Testing Frozen-Spin HD Targets with Electron BEAMS

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Jefferson Lab

(for HDice group and CLAS collaboration)

Workshop on Polarized Sources Targets and Polarimetry 2022 (PSTP22)

HDice

Jefferson Lab
Thomas Jefferson National Accelerator Facility

JSA

Motivation

- Developing a large acceptance transversely polarized proton target for the CLAS12 transversity program with electron beams.

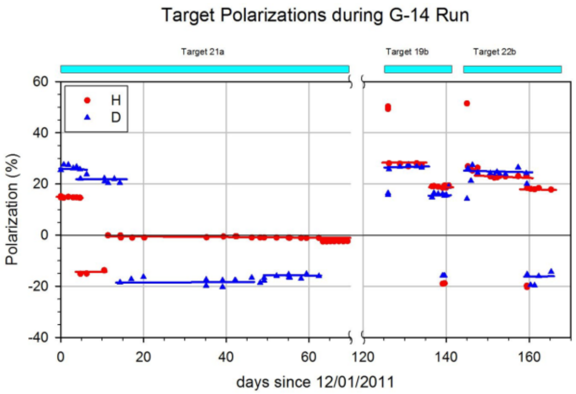
- The HDice target became the prime candidate for CLAS12 transverse polarization experiments, due to its excellent performance with photon BEAMS, and Frozen-Spin properties.

- Electron beam induced polarization loss and related relaxation times, T_1, can be studied by tracking NMR signals under various beam and target conditions.

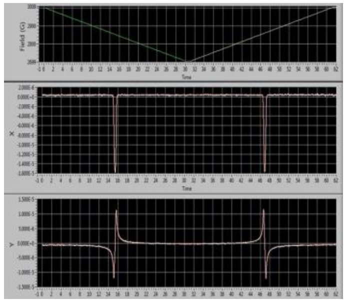
3 ***High Impact*** (✪) transverse experiments for CLAS12:

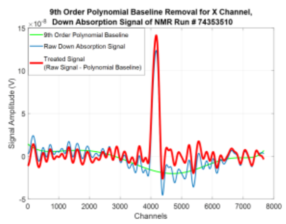
	PAC 39 rating	PAC 41 decision	impact
• SIDIS, C12-11-111, Contalbrigo,	A	C1	✪
• dihadron production, PR12-12-009, Avakian,…	A	C1	✪
• DVCS, PR12-12-101, Elouadrhiri,…	A	C1	✪

C1: successful demonstration of viable performance in an ***eHD*** test.

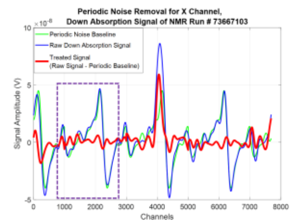


For photon beams T_1^H, T_1^D > 1 year.





Normal background



periodic backgroupnd

Hints from a quick eHD test in 2012

Quick test results: polarization lost in hours with unfavered beam-target conditions.
(Raster rate, target temperature, spin-field alignment…)

⇒ Mechanisms for beam-induced depolarization:

I. beam-heating

- *heat ➤ partially polarized molecular electrons ➤ interact with HD spins*
- *solution: keep HD cold so that molecular electrons are 100% polarized and frozen*
  ⇔ new target cells and new fast raster

II. Hyperfine mixing

- $\vec{\mu}$(e) opposite to $\vec{\mu}$(p) ➤ *polarized electrons mix and dilute H polarization*
- *solution: flip H spin against field, so that e and H polarizations are parallel*

III. Radiation damage

- *beam ionization ➤ chemical changes that could bring HD out of frozen-spin state*
- *expected to be temperature dependent ⇔ needs detailed study*

Collaborators

Jefferson Lab - HDice Group-Physics Division:
G. Dezern, C. Hanretty, T. Kageya, M.M. Lowry, A. M. Sandorfi, and **X. Wei**

***Jefferson Lab – Injection Group-Accelerator Division*:**
J. Grames, M. Poelker, M. Bruker, M. McCaughan, R. Suleiman, Y. Wang

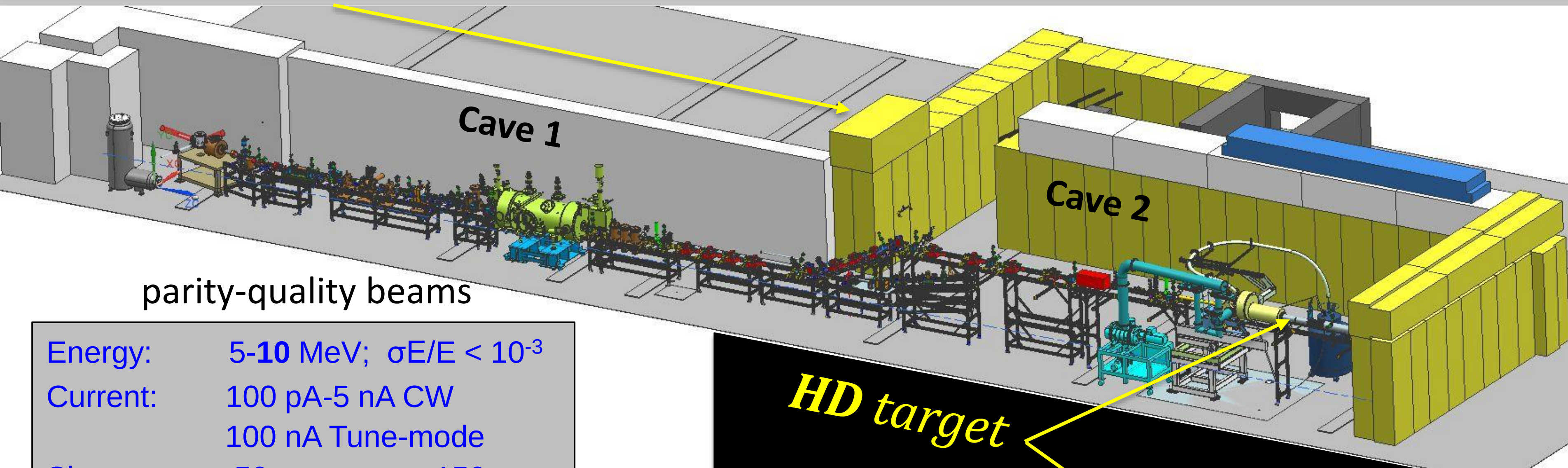
***Jefferson Lab - Engineering Division*:**
S. Gregory

University of Connecticut:
T. O'Connell, K. Joo, K. Wei

Universita di Ferrara and INFN di Ferrara:
L. Barion, M. Contalbrigo, R. Malaguti

Universita di Roma "Tor Vergata" and INFN-Sezione di Roma2:
A. D'Angelo

Upgraded Injector Test Facility (UITF)

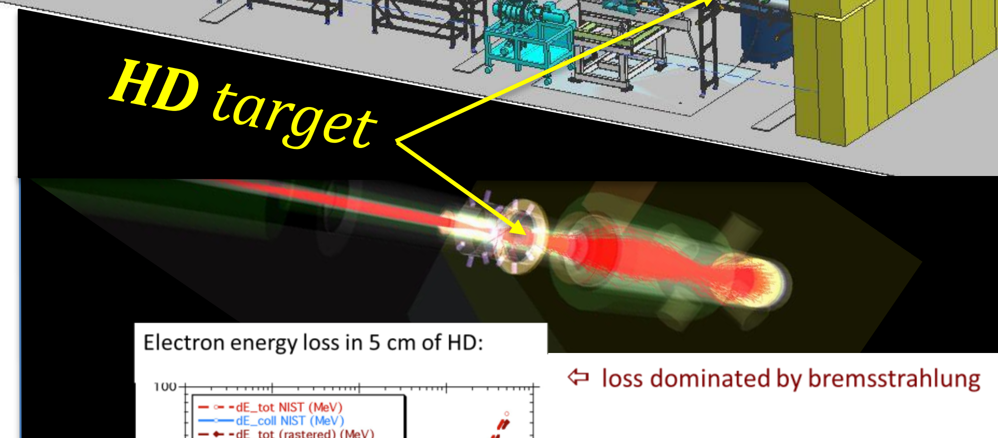


parity-quality beams

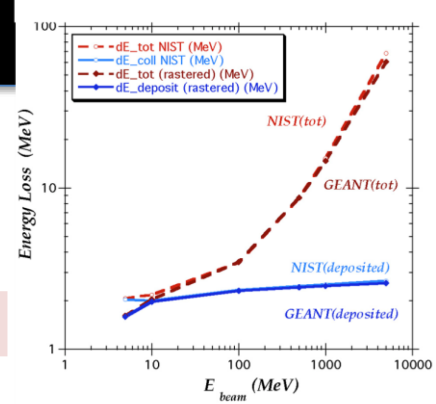
Energy:	5-**10** MeV; σE/E < 10^{-3}
Current:	100 pA-5 nA CW
	100 nA Tune-mode
Size:	50 μm < $\sigma_{x,y}$ < 150 μm
Stability:	within $\sigma_{x,y}$
Beam Halo:	< 10^{-4}
Polarization:	> 70%
Helicity flip:	1-30 Hz

- ⇔ qualify CEBAF injector components
- ⇔ study HD characteristics with 10 MeV electrons

10 MeV beams will test the HD performance at 10 GeV !



Electron energy loss in 5 cm of HD:

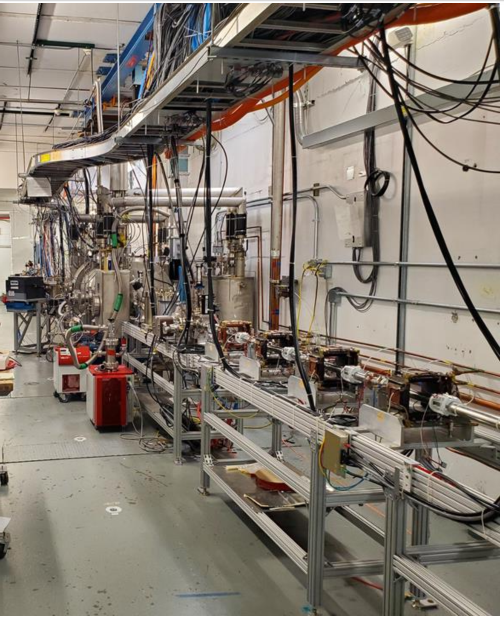


⇦ loss dominated by bremsstrahlung

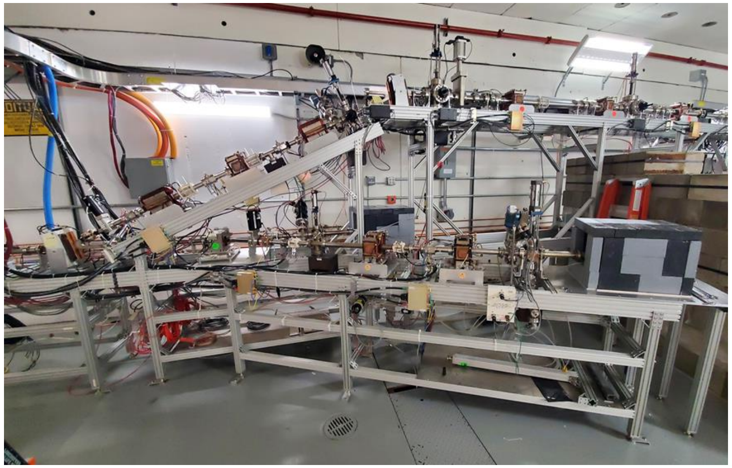
- deposition dominated by Møllers
  $\sigma_{Møller}$ ~ $(1 + 1/\gamma)^2$
  ~ independent of beam energy

⇦ deposition: 2 Mev/e⁻ = 1 mW/½ nA
  ~ independent of beam energy

Upgraded Injector Test Facility (UITF)

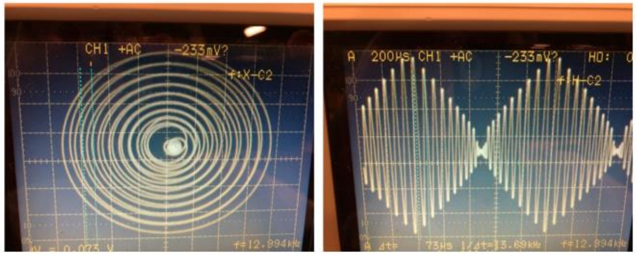


UITF Beamline
(250keV – 9.7MeV)

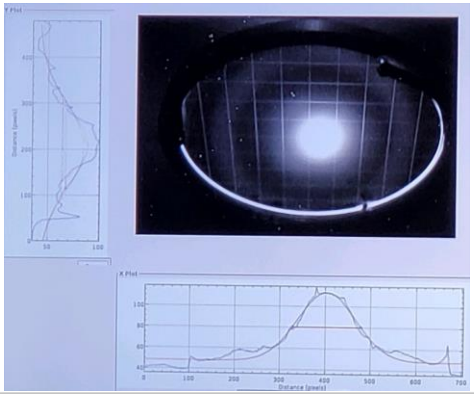


HDice Beamline
(9.7MeV)

HDice Target
(1.1Tesla, 0.06K)



Beam reastered at ~ 14 KHz with ~1 KHz repeating pattern.



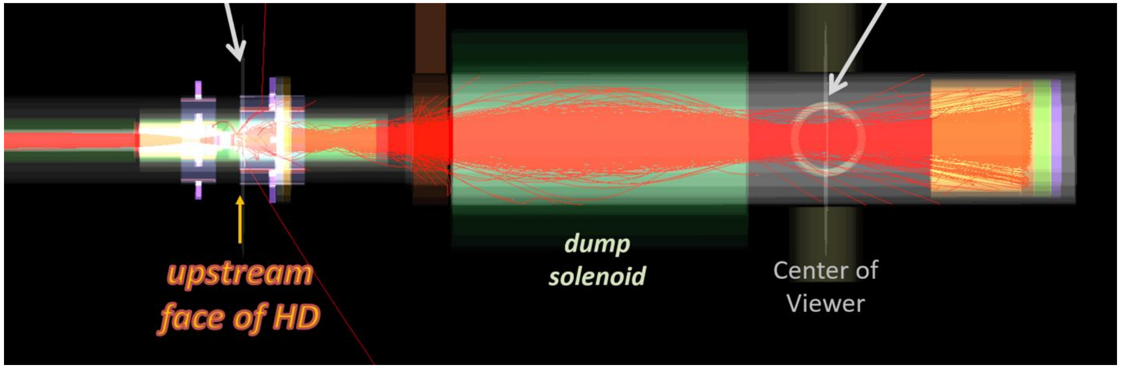
Rastered beam profile on a YAG viewer near the beam dump

Challenges related to the eHD test

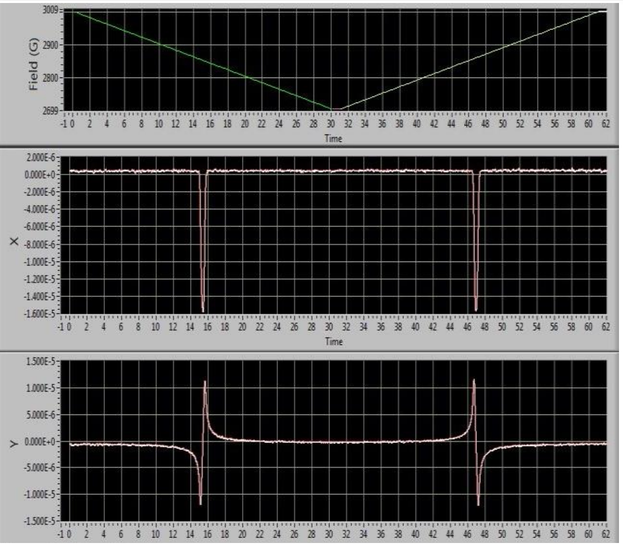
- *10MeV electron beams were bent easily by multiple magnets along the beam path.*
- *Multiple scattering inside the HDice target smeared the beam further.*
- *Beam current determination below 1 nA was a challenge itself.*
- *The activities of nearby facilities in the shared building generated heavy noises electrically and mechanically.*

  ⇒ *Large random and/or periodic NMR noises*

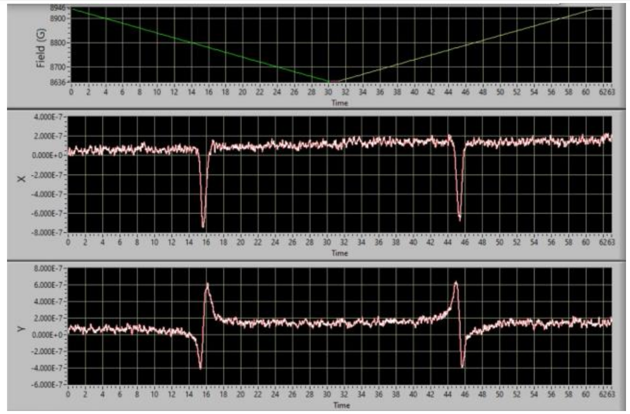
  (less in late night and weekends)
- *Local temperature of HD varies as electrons passed through.*
- *……*



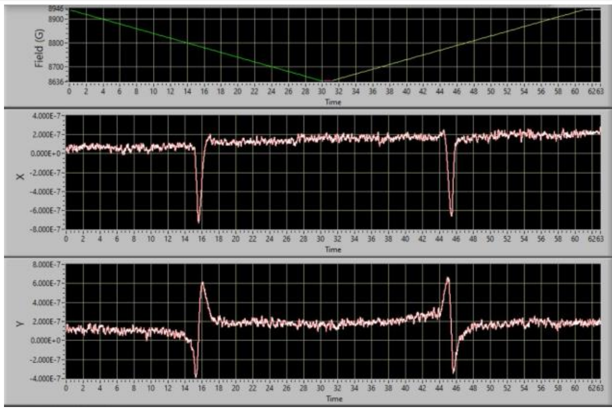
Results: NMR Signals



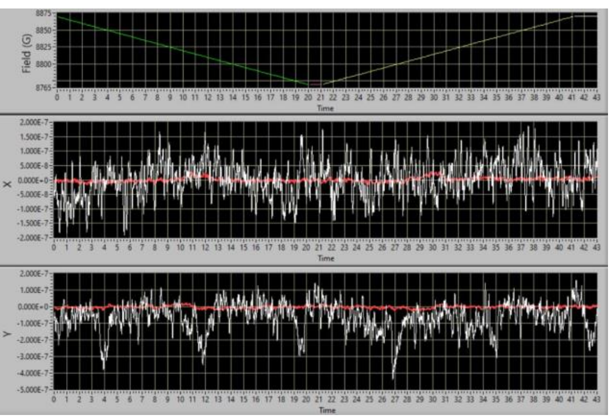
Proton Signal from PD, ~40% Polarization



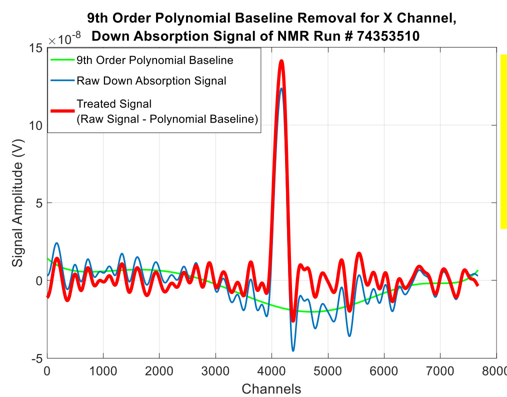
Proton Signal from IBC, ~40% Polarization, I_e = 0 pA.



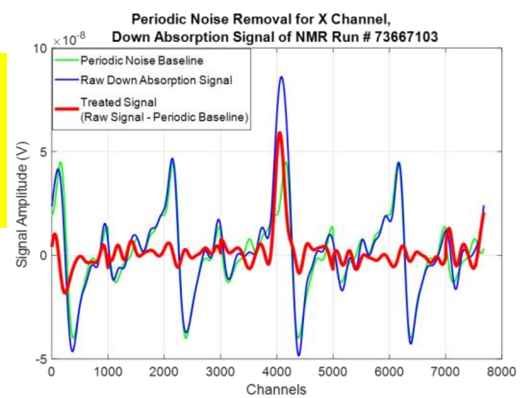
Proton Signal from IBC, ~40% Polarization, I_e = 125 pA.



Typical TE Signal from IBC, 170 scans, I_e=0pA



Background
Raw Signal
Background removed

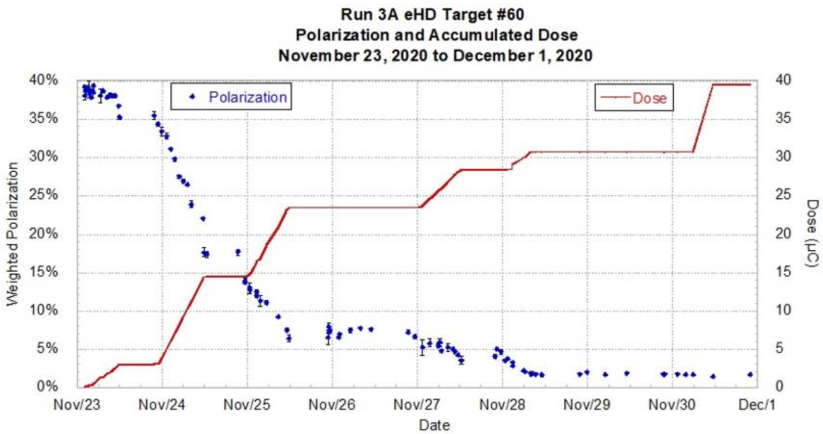


Signal with random background

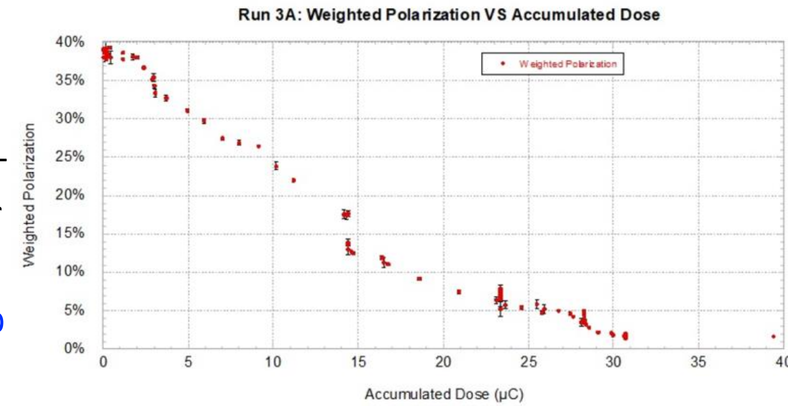
Signal with periodical background

Results: Polarization Tracking for Target #60 and #66

Tgt #60, P_i ~40%

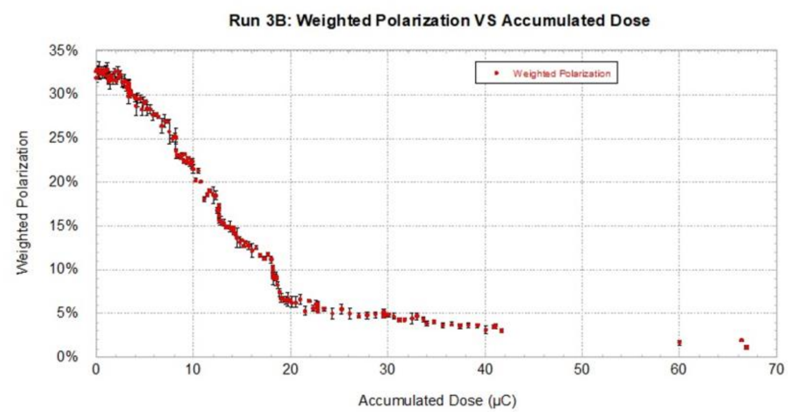


Tgt #60, P_i ~40%



Tgt #66, P_i ~34%

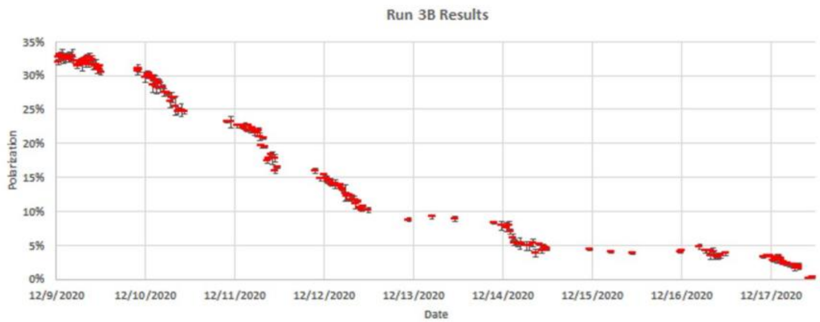
Tgt #66, P_i ~34%

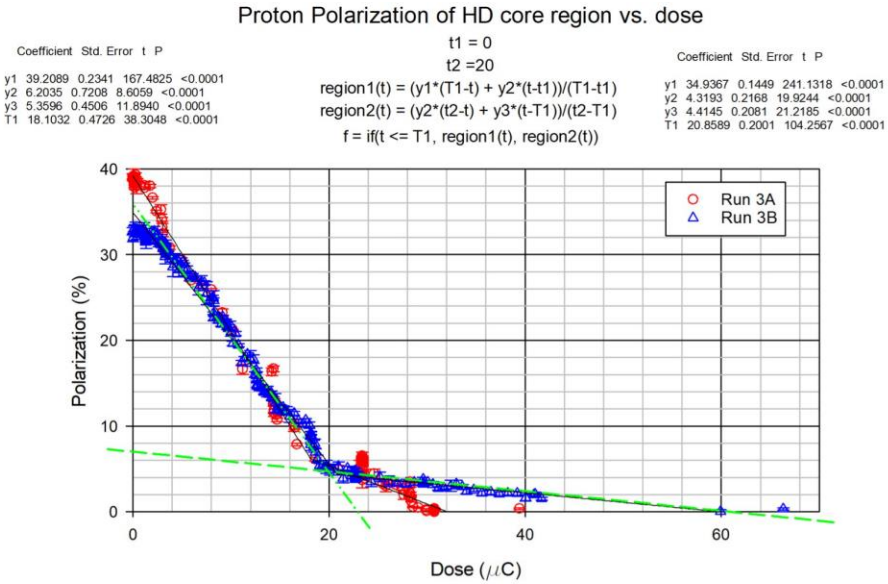


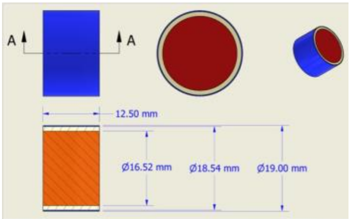
P vs. Time

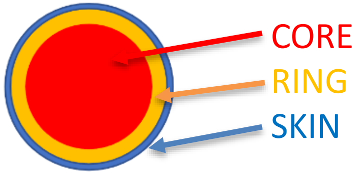
P vs. Total Dose

Results: CORE-RING-SKIN MODEL









- 3 dose ranges (μC) (0<=D<20, 20<=D<60 and D>=60):

CORE (r<Rcore, uniform beam)
RING (Rcore<=r<Rskin, shoulder beam)
SKIN (Rskin<=r<RHD, no beam)

The polarization vs dose in Run 3B can be described as:

1. P=-1.39D+34 (0<=D<20, CORE+RING)
2. P=-0.124D+7.00 (21<=D<60, RING)
3. P=0 (D>=60, SKIN) (P=1.66 without SKIN subtraction).

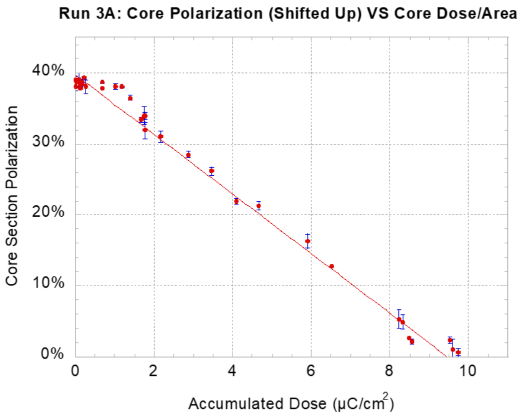
- The relative portions of HD target in each region:

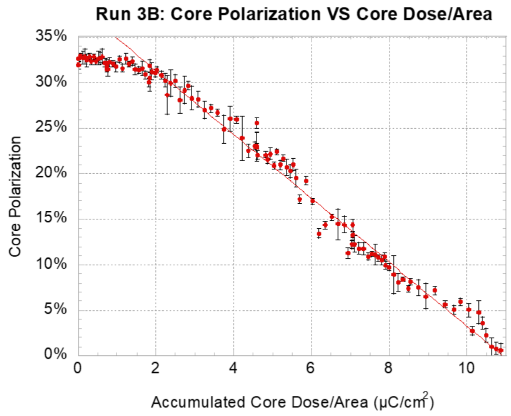
CORE/total=0.756
RING/total=0.196
SKIN/total=0.048

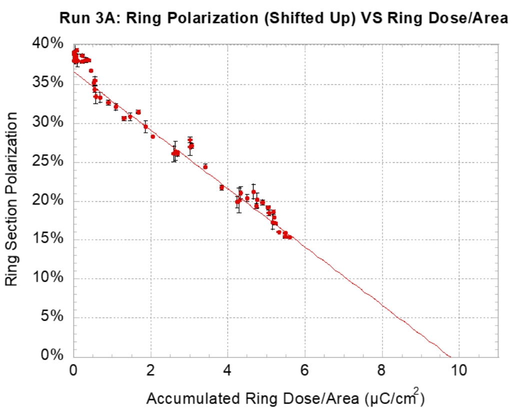
⇒ RHD=9.50mm, Rcore=8.26mm, Rskin=9.27mm.
⇒ The 3 HD volumes contributed NMR signals:
were 2.679cc, 0.695cc and 0.173cc for the L=12.5mm target.

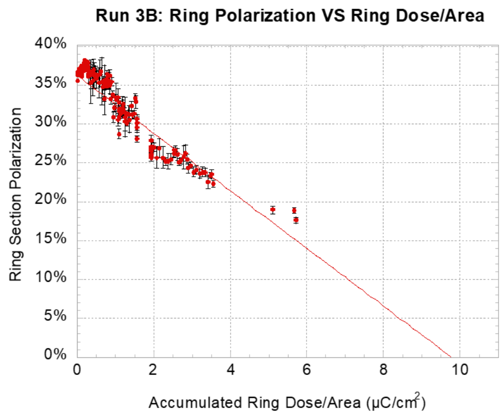
The Run 3A were treated the same way.

Polarization vs Dose/Area for CORE and TRANSITION









Run 3A, TGT #60

Run 3B, TGT #66

Target polarization lost (almost) linearly as Areal Dose accumulated.

$$\frac{dP}{d\left(\frac{Dose}{Area}\right)} \cong 3.8\% \, {cm^2}/{\mu C}$$

For both CORE and RING

(The difference between 3A and 3B at CORE region was caused by different raster patterns.)

HD Polarization Loss Modeling

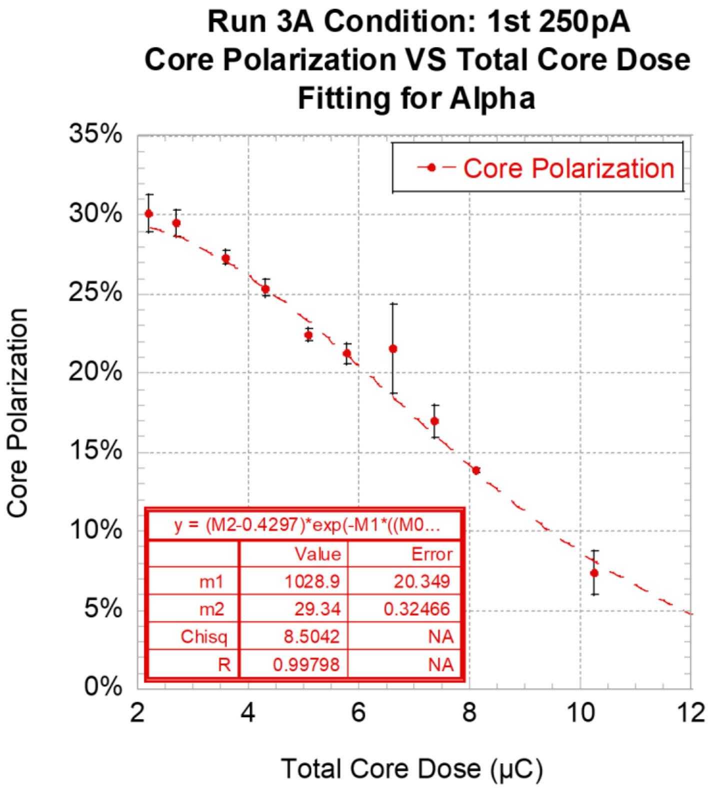
- Starting with a model developed by C. Keith (SPIN 2016) and rewriting time in terms of the relative dose received during a beam condition,

$$P(t) = (P_0 - P_{TE})e^{-\frac{\alpha * D_{rel} * D_T * \beta}{I_e}} + P_{TE}$$

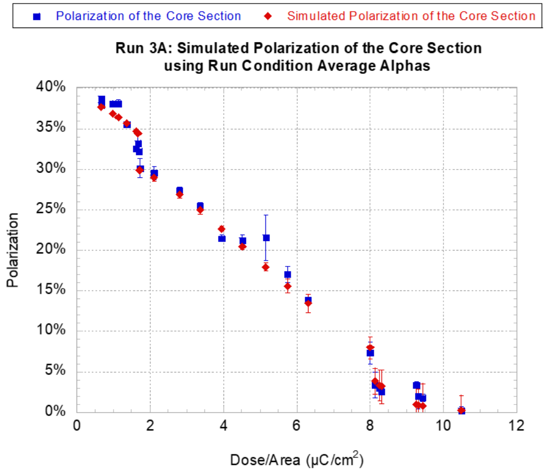
$$where\ \beta = B^3 e^{-\frac{2\mu_e B}{kT}}\ and\ t = \frac{D_{rel}}{I_e}$$

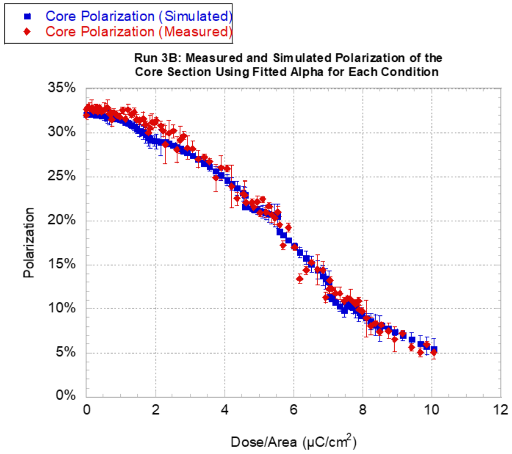
the value of α can be found by fitting it with the expression.

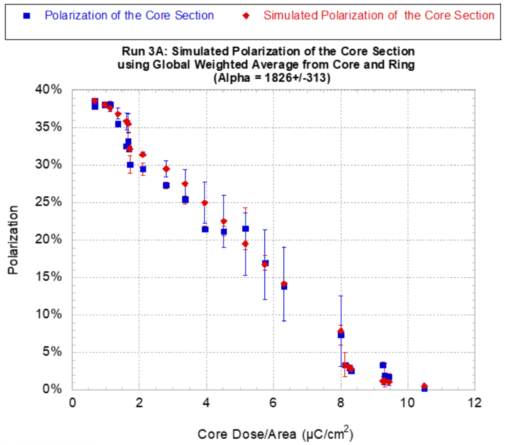
- Once α is determined for each condition (both core and ring), a global alpha found from the weighted average of all individual values.

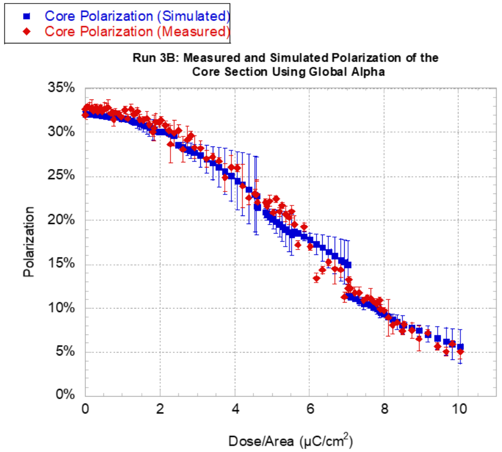


Core Simulation Using Separate Condition Alphas (Top)
Core Simulation Using Global Alpha (Bottom)





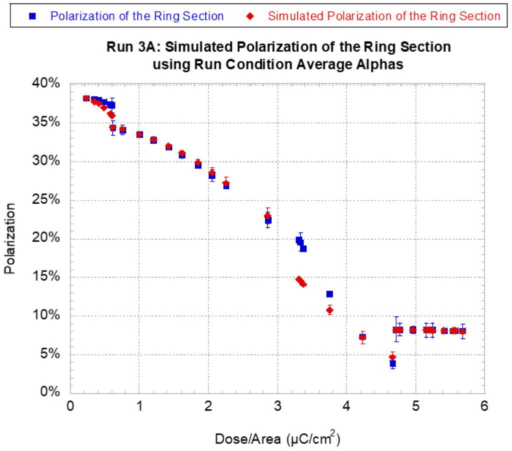


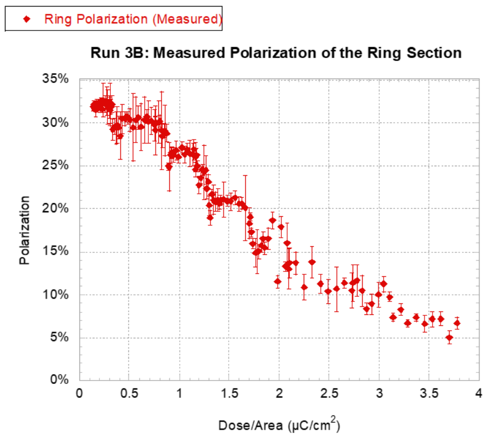


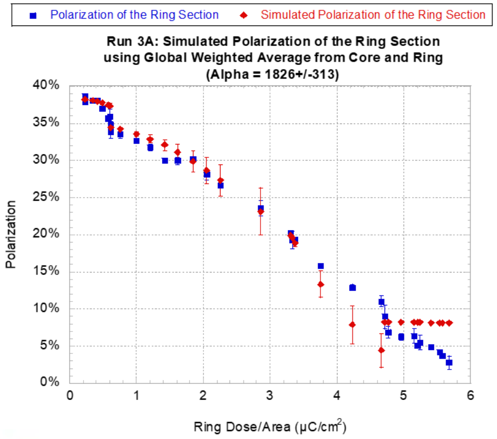
Run 3A, TGT #60

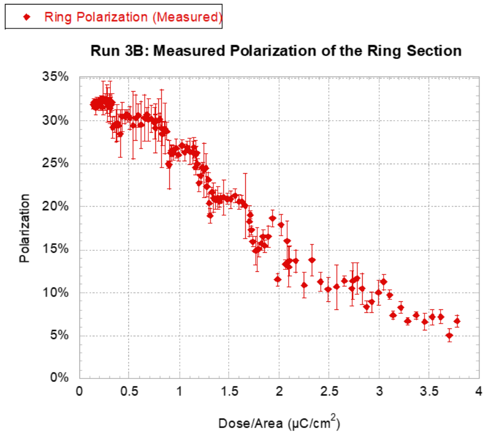
Run 3B, TGT #66

Ring Simulation Using Separate Condition Alphas (Bottom)
Ring Simulation Using Global Alpha (Bottom)









Run 3A, TGT #60

Run 3B, TGT #66

T_{HD} Calibration Curve from HDice Run 2A & 2B

- Temperature calibration for T_{HD} required for beam on NMR measurements.

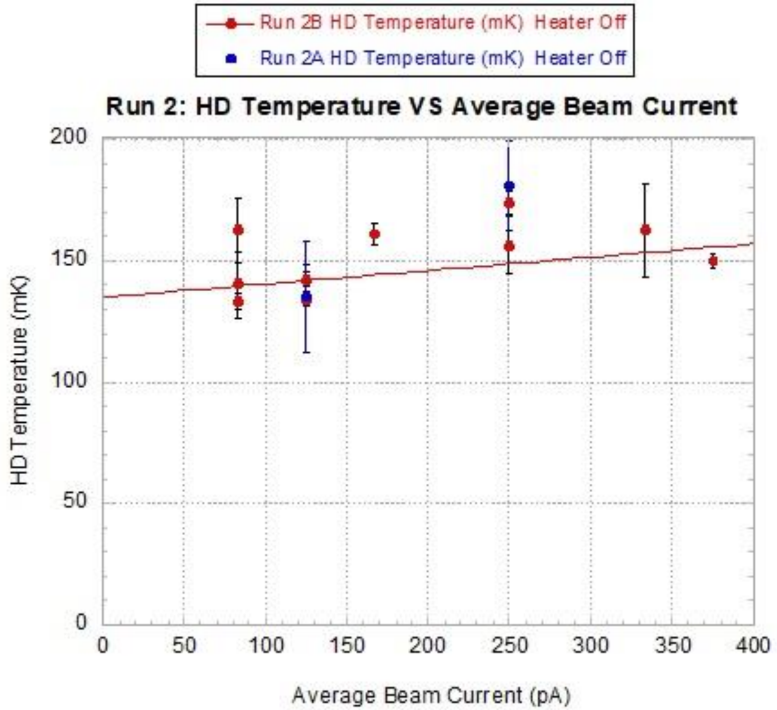
  (Run 2A and 2B, 2 TE targets, $T_1^H < 1s$)

- From Curie's Law ⇔ The product of NMR Signals from beam-off conditions and the HD temperature were calculated across the Run 3A run period:

$$S_{(beam-on)} * T_{HD(beam-on)} = S_{(beam-off)} * T_{HD(beam-off)}$$

- The HD temperature at various beam currents is determined from the relationship above:

$$T_{HD(beam-on)} = \frac{S_{(beam-off)} * T_{HD(beam-off)}}{S_{(beam-on)}}$$

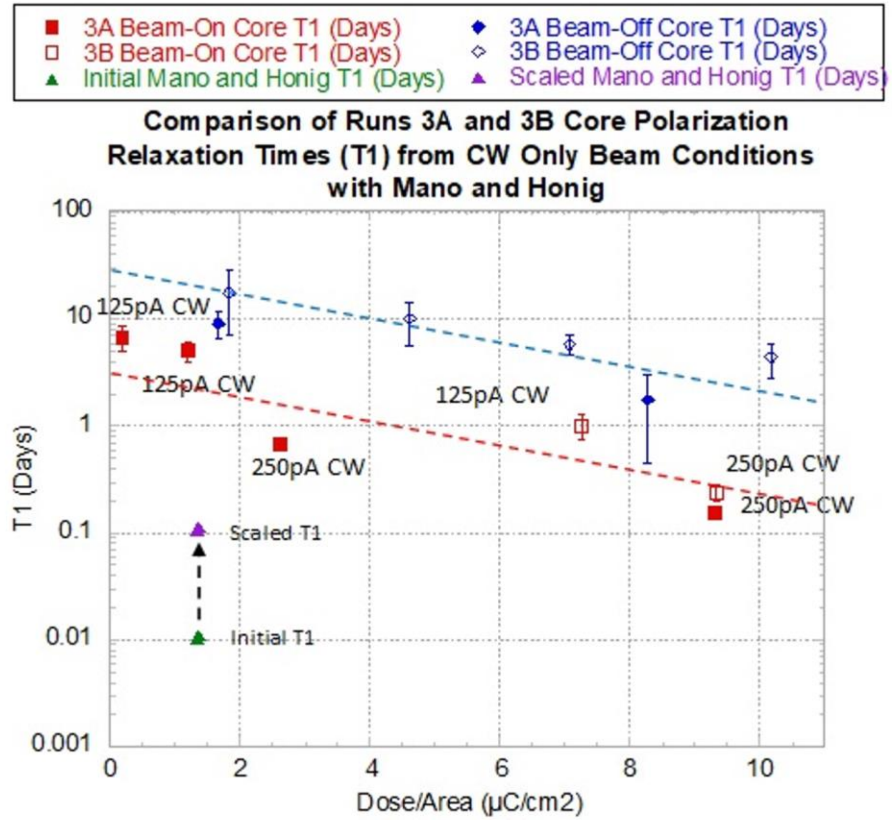


Comparison to Previous Work (Cornell 1976)

- The model was used to determine the scaling factor between the HDice T_1 values and the T_1 value from the Mano and Honig experiment.

$$\frac{T_1^{H_I}}{T_1^{H_{II}}} = \frac{\left(\frac{1}{(B_I=1.04T)^3}\right)\exp\left(\frac{2\mu_e(B_I=1.04T)}{k(T_I=0.15K)}\right)}{\left(\frac{1}{(B_{II}=0.28T)^3}\right)\exp\left(\frac{2\mu_e(B_{II}=0.28T)}{k(T_{II}=4.2K)}\right)} = 10.30$$

- The scaling factor was determined to be an order of magnitude, which isn't enough to account for the difference between the results.
- The remaining difference could be due to a higher effective dose during the Mano and Honig experiment, due to the production of secondaries in the relatively thick walls of their cryostat.



Projection to a Colder HD Target

The same model used to scale Mano and Honig's T_1 values can be used to project the relaxation times for ideal conditions.

If the HD temperature and field were maintained at 120mK and 1.25 T, the T_1 values increase by:

Run 3B Beam On:

$$\frac{T_1^I}{T_1^{3B}} = \frac{\left(\frac{1}{(B_I)^3}\right)\exp\left(\frac{2\mu_e(B_I)}{k(T_{HD}^I)}\right)}{\left(\frac{1}{(B_{3B})^3}\right)\exp\left(\frac{2\mu_e(B_{3B})}{k(T_{HD}^{3B})}\right)} = \frac{\left(\frac{1}{(1.25T)^3}\right)\exp\left(\frac{2\mu_e(1.25T)}{k(0.120K)}\right)}{\left(\frac{1}{(0.88T)^3}\right)\exp\left(\frac{2\mu_e(0.88T)}{k(0.220K)}\right)} = 1.95 * 10^4$$

Run 3B Beam Off:

$$\frac{T_1^{Beam-Off}}{T_1^{Beam-On}} = \frac{\left(\frac{1}{(B_{Beam-Off})^3}\right)\exp\left(\frac{2\mu_e(B_{Beam-Off})}{k(T_{HD}^{Beam-Off})}\right)}{\left(\frac{1}{(B_{Beam-On})^3}\right)\exp\left(\frac{2\mu_e(B_{Beam-On})}{k(T_{HD}^{Beam-On})}\right)} = \frac{\left(\frac{1}{(0.88T)^3}\right)\exp\left(\frac{2\mu_e(0.88T)}{k(0.070K)}\right)}{\left(\frac{1}{(0.88T)^3}\right)\exp\left(\frac{2\mu_e(0.88T)}{k(0.150K)}\right)} = 8.30 * 10^3$$

Potential T_1 enhancements, are quite large (~10^4 times larger), but the beam-off T_1 dominated by another polarization loss mechanism. This imposes a limit on the gains in the beam-on T_1 that might be achieved with more ideal conditions.

Summary

- During the initial ~1.9μC/cm^2 for both targets, the polarization loss was insignificant.
- By 6μC/cm^2 the polarization of the each section dropped to *1/e* of their initial values with complete polarization loss at ~10μC/cm^2.
- Beam-on spin-relaxation rates (T_1) dropped with dose. Beam-off T_1 values followed similar trend, but about 10x larger.
- With both Run 3A and 3B data, it became evident that at a fixed dose, T_1 also drops with increasing current.
- The ***eHD*** experiments showed significantly better performance than the Mano and Honig experiment.
- Improvements to Beam On T_{HD} and B could greatly improve the T1, but the additional Beam Off depolarization mechanism limits the potential gains.
- 2 PhD theses produced:

  Kevin Wei, Univ. of Connecticut, 2021.

  "*The Response of Polarized Protons in Solid Hydrogen-Deuteride(HD) to Electron Beams*"

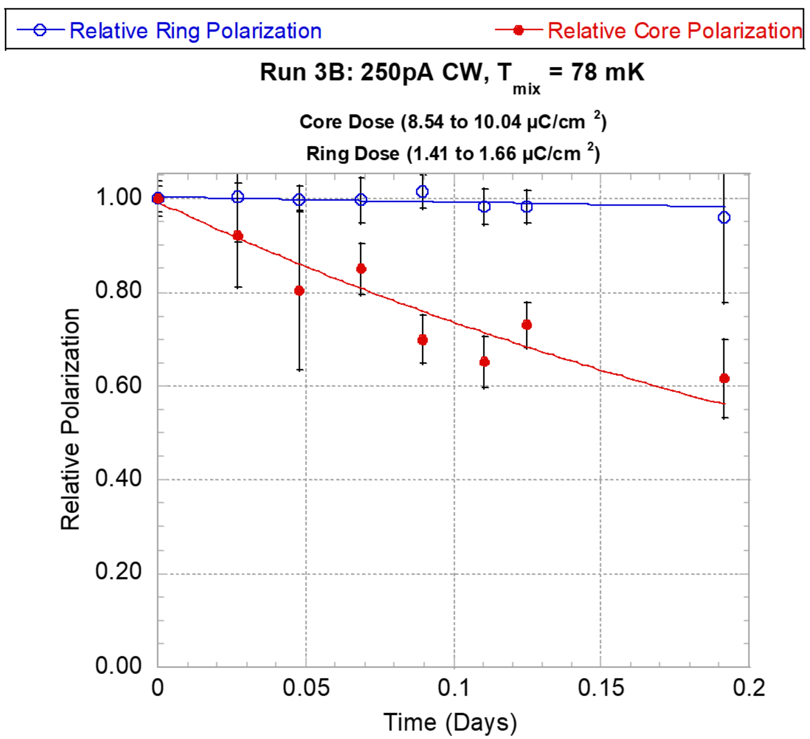
  Thomas O'Connell, Univ. of Connecticut, 2022.
  "*Measurements of Electron Beam Induced Spin Relaxation in Frozen Spin Hydrogen Deuteride HD*"

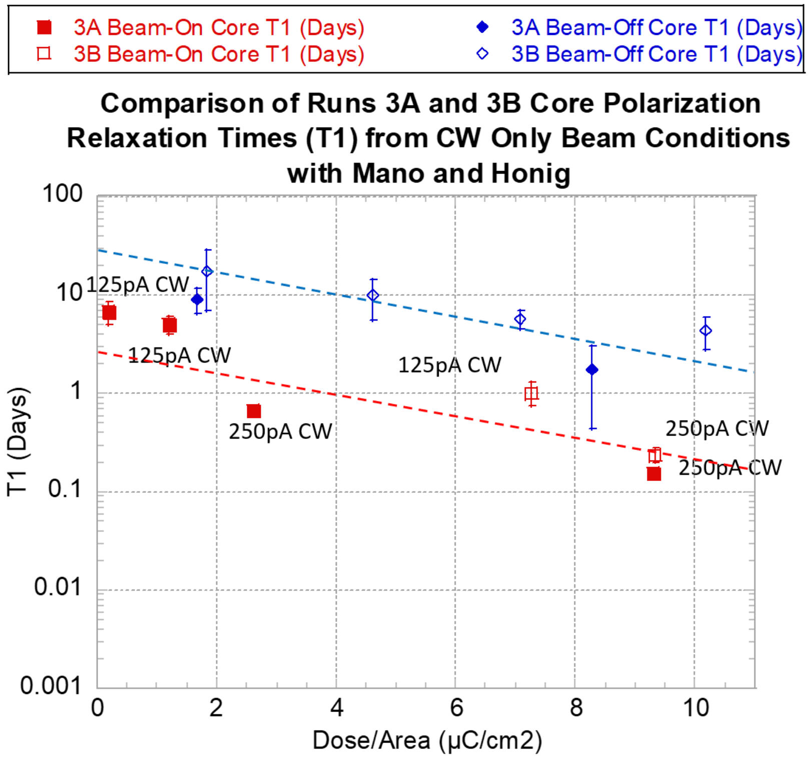
Extra: Relaxation Time (T_1) Values in Runs 3A & 3B

- The polarization relaxation times (T_1) could be determined by fitting the polarization values of each of the beam on\off conditions to the following equation:

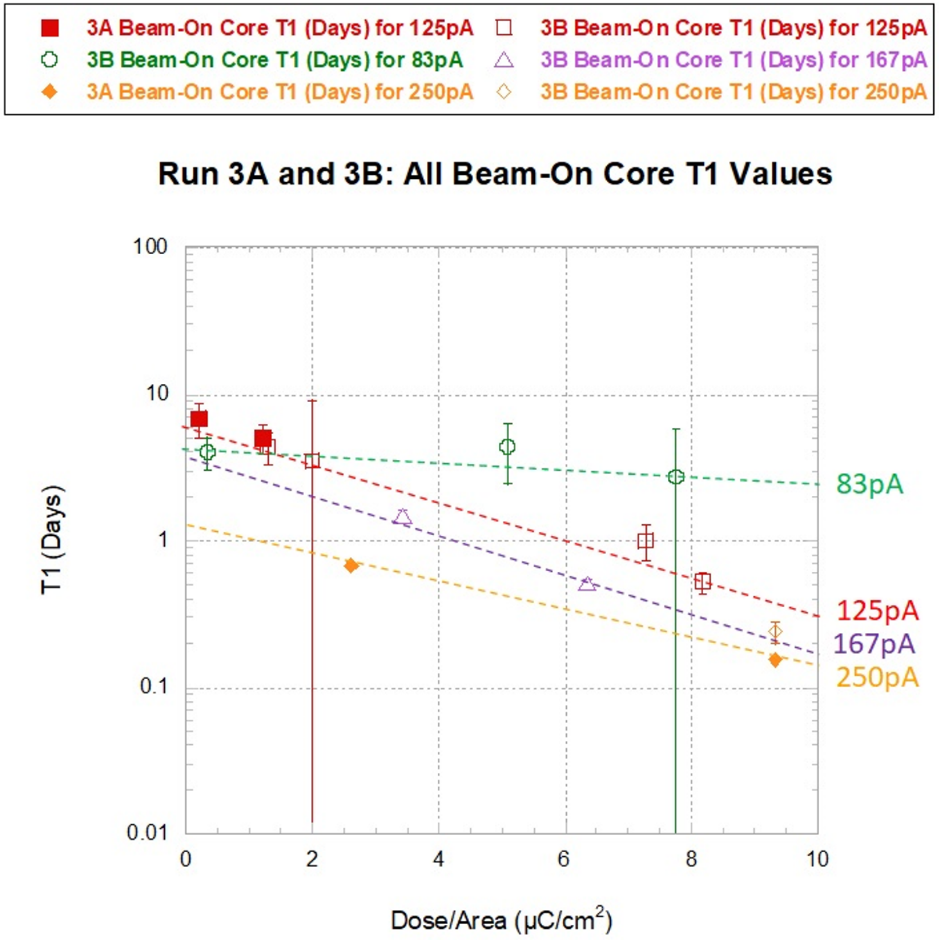
$$P(t) = (P_0 - P_{TE})e^{-t/T_1} + P_{TE}$$

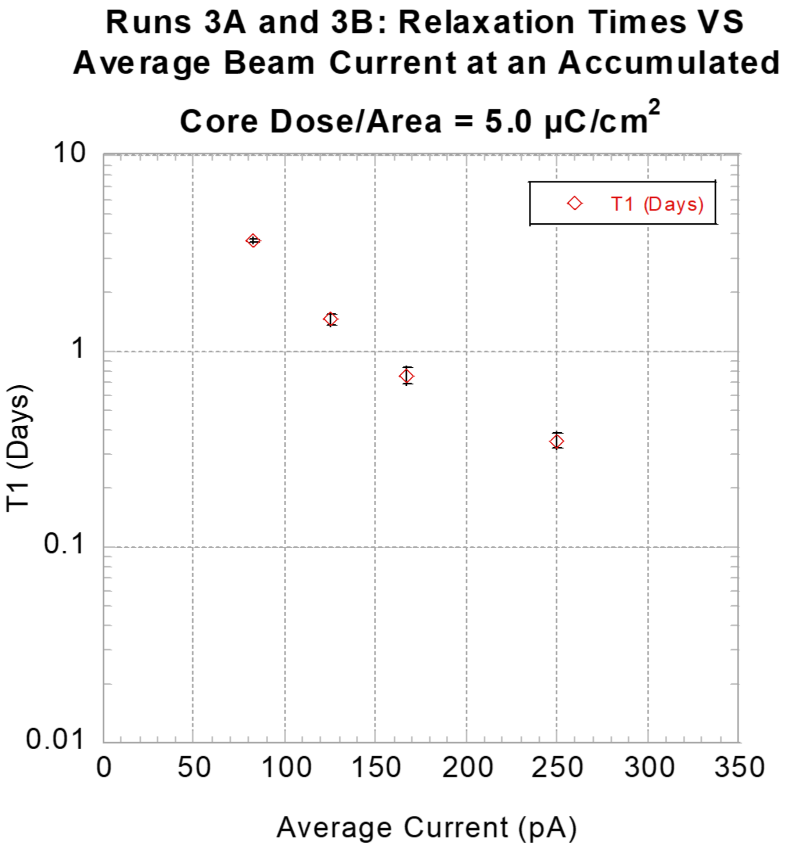
- A difference of an order of magnitude seen between the T_1 values from beam-on and beam-off conditions.





Extra: Relaxation Time (T_1) Values in Runs 3A & 3B





Extra: Beam Profile at Target, viewer, and along axis