Storage Ring Polarimetry
Recent developments (mainly for EDM search)
Cooler Synchrotron (COSY) at Juelich

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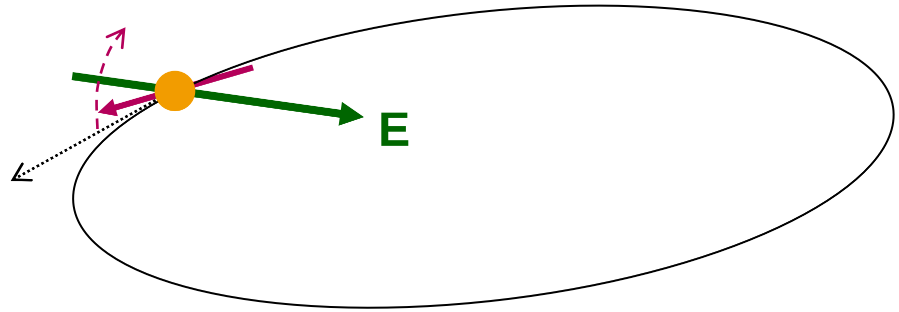
High efficiency
Control of systematic errors
Preservation of horizontal plane polarization
Prospects for ^{3}He

Working with deuteron beam at 0.97 GeV/c

Introduction and Background

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.



Feasibility Questions:

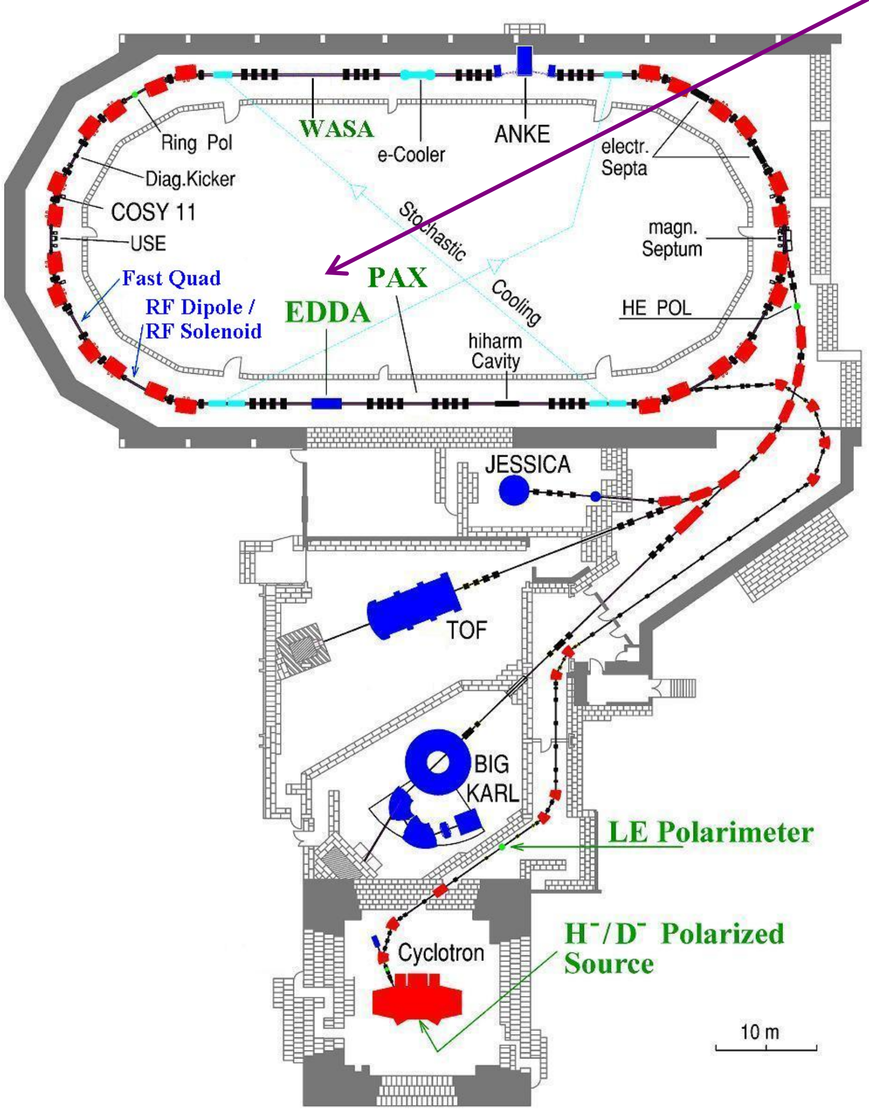
- How can the polarization be “frozen” parallel to the velocity?
- Can a nuclear-scattering polarimeter be built with high efficiency (~1%), high effective analyzing power (> 0.5), and continuous operation?
  (Efficiency is the ratio of particles detected/used to particles extracted from the beam.
- How can systematic polarimeter errors be controlled at the ppm level?
- How can the lifetime of the initial longitudinal polarization be extended to 10^3 s?
- How can large electric fields be created around the ring?
- Can we detect systematic error fields through beam position monitoring?

Reaching these goals results in a statistical sensitivity of 10^{-29} e·cm in 1 year.

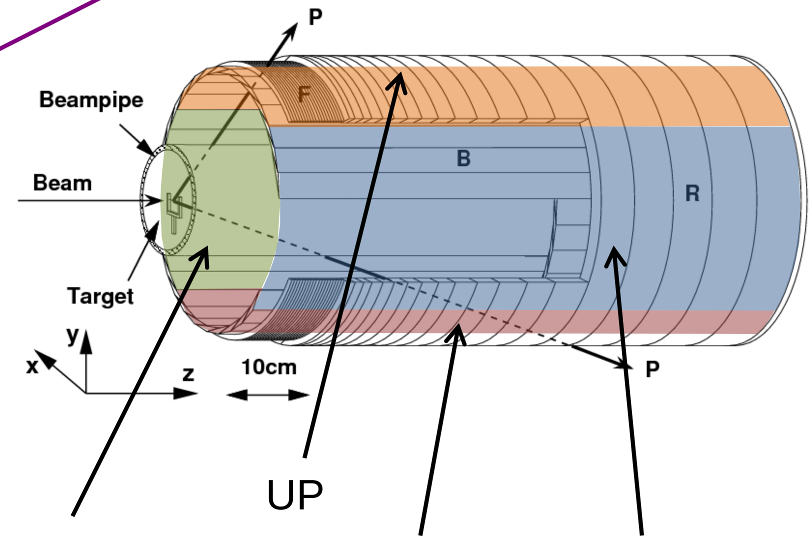
Since 2007, items in red are being studied at COSY in Jülich, Germany.

COSY storage ring

polarized deuterons, 0.97 GeV/c



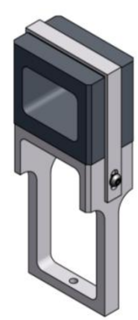
EDDA detector

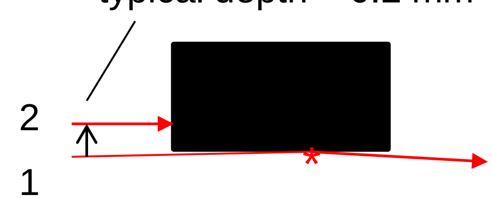


Azimuthal angles yield two asymmetries:

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

17 mm C target

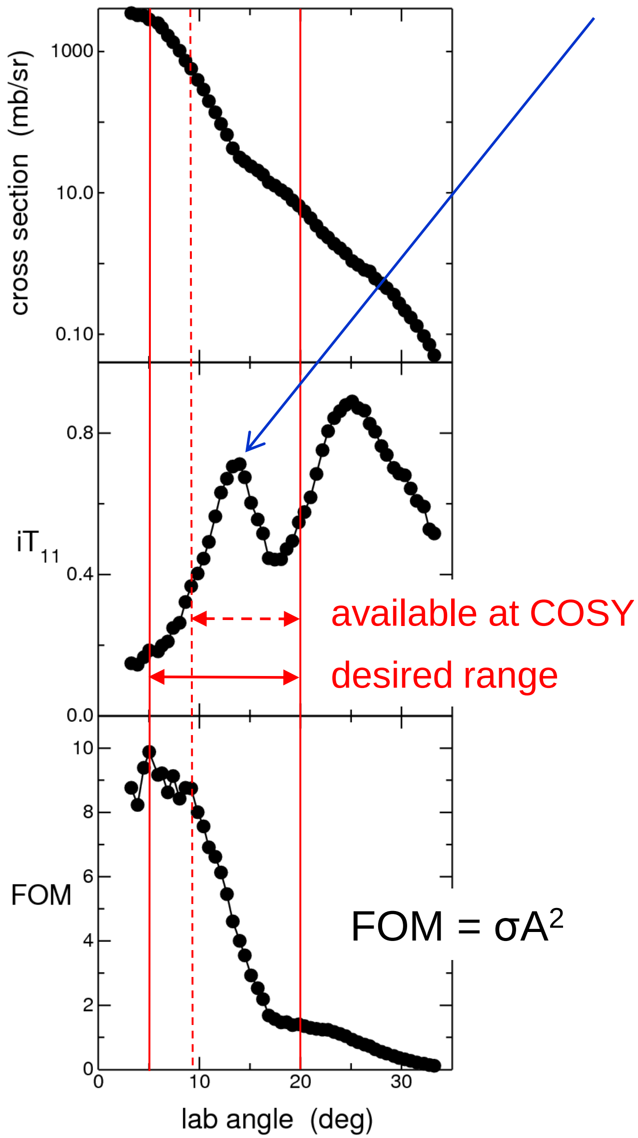




double-hit extraction?:
deflect at (1), then oscillate to (2)

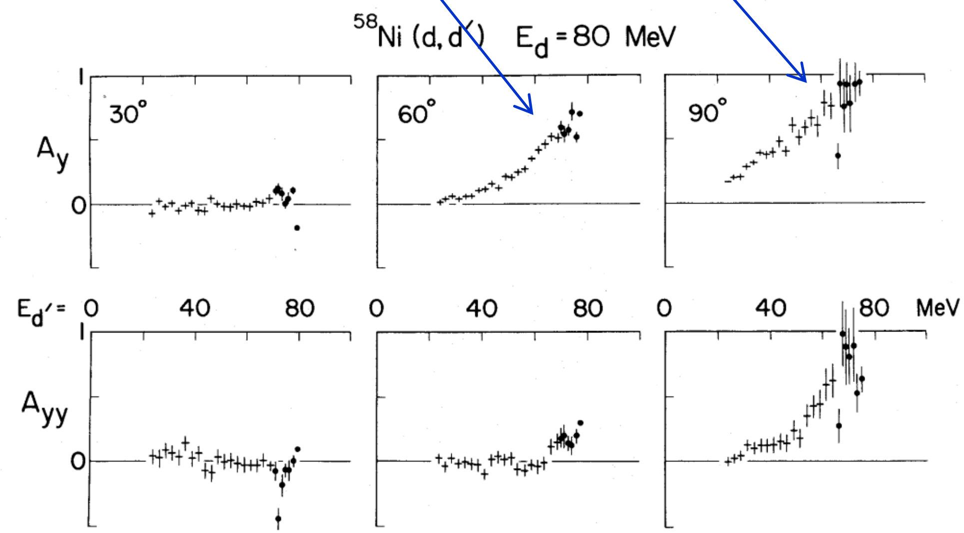
d+C elastic, 270 MeV

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

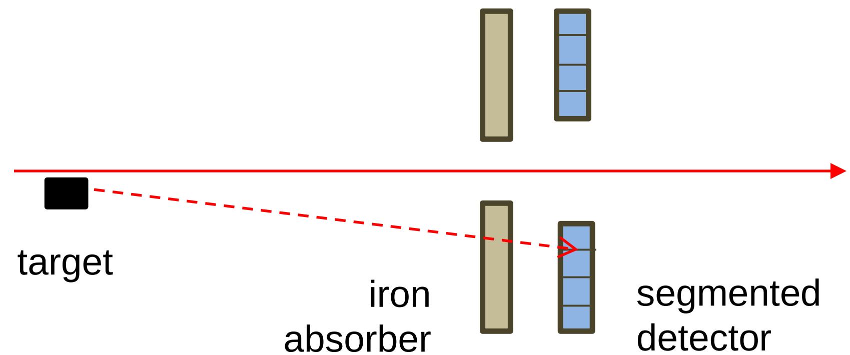


Y. Satou, PL B **549**, 307 (2002)

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



Simplest polarimeter is absorber/detector:



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:

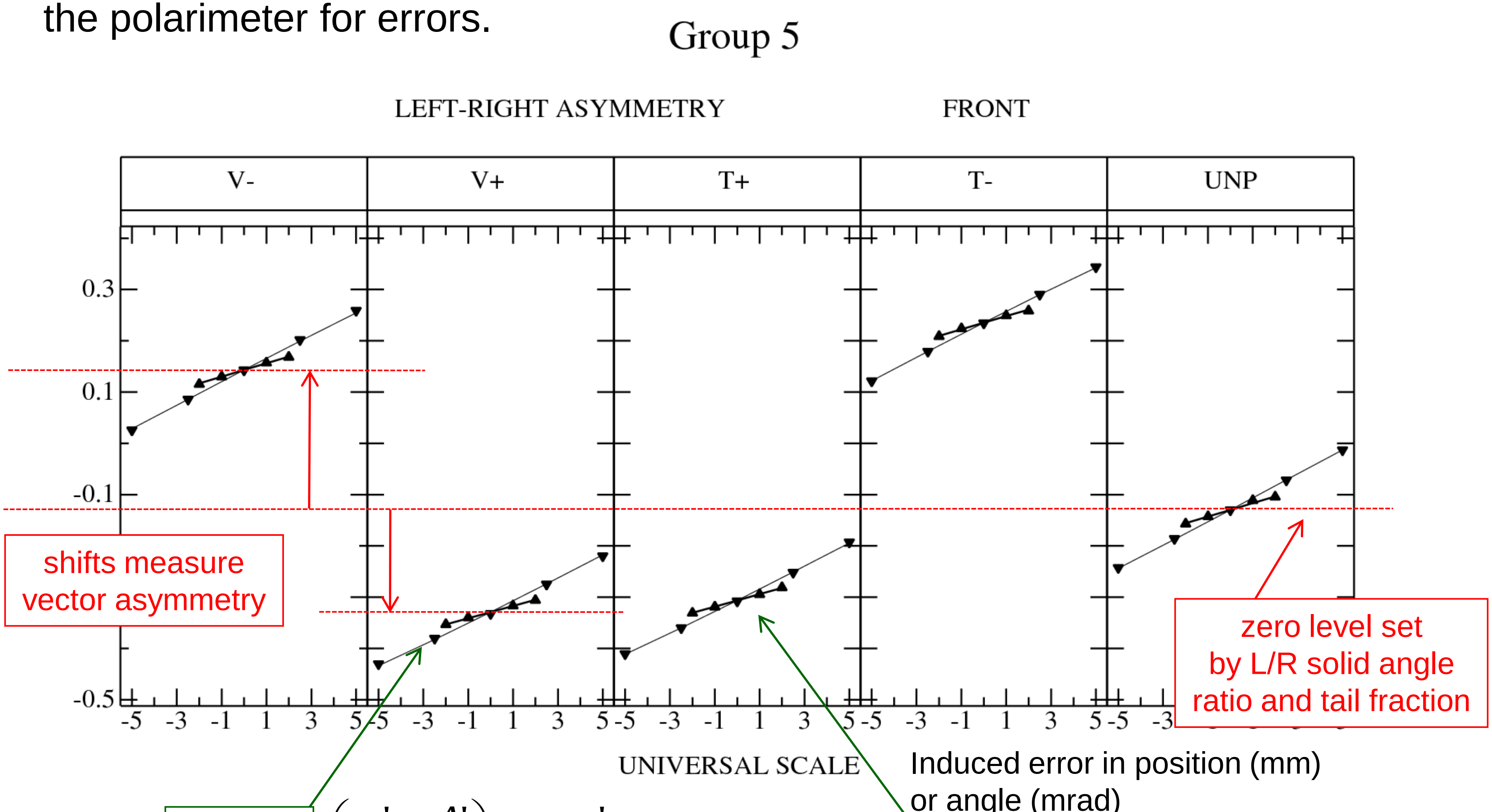
$$\phi = \frac{s-1}{s+1} \qquad s^2 = \frac{L(+)L(-)}{R(+)R(-)},$$

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.



slopes given by

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

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

slope difference measures "effective" distance to detector

X/θ = 52.4(8) cm

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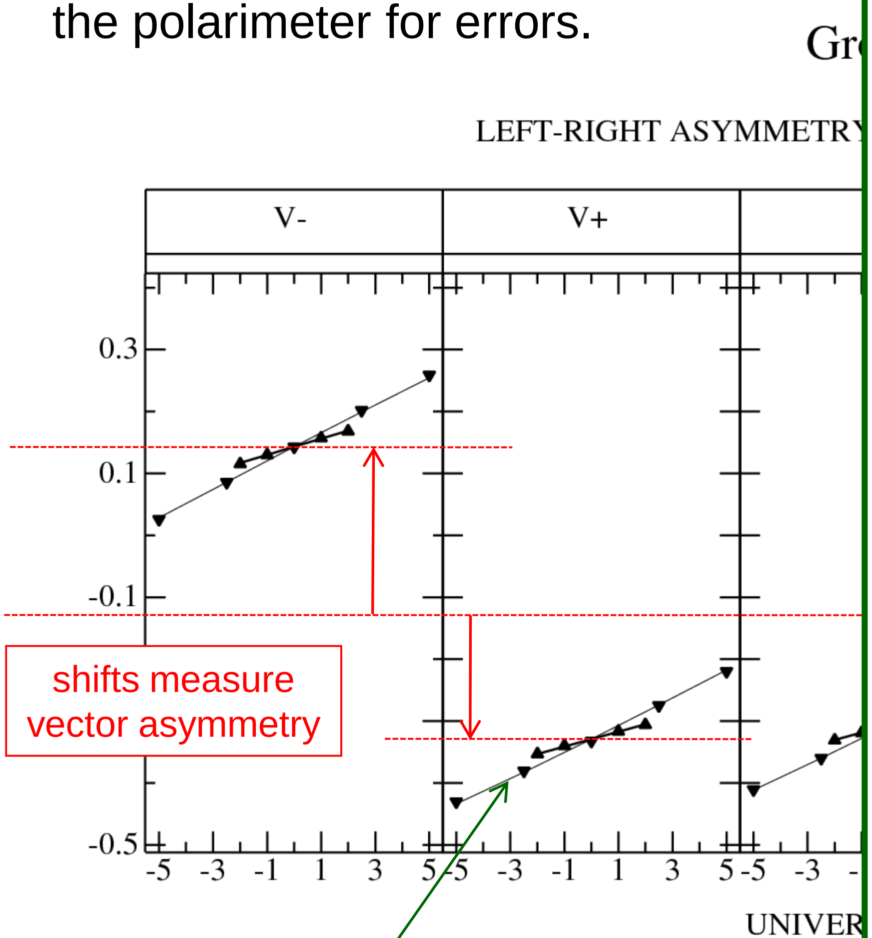

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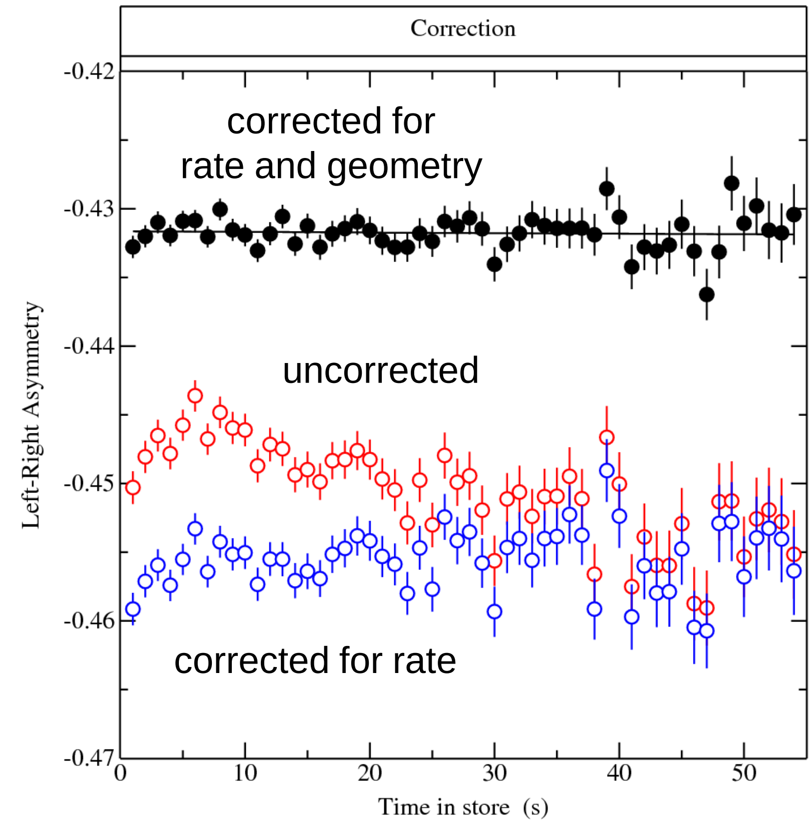
Application to data with errors shows correction in real time.



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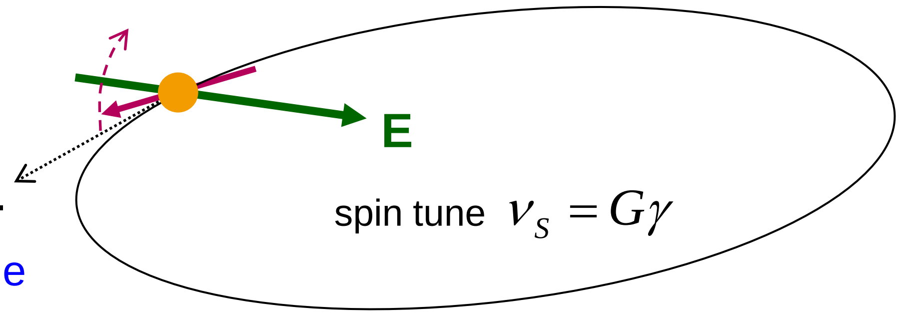
Feasibility of maintaining in-plane polarization

The EDM would be aligned with the spin.
Goal is to observe the precession from the velocity direction toward the vertical due to radial electric field in particle frame.



Polarization spreads in horizontal plane from momentum variations and is lost.

Strategy to minimize spin effects of spread:

Bunch the beam: minimizes first-order effect from momentum Δp/p.

Electron-cool the beam: minimize betatron (transverse) beam oscillations
minimize synchrotron (longitudinal) beam oscillations

Adjust sextupole fields for final correction (orbit radius adjustment).
Despite betatron/synchrotron oscillations, allow no variations (on average) in orbit length (ΔL/L = 0), momentum ($(\Delta p/p)^2 = 0$), or spin tune.
This is associated with zero chromaticity ($\xi_X = \xi_Y = \partial Q_{X,Y} / \partial p = 0$).

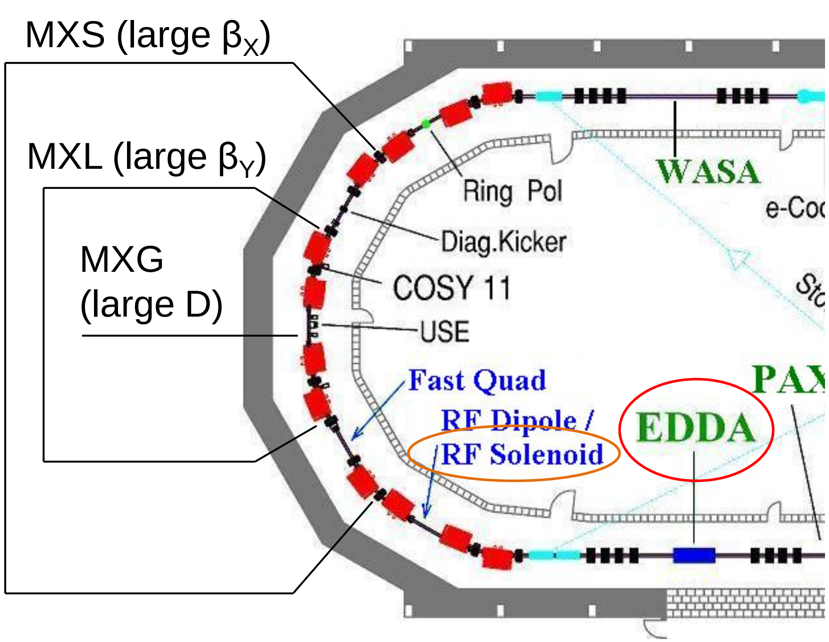
Polarized deuterons

p = 0.97 GeV/c

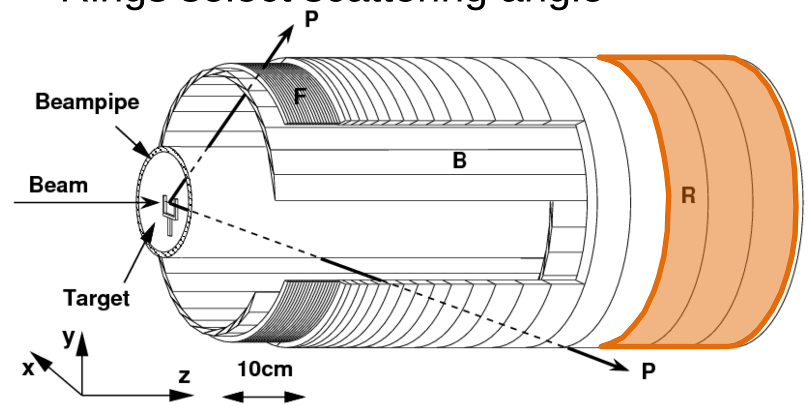
Carbon block target (17 mm thick)

EDDA detectors as polarimeter

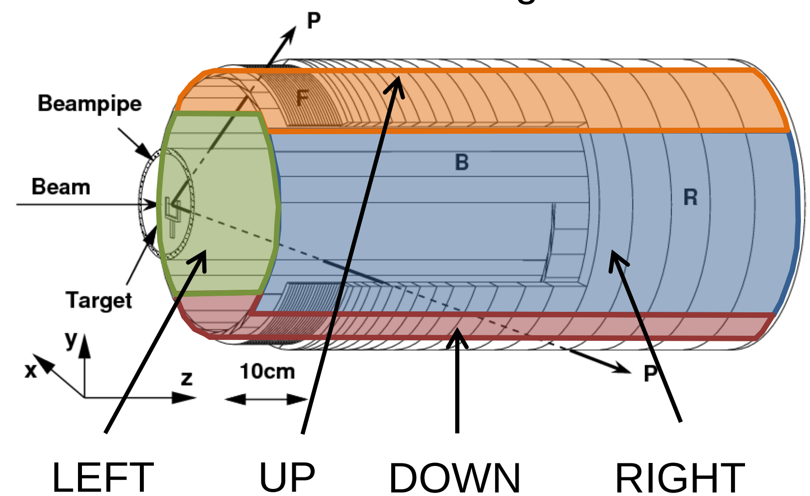
Three sextupole magnet families:



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

New data acquisition procedure – time stamp every event

Count turn number (bunched beam) → distribution of turn number fraction yields beam distribution

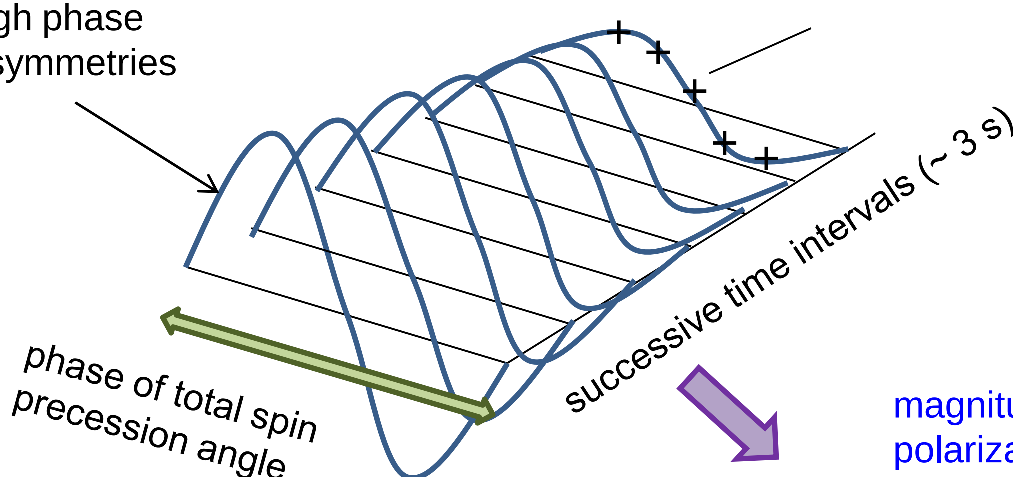
Compute total spin precession angle → based on integral part of turn number

Bin by phase around the circle

Compute asymmetry in each bin

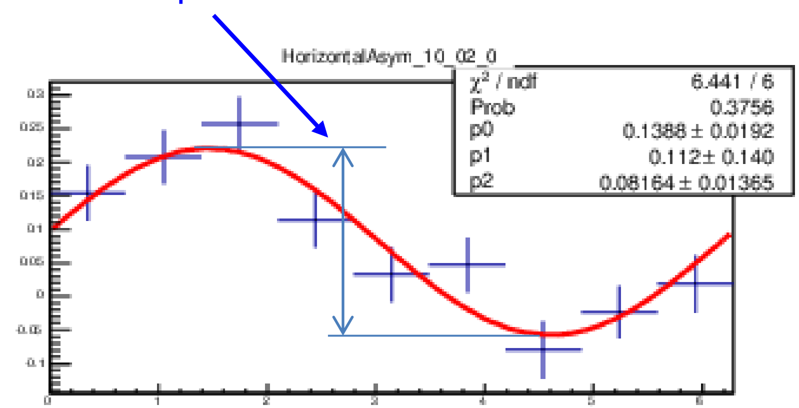
smooth curves through phase bin asymmetries

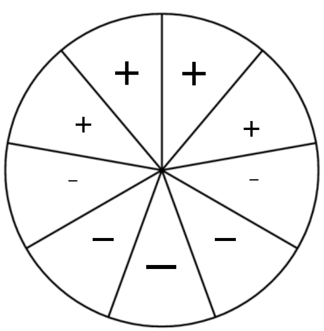
these curves determined by asymmetry measurements for 9 angle bins



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

magnitude gives horizontal polarization

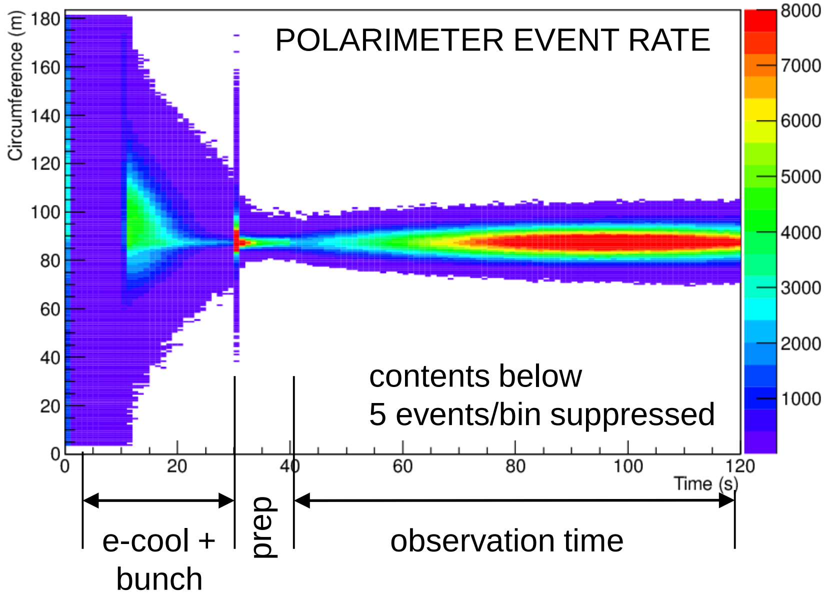




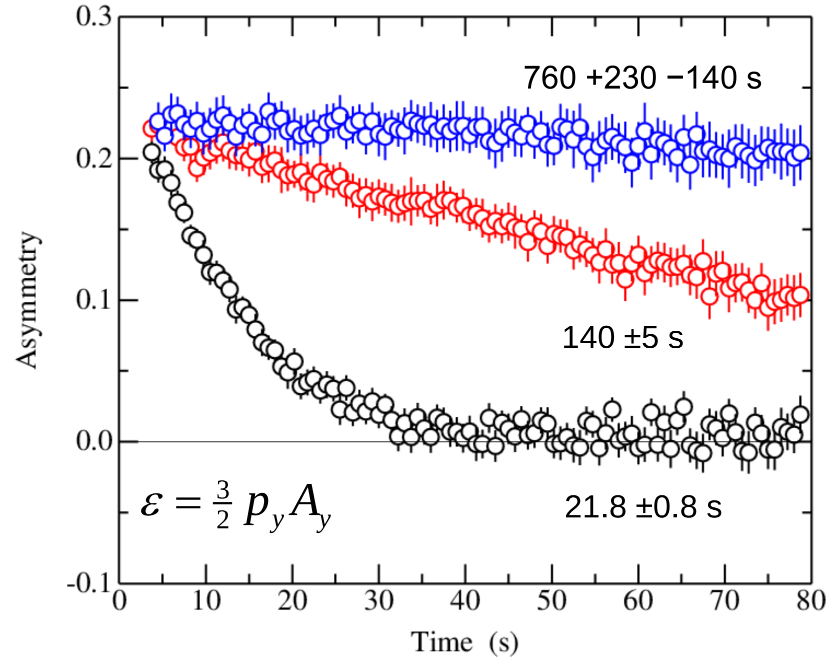
As the polarization rotates the down-up asymmetry reflects the sideways projection of the polarization.

Sample data

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

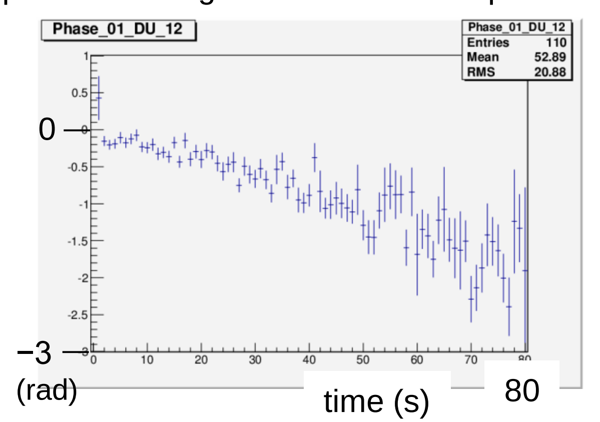


Sample measurements of horizontal polarization loss (corrected for positive bias)



Times are exponential decay rates.

phase is 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.

Expected sensitivity of polarization lifetime (inverse) to sextupole strength

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

natural value

sensitivities

sextupole currents (MXS, MXL, MXG)

drivers: emittance, sync. osc.

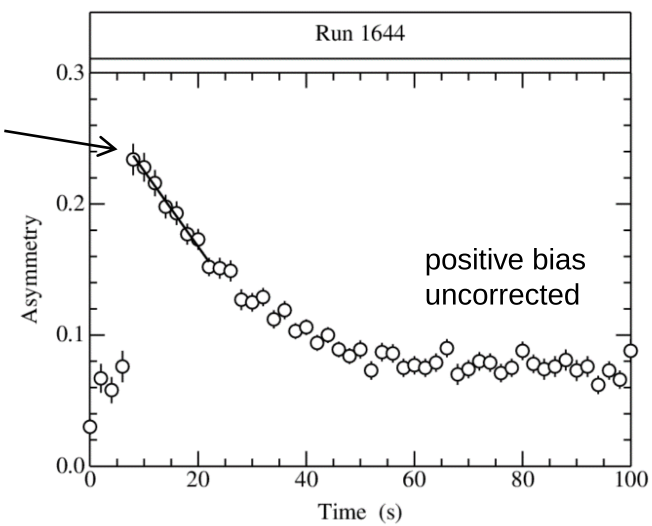
1 Set chromaticities to zero (X and Y). Make horizontally wide beam.

2 Measure initial polarization slopes.

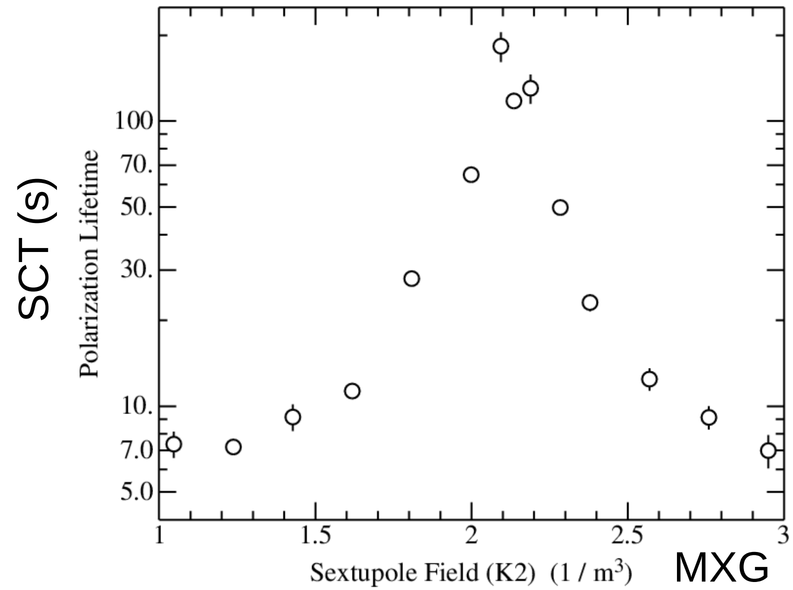
Make linear fit to early part.

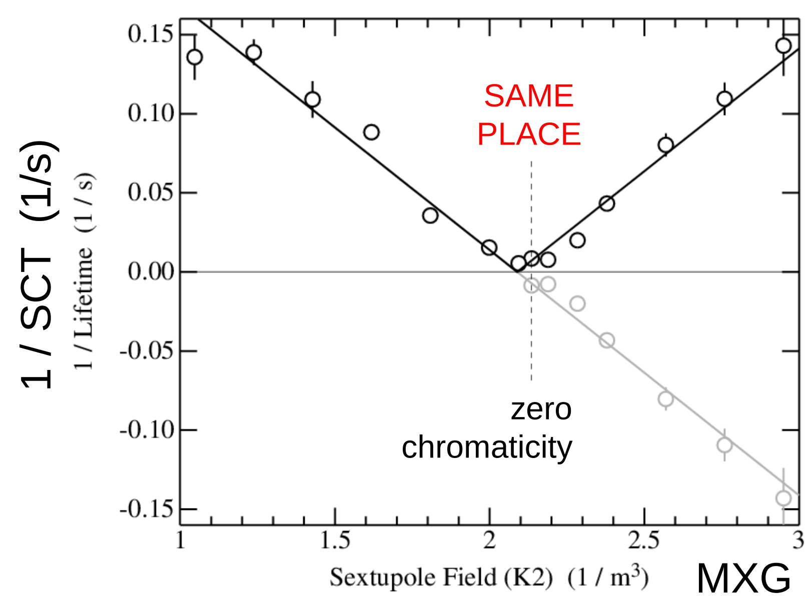
$$\varepsilon = a_0 + a_1 t$$

$$SCT = -\frac{a_0}{a_1}$$



3 Repeat for changing MXG.





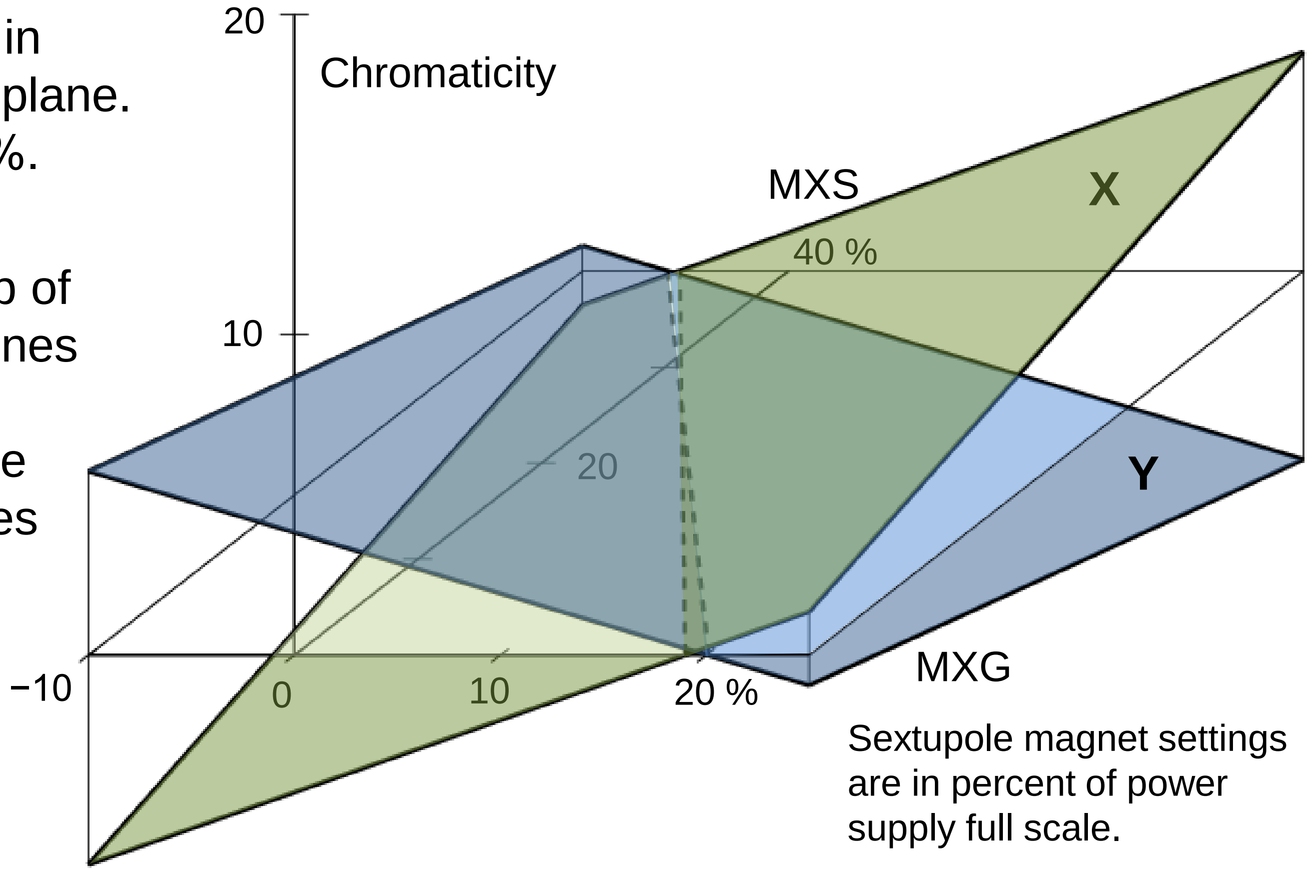
Can we maximize the polarization lifetime using all 3 sextupole families?

Use two machine setups to separately check:
[1] horizontal emittance. E-cool and bunch together, then heat with white noise.
[2] synchrotron Δp/p. E-cool first, bunch second. No horizontal heating.

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

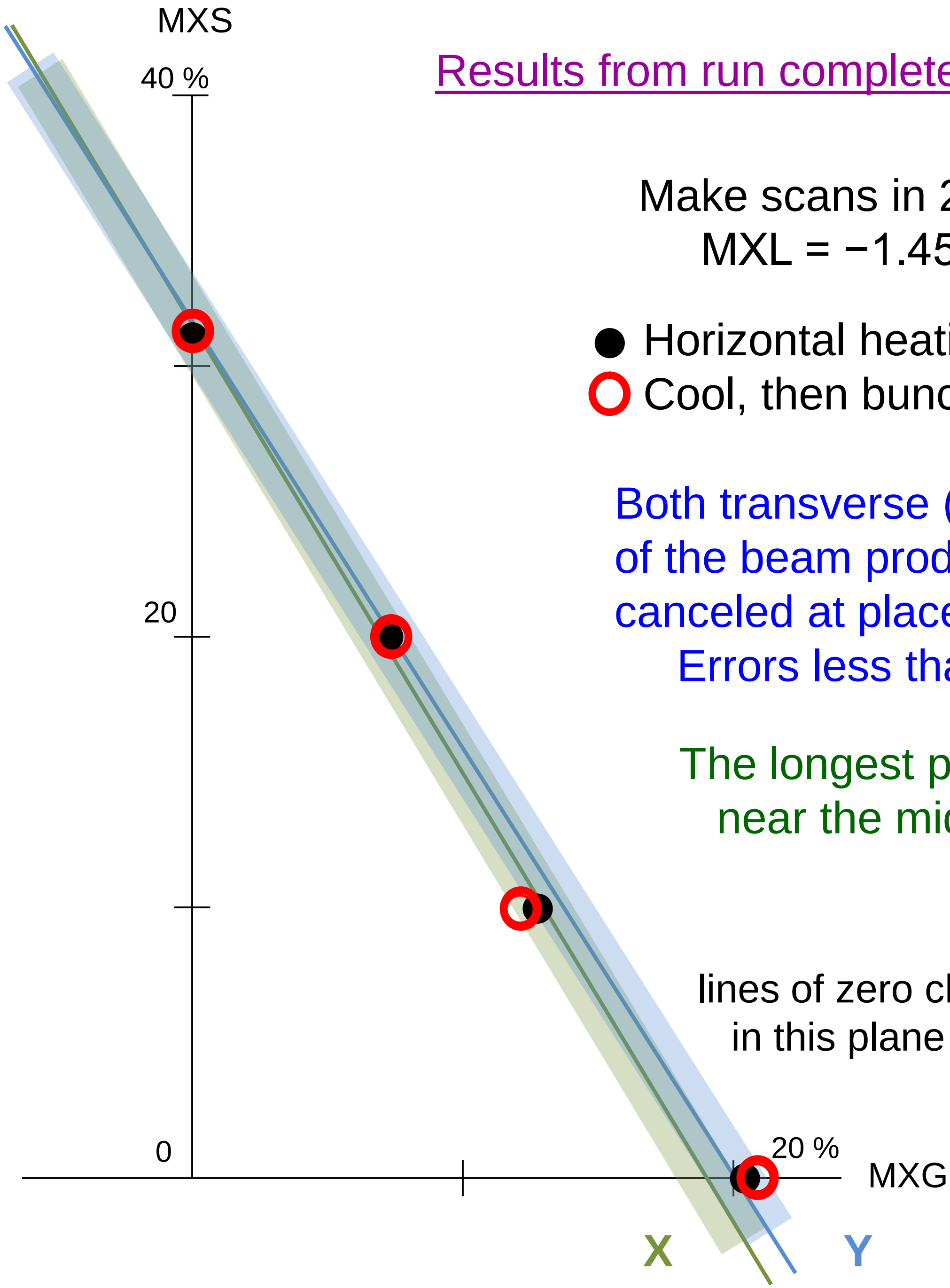
Chromaticity in MXG x MXS plane. MXL = −2.0 %.

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



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

Results from run completed in August, 2014.



Make scans in 2D MXS x MXG space with
MXL = −1.45%

● Horizontal heating (large X emittance)
○ Cool, then bunch (large synchrotron orbits)

Both transverse (X) and longitudinal spreads of the beam produce decoherence; both are canceled at places of zero chromaticity.
Errors less than the size of the symbols.

The longest polarization lifetimes are found near the middle of this range.

lines of zero chromaticity (X or Y)
in this plane – errors ~ 1 %

Scales are in percent of power supply full range.

CONCLUSIONS:

In a magnetic storage ring, it has been demonstrated that the lifetime of a horizontally polarized deuteron beam may be substantially extended (up to ~ 1000 s) through a combination of:

beam bunching on the first harmonic,
electron cooling, and
orbit corrections with multiple sextupole families.
Setup that makes both X and Y chromaticities zero.

This meets the requirement for a storage ring to search for an EDM.

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 precursor experiment.

Polarimetry for ^{3}He beams

1 RHIC energy beams for exploration of down quark effects (polarized source developed and installed by MIT)

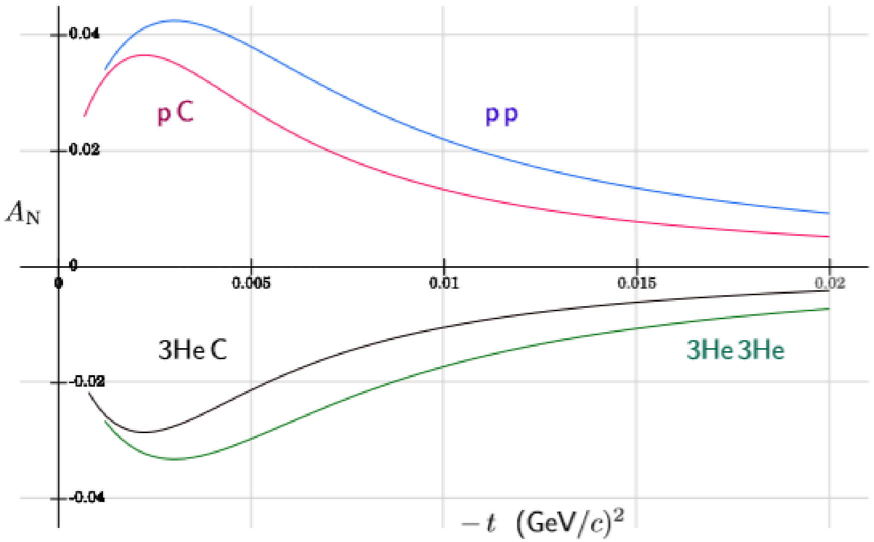
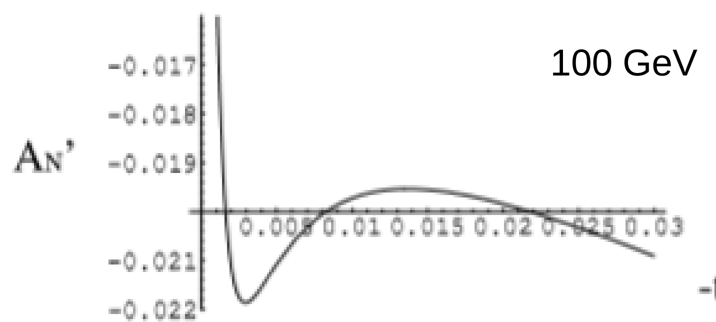


Figure 1: Analyzing power A_N versus invariant momentum transfer (-t) in (GeV/c)^2 for (1) p p and p h scattering, (2) p C scattering, (3) h C scattering, (4) h h and h p scattering

Buttimore, PSTP 2013

Simple nucleon interaction (P or N) with a target produces positive A_N for the proton and negative A_N for the neutron (as valence nucleon).

But spin-flip amplitudes may weaken the effect at all but the lowest momentum transfers.



100 GeV

Trueman

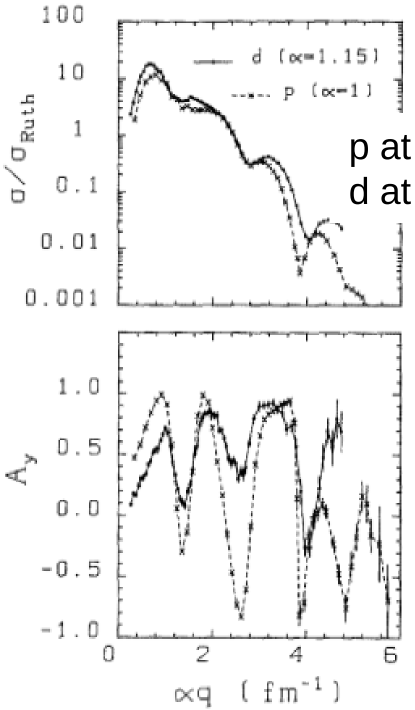
Tests at RHIC show a clear carbon recoil locus for a ^{3}He+C polarimeter.

Prospects look hopeful.

2

At “intermediate” energies (few hundred MeV), the analyzing powers should be the largest. This is a good place to conduct a storage ring EDM search.

The light mass beams all have Similar cross section and A_N.

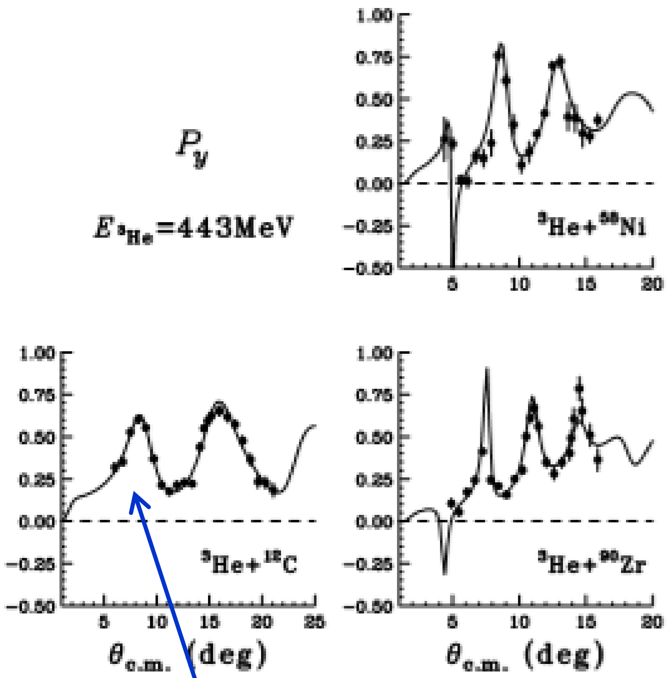


p at 200 MeV
d at 400 MeV

Van Sen, NP A464, 717 (‘87)

Same energy/nucleon matches spin-orbit effects; plotting versus momentum transfer matches Interference pattern.

A single measurement has been made at 443 MeV.



Kamiya, PRC 67, 064612 (‘03)

This region should be useful for a highly efficient ^{3}He polarimeter.