Deuteron Polarimeter Developments for a Storage Ring EDM Search

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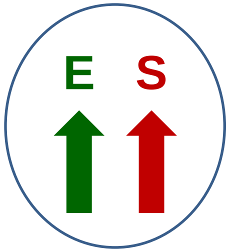
The 2015 International Workshop on
Polarized Sources, Targets and Polarimeters
RUHR-UNIVERSITÄT BOCHUM
14 – 18 September 2015

ELECTRIC DIPOLE MOMENT



Electric dipole (vector) parallel to spin (pseudo-vector)

opposite magnetic moment result

Parity flips EDM
Time reversal flips spin

both are odd

CPT theorem means EDM is CP-violating.
Possibly explains matter dominated universe.

- Known CP violations too weak.
- EDM may be modern remnant of new source.
- Small EDM challenges SUSY theories.

Sakharov conditions for matter-dominated universe:
- violation of baryon number
- violation of C and CP
- not in thermal equilibrium

SEARCHES FOR AN EDM

Examine neutral systems in a trap (align with **B**, flip **E**, see frequency change)

	Current Limits	
neutron	2.9 e−26 e·cm ('06)	
electron	8.7 e−29 e·cm ('14)	indirect
proton	7.9 e−25 e·cm ('09)	indirect

Other methods include bulk magnetization in **E** field.

Standard Model: ~ 10^{-31} e·cm

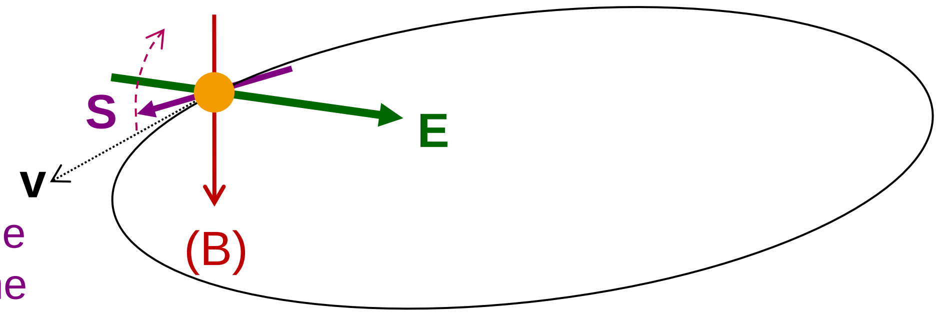
Storage ring goal: 10^{-29} e·cm (statistical limit in about one year)
Systematic limits being studied !!! (Can we get close?)

Candidate systems: proton, deuteron (known polarimetry)

STORAGE RING SEARCHES

Storage ring = charged particle trap (direct measurement on e, p, d, etc.)

For *charged* particles circulating in a storage ring, an electric dipole moment (EDM) will cause the polarization initially parallel to the velocity to rotate out of the ring plane in response to the radial **E** field in the particle frame.



P_Y is stable against in-plane decoherence; holds result.

Managing the anomalous precession

G > 0 (proton): choose (magic) *p*

$$p = \frac{m}{\sqrt{G}} = 0.701 \ GeV/c$$

G < 0 (deuteron): **E** × **B** deflectors

$$E = \frac{GBc\beta\gamma^2}{1 - G\beta^2\gamma^2}$$

(applied to buck **B** field)

Key Polarimeter/Spin Technologies addressed at COSY

- high efficiency (~ 1%)
- high analyzing power (> 0.5)
- continuous operation
- suppress systematic errors
- measure horizontal component
- maintain polarization (~ 1000 s)

Statistical precision (Deuteron)

$$\sigma_d = \frac{2\hbar}{3 p_Y A_Y E \sqrt{T_{TOT} N f \tau_{POL}}}$$

electric field

running time
(~ one year)

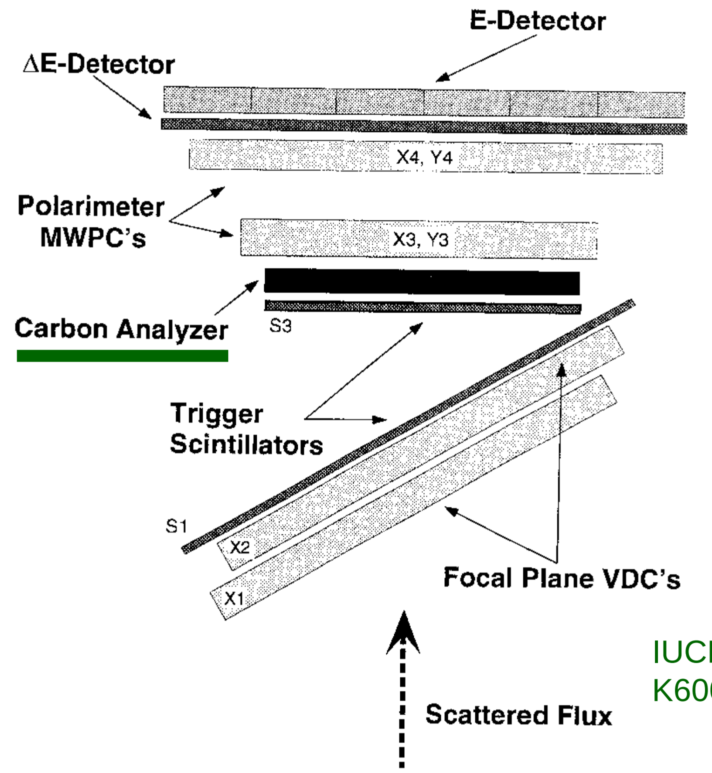
MAXIMIZE THIS

N = deuterons/fill (~10^{11})
f = polarimeter efficiency (~ 1%)
τ_{POL} = polarization lifetime (1000 s)
A_Y = analyzing power (> 0.5)

Goals are a balance between polarization lifetime and polarimeter sensitivity (1 ppm).

Demonstrate:
ability to handle errors at 1 ppm
long in-plane polarization lifetime

Copy double scattering



IUCF
K600

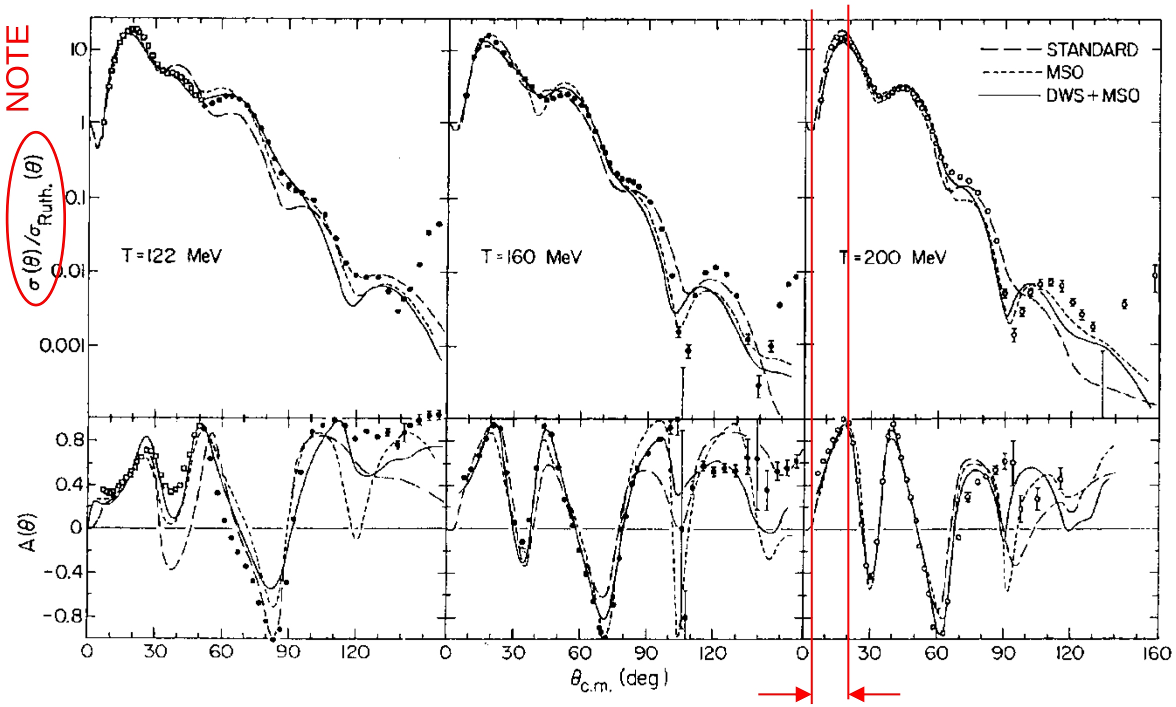
Carbon analyzer
Thick target (5 cm)
Forward angles
- > 5°, away from Coulomb
- < 20°

Both protons, deuterons

Examples of elastic scattering data

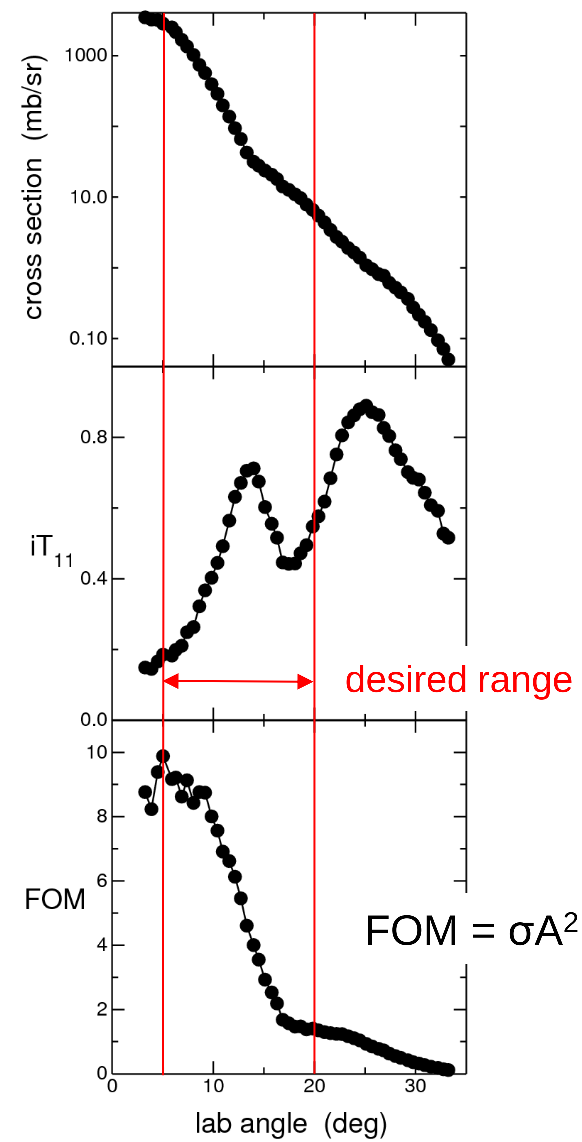
Large forward analyzing power due to nuclear spin-orbit force.

p+C elastic



H.O. Meyer, PRC **27**, 459 (1983)

d+C elastic, 270 MeV



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

Examples of elastic scattering data

Large forward analyzing power due to nuclear spin-orbit force.

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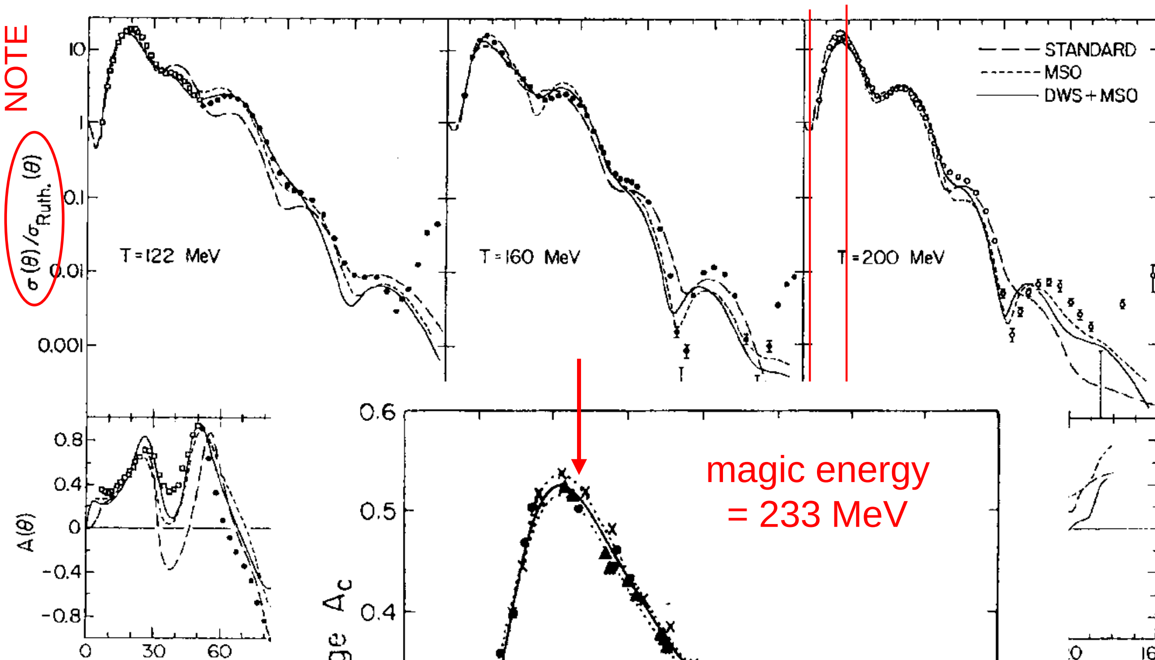
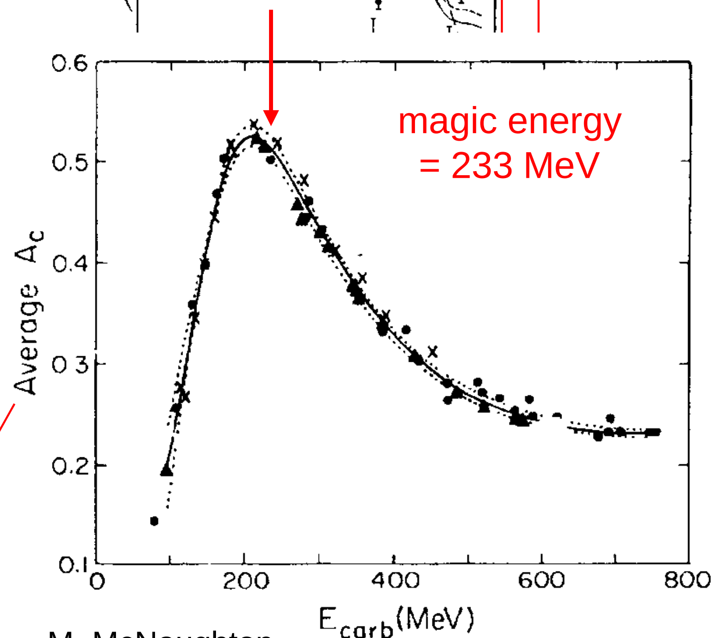
NOTE



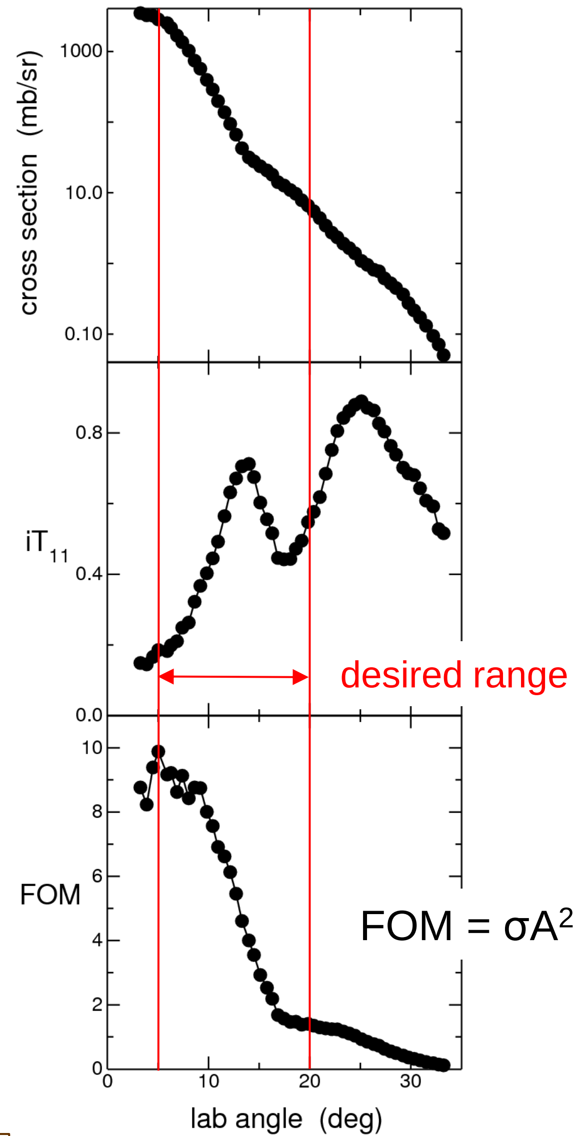
H.O. Meyer, PRC



Thick target polarimeter analyzing powers

M. McNaughton

d+C elastic, 270 MeV



$FOM = \sigma A^2$

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

Include some inelastic scattering.
Exclude deuteron breakup.

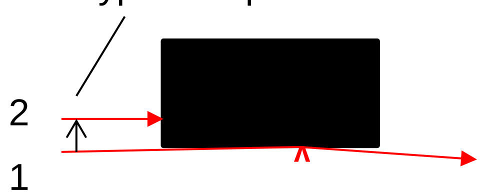
Polarized deuterons p = 0.97 GeV/c

Carbon block target (17 mm thick)

EDDA detectors as polarimeter

The 2-step extraction process from the edge of the beam makes use of the full target thickness.

typical depth ~ 0.2 mm



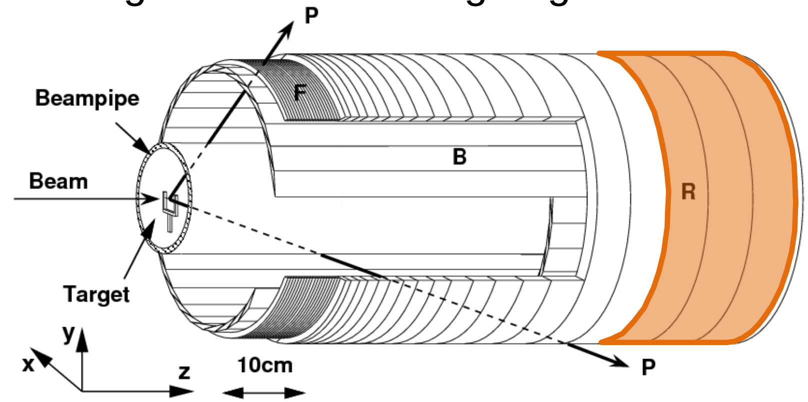
double-hit extraction:
deflect at (1),
then oscillate to (2)
Assume polarization
does not change.

<u>Continuous</u>
extraction methods:

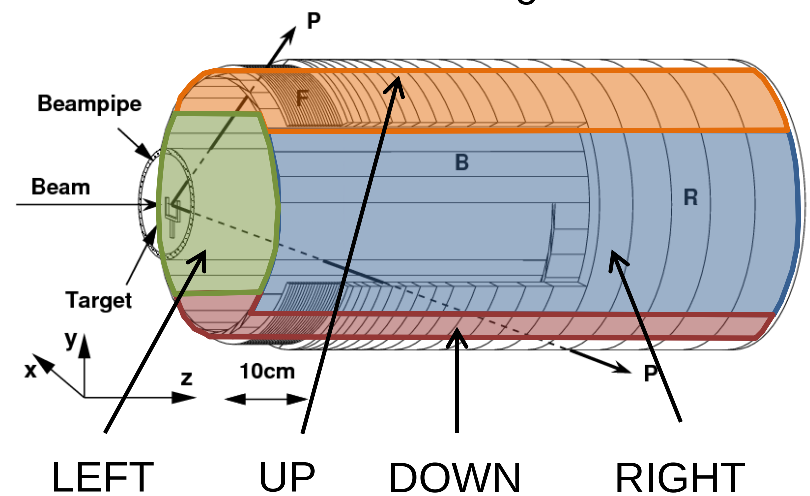
vertical white noise
ramp beam position
scatter from target

(All have spin issues.)

Rings select scattering angle



Bars select azimuthal angle



Azimuthal angles yield two asymmetries:

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

sensitivity to horizontal component is here

Measured efficiency agrees with Monte Carlo.
In this geometry, efficiency = 7 e−4.

How to manage systematic errors:

(measuring left-right asymmetry)

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).

From experiments with large induced errors and a model of those errors:

$$pA = \varepsilon = \frac{r-1}{r+1} \qquad r^2 = \frac{L(+)R(-)}{L(-)R(+)}$$

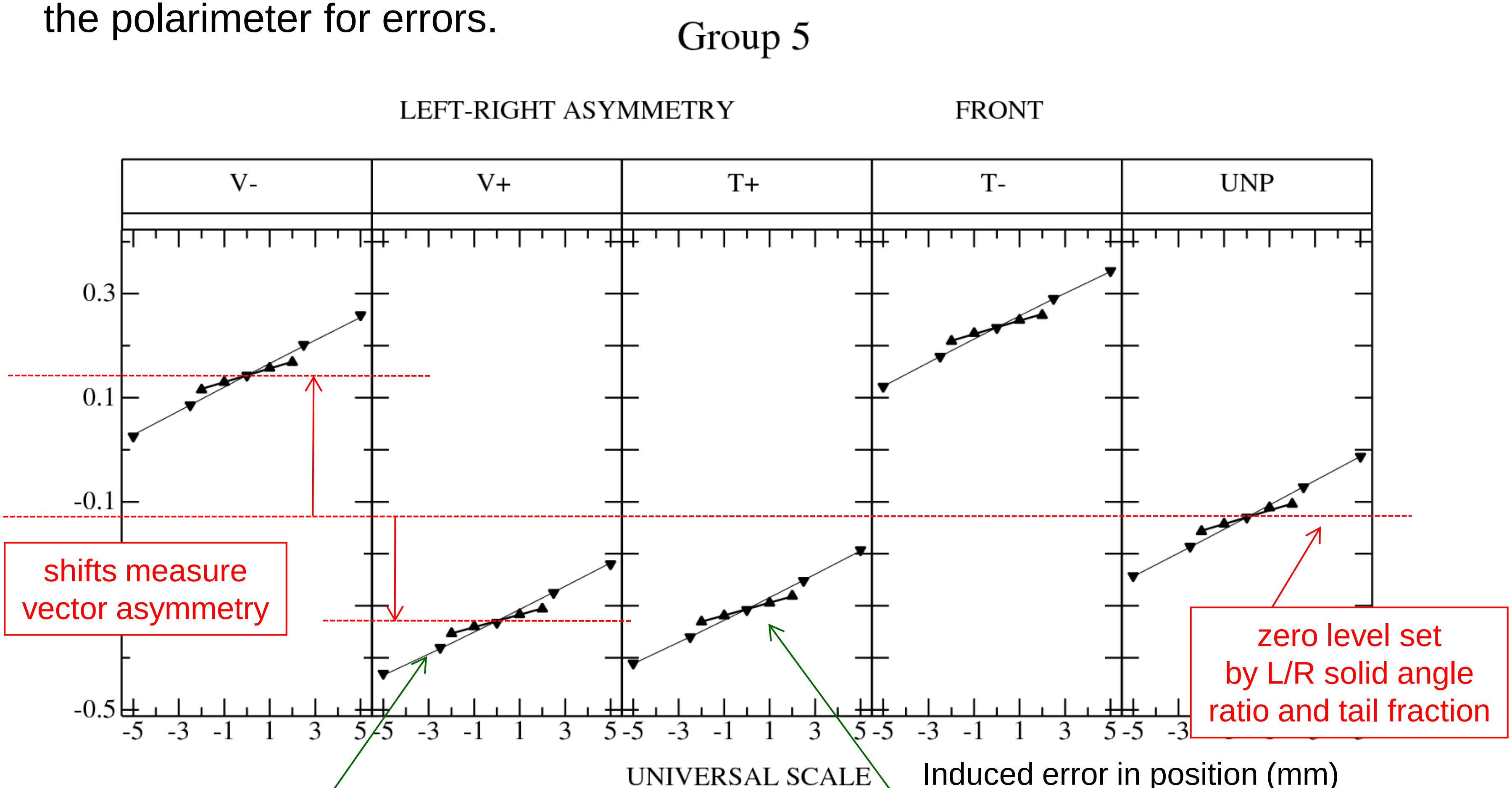
But this fails at second order in the errors.

Using the data itself, devise parameters: $\phi = \frac{s-1}{s+1} \quad s^2 = \frac{L(+)L(-)}{R(+)R(-)},$ and rate $W = L + R$

Calibrate polarimeter derivatives and correct (real time):

$$\varepsilon_{CR,corr} = \frac{r-1}{r+1} - \left(\frac{\partial \varepsilon_{CR}}{\partial \phi}(\phi)\right)_{MODEL} \Delta\phi - \left(\frac{\partial \varepsilon_{CR}}{\partial W}(W)\right)_{MODEL} \Delta W$$

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



Induced error in position (mm) or angle (mrad)

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

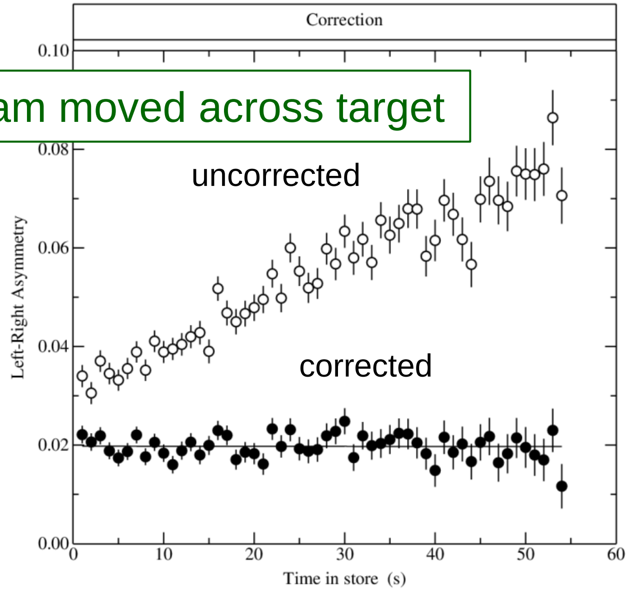
slope difference measures "effective" distance to detector

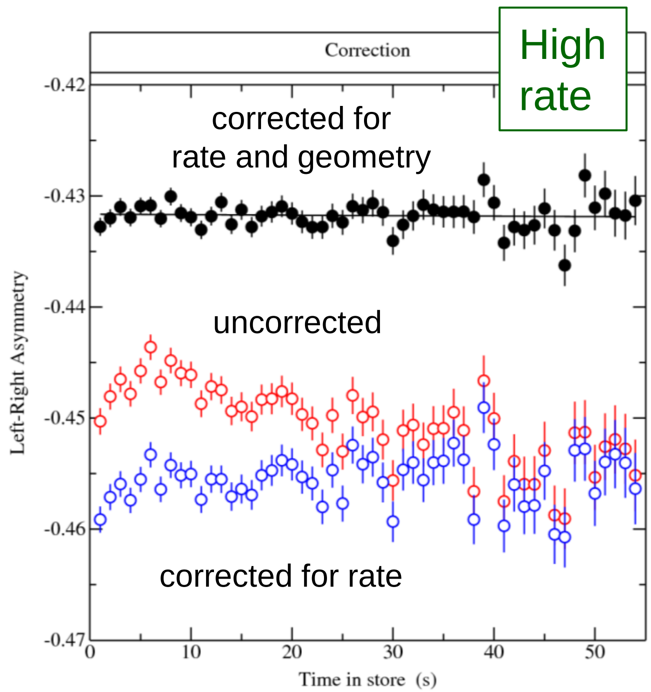
$\frac{\sigma'}{\sigma}=-0.02562(9) \quad \frac{A'}{A}=0.0055(3) \quad \frac{1}{rad}$

X/θ = 52.4(8) cm

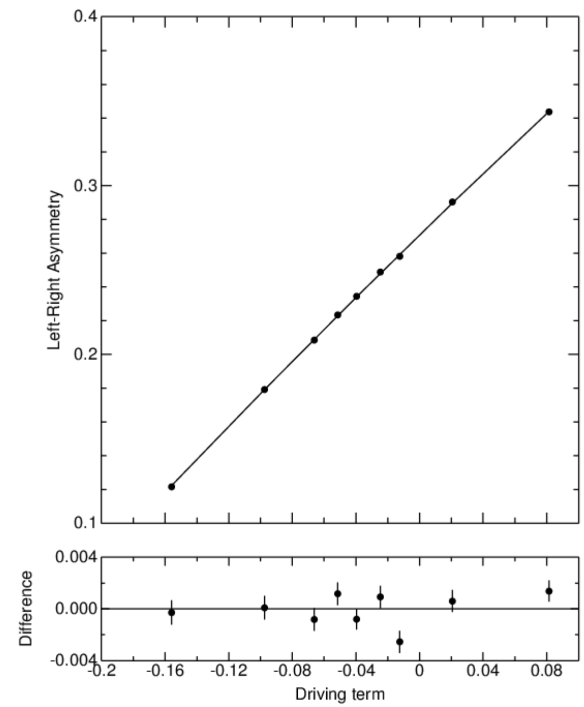
Tests demonstrate ability to correct data for geometry and rate.

Corrected slopes (black) < 10^{-5} /s
(Left-right asymmetry chosen for clarity.)





Comparison of correction vs. φ
for <u>position</u> and <u>angle</u> changes.
Results are indistinguishable.
One parameter suffices for both.



residual

Previous corrections used constant polarization.

Examples with changing polarization require a model of all observed systematic errors.

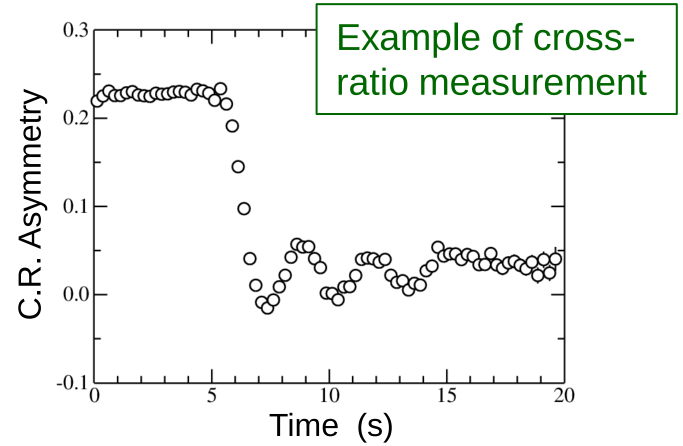
$$\sigma_L = \sqrt{\frac{C_2}{C_{15}}[1-C_3\Delta\theta+C_4(\Delta\theta)^2][1+p_V C_5(1-C_6\Delta\theta+C_7(\Delta\theta)^2)} \\ \overline{-p_T C_8(1-C_9\Delta\theta+C_{10}(\Delta\theta)^2)]} \qquad (17)$$

$$\sigma_R = \sqrt{\frac{1}{C_2 C_{15}}[1+C_3\Delta\theta+C_4(\Delta\theta)^2][1-p_V C_5(1+C_6\Delta\theta+C_7(\Delta\theta)^2)} \\ \overline{-p_T C_8(1+C_9\Delta\theta+C_{10}(\Delta\theta)^2)]+C_{16}[1+C_{18}\Delta\theta]}$$

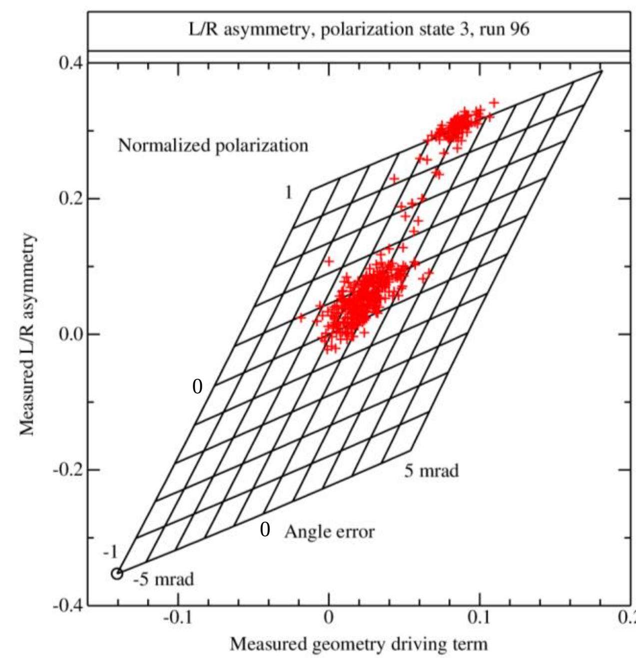
Table 2
The geometry error parameters described under "Name" appear as the C_i in Eq. (18) and took on the values listed in the model.

C parameter	Name	Value
1	Effective detector distance	0.524(6) m
2	Left/right solid angle ratio	1 (fixed)
3	$\partial\sigma/\sigma\partial\theta$	0.02561(7) mrad^{-1}
4	$\partial^2\sigma/2\sigma\partial\theta^2$	0.00029(2) mrad^{-2}
5	$iT_{11}=C_5/\sqrt{3}$	0.3884(4)
6	$\partial A/A\partial\theta$	$-0.0055(2)$ mrad^{-1}
7	$\partial^2 A/2A\partial\theta^2$	0.00008(6) mrad^{-2}
8	A_T	0.0444(2)
9	$\partial A_T/A_T\partial\theta$	0.008(5) mrad^{-1}
10	$\partial^2 A_T/2A_T\partial\theta^2$	0.0013(9) mrad^{-2}
11	Down/up solid angle ratio	1.0438(3)
12	Position mixing	$-0.032(5)$
13	Angle mixing	0.036(2)
14	Effective rotation	0.0260(5)
15	(Down–up)/(left–right) solid angle ratio	1.3046(2)
16	Tail fraction, T	0.2985(2)
17	$\partial T/\partial x$	0.0122(7) mm^{-1}
18	$\partial T/\partial\theta$	0.0086(3) mrad^{-1}

N.P.M. Brantjes, NIM A **664**, 49 (2012)



Model provide transform from φ and raw asymmetry to corrected values.



Measuring in-plane polarization (IPP):

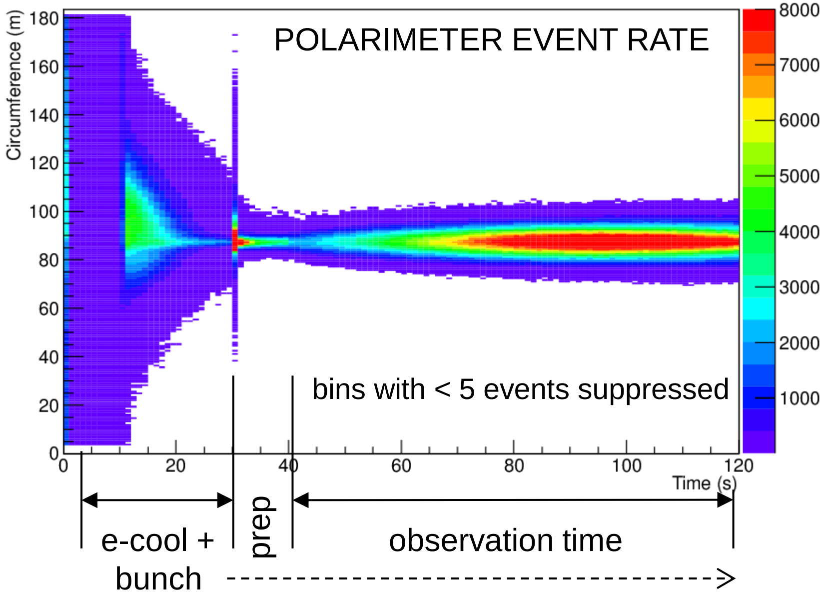
1 Deuteron (0.97 GeV/c) rotates at 120830 Hz in COSY.
Measure p_X. Mark events with clock time. Unfold precession.
Event set is sparse (1 in ~20 spin revolutions), so bin for Δt (seconds).

2 Make IPP long:
Bunch the beam (removes first-order Δp/p contribution).
Electron cool (reduces phase space size), but not during measurement.
Rotate polarization into horizontal plane with RF solenoid on spin resonance.
Compensate path lengthening from betatron oscillations using sextupoles.
Pay attention to chromaticity, also adjusted by sextupoles.

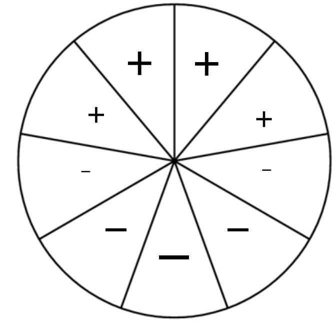
Calibrate event clock against RF-cavity oscillator to obtain turn number (T).

The fractional part of T gives the longitudinal bunch distribution.

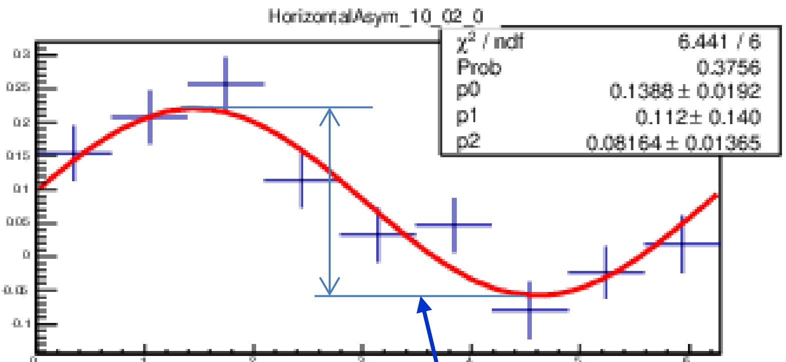
(Along with residual gas ionization monitors, we obtain all beam profiles.)



Multiply the integer part of T by *Gγ* to get polarization total rotation angle Θ (revolutions).
Sort events by the fractional part of Θ into direction bins.

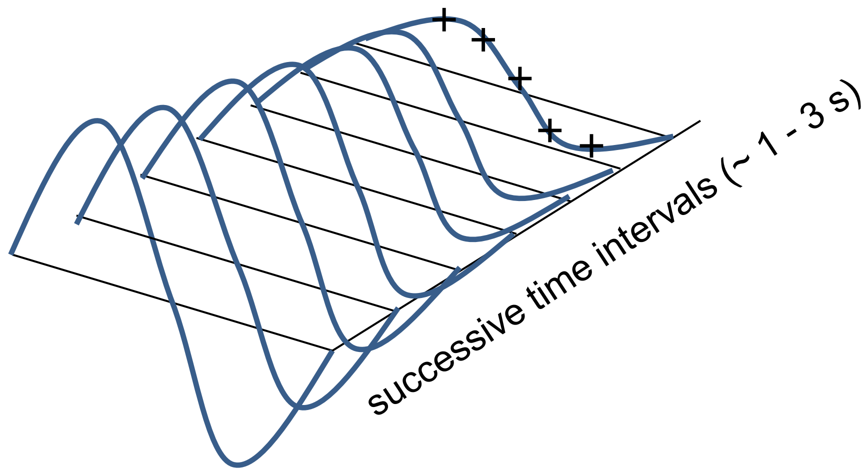


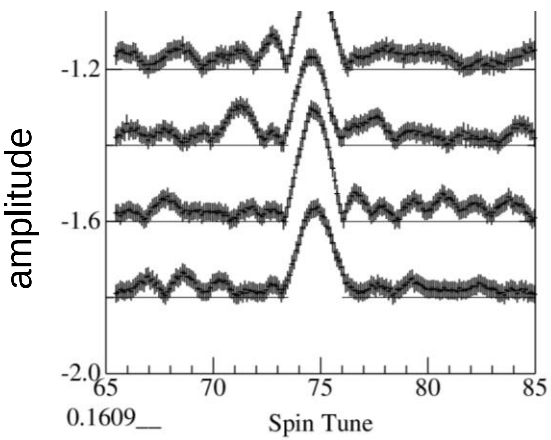
Compute the down-up asymmetry in each bin.



magnitude gives IPP

Arrange results into a time sequence.

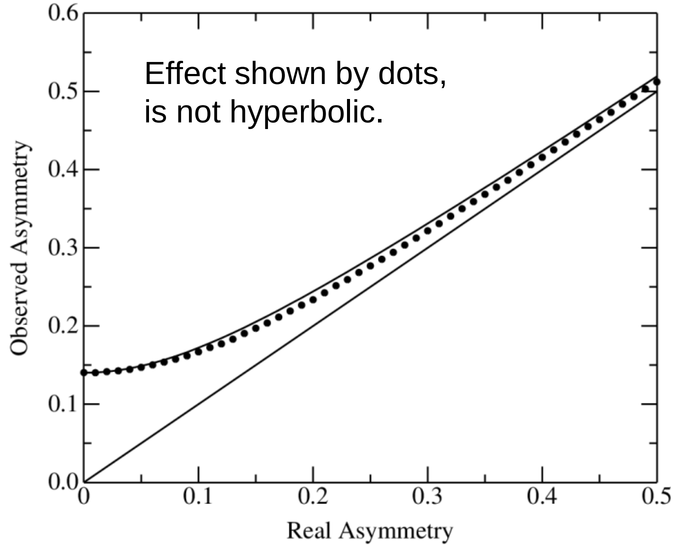




In most cases, *Gγ* is not known well enough for the direction bins to contain a clear signal. So scan the spin tune, repeating the analysis, and find a peak.

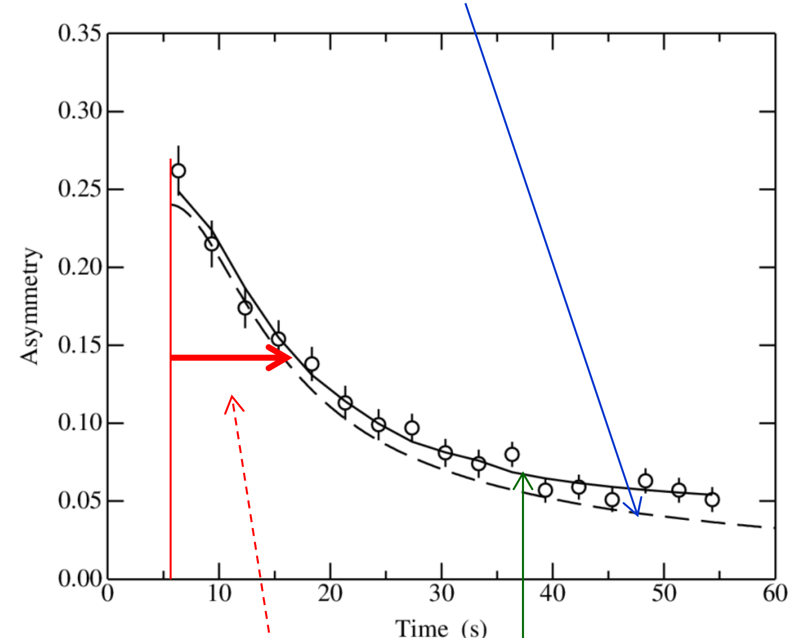
Note that the answers are all positive.

Sine wave fits to random distributions always yield a positive magnitude. This scales with the size of the statistical error.



To extract an IPP lifetime, use a “template” that models IPP loss due to betatron oscillations. (dashed line)

“Data point” shows error in one direction bin for one machine cycle.



This effect creates a “floor” in the data below which you don’t record any values of the IPP.

IPP lifetime is width at 60% of maximum. (10.5 s)

Apply correction for positive bias (solid).

Expected sensitivity of IPP lifetime (inverse) to sextupole strength

Beam is bunched, pre-cooled, and horizontally heated.

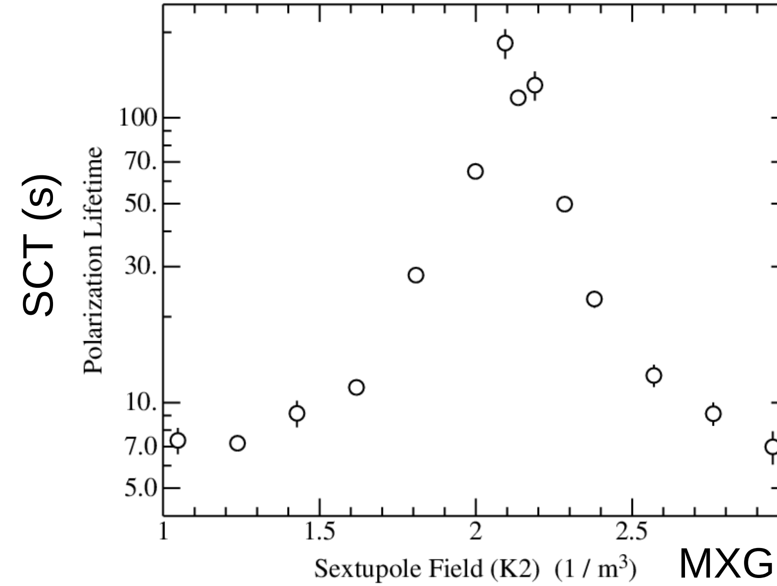
$$\frac{1}{\tau_{SCT}} = |A + a_1 S + a_2 L + a_3 G|\theta_X^2 + |B + b_1 S + b_2 L + b_3 G|\theta_Y^2 + |C + c_1 S + c_2 L + c_3 G|\sigma_P^2$$

natural value

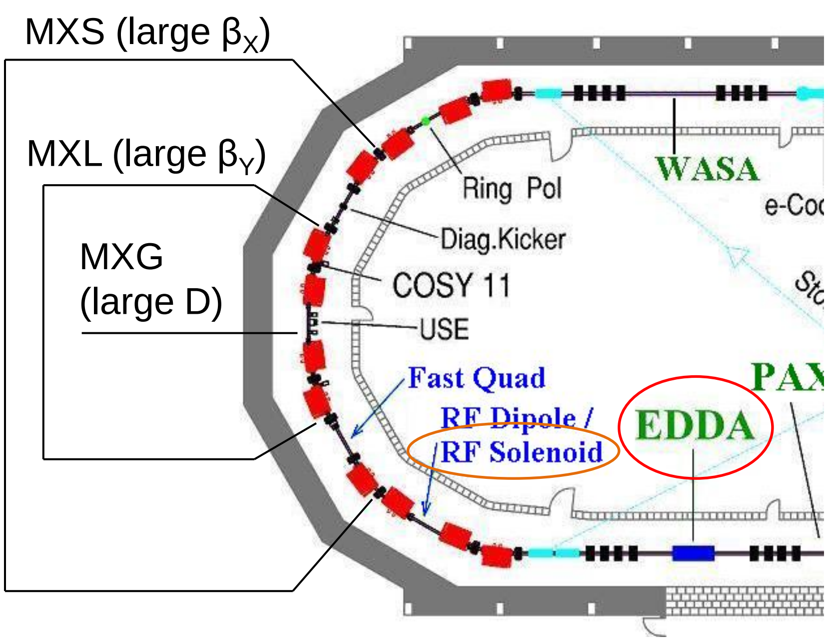
sensitivities

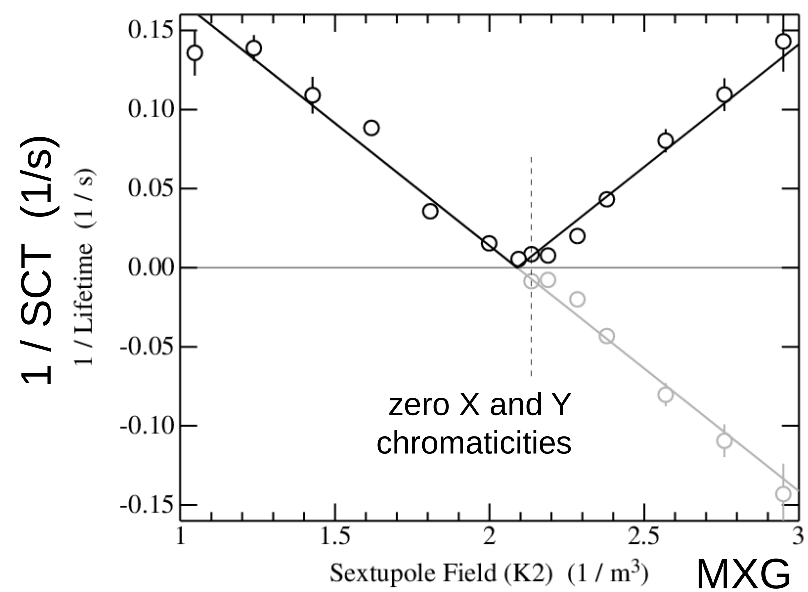
sextupole currents (MXS, MXL, MXG)

drivers: emittance, sync. osc.



Three sextupole magnet families:





Can we maximize the polarization lifetime using all 3 sextupole families?

Use two machine setups to separately check:

[1] horizontal emittance. E-cool and bunch together, then heat with white noise.

[2] synchrotron Δp/p and vertical emittance. E-cool first, bunch second.

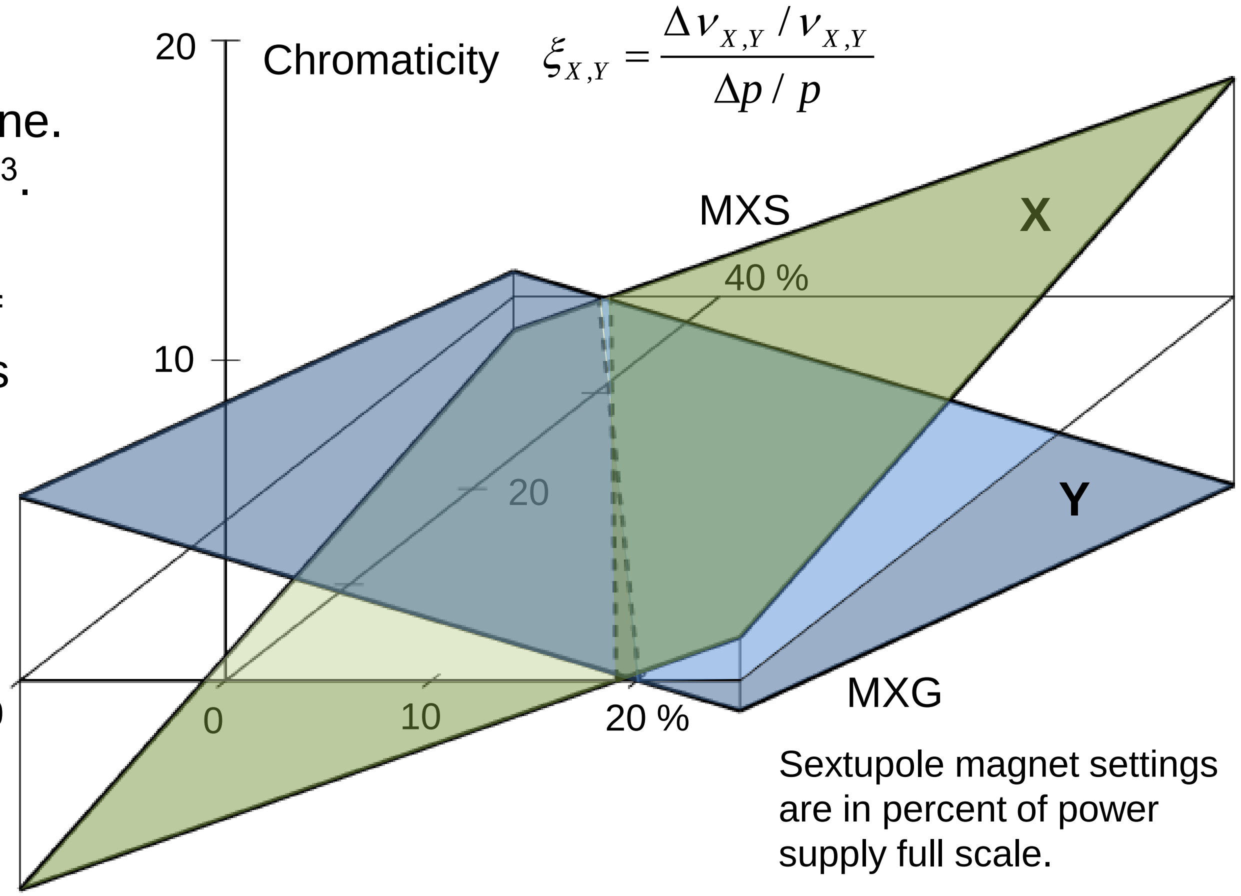
Extraction onto polarimeter target uses vertical white noise (always present).

Take advantage of expected overlap of chromaticity zeros and long IPP lifetime.

Chromaticity in MXG x MXS plane. MXL = −0.14 m^{-3}.

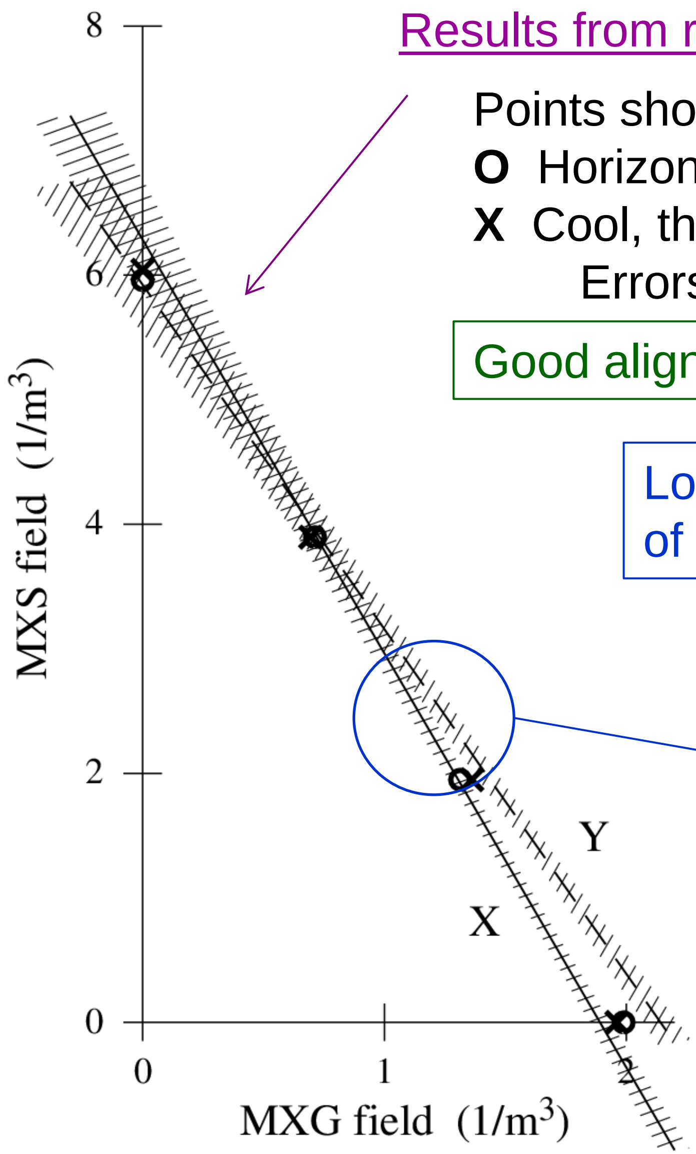
Note the overlap of the two dotted lines that represent the places where the chromaticities vanish.

Planes determined by multiple measurements.



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

Results from run completed in August, 2014.



Points show location of maximum IPP lifetime.

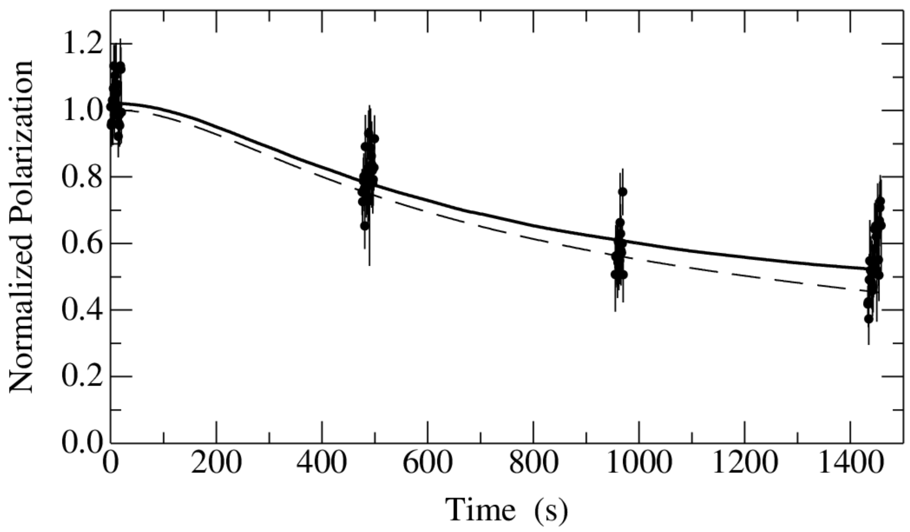
O Horizontal heating (large X emittance)

X Cool, then bunch (all contributions)

Errors less than size of symbols.

Good alignment of zero chromaticity and IPP lifetime.

Longest IPP lifetimes appear in the middle of the map. (Data taken in June, 2015.)



Bands determined by tune errors.
MXL = −0.14 m^{-3}.

IPP lifetime = 814 ± 43 s
1/e point = 2060 ± 110 s

THANKS TO **COSY** STAFF AND **JEDI COLLABORATION**

RESULTS

Thick targets work. High efficiency and analyzing power are possible.
Beam sampling allows continuous polarization monitoring.
Calibration allows correction of geometry and rate errors below 1 in 10^5.
Event time marking and spin tune unfolding allows measurement of IPP.
Bunching, cooling, and sextupole corrections yield long IPP lifetime.

FUTURE PLANS AT **COSY**:

Approval and financing have been granted to redirect the in-house physics program from hadron studies toward the EDM search during 2015-19.
Work will move forward along two tracks:
(1) preparation of a design document describing an on-site EDM ring,
(2) using the present ring for a lower-sensitivity experiment to study systematic limitations in the method.