# LANL/UVA Solid Polarized Targets

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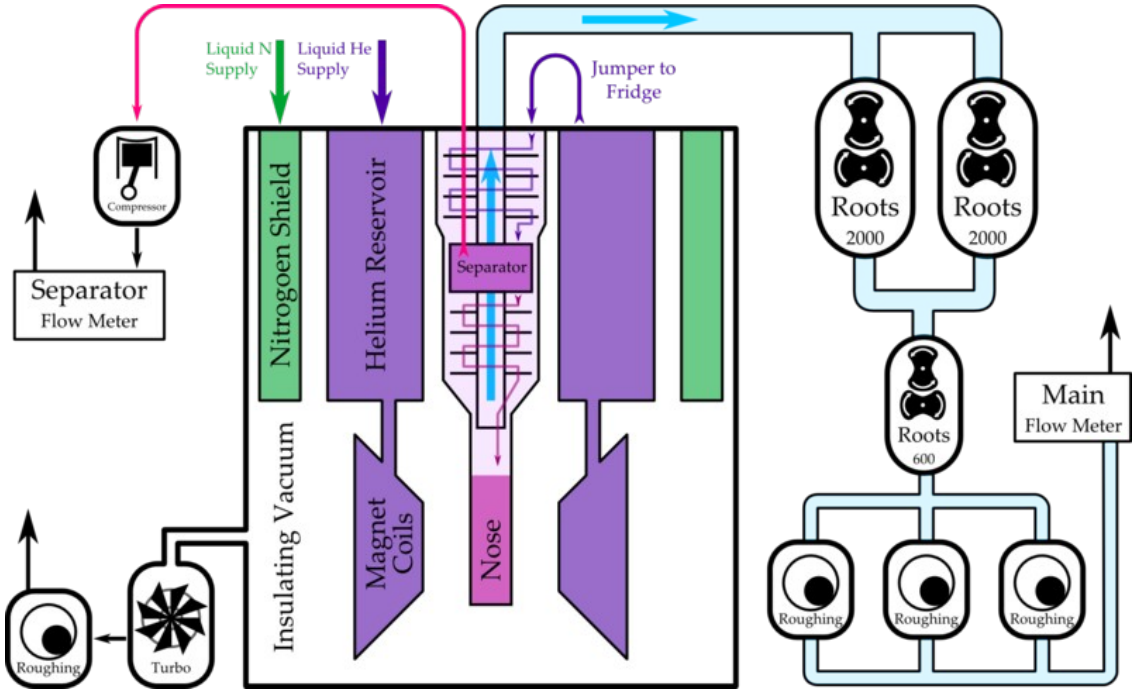
University of Virginia

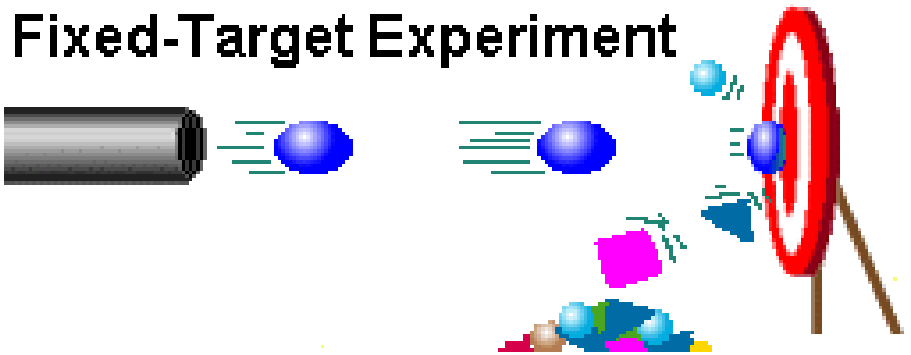
*Progress and developments with E1039 polarized target system*

# Outline

- Status on the Target
- Results of UVA Test Run
- SPT Behavior and Expectations
- Needed from FNAL
- Looking Forward

# Solid Polarized Target System




- A marriage of sciences for the purpose of improving the statistical significance of interaction of a particular helicity (for fixed targets)
- Reach for the Highest Possible Figure of Merit (highest polarization over the course of the experiment)

# Best Way To Get Things Done For E1039

- 1K 5T High Cooling power with Dynamic Nuclear Polarization

  - Dope target material with paramagnetic centers:

  Irradiation doping to just the right density ($10^{19}$ spins/cm$^3$) usually done at NIST ~$10^{17}$ electrons/cm$^2$ under 87K Ar (called warm dose, can achieve more than 90% for $NH_3$)

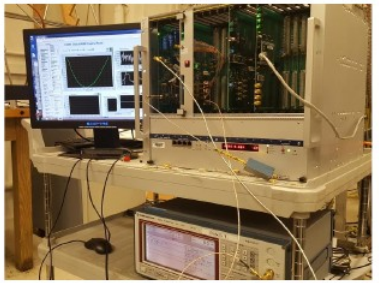
  $ND_3$ requires warm and cold dose (~1 K) to be optimized

  - Polarize the centers: Just stick it in a magnetic field

  - Use microwaves to transfer this polarization to nuclei: mutual Electron-proton spin flips re-arrange the nuclear Zeeman populations to favor one spin state over the other

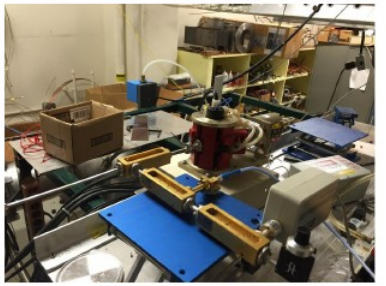
- Optimize so that DNP is performed at *B/T* conditions where electron $t_1$ is short (ms) and nuclear $t_1$ is long (minutes or hours)
- For our target material (Ammonia) electrons ~few milliseconds and protons 10s of minutes

# E1039 Polarized Target



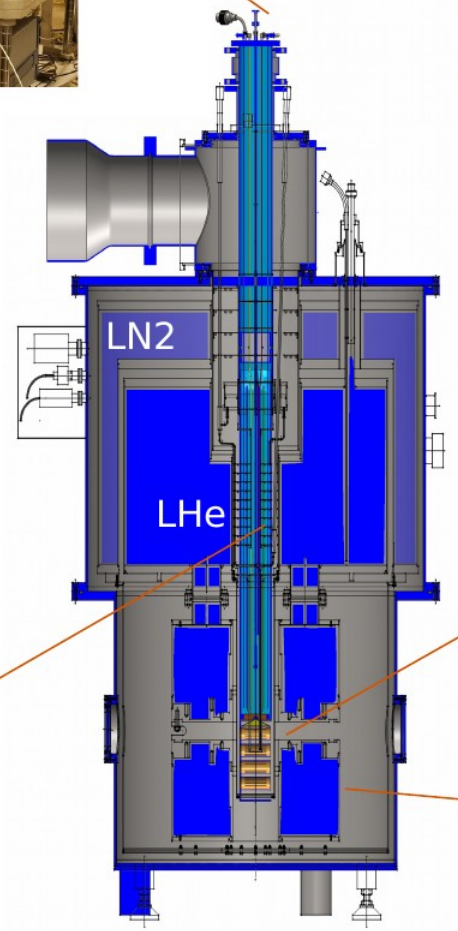
NMR

Insert



Microwave

Pumps




Target material

Fridge

Magnet

# So Far Accomplished

- Rotation/Modification of Magnet
- Fridge Repairs/Modifications
- Design Build Target Insert
- Redesign/Build NMR for VME
- Machine 2 nose pieces with beam window
- Production of some material
- Automated Microwave Control system
- Fully integrated target run
- Multiple cooldowns and target testing

# POLARIZED TARGET SUBSYSTEMS

Magnet | Fridge | Insert | NMR | Microwave | Pumps | Target material

Original design by S.Penttila, Oxford Instr.

kept at LANL storage since ~2000

Feasibility study

shipped to UVA in 2013

1st cooldown 06/2013

Rotation of the coils

shipped to Oxford Instruments

new configuration, 2nd cooldown

$dB/B < 10^{-4}$ on 3d grid, 5T over 8cm

Back to UVA

3rd cooldown, rotated coils test

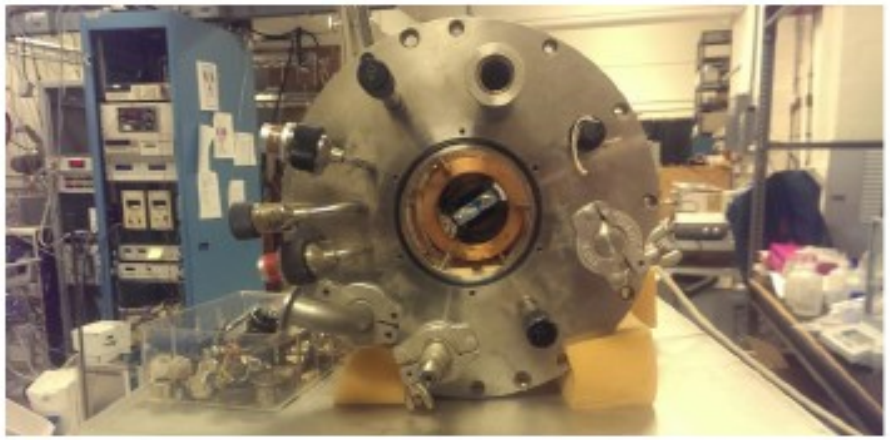
magnet is in a very good shape

# POLARIZED TARGET SUBSYSTEMS

Magnet | **Fridge** | Insert | NMR | Microwave | Pumps | Target material

## Fridge modifications

- replaced separator can
- cleaned heat exchangers oxide/corrosion
- leak checked
- refitted run and bypass valves
- installed new LHe channel
- installed 8 temperature sensors
- manufactured new nose, 10mil window



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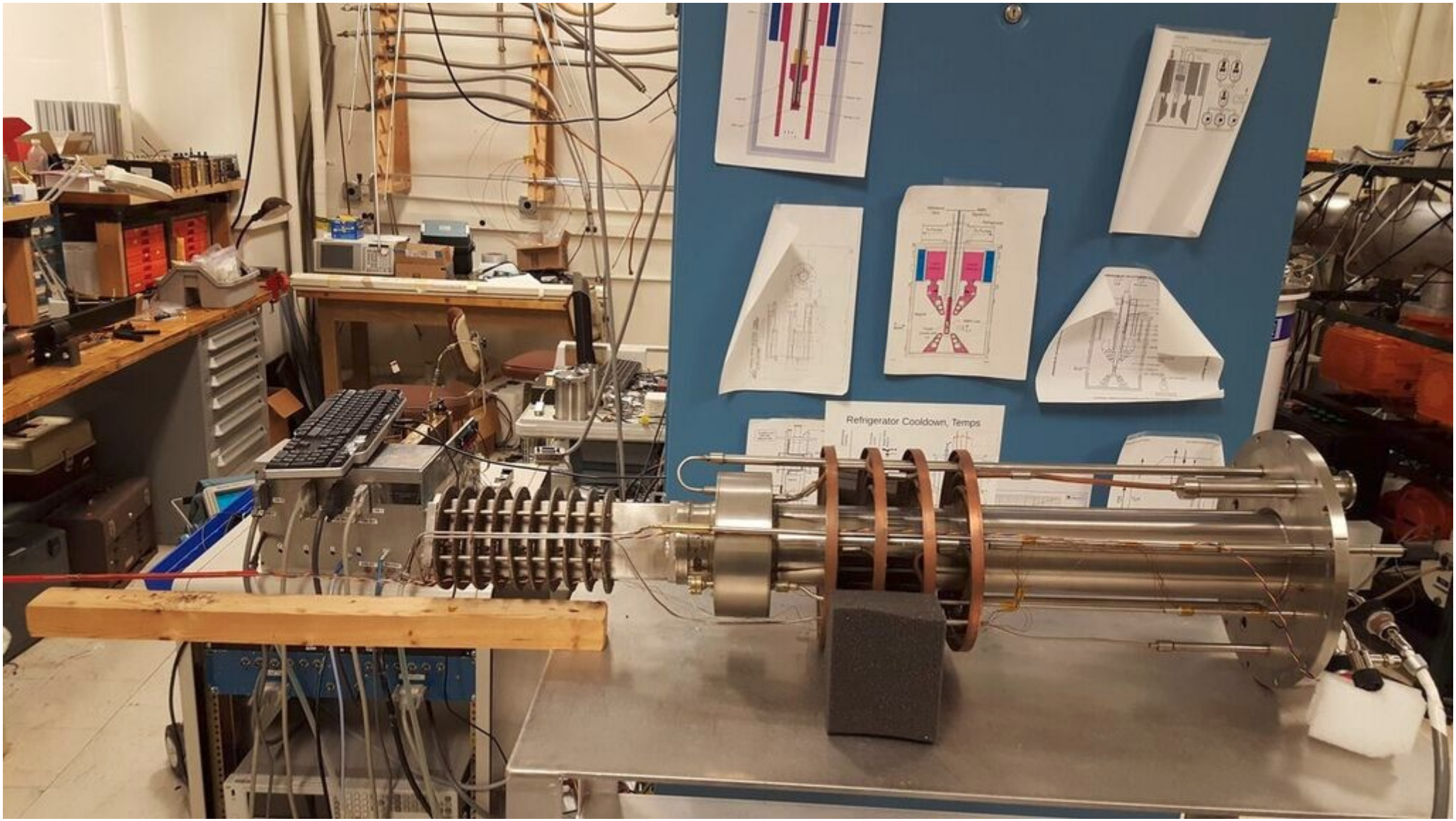
## Fridge alignment

- made laser setup
- shell, fridge, turret and piston rotation
- target insert length

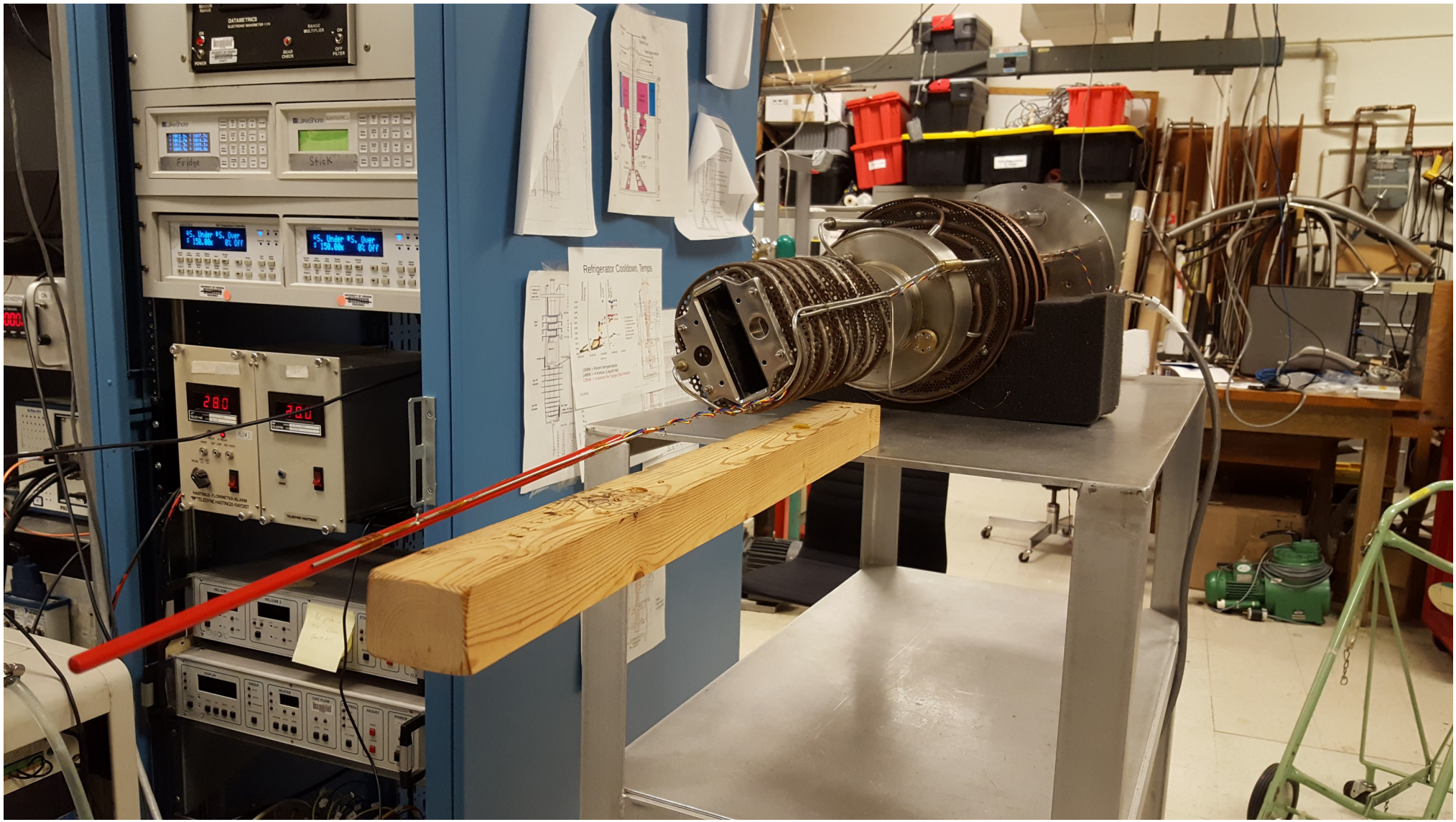
## Fridge tests

- 4th and 5th cooldowns
- reached 1K 07/2015

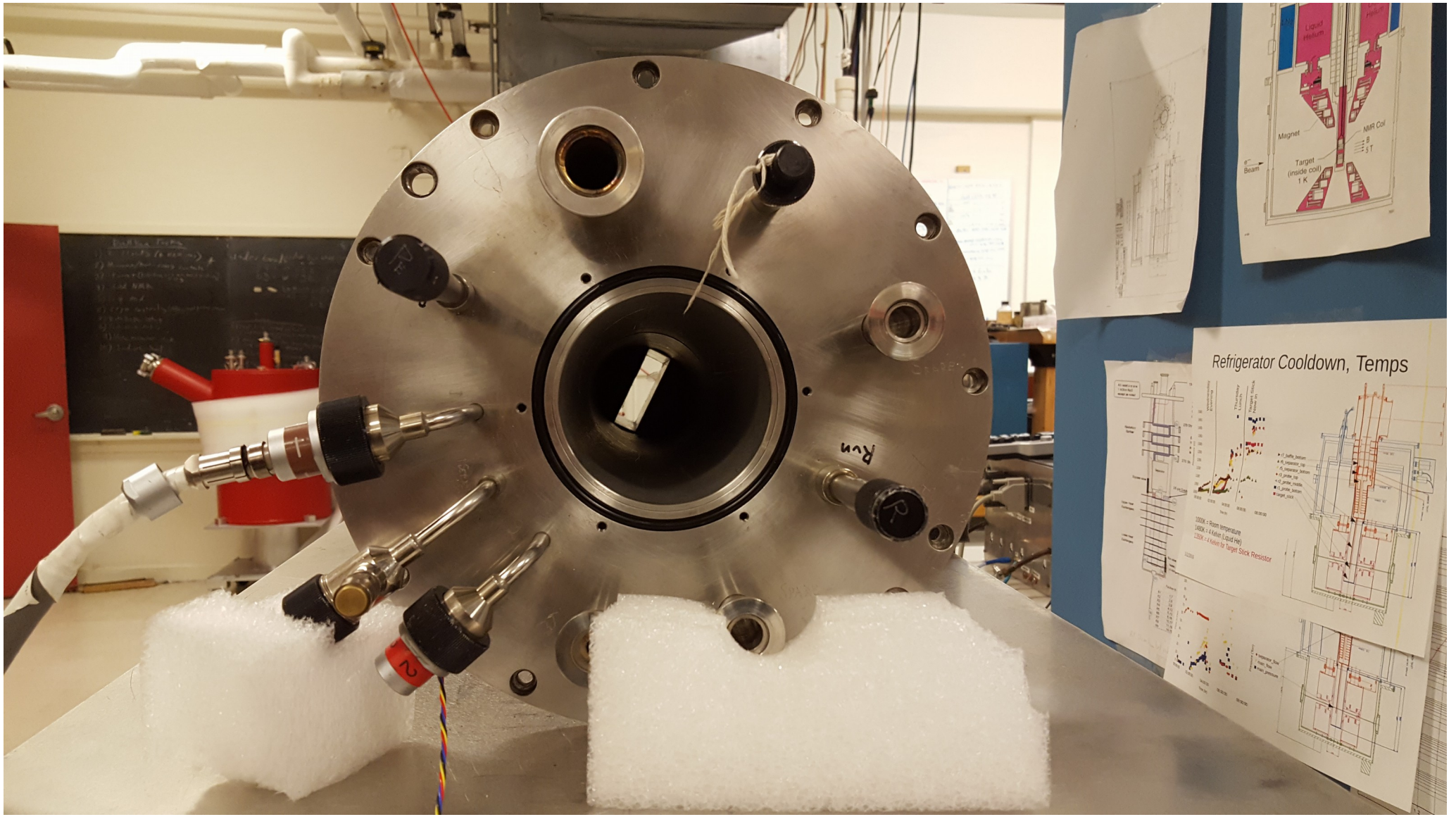
# Recent Modifications



# Bottom of Fridge



# Top of Fridge



# Inside Looking Down

# POLARIZED TARGET SUBSYSTEMS



New insert

- four 2.7x2x80mm long target cups
- NH3, C disk, empty
- six NMR channels (3 per cup)
- microwave horn for full cup volume
- temperature sensors
- He3 bulb line
- copper thermal barrier
- carbon fiber enclosure





# POLARIZED TARGET SUBSYSTEMS

Magnet Fridge **Insert** NMR Microwave Pumps Target material

## New insert

- four 2.7x2x80mm long target cups
- NH3, C disk, empty
- six NMR channels (3 per cup)
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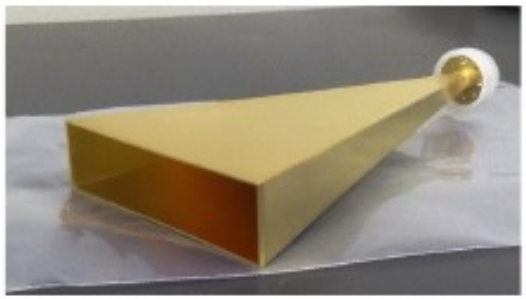
## Insert test

- Warm test is complete
- Load and polarization test



# POLARIZED TARGET SUBSYSTEMS

Magnet Fridge Insert **NMR** Microwave Pumps Target material

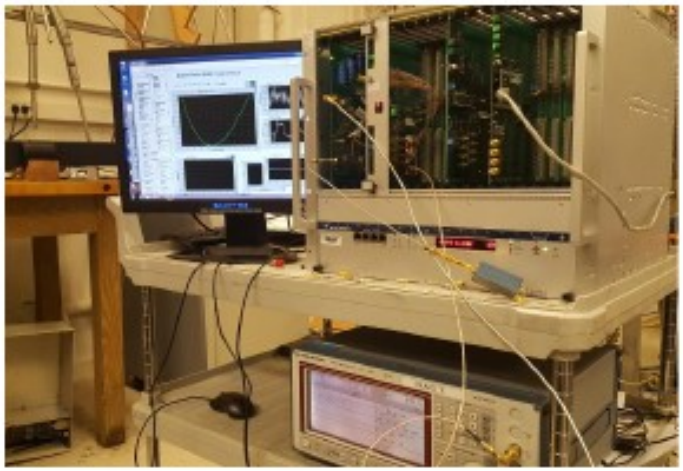
New NMR system developed by LANL

- followed general Liverpool design
- Q-meter as double wide VME module
- 1 analog / 1 digital boards, crate controller
- 16 bit ADCs/DACs, modern RF electronics
- USB/Ethernet interface, LabView based DAQ




LANL NMR system tests at UVA

- 1st NMR cooldown 2014 (total 3 cold tests)
- 04/2016 full comparison to Liverpool Q-meter
- signal/noise ratio - waiting for results



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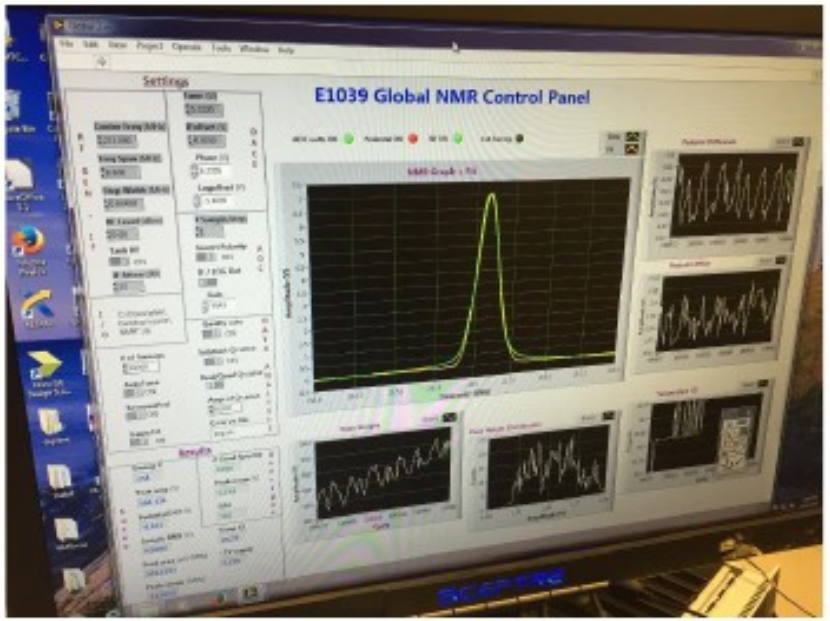


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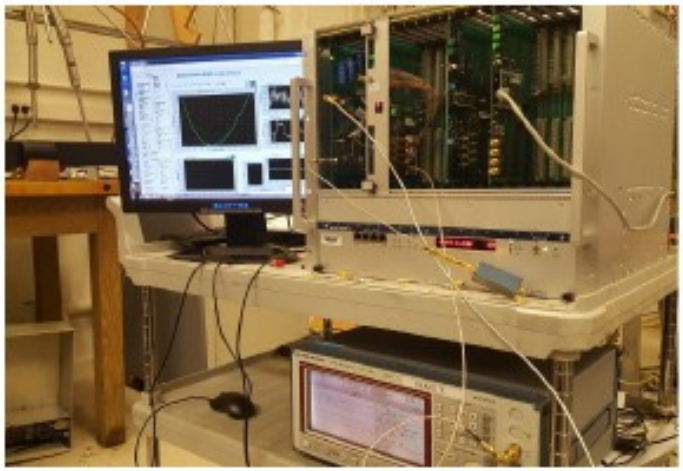
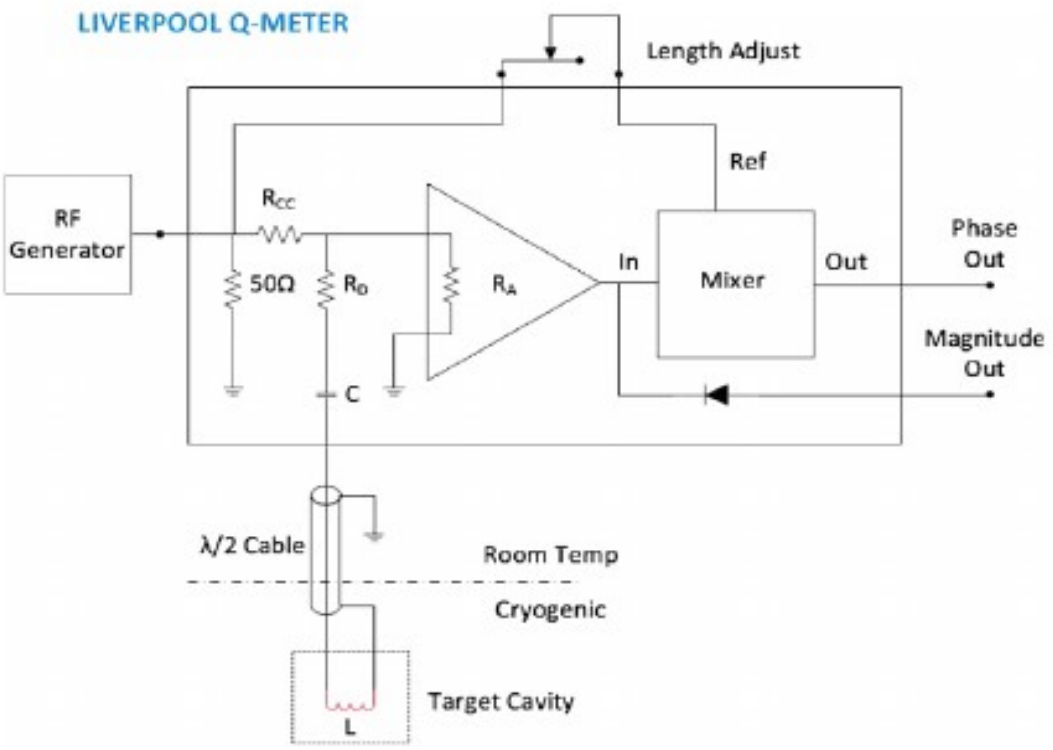
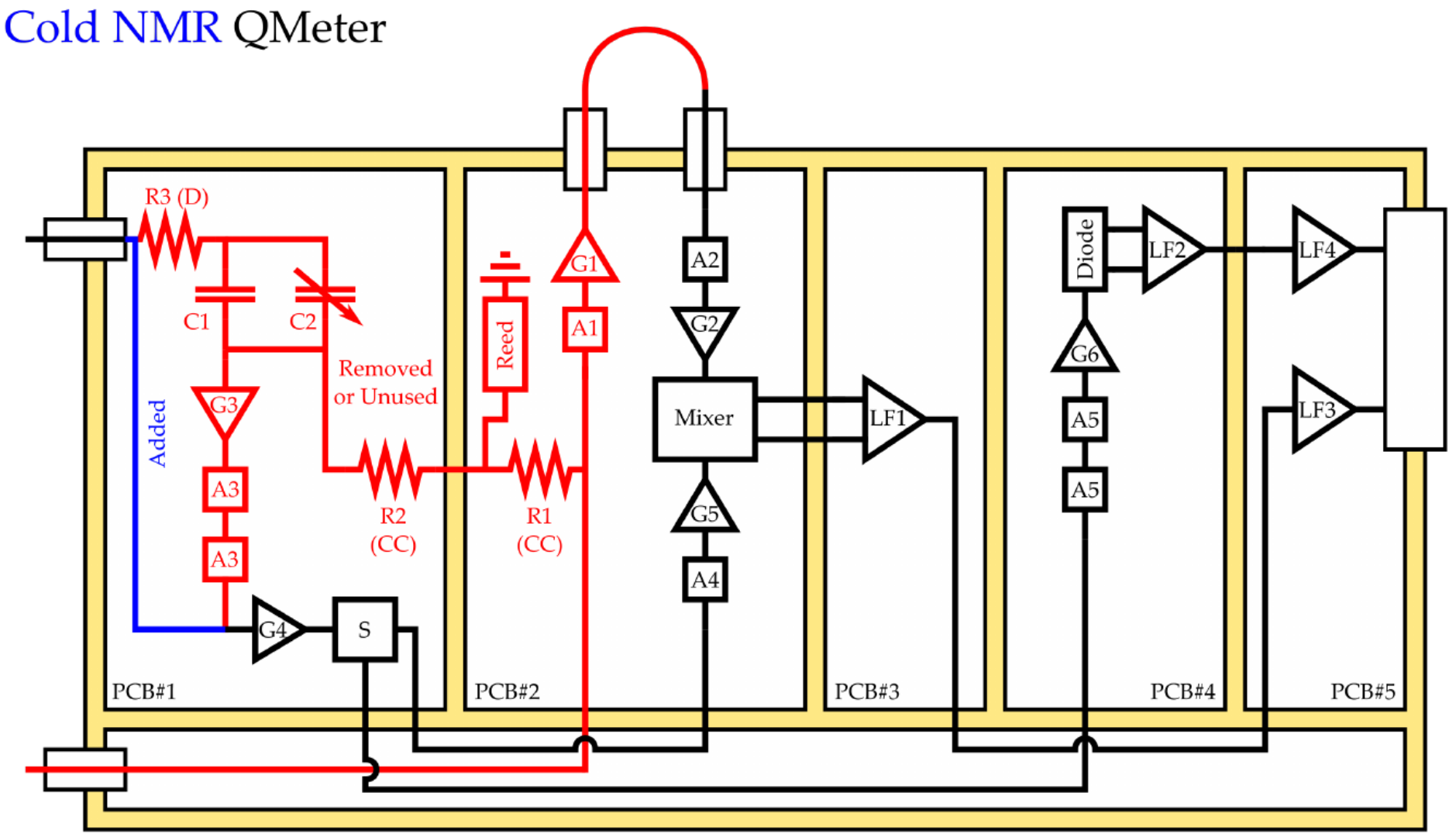


# NMR: Based on Liverpool Q-meter



# Cold NMR

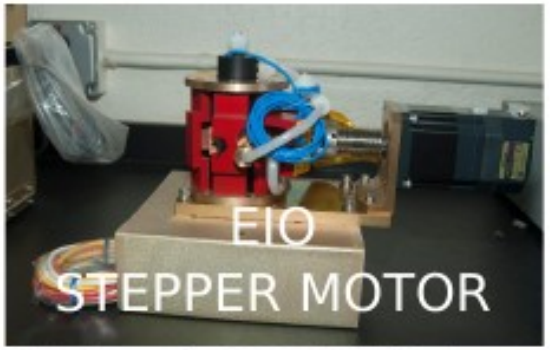

Cold NMR QMeter
R3 (D)
C1
C2
Removed
or Unused
Added
G3
A3
A3
G4
S
R2
(CC)
Reed
R1
(CC)
G1
A1
A2
G2
Mixer
G5
A4
LF1
Diode
G6
A5
A5
LF2
LF4
LF3
PCB#1
PCB#2
PCB#3
PCB#4
PCB#5

# POLARIZED TARGET SUBSYSTEMS



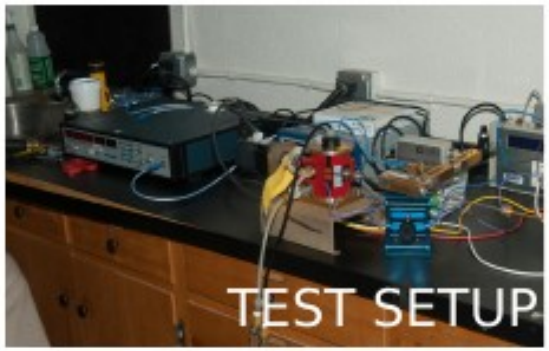
## New microwave source

- purchased by LANL
- new EIO tube from CPI, 20W output
- controlled by stepper motor
- new PS with software control UI



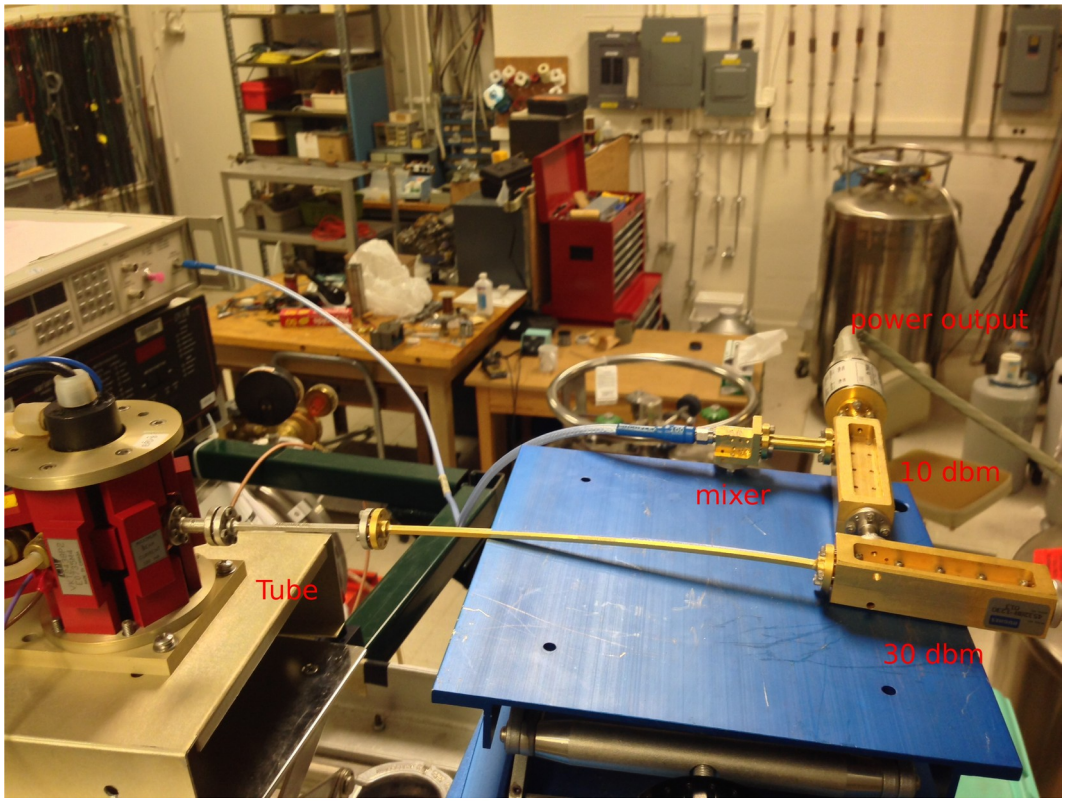

## Microwave source test

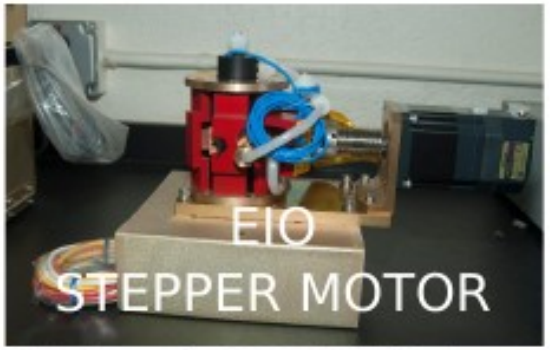
- built setup at UVA in 2015
- checked freq adjustments
- checked cathod HV adjustment


# POLARIZED TARGET SUBSYSTEMS

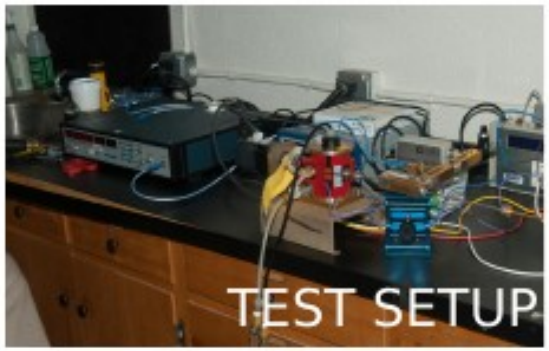
Magnet · Fridge · Insert · NMR · **Microwave** · Pumps · Target material



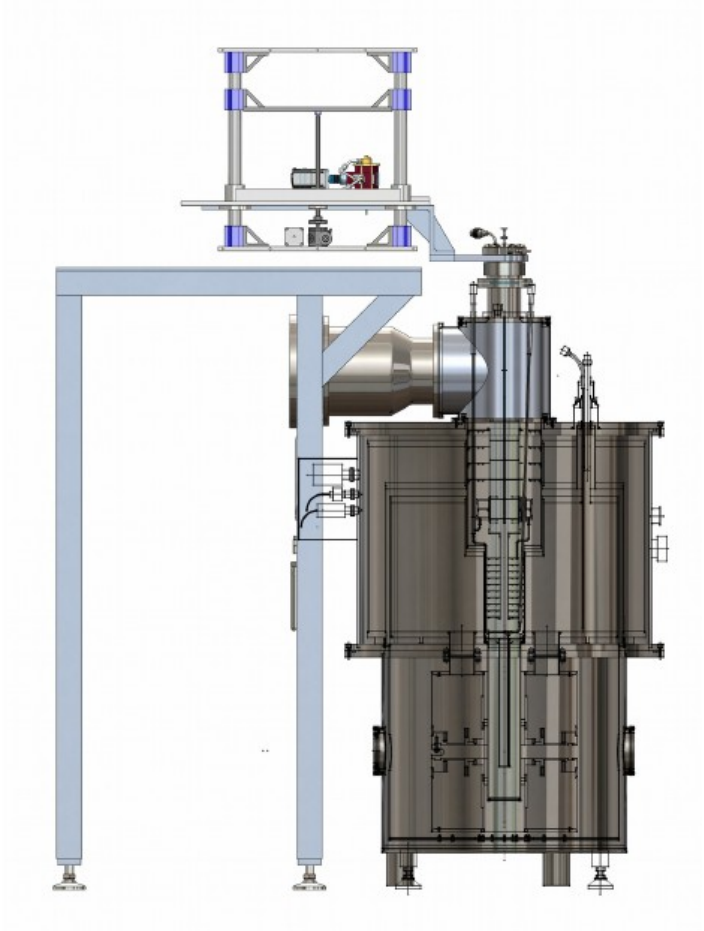


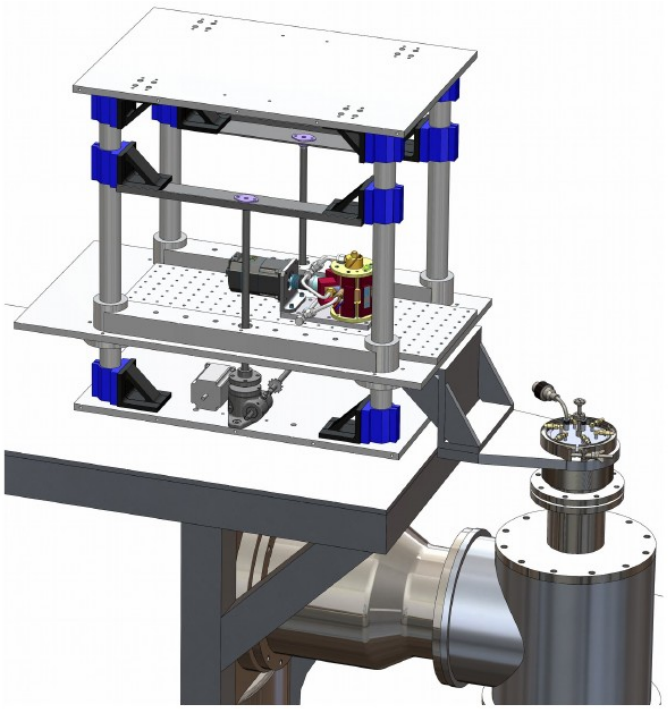
CPI

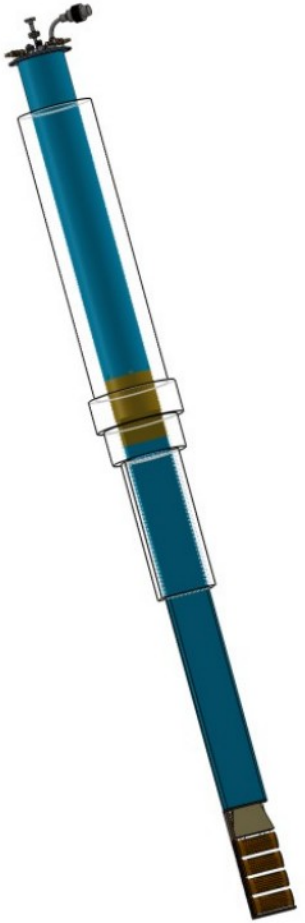



- Variation of the beam voltage allows up to 0.4% frequency tuning
- Cavity size adjustment allows an additional 1.5%
- D-band (~140 GHz)

# Microwave Setup



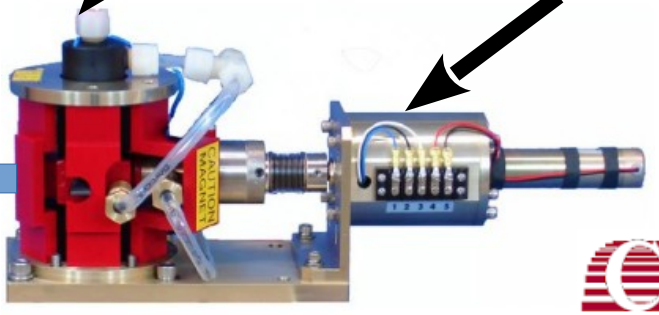





Target

water

Cavity Adjustment

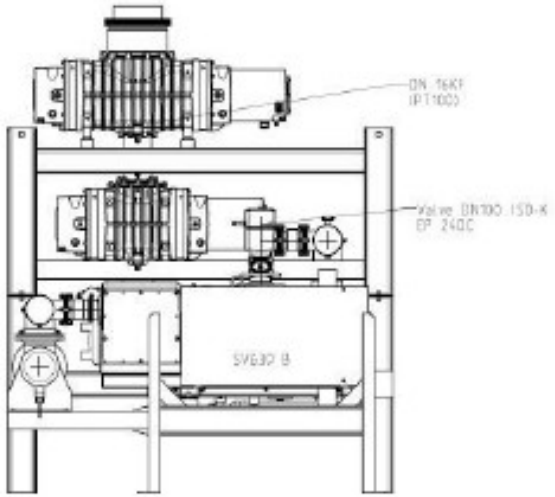


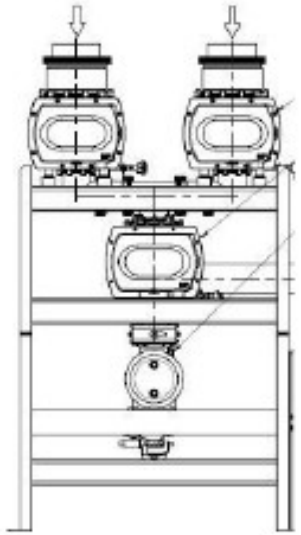
# POLARIZED TARGET SUBSYSTEMS



## Pumping system

- designed and built by Oerlikon
- target heat load ~1.4W
- $\mu$-wave:~1W, beam:~0.37W
- 3 roots (7000), 1 rotary vane (840)
- requires 100L LHe per day
- 14000 m3/hr pumping capacity






## Construction and tests

- first assembly at LANL spring 2015
- tested and shipped to FNAL
- assembled and tested 10/2015

# POLARIZED TARGET SUBSYSTEMS

Magnet Fridge Insert NMR Microwave Pumps **Target material**

## Production

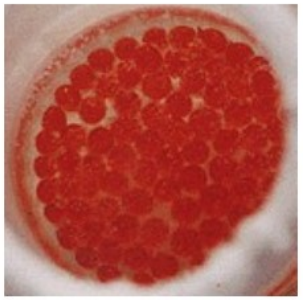
- dedicated setup to produce NH3 beads
- NH3 gas slowly frozen above LN2 bath
- ~1000 g is needed for 2 yr run
- ~450 g currently produced
- purchased three LN2 dewars for storage

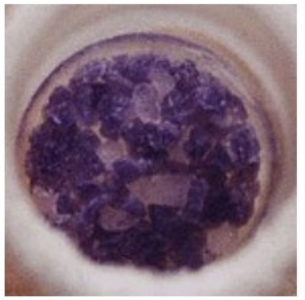
## Pre-Irradiation

- creates paramagnetic centers for DNP
- 14 MeV electron beam under LAr bath
- routinely done at NIST (Gaithersburg)
- time consuming, trained manpower
- ~100 g irradiated and ready for experiment

# Target Material

- Successful material for DNP characterized by three measures:
  1. Maximum polarization
  2. Dilution factor
  3. Resistance to ionizing radiation



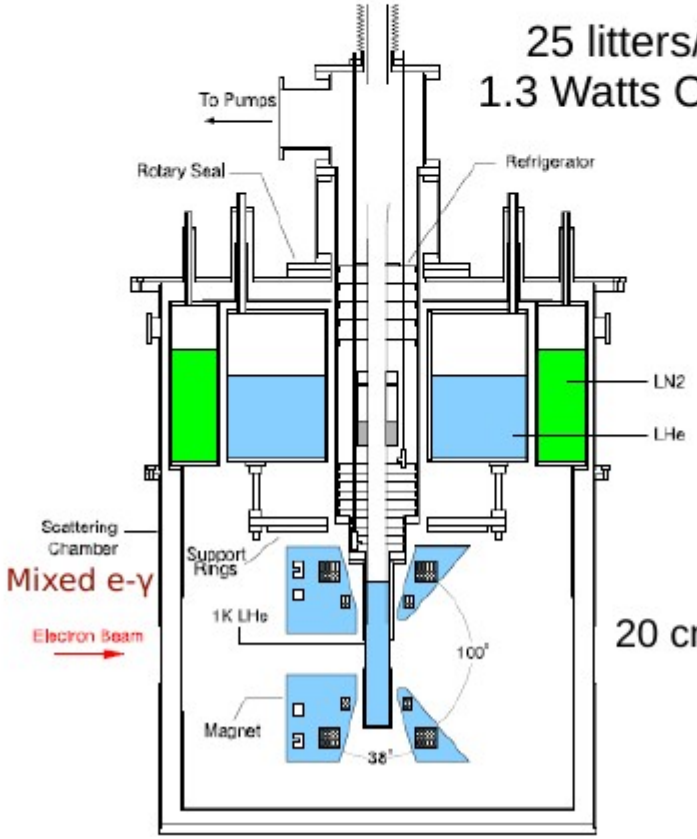


| | | | |
|---|---|---|---|
| Material | Butanol | Ammonia, $NH_3$ | Lithium Hydride, $^7LiH$ |
| Dopant | Chemical | Irradiation | Irradiation |
| Dil. Factor (% ) | 13.5 | 17.6 | 25.0 |
| Polarization (% ) | 90-95 | 90-95 | 90 |
| Material | D-Butanol | D-Ammonia, $ND_3$ | Lithium Deuteride, $^6LiH$ |
| Dil. Factor (% ) | 23.8 | 30.0 | 50.0 |
| Polarization (% ) | 40 | 50 | 55 |
| Rad. Resistance | moderate | high | very high |
| *Comments* | *Easy to produce and handle* | *Works well at 5T/1K* | *Slow polarization, but long $T_1$* |

# UVA/Jlab Polarized Target

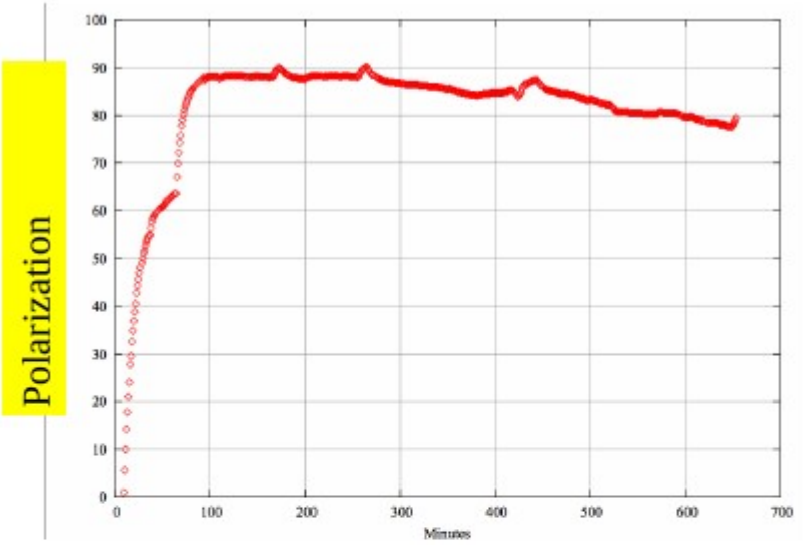
Solid polarized proton target, $NH_3$

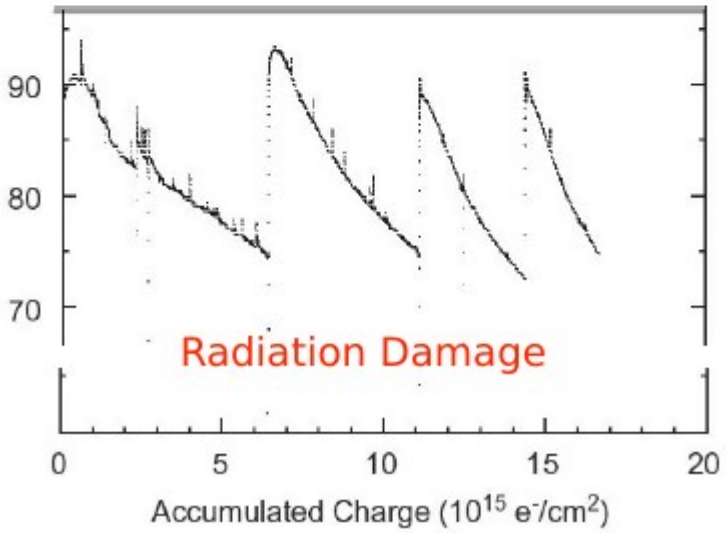
- 4He evaporation refrigerator
- 5 T polarizing field
- Dynamic Nuclear Polarization



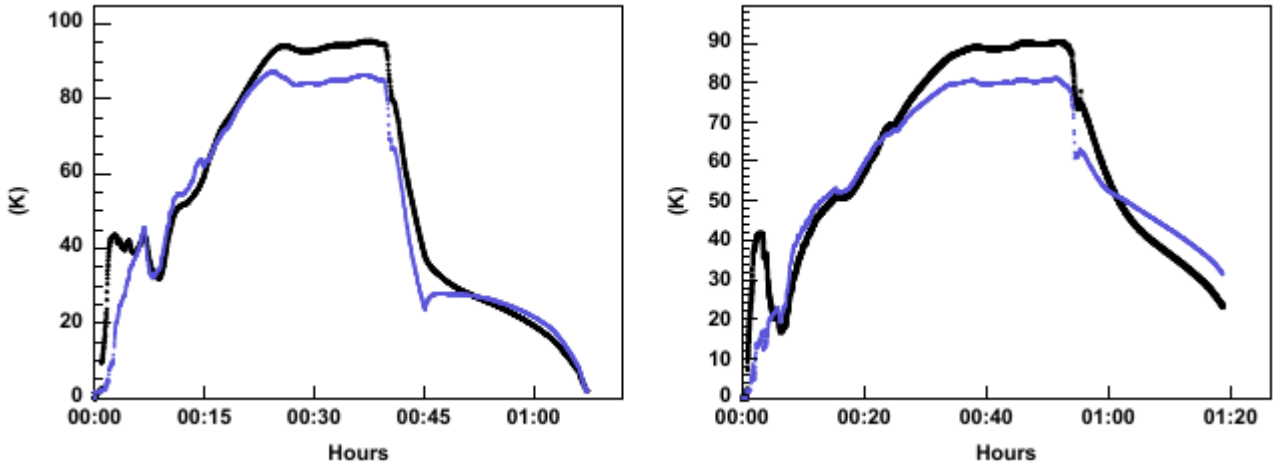

25 litters/min
1.3 Watts Cooling

20 cm bore



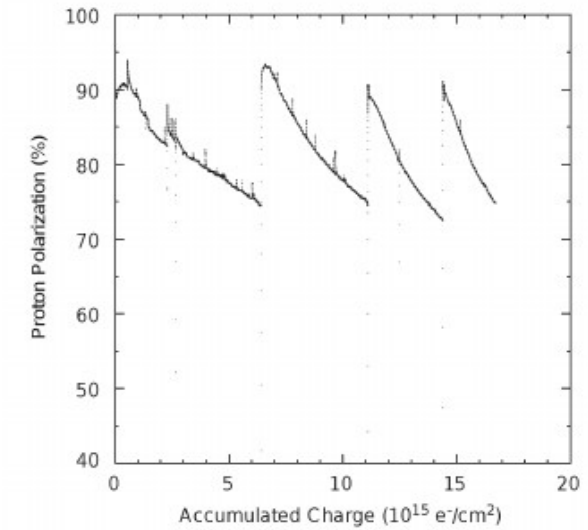



# Radiation Damage and Recovery



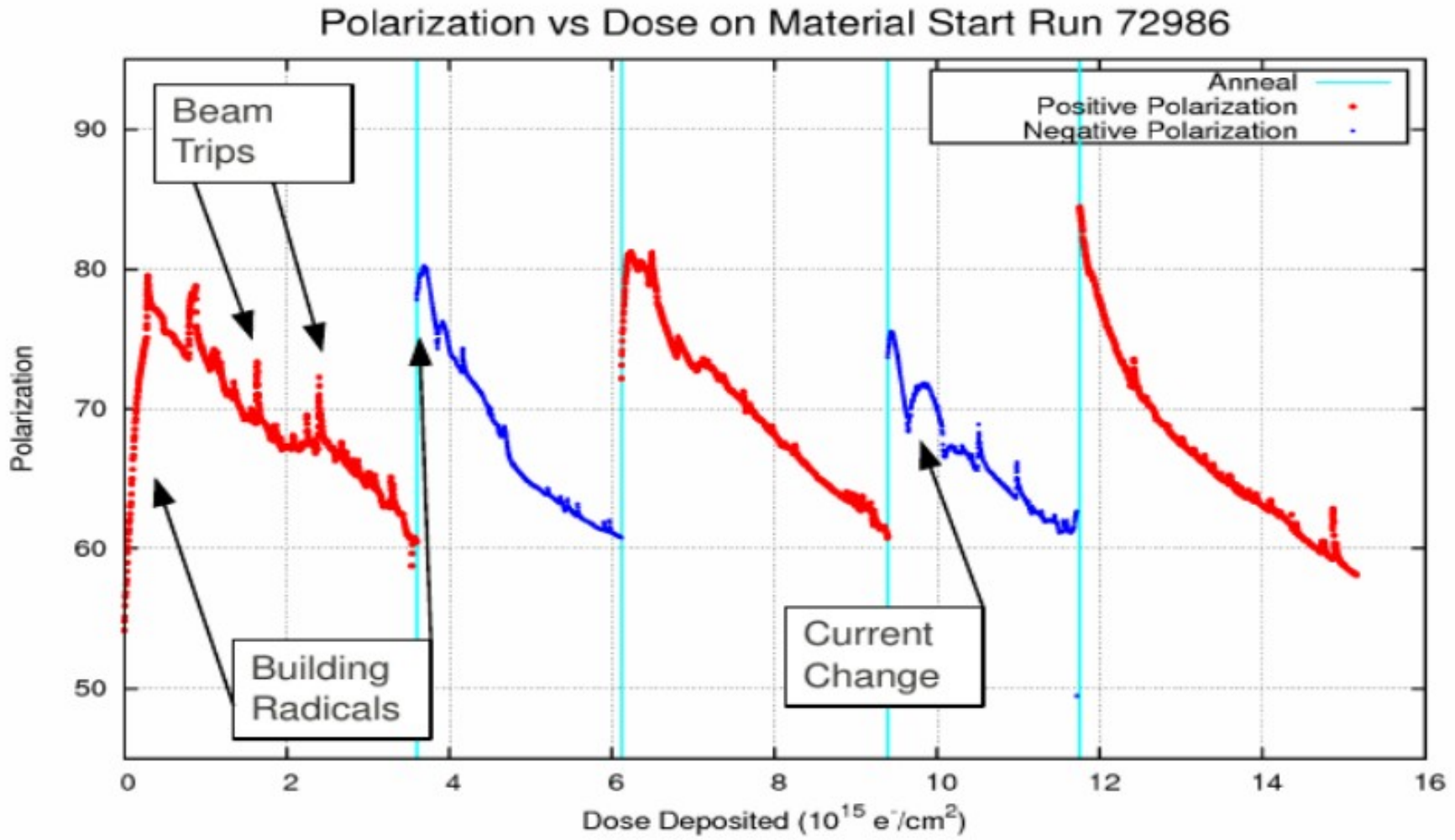

- Maximum Polarization decays as a function of dose
- Heat material (Anneal) to allow radicals to recombine
- Done by heat wire around target cell raising to 80-100K for 20-60 minutes
- Needed at 4Pprotons/cm$^2$ (about every shift)
- Once exhausted need target material replacement

# Target Material Exhaustion




- The collection of free radicals eventually leads to material exhaustion where annealing is no longer beneficial
- Material can go as far as 40 Pprotons/cm$^2$
- Time to replace target material : Requires pulling the target insert and removing material and replacing with optimized material
- For every target load need at least 3 TE target calibrations

# Characteristics of Polarization



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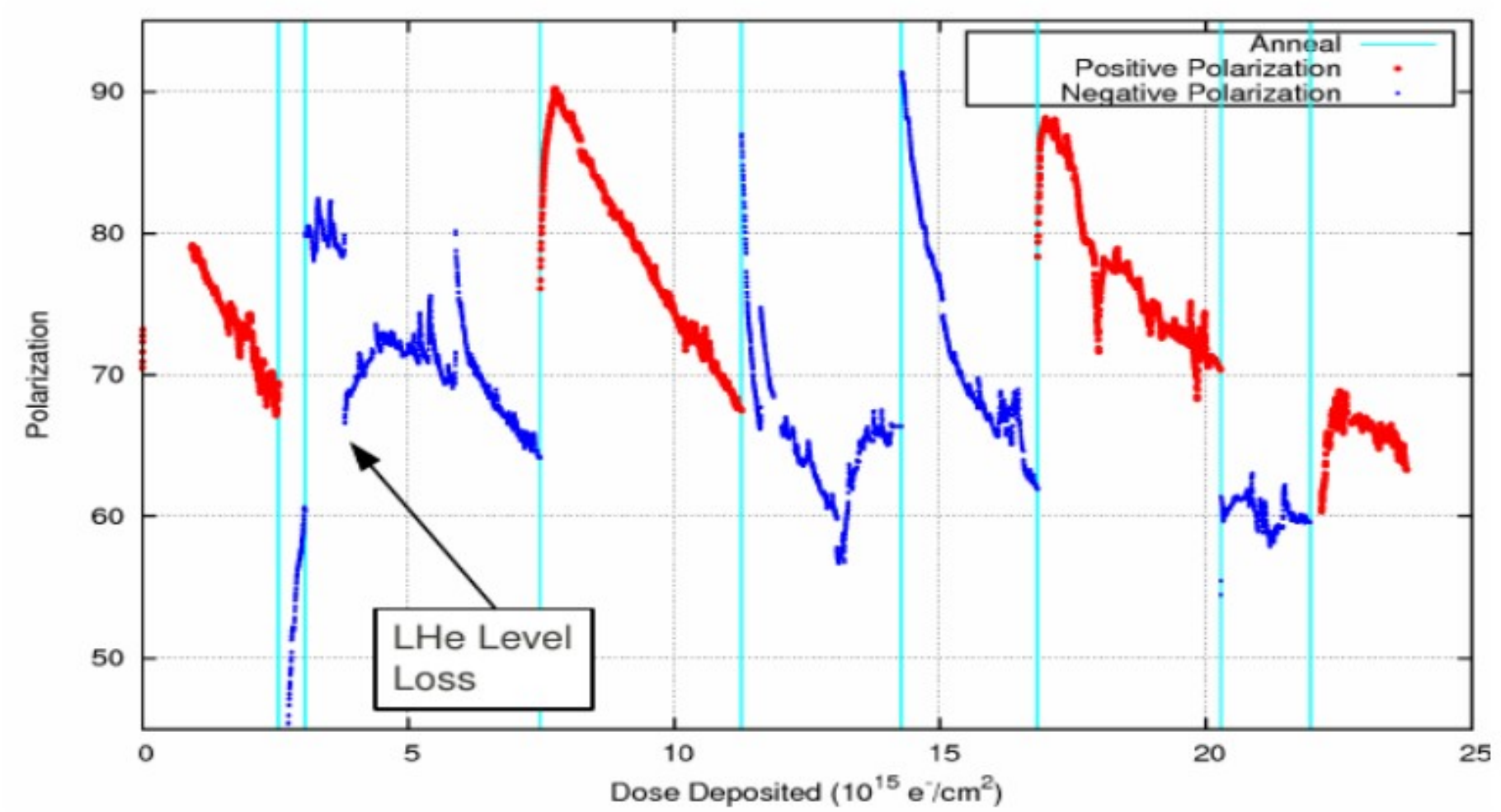
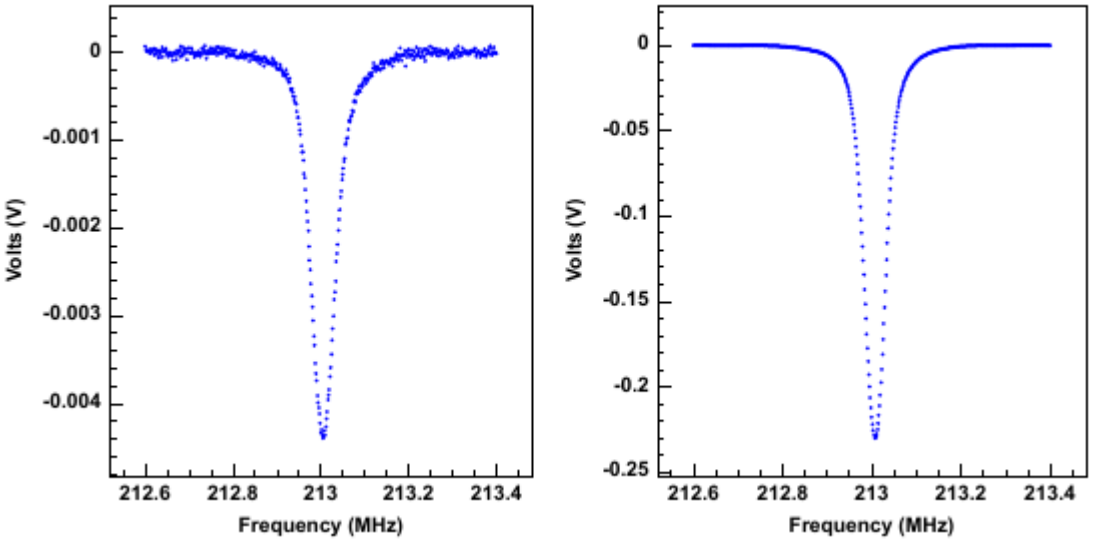
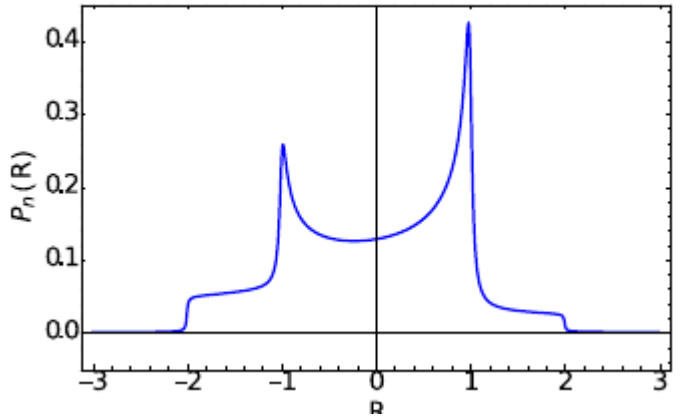


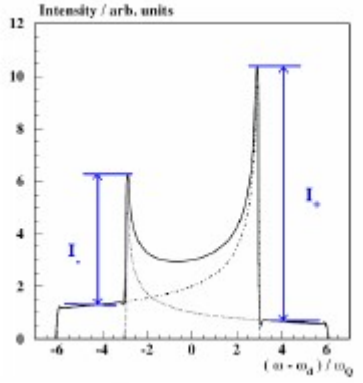
# Polarization Calibration and Measurement




Proton

$$P_{TE} = \tanh\left(\frac{\mu B}{kT}\right)$$




Deuteron

$$P_{TE} = \frac{4 + \tanh\frac{\mu B}{2kT}}{3 + \tanh^2\frac{\mu B}{2kT}}$$

$$P_z = \frac{R^2 - 1}{R^2 + R + 1}$$

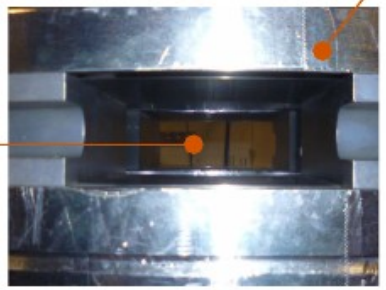
Neutron

$$P_n = (1 - 1.5\alpha_D)P_d \approx 0.91 P_d$$

# Putting it all Together

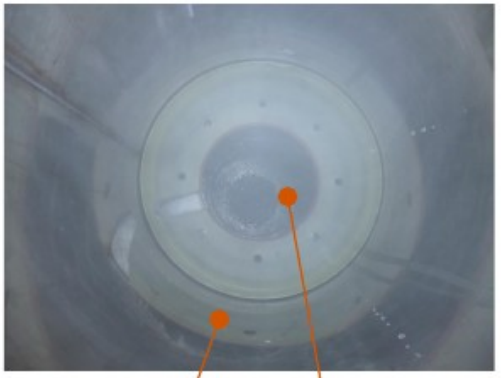
Final preparations and run

put vacuum chamber back together





leak checked fridge shell + nose

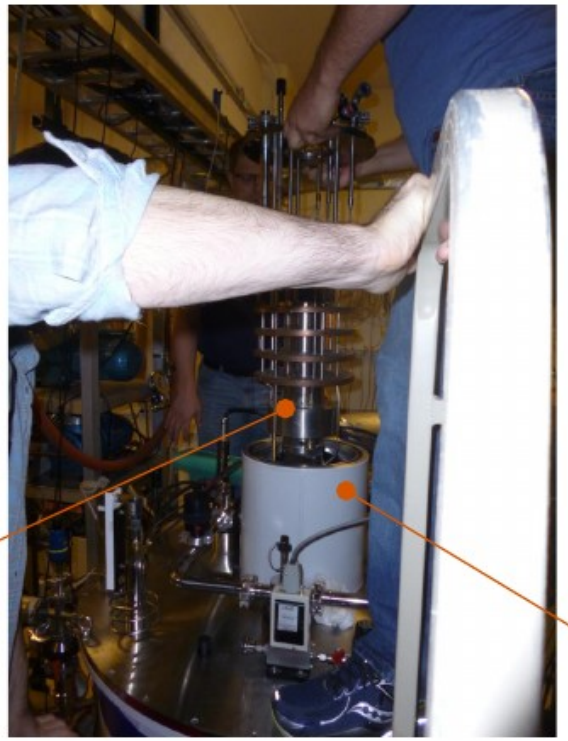



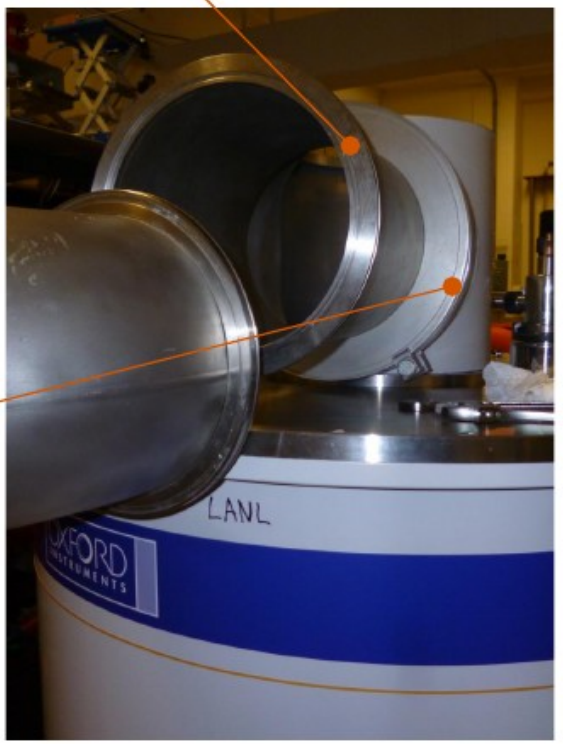
# Putting it all Together

Final preparations and run

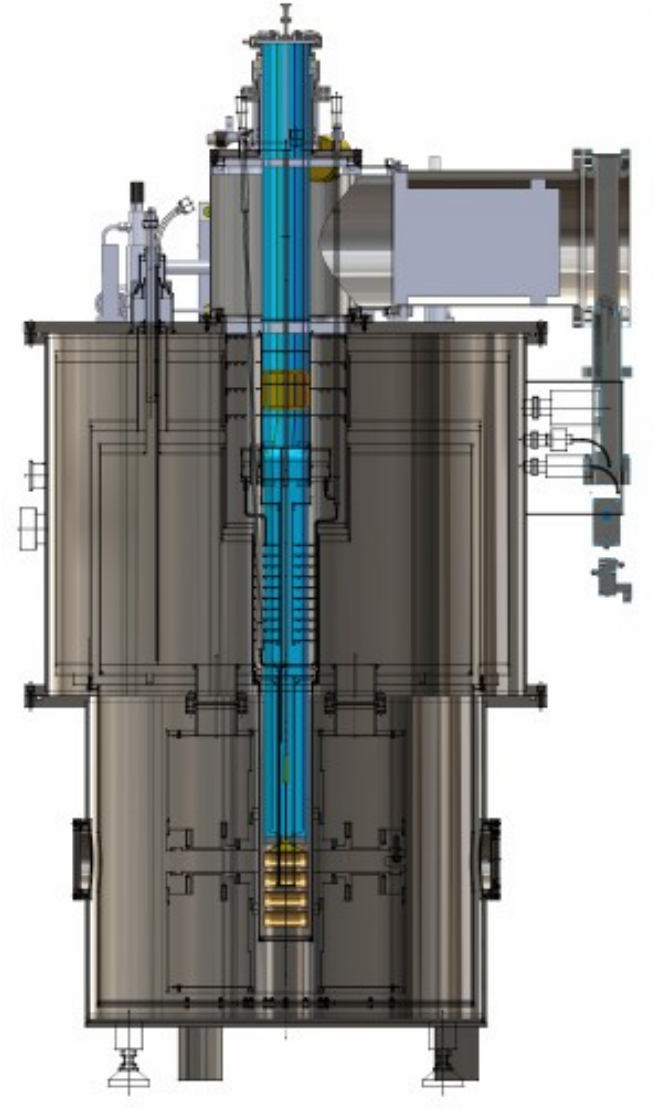
installed fridge

fitted turret to UVA pumping system



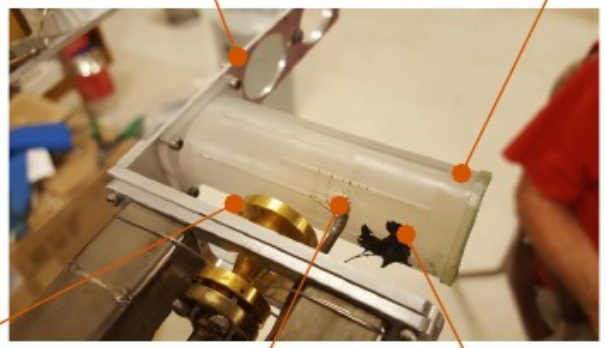
# Putting it all Together



# Test Full System

Final preparations and run

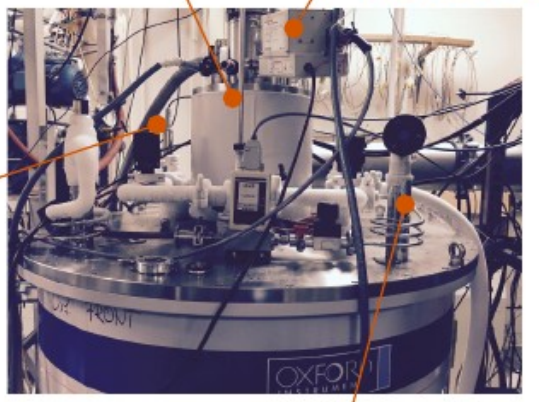
made test target insert, practiced installation





getting cold





# Cryogenic Performance

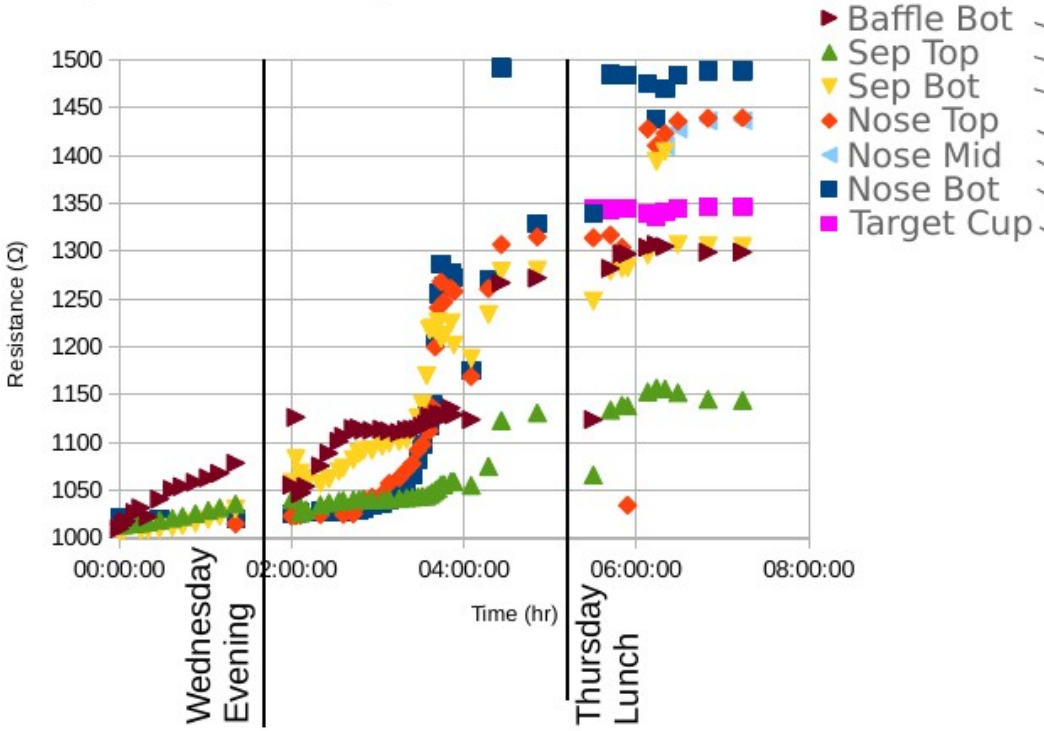
Test results

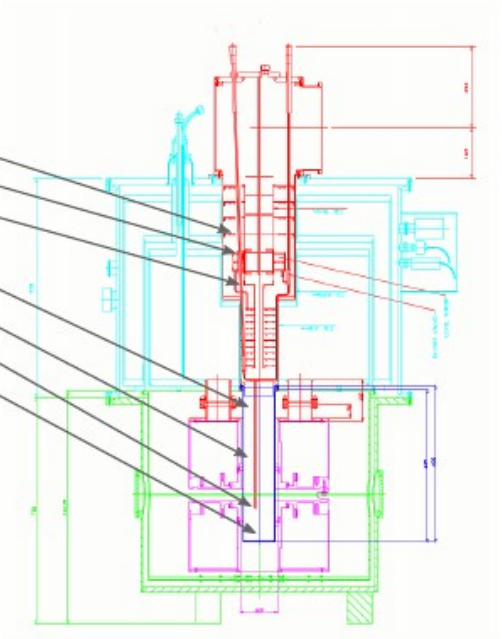
Fridge performance

separator and nose fill

~1hr to fill the nose after a night on standby

very stable, very little attention required



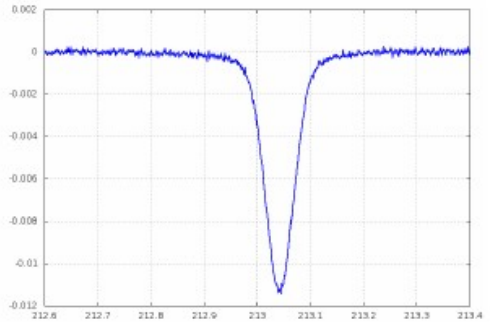



# Results of All the Work

Test results

Polarization

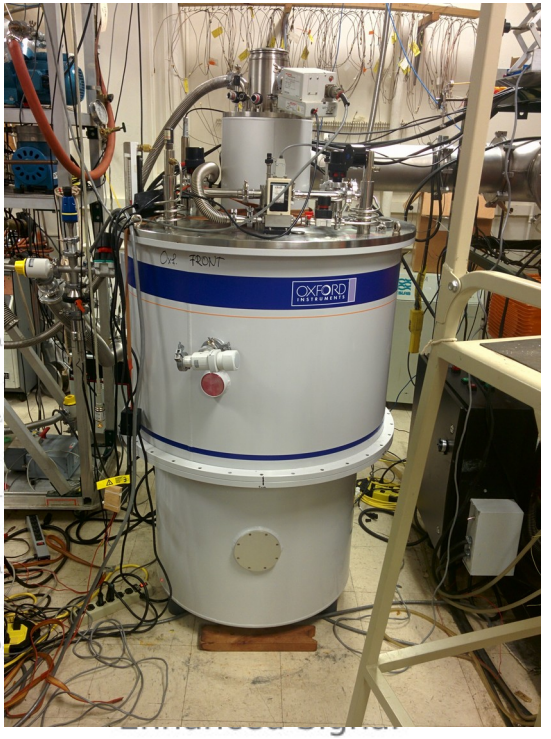
- polarized fresh NH3 both positively and negatively
- took extensive TE measurements
- alternated UVA and new LANL NMR systems

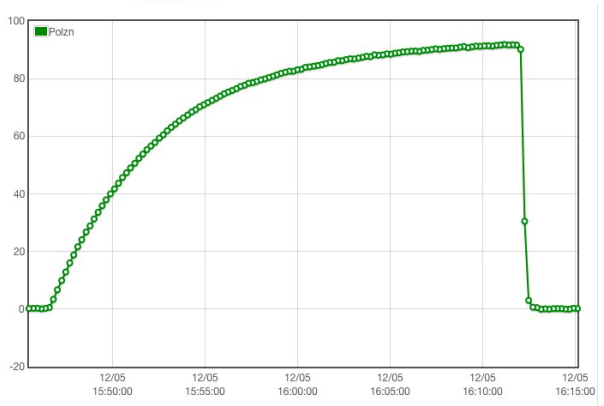


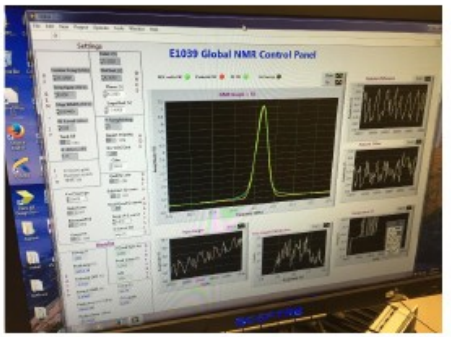

Frequency, MHz

TE signal

UVA NMR Signal

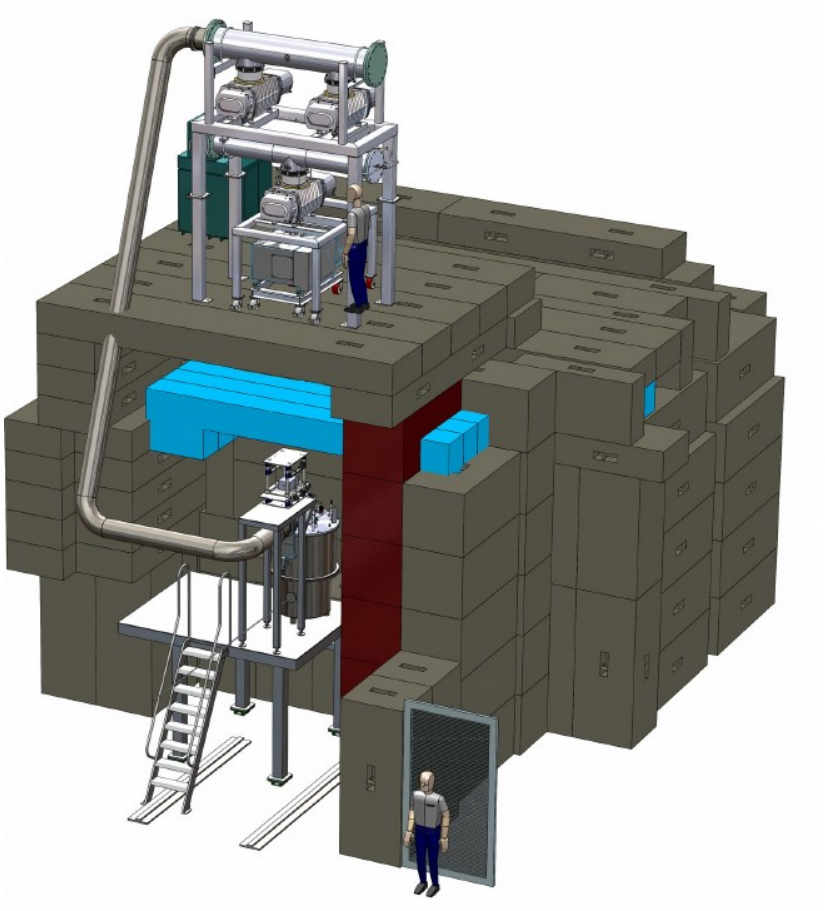





LANL NMR Signal

# Experimental Setup for E1039



## Required From FNAL

- Hoist above target

  (Magnet ~ 2000 lbs)
- Hoist for insert

  (~25 lbs)
- Borated Polyethylene
- Electrical Service lines
- Cooling for liquefier and pumps

# Still to Come

- Secondary pressure/temp sensor ($^3$He bulb)
- Additional Fridge Modifications for ease of target change-out
- Cold NMR system needed for optimal signal to noise for Deuteron/Neutron
- Maximize active number of target cells equipped with cold NMR (2 lines/coil) and field dimensions
- Remote Control for Microwave Power Supply
- Cryosystem auto-control
- Annealing system
- Material purchase and irradiation ($ND_3$ ~$40K)
- Making material and doing the irradiations (only 400g done out of 2.6kg)

# Summer Cooldown Group

Thank You