The Storage Ring Search for an Electric Dipole Moment (with comments on axion hunting)

Ed Stephenson
Indiana University

FRIB Theory Alliance Topical Program
Hadronic Electric Dipole Moments in the FRIB Era: from the proton to protactinium
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Brief History

1990s – Idea developed as a follow-up experiment to muon g-2.

2004 – Proposal made to BNL for a deuteron experiment reaching 10^{-27} e·cm.
Spokesperson: Yannis Semertzidis. PAC found that it was not competitive.

2005 – Initial deuteron polarimeter tests made at the KVI, Groningen.

2007 – Proposal made to COSY (Jülich) for deuteron storage ring tests.

2008 – Proposal renewed for the deuteron at 10^{-29} e·cm. Reviewed; OK at BNL.
Following year sent to DOE as a proton proposal. Shelved.

2009 – COSY demonstration completed for 10^{-5} polarimeter sensitivity.

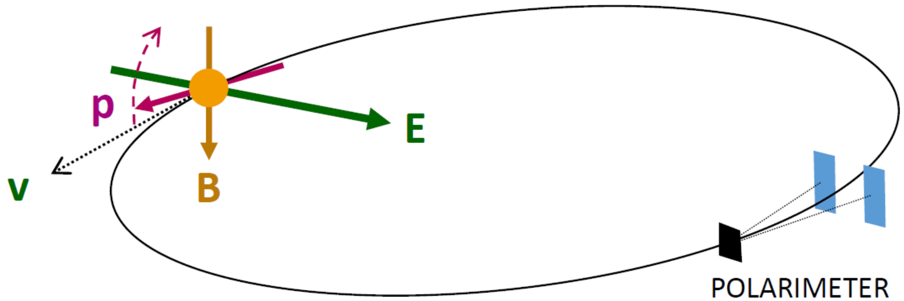
2011 – JEDI Collaboration forms at COSY.

2014 – EDM group forms at KAIST in S. Korea.

2015 – COSY demonstration of long in-plane polarization lifetime, spin control.

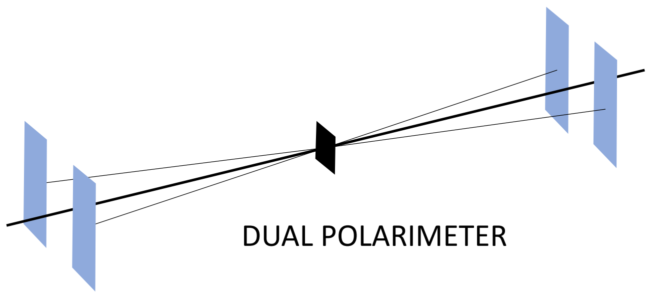
Experimental Concept and Main Features

Initially, *charged* particle spin
is aligned along velocity.
In particle frame, magnetic
field appears as radial electric.
For EDM aligned with spin,
torque rotates it vertically.



Polarimeter detectors see rising
left-right asymmetry as signal.

Comparing results with the time-reversed experiment allows systematic effects to be subtracted.



The polarimeter becomes bi-directional. Calibration errors limit the quality of the comparison.

Backscattering is smaller than forward scattering by > 10^7.

Both beam direction and all magnetic fields must reverse.

In general, all polarizations will rotate in the ring plane due to ring fields (B or E). We must find a choice that keeps momentum along velocity, a condition called “frozen spin.”

For particles with a positive magnetic anomaly ($G > 0$), an all electric solution exists. The box gives the proton result.

$$\boxed{\begin{gathered} \gamma = \sqrt{1 + \frac{1}{G}} \\ G = 1.79285 \\ \gamma = 1.2481 \\ p = 0.7007\ GeV/c \\ T = 232.8\ MeV \end{gathered}}$$

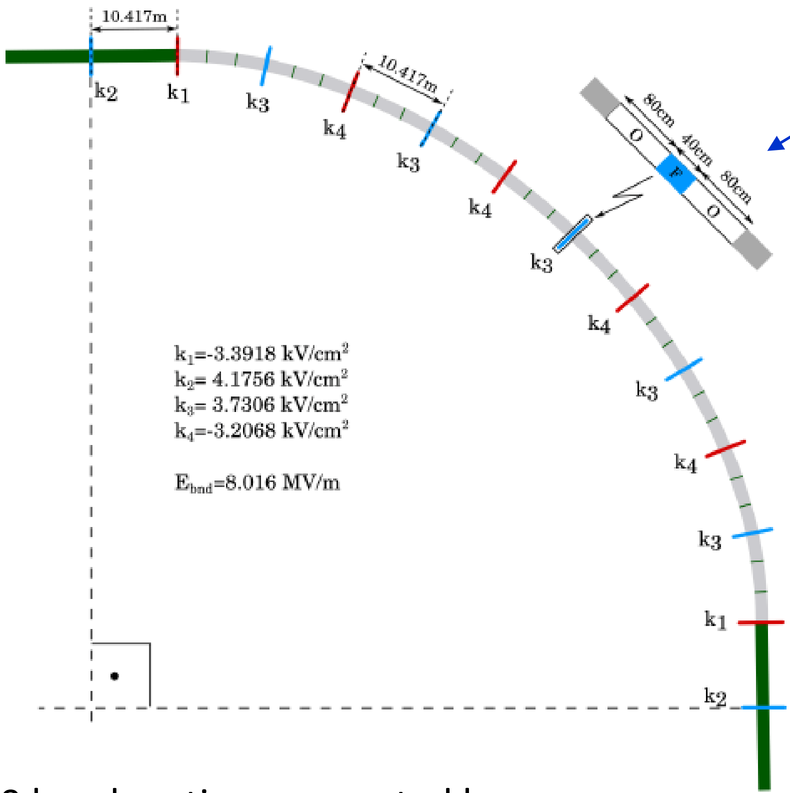
For the deuteron, $G = -0.142987$. Both electric and magnetic bending are required as shown.

$$E_r = \frac{G B_v c \beta^2 \gamma}{1 - G\beta^2\gamma^2}$$

CW and CCW operation are not simultaneously possible.

These results require the construction of a new “EDM” storage ring.
For the moment, design requirements are not site specific.

V. Anastassopoulos *et al.*, Rev. Sci. Instrum. **87**, 115116 (2016).



Suggested layout for EDM ring

40 bend sections separated by
36 straight sections each 2.7 m long
Electrostatic quadrupoles, alternating gradient
Four 20.8-m straight sections, polarimetry/beam injection
SQUID magnetometers distributed around the ring
Circumference is 500 m

Statistical error in EDM:

$$\sigma_{\text{stat}} \approx \frac{2\hbar}{\sqrt{Nf\tau} PAE}$$

beam intensity	$N = 4 \cdot 10^{10}$ per fill
polarization	$P = 0.8$
spin coherence time	$\tau = 1000\,\text{s}$
electric fields	$E = 8\,\text{MV/m}$
polarimeter analyzing power	$A = 0.6$
polarimeter efficiency	$f = 0.005$

For a running time of 10^7 s (1 yr)

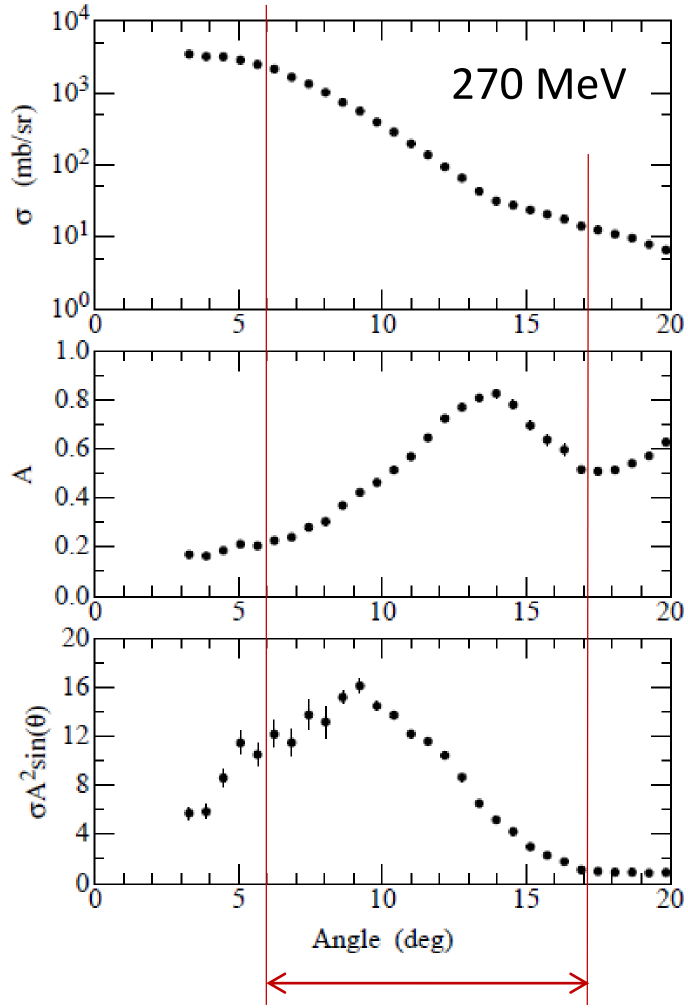
$\sigma_{STAT} = 2.4 \times 10^{-29}$ e·cm

The primary challenge will be systematic error control.

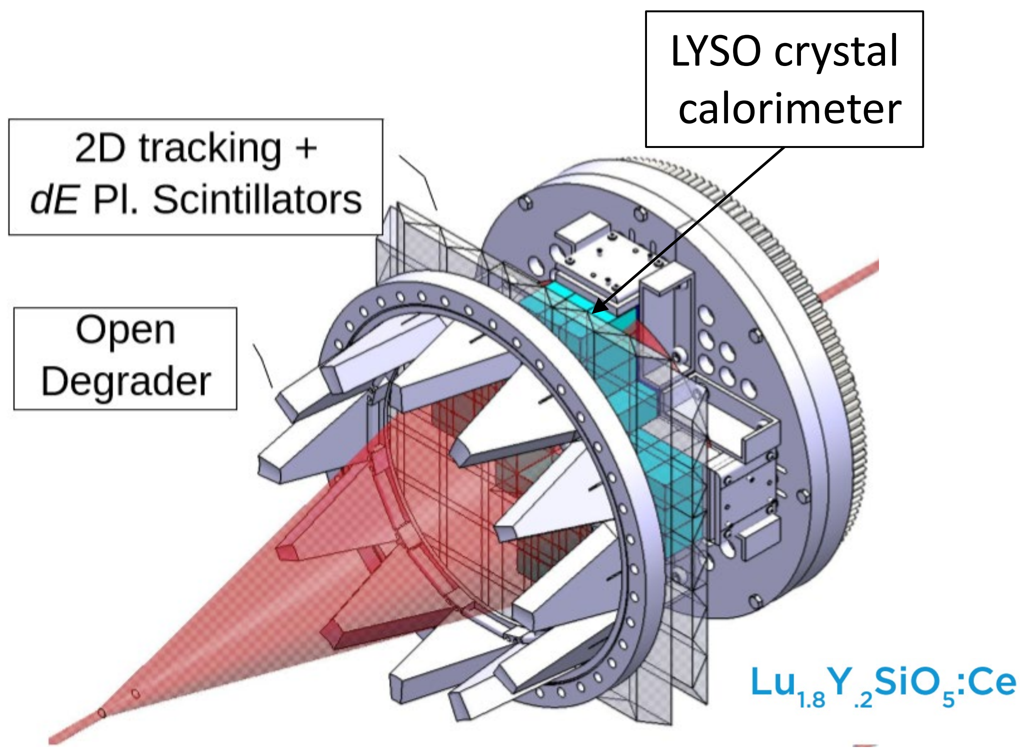
Polarimeter

Use forward angle elastic scattering.
Typical target is carbon.
Spin sensitivity comes from spin-orbit force.
Proton and deuteron responses are similar.
Figure of merit shows optimal angle ranges.
In deuteron case, exclude breakup.

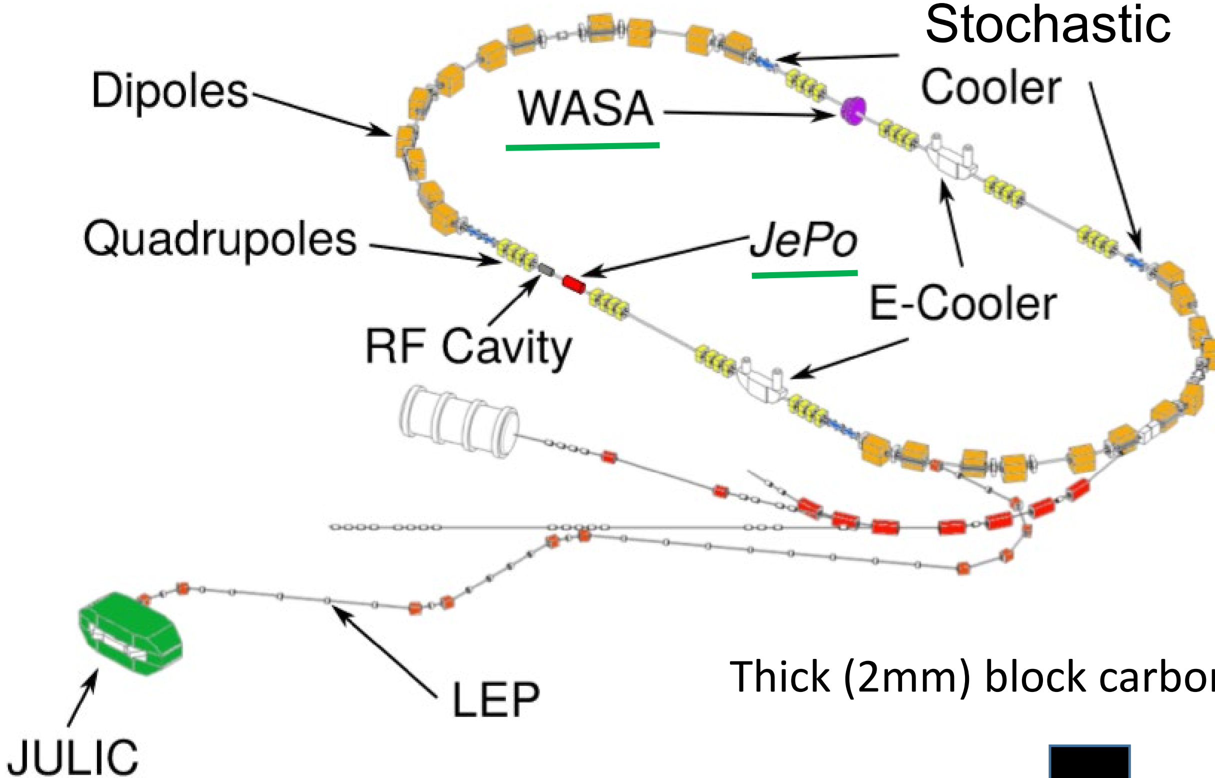
d + ^{12}C elastic scattering



Typical detector range
Average 1.5·A = 0.55



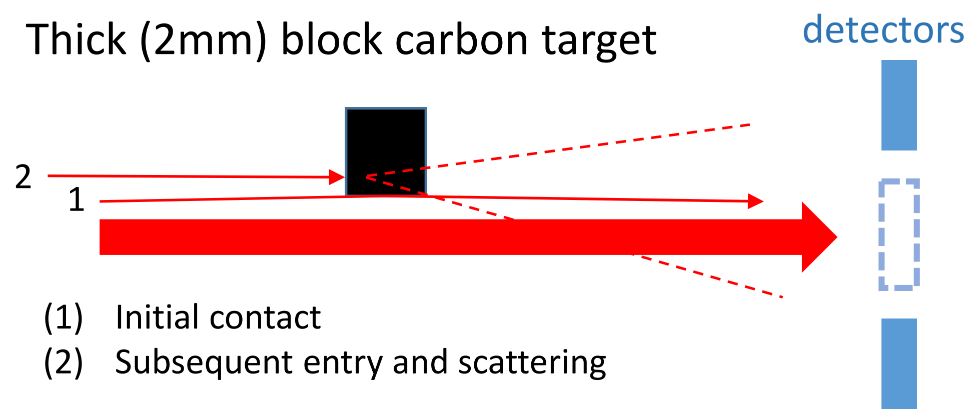
Feasibility studies with Jülich Cooler Synchrotron COSY



"standard" beam
0.97 GeV/c deuterons
T = 238 MeV

Other Equipment:
RF solenoid
RF Wien filter
Beam diagnostics

Thick (2mm) block carbon target

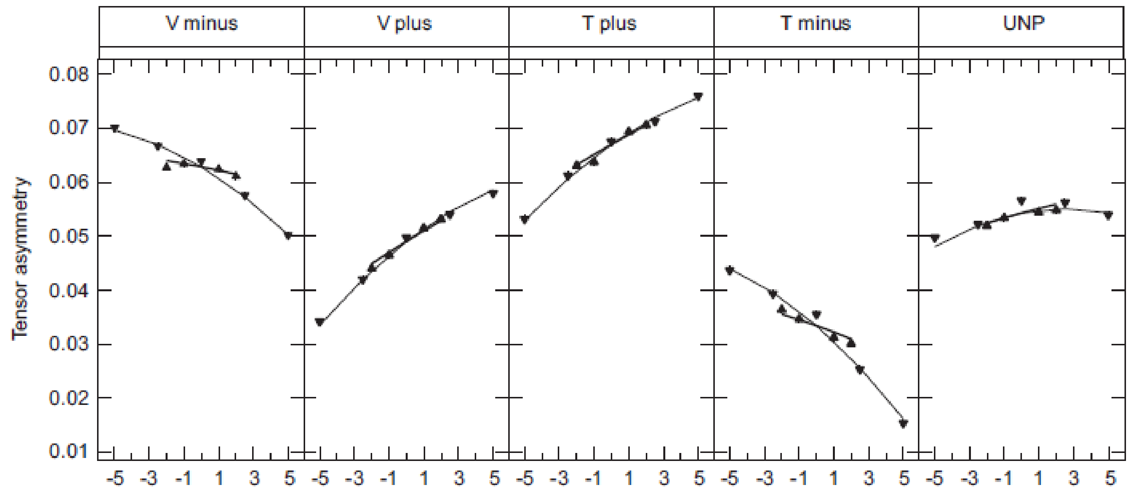


(1) Initial contact
(2) Subsequent entry and scattering

White noise beam extraction.
Most beam enters target (efficiency ≈ 1%).
(−) Sampling favors beam halo.

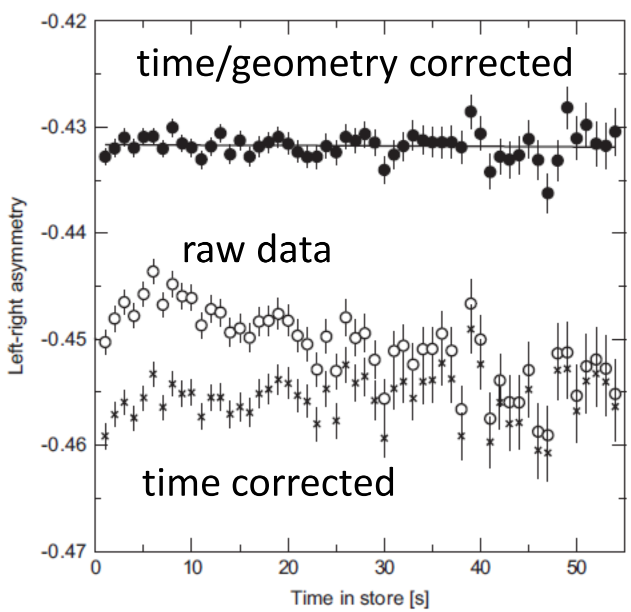
1 Reducing polarimeter systematic errors

Rate and geometry variations were studied for several polarization observables.



Position (up triangles, mm) or angle (down triangles, mrad) horizontal variations in beam

A model was made and calibrated to simulate effects.



With two polarization states, there is enough data to determine error size independent of polarization. In addition, rate may be monitored.

Sample shows result for time/geometry corrections. Result is constant to < 10^{-5} /s (linear fit).

Experiment was statistics limited.

Corrections possible in real time to < 10^{-5}.

NIM A 664, 49

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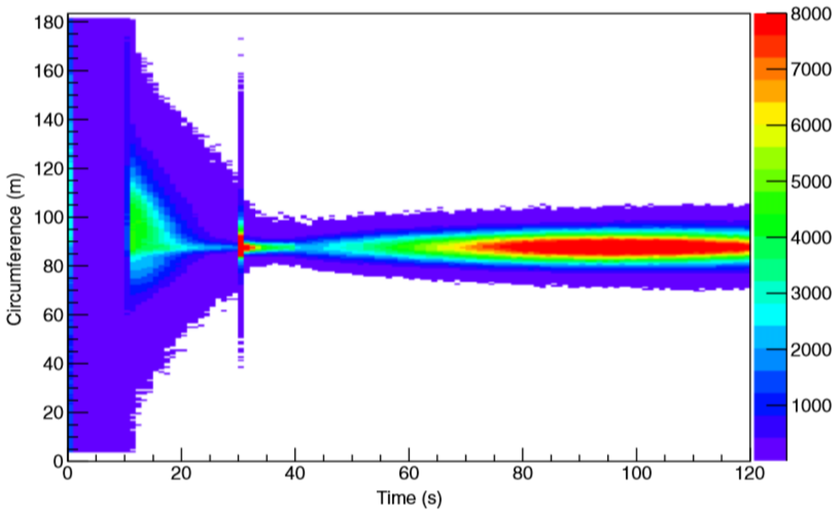
Increasing horizontal polarization lifetime

Coasting beam loses horizontal polarization in about 10 ms due to momentum spread.
A much longer time is needed to allow EDM effect to build up to μrad level.

Improvements:
- bunch beam
- electron cool
- adjust sextupole fields

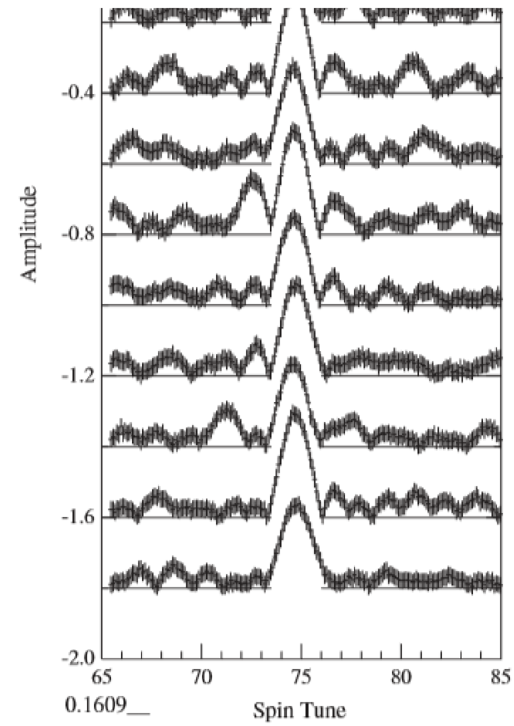
But first, how to measure the rotating polarization?
Frequency = 121 kHz
In each time interval (1 – 4 s) scan spin tune and find value where horizontal polarization is maximized.

Time resolution must show structure of beam around the ring.



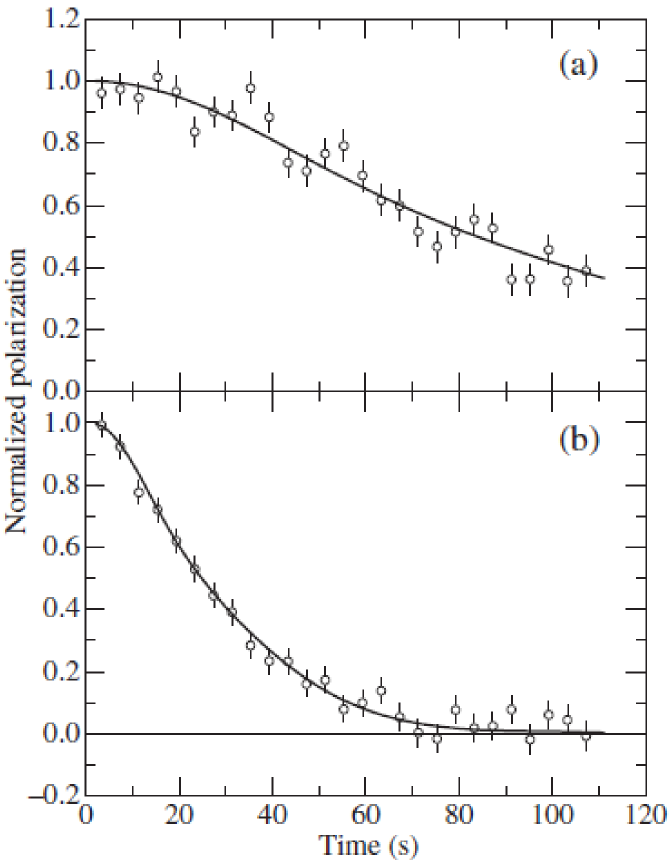
Scans of spin tune show peak where tune matches rotation frequency.

(Vertical to in-plane rotation is made using RF solenoid.)

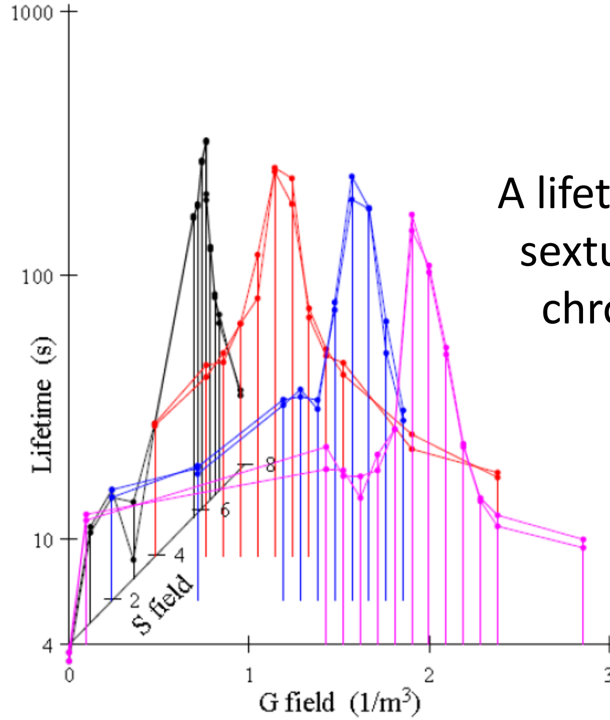


PRL 117, 054801

Two polarization lifetime curves show effect of changing sextupole field in ring.

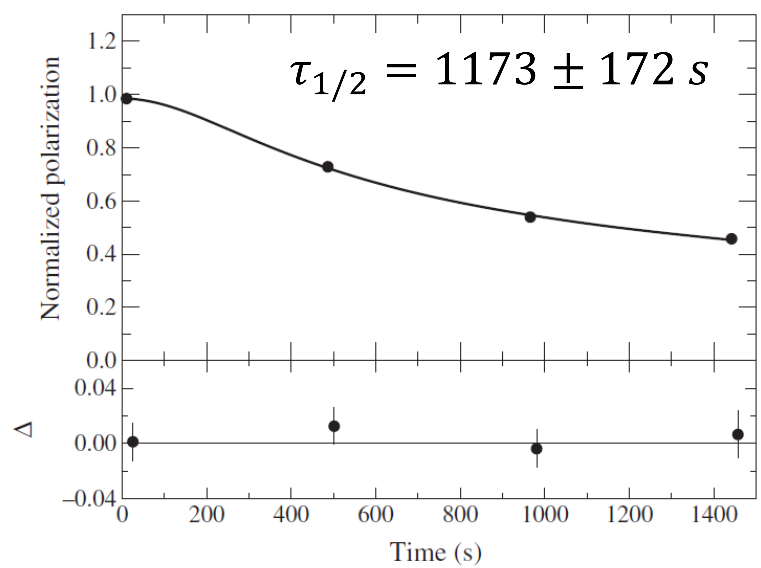


Curves are model shapes.



A lifetime ridge appears in sextupole space where chromaticity vanishes.

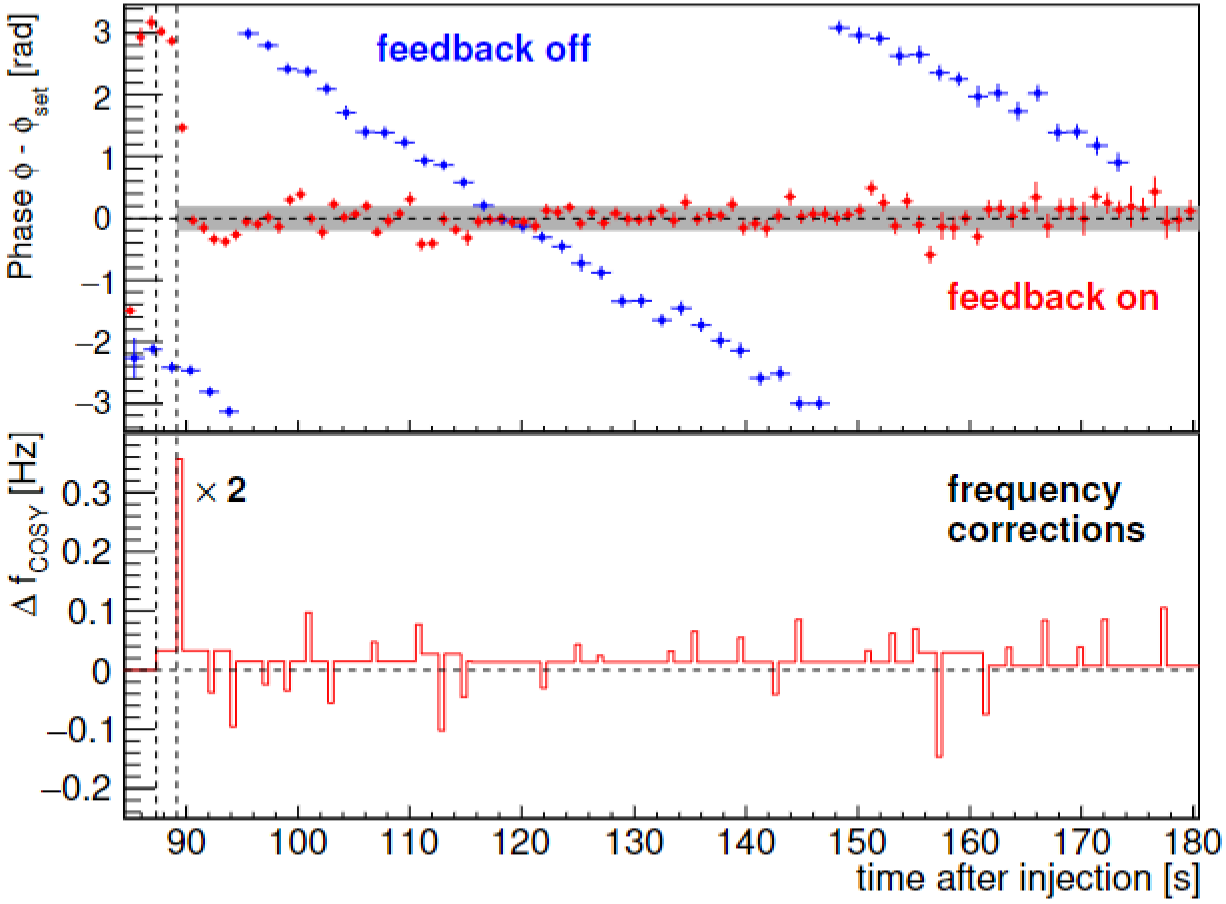
Lifetime curve for best magnet values.



3 Spin tune and phase feedback control

Maintaining polarization parallel to velocity requires regulation to 1 part in 10^9.

This demonstration adjusted the beam revolution frequency (RF cavity).



Width = 0.21 rad

PRL 119, 014801

Managing systematic errors

This experiment's success depends on mitigating systematic errors.

Do the routine things that are needed:

Repeat experiment with polarizations reversed (among different bunches).
Balance left-right and down-up detection systems.
Run with counter-rotating (CW/CCW) beams at the same time.
Build machine to tight tolerances.
Minimize orbit deviations (beam-based alignment).
Lengthen signal accumulation time (1 nrad/s for 10^{-29} e·cm).
Monitor and log as much as possible.

Do some non-routine things:

Radial magnetic fields and vertical electric fields mimic EDM effects.
- Build in sum rule cancellation.
- Use SQUID magnetometers to monitor CW/CCW vertical separation.
- Wobble/reduce vertical tune to tag signal, improve polarization lifetime.

Minimize field imperfections and other moments in RF cavities.

Effects currently being studied:

- Orbit deviations within electrostatic components (dipole + quad).
- Effects of gravity (induces signal at 10^{-28} e·cm, CW/CCW comparison helps).
- Coupling to sideways polarization components.
- RF cavity misalignment.

Effects that need further study:

- Differences in CW/CCW betatron oscillations distributions.
- Polarization profiles in the beam (known to exist at COSY).
- Effects of induced fields in companion beam or beam pipe structures.
- One-sided effects such as energy loss on residual gas.
- …

Management and planning

COSY (Cooler Synchrotron) is supported through:
Forschungszentrum Jülich (general purpose government research laboratory)
Helmholtz Foundation (HGF) for base funding (facility and personnel)
European Union for project funding (non-renewable 5-year grants)
Other sources (personnel, project, and bridge funding)

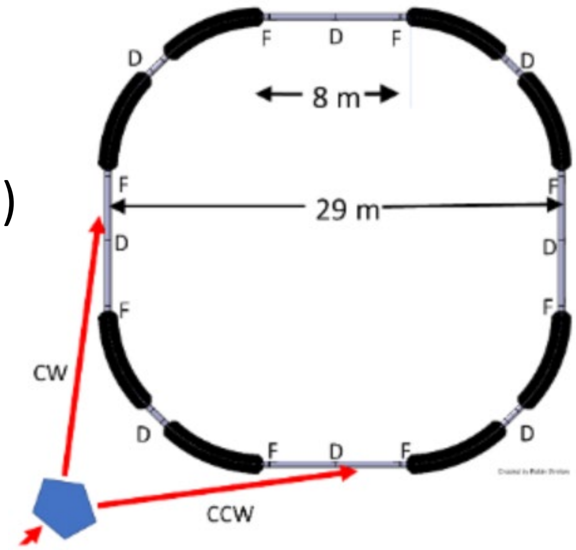
Significant Events:

2016 – The FZJ changed its mission to include only applied research !!!
Basic (nuclear and plasma) research closes at the end of 2021.
`Precursor' experiment for deuteron EDM limit begins.
2017 – Sig Martin hired to become lead for accelerator design.
2018 – Decision made to introduce intermediate step, the prototype ring.
Proton EDM added to list of `Physics Beyond Collider' projects.
Access available to CERN personnel and resources.
Begin preparation of large report on proton EDM.
2019 – Discussions begin to move COSY to GSI-Darmstadt oversight.

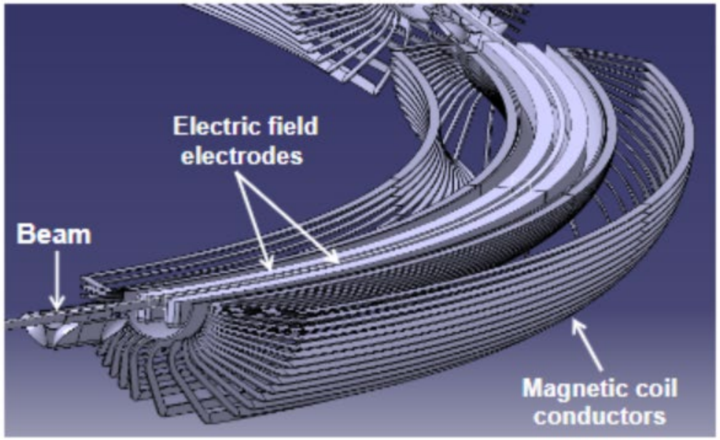
Prototype Ring

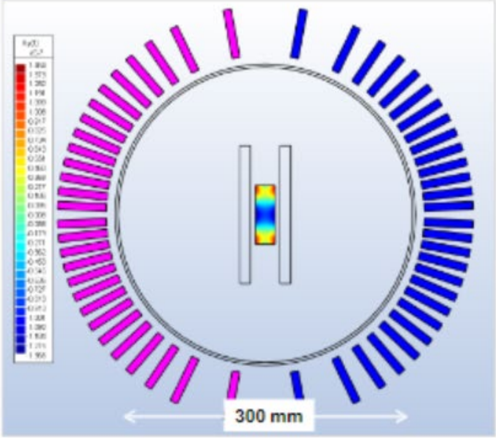
30-MeV all electric, dual beam (CW/CCW)
45-MeV E × B, frozen spin, single beam

To demonstrate:
- high intensity beams in all-electric ring
- multiple polarization state preparation
- magnetic field shielding
- cooled beam (electron pre-cooling)
- lattice elements for 500-m ring

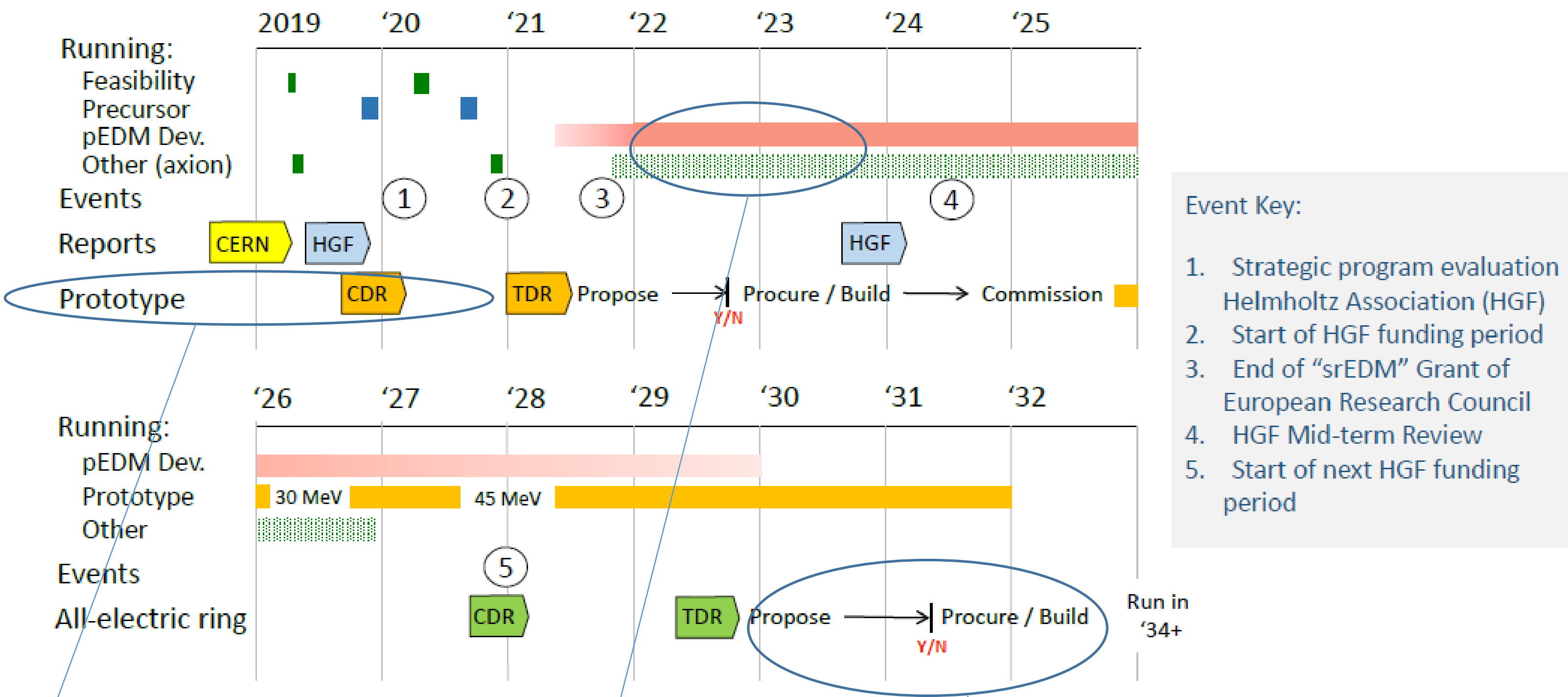


100-m circumference
6.7 – 7 MV/m electric field
0.0327 T magnetic field (air core)





Timeline



Start of work on prototype planning and design. Begin operation about 2025.

COSY continues operation. Main efforts are proton feasibility and axion search.

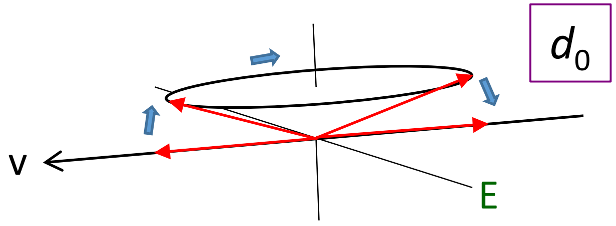
Construction and commissioning of EDM ring at CERN. Operation starts mid-2030s. Initial efforts devoted to demonstrating method and systematic error handling.

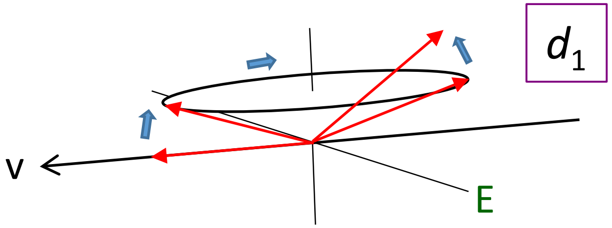
Axion-like particle search at COSY

Assume that the axion field generates an oscillating EDM:

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

Frozen spin (polarization parallel to velocity) allows d_0 to accumulate.
Rotating spin allows d_1 to accumulate.





Assumption about axion field:

Field has large spatial coherence. Axions are dense.

Field extends beyond the storage ring laboratory.

Field causes all EDMs to oscillate in phase. The phase is unknown.

Field has large time coherence.

Any oscillating EDM maintains frequency for duration of scan.

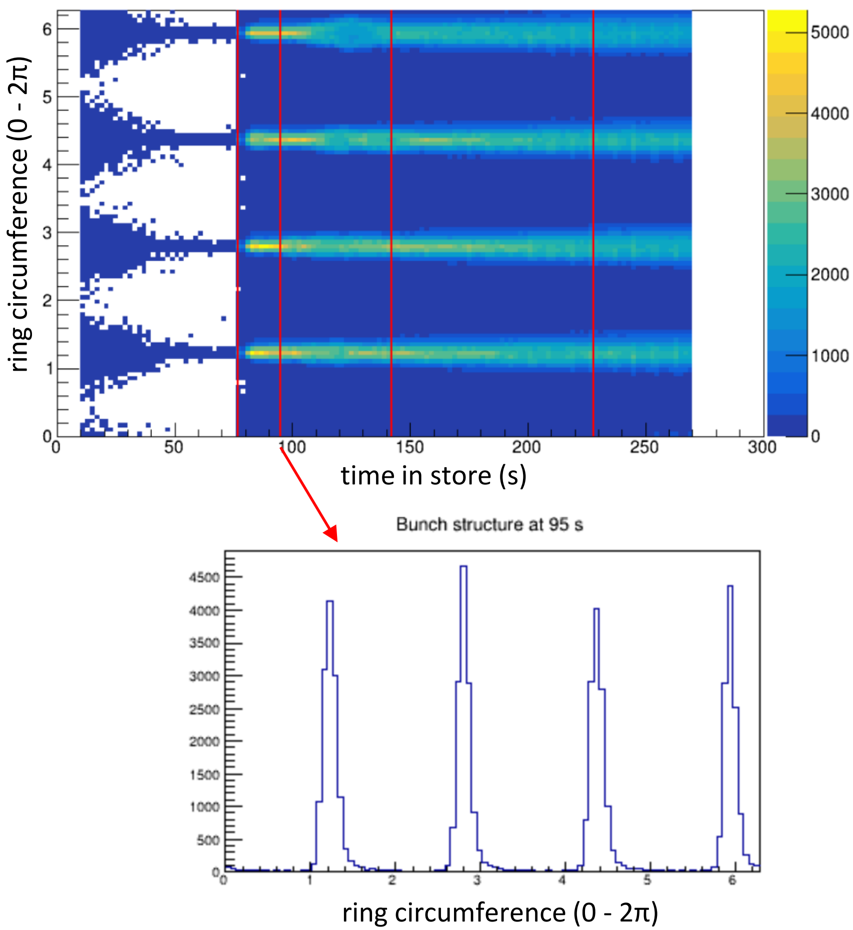
(Assumptions tied to capture of axion within local galaxy and Q > 10^6. There is a possible connection to dark matter.)

Problem: Axion phase is unknown.

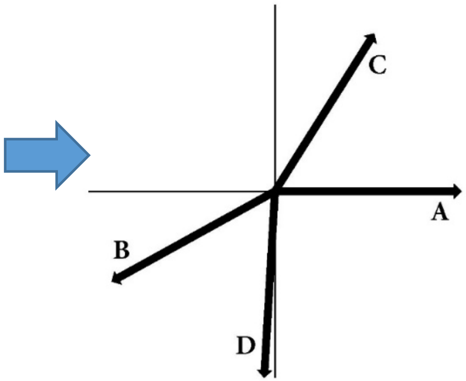
Conduct search simultaneously with beams having perpendicular polarizations.

Combine results for better signal.

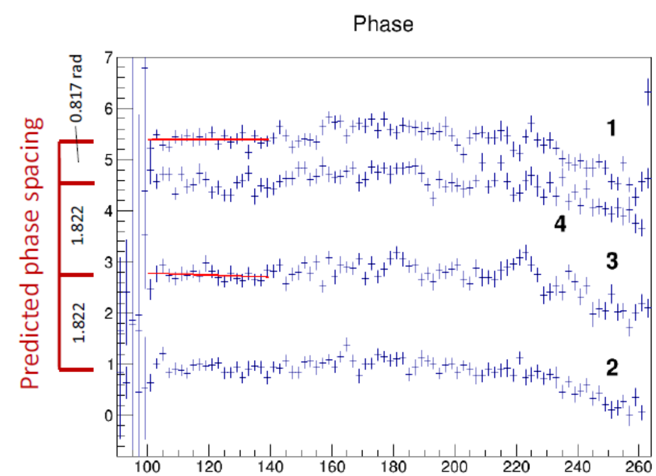
Plan: Use 4 bunches…



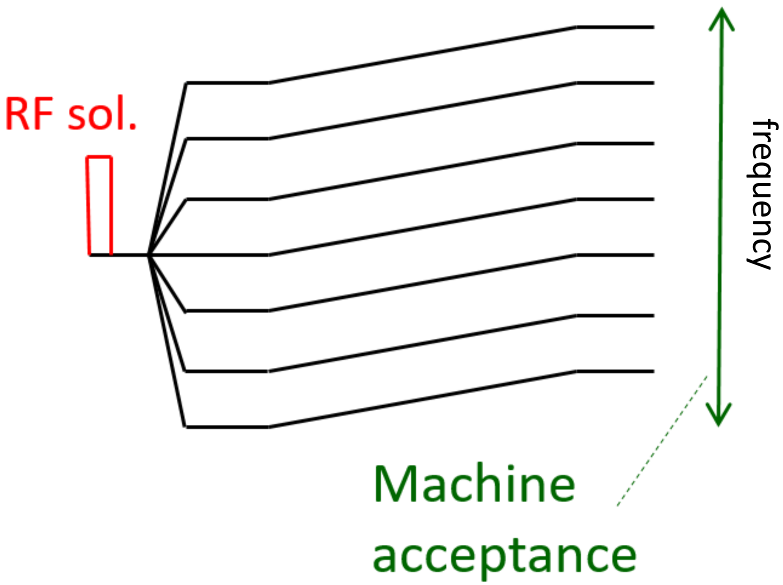
Operate RF solenoid at $f_{REV}(1+G\gamma)$ = 629771.9 Hz



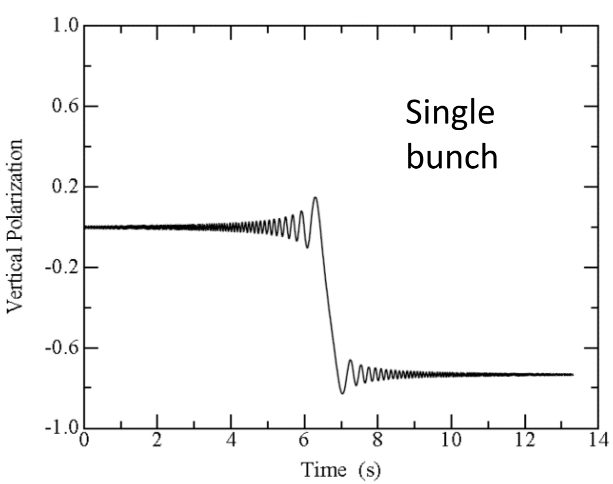
verification for $f_{REV}(1-G\gamma)$ = 871443.1 Hz



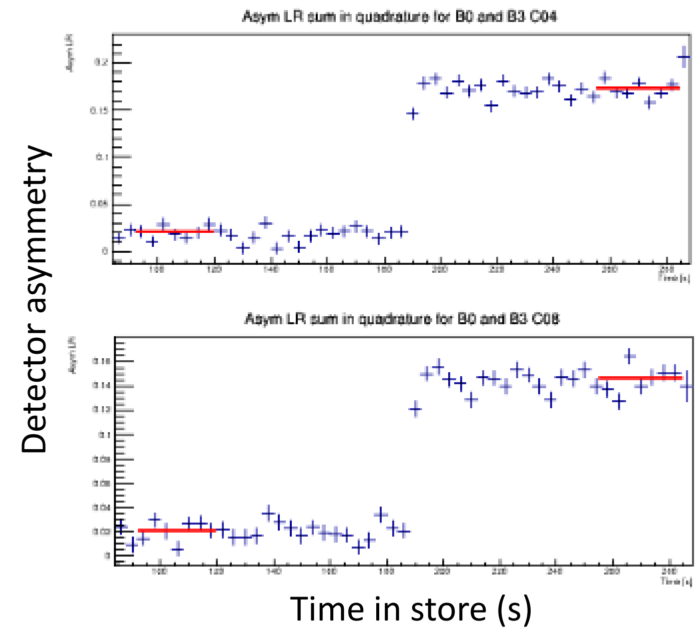
Run a series of scans in frequency



expected signal



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.



Best sensitivity scans produced a 2σ upper limit of $d_1 > 2 \times 10^{-22}$ e·cm over 1.5% frequency range near 121 kHz.

PRELIMINARY

Graph showing result located on plot from literature:

S. P. Chang et al., PRD 99, 083202 (2019)