Feasibility Demonstrations for EDM Experiments

Edward J. Stephenson
Indiana University
JEDI Collaboration

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2016

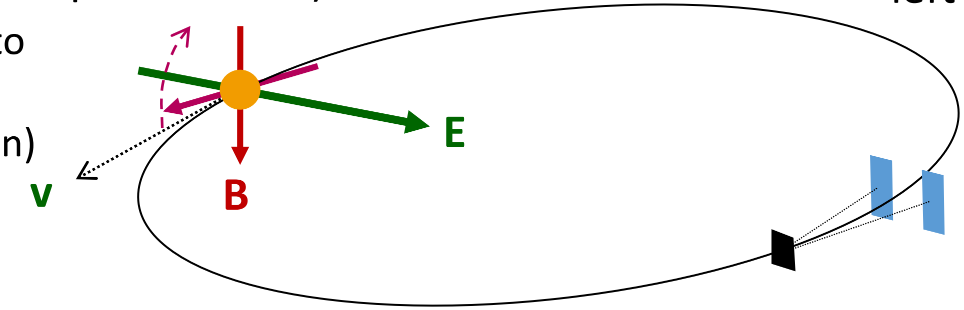
EDM experiment concept

Trap for charged particles with large E-field.

Start: polarization parallel to velocity

Signal: polarization rotates in E field
(vertical component rises)

(unstable to stable polarization)



Measurement

Elastic scattering from carbon
Vertical polarization generates left-right rate asymmetry, observe change from early to late in store.

Deuteron beam (p ~ 1 GeV/c)

Proton beam ("magic" p = 0.7007 GeV/c)

Long-term goal, sensitivity of 10^{-29} e·cm.

Experiment is challenging.
A number of things need to be demonstrated.

Large efficiency (~1%)
Large analyzing power (> 0.6)
Continuous event rate

Thick target (few cm)
Thin target comparable (× 10) with lost energy replaced by RF bunching cavity.

Things that you need to be able to do (★ = done)

"FROZEN SPIN"

Hold the polarization within ~20° of the velocity direction.

For negative anomalous moments, crossed E and B fields required.

For protons (positive anomalous moment), p = 0.7007 GeV/c can be done with only E.

Create bending elements with crossed E and B field and very high E.

★ Regulate polarization direction with feedback.

Frozen spin may be replaced by an RF Wien filter (reduced sensitivity).

POLARIZATION MEASUREMENT

★ Measure a spin rotation angle of 1 μrad, controlling rate/geometry errors.

★ Arrange the ring lattice so that in-plane polarization lasts ~1000 s.

Effectively use 1e11 particles/fill.

SUPPRESS SYSTEMATIC ERRORS

Repeat experiment running in CW and CCW directions.

The orbit must reproduce to high accuracy (be monitored and controlled).

Machine must be stable over time (vibration, environmental changes).

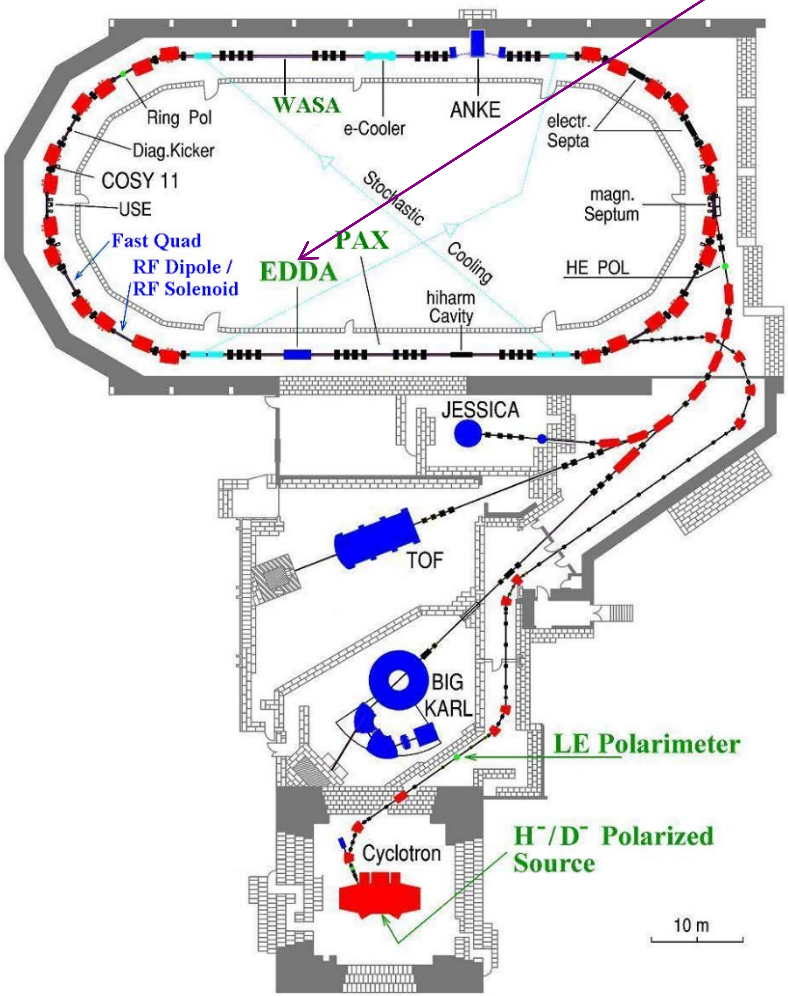
(This can be effective against radial B-field and rotation non-commutativity errors.)

For protons where CW/CCW overlap, detect orbit differences sensitively.

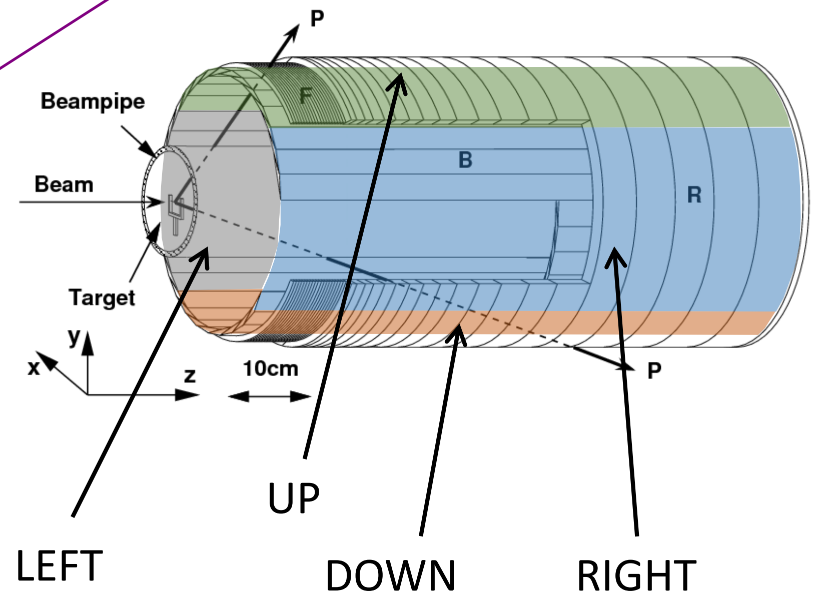
Polarimeter Study

COSY storage ring

polarized deuterons, 0.97 GeV/c



EDDA detector

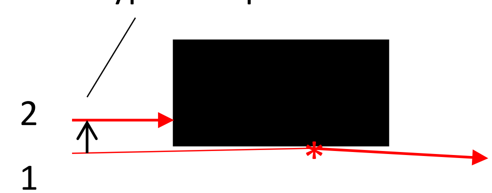


Azimuthal angles yield two asymmetries:

$$\varepsilon_{EDM} = \frac{L-R}{L+R} \qquad \varepsilon_{g-2} = \frac{D-U}{D+U}$$

17 mm C target

typical depth ~ 0.2 mm



double-hit extraction?:
deflect at (1), then oscillate to (2)

Plan for handling geometry and rate errors

considering that beam properties are continuously changing
error correction must respond in real time

1 Use as robust a scheme as possible:

Usual tricks: Locate detectors on both sides of the beam (L and R).
Repeat experiment with up and down polarization.
Cancel effects in formula for asymmetry (cross-ratio).

Cross ratio: $pA = \varepsilon = \frac{r-1}{r+1}$ $\quad r^2 = \frac{L(+)R(-)}{L(-)R(+)}$ But this fails at second order in the errors.

2 Measure sensitivity of all observables to geometry and rate errors.

Choose index variables for all error types.

Build a model that explains all effects. Does it have a simple dependence in terms of the index variables?

Other observable options (3 more):

1) $\phi = \frac{s-1}{s+1}$ $\quad s^2 = \frac{L(+)L(-)}{R(+)R(-)}$

Good! Sees geometry errors, not p.

2) ~~$\chi = \frac{t-1}{t+1}$ $\quad t^2 = \frac{L(+)R(+)}{L(-)R(-)}$~~

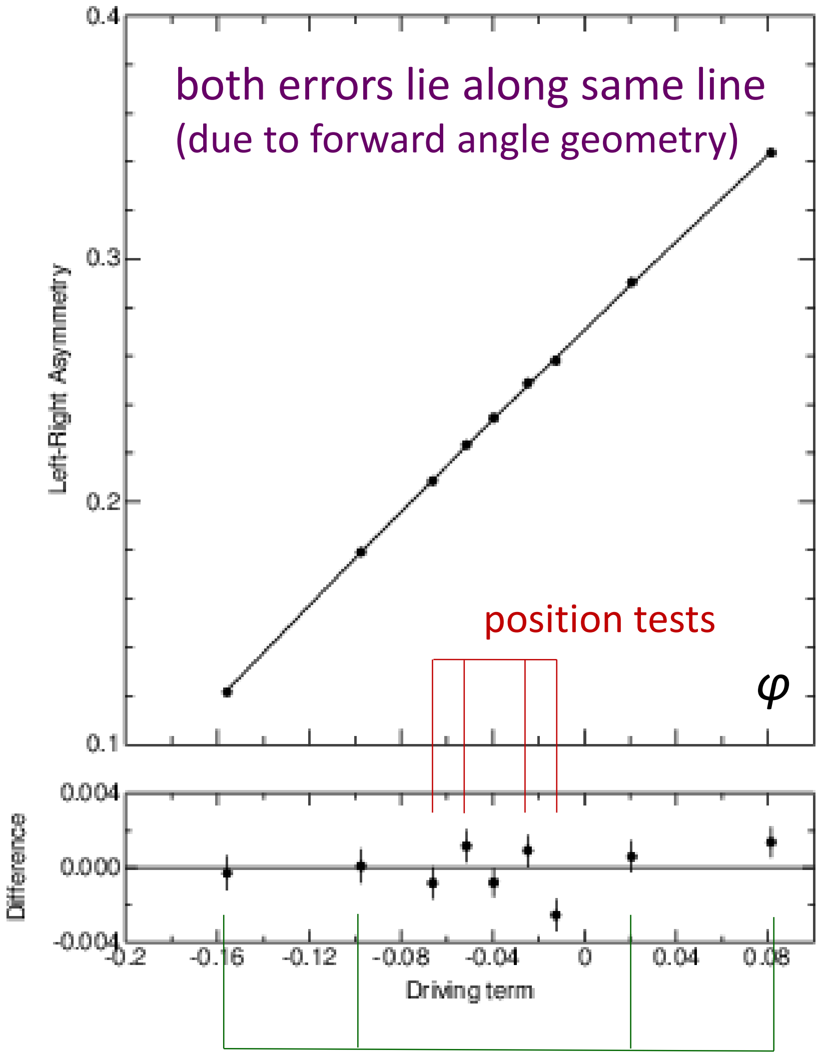
Useless! Sees luminosity difference.

3) $W = L(+) + R(+) + L(-) + R(-)$

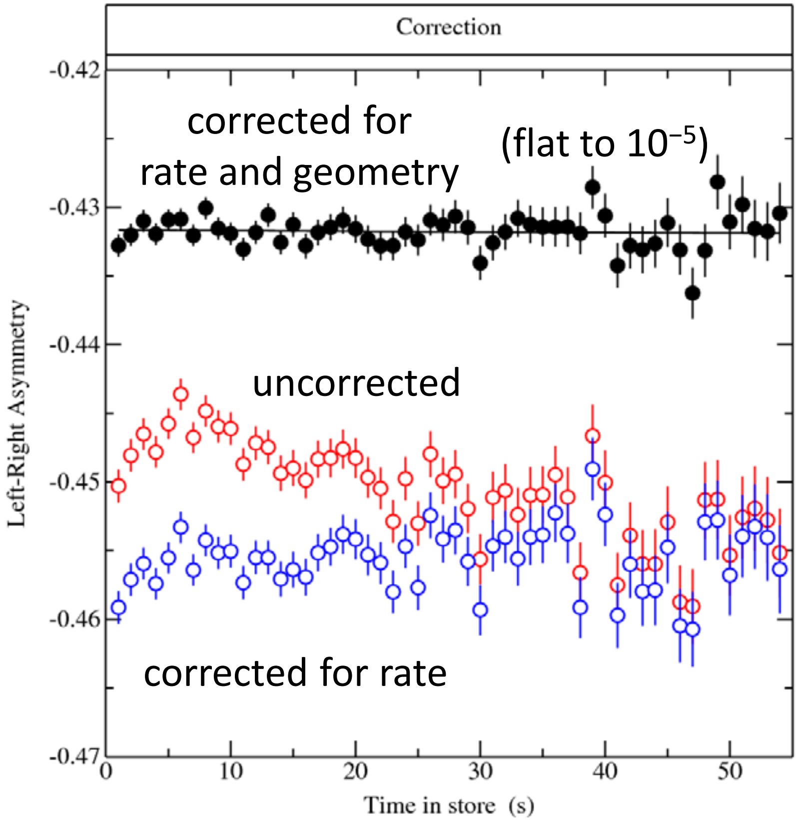
Good for rate effects!

Does this work? (Test by comparing position and angle sensitivity.)

data from 2009 long run



test with constant polarization

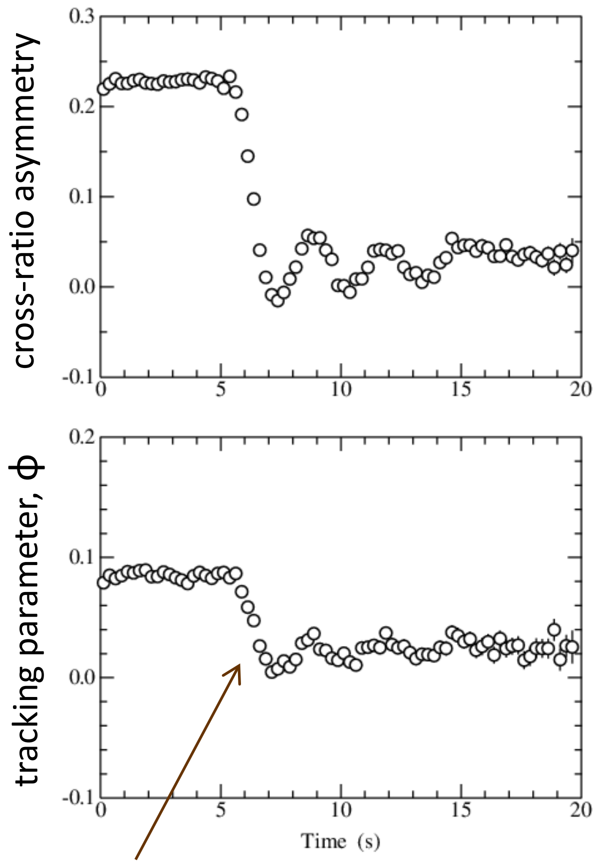


Application to data with errors shows correction in real time.

What about a varying polarization signal?

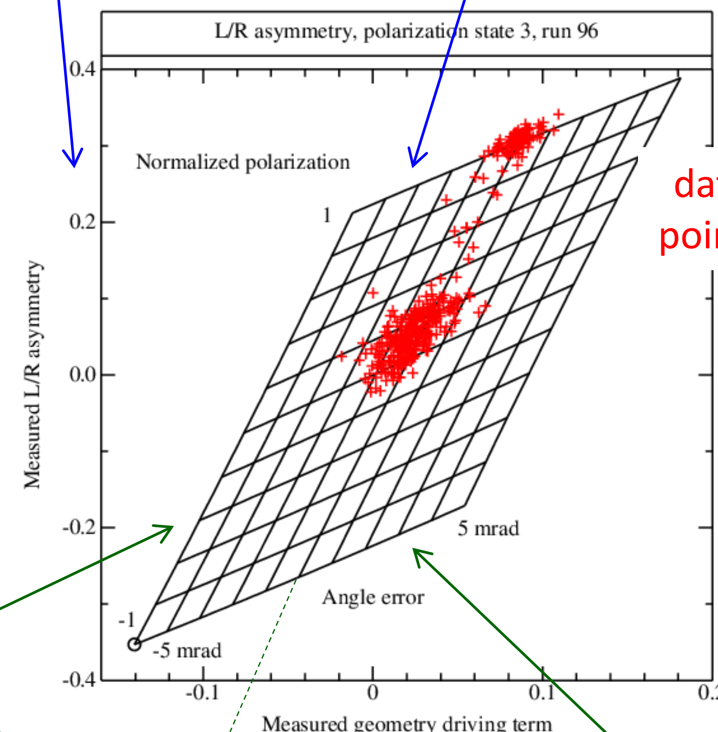
What happens when the polarization itself is changing?

First data available in 2011 from runs made with RF solenoid on spin resonance.



data

The model can also address this situation, projecting the data from the lab system onto the corrected system.



data points

0

The error indexing parameter also contains some remnant of the signal (from unequal state polarizations).

Axis renormalized, as model knows about polarization.

Other axis shows scatter in the systematic error

Progress on polarization lifetime and feedback control apply to frozen spin.
This is not possible with (only) magnetic ring.
Do tests with precessing polarization (~ 120 kHz) as a substitute.

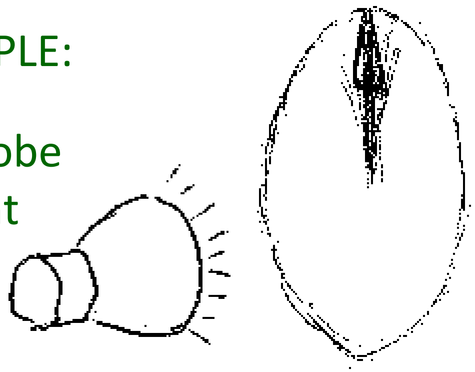
New tool needed:

Mark clock time of each polarimeter event, unfold polarization direction.

(Look for up-down asymmetry only when polarization points sideways.)

EXAMPLE:

Strobe light



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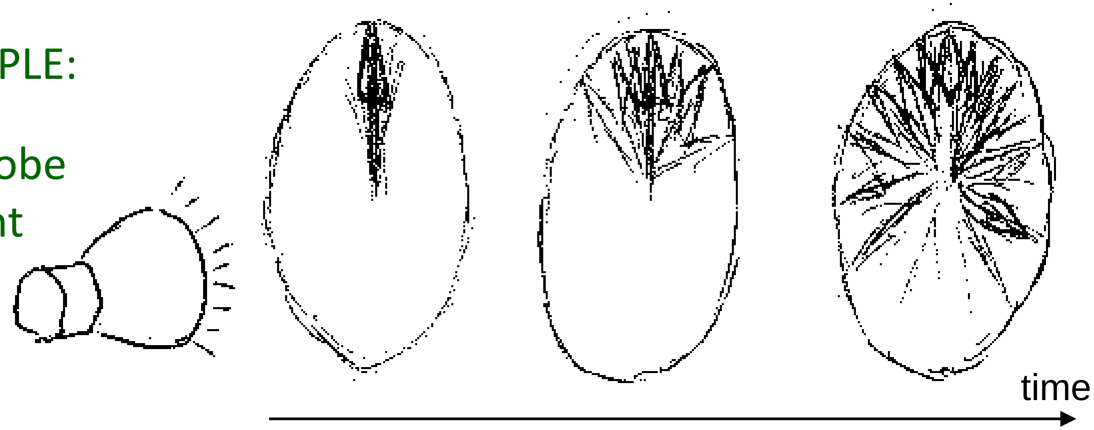
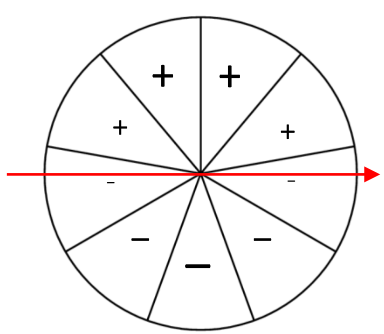
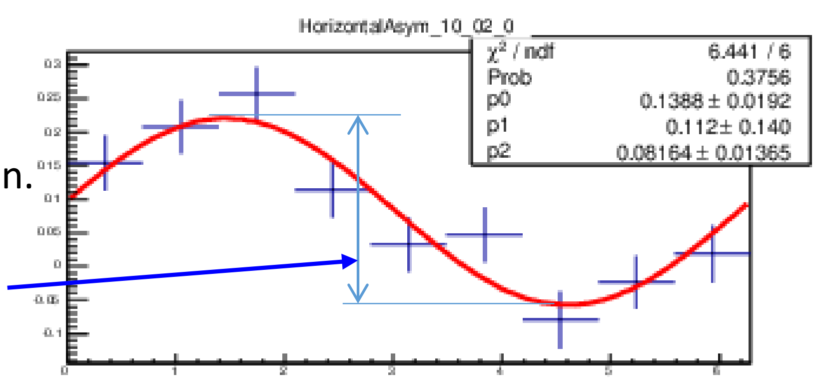


Bin into intervals of 1 to a few seconds. Watch polarization spread with time.

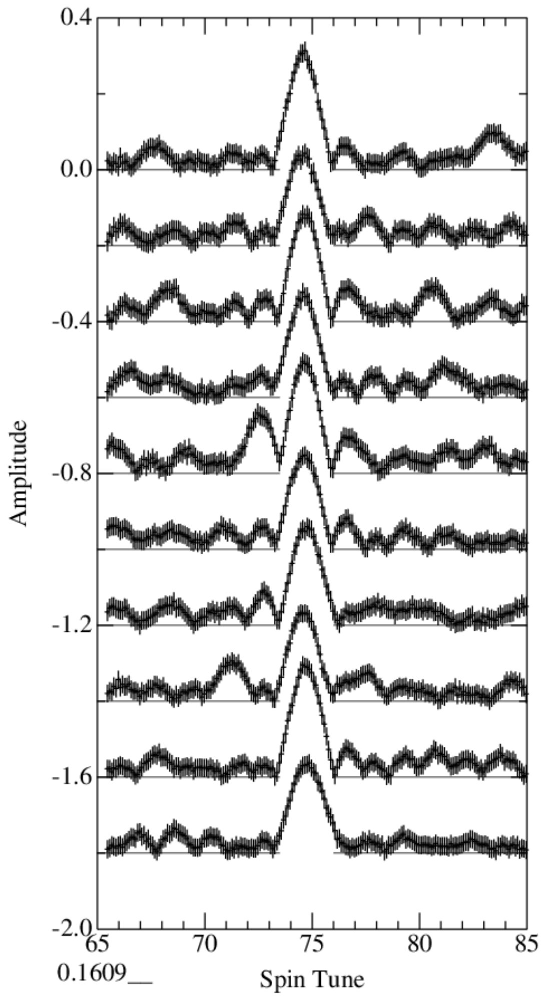


As the polarization rotates the down-up asymmetry reflects the sideways projection of the polarization.

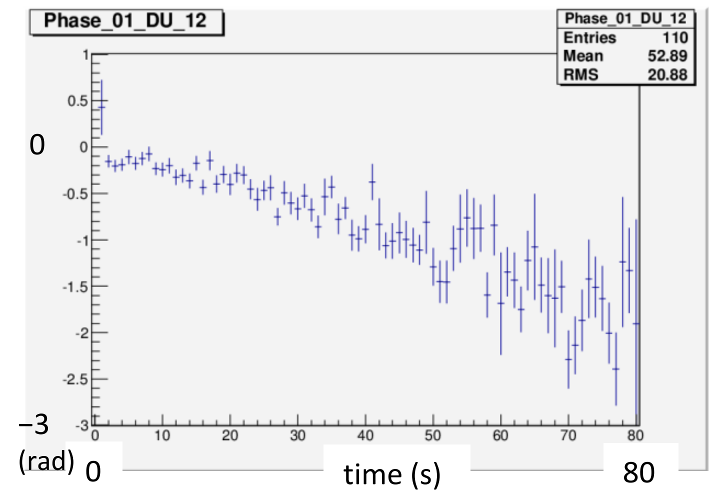
magnitude gives horizontal polarization



Program searches for highest amplitude in a narrow range by varying the rotation frequency.



phase in a single store with fixed frequency



To get maximum asymmetry stationary in one angle bin for one second, the frequency must be accurate to < 1e-6.

The normal scatter is usually < 1e-7.

<u>For phase:</u>

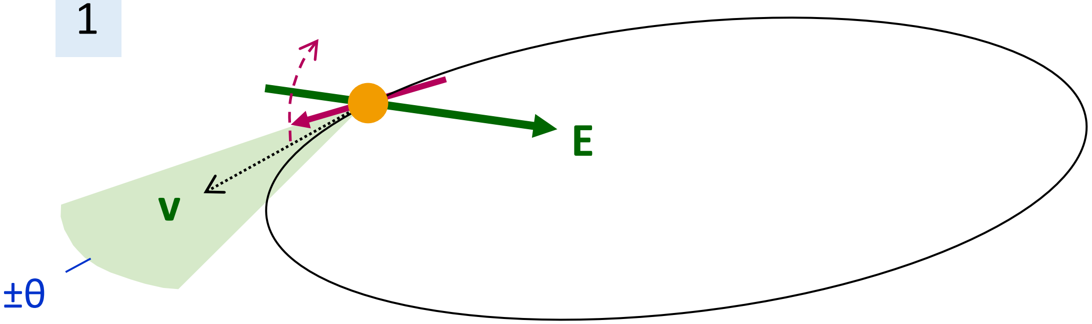
The best error in phase is ~ 3° /s.

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

EDM ring requirement is 1e-9 from feedback.

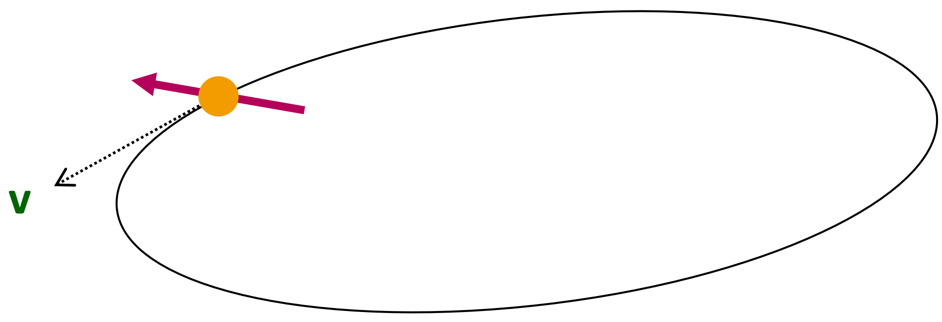
Requirements on polarization control:

1



Maintain polarization within some limited angular range on either side of the velocity for ~ 1000 s. From beginning to end, 10^{-9} precision is needed.

2



Periodically rotate sideways and hold for a check of the polarization. (For tensor polarized deuterons, this is possible in place.)

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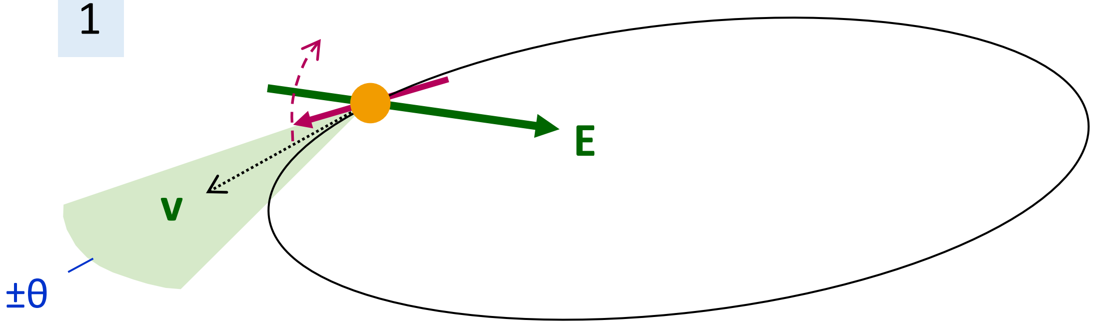

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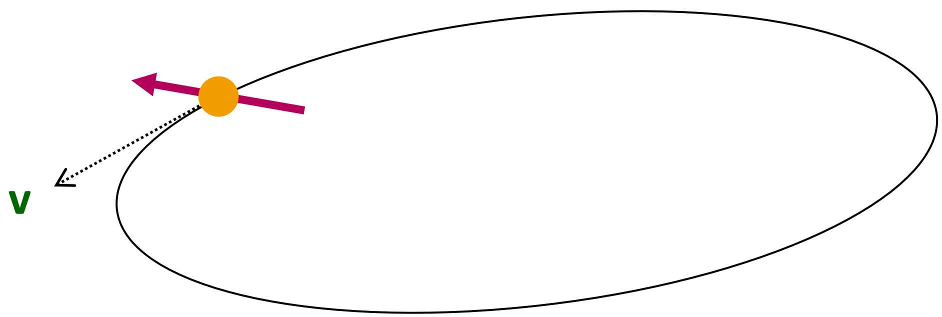

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polarimeter rates (U, D, L, R)
COSY RF timing

clock TDC

DAQ

online analysis for magnitude, spin tune, and phase (from t = 0)

NEW

Calculate correction

RF frequency generator

Make 2 kinds of corrections:

1 Δf to
choose a new spin tune
regulate spin tune

2 Δf for Δt to
go to a new phase
(new direction)

Calibration of feedback to RF cavity

$$\frac{\Delta\nu_S}{\nu_S} = \frac{\Delta\gamma}{\gamma} = \beta^2\frac{\Delta p}{p} = \frac{\beta^2}{\eta}\frac{\Delta f}{f}$$

spin tune — revolution frequency

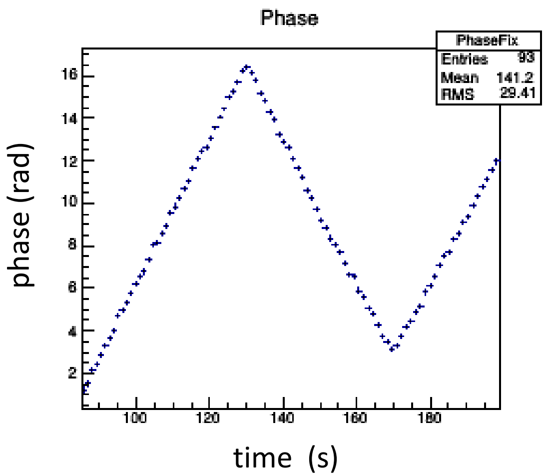
for the deuteron beam:

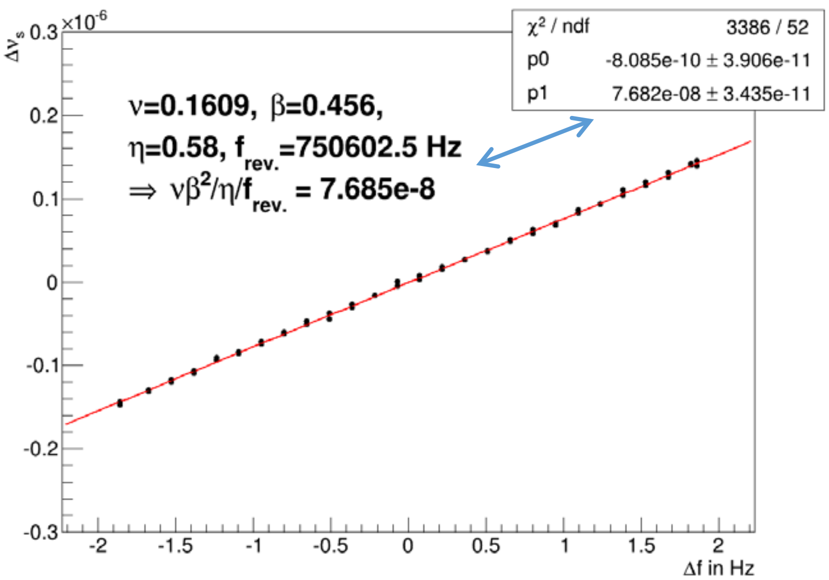
$$p = 0.97\,GeV/c$$
$$\beta = 0.456$$
$$\eta = 0.58$$

Δf is adjustable in steps of 3.7 mHz, or $\frac{\Delta\nu_S}{\nu_S} = 2\times10^{-9}$

$$\nu_S = \nu_0 + \frac{\partial\phi}{\partial t}$$

Initial slope is mismatch between real spin tune and reference spin tune.





Slope match is excellent.
This tests case 1.

Calibration of feedback to RF cavity

$$\frac{\Delta \nu_S}{\nu_S} = \frac{\Delta \gamma}{\gamma} = \beta^2 \frac{\Delta p}{p} = \frac{\beta^2}{\eta}\frac{\Delta f}{f}$$

spin tune (ν_S); revolution frequency (f)

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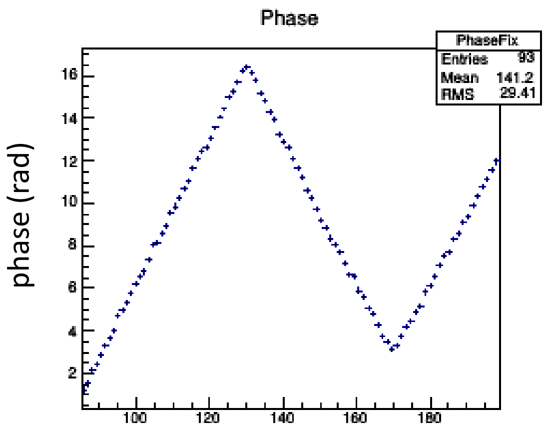

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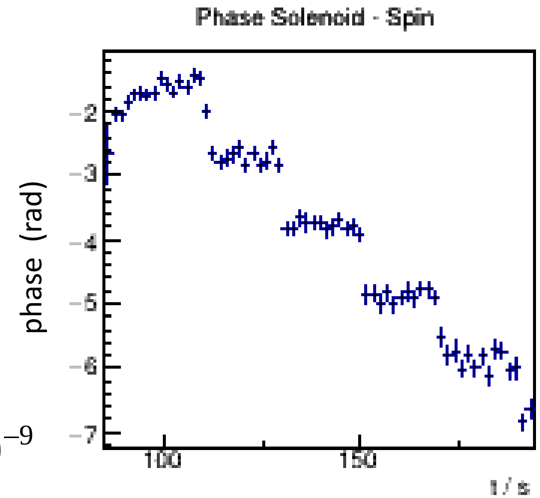
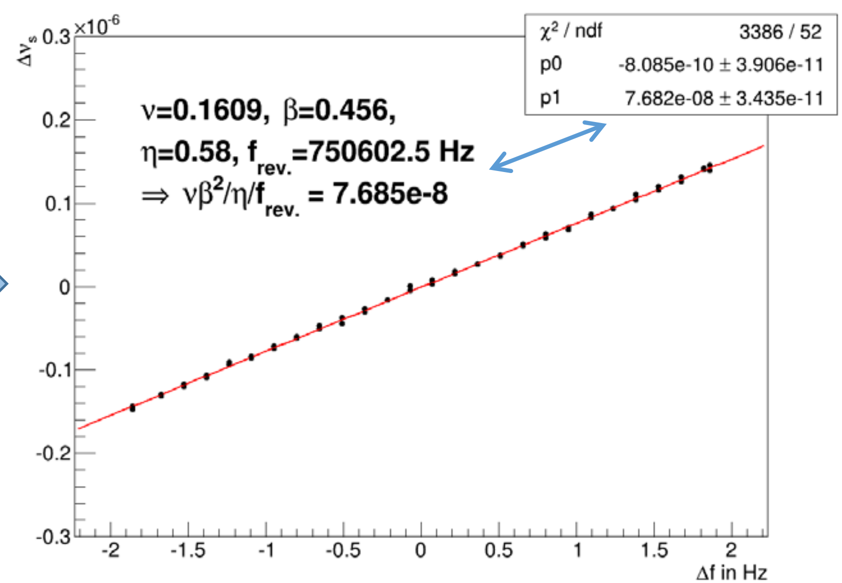
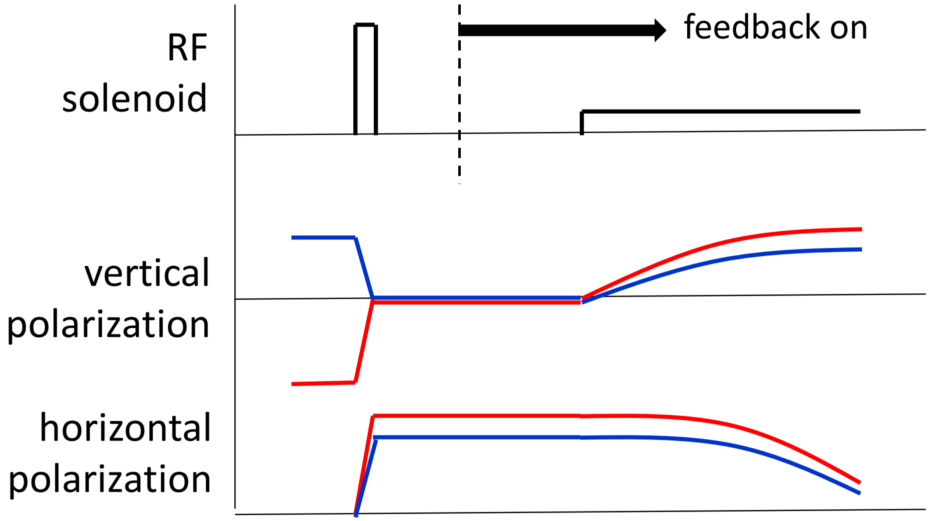
Case 2: Making steps of 1 rad in phase

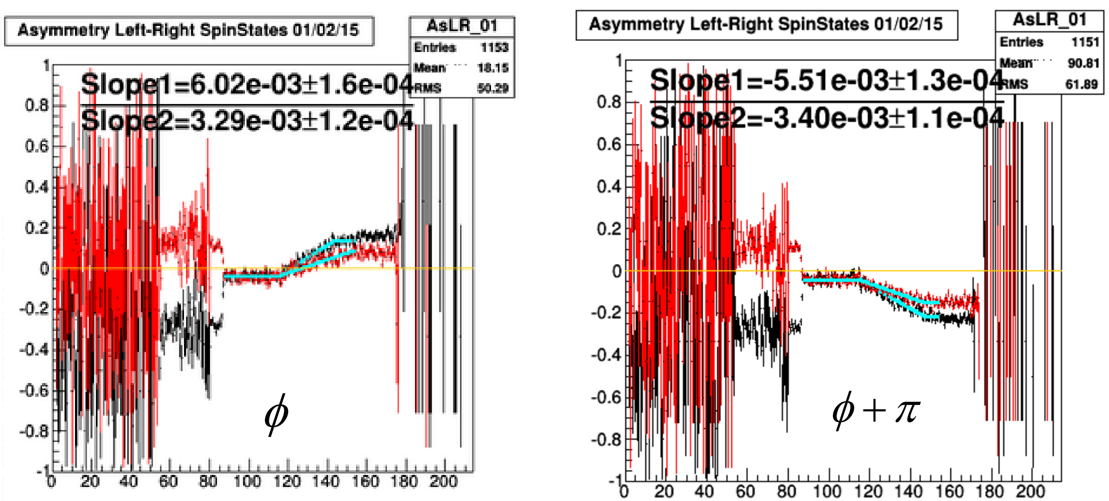




Recapture of polarization

(working demonstration for use with RF Wien filter, etc.)





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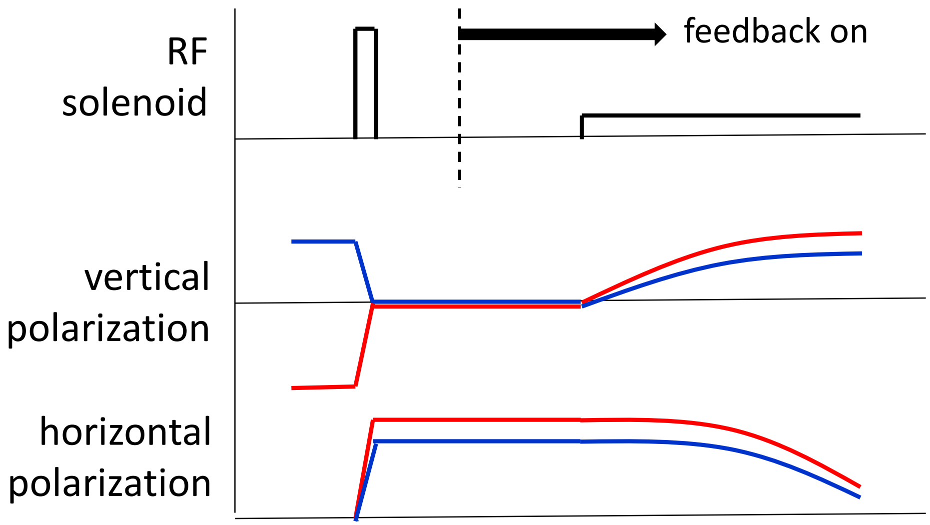
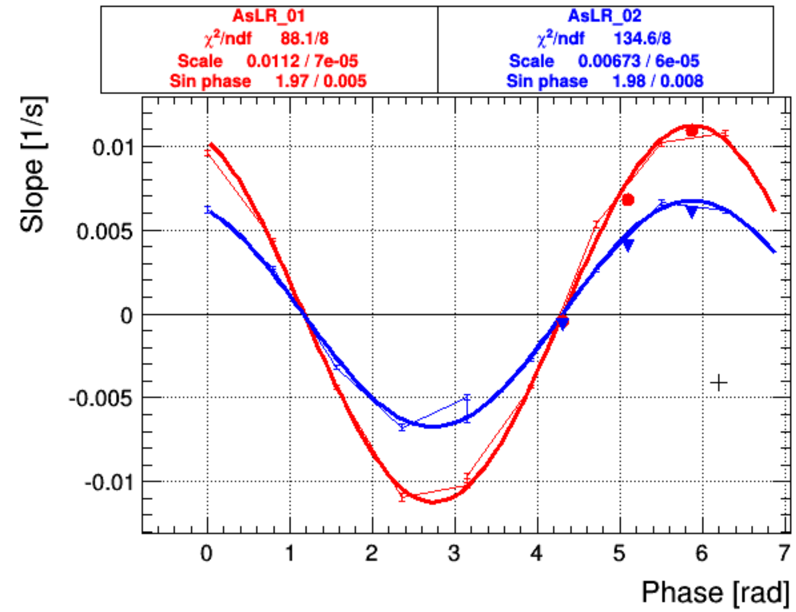
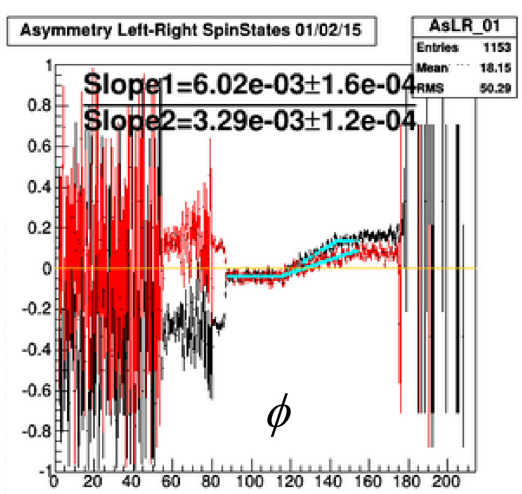
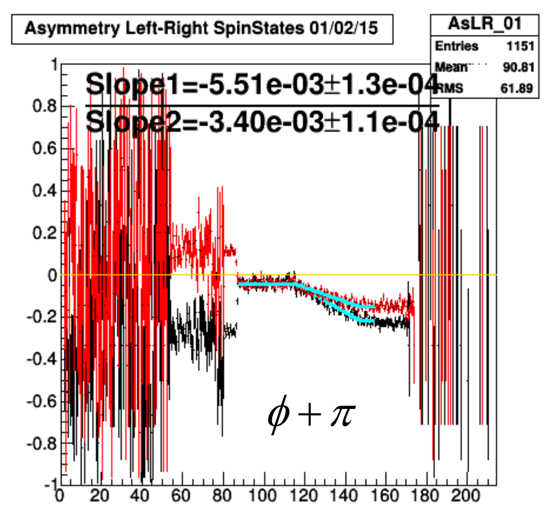








Plot of initial slope as a function of the target phase for the feedback circuit.

Completes requirement for the precursor and EDM experiments.

Work based on significant in-plane polarization lifetime (10s of seconds). This capability was developed prior to feedback control.

Only polarization component along magnetic field direction is stable. The other components precess according to in-plane bending of orbit.

relative to velocity: $f_{PREC} = G\gamma f_{REV}$

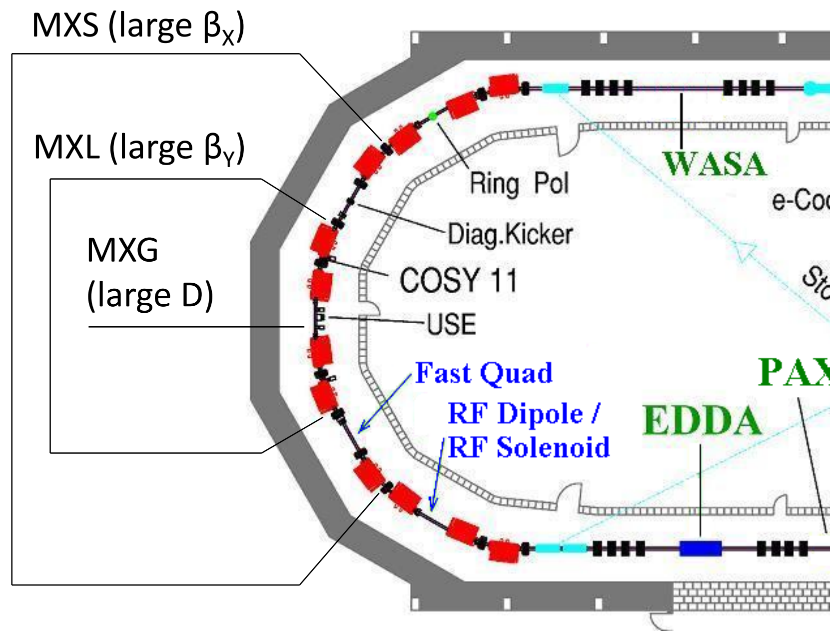
Small momentum variations allow for individual spins to decohere, polarization is lost.

<u>Bunching</u> the beam and <u>electron cooling</u> serve to decrease spread. Deuteron polarization lifetimes become several seconds, visible in system.

Decoherence goes as square of transverse oscillations, orbit may be corrected with sextupoles.

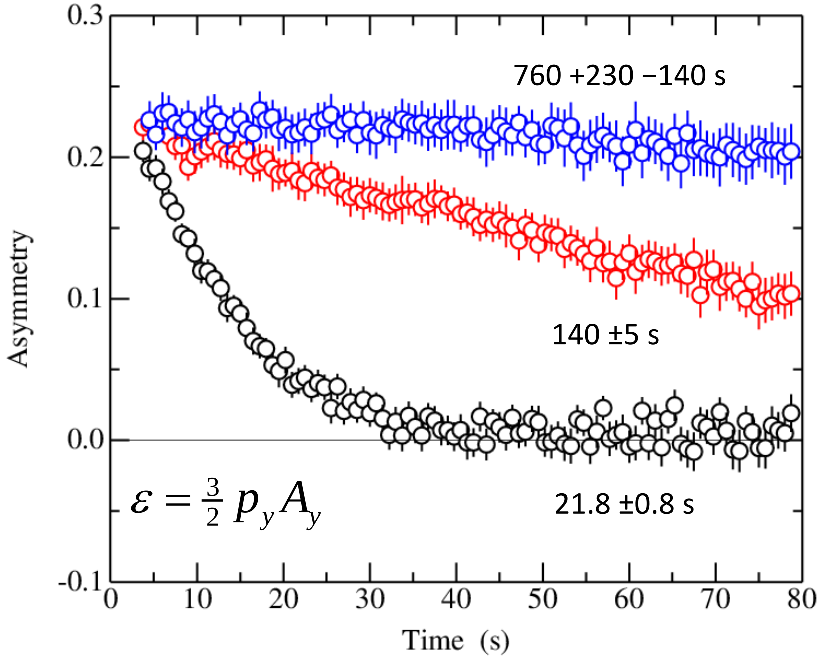
(Vertical correction is small. Look at horizontal size and dispersion.)

Three sextupole magnet families:



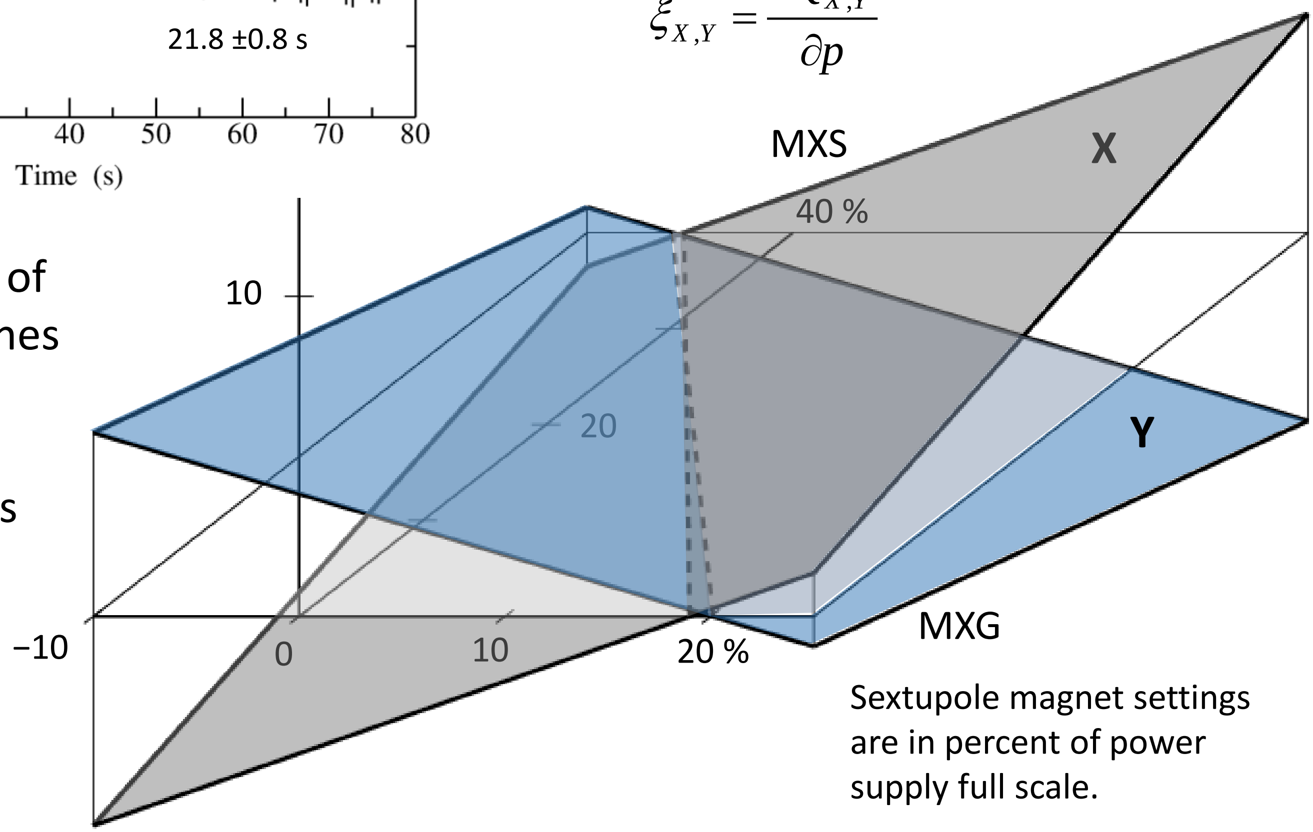
Measurements of polarization history for different sextupole settings.

Times are exponential decay rates.



Measurements of X and Y chromaticity in plane of MXS and MXG sextupole values.

$$\xi_{X,Y} = \frac{\partial Q_{X,Y}}{\partial p}$$

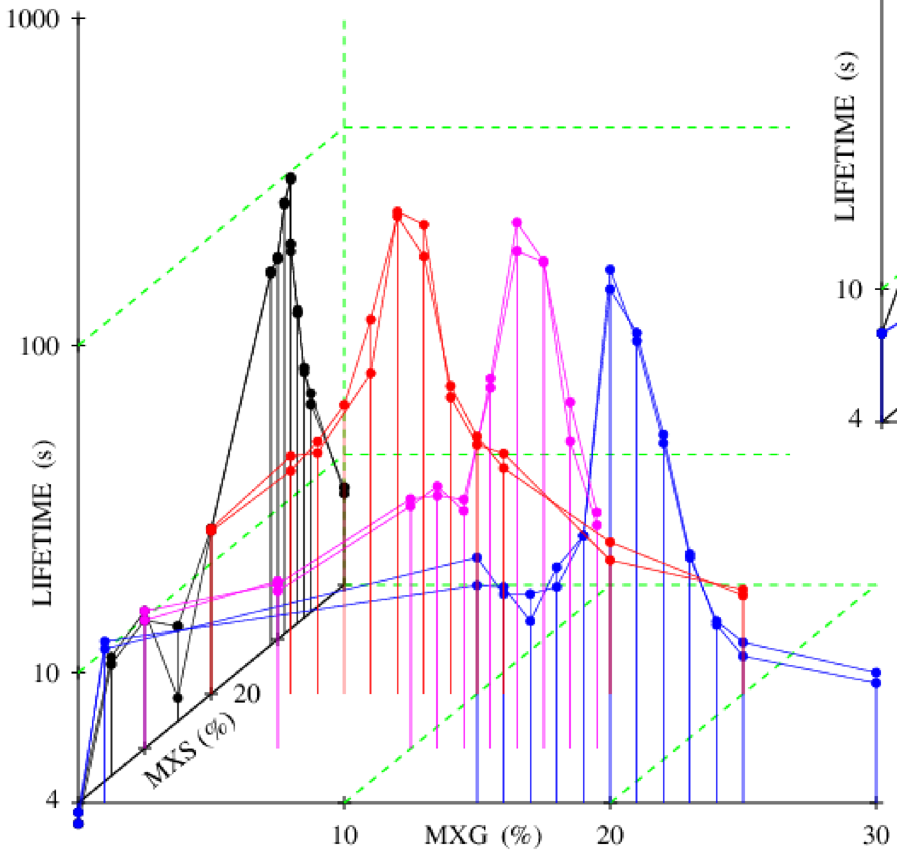


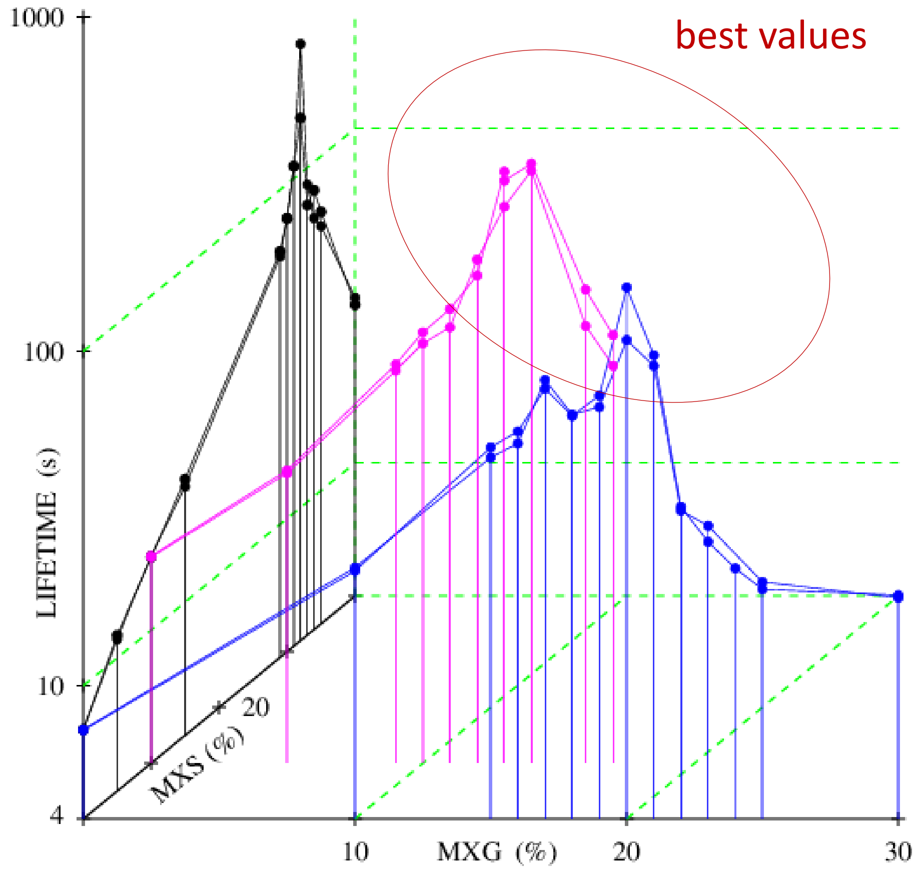
Note the overlap of the two dotted lines that represent the places where the chromaticities vanish. Best polarization lifetimes may be here.

Sextupole magnet settings are in percent of power supply full scale.

Lifetime Scans

Made with horizontally heated beam. Note narrow distribution around peaks. This confirms the effect of transverse oscillations.



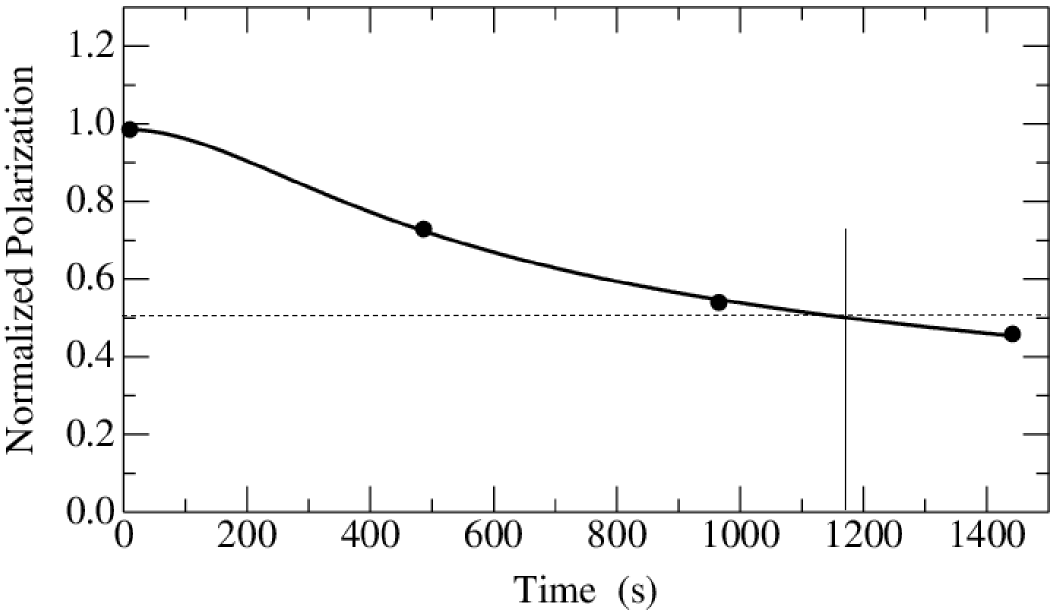


Made with expanded bunch length

Limitations related to complicated (collective?) behavior seen with large beam intensities.

Longest horizontal polarization lifetime:

Electron pre-cooling time 75 s. No cooling afterward…



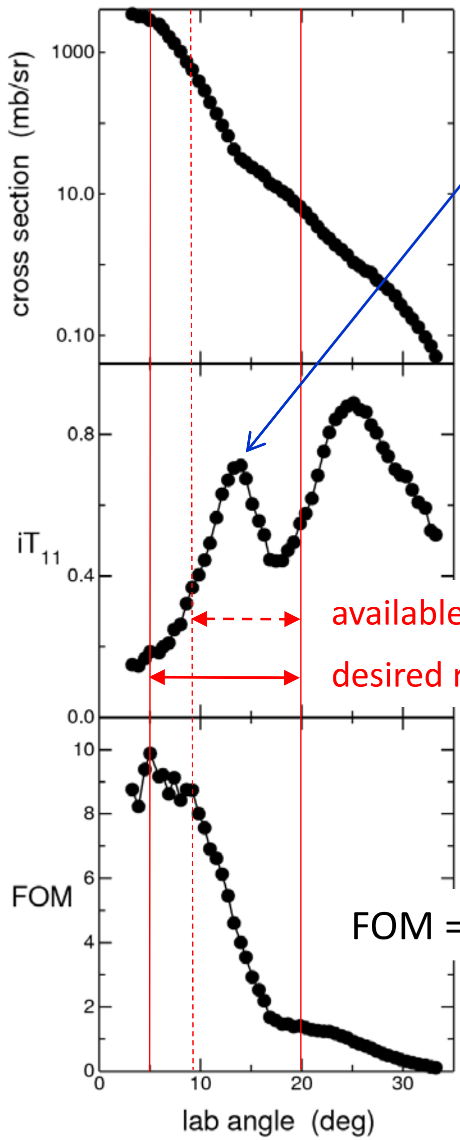
Smooth template based on Gaussian distribution of betatron amplitudes.

Reported in PRL **117**, 054801 ('16)

Half-life = 1173 ± 172 s
This meets EDM requirement.

extra pages

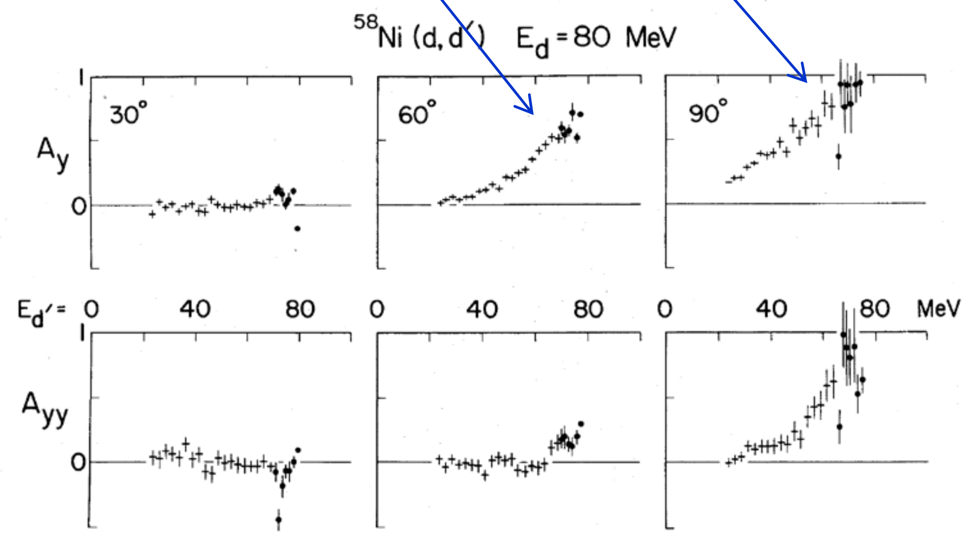
d+C elastic, 270 MeV



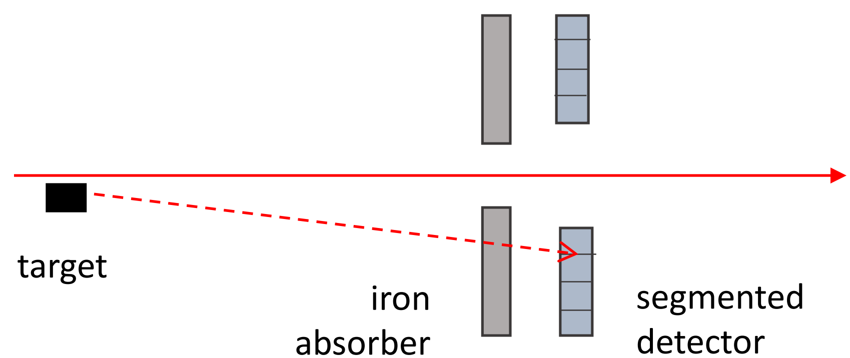
Y. Satou, PL B **549**, 307 (2002)

Deuteron-carbon analyzing powers are large at forward angles (optical model spin-orbit force).

Inelastic and (d,p) are similar, and should be included.



Simplest polarimeter is absorber/detector:



Geometry model

Parameters we know we need to include:

EDDA Analyzing power: A_y and $A_T = \frac{\sqrt{6}T_{22}}{\sqrt{8} - p_T T_{20}}$

Polarizations: p_V and p_T for the states V+, V−, T+, T−

There is some information available from the COSY Low Energy Polarimeter.

Logarithmic derivatives: $\frac{\sigma'}{\sigma}, \frac{\sigma''}{\sigma}, \frac{A_y'}{A_y}, \frac{A_y''}{A_y}, \frac{A_T'}{A_T}, \frac{A_T''}{A_T}$

Solid angle ratios: L/R D/U (D+U)/(L+R)

Total so far: 19 parameters

Parameters we found we needed (peculiar to COSY detector):

Rotation of Down/Up detector (sensitive to vertical polarization): θ_{rot}

X – Y and θ_X – θ_Y coupling (makes D/U sensitive to horizontal errors): C_X, C_θ

Ratio of position and angle effects (effective distance to the detector):

$X/\theta = R$

Tail fraction: multiple-scattered, spin-independent, lower-momentum flux that is recorded only by the "right" detector (to inside of ring)

F = fraction F_X, F_θ sensitivities to position and angle shifts

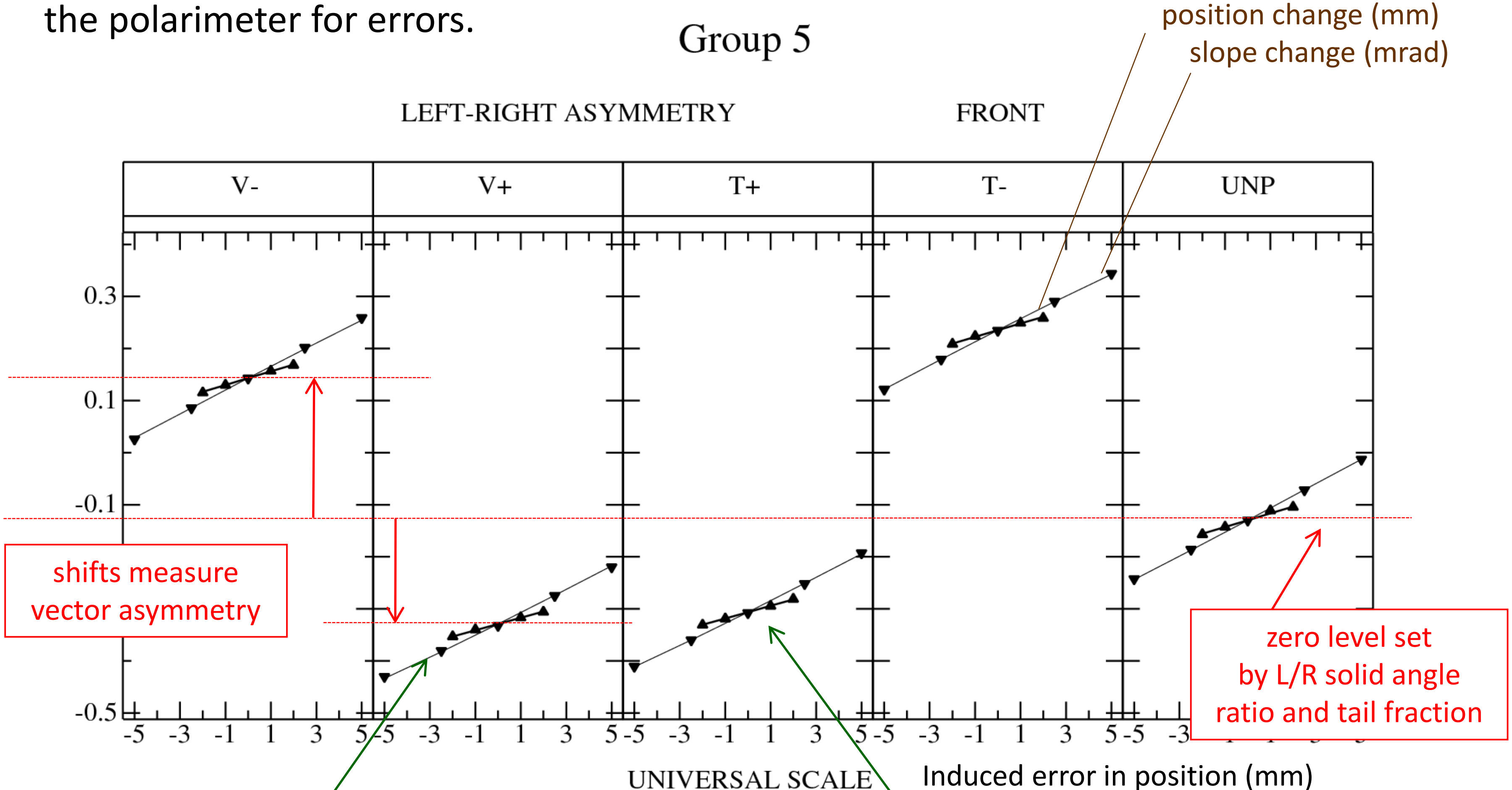
Total so far: 26

Rate model

Linear correction based on rate for each polarization observable (5)

Total parameters: 31

Changes to beam position/angle produced effects that calibrate the polarimeter for errors.



slopes given by $\left(\frac{\sigma'}{\sigma}+\frac{A'}{A}\right)\varepsilon^2-\frac{\sigma'}{\sigma}$

slope difference measures “effective” distance to detector

$\frac{\sigma'}{\sigma}=-0.02562(9)$ $\frac{A'}{A}=0.0055(3)$ $\frac{1}{mrad}$

X/θ = 52.4(8) cm