A Polarized Target in Hall D:
Design & Capabilities

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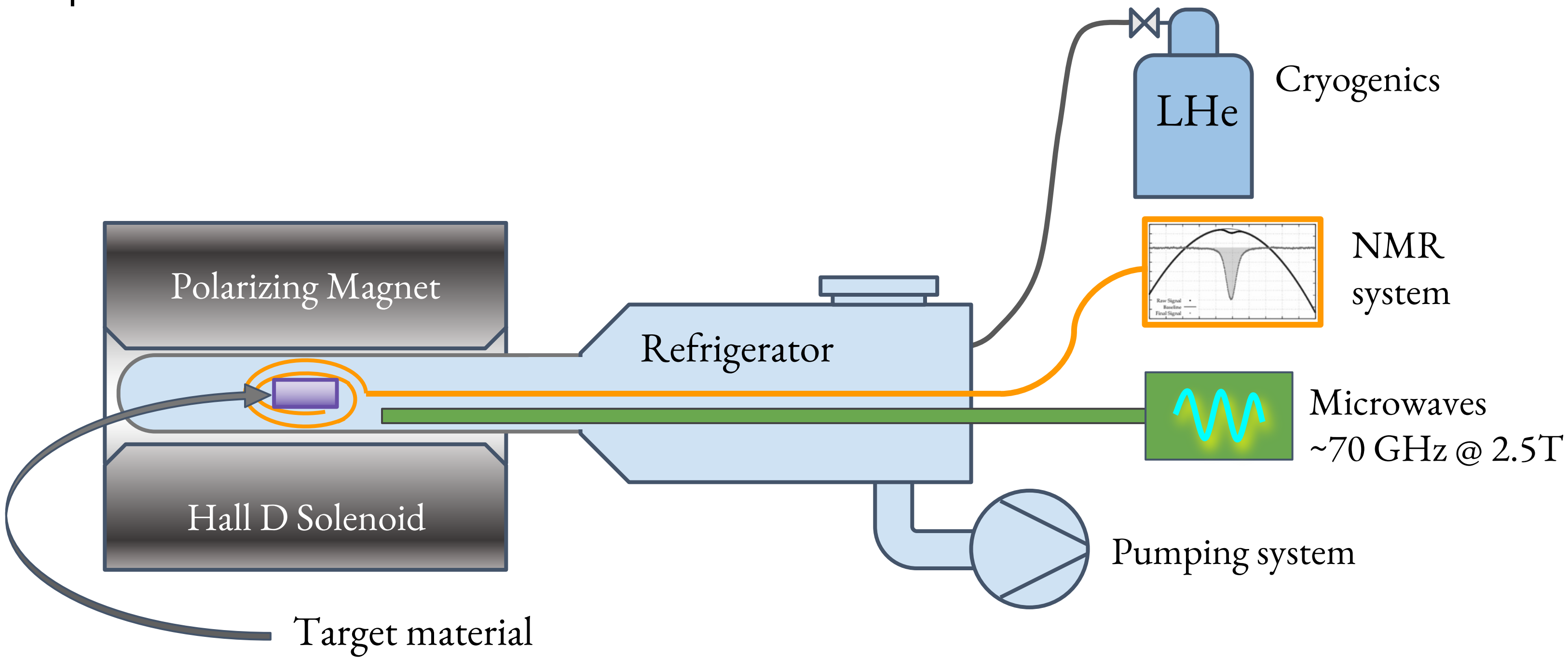
Dynamic Nuclear Polarization

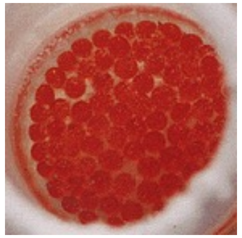
- Implant unpaired electrons in target sample
- Polarize electrons at high *B*, low *T*
- Use microwaves to transfer electron polarization to nuclear spins
- Measure polarization with NMR

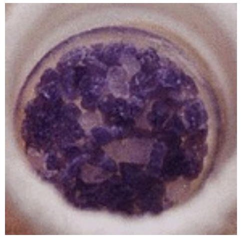


A DNP target sample has two components:

- A solid, dielectric matrix containing the nuclear spin of interest (ammonia, butanol, LiH, CaF, …)
- A persistent radical that provides an unpaired electron spins

The sample is usually in mm-sized granular form and immersed in superfluid for optimum heat transfer





Material Dil. Factor (%) Polarization (%)	Butanol, C_4H_9OH 13.5 > 90%	Ammonia, NH_3 17.7 > 90%	Lithium hydride, ^7LiH 25.0 90%
Material Dil. Factor (%) Polarization (%)	D-Butanol, C_4D_9OD 23.8 > 80%	D-Ammonia, ND_3 30.0 50%	Lithium deuteride, ^6LiD 50.0 55%
Doping method Rad. resistance	Chemical moderate	Radiation high	Radiation extremely high
Comments	*Easy to produce and handle*	*Works well at 5T and 1K*	*Slow polarization, long relaxation*

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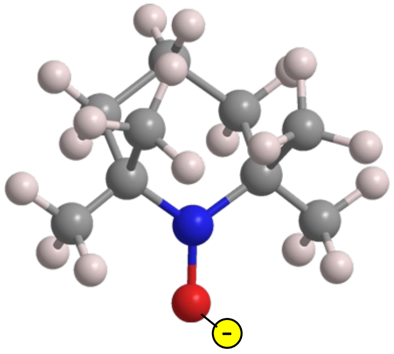
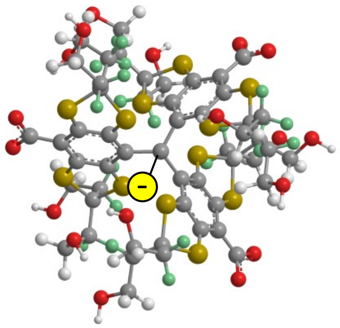


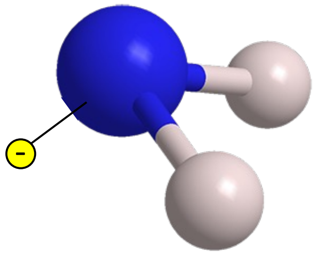
The TEMPO radical

- Soluble in alcohols and diols
- Polarizes protons well



The Trityl radical(s)

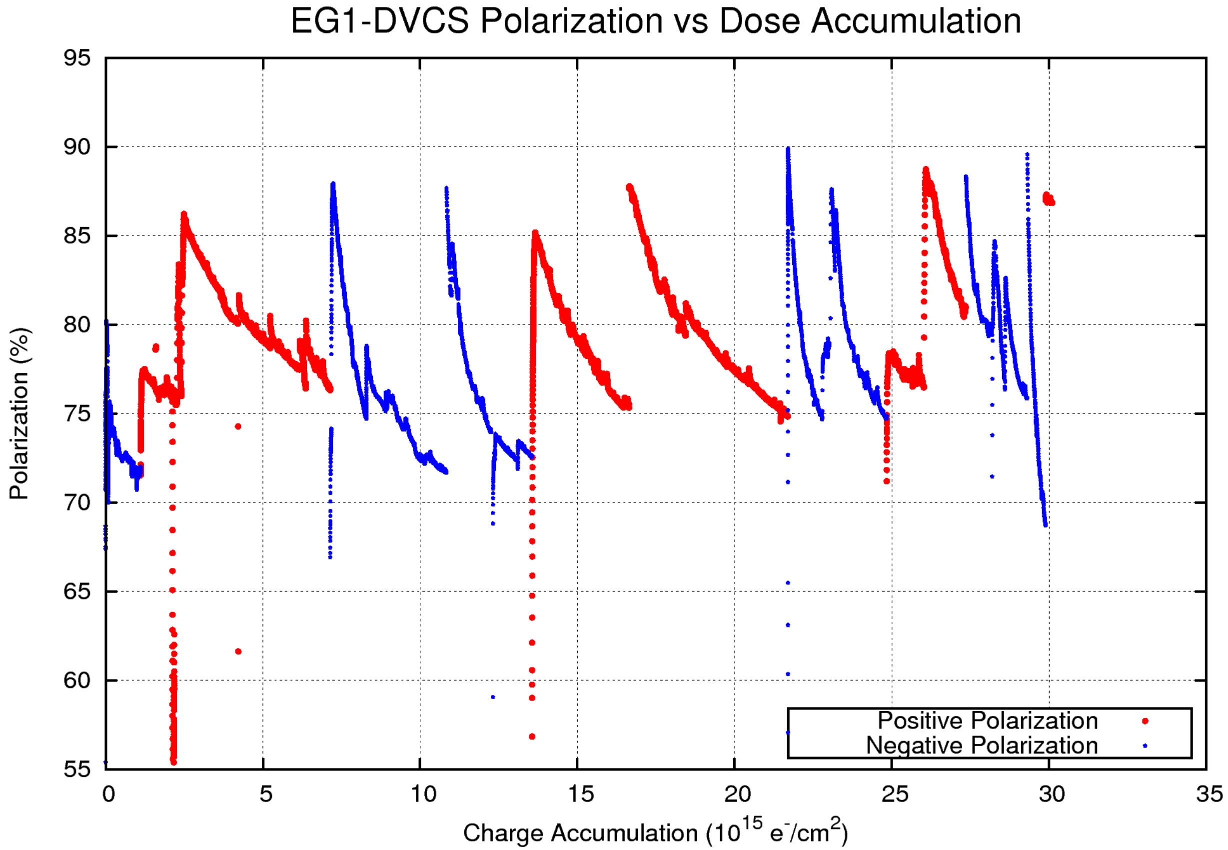
- Possess a very narrow EPR line
- Good for polarizing low-γ nuclei (^{2}H, ^{13}C…)



The Amine radical (NH_2)

- Produced by irradiating solid ammonia at cryogenic temperatures

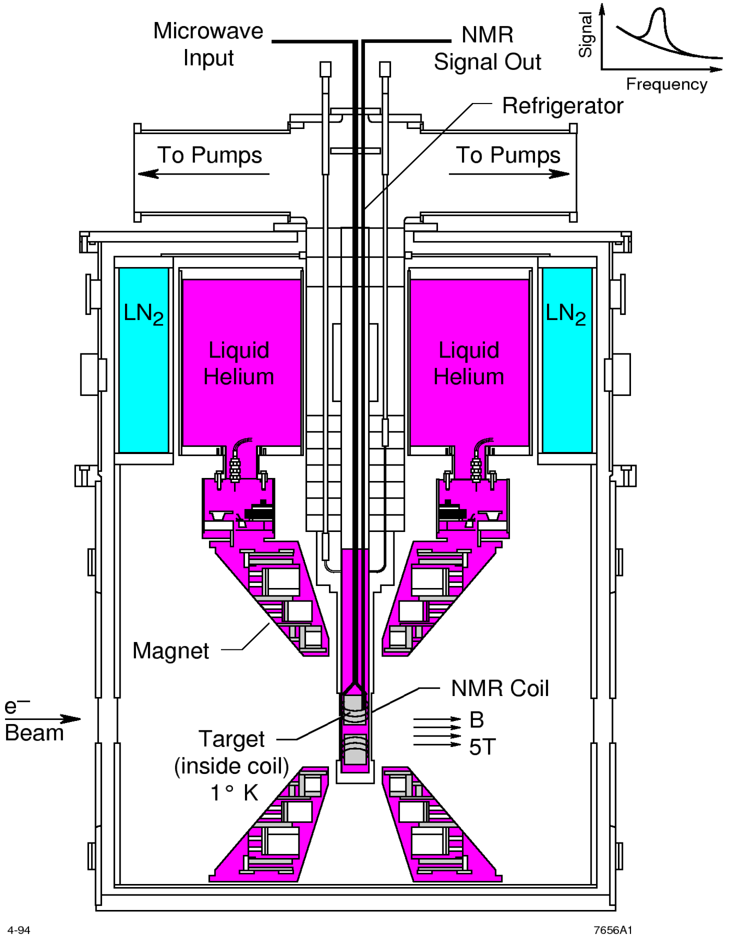
Ionizing radiation can damage the radical and/or produce unwanted radicals that destroy the polarization → **Radiation Damage**

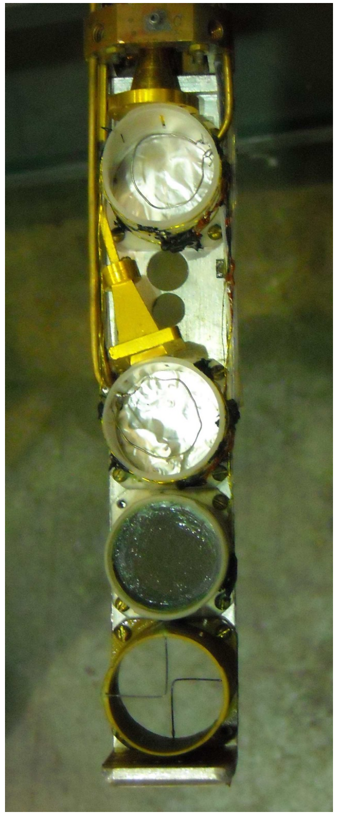


Warming the sample to about 100 K for several minutes (annealing) can restore the polarization.

Continuously Polarized Targets

DNP Targets can operate up to $\gtrsim 10^{12}$ particles s^{-1} cm^{-2} *if the microwaves stay ON*





For electron beam experiments in Halls A, B, & C our targets utilize irradiated NH_3 and ND_3 that are polarized at 5 T & 1 K

- Rad-hard
- "High" cooling power
- "Easy" operation

Proton pol. > 90%

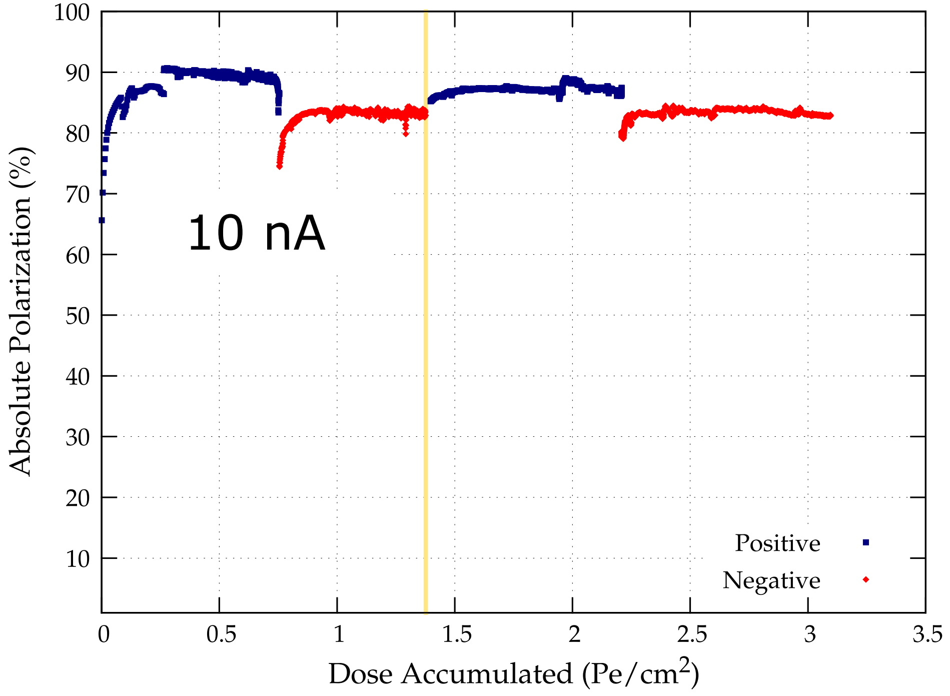
Deuteron pol. > 40%

1 K Polarizations are much worse at 2.5 T

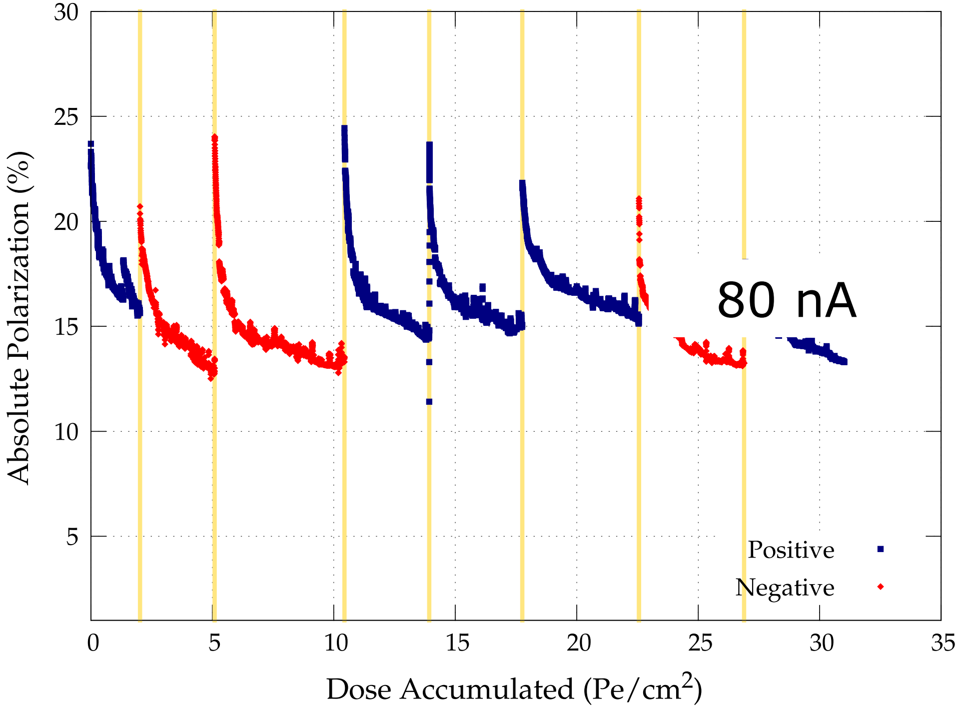
Data from g2p/GpE experiments in Hall A (2012)

J. Pierce et al. NIM A 738 (2014) 54.

Proton polarization @ 1 K, 5 T



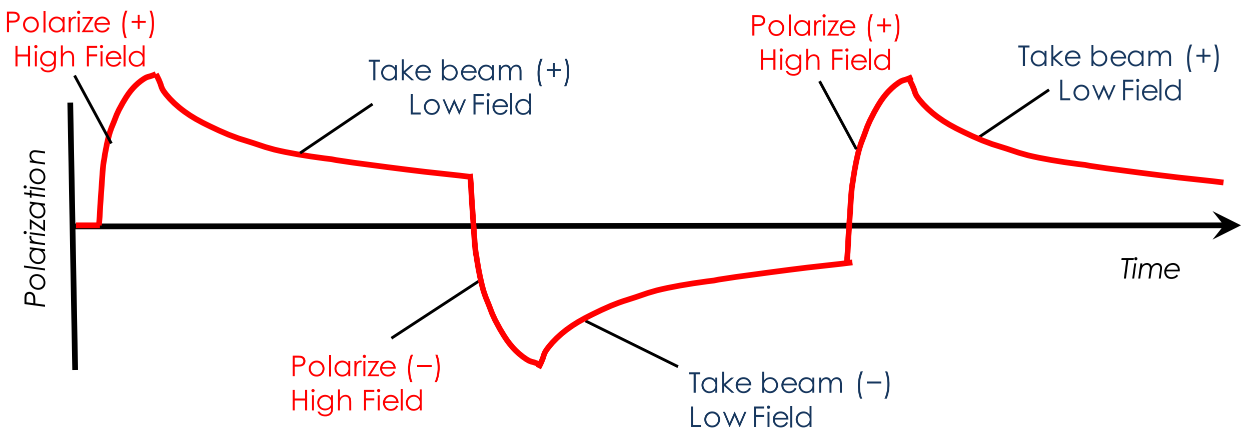
Proton polarization @ 1 K, 2.5 T



Solution: Polarize at T < 1 K (^3He-^4He dilution refrigerator)

2.5 T & 0.3 K is "standard" for low-intensity beams & Frozen Spin Targets

Frozen Spin targets are primarily used with low-intensity, secondary beam and high acceptance detectors.

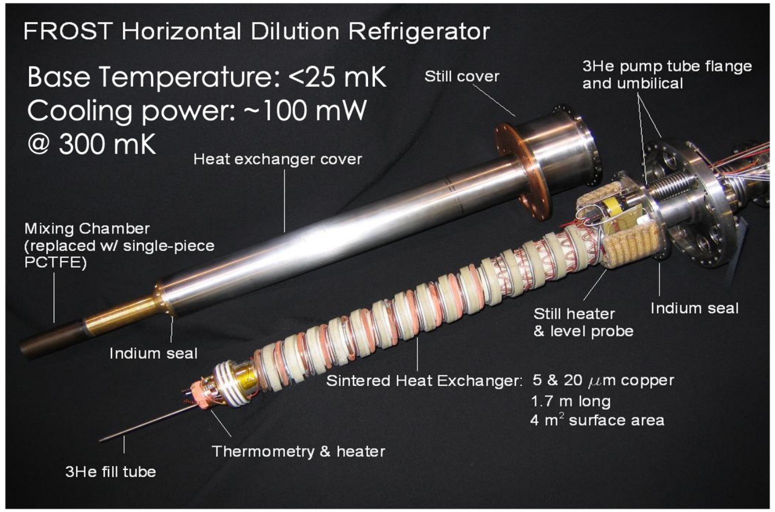


The target sample must be cooled to an ultra-low temperature ≳50 mK to maintain its polarization without the microwaves.

Beam-heating and radiation damage limit the beam intensity for heavily ionizing particles to about 10^8 s^{-1} cm^{-2}

FROST, Hall B 2007

- Polarize outside CLAS, 0.3 K & 5 T
- Take beam inside CLAS, 0.03 K & 0.5 T
- Proton Pol: 90%
- Deuteron Pol: -87%
- Relaxation time: 2000-4000 hr

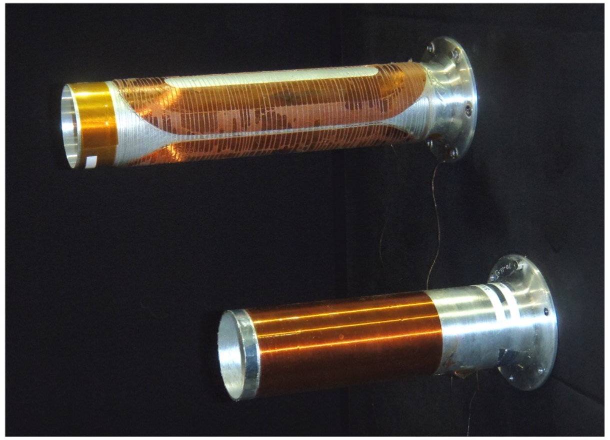


<u>FROST ^{3}He-^{4}He dilution refrigerator</u>

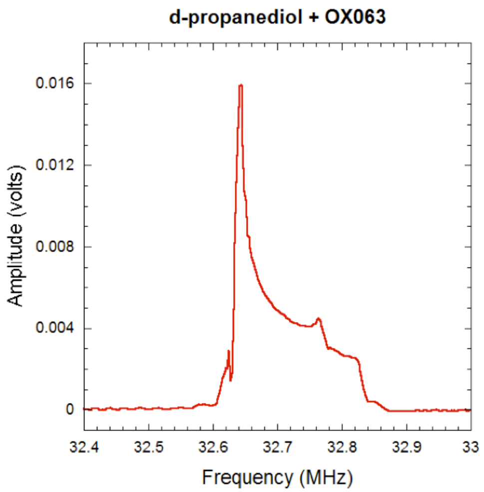
base temperature: < 25mK

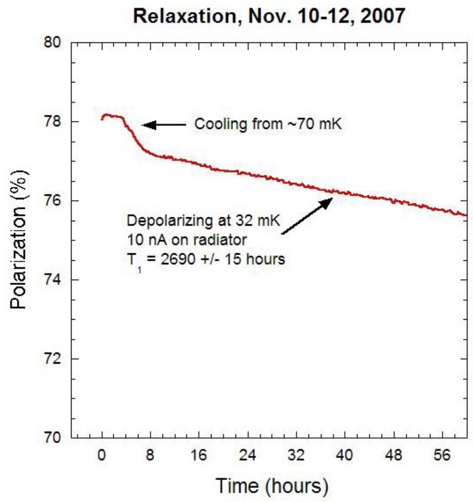
cooling power: 0.1 W @ 0.3 K

FROST Polarizing Solenoid, 5 T



FROST Holding Coils, 0.5 – 0.6 T





Q: Which target is best for Hall D, Continuously Polarized or Frozen Spin?

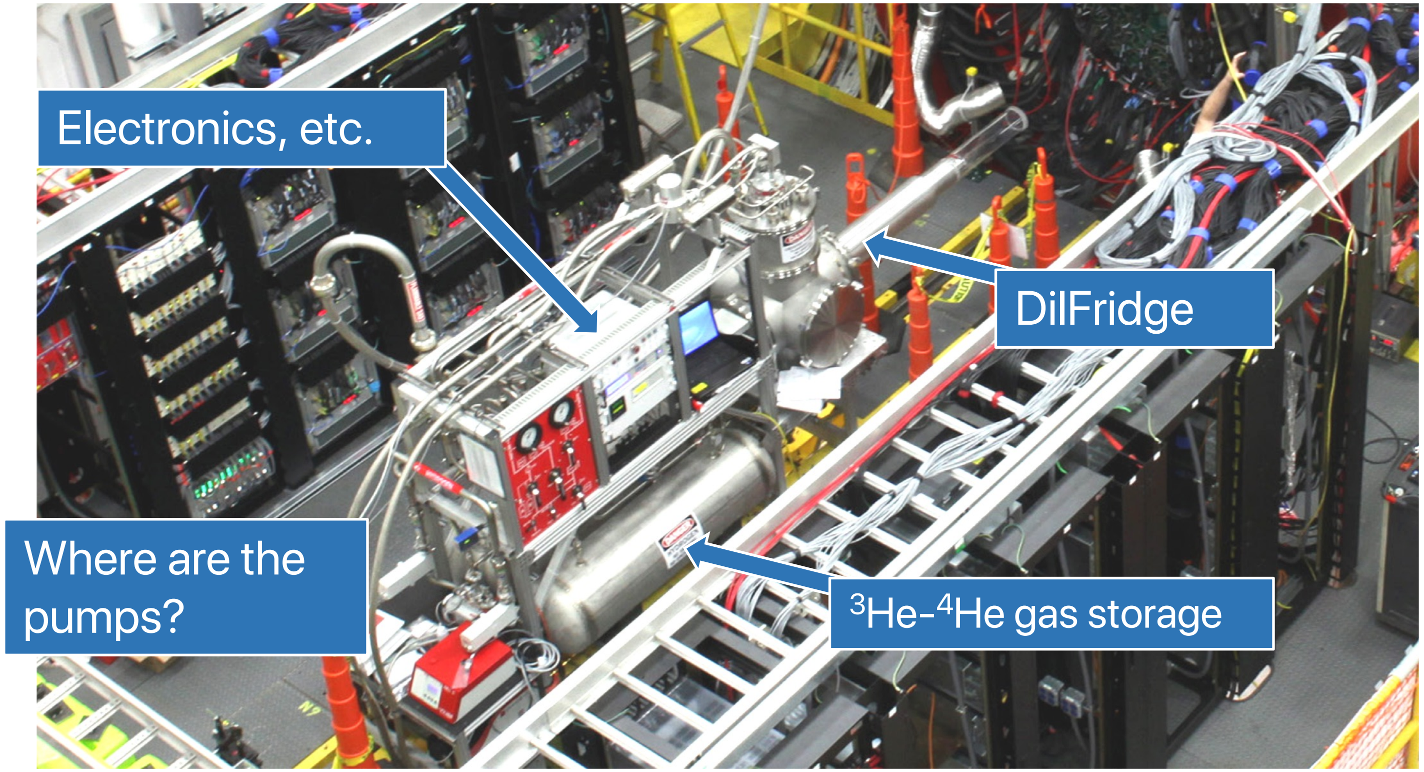
A: Both!

I propose a dynamically polarized target very similar to FROST.

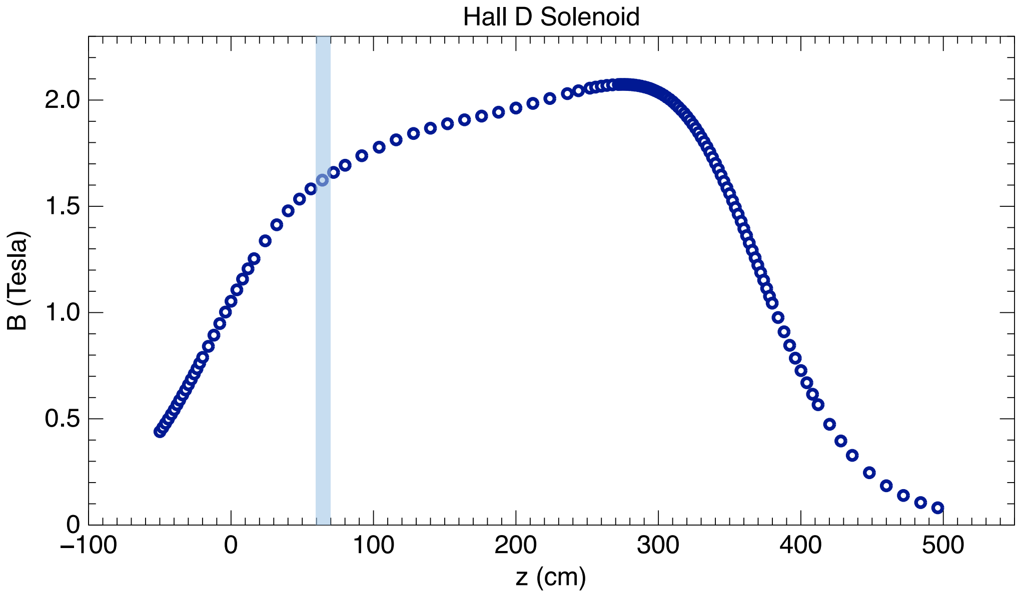
- A high cooling power dilution refrigerator to polarize samples inside the 2.5 T field of the Hall D solenoid
  - Polarize up to 20 cm^3 target

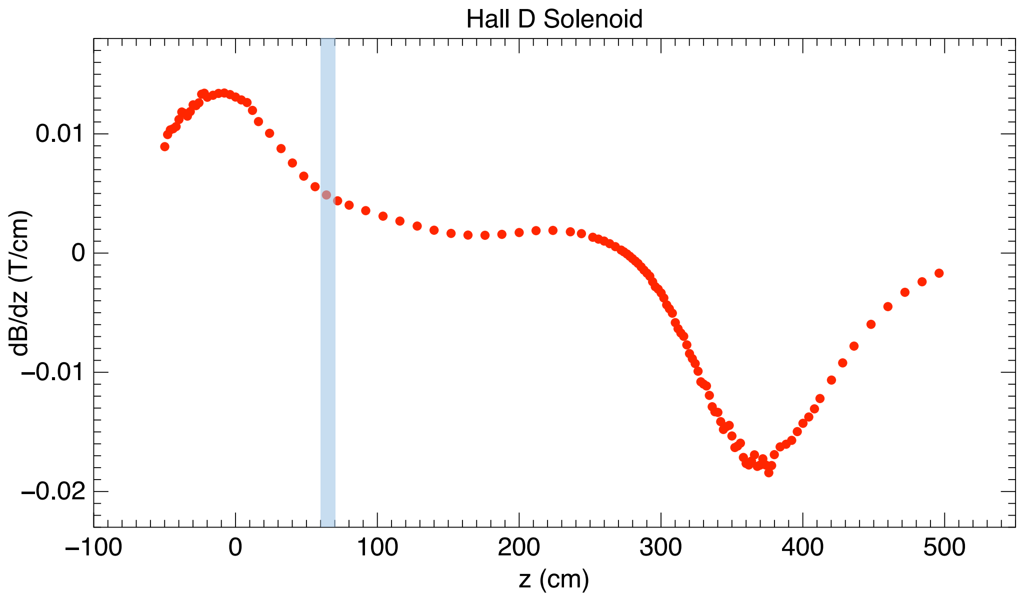
- Keep the microwaves on and polarize the target samples continuously, unless there is a good reason not to…
  - Cool ≲ 50 mK and maintain frozen-spin polarization with 2.5 T field for possible tensor-polarization experiments (see Mark Dalton's talk later today)

My hope is that the polarized target doesn't take up a lot more space than the current Hall D cryotarget.



Problem: The Hall D solenoid isn't 2.5 T.
And it isn't very homogeneous.





At the nominal cryotarget position, 75 cm, the field is 1.6 T, with a gradient of 5 mT/cm

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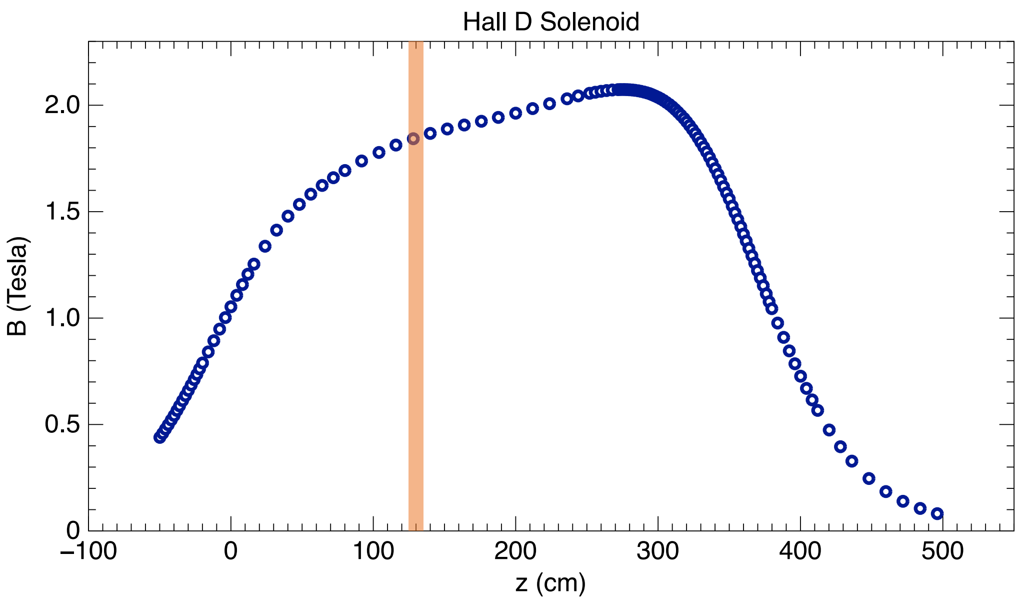
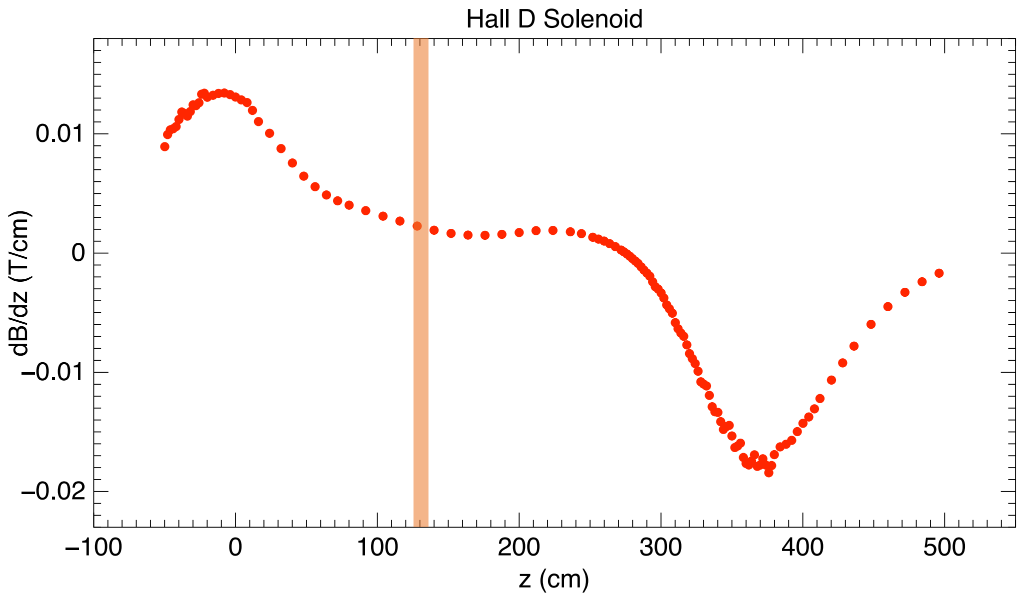


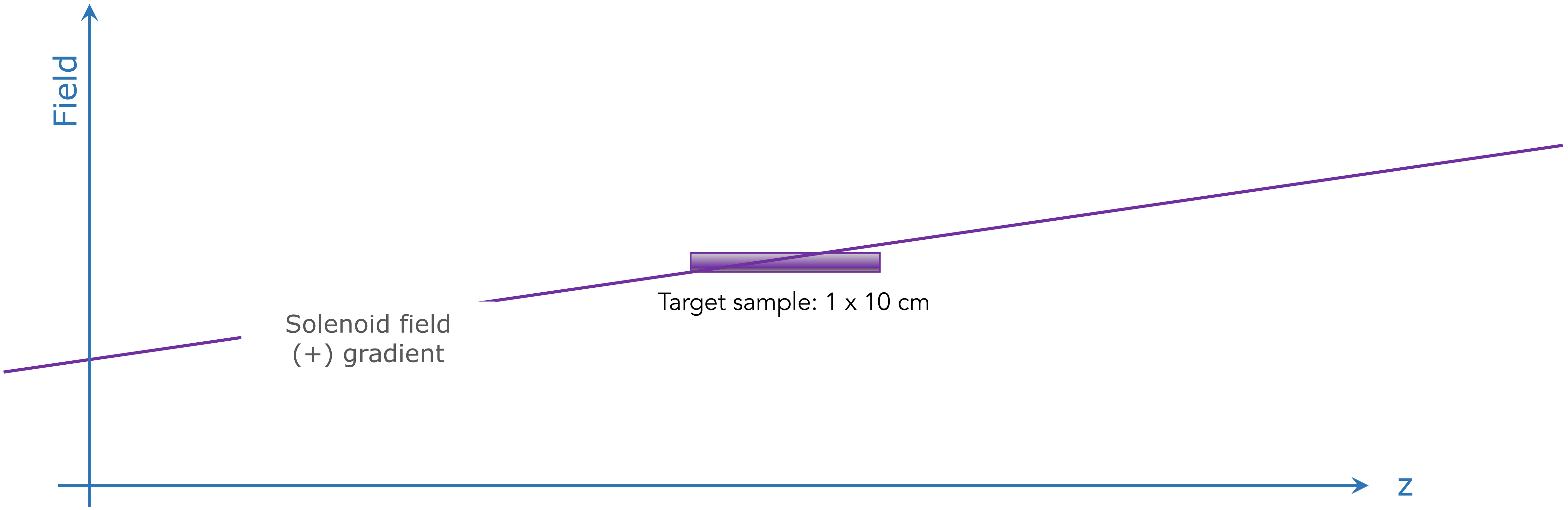


The situation improves farther downstream   @ 130 cm B = 1.8 T
dB/dx = 2 mT/cm

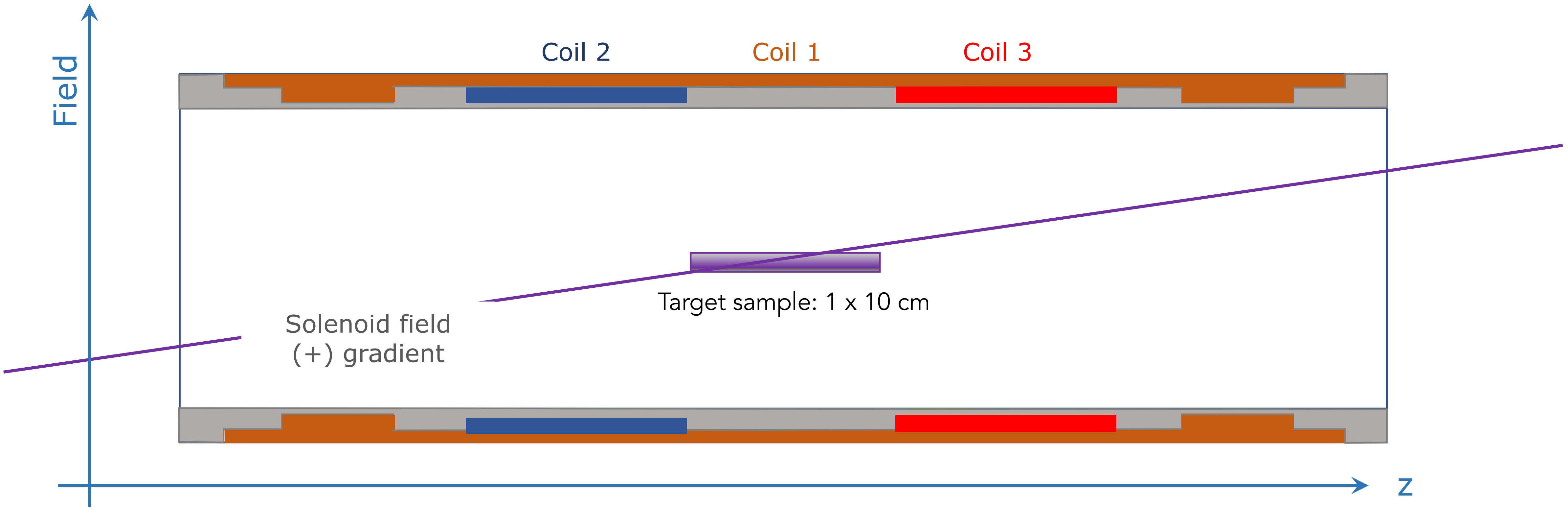
Is this a viable option?

For optimal DNP, the solenoid field must be flatter:

- ➢ $\Delta B/B$ ~ few 10^{-4} over the length of the target (or about 0.25 mT/cm)



I think we can accomplish this with a series of small, internal shim coils around the target



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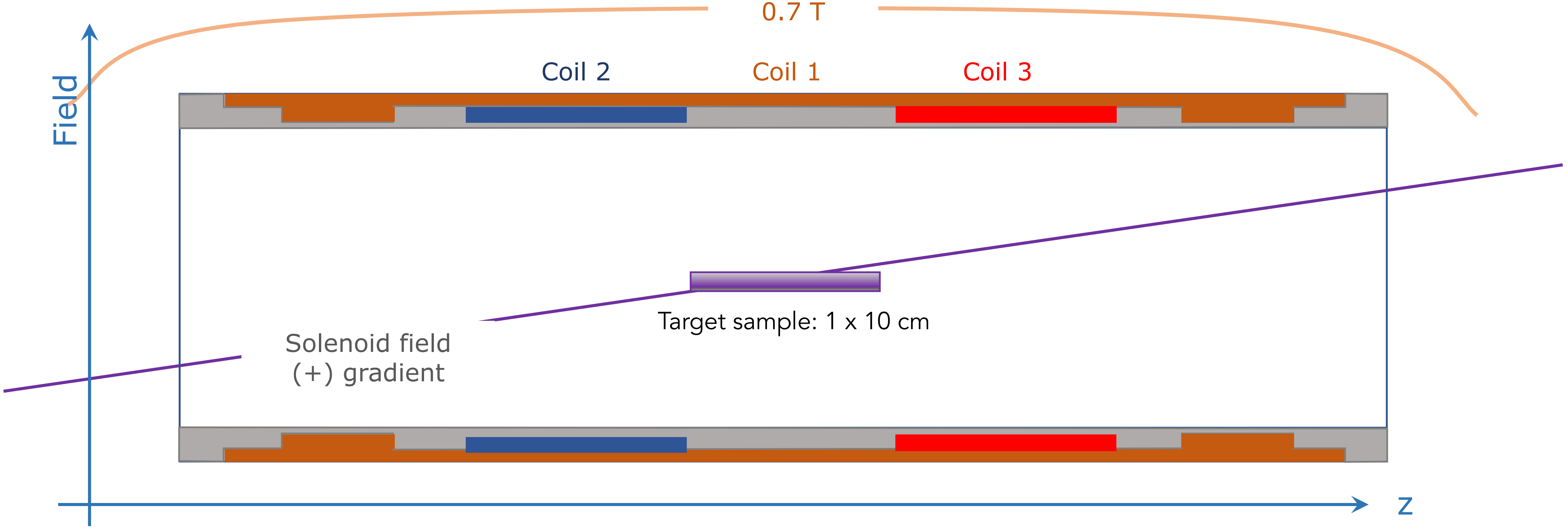

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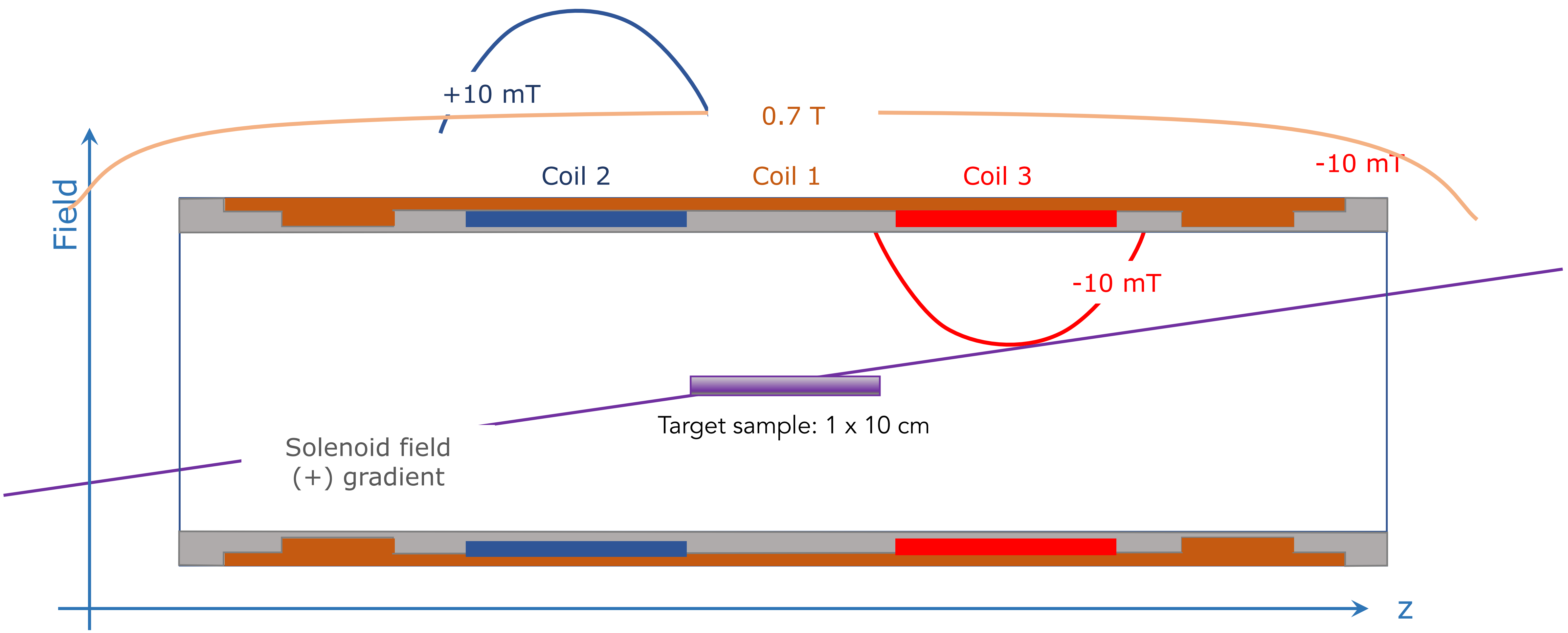

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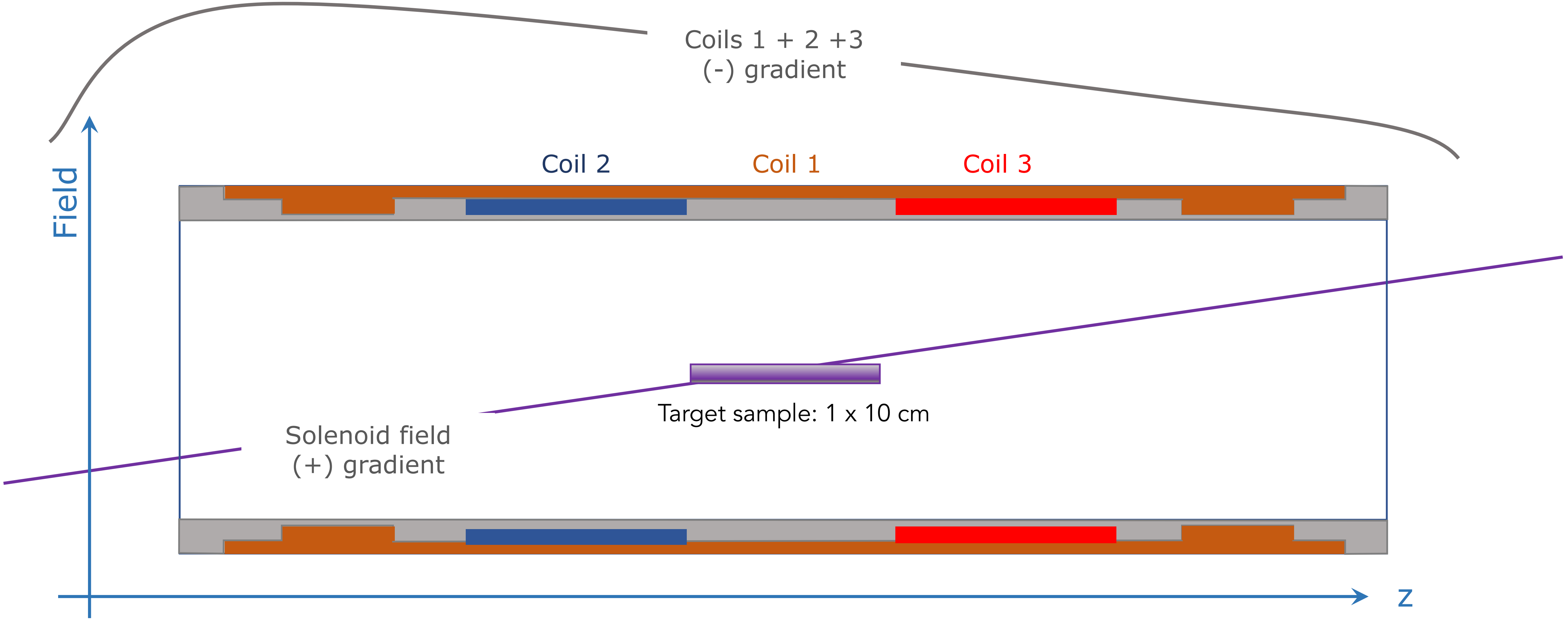

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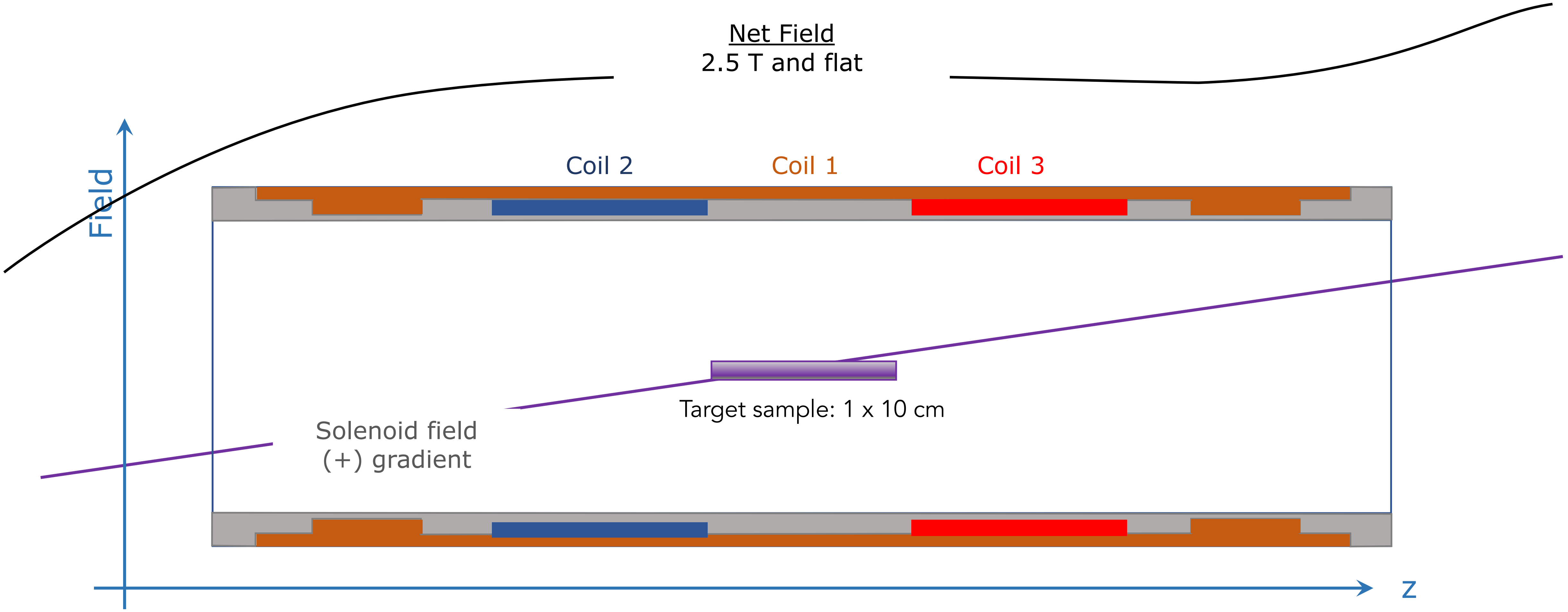

These are results previously demonstrated by the polarized target community

Nucleus	Spin	Polarization	Material	Conditions
^{1}H	½	90%	$CH_3(CH_2)_3OH$ + TEMPO	0.3 K, 2.5 T
^{2}H	1	80%	$CD_3(CD_2)_3OD$ + Trityl	0.3 K, 2.5 T
^{6}Li	1	55%	^{6}LiD + irradiation	0.3 K, 2.5 T
^{7}Li	3/2	90%	^{7}LiH + irradiation	0.3 K, 2.5 T
^{13}C	1/2	75%	$C_3H_4O_3$ + Trityl	0.9 K, 5 T
^{14}N	1	15%	NH_3 + irradiation	0.3 K, 2.5 T
^{15}N	1/2	15%	NH_3 + irradiation	0.3, 2.5 T
^{19}F	3/2	80%	$(CF_3)_2CHOH$ + EHBA-Cr(V)	0.4 K, 2.5 T
^{139}La	7/2	50%	Nd^{3+}: $LaAlO_3$	0.3 K, 2.3 T

Dynamically polarized by the MRI & Solid State Communities: ^{17}O, ^{29}Si, ^{119}Sn …

Summary

There is currently one, *brief* polarized target experiment approved for Hall D

- E12-20-11 (A-, 33 days)

The polarized target will be a major, multi-year R&D, construction, and testing effort

- Hopefully it can serve as the basis for a fuller scientific program

The JLab Target Group has extensive experience building these devices

- Very high proton and deuteron polarizations can be expected at 2.5 T & 0.3 K
- Heavier nuclei can also be polarized with high confidence: $^{6,7}Li$, ^{13}C, $^{14,15}N$, ^{19}F

In frozen spin operation, interesting things can be done to the deuteron polarization

- See Mark Dalton's flash talk @ 11:50am