A New Solid Polarized Target for CLAS12

J. Maxwell

for the Jefferson Lab Target Group
& the CLAS12 Polarized Target Collaboration

Jefferson Lab

Spin 2016, Urbana-Champaign, IL
September 26th, 2016

Outline

1. Dynamic Nuclear Polarization
    - Introduction
    - Polarized Targets at JLab
2. A New CLAS12 Target
    - Challenges and Improvements
    - Current Design
3. Future Projects

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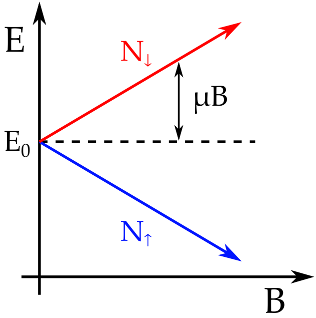
A Starting Point for a Polarized Target

- How do we control spin degrees of freedom in a target material?
- Try to align spins in a large magnetic field B and low temperature T
- Polarization is then:

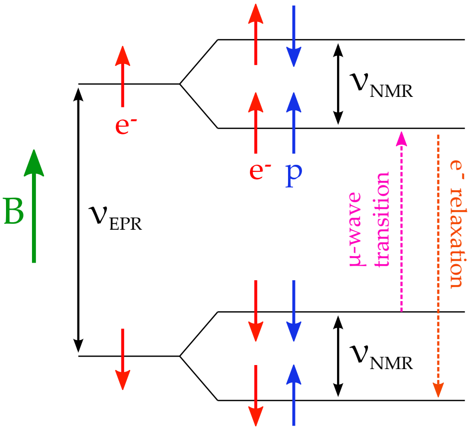
$$P = \frac{e^{\frac{\mu B}{kT}} - e^{\frac{-\mu B}{kT}}}{e^{\frac{\mu B}{kT}} + e^{\frac{-\mu B}{kT}}} = \tanh\left(\frac{\mu B}{kT}\right)$$

- $\mu_e \approx 660\mu_p$
    - Electrons at 1 K, 2.5 T: 92%
    - Protons at 1 K, 2.5 T: 0.25%



Dynamic Nuclear Polarization (Solid Effect)

- Take advantage of e–p spin coupling
- Induce "forbidden" transitions with μ-waves to match energy gaps
  - $\nu_\mu = \nu_{\text{EPR}} - \nu_{\text{NMR}}$
- Relaxation times key
  - $e \approx$ milliseconds
  - $p \approx$ 10s of minutes
- Choose alignment without changing magnetic field
  - $\nu_\mu = \nu_{\text{EPR}} + \nu_{\text{NMR}}$



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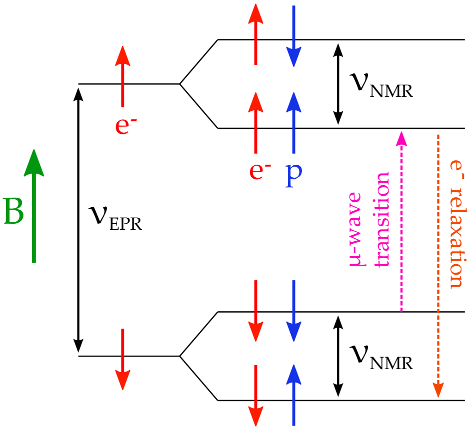

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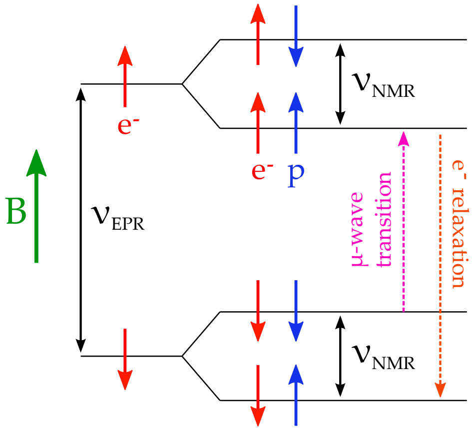
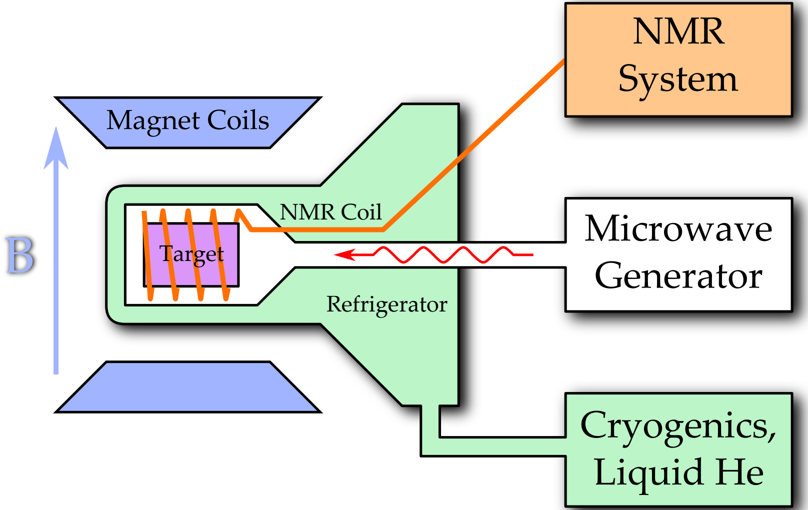
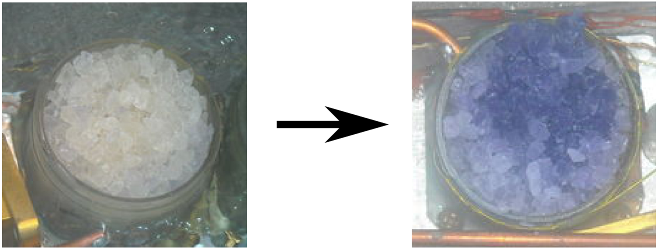


DNP in Practice



DNP for Electron Scattering Experiments

- Key to usefulness for our purposes is radiation hardiness
  - NH_3, ND_3, LiH, LiD are commonly used
  - Irradiation provides radicals with free electrons to allow polarization
- Allow beam currents from 5 to 100 nA at 1K
  - Anneals after 4 Pe/cm^2 (8-100 hours)
  - Replacement after 20-30 Pe/cm^2 (1-8 weeks)



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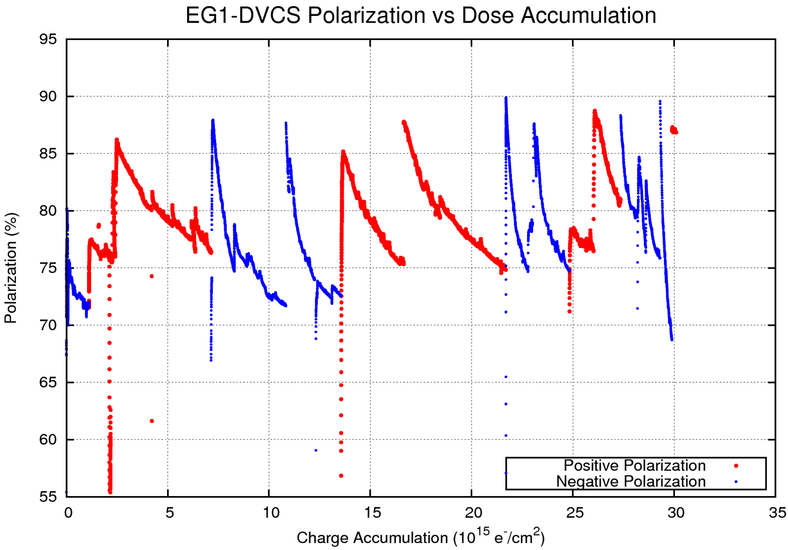


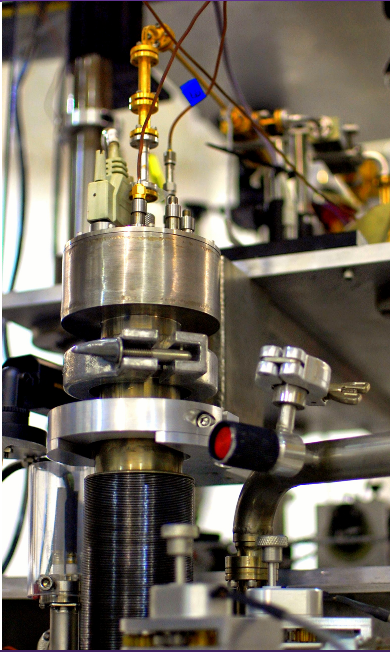
Polarized Targets at JLab


D
A
B
C

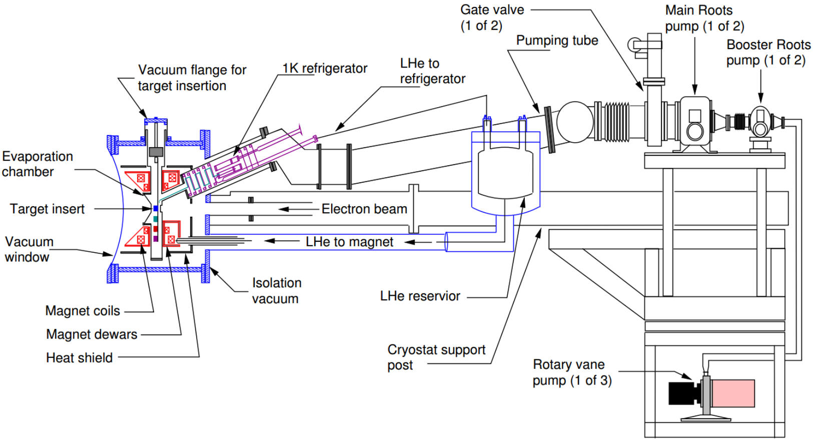
Polarized Targets at 6 GeV

- Solid Targets in the 6 GeV era: UVa, Hall B, FROST, HDIce

- Hall A DNP:
  - g2p (2012),GEp (2012)
- Hall B DNP:
  - Eg1 (1999), Eg1b (2000), Eg4 (2004), Eg1-DVCS (2008)
- Hall C DNP:
  - GEn (1998), GEn 2 and RSS (2000), SANE (2008)



Hall B DNP Target



Hall B DNP Target

Hall B 12 GeV DNP Target Program

- (E12-06-109) Longitudinal spin structure of the nucleon
- (E12-06-119) DVCS with CLAS at 12 GeV
- (E12-07-107) Spin-orbit correlations with a longitudinally polarized target
- (E12-09-009) Spin-orbit correlations in kaon electroproduction in DIS
- (E12-12-001) EMC effect in spin structure functions
- (C12-15-004) DVCS on the neutron with a longitudinally polarized target

Over 240 PAC days of DNP running, with more to come

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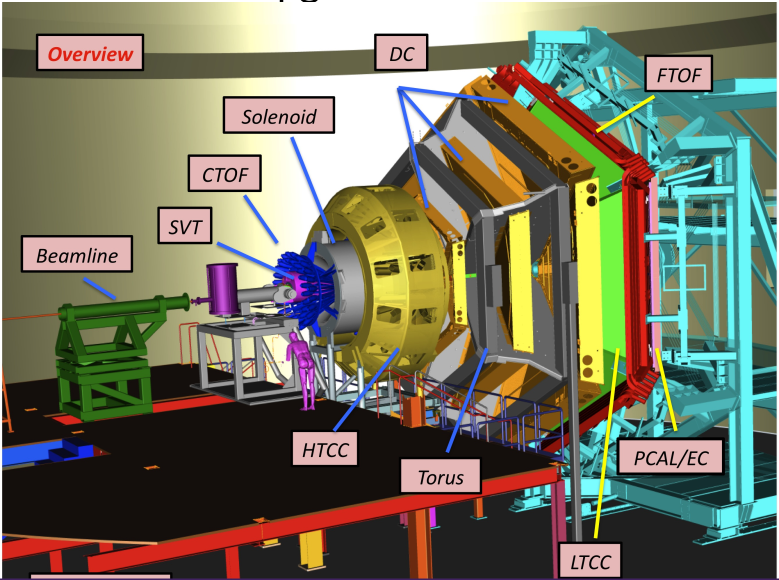
Hall B's CLAS12 Upgrade



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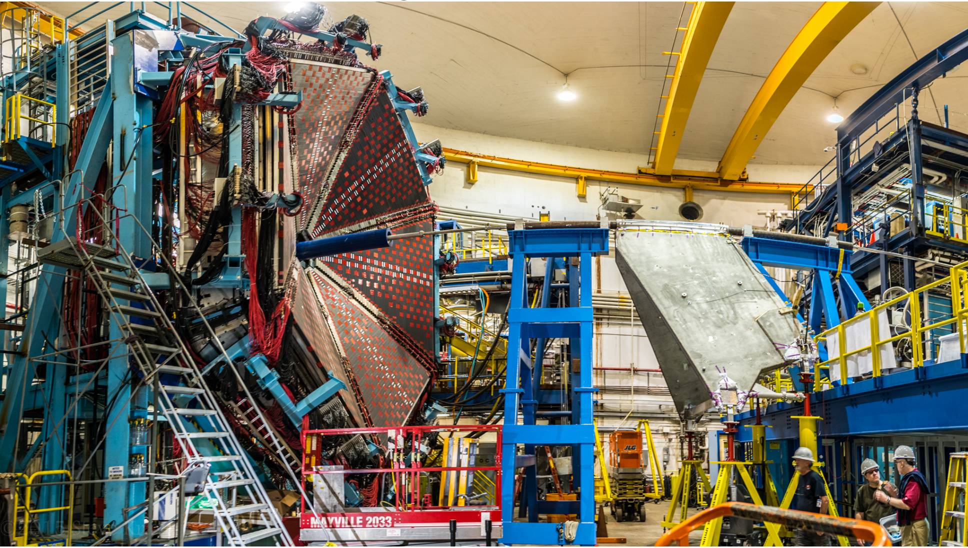


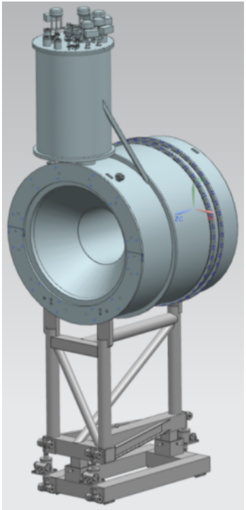
Steve Krave, flickr

DNP in Hall B at 12 GeV

- DNP is a proven technique, what's new?
- Constraints from CLAS12
  - Uniformity of 5T CLAS12 Solenoid
  - Tight space requirements
  - External NMR coils
- Improvements, additions
  - Two target samples at opposing polarizations
  - NMR advancements, remote tuning
  - μ-wave delivery

CLAS12 Solenoid

- 5.0 T Superconducting, Warm-bore Solenoid
  - Provides tracking field
  - Moeller e^- shield
- $\Delta B/B < 10^{-4}$ in Ø2.5 x 4 cm
- Magnet not yet delivered, final uniformity unknown
- Small shim magnet may be added to improve uniform field region needed to polarize



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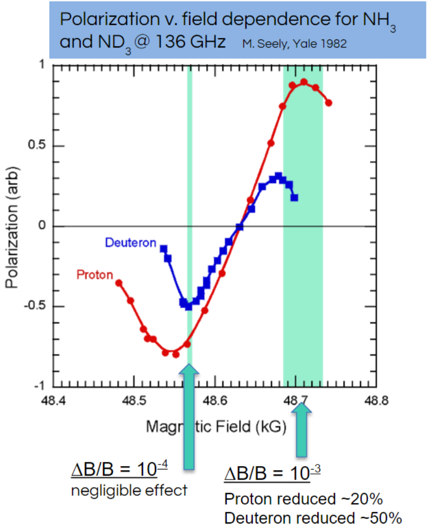
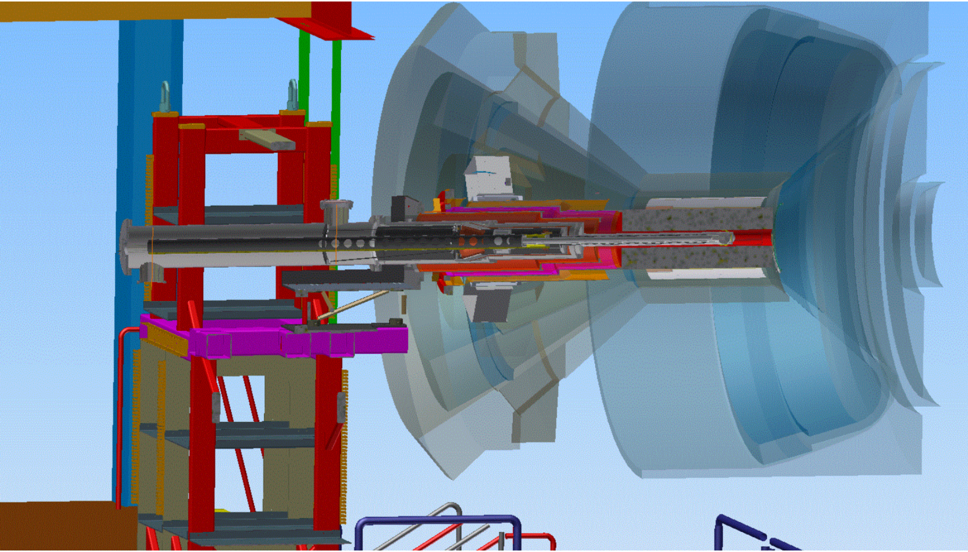
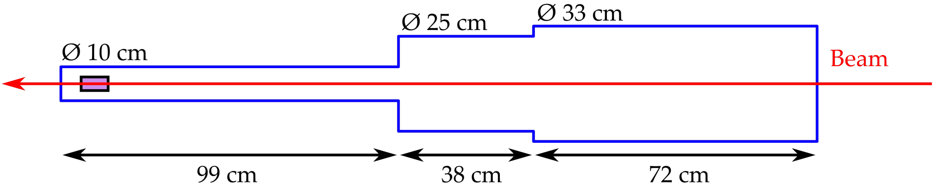


Dealing with Space Constraints



Dealing with Space Constraints

- The "Keep-in" area from CLAS12 is tight!
  - SVT and electronics racks mostly responsible
- Horizontal refrigerator needed
- A standard target insert would need to be $\sim$ 3 m long!
- We are exploring a short insert to "load" like a gun
  - Design by J. Brock, C. Keith
  - NMR and μ-wave infrastructure must be moved off insert



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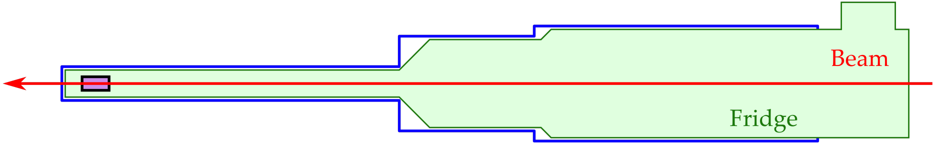

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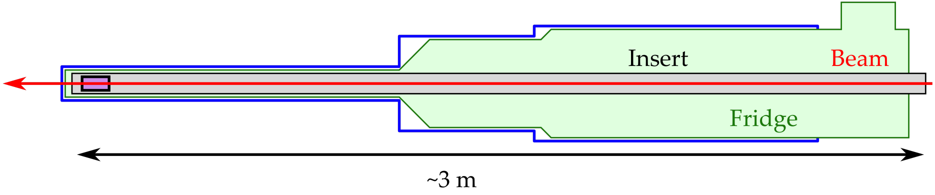

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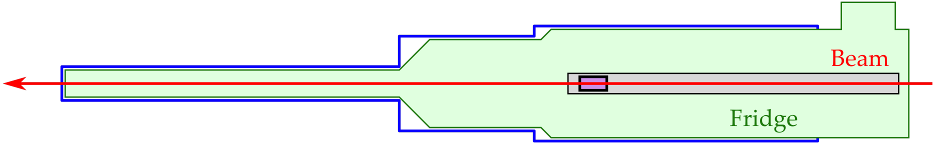

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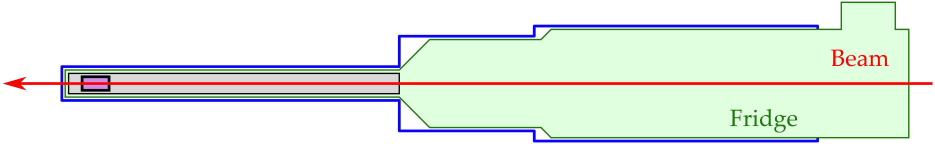
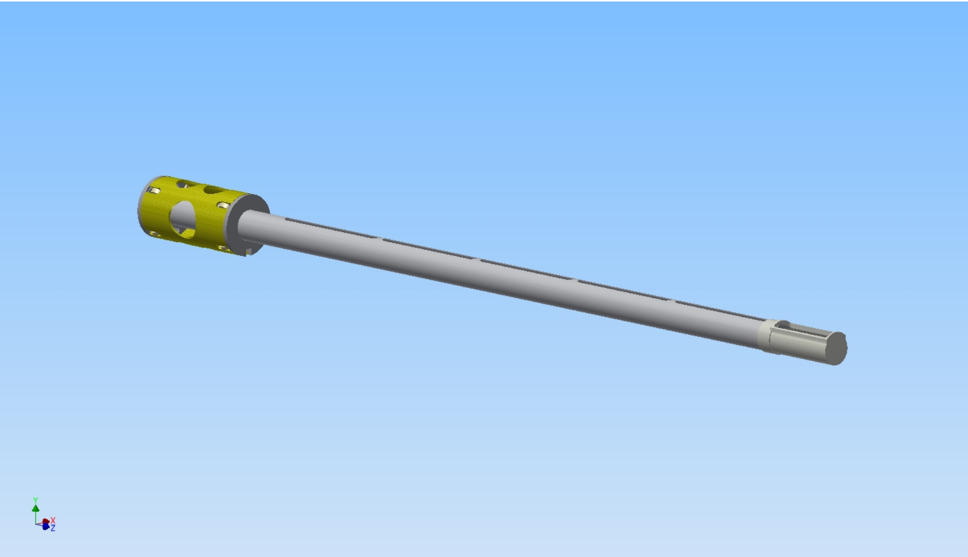


Trolley? At 1 K?

Design Walkthrough

"Trolley" insert



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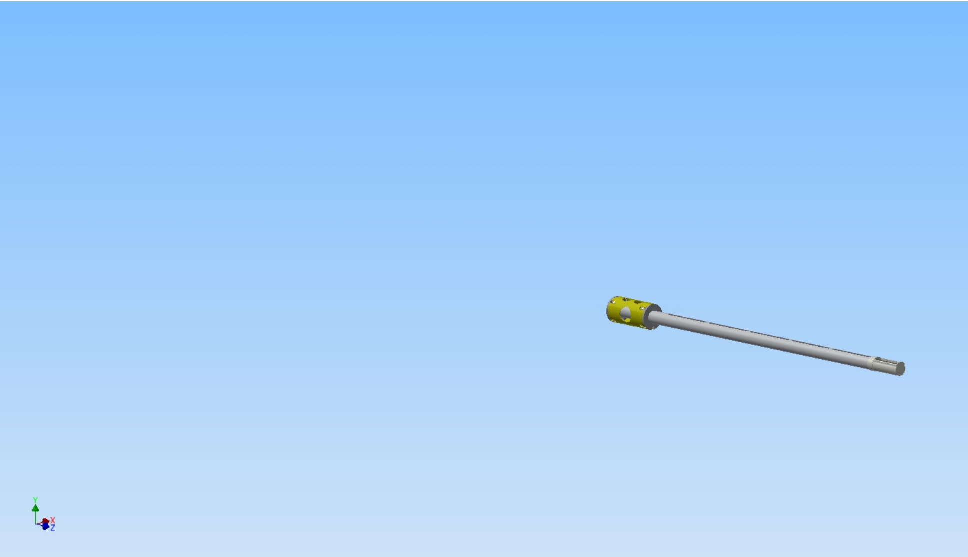
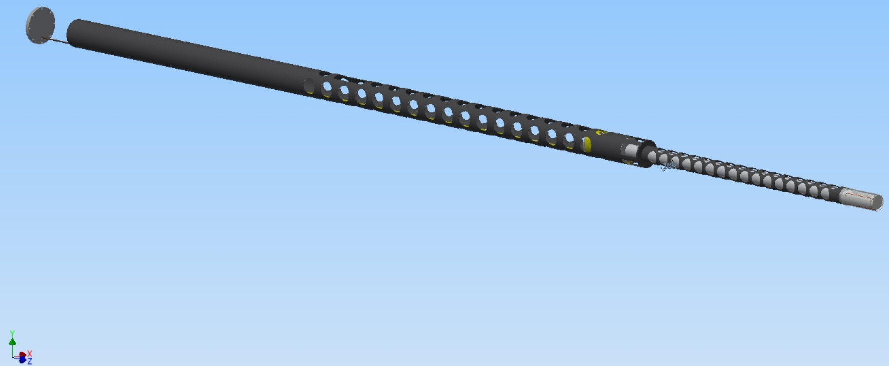


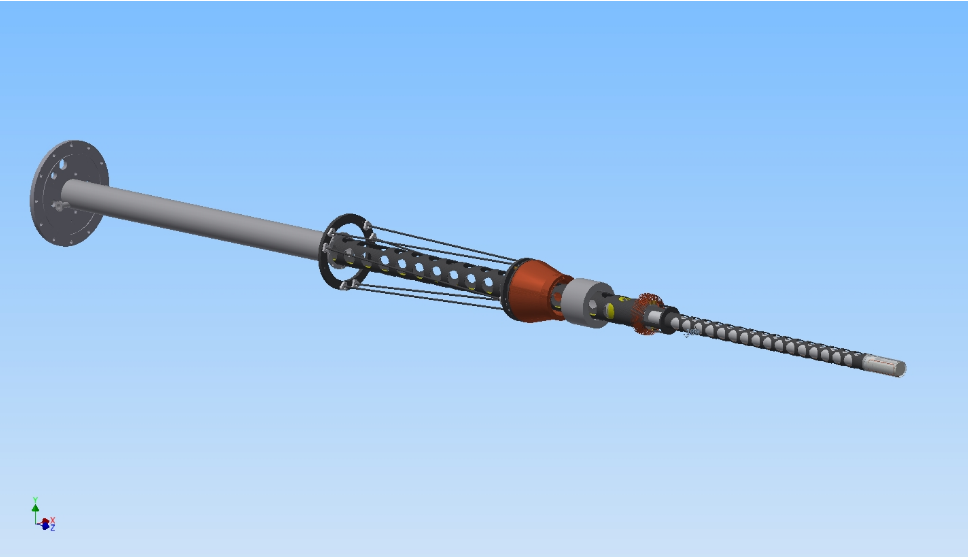
Design Walkthrough

NMR, μwave, shim insert



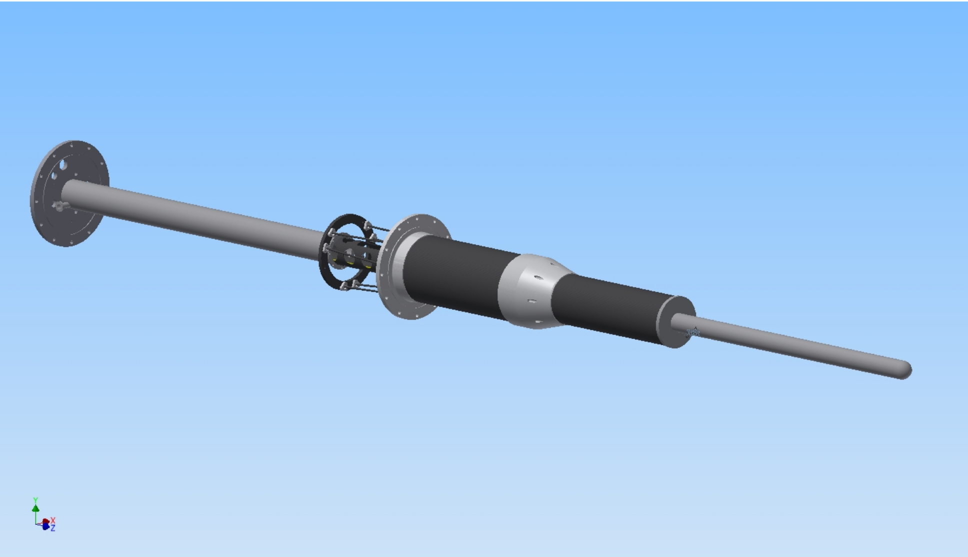
Design Walkthrough

Refrigerator



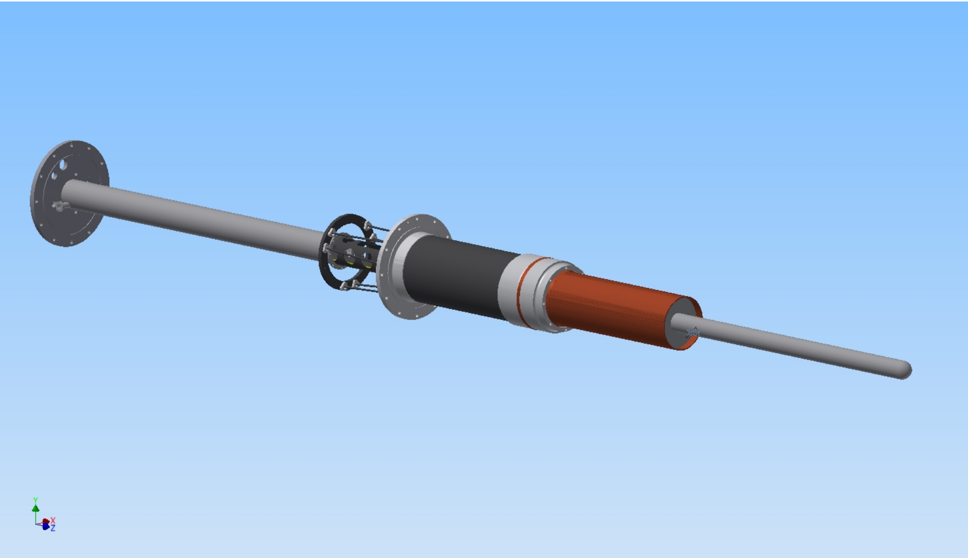
Design Walkthrough

Inner heat shield



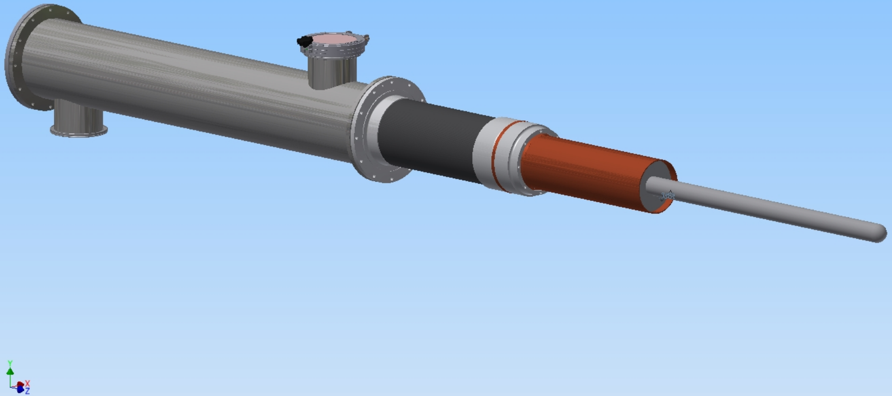
Design Walkthrough

Outer heat shield



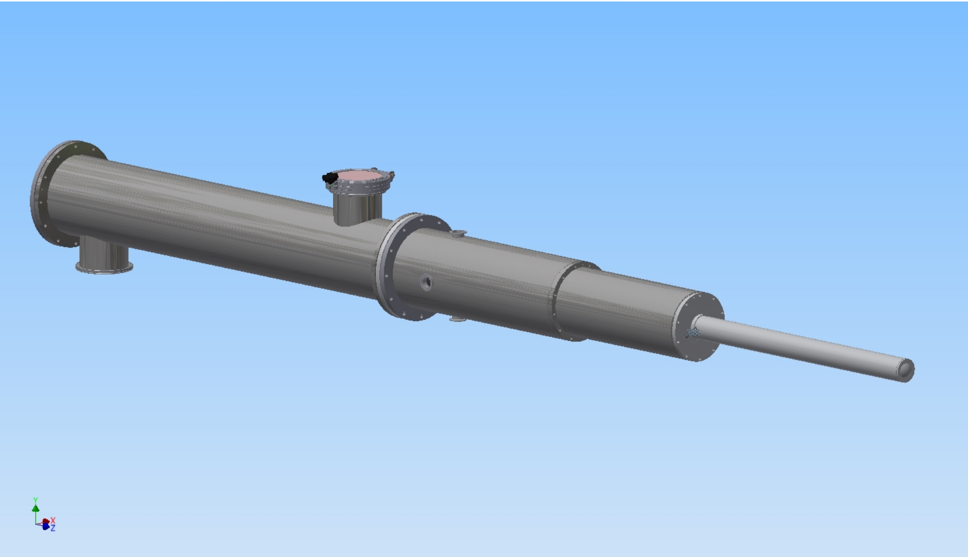
Design Walkthrough

Pumping line



Design Walkthrough

Outer vacuum can



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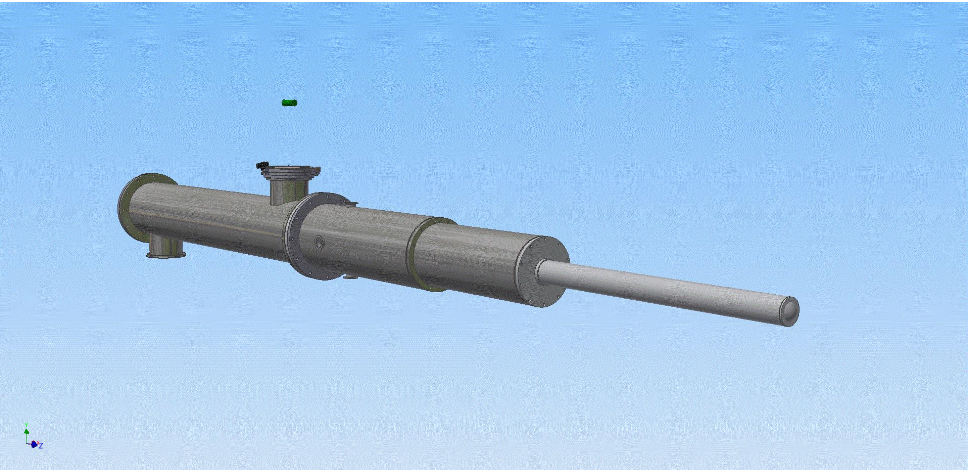

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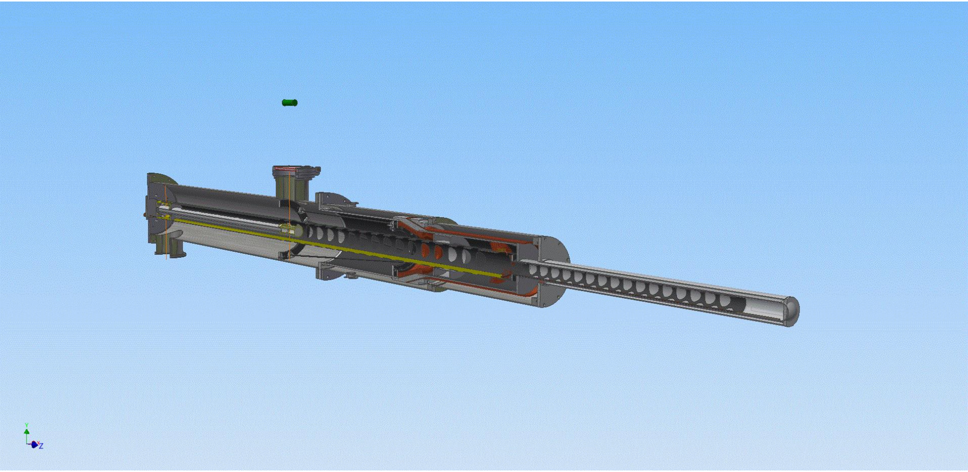

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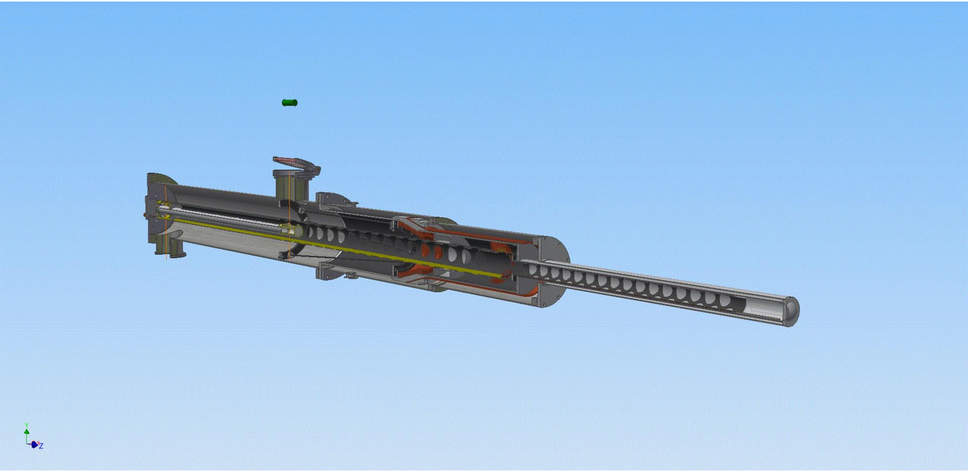

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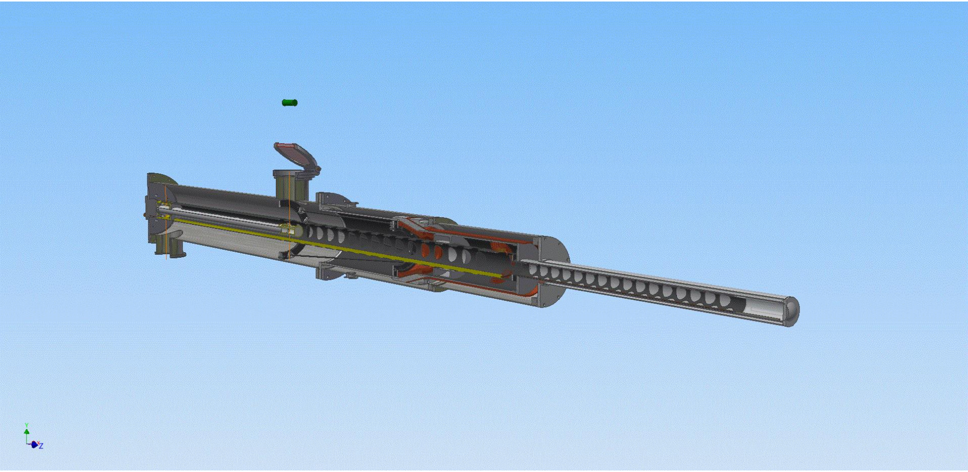

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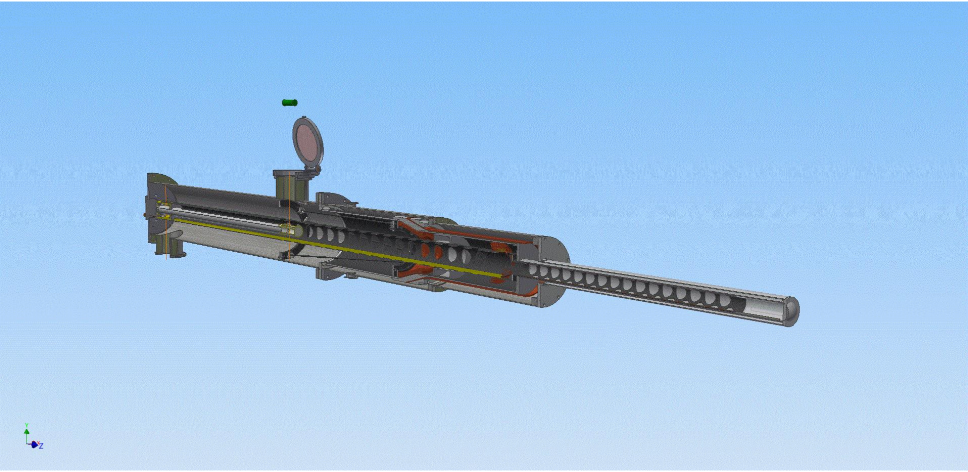

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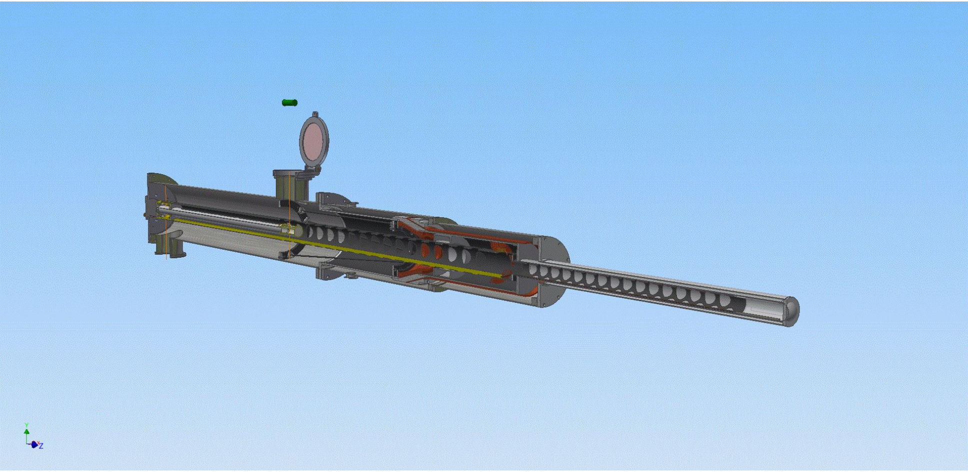

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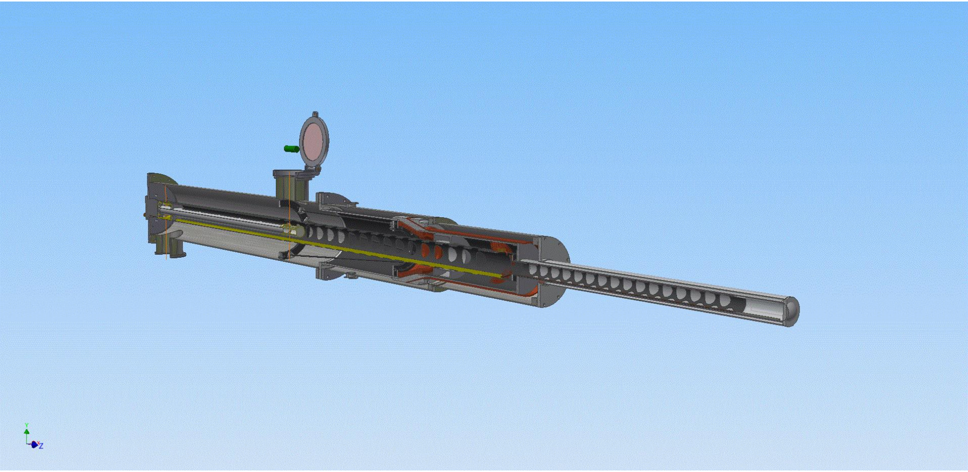

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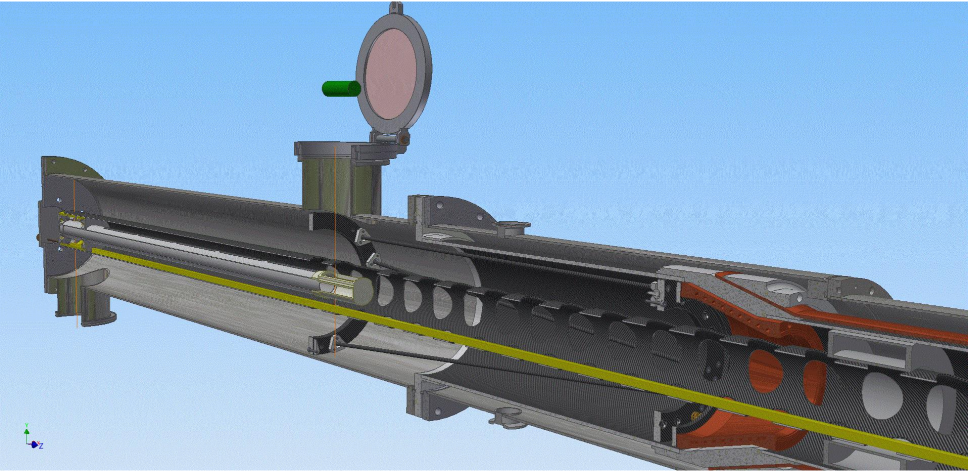

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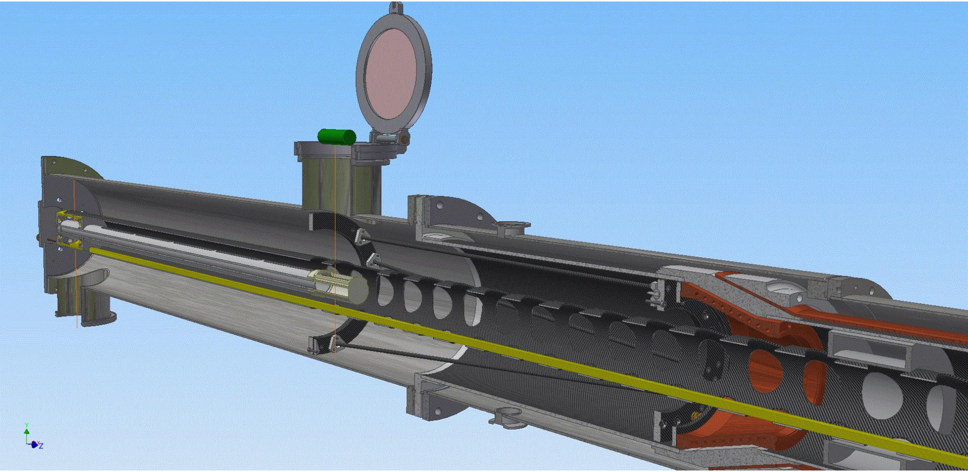

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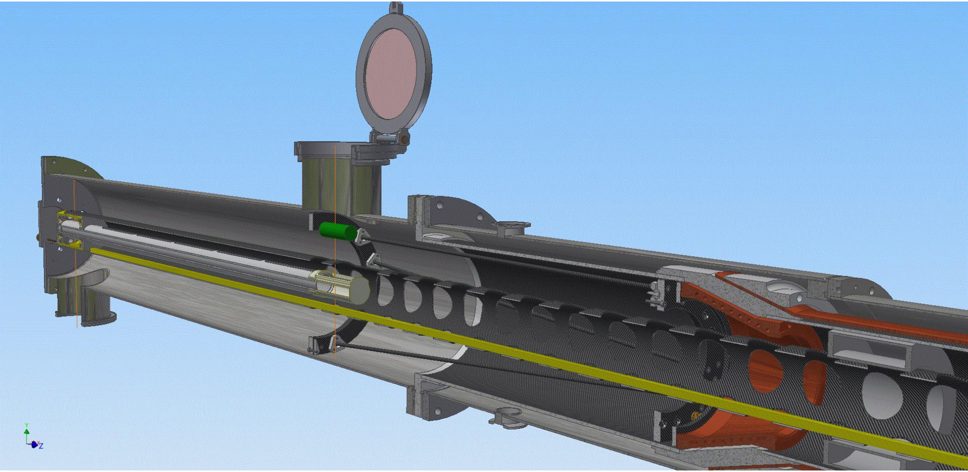

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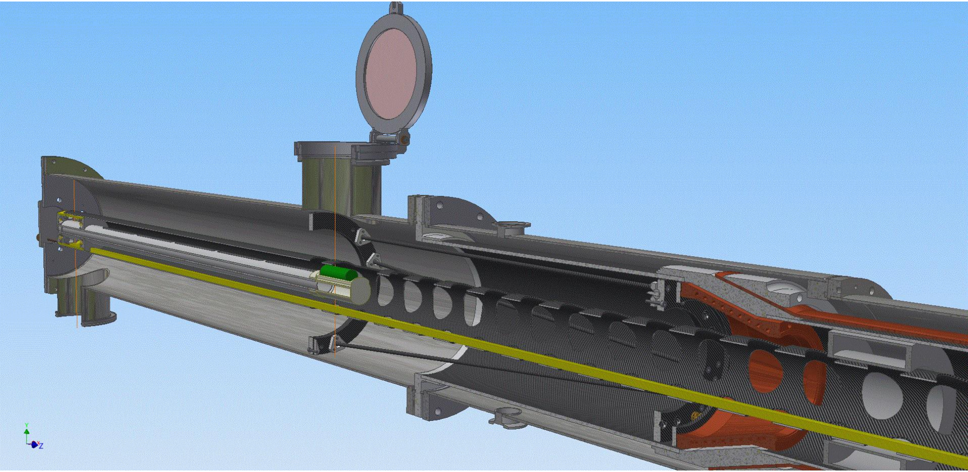

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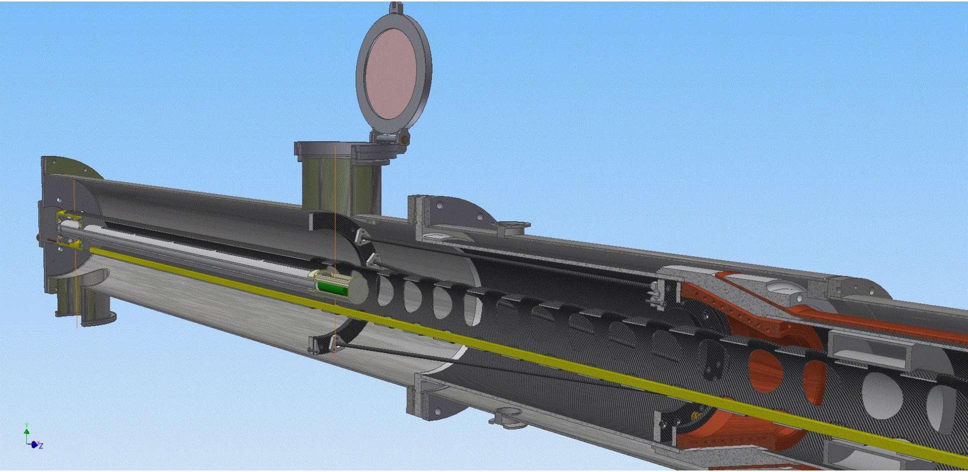

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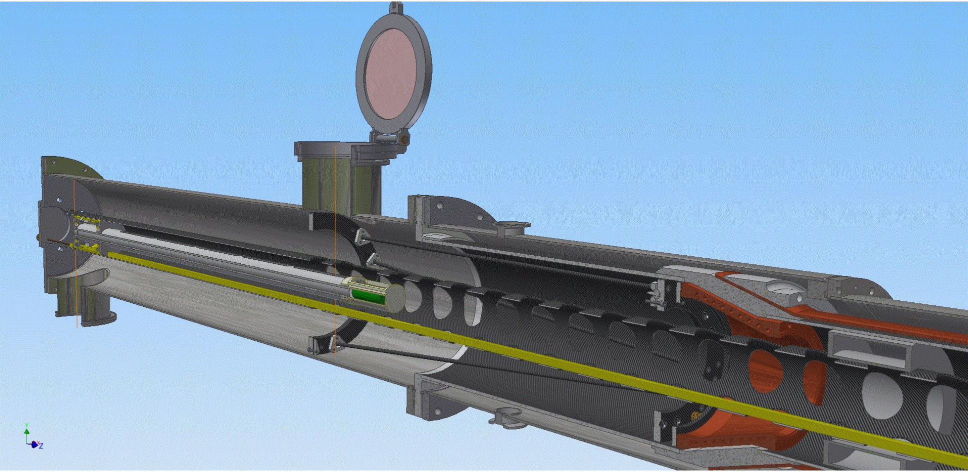

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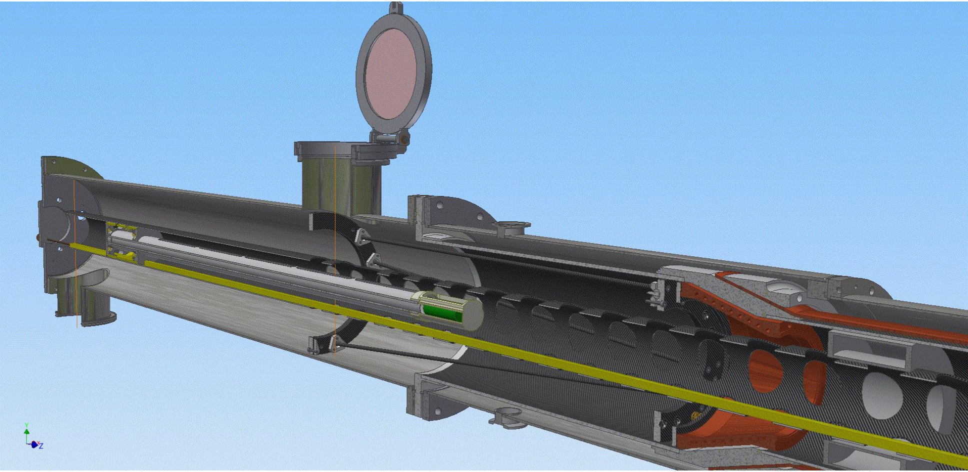

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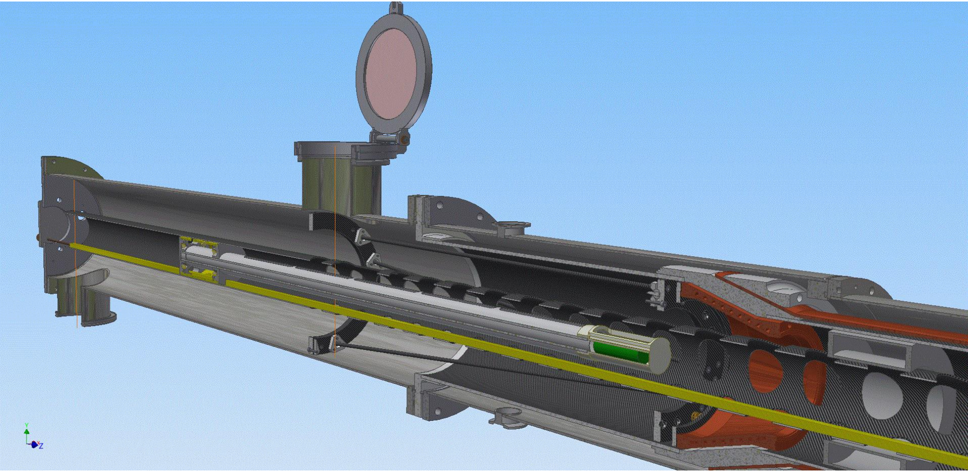

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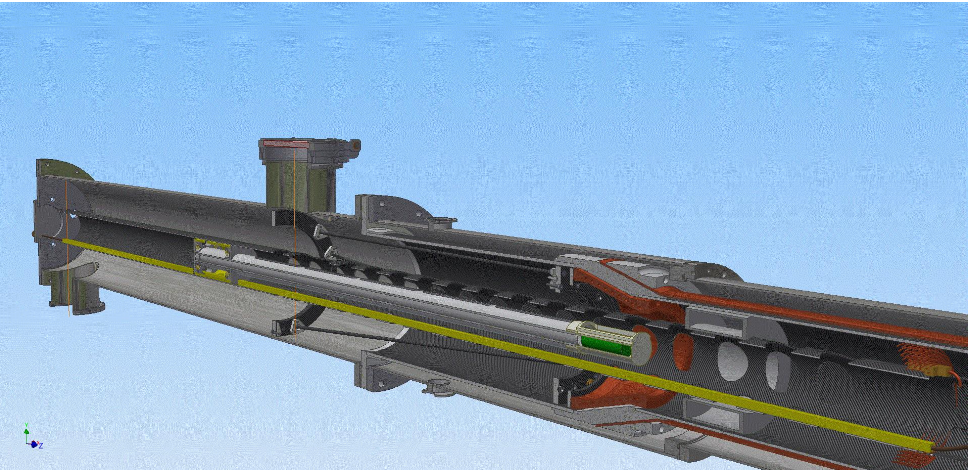

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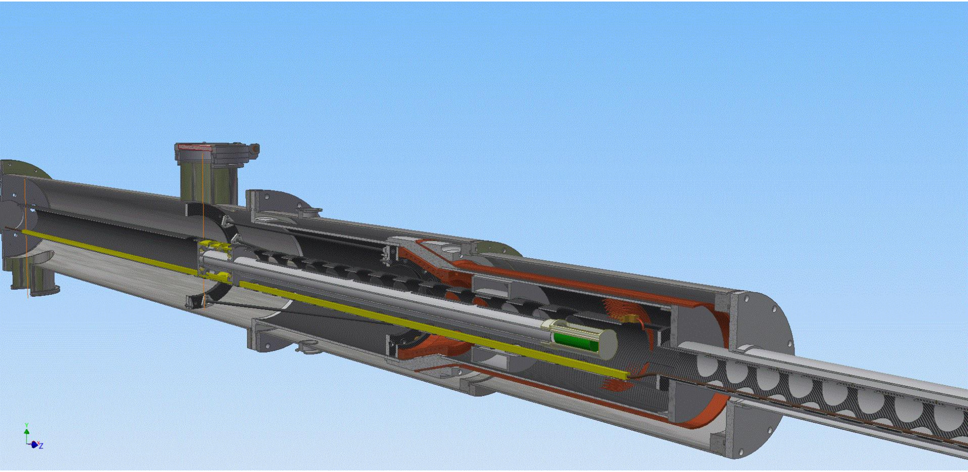

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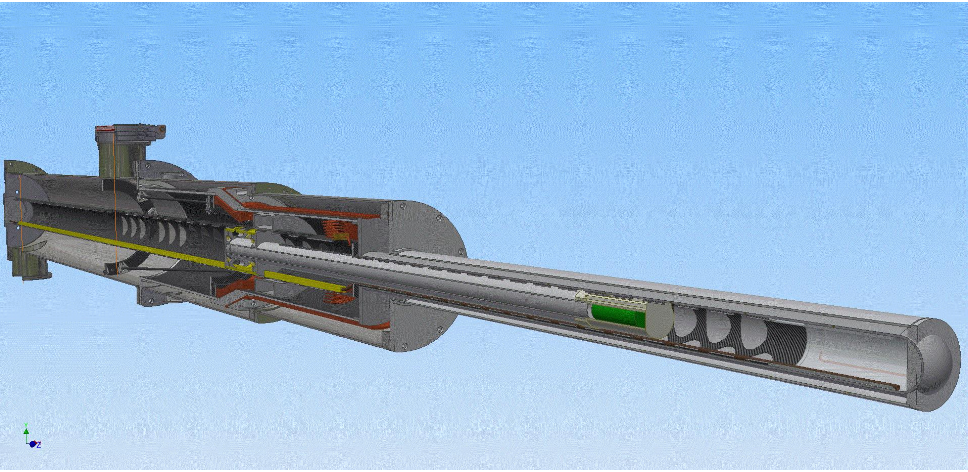

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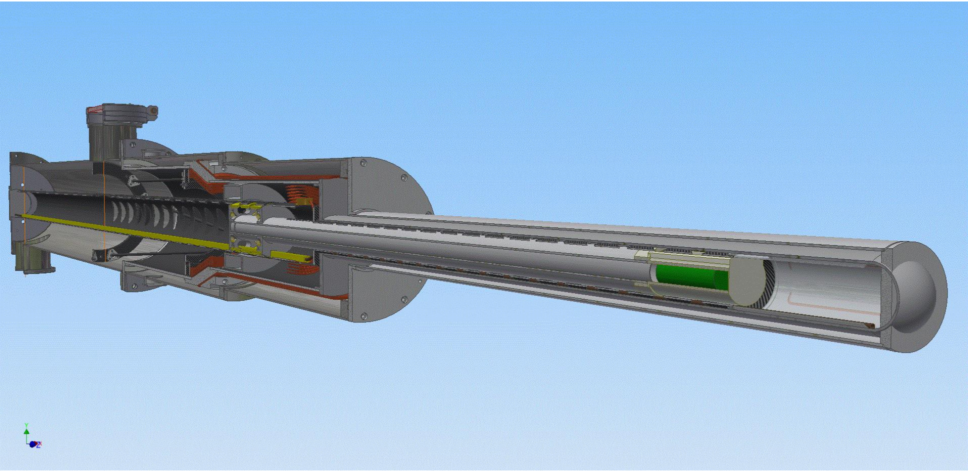

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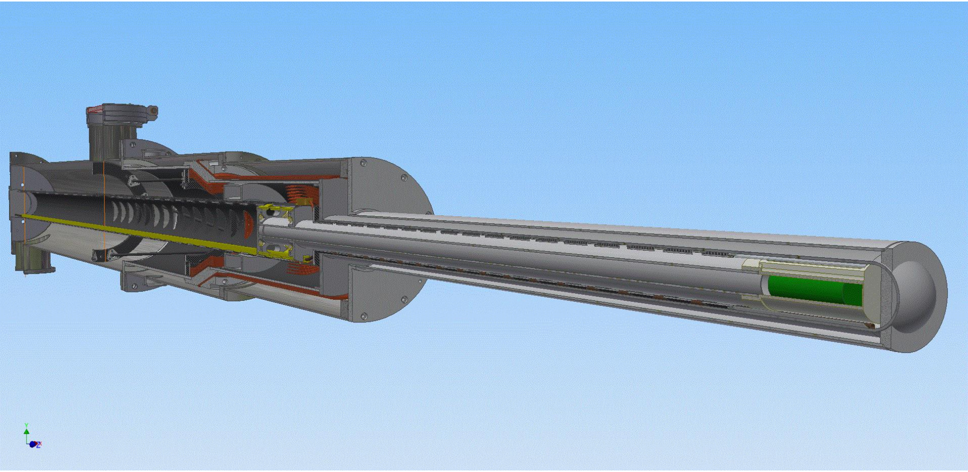
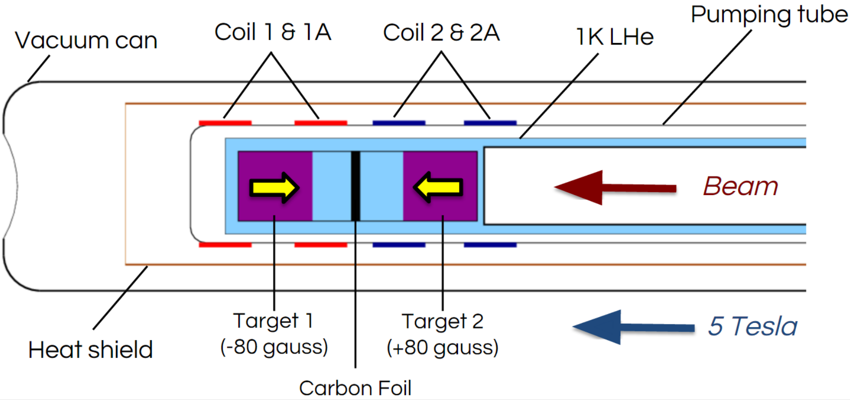


Multiple Samples

- Internal, superconducting coils to adjust the polarizing field for two target samples, using the same μ-wave frequency, and take data on + and – simultaneously.



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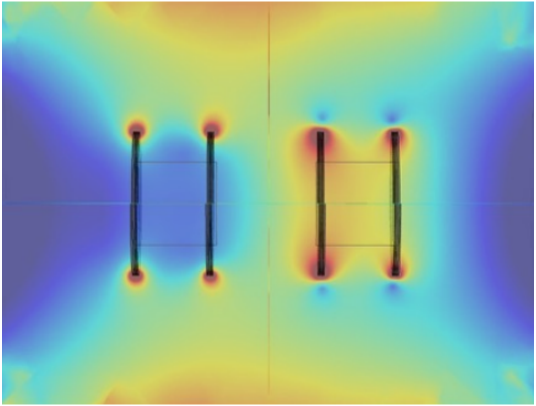

UVa

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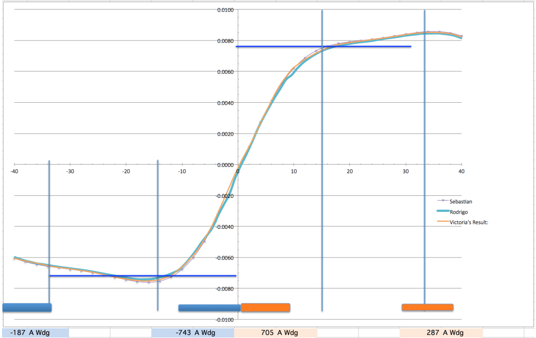
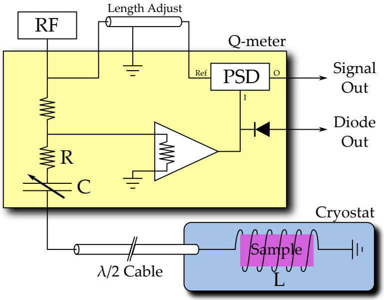


ODU

NMR Polarization Measurement

- External coils needed
- Old system works well, but Liverpool Q-meter aging
- Cold passive components
- Remotely tunable varactor diodes
  - A big plus for a two cell setup when adjusting shims
- Watching efforts of other groups: PSTP 2015 Herick, Ohta talks, Spin 2016 Reicherz



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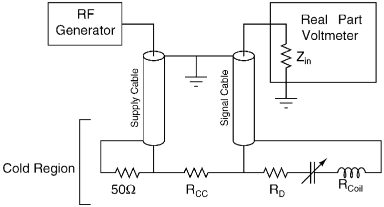

Court et al, NIM A, 2004.

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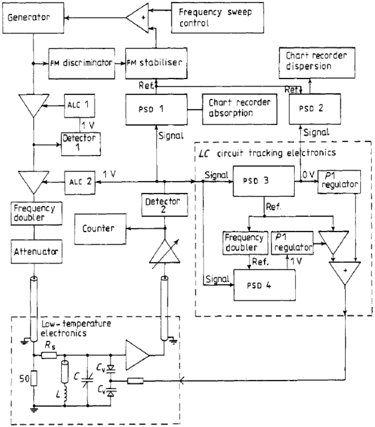
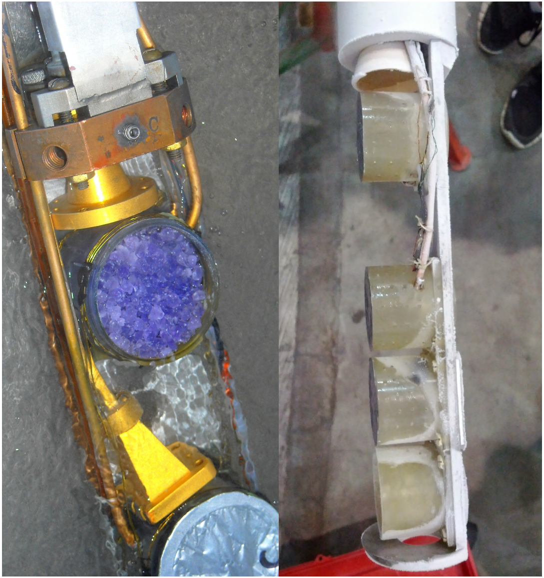


Veenendaal et al, J. Phys E, 1983.

Microwave Delivery

- Waveguide horns traditionally used
- This will be difficult with trolley insert, very tight space available
- Testing reflecting surfaces
    - Heat sensitive paper
    - Thermocouple array
- Simulations of full cavity



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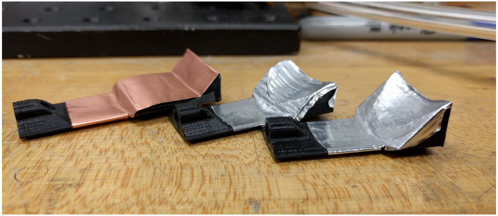

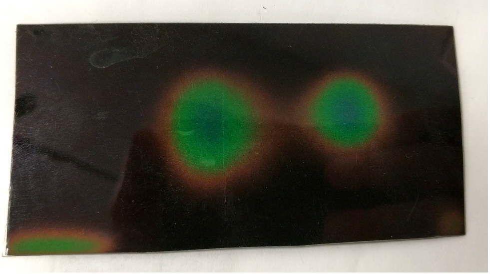

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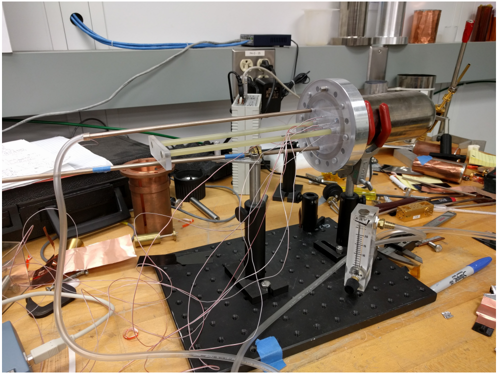

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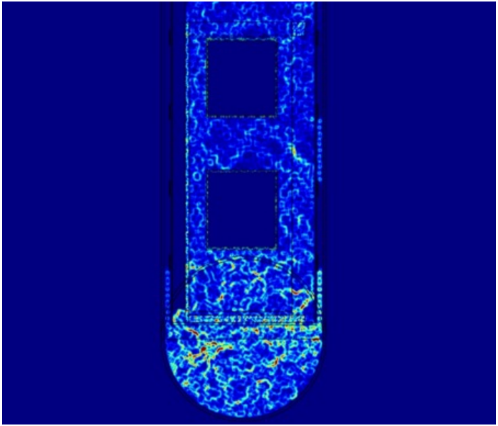
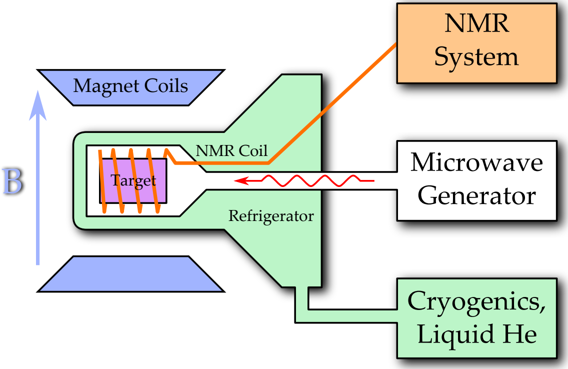


Keller, Worcester at UVa

CLAS12 Polarized Target Colloboration

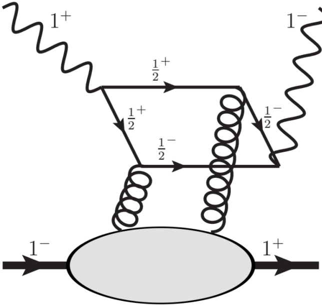
- JLab: CLAS12 Solenoid
- U of Virginia: Refrigerator
- Old Dominion U: Pumps, NMR
- Christopher Newport U: Microwaves



Outline

Novel DNP Application: Nuclear Gluonometry

- $\Delta(x, Q^2)$ corresponds to helicity amplitude $A_{+-,-+}$
- Photon helicity flip of two
- Unavailable to bound nucleons or pions in the nucleus
- Virtual ρ or Δ? Gluons not associated with a nucleon?



- New lattice QCD result for first moment of $\Delta(x, Q^2)$ in a ϕ meson is preliminary, but very promising[1]
- Primary challenge of measurement is polarized target or source

[1] Detmold, Shanahan, arXiv:1606.04505

A Polarized N Target for Nuclear Gluonometry

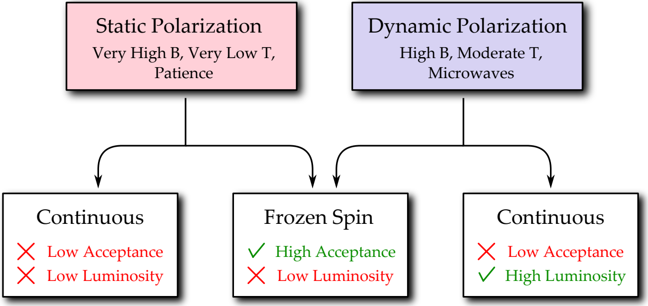
- Need a spin$\geq$1 nucleus, but this is a **nuclear** effect
  - Higher atomic number, higher spin more likely to reveal exotic gluonic components
- Deuteron? Expect two nucleons to good approximation
- Something heavier: Li? $\alpha + d$
- Our long experience leads us to N in NH_3
- N polarization due to EST in NH_3 17% with H is 95%
  - SMC studied polarized N in NH_3 (getting 40%) by moving B field
  - RF Spin transfer to polarize N dynamically?
  - New NMR techniques needed

CLAS12 Polarized Target Collaboration:

- JLab: C. Keith, J. Maxwell, D. Meekins, J. Brock
- CNU: R. Fersch, S. Clark
- ODU: S. Kuhn, V. Lagerquist
- UVa: D. Crabb, D. Day, D. Keller, M. Worcester

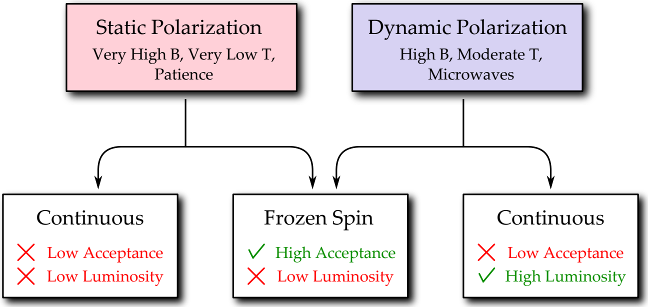
Thank you for your attention!

Solid Polarized Target Methods



- Static Polarization: Very high B, Very low T (HDIce)
- Dynamic Polarization: Induce spins flips; high B, mod. T (UVa)
- Frozen Spin: Dynamically polarize, then "freeze" spin at low T, with small B (CERN, Bonn, JLab)

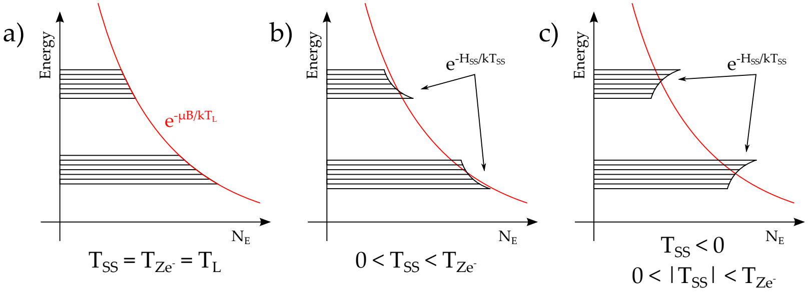
Solid Polarized Target Methods



- General limitations:
  - Large B field → physically large magnet; access can be occluded
  - Small T → large refrigerator; heat load is limited so beam current is limited

Equal Spin Temperature

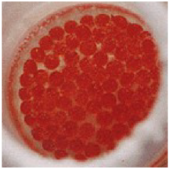
Can't ignore interactions between electron spins.

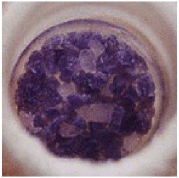


- Extra energy reservoir T_{SS} which is dependent on the Zeeman and lattice energies only through relaxation.
- Microwaves pump the spin–spin reservoir, and thermal mixing transfers to the Zeeman reservoir of proton via flip-flops (2 electron flips and a proton flop)

Commonly Used DNP Materials

Material	Type	Dopant	Dilution	Polarization	Rad. Res.
Butanol	C_4H_9OH	TEMPO	13.5%	90-95%	Moderate
D-Butanol	C_4D_9OD	TEMPO	23.8%	40%	Moderate
Ammonia	$^{14(15)}NH_3$	Irrad.	17.6%	90-95%	High
D-Ammonia	ND_3	Irrad.	30.0%	50%	High
Lithium-H	^7LiH	Irrad.	25.0%	90%	Very High
Lithium-D	^6LiD	Irrad.	50.0%	55%	Very High





Creating Paramagnetic Centers

DNP requires free electrons to couple to nuclei: radicals doped throughout the material.

- Chemical Dopants
  - Radicals like TEMPO, EHBA-CR(V)
- Irradiation Doping
  - Create radicals by ionization, for example making $N\dot{H}_2$ from NH_3