A Transversely Polarized Solid Target for Hall B at Jefferson Lab

Chris Keith

Jefferson Lab Target Group

25th International Spin Symposium

Durham, NC

Jefferson Lab TARGET GROUP

Jefferson Science Associates, LLC

Thomas Jefferson National Accelerator Facility

U.S. DEPARTMENT OF ENERGY | Office of Science

Run Group H comprises three highly rated, high-impact experiments utilizing a transversely polarized target

SIDIS on a transversely polarized target (2011)


New Research Proposal to Jefferson Lab PAC38

Transverse spin effects in SIDIS at 11 GeV with a transversely polarized target using the CLAS12 Detector

H. Avakian[1], S. Boyarinov, V.D. Burkert, A. Deur, L. Elouadrhiri, T. Kageya, V. Kubarovsky, M. Lowry, B. Musch, A. Prokudin, A. Sandorfi, Yu. Sharabian, S. Stepanyan, X.Wei
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IPNO (Orsay), SPhN (Saclay) France

[1]Co-spokesperson
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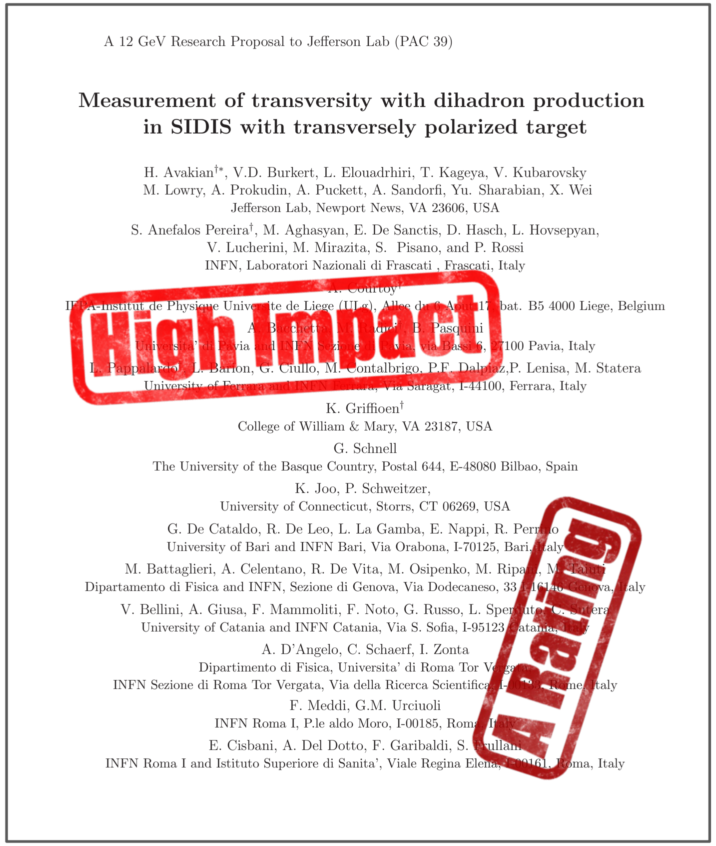
1

Dihadron production on a transversely polarized target (2012)


A 12 GeV Research Proposal to Jefferson Lab (PAC 39)

Measurement of transversity with dihadron production in SIDIS with transversely polarized target

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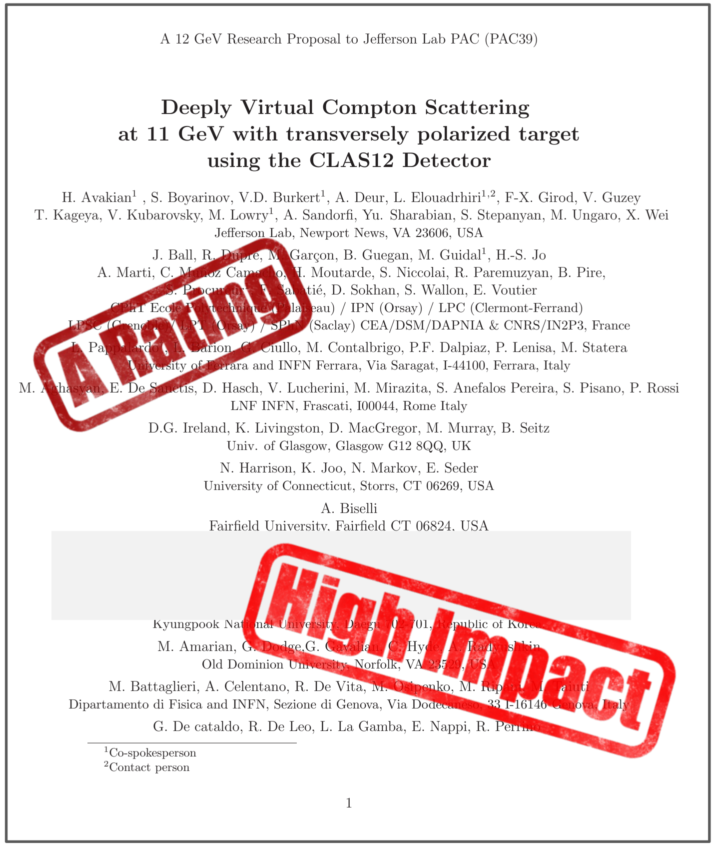
DVCS with a transversely polarized target (2012)


A 12 GeV Research Proposal to Jefferson Lab PAC (PAC39)

Deeply Virtual Compton Scattering at 11 GeV with transversely polarized target using the CLAS12 Detector

H. Avakian[1] , S. Boyarinov, V.D. Burkert[1], A. Deur, L. Elouadrhiri[1,2], F-X. Girod, V. Guzey
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J. Ball, R. Dupré, M. Garçon, B. Guegan, M. Guidal[1], H.-S. Jo
A. Marti, C. Munoz Camacho, H. Moutarde, S. Niccolai, R. Paremuzyan, B. Pire, F. Sabatié, D. Sokhan, S. Wallon, E. Voutier
IPN (Orsay) / LPC (Clermont-Ferrand) / SPhN (Saclay) CEA/DSM/DAPNIA & CNRS/IN2P3, France

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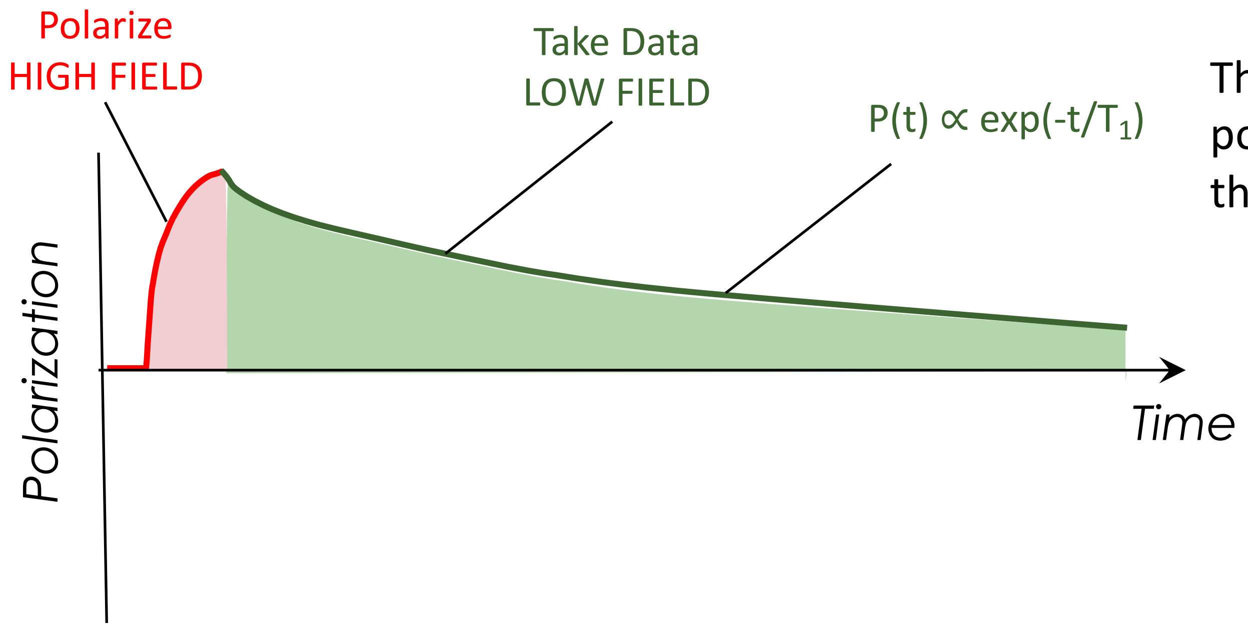
All proposals assumed the use of HDice , a *frozen-spin target* of solid hydrogen deuteride.

PAC Condition: the target must maintain its polarization for at least 21 days under a beam current of 1 nA (~10^{13} s^{-1})



The exponential decay of polarization is characterized by T_1, the *spin-lattice relaxation time*.

Plan A: a frozen-spin target

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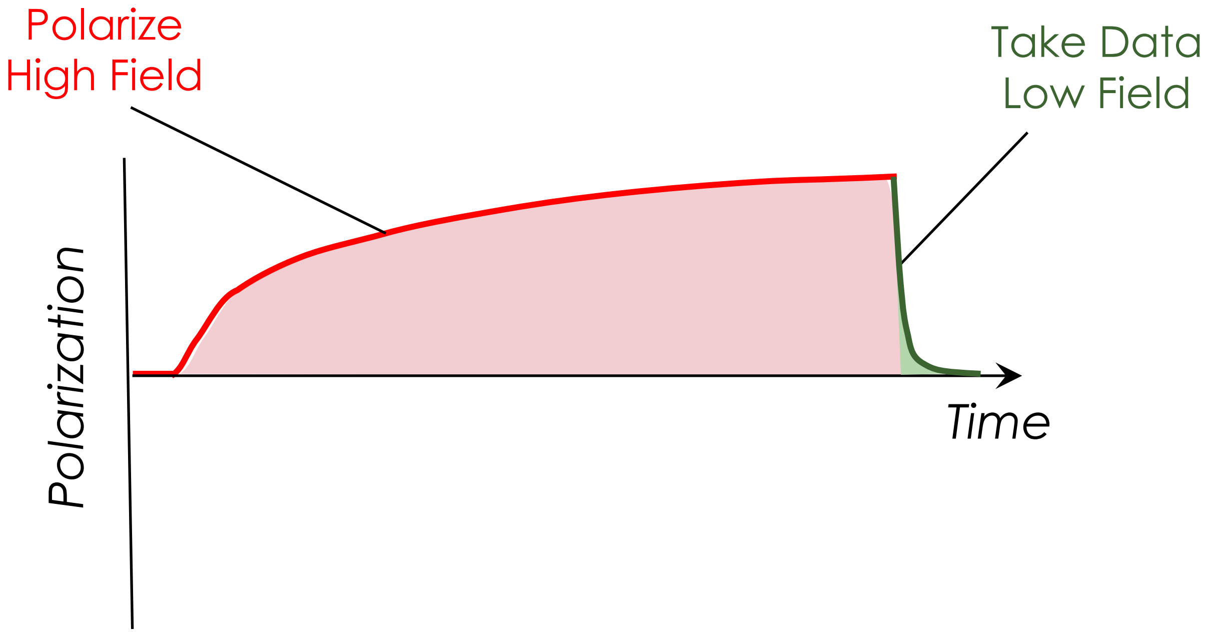

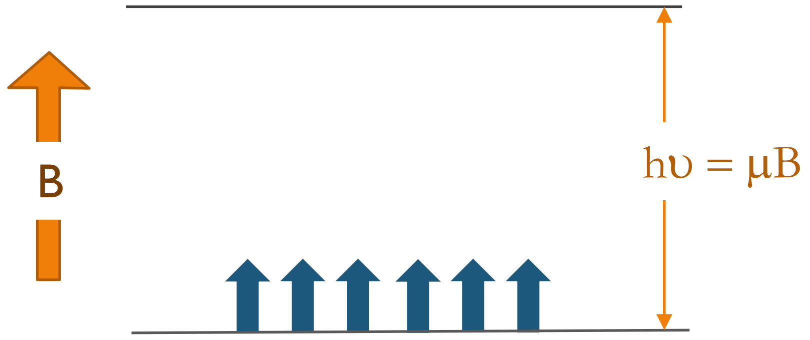

Q: What causes the nuclear spins to flip and the target to lose polarization?

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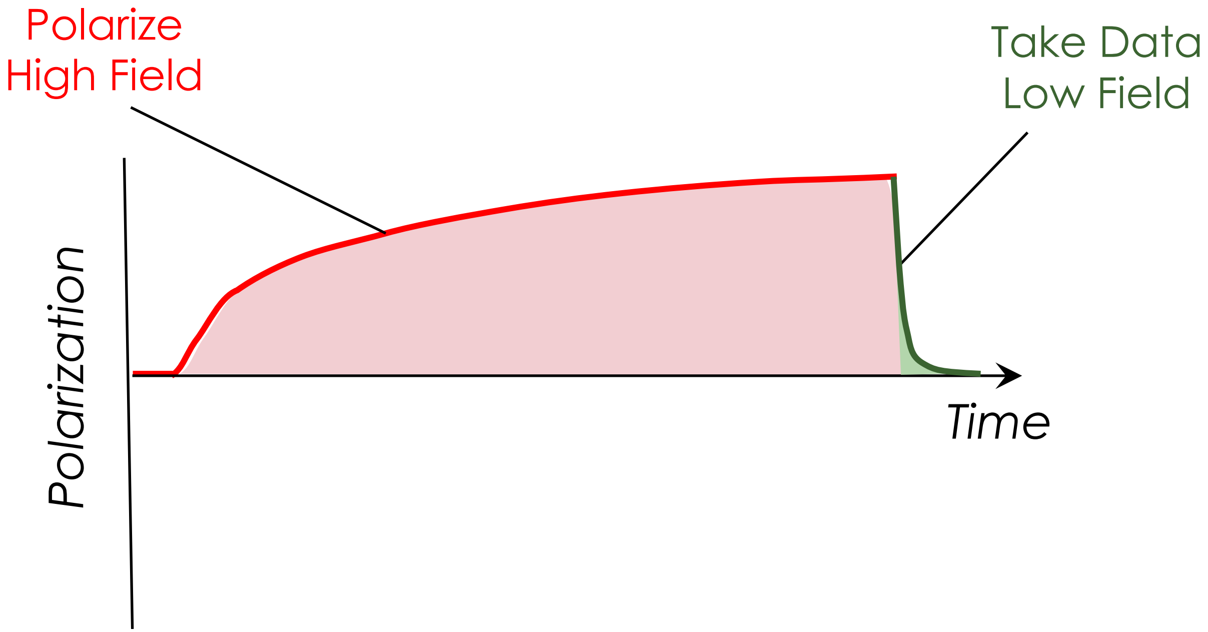

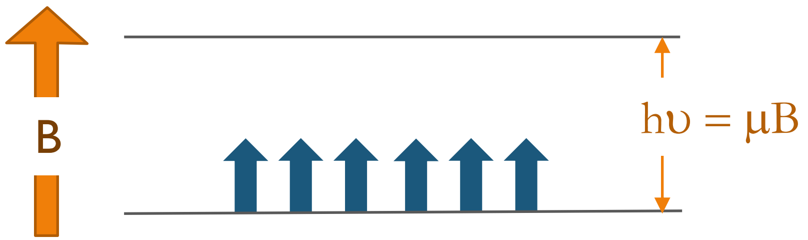

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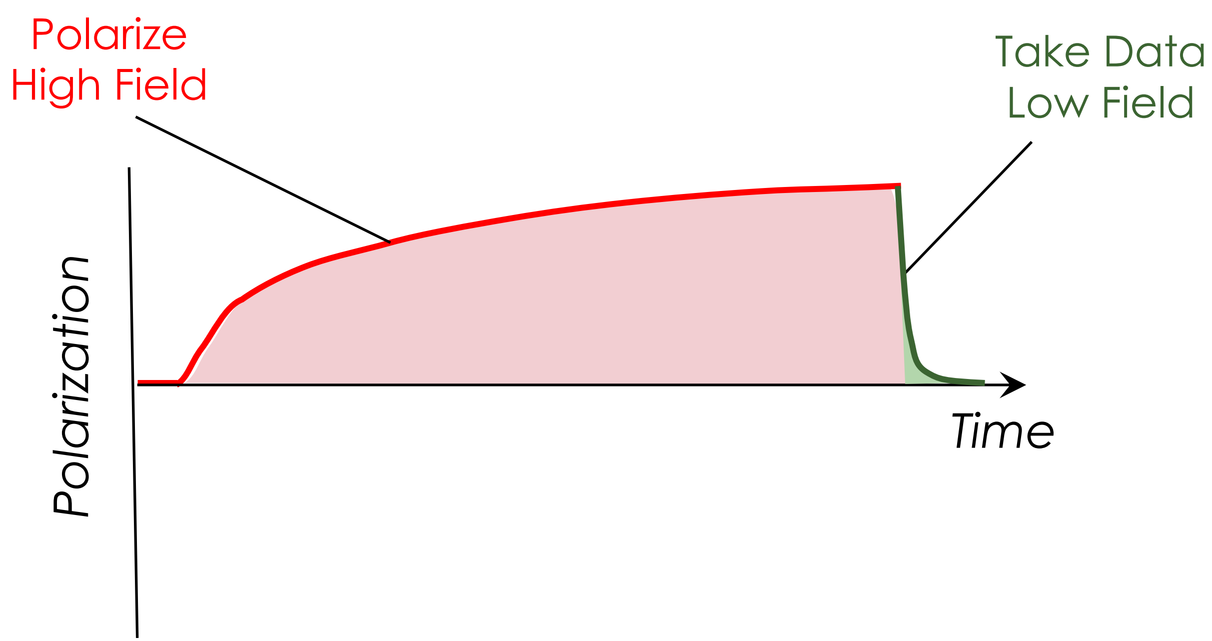

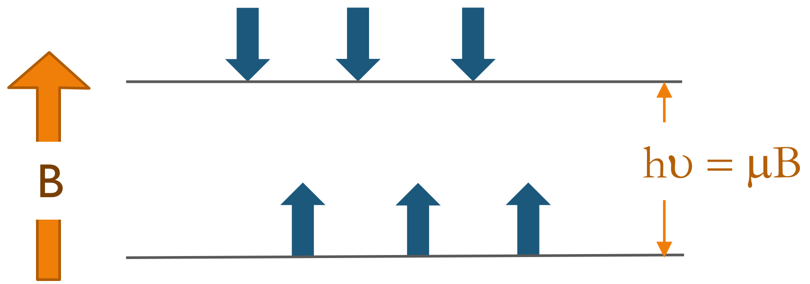

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A: Lattice vibrations produce spin flips of *paramagnetic impurities* in the sample. These flip the nuclear spins via dipole-dipole coupling.

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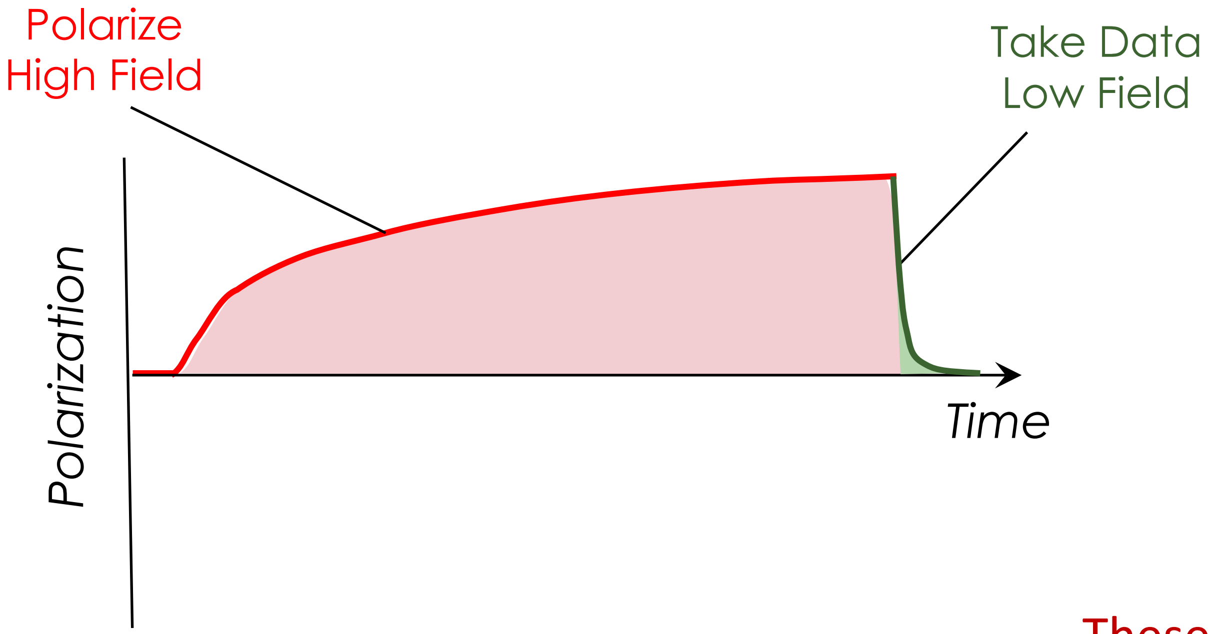

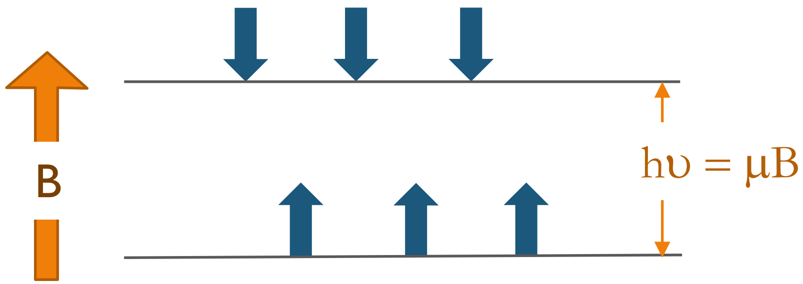

Q: What causes the nuclear spins to flip and the target to lose polarization?

A: Lattice vibrations produce spin flips of *paramagnetic impurities* in the sample. These flip the nuclear spins via dipole-dipole coupling.

These impurities can be created by ionizing radiation.
In solid HD, an electron beam creates (paramagnetic) H and D *atoms*.

Three irradiations of polarized, solid HD with high energy electrons

- Cornell Synchrotron (1975): T_1 decreased from about 14 h to 15 m after 1 μC/cm^2
- JLab Hall B (2012): T_1 decreased from 20 d to ~3 h after 10 μC/cm^2
- JLab UITF (2019): T_1 decreased from 5 d to 2.4 h after 10 μC /cm^2

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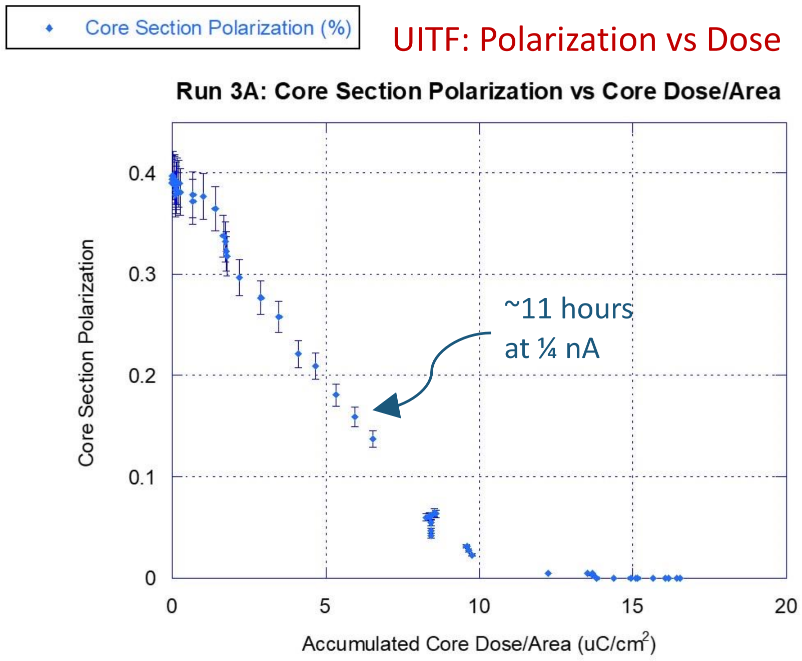
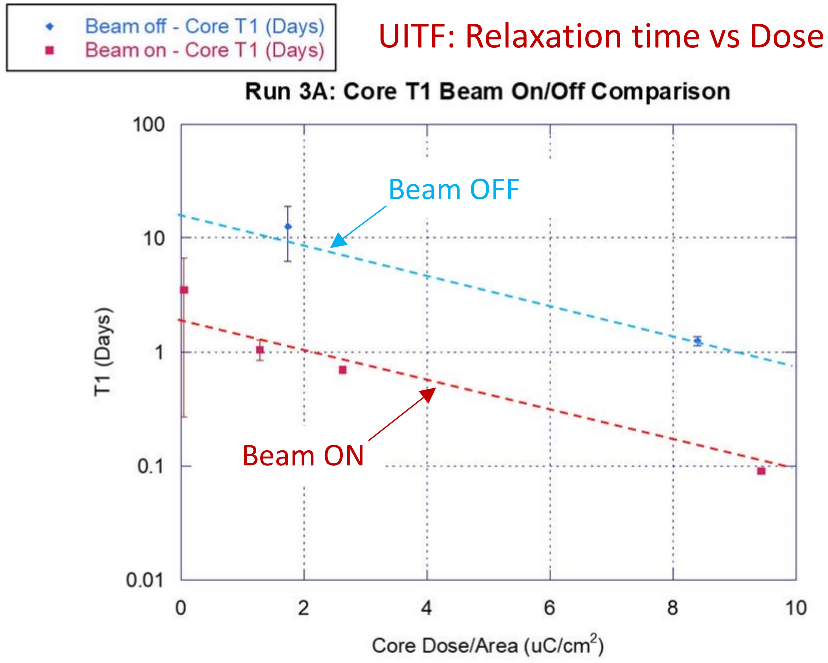
UITF: Polarization vs Dose



Kevin Wei, U. Connecticut

UITF: Relaxation time vs Dose



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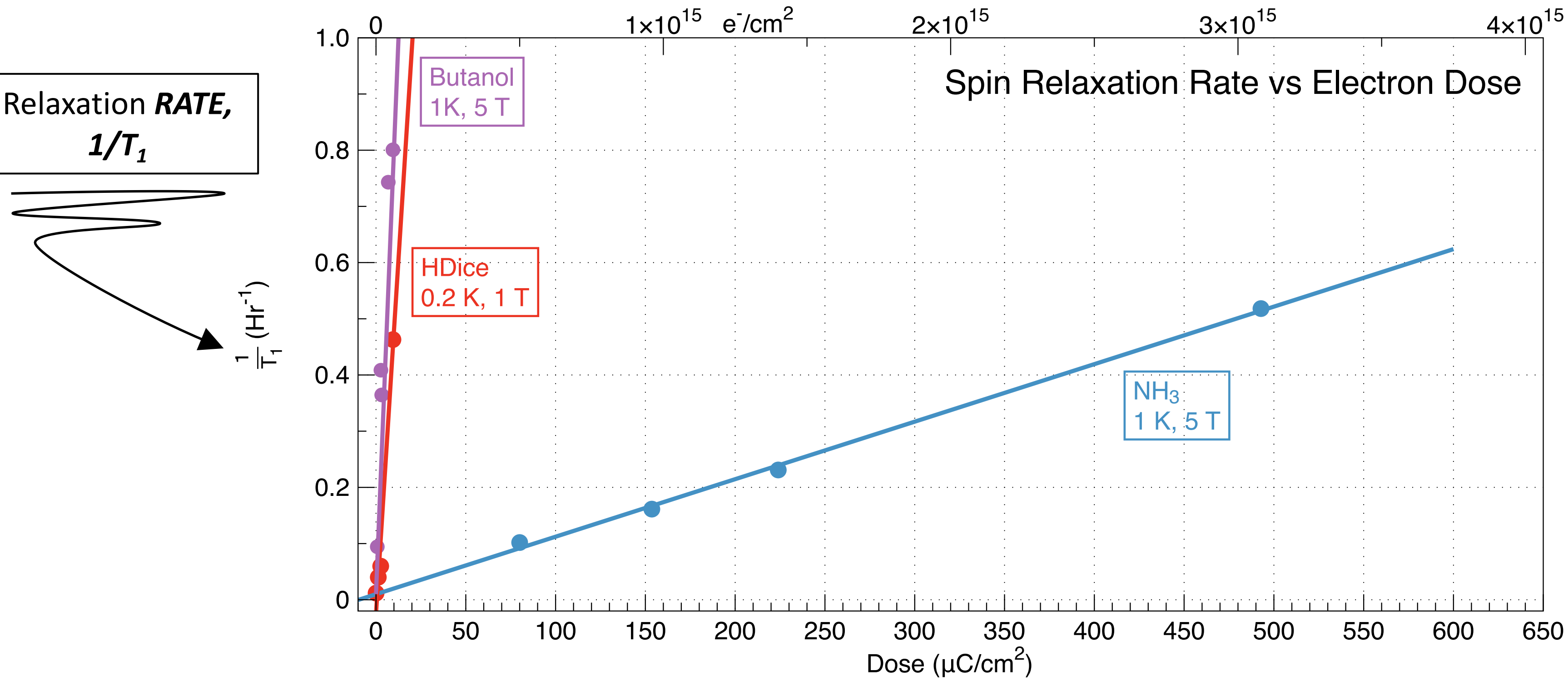
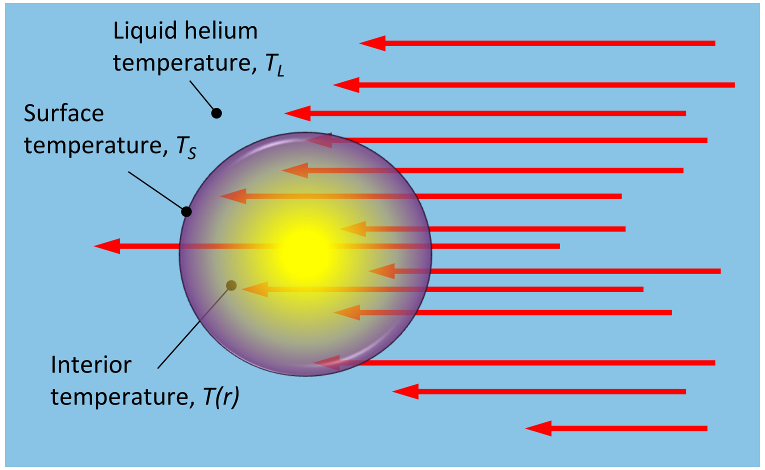
The *de facto* solid polarized target material for intense electron beams is ammonia, NH_3

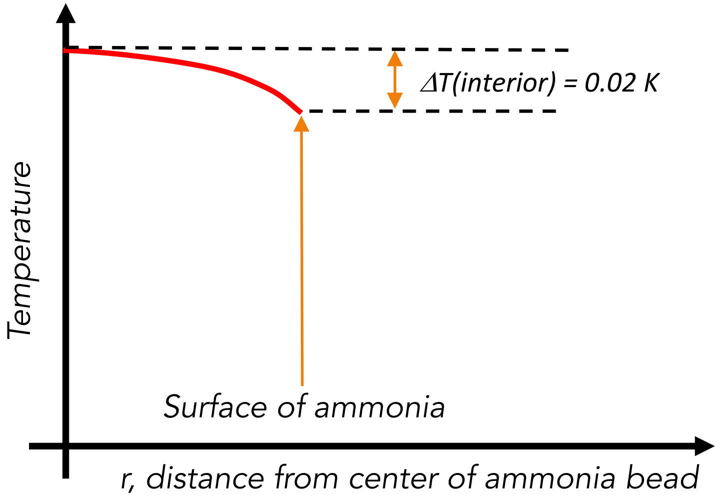
Relaxation ***RATE, 1/T₁***



Is a frozen-spin ammonia target feasible?

A 1 nA electron beam will deposit a *time-averaged* power of about 3 μW into each ammonia bead (radius = 1 mm)





$$T(r) = \frac{q}{v}\frac{r_o^2}{6}\Re\left(1 - \frac{r^2}{r_o^2}\right) + T_s$$

q = heat deposited by beam
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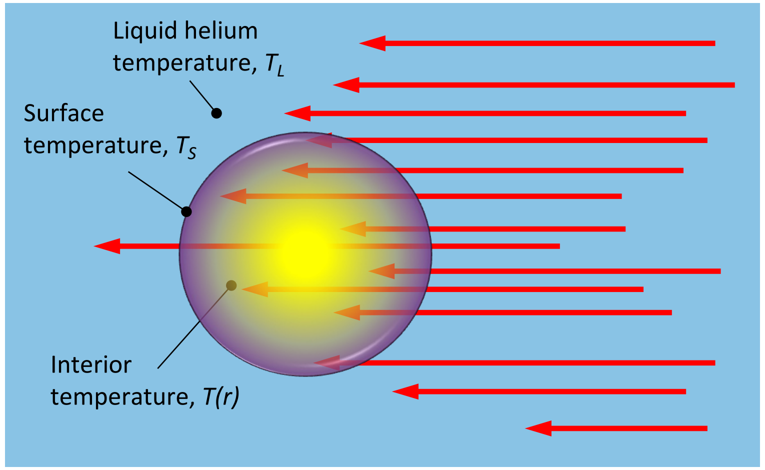

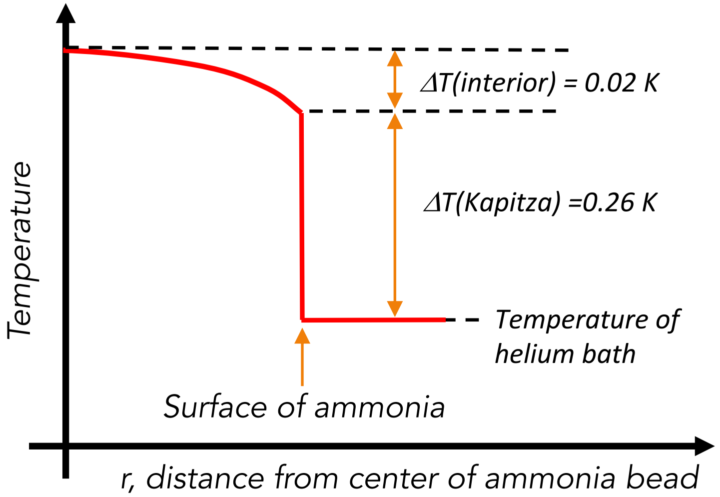

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An ammonia frozen spin target?

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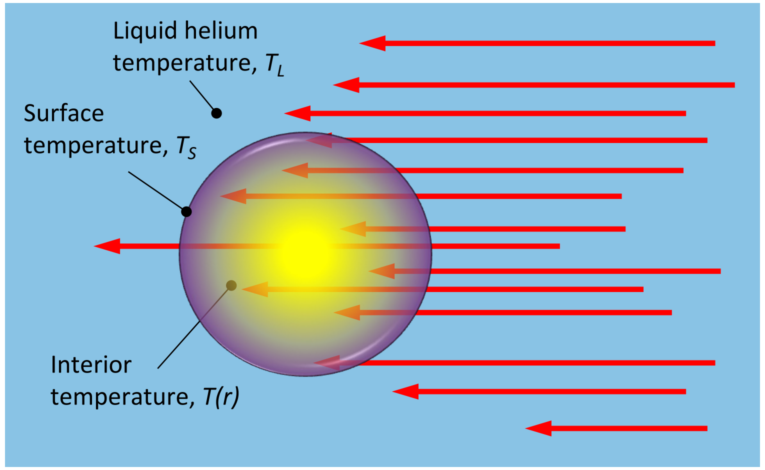

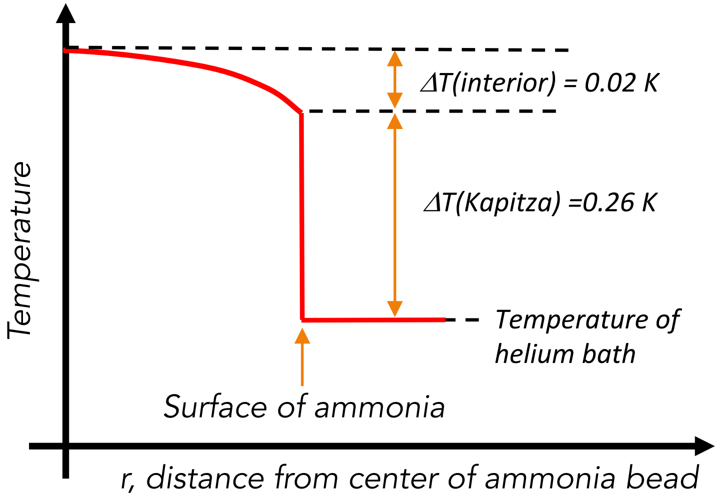

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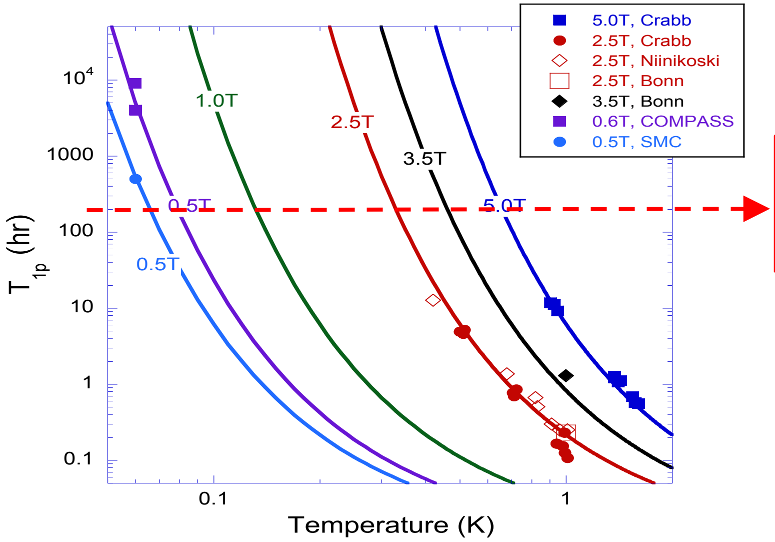
A simple calculation estimates the ammonia will be warmed ~0.28 K above the bath temperature.

The lowest temperature that can be expected is about 0.3 K.



Assume 200 hours is the minimum relaxation time for a useful target.

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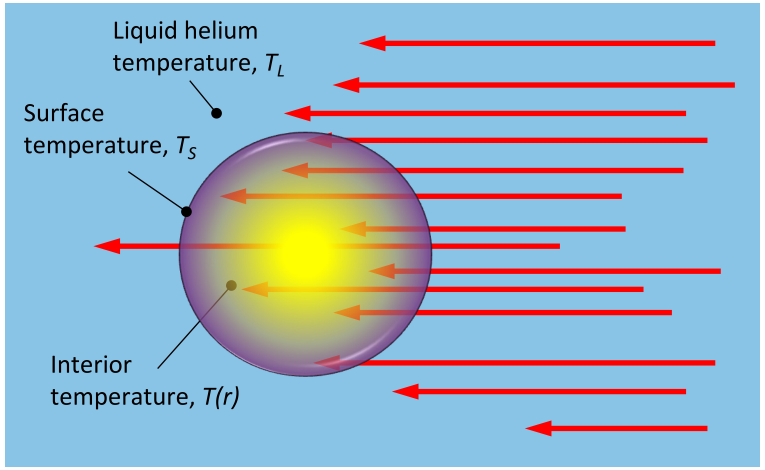

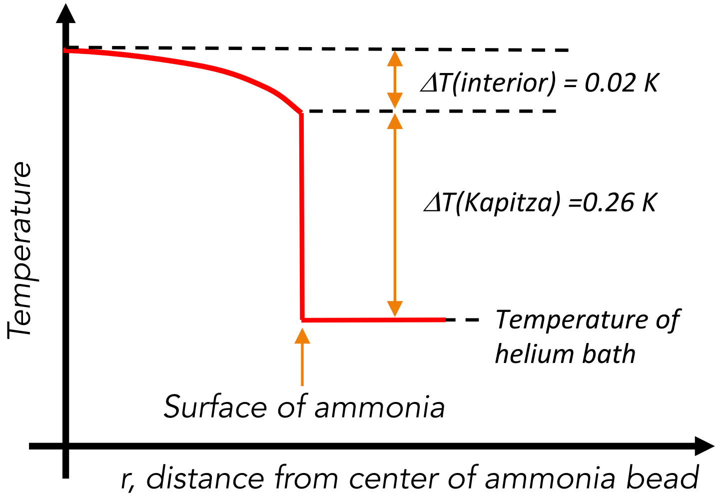

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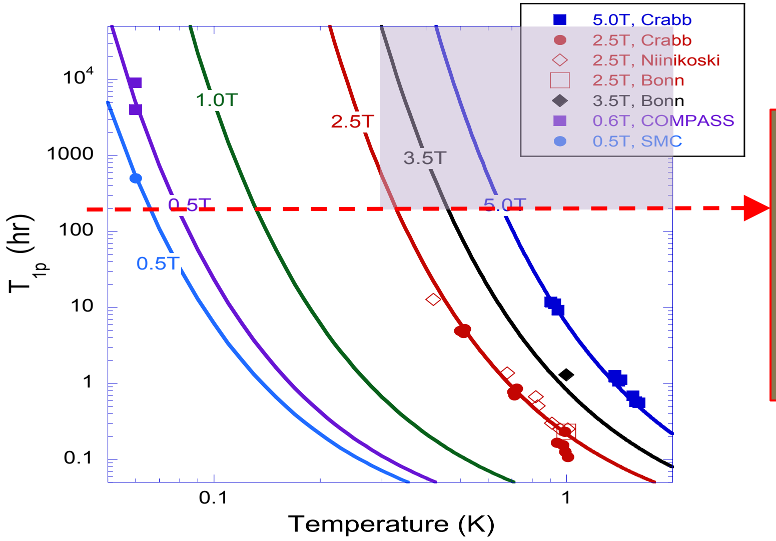
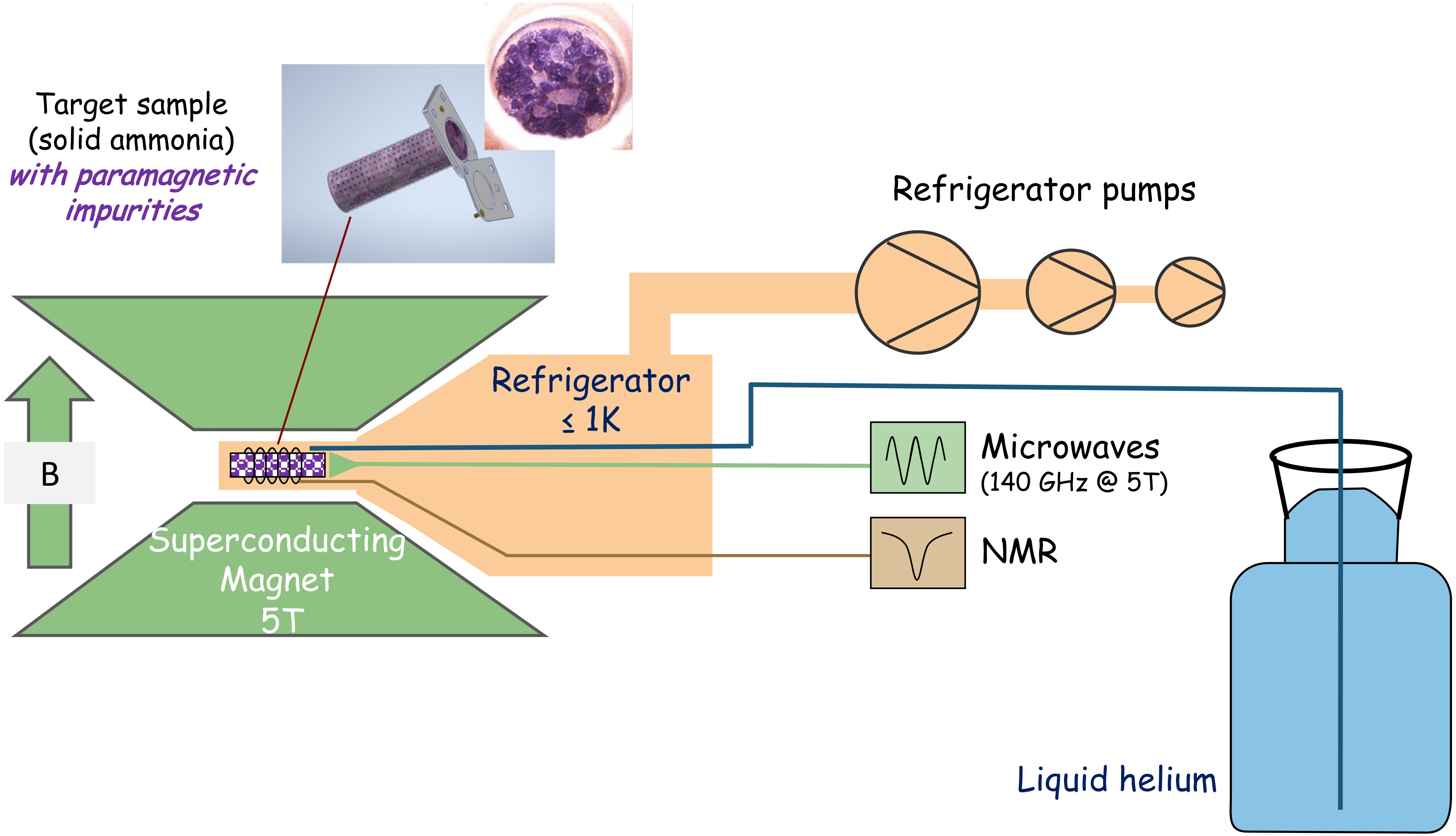


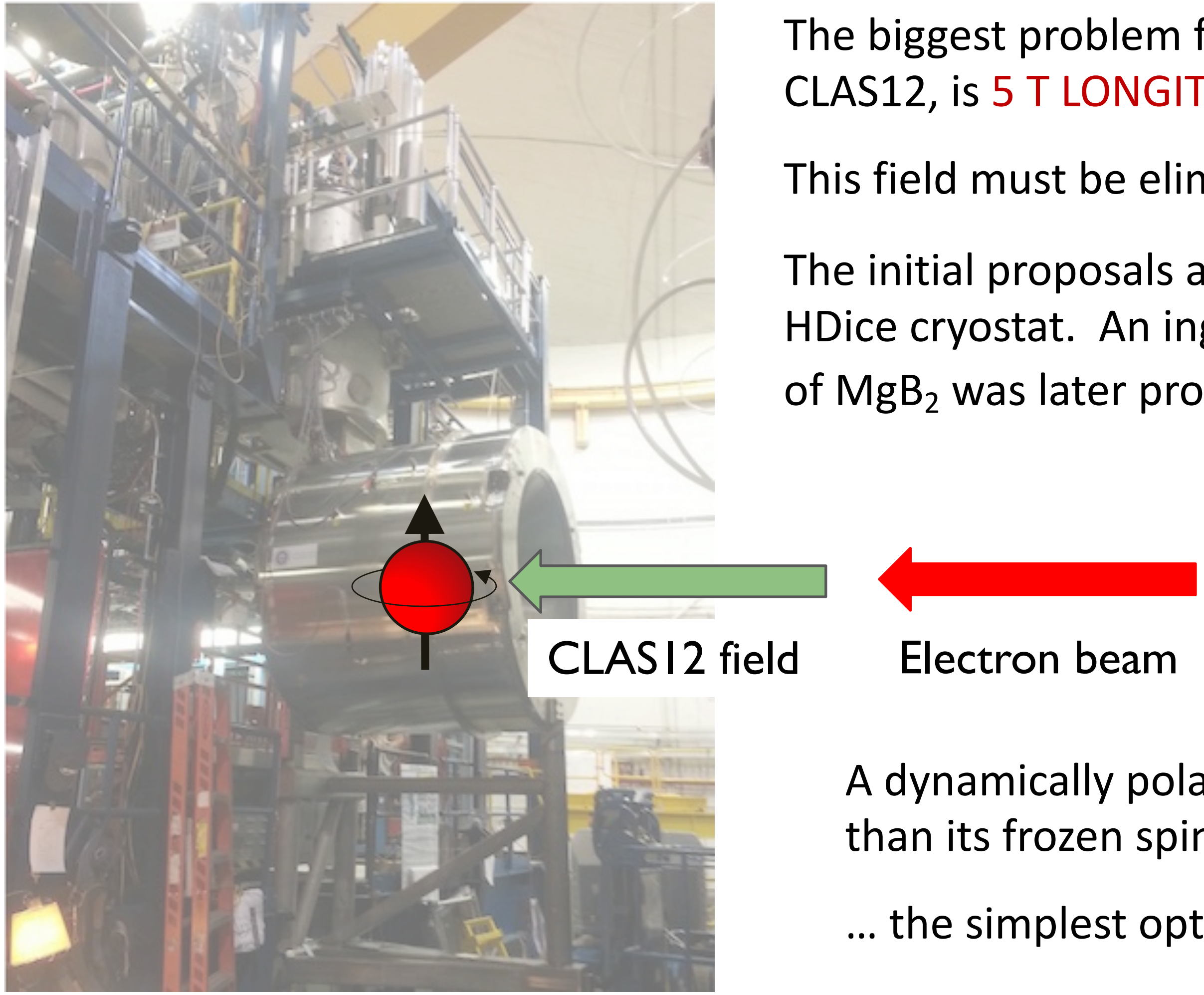
This means the holding field needs to be at least 2.5 T.

In that case, you might as well use the field to dynamically polarize the target on a continual basis!

Plan B: A dynamically polarized target



Plan B: A dynamically polarized target



The biggest problem for designing a transversely polarized target for CLAS12, is 5 T LONGITUDINAL magnetic field from the CLAS12 solenoid.

This field must be eliminated and a transverse field created in its place.

The initial proposals assumed a series of superconducting coils inside the HDice cryostat. An ingenious high-temperature superconducting shield of MgB_2 was later proposed but is still in the R&D stage.

A dynamically polarized target requires a higher and more uniform field than its frozen spin counterpart, sooo….

… the simplest option is to just remove the solenoid…

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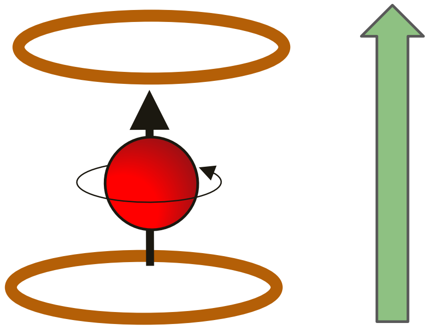


Target field

Electron beam

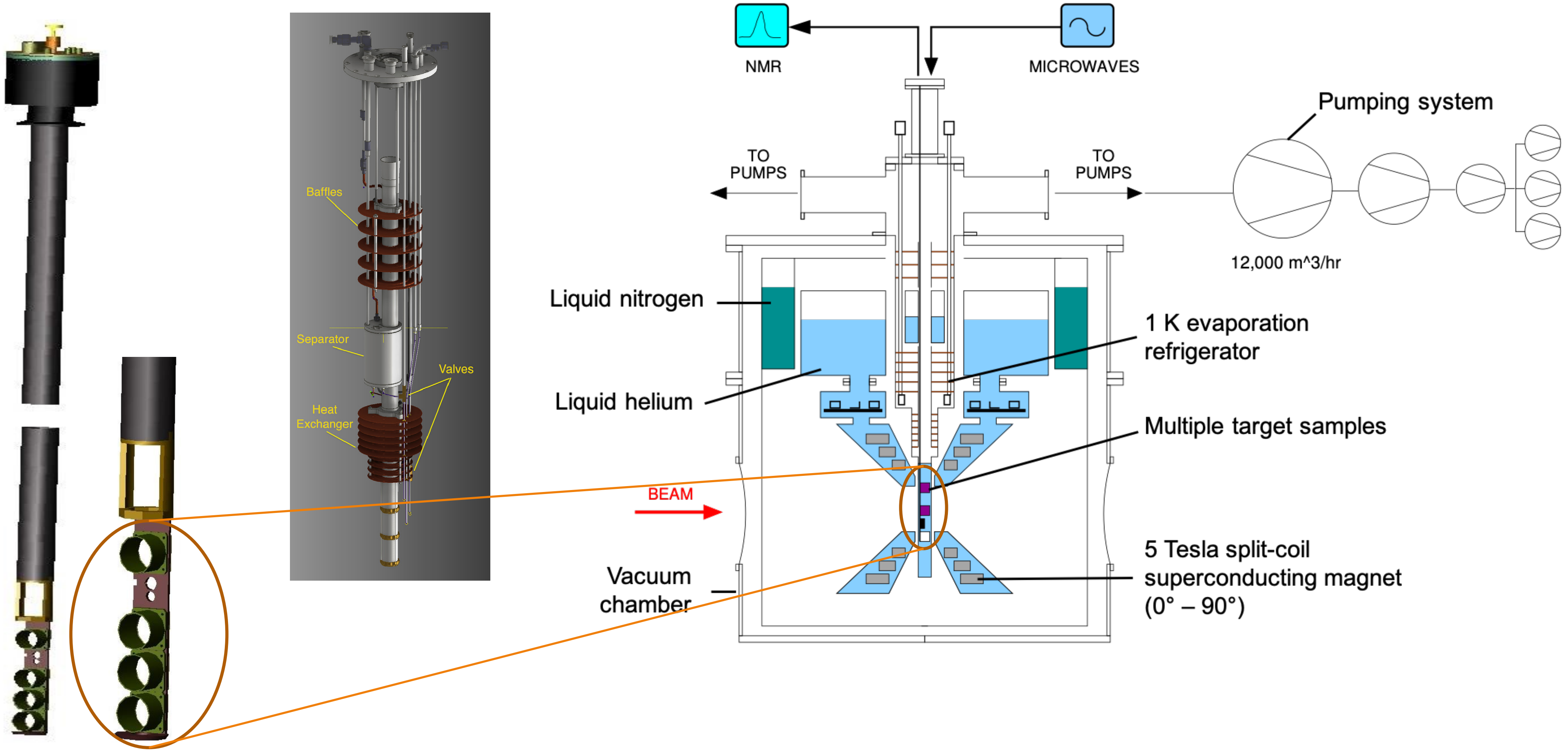
A dynamically polarized target requires a higher and more uniform field than its frozen spin counterpart, sooo….

… the simplest option is to just remove the solenoid…

… and replace it with a field dedicated to polarizing the target.

Plan B: A dynamically polarized target

The new, proposed, design looks like the standard 5T/1K dynamically polarized target already used in Halls A, B, & C.



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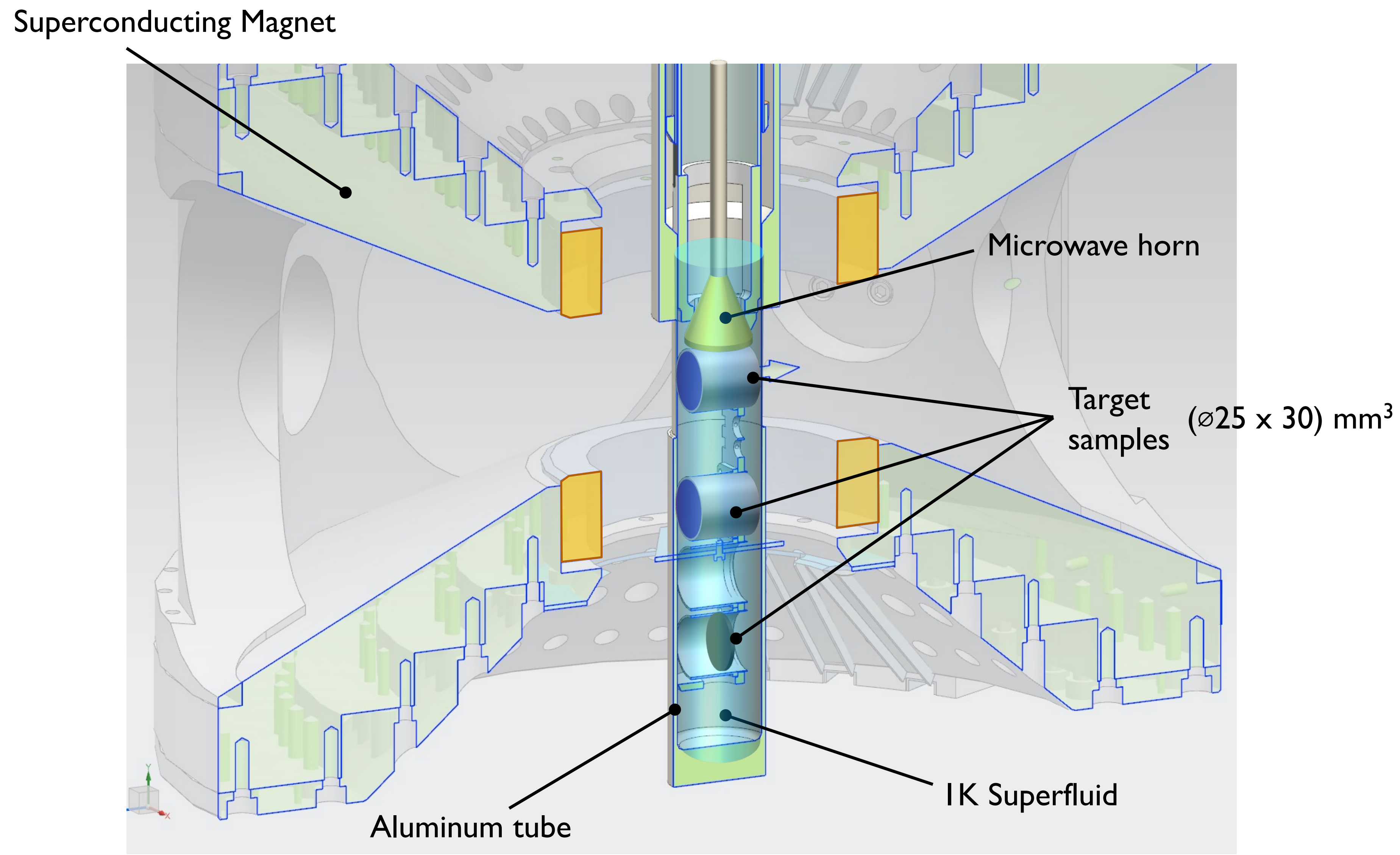

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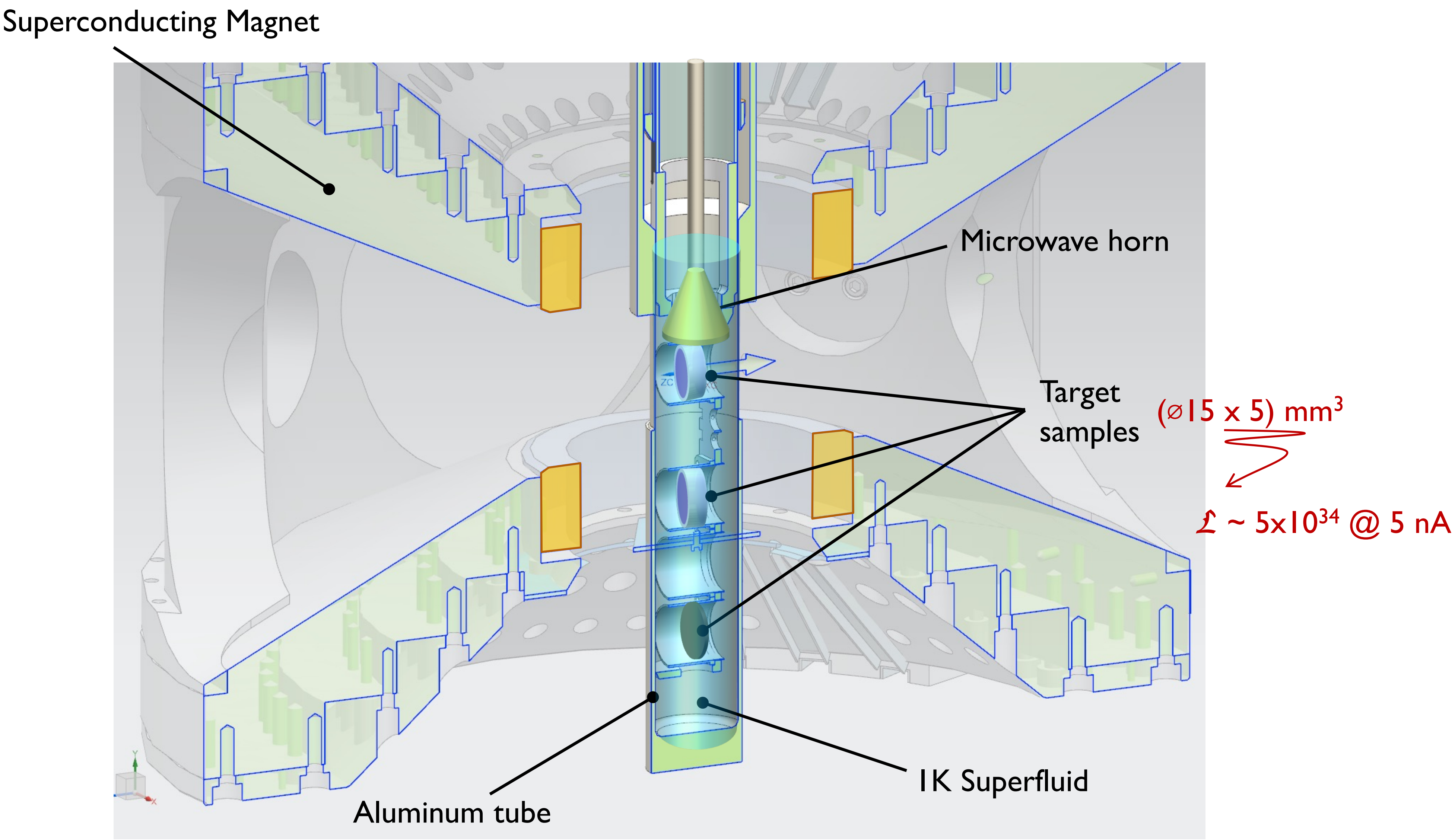
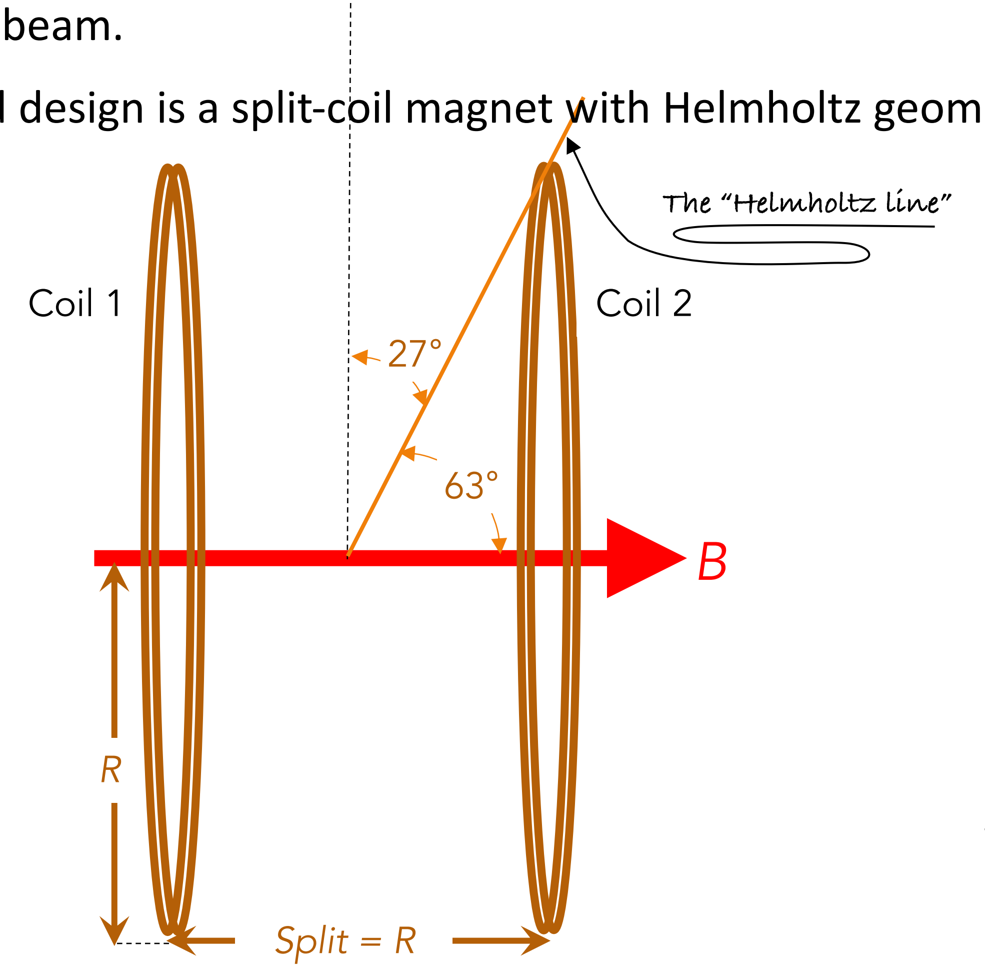
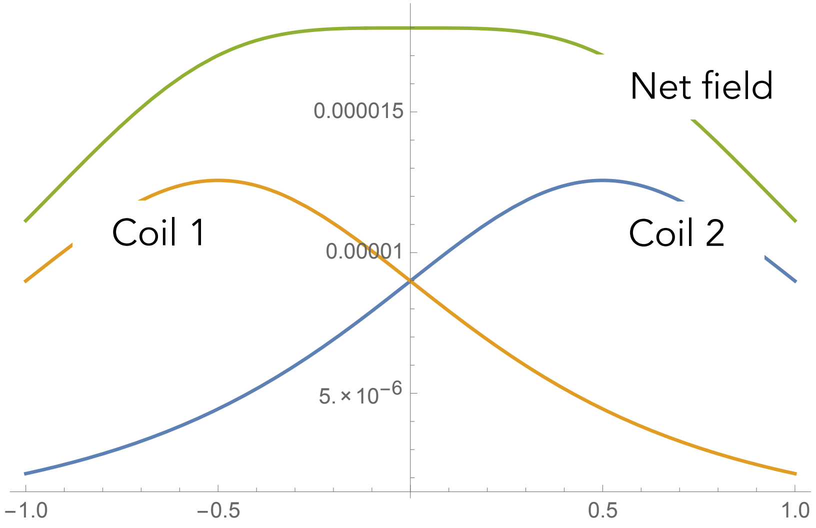


DNP requires the magnetic field around the target to be uniform to about 100 ppm or so.

This is easy to achieve with a solenoid, but this design doesn't work so well when the field is perpendicular to the electron beam.

The standard design is a split-coil magnet with Helmholtz geometry.

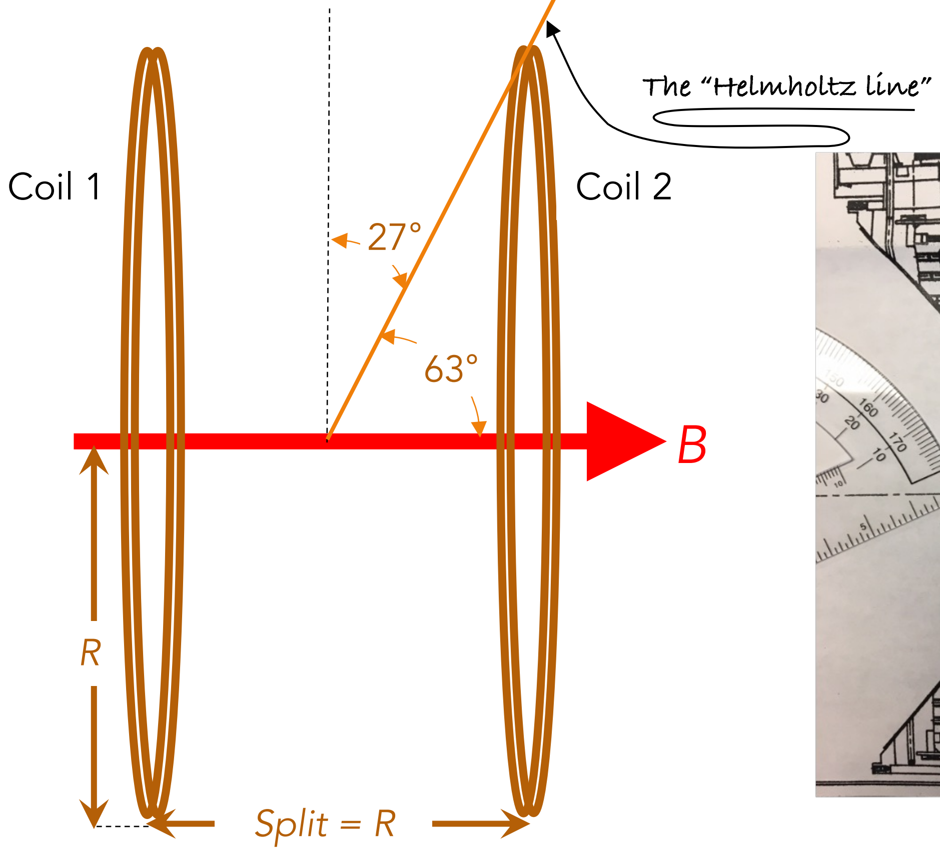


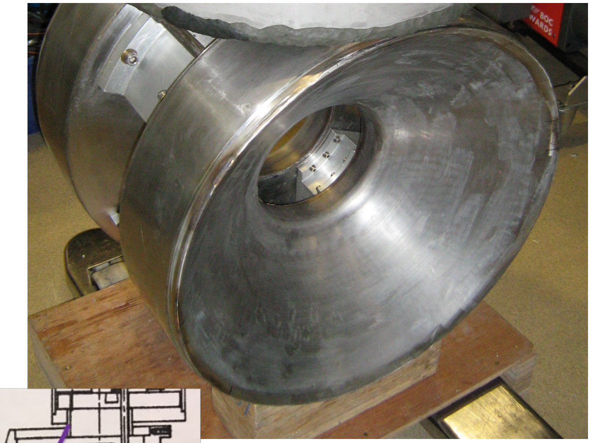


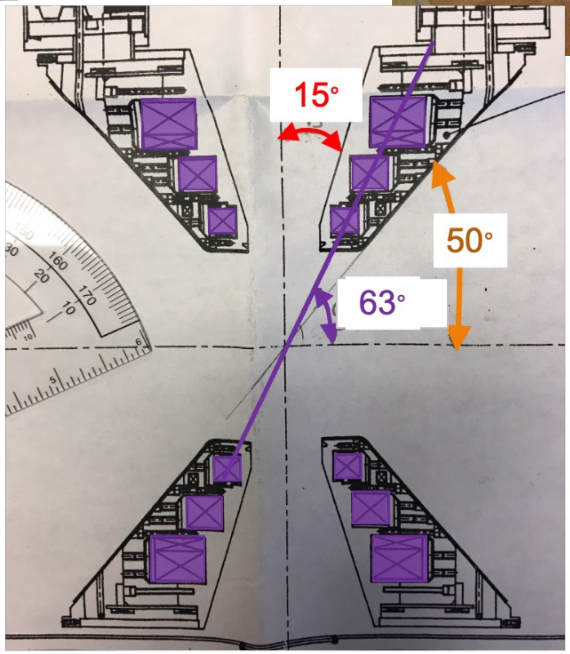
About that superconducting magnet

The magnets for the original targets in B & C had three sets of Helmholtz pairs, producing 5 T at the center.

The coil sizes and supports limited the scattering angles to ±50° along the field, and ±15° perpendicular to it.

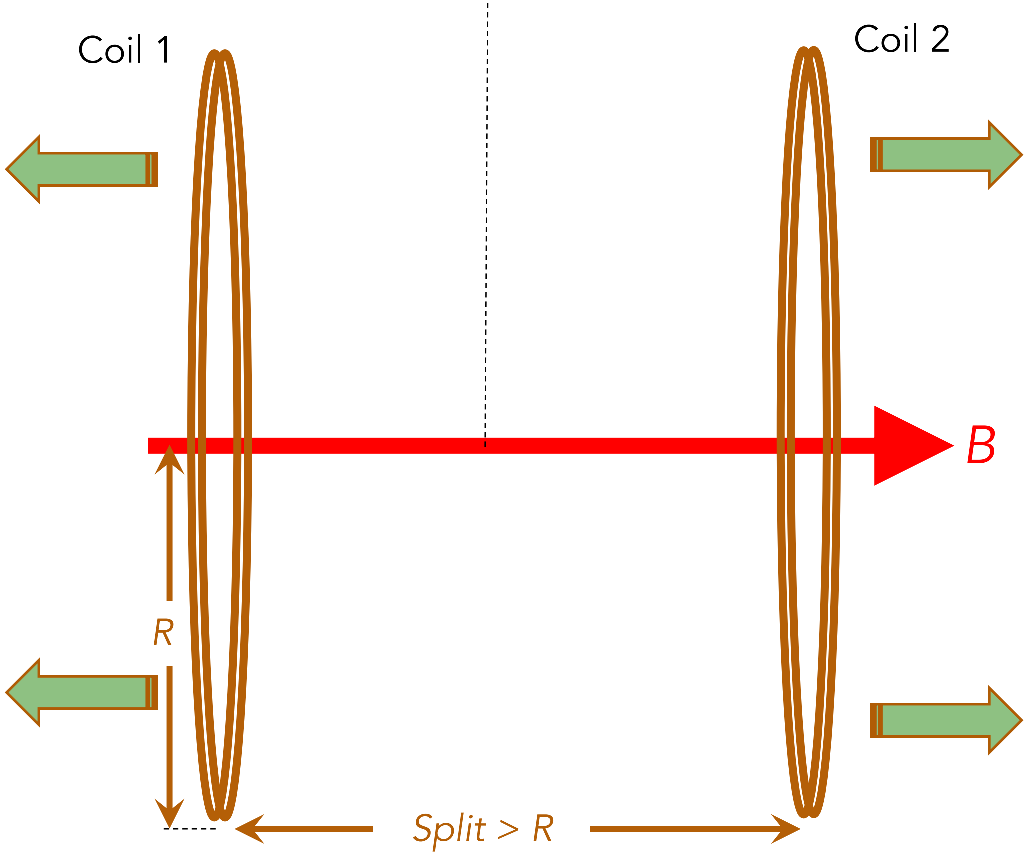




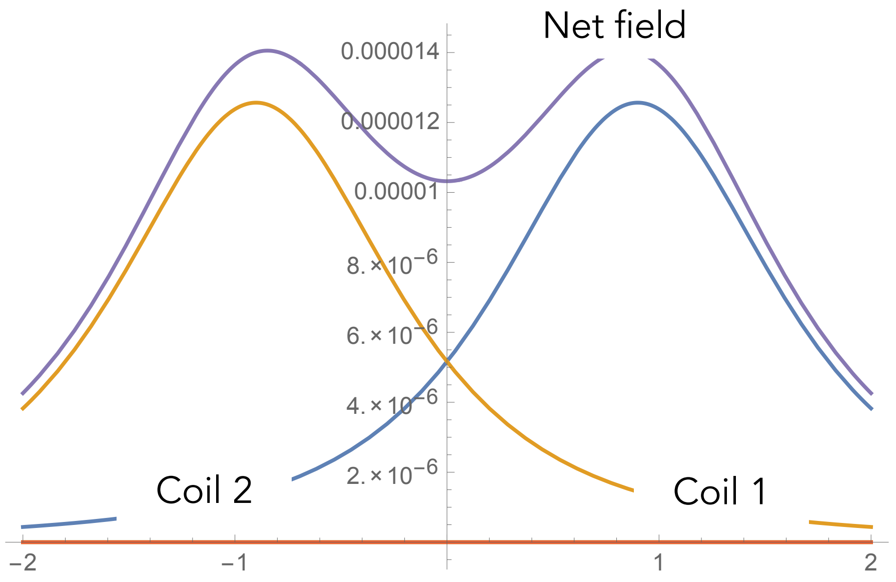


About that superconducting magnet

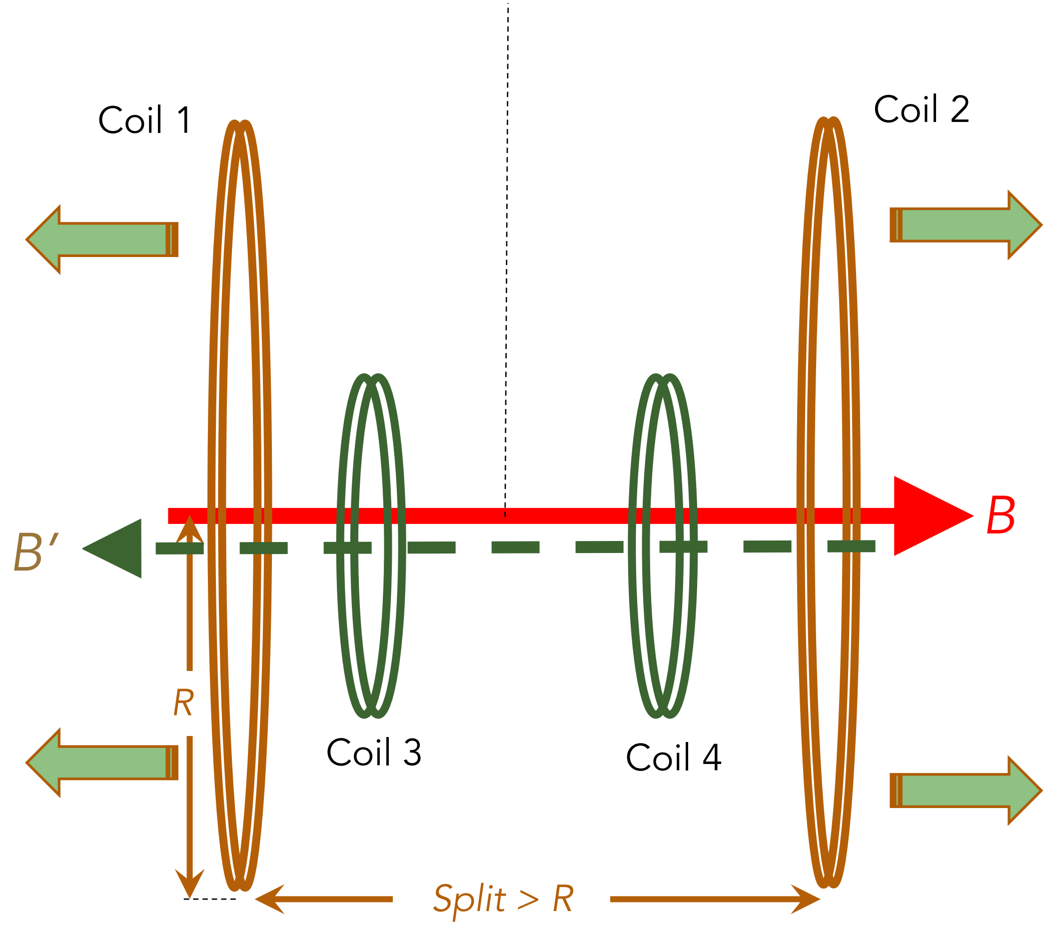
To increase the opening in the direction transverse to the field, the coils must be moved apart.

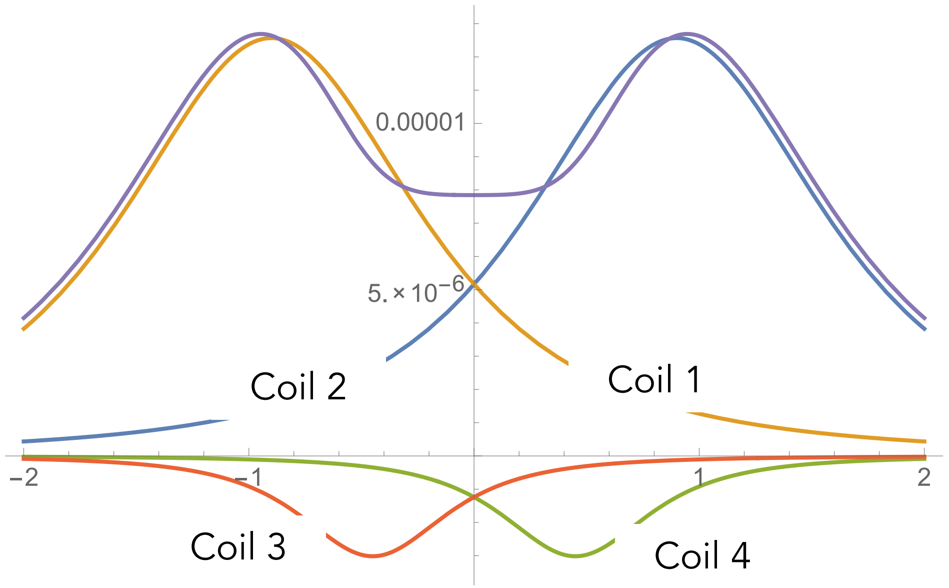


This produces a depression in the central field region.



Additional coils or ferromagnetic shims can further depress the central field and make it more uniform.

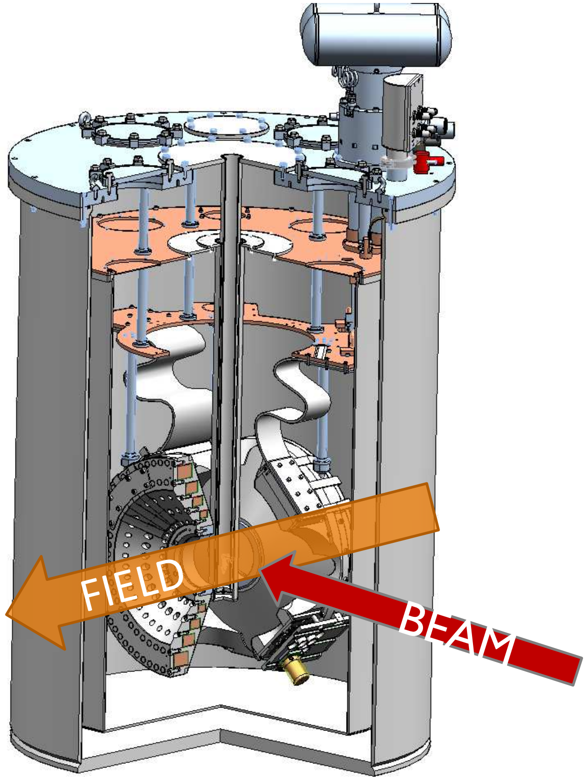




The field is now larger outside the central region.

About that superconducting magnet

SCIENTIFIC MAGNETICS
a MAGNETICA company



In 2019, I began procurement of a 5 T magnet with an increased opening for transversely polarized experiments in Hall C.

The opening angles for forward-scattered particles are
Longitudinal (field || to beam): ±35°
Transverse (field ⊥ to beam: ±25°

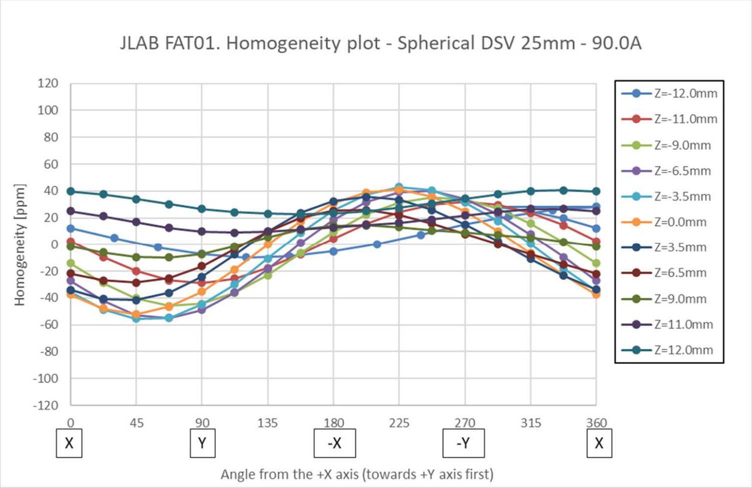


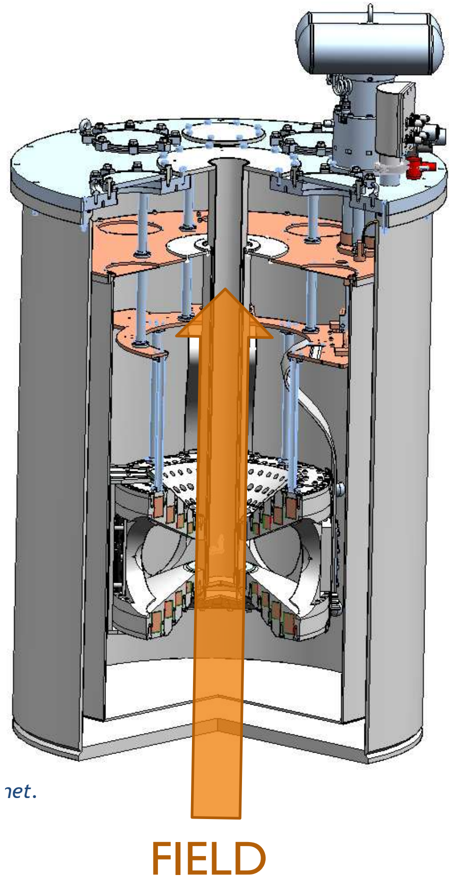
Figure 13: Plot of homogeneity on a 25mm DSV at 90.0A (max=43ppm, min=-55pm).

Homogeneity is ± 50 ppm over a 25 mm diameter spherical volume (DSV)

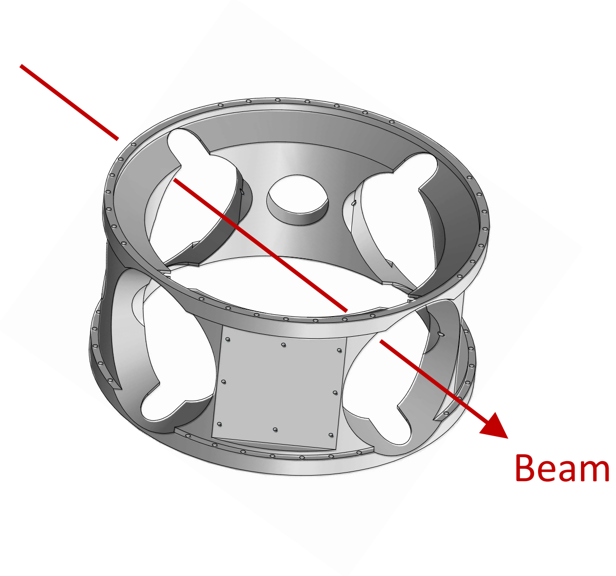
Received and tested at JLab in 2021

About that superconducting magnet

The magnet can also be oriented to produce a vertical field (preferred for Hall B), but the opening angle of ±25° is insufficient for the DVCS experiment.



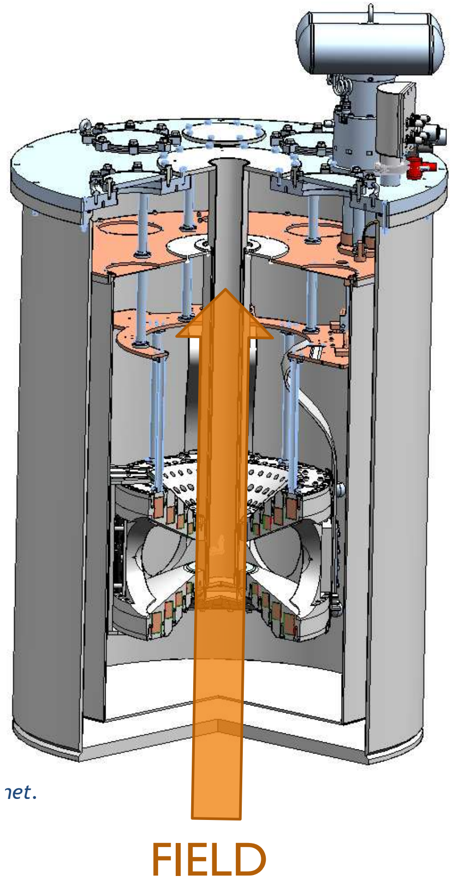
net.

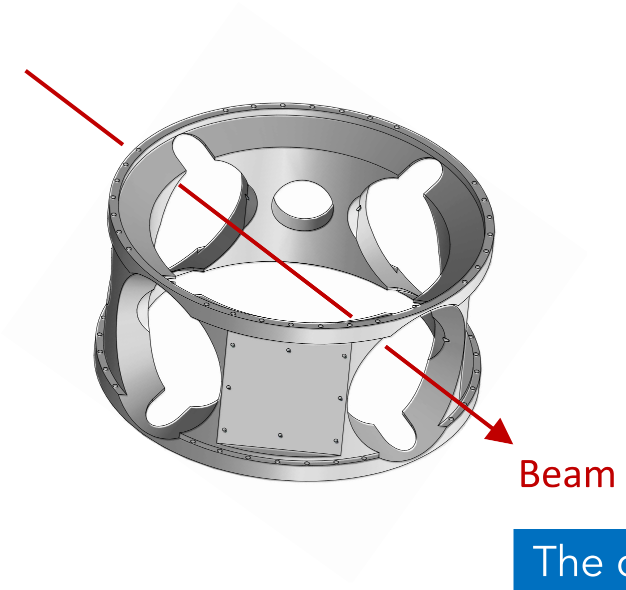


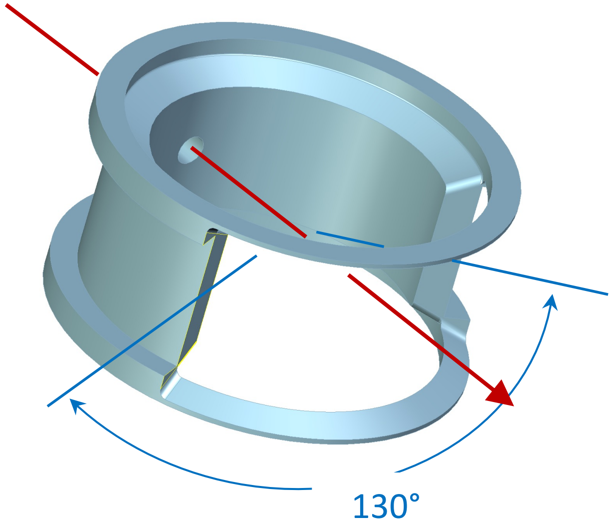
The aluminum ring separating the upper and lower sets of superconducting coils *(Cold Mass Intercoil Support)* has four large circular openings that limit the scattering angle to ±25° in both horizontal and vertical planes.

About that superconducting magnet

The magnet can also be oriented to produce a vertical field (preferred for Hall B), but the opening angle of ±25° is insufficient for the DVCS experiment.



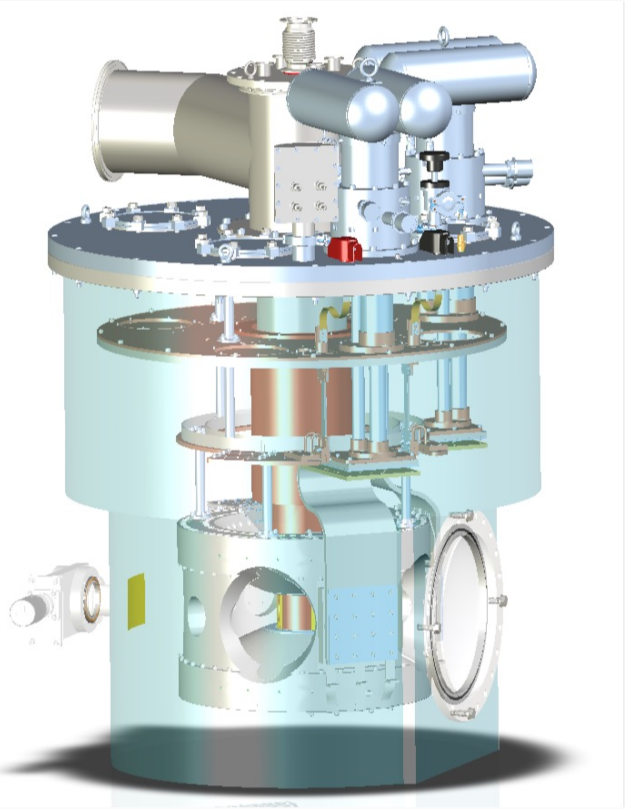


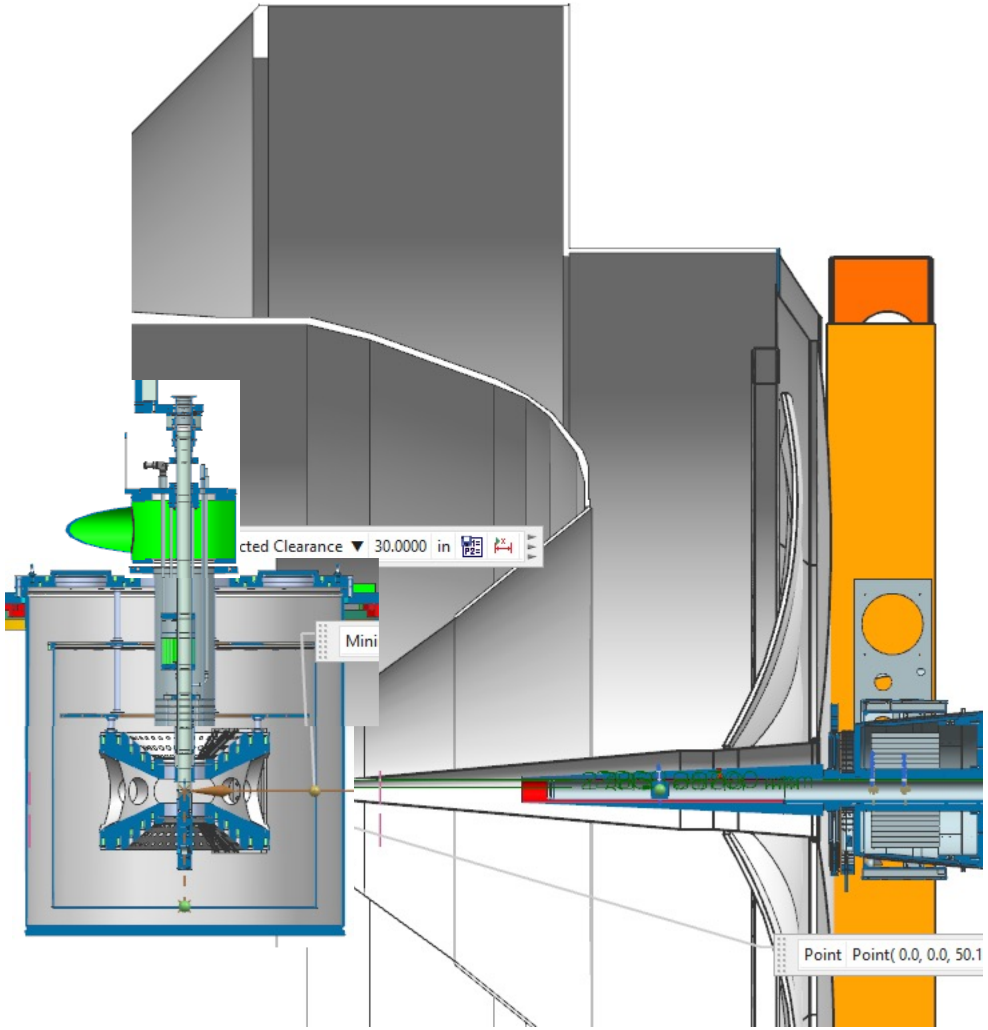


The current plan is to replace the existing magnet with an identical coils, but a support ring that gives ±25° in the vertical plane and ±65° in the horizontal.

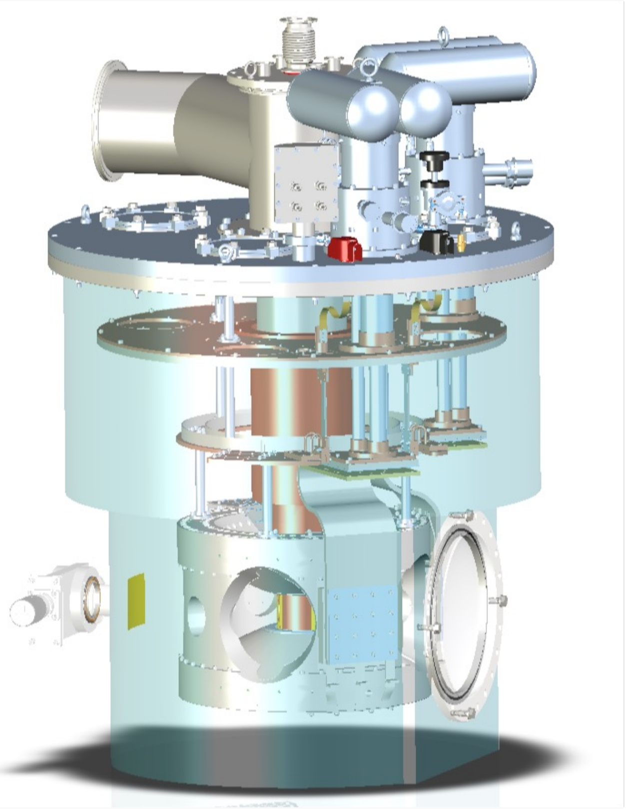
Conceptual design of the target

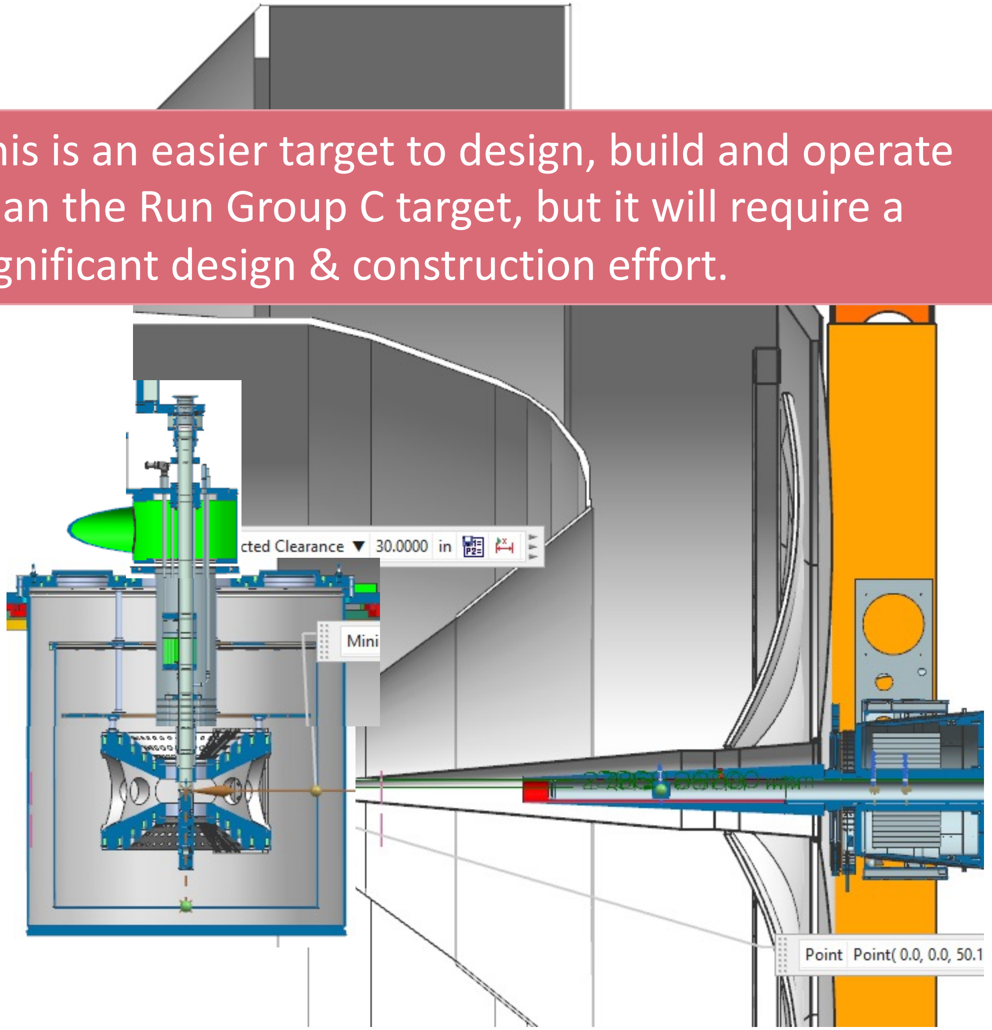
The target system must be substantially "compressed" in order to fit inside the HTCC, but it's probably possible.





The target system must be substantially "compressed" in order to fit inside the HTCC, but it's probably possible.





This is an easier target to design, build and operate than the Run Group C target, but it will require a significant design & construction effort.

- The Run Group H remains a compelling suite of experiments in Hall B
- The original idea to use a frozen-spin polarized target will not work
- An alternative approach, dynamically polarized NH_3 at 5T/1K is expected to work very well (albeit with compromised acceptance)
- A new magnet design is being pursued based on an existing system with a different Intercoil Support
- The goal is a design that provides ±25° vertical acceptance and ±65° horizontal
- Once the magnet issue is settled, the Target Group can commence work on the rest of the polarized target components

Instead of the Kapitza conductance κ, it is more common in the literature to quote the Kapitza *resistance* R_k

$$q = \kappa A(T_S^4 - T_L^4)$$

$$\rightarrow \quad q = 4\kappa A T^3 \Delta T$$
$$= \Delta T / R_k$$

Or, $$R_k A T^3 = \frac{1}{4\kappa}$$

Reasonable estimates of $R_k A T^3$ for solid ammonia vary 10 – 100 cm^{2}K^4/W

~70 cm^{2}K^4/W is the most probable
➔ κ = 3.6 mW/cm^{2}K^4

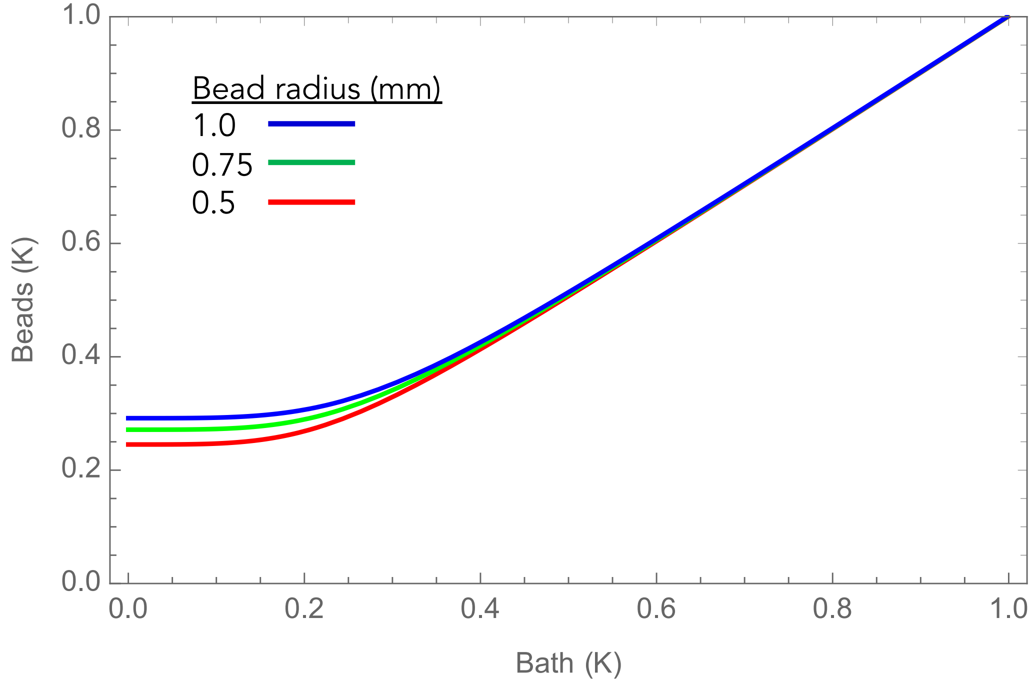
Values of $R_k AT^3$ for liquid helium and a variety of solids can be found in the literature. I will consider a number of sources to estimate the Kapitza conductivity between liquid helium and solid ammonia. These estimates vary by one order of magnitude, from about 10 to 100 cm^{2}K^4/W.

- In a paper describing an early frozen spin target, Niinikoski assumes a value $R_k AT^3 = 100$ cm^{2}K^4/W, "common for most light dielectric materials in helium" [2].
- A measurement between superfluid helium and mylar, a dielectric slightly denser than solid ammonia, reports $R_k AT^3 = 12.8$ cm^{2}K^4/W at 1.4–2.1 K [3]. A measurement for kapton reports $R_k AT^3 = 10.5$ cm^{2}K^4/W in the same temperature range [4].
- For temperatures below 100 mK, Pobell indicates values of 20–40 cm^{2}K^4/W between liquid helium and dielectrics such as teflon and kapton [5].
- Boyes *et al.* extracted both the Kapitza and bulk thermal resistances of butanol at 1.08 K using microwaves to heat samples of various sized beads and determining the average bead temperature from the measured spin-relaxation time. A value $R_k AT^3 = 74 \pm 35$ cm^2 K^4/W was reported [6].
- The Bonn polarized target group measured the temperature difference between superfluid helium and NH_3 with electron beam currents up to 70 nA [7]. The temperature of the 1.5 mm target granules was determined from their thermal equilibrium polarization at 2.5 T. My simple analysis of the results indicates $R_k AT^3 \approx 80$ cm^{2}K^4/W.
- Modeling the temperature of NH_3 in the COMPASS polarized target, Doshita assumes a value $R_k AT^3 = 50$ cm^{2}K^4/W, based on the Kapitza resistance of CrK crystals in liquid helium at low temperatures [8].
- The KEK frozen spin target of 1,2-propanediol was utilized on multiple occasions with 650–1200 MeV proton beams. By comparing the polarization lifetime with beam on and beam off, Ishimoto et al extracted a value $R_k AT^3 = 70 \pm 7$ cm^{2}K^4/W [9].

C.D. Keith, "eFROST" (2008) unpublished

Beam Heating

Smaller beads help a little (larger surface-to-volume).



If the target is exposed to ionizing radiation, the rate of polarization loss *will not be constant.*

Instead, the rate will increase in proportion to the dose (particles/cm^2) on the target:

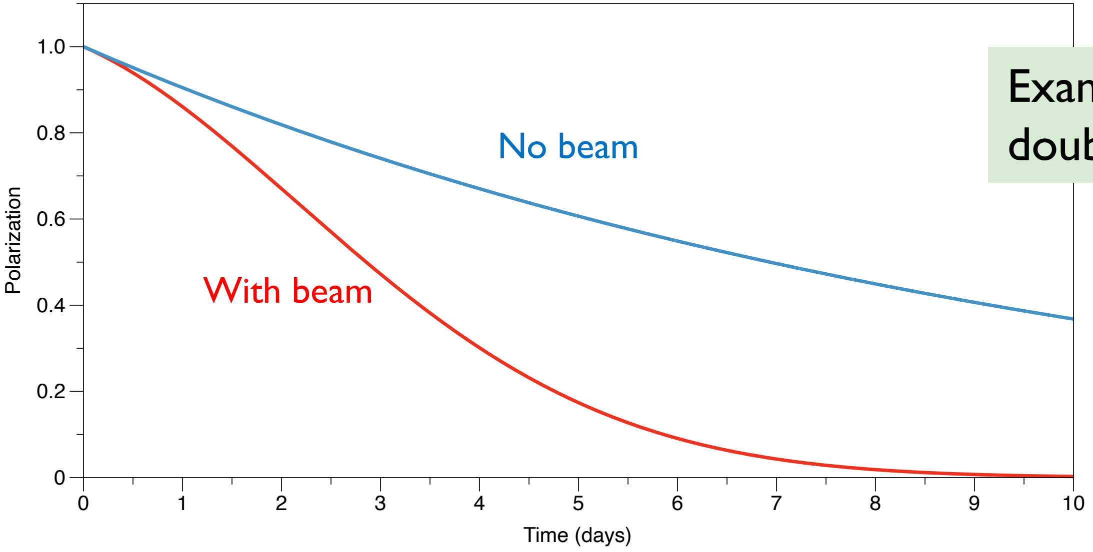
$$R_1 = a \cdot \text{dose}$$

Assuming a constant beam current, this will add a linear time dependence to the relaxation rate:

$$R_1(t) = R_1(0) + bt$$

and a quadratic term to the relaxation curve

$$P(t) = P_o \exp(-R_1(0)t - bt^2)$$



Example: The initial decay rate doubles after 2 days

Brute-force Polarization of Solid HD in 5 easy steps

1. HD gas is highly purified to remove all impurities, including molecular H_2 and D_2
2. A small quantity of *ortho*-H_2 is added to the gas to promote fast spin relaxation
3. The gas is frozen and brute-force polarized at an ultra-low temperature and high magnetic field
4. Wait (and wait and wait…) until the paramagnetic ortho-H_2 has converted to the nonmagnetic *para*-H_2
5. Transfer frozen-spin polarized sample into an “in-beam” cryostat at start taking data