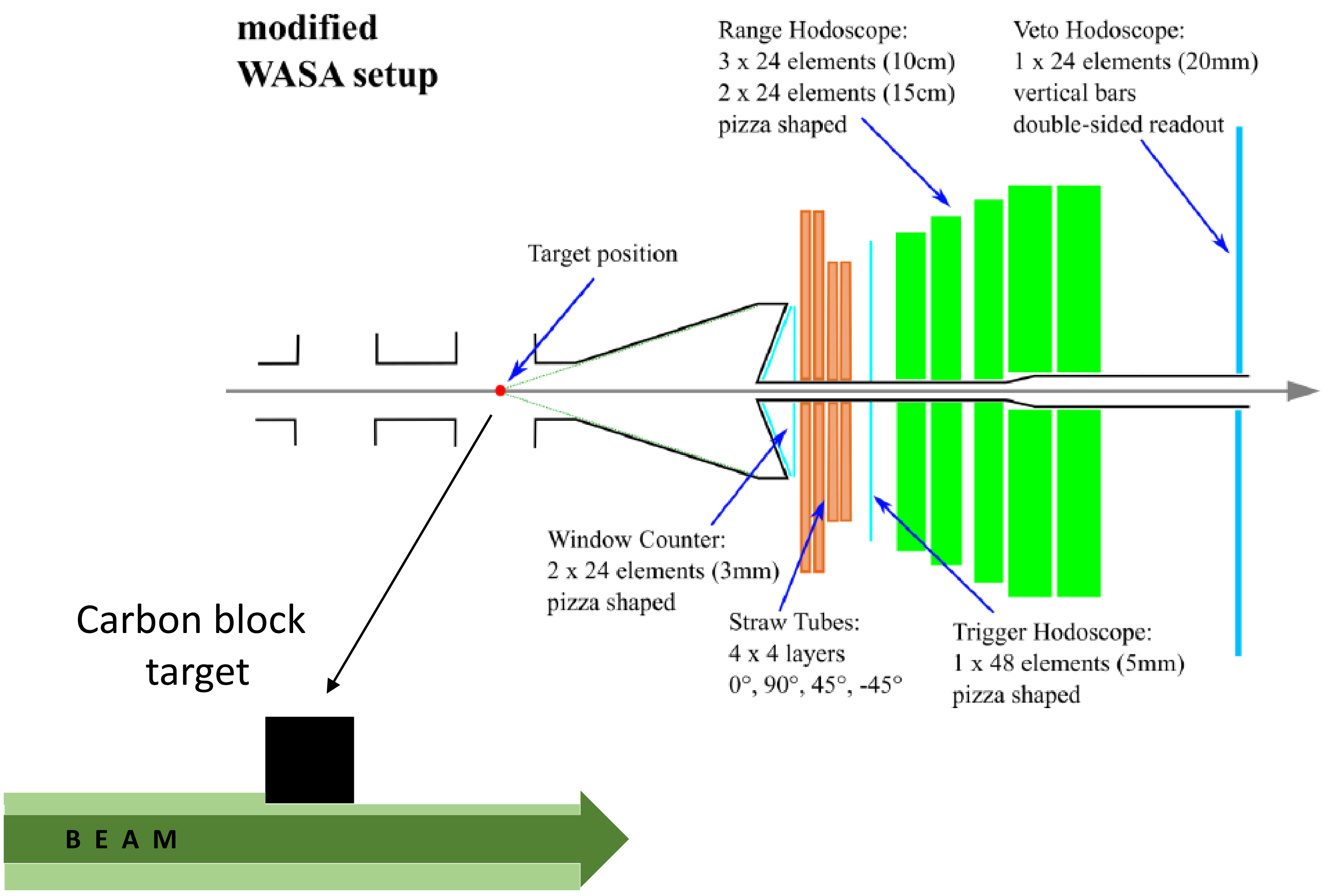


Critical assumptions:
> The axion is coherent in space.
All particles oscillate together.
The axion is present in all of COSY.
Axions are dense.
> The axion is coherent in time.
It takes a few seconds to pass COSY.
(only slow axions stay in galaxy,
v[esc] ~ 550 km/s)





Electron cooling and adjustment of sextupole fields are essential for a long horizontal polarization lifetime.


modified
WASA setup
Range Hodoscope:
3 x 24 elements (10cm)
2 x 24 elements (15cm)
pizza shaped
Veto Hodoscope:
1 x 24 elements (20mm)
vertical bars
double-sided readout
Target position
Window Counter:
2 x 24 elements (3mm)
pizza shaped
Straw Tubes:
4 x 4 layers
0°, 90°, 45°, -45°
Trigger Hodoscope:
1 x 48 elements (5mm)
pizza shaped
Carbon block
target
B E A M

New data acquisition procedure – time stamp every event

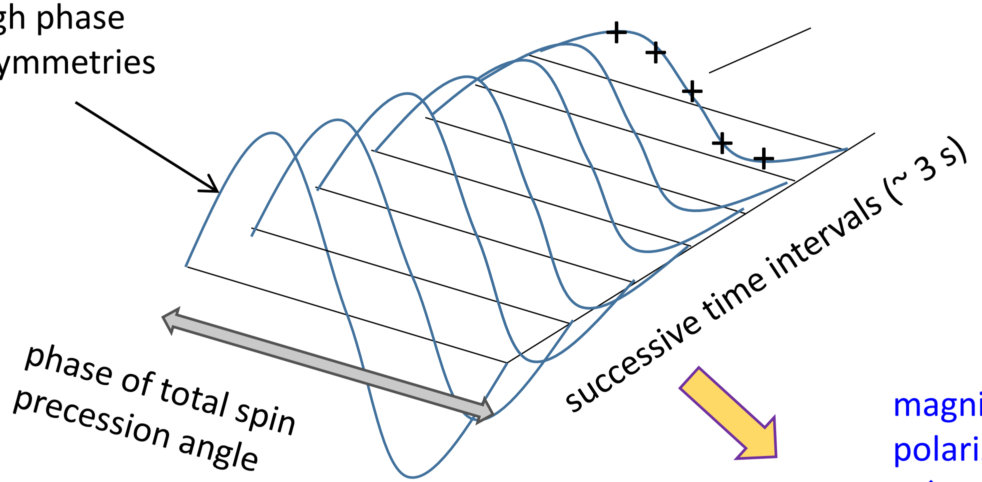
Count turn number (bunched beam)
Compute total spin precession angle
Bin by phase around the circle
Compute asymmetry in each bin

→ distribution of turn number fraction yields beam distribution

→ based on integral part of turn number

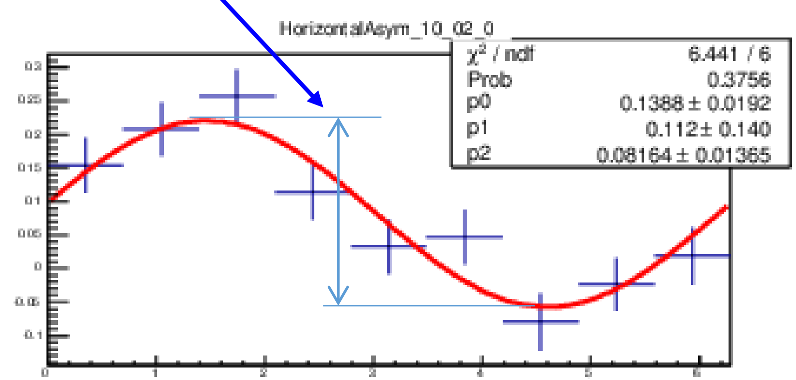
smooth curves through phase bin asymmetries

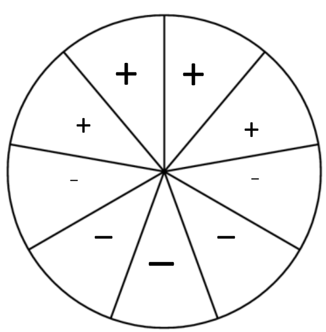
these curves determined by asymmetry measurements for 9 angle bins



correcting phase slip from one bin to the next adjusts the spin tune

magnitude gives horizontal polarization

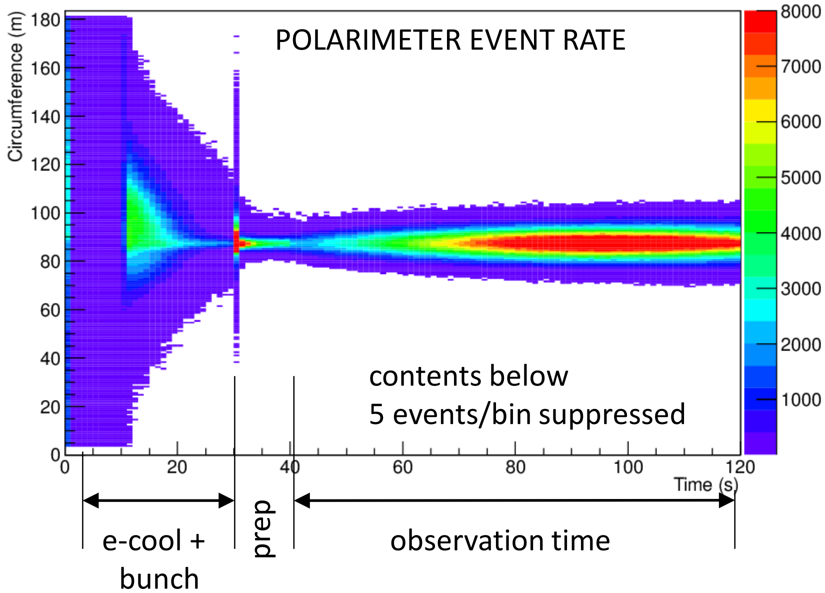




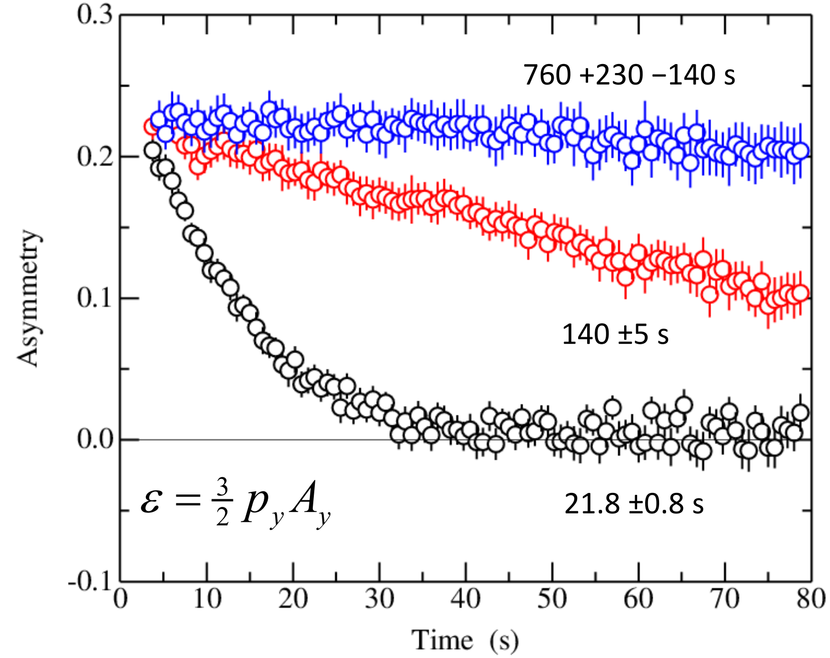
As the polarization rotates the down-up asymmetry reflects the sideways projection of the polarization.

Sample data

Distribution of beam around the ring as a function of time in the store.

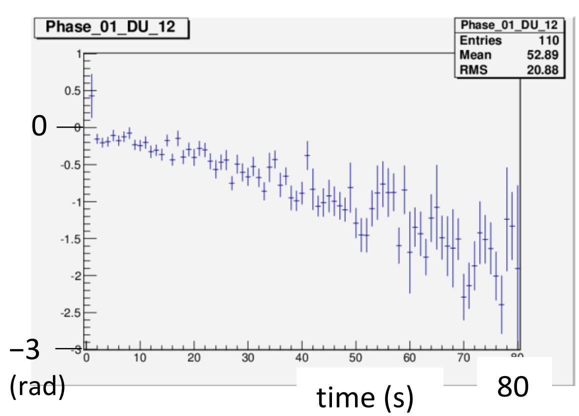


Sample measurements of horizontal polarization loss (corrected for positive bias)



Times are exponential decay rates.

phase in a single store with fixed spin tune



Program searches for highest amplitude in a narrow range.

To get maximum asymmetry stationary in one angle bin, spin tune must be accurate to < 1e-6. Normal scatter is usually < 1e-7.

Best error in phase is ~ 3° /s.

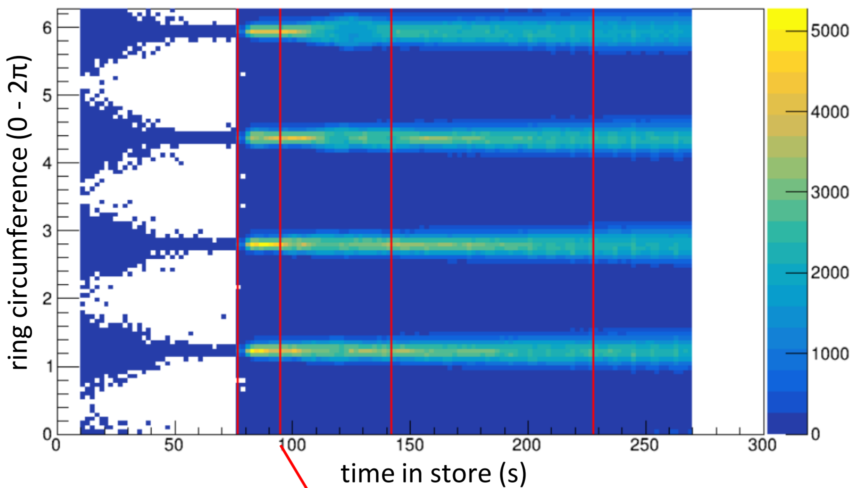
Downward slope means spin tune wrong by 3e-8 (δ ~ 10%).

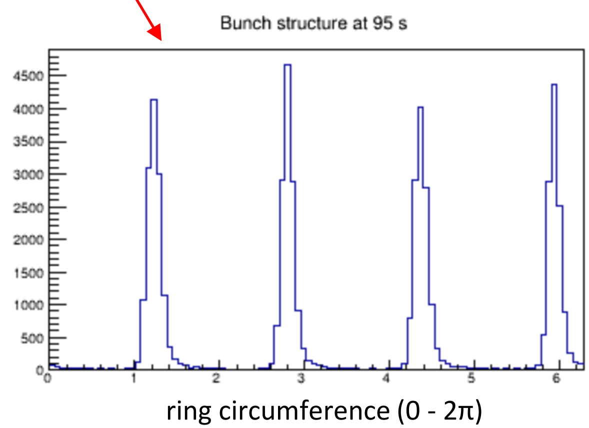
EDM ring requirement is 1e-9 from feedback.

Problem: Axion phase is unknown.

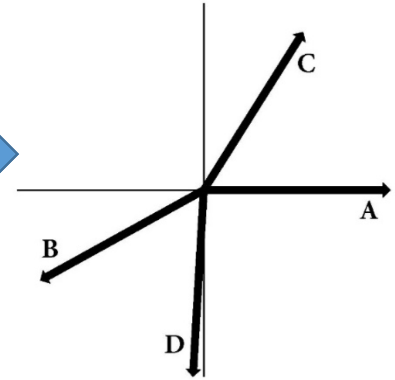
Conduct search simultaneously with beams having perpendicular polarizations.
Combine results for better signal.

Plan: Use 4 bunches…

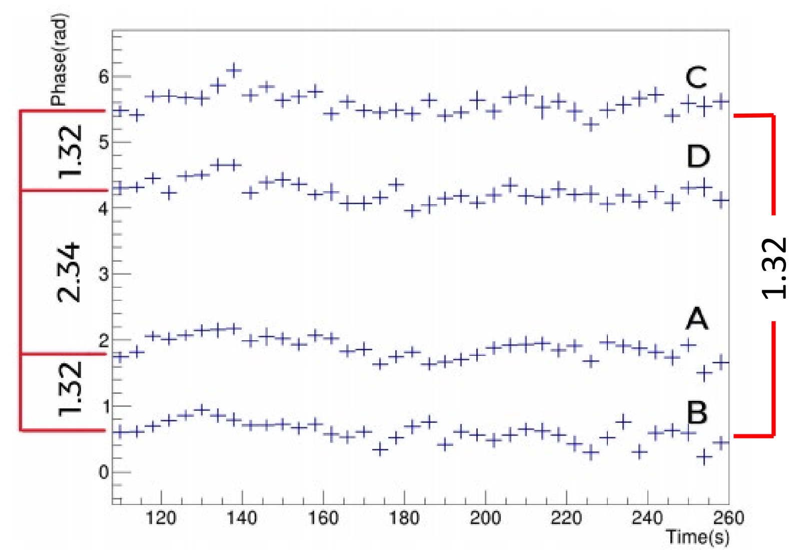




Operate RF solenoid at $f_{REV}(1+G\gamma)$ = 629771.9 Hz



verification



Calibration based on tracking through rotational history

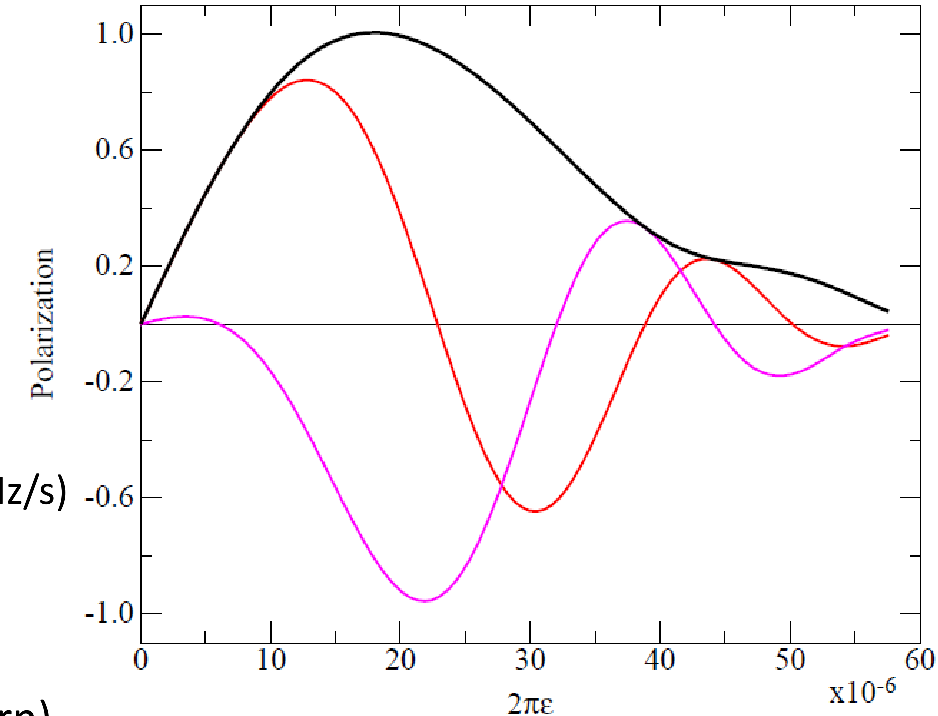
Calculation shows size of jump as a function of oscillating EDM size.

Red – axion in phase (0°)
Magenta – phase = 90°
Black – sum in quadrature

Ramp rate = 10 Hz/s
(most data taken at 0.1 or 0.05 Hz/s)

For any other ramp rate, scale by $1/\sqrt{r}$.

ε is the EDM rotation (rad/turn), so $\omega_{EDM} = f_{REV}\varepsilon$.

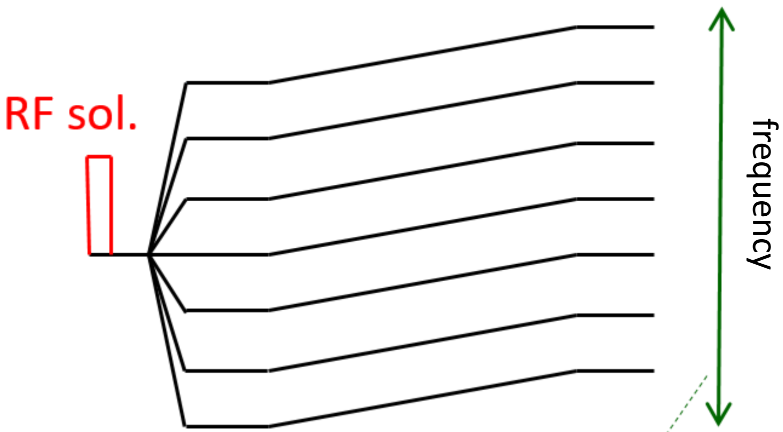


Ring circumference

Electric dipole: $$d = (6.242 \times 10^{20})\,\frac{\hbar\omega_{EDM}(2\pi R)}{v(B\rho)}$$

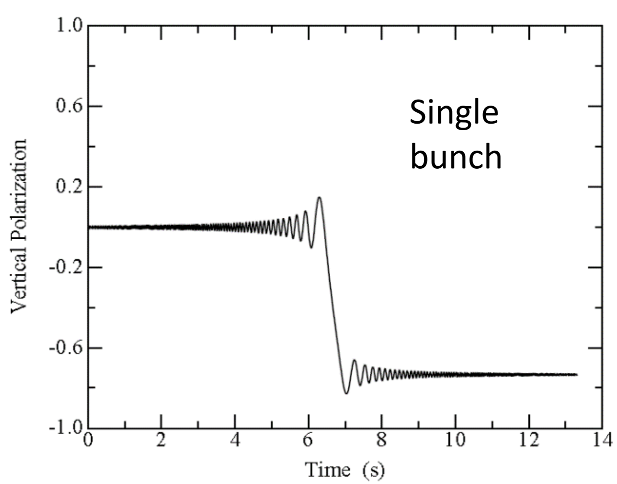
conversion to e·cm

Run a series of scans in frequency



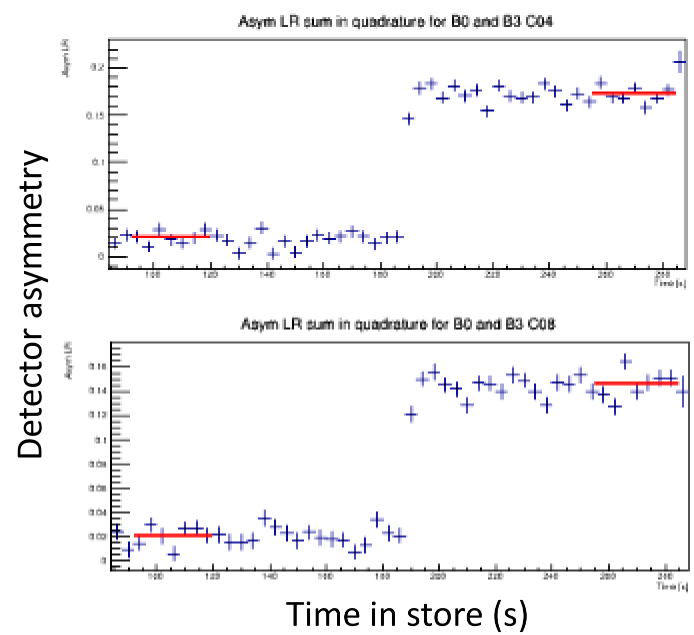
Machine acceptance

expected signal

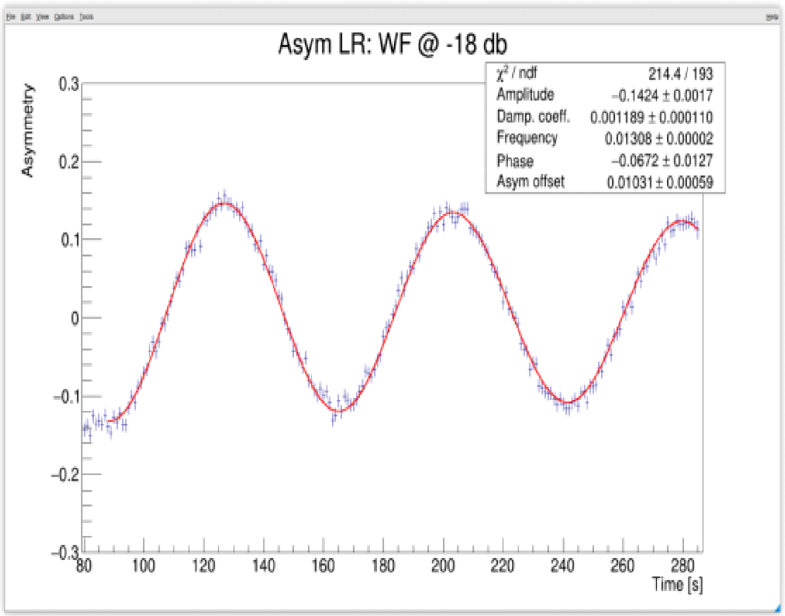


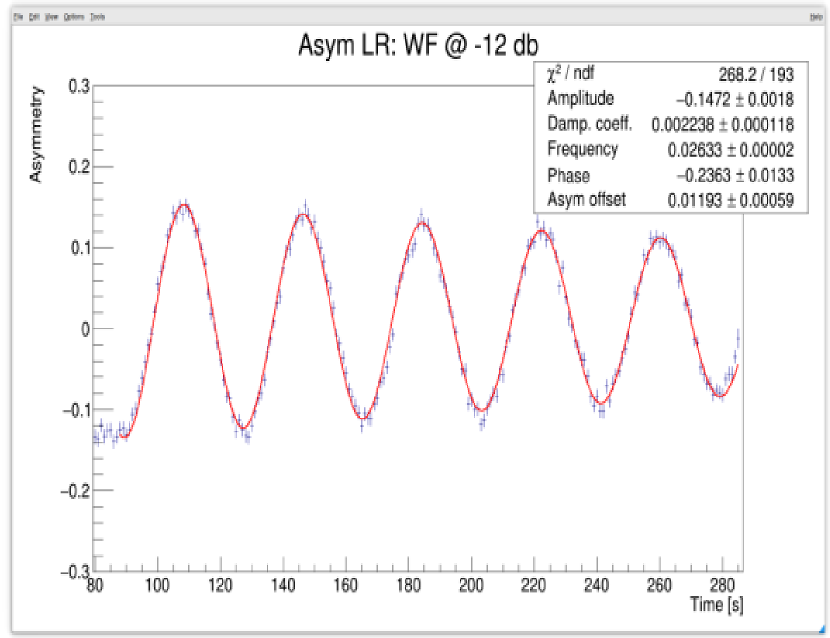
Test calibration

A system test was made using an RF Wien filter to generate signals similar to an axion. The signal response was also used to calibrate the polarization jump.



Check against Wien filter:





Frequency at maximum power level produces average $\varepsilon = 1.42 \times 10^{-7}$

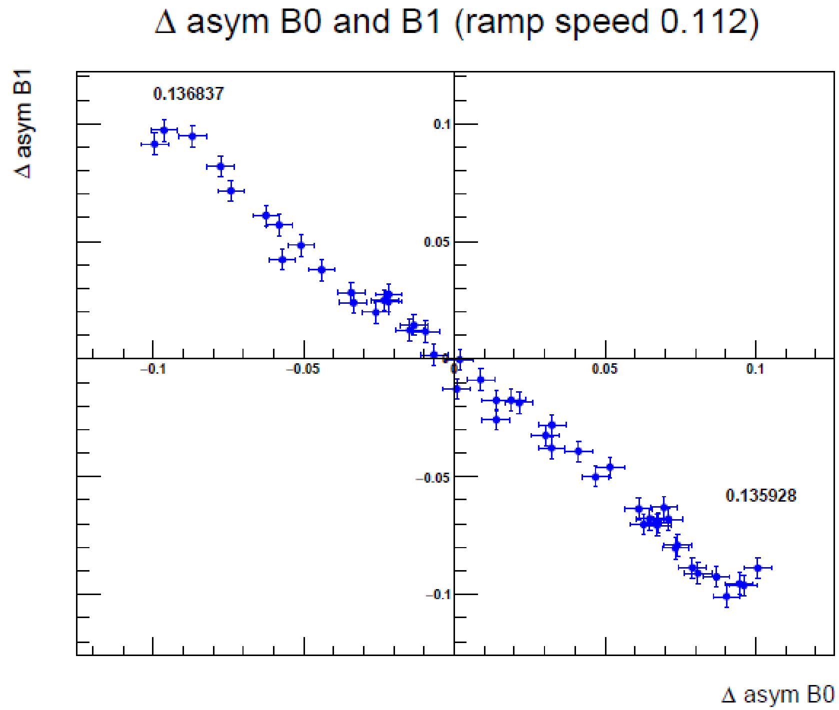
Scale for ramp rate

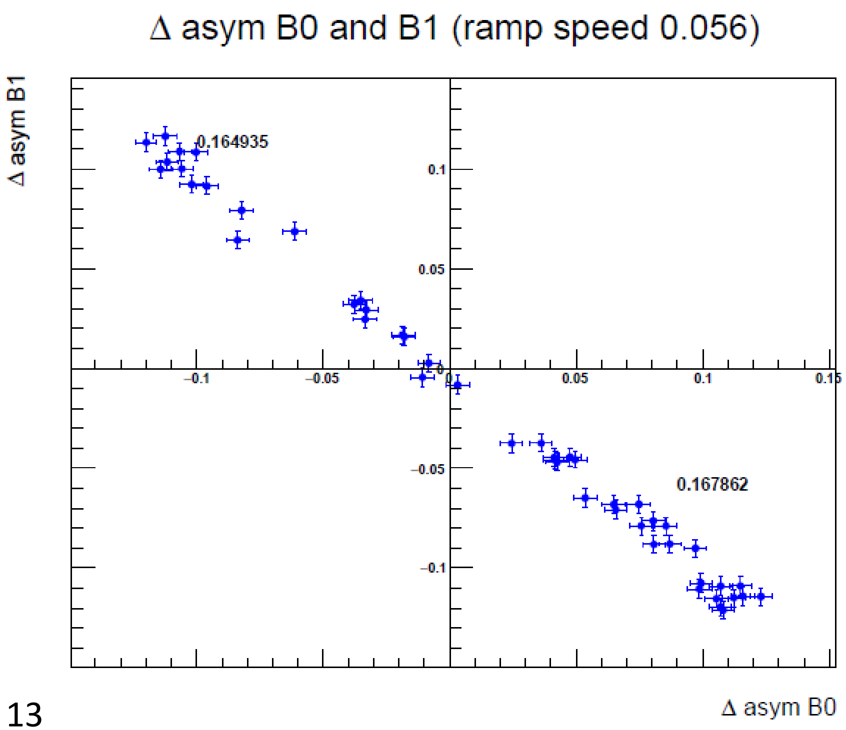
predicted for 0.1 Hz/s $\Delta p = 0.736$

predicted for 0.05 Hz/s $\Delta p = 0.915$

In practice, random phase distributions resulted in a spread of jumps. We want the maximum.

Values in figures are the length of the diagonals.





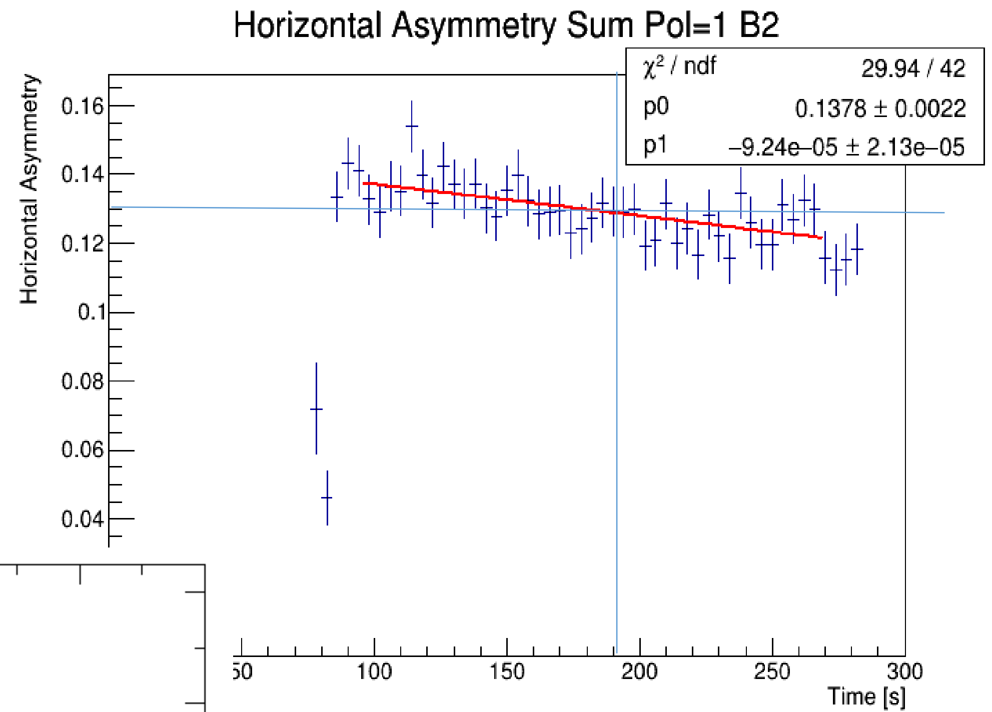
Typical jumps averaged over all cases:

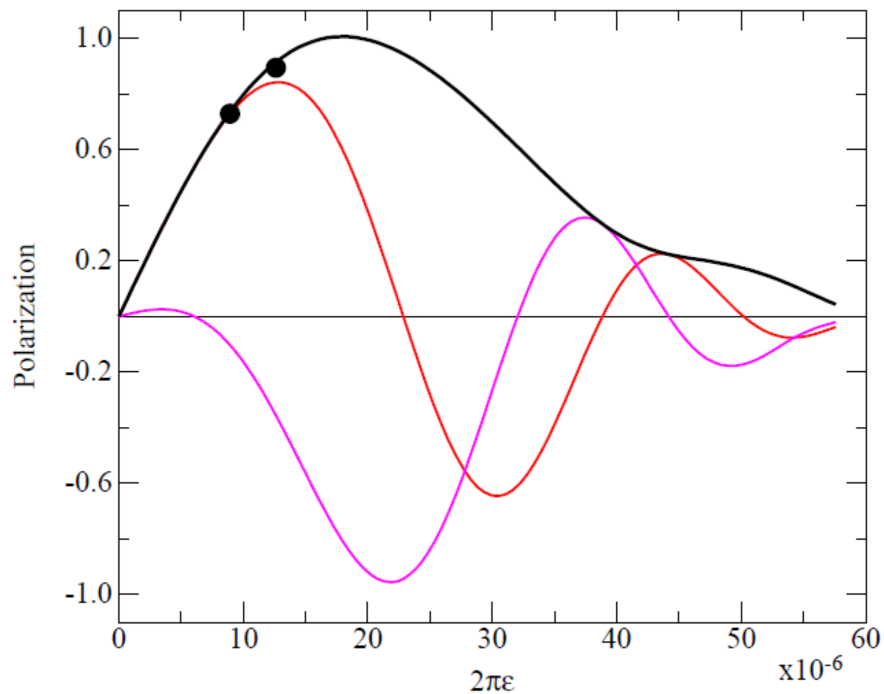
0.1 Hz/s → Δ(pA) = 0.0948

0.05 Hz/s → Δ(pA) = 0.1163

At 190 s average horizontal polarization is 0.13.

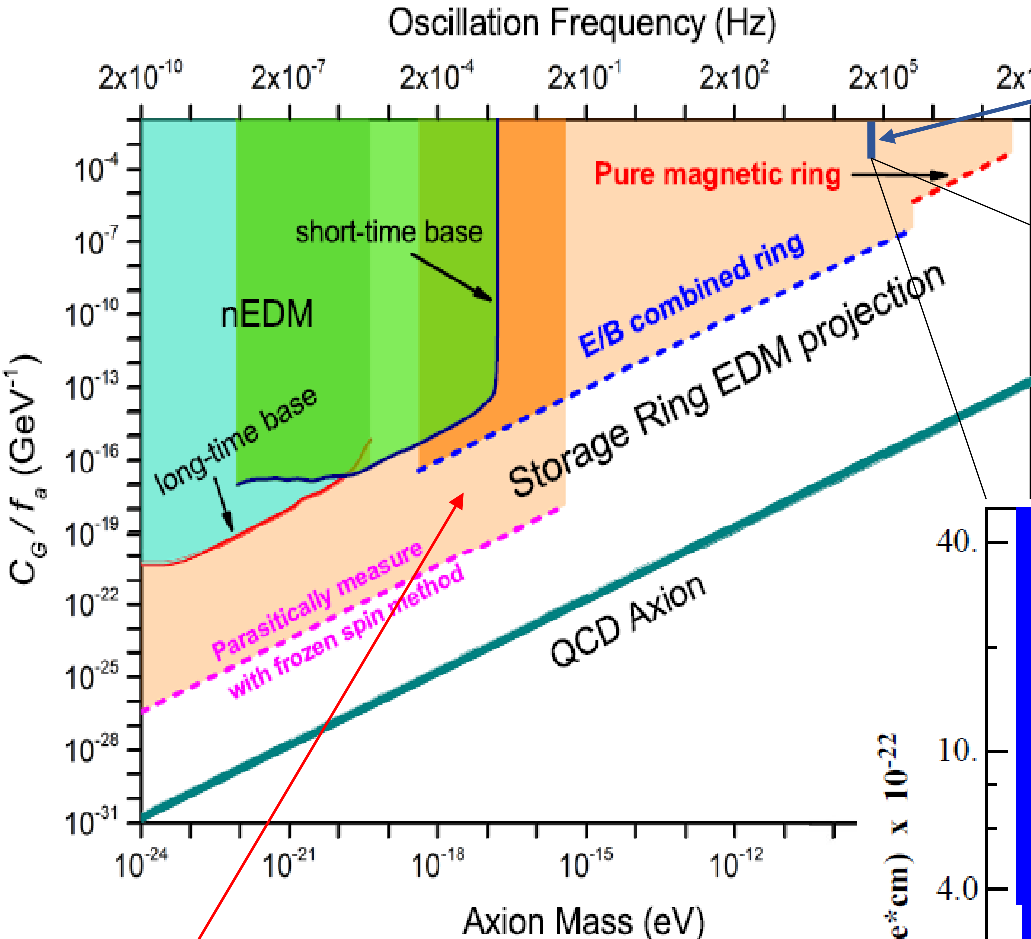
Scales polarizations to 0.73 and 0.90



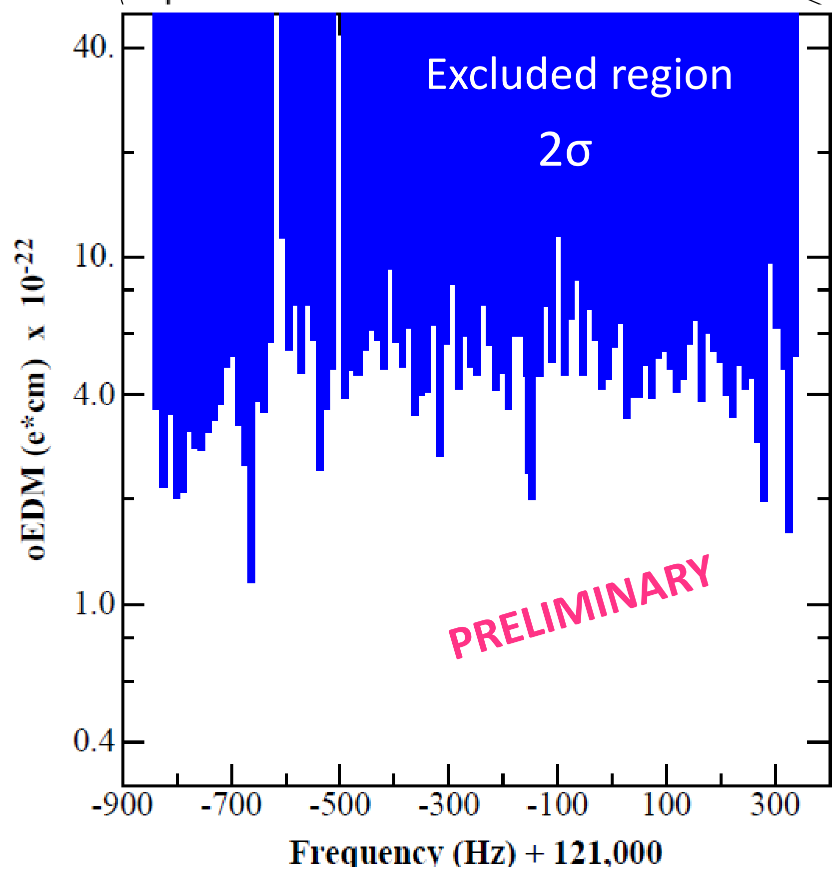


The Wien filter test confirms the calibration from the rotation model.

Location of axion result



First upper limit on deuteron oscillating EDM



Anticipated limit achievable using:

- Deuteron/proton beams
- Combined electric/magnetic ring
- Parasitic analysis using all-electric ring

see S.P. Chang et al., PRD **99**, 083002 (2019)