The SANE Polarized Target;
A Synopsis

Hall C Users Meeting, Fall 2009

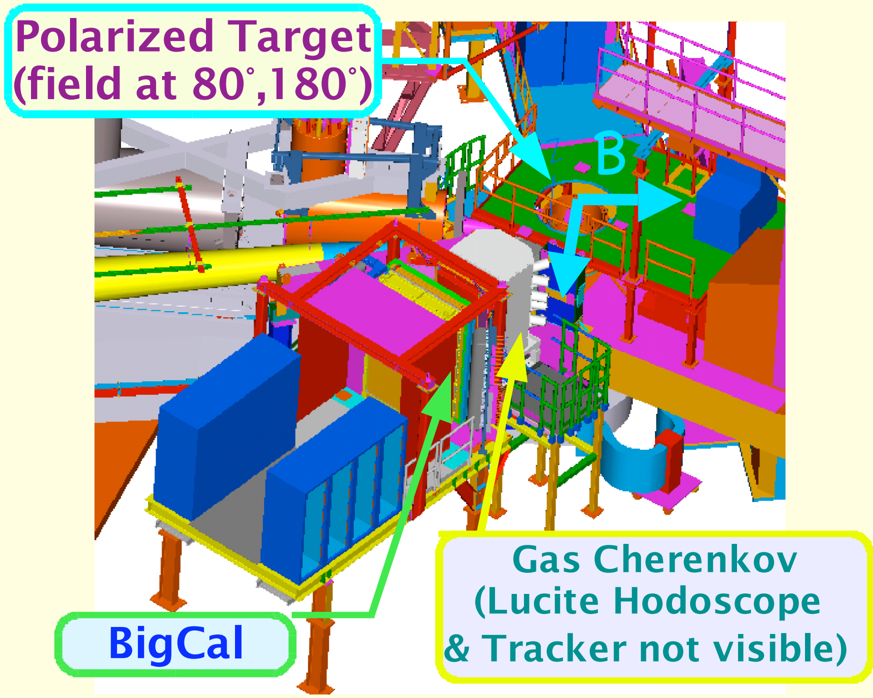
For the SANE Collaboration,
Narbe Kalantarians
University of Virginia

Outline

- Experiment
- Technique
- Apparatus
- Performance
- Status

Spin Asymmetries of the Nucleon Experiment - SANE
(TJNAF E07-003)

- PHYSICS: proton spin structures g2(x, Q^2) and A1 (x, Q^2) for $2.5<Q^2<6.5\text{GeV}^2$, $0.3<x_{Bj}<0.8$
- Address DOE 2011 Milestone for Proton Spin Structure
- Measure inclusive double polarization near-orthogonal asymmetries to:
- access quark-gluon correlations using LO twist-3 effects from $d2 = \int_0^1 x^2(2g1+3g2)dx$: compare with Lattice QCD, QCD sum rules, bag model, chiral quarks
- test nucleon models (x dependence) and Q^2 evolution
- explore A1(x->1); test polarized local duality
- METHOD: Detect 4.8 & 6 GeV polarized electrons scattered on solid polarized ammonia target with BETA, a novel large solid angle electron telescope (BigCal + Cherenkov + Lucite + Tracker)

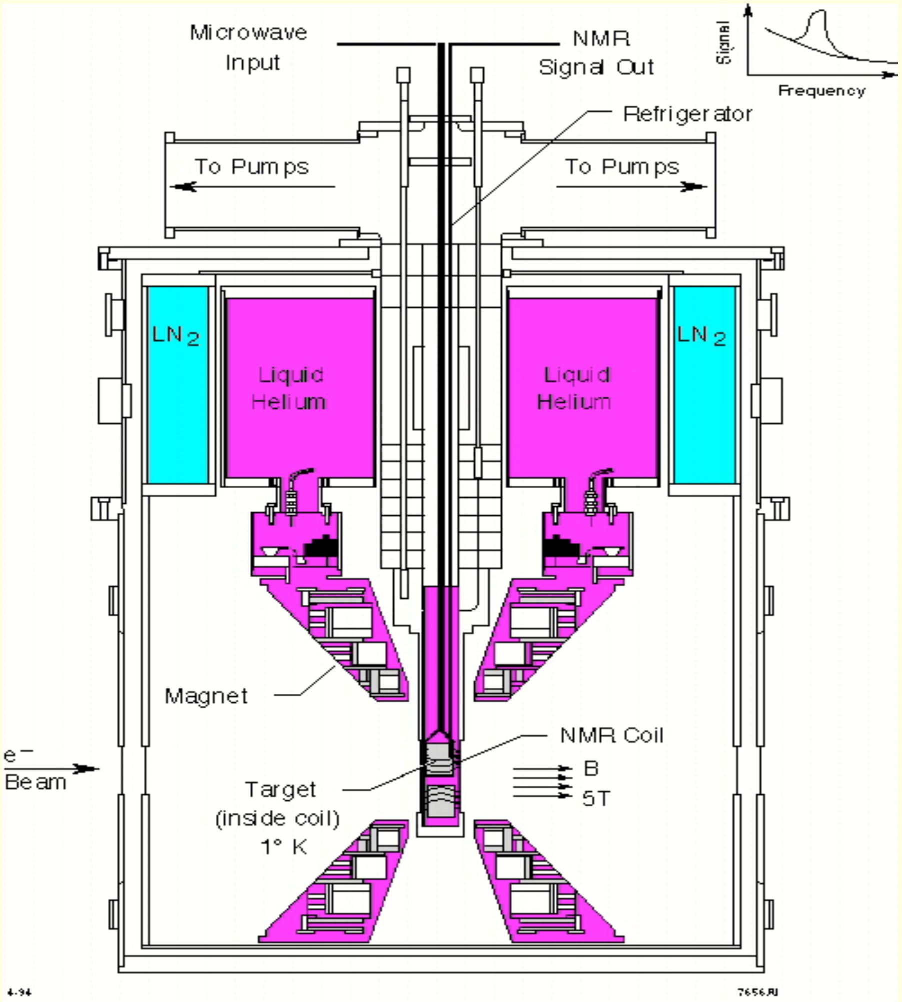


Polarized Target
(field at 80°,180°)

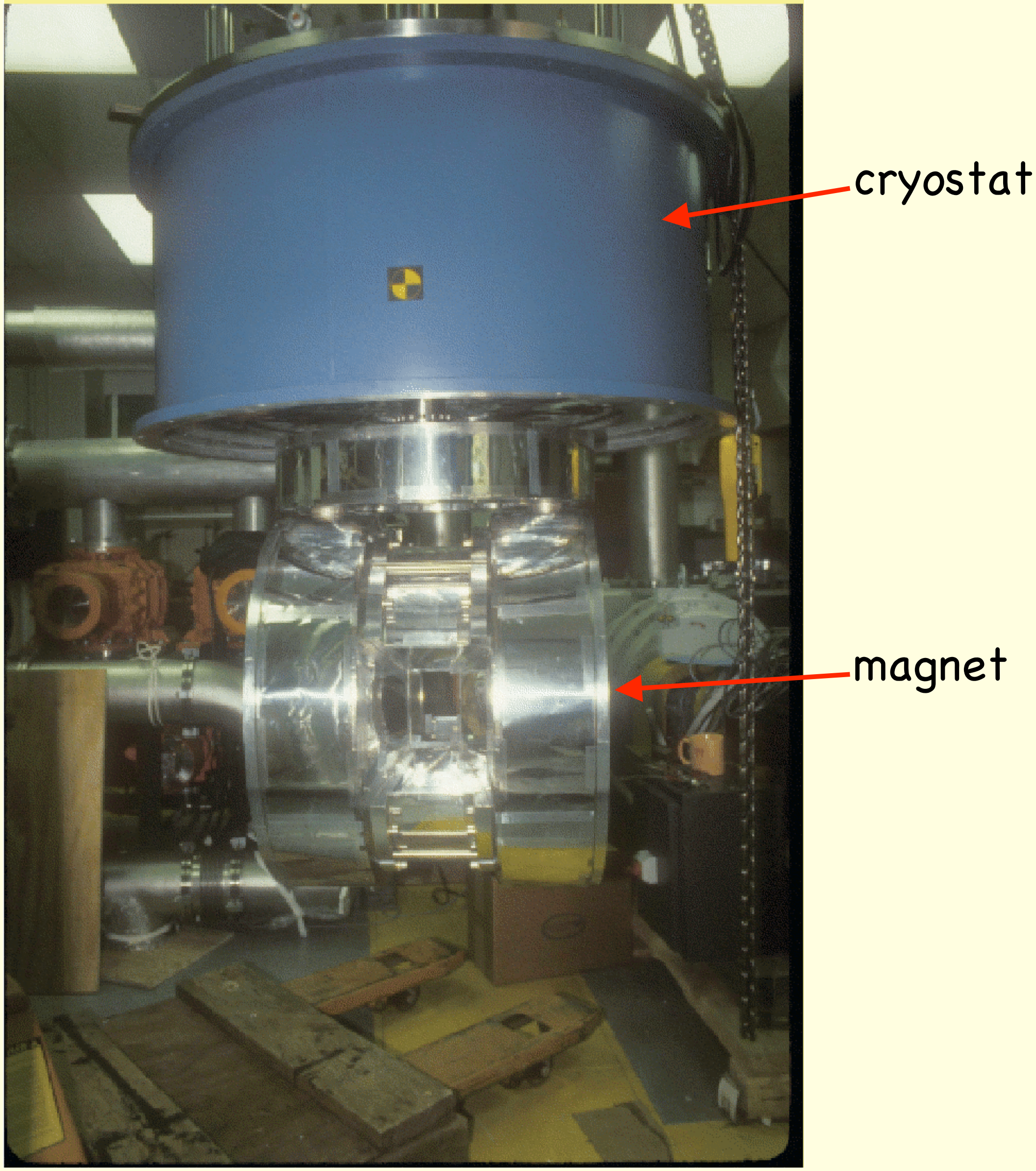
BigCal

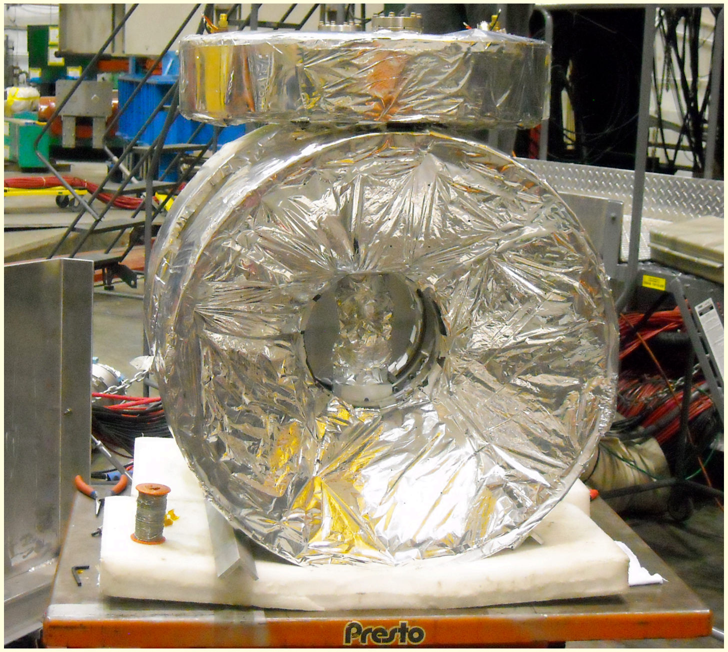
Gas Cherenkov
(Lucite Hodoscope
& Tracker not visible)

SANE Polarized Target

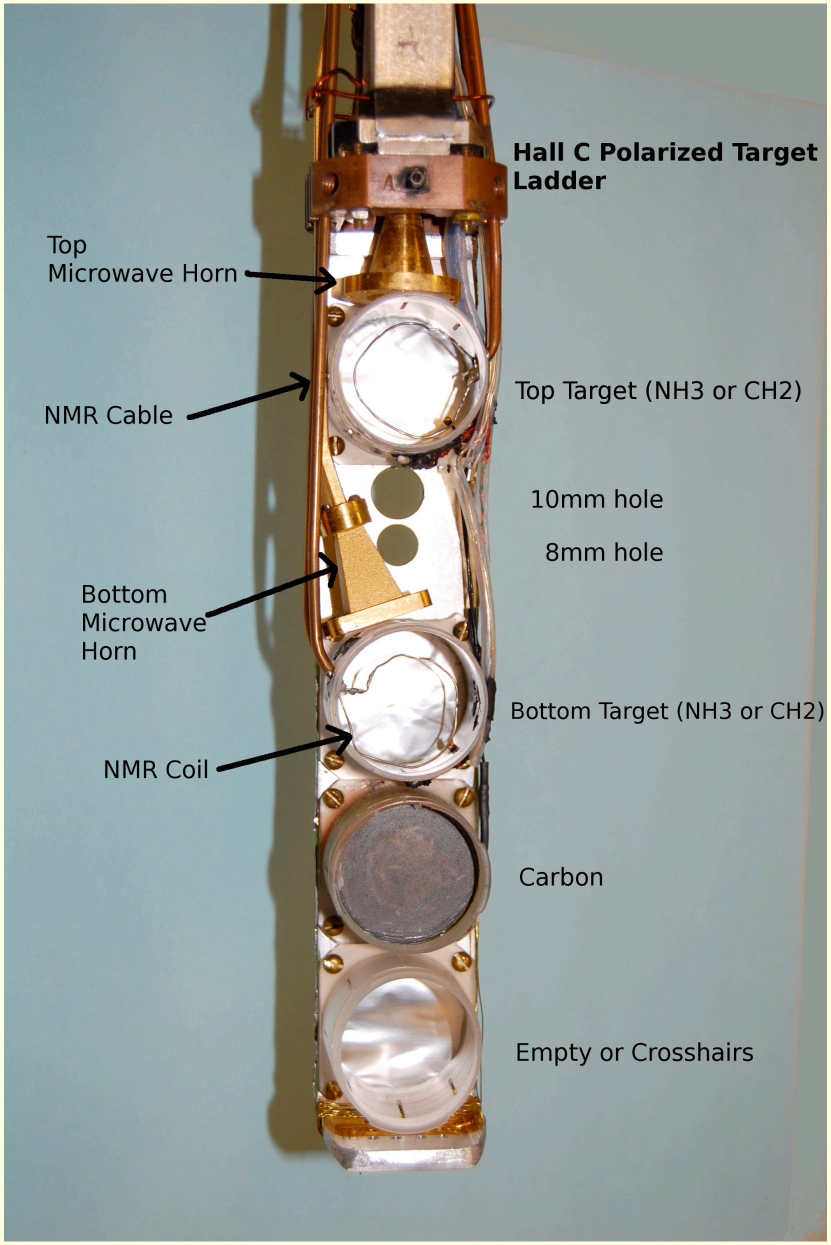


- Helmholtz-pair superconducting magnet made of NbTi, from Oxford Instruments.
- Operates at up to 5.1T (79A); 1×10^{-4} uniformity in $3\times3\times3\text{cm}^3$ volume; persistent to 5×10^{-8} per hour.
- Dynamic Nuclear Polarization; hyperfine transitions induced by microwave pumping.
- Polarization measured by Nuclear Magnetic Resonance.
- Frozen solid NH_3 target.


cryostat
magnet

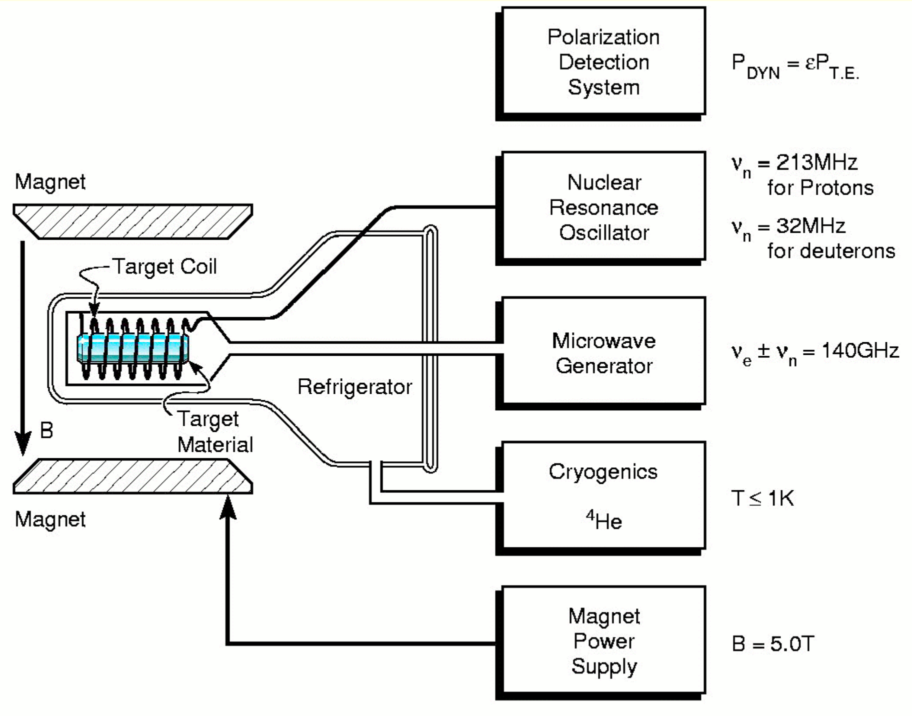

Presto

Target Ladder



Dynamic Nuclear Polarization

- Refrigerator: 0.5-1.0 K
- Magnetic Field: 2-6 T
- Microwaves: 55-165 GHz
- NMR
- DAQ



Polarization
Protons: 70-100%
Deuterons: 20-50%

Proton:
Lamor frequency $\upsilon_n \cong 42.6 MHz/T$

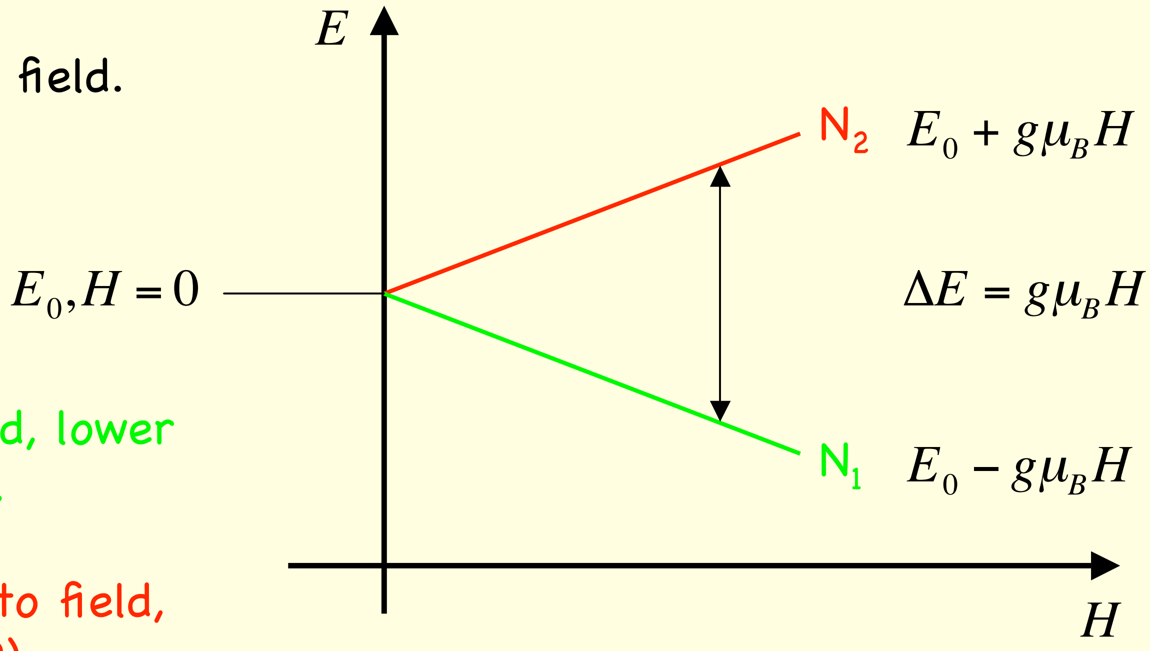
$$\Rightarrow 42.6 MHz/T \times 5T = 213 MHz$$

Paramagnetism

Assembly of paramagnetic atoms (one unpaired electron); dilute enough such that there is no magnetic interaction between the atoms.

Apply external magnetic field.

Zeeman splitting



N_1: atoms parallel to field, lower energy state (m_S = -1/2).

N_2: atoms anti-paralllel to field, higher energy (m_S = +1/2).

$N_1 > N_2$ =>net magnetization parallel to field

Thermal agitation => random orientation

Lower temperature => less agitation

=> N_1 > N_2 => larger magnetization

Increasing H and decreasing T would eventually result in N_2 -> 0.

At thermal equilibrium (spin = 1/2)

$$\frac{N_2}{N_1} = \exp\left(-\frac{g\mu_B H}{kT}\right)$$

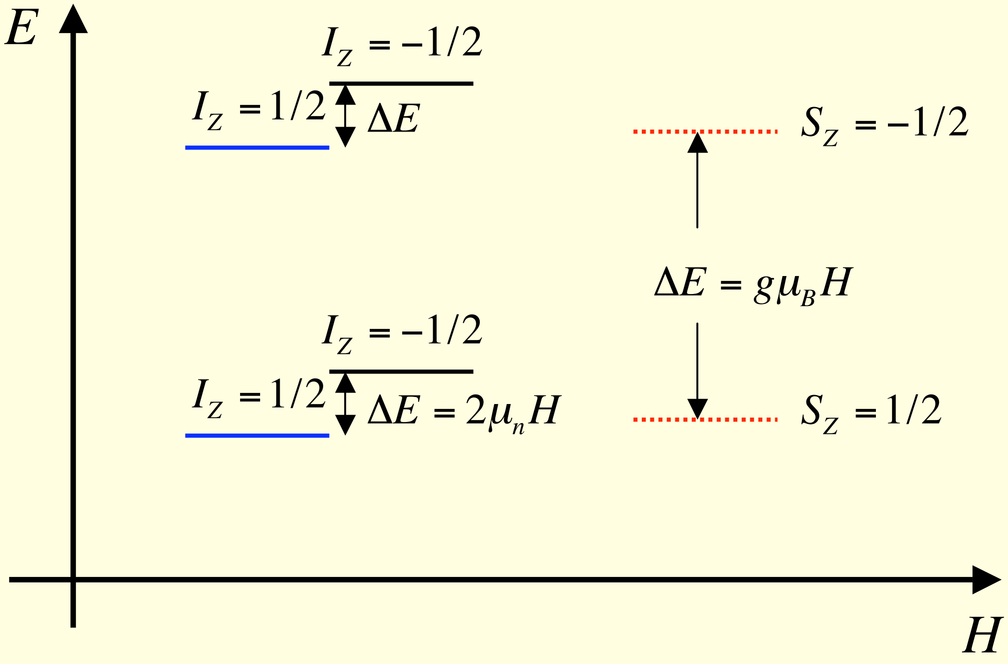
$$P = \frac{N_1 - N_2}{N_1 + N_2}$$

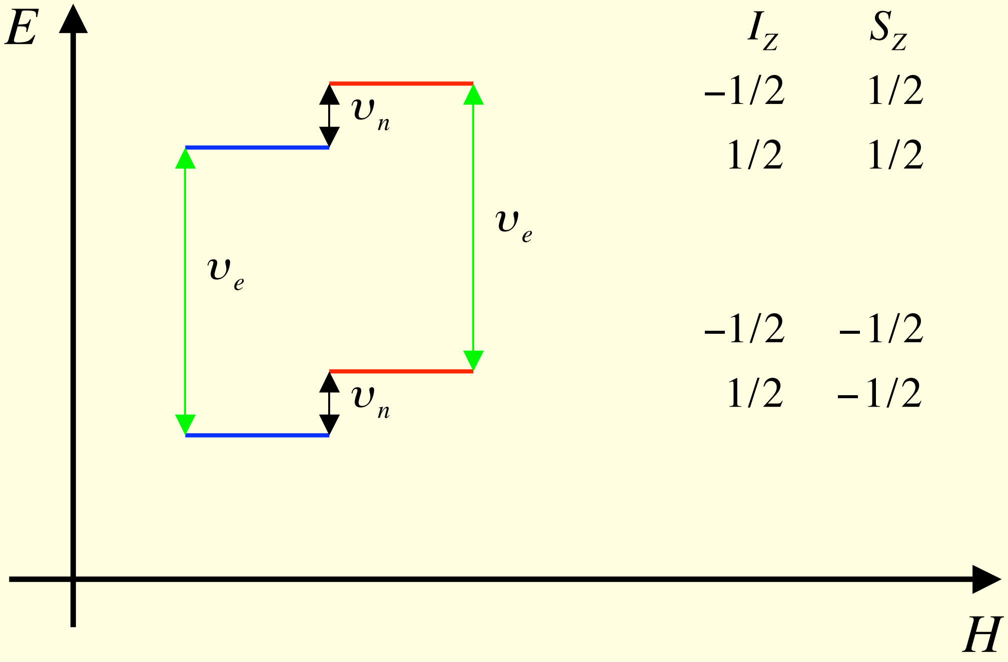
$$= \tanh\left(\frac{\mu_B H}{kT}\right)$$

Nucleons also posses magnetic moments, although:

nuclear moments / electron moments -> 10^{-3}

Including nuclear moments => hyperfine splitting





I_Z	S_Z
$-1/2$	$1/2$
$1/2$	$1/2$
$-1/2$	$-1/2$
$1/2$	$-1/2$

RF fields can be used to induce transitions between spin-states.

Allowed transitions

$\Delta I_Z, \Delta S_Z = 1$

1) $\upsilon_{rf} \approx \upsilon_e$ get transitions $-- \leftrightarrow -+$, $++ \leftrightarrow +-$

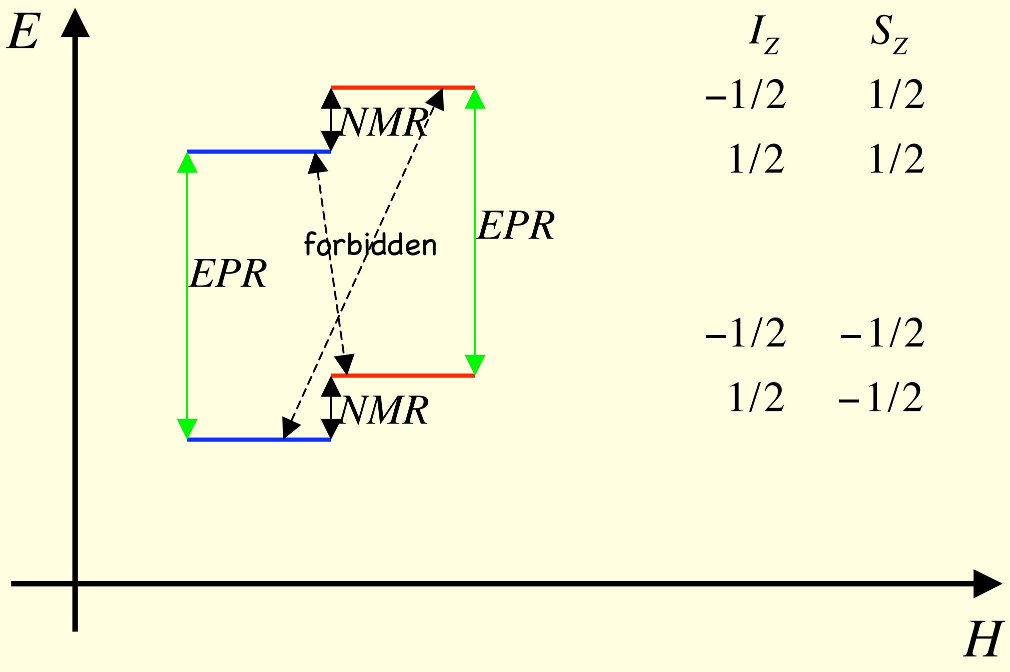
where $\Delta E = g\mu_B H = h\upsilon_e$

Pure electron spin is electron paramagnetic (EPR)

2) $\upsilon_{rf} \approx \upsilon_n$ get transitions $+- \leftrightarrow --$, $++ \leftrightarrow -+$

$\Delta E = 2\mu_B H = h\upsilon_n$

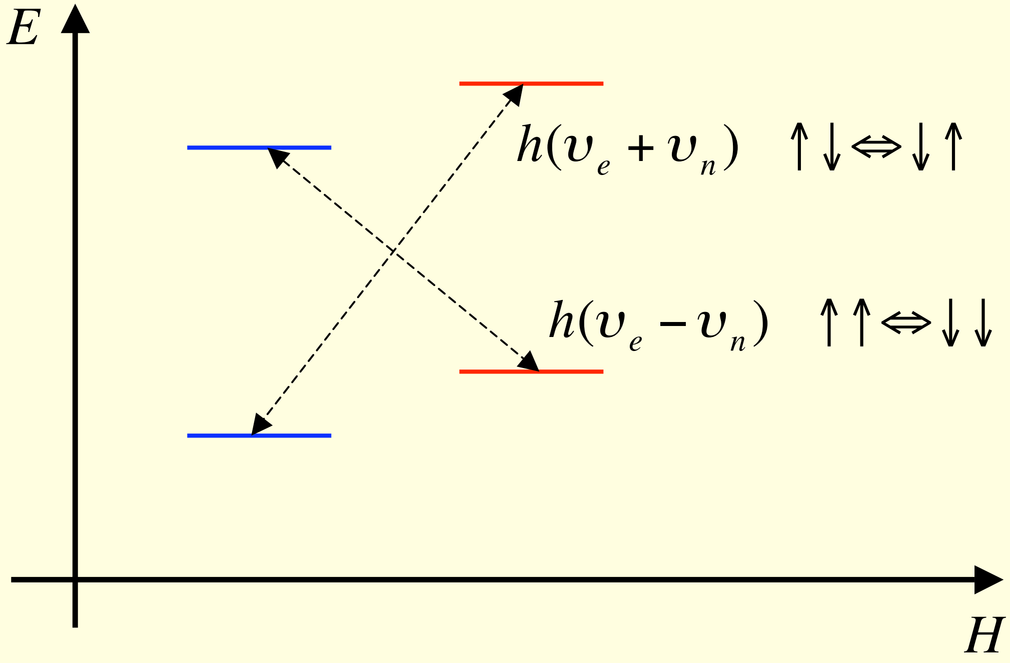
Forbidden Transitions



The desired transitions -- <-> ++ and +- <-> -+ are forbidden.

Use the fact that the dipole-dipole interaction exists:
2 distant magnetic moments => dipole-dipole interaction << Zeeman

This results in a mixing of nuclear states, allowing for the desired transitions though with a much less probability (10^{-4}) than those that are allowed.



$h(\upsilon_e + \upsilon_n)$ $\uparrow\downarrow \Leftrightarrow \downarrow\uparrow$

$h(\upsilon_e - \upsilon_n)$ $\uparrow\uparrow \Leftrightarrow \downarrow\downarrow$

The rf field drives the forbidden transitions

flips-flops: $\uparrow\downarrow \Leftrightarrow \downarrow\uparrow$

flips-flips: $\uparrow\uparrow \Leftrightarrow \downarrow\downarrow$

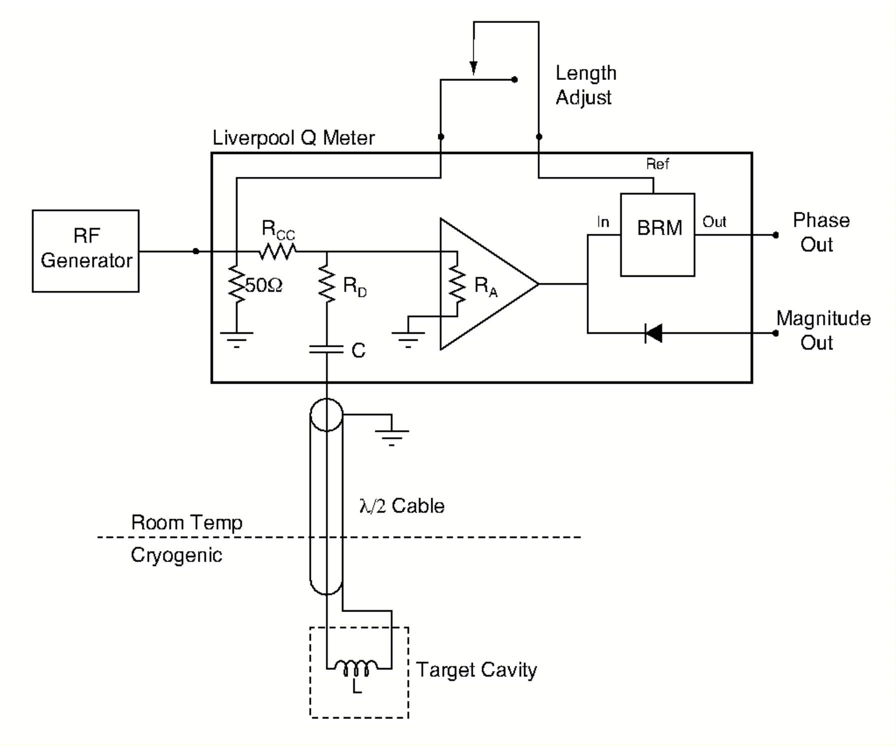
$$\Delta(S_Z - I_Z) = 0{,}2$$

Measurement of Polarization

- Measuring polarization is equivalent to measuring the net nuclear magnetization of the material Nuclear Magnetic Resonance (NMR).
- Exposed to rf field at Lamor frequency a spin system in a magnetic field absorbs or emits energy. The response is described by the magnetic susceptibility

$$\chi(\omega) = \underset{\substack{\uparrow \\ \text{dispersive}}}{\chi'(\omega)} + \underset{\substack{\uparrow \\ \text{absorptive}}}{\chi''(\omega)}$$

$$P = K\int_0^\infty \chi''(\omega)d\omega$$



Q-meter connected in series to NMR coil with inductance L_C and resistance r_C, which is embedded in target material.

$$Z_C = r_C + i\omega L_C(1 + 4\pi\eta\chi(\omega))$$

Inductance and impedance change when the material absorbs or emits energy giving a voltage.

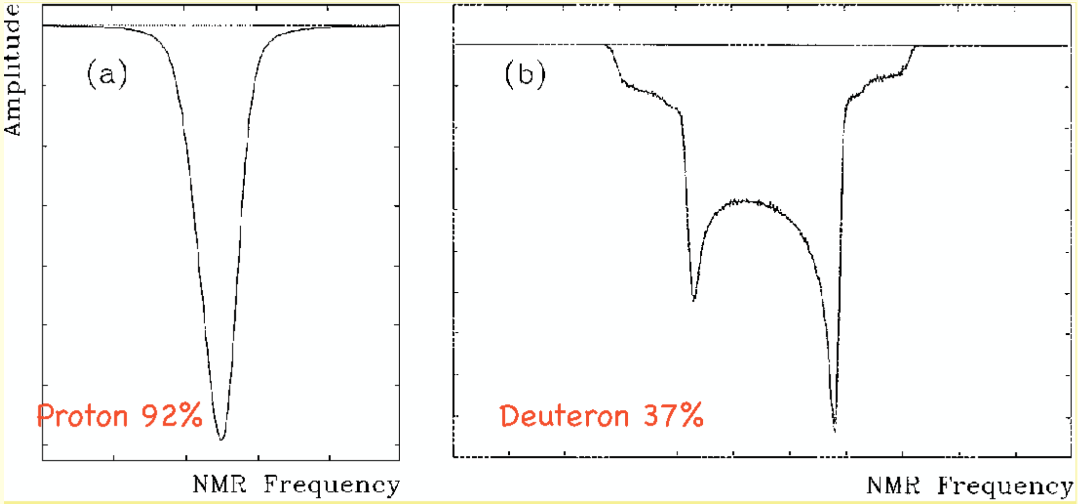
$$V(\omega,\chi)$$

$$S(\omega) = \mathrm{Re}\big(V(\chi,\omega) - V(\chi,0)\big) \cong \chi''(\omega)$$

The polarization is calibrated by using the calculable thermal equilibrium polarization.

$$P_{TE} = \tanh\left(\frac{\mu_N H}{kT}\right)$$

$$P = \frac{\int S_{enh}(\omega)d\omega}{\int S_{TE}(\omega)d\omega}$$



Important Criteria:

- Degree of polarization P.
- Dilution factor f, which is the ratio of free polarizable nucleons to the total number of nucleons.

$$A = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \qquad \varepsilon = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

$$A = \frac{1}{Pf} \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

$$f = \frac{f_A}{(1 - f_A)\sigma_0 + f_A \sigma}$$

$$\sigma = \sigma_0 (1 \pm PA)$$

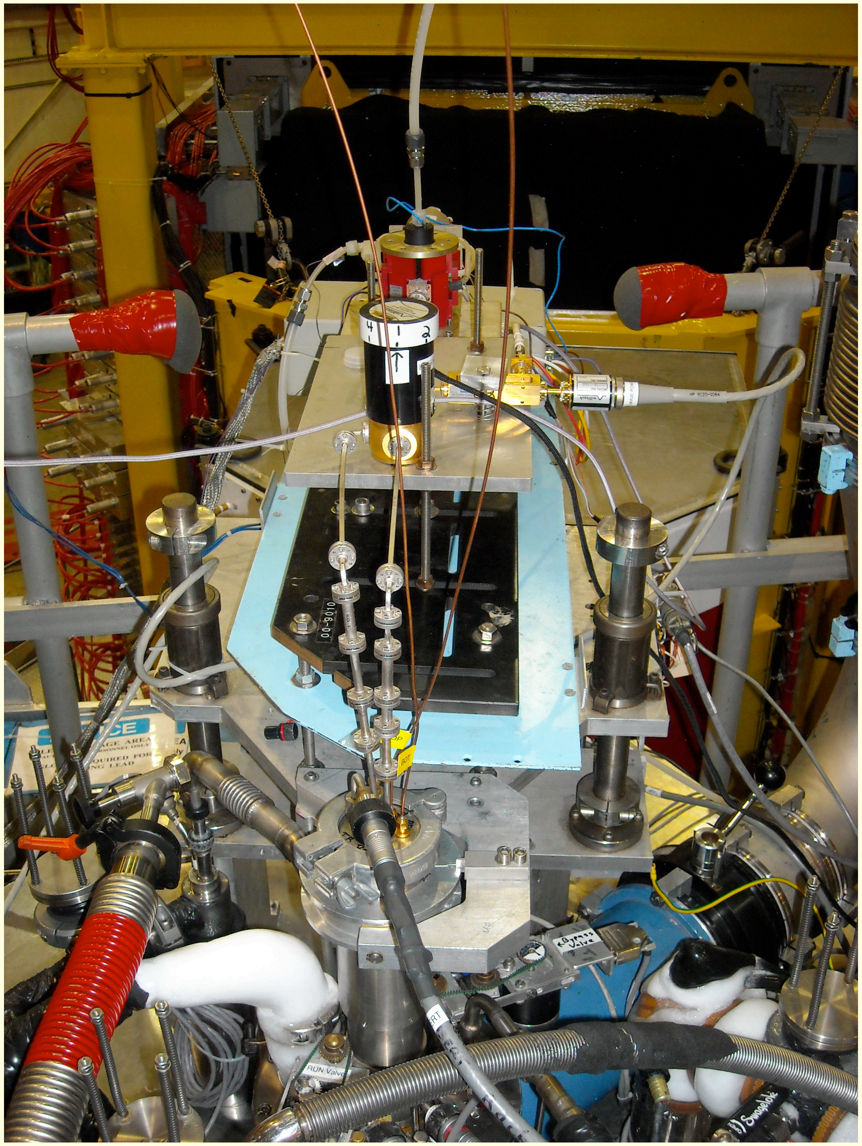
f_A = fraction of polarized nuclei

Here P and f correct for the fact that target is not 100% polarized and contains other materials.

Beam time t needed to obtain a statistical error ΔA has the dependency

$$t \propto \frac{1}{\rho (f \cdot P)^2}$$

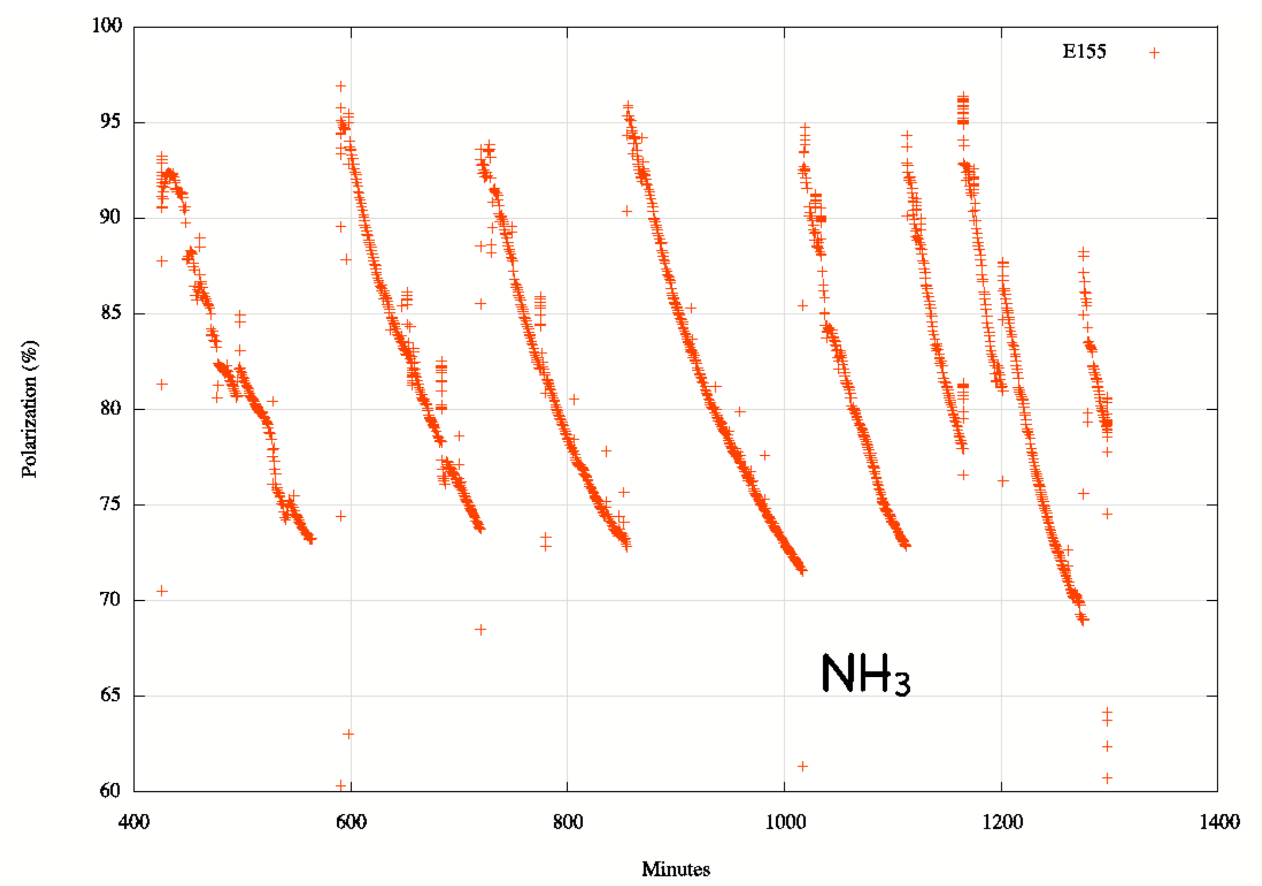
Microwaves



For DNP, the required frequency is about 28GHz/T (140GHz at 5T) where the required power 20mW/g at 5T and 1K.

The power is inversely related to frequency. Power absorption in microwave components increases with frequency => limit at 210GHz, corresponding to 7.5T.

Performance and Experience

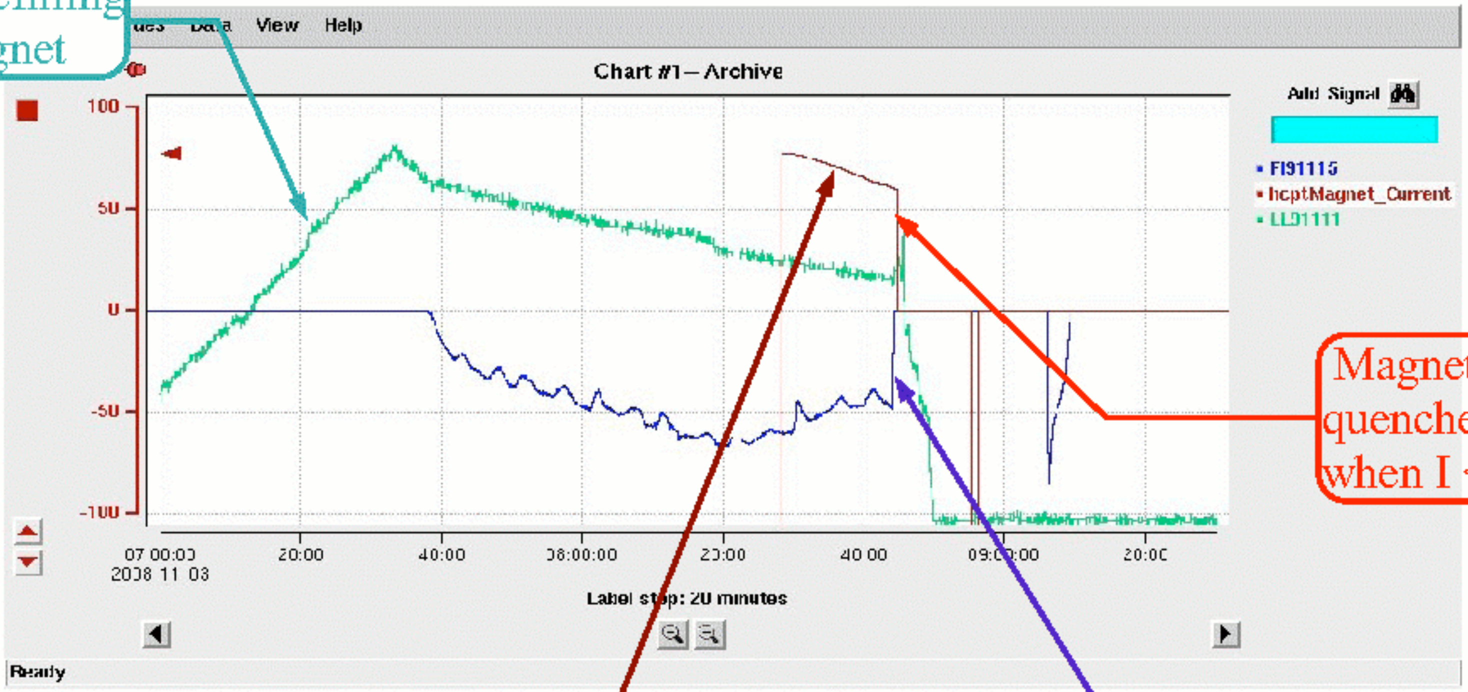


NH_3 target material; Polarization growth, radiation damage, decay of material

Quenches

- Several quenches occurred in late October and early November of 2008, which caused the magnet to be inoperable.
- This was diagnosed and fixed by the Hall C staff, target group, and an Oxford Instruments Specialist. The magnet was then placed back in the beam-line December 2008.
- Since then there have been some spontaneous quenches that did not damage the magnet, due to the new protection circuits working.
- Detailed procedures have been implemented to minimize occurances.

Quench of 11/3/08 AM



LHe refilling
of magnet

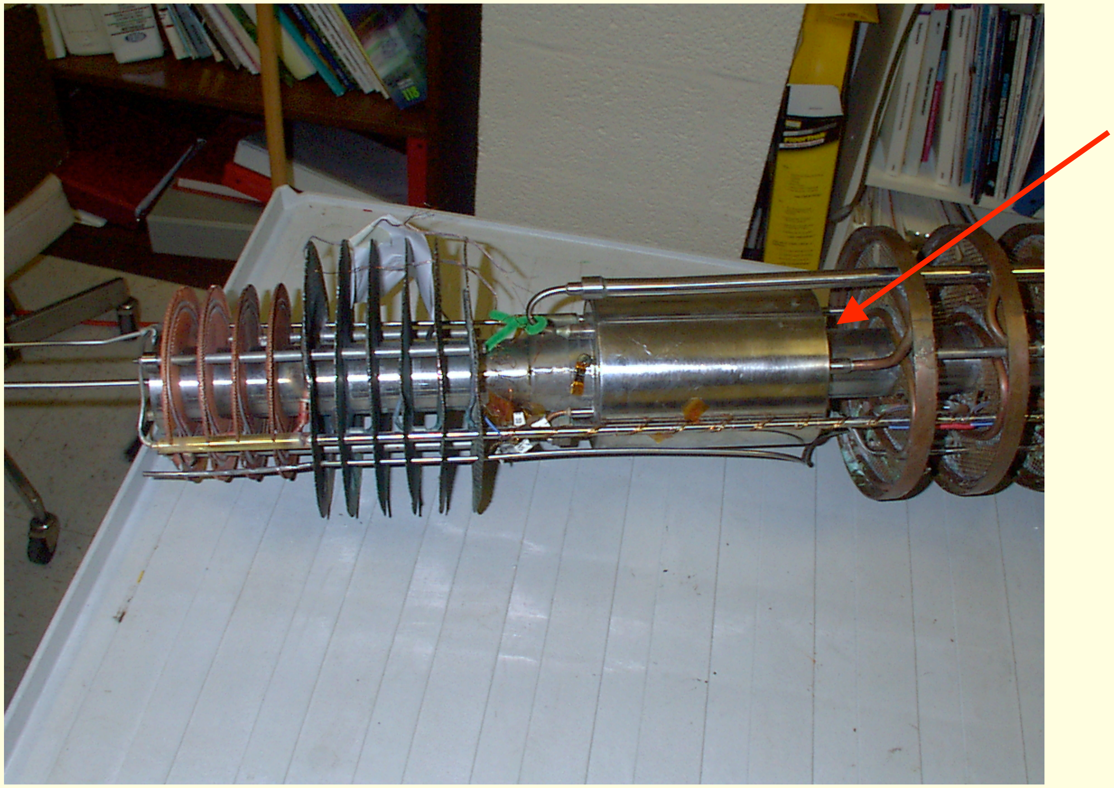
Magnet
quenches
when I < 60 A

Magnet de-energized
at three rates:
1 A/min to 72 A
1.5 A/min to 60 A
2 A/min to zero

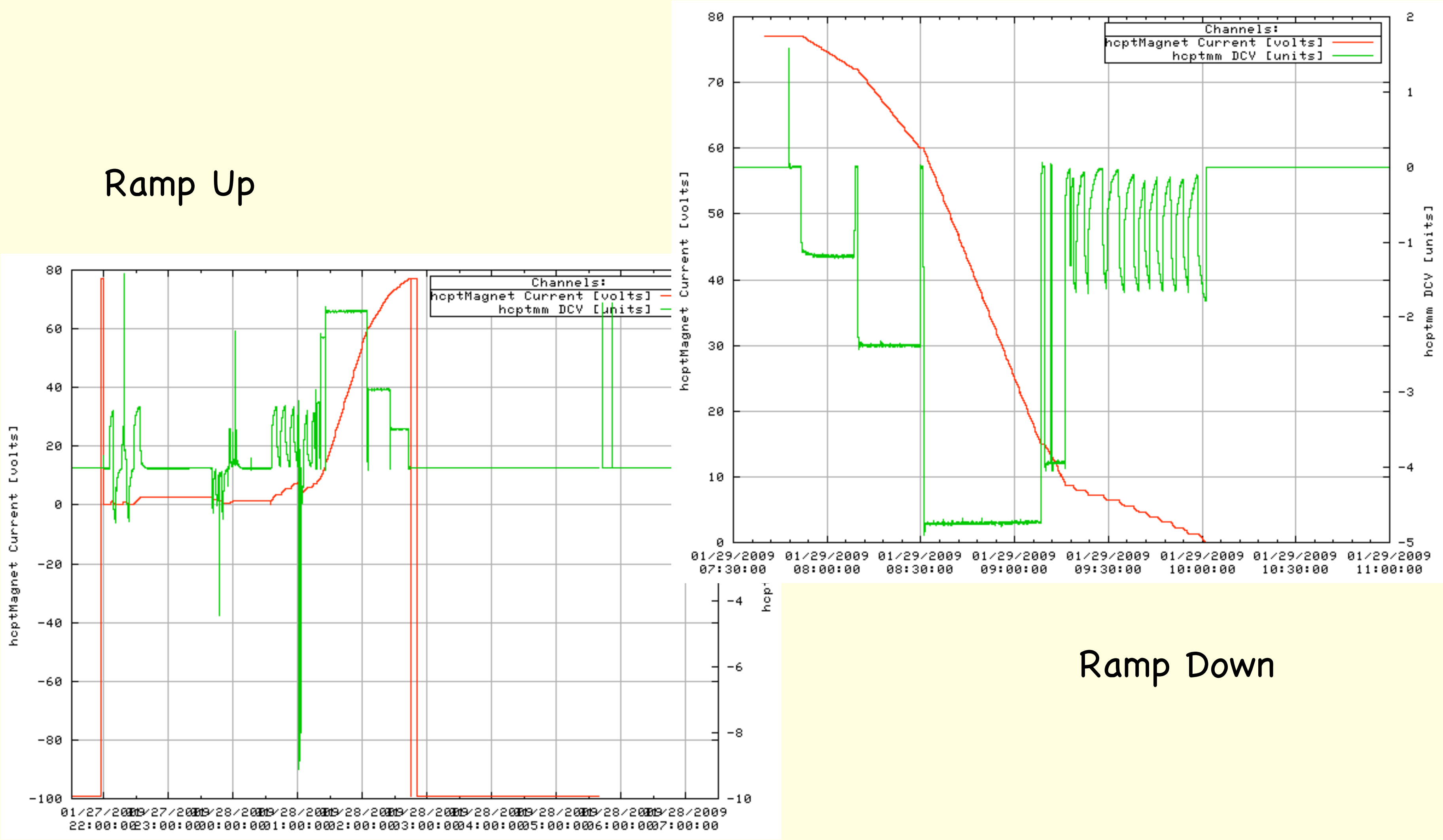
He boil-off jumps
at time of quench
(vertical scale
not selected on plot)

Refrigerator

- A large leak that was found in December 2008 in the ^{4}He evaporation frig that is used to cool NH_3 to 1K, in the vapor-liquid separator.
- This was irreparable and was replaced by one from Uva.



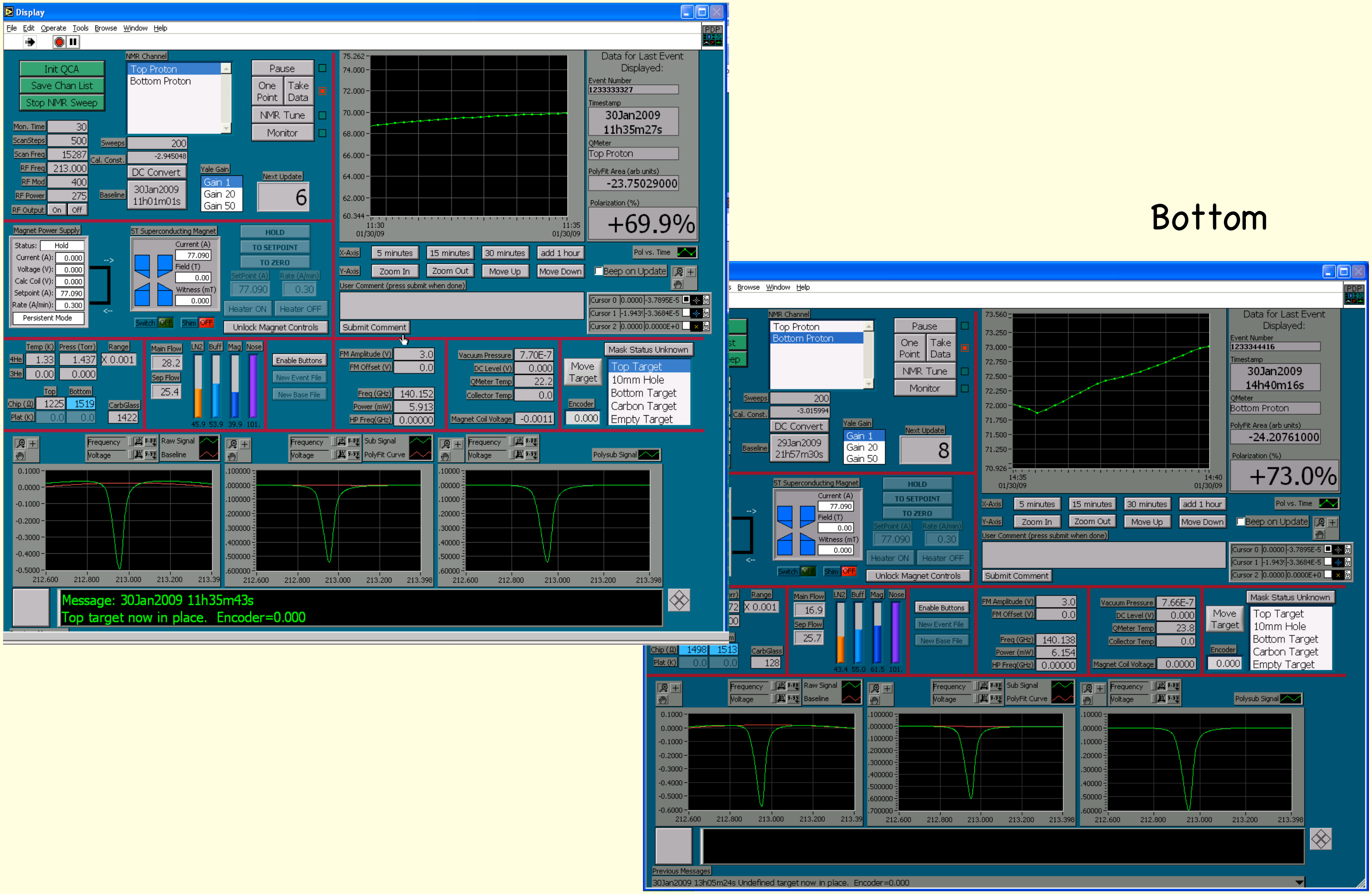
Ramp Up



Ramp Down

Top

Bottom



Data for Last Event Displayed:

Event Number: 1233333327

Timestamp: 30Jan2009 11h35m27s

QMeter: Top Proton

PolyFit Area (arb units): -23.75029000

Polarization (%): +69.9%

Message: 30Jan2009 11h35m43s
Top target now in place. Encoder=0.000

Data for Last Event Displayed:

Event Number: 1233344416

Timestamp: 30Jan2009 14h40m16s

QMeter: Bottom Proton

PolyFit Area (arb units): -24.20761000

Polarization (%): +73.0%

Previous Messages: 30Jan2009 13h05m24s Undefined target now in place. Encoder=0.000

Achieved polarization on NH_3 and proper NMR signal. Have gotten above 70%.

Summary

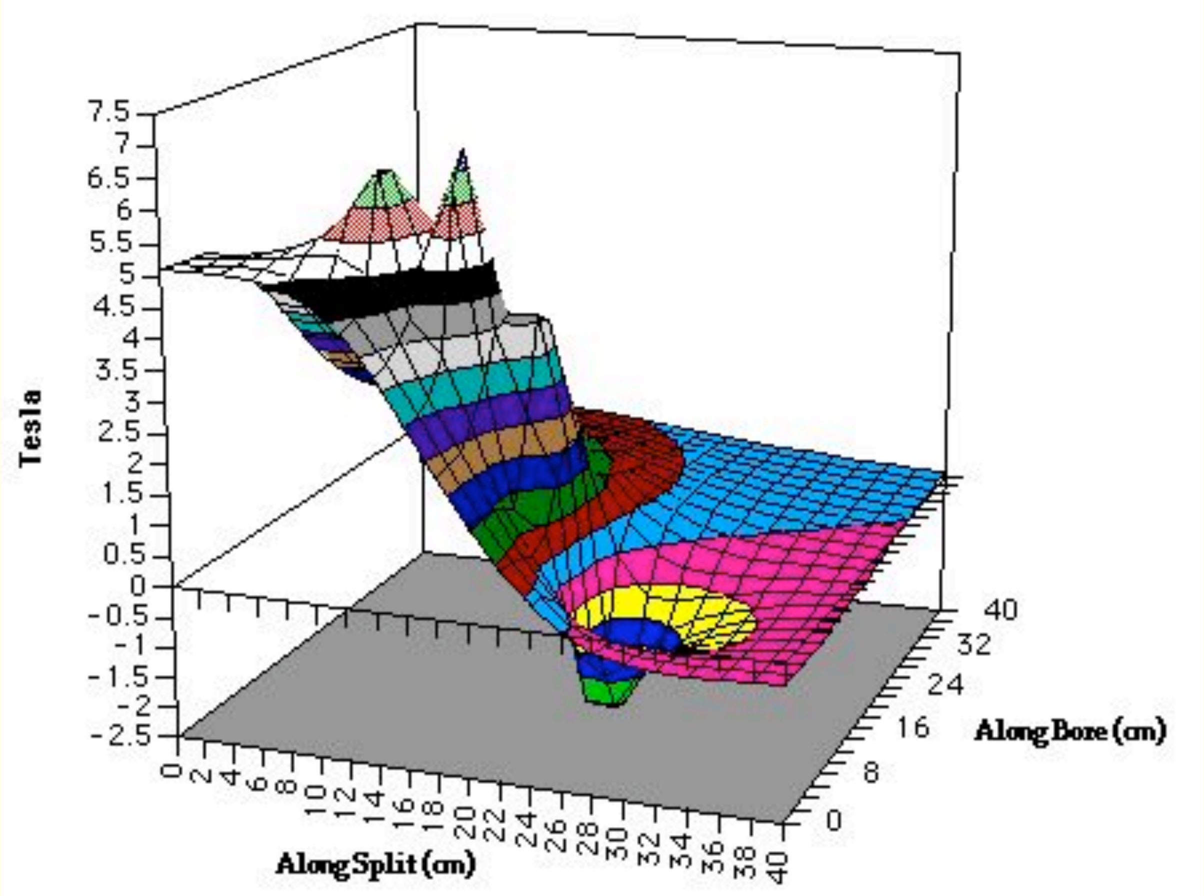
- Target used for SANE operates on DNP and capable of longitudinal and transverse polarization .
- (High) Polarization, measured by NMR.
- There have been setbacks.
- Target is now operational.

Acknowledgments

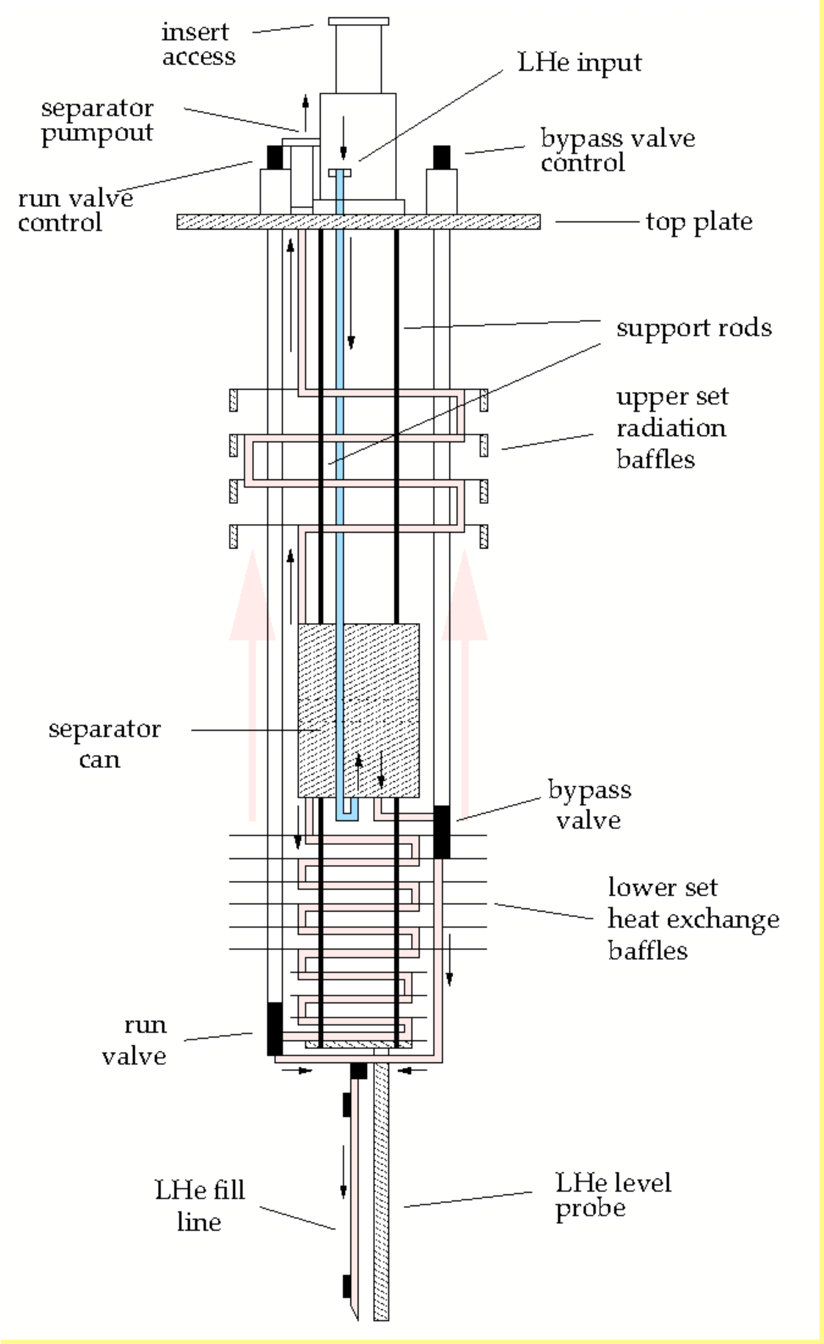
A great deal of thanks to the Hall C staff, Accelerator, and especially the Jlab target group.

Support Slides

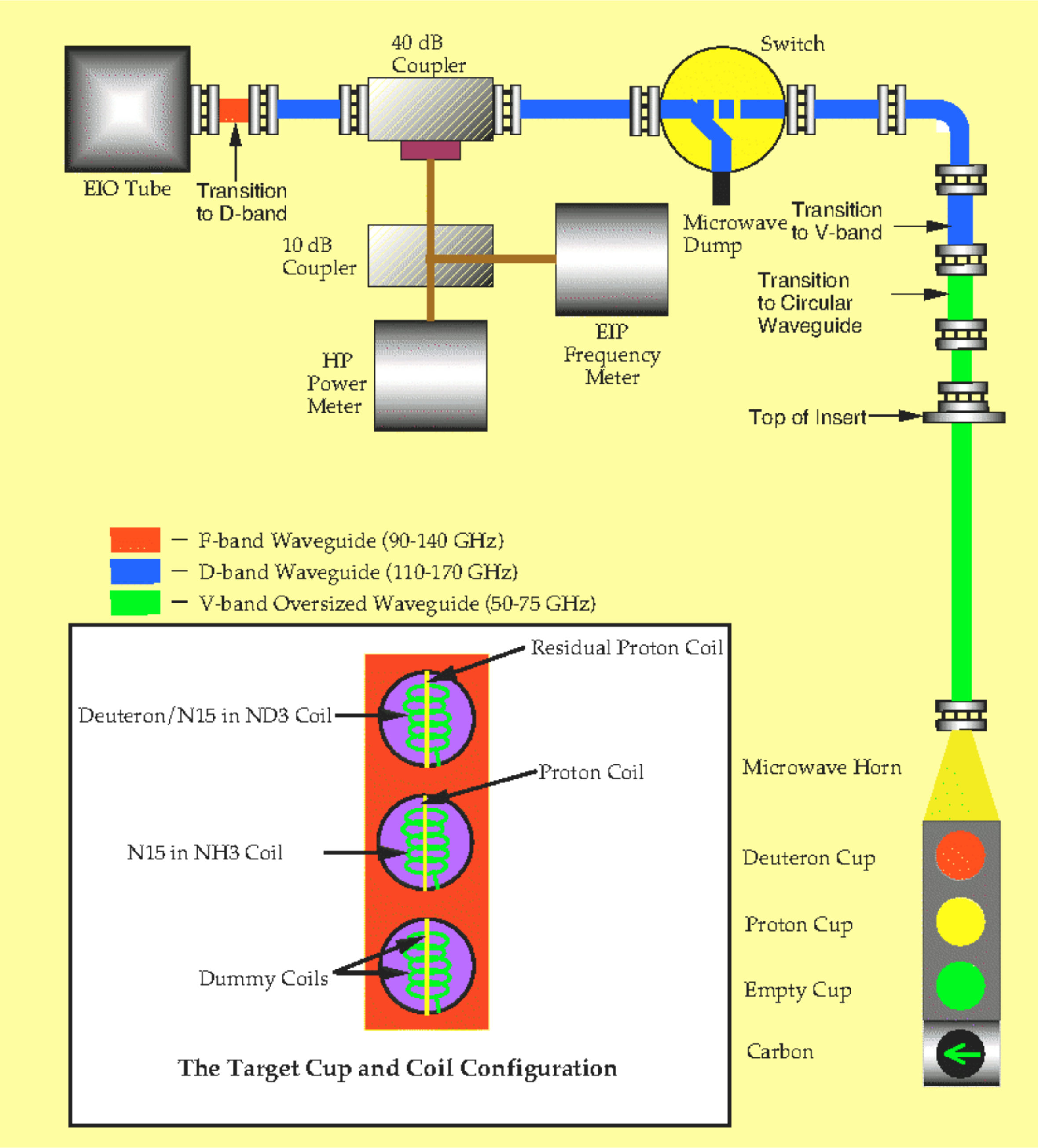
Magnetic Field Profile



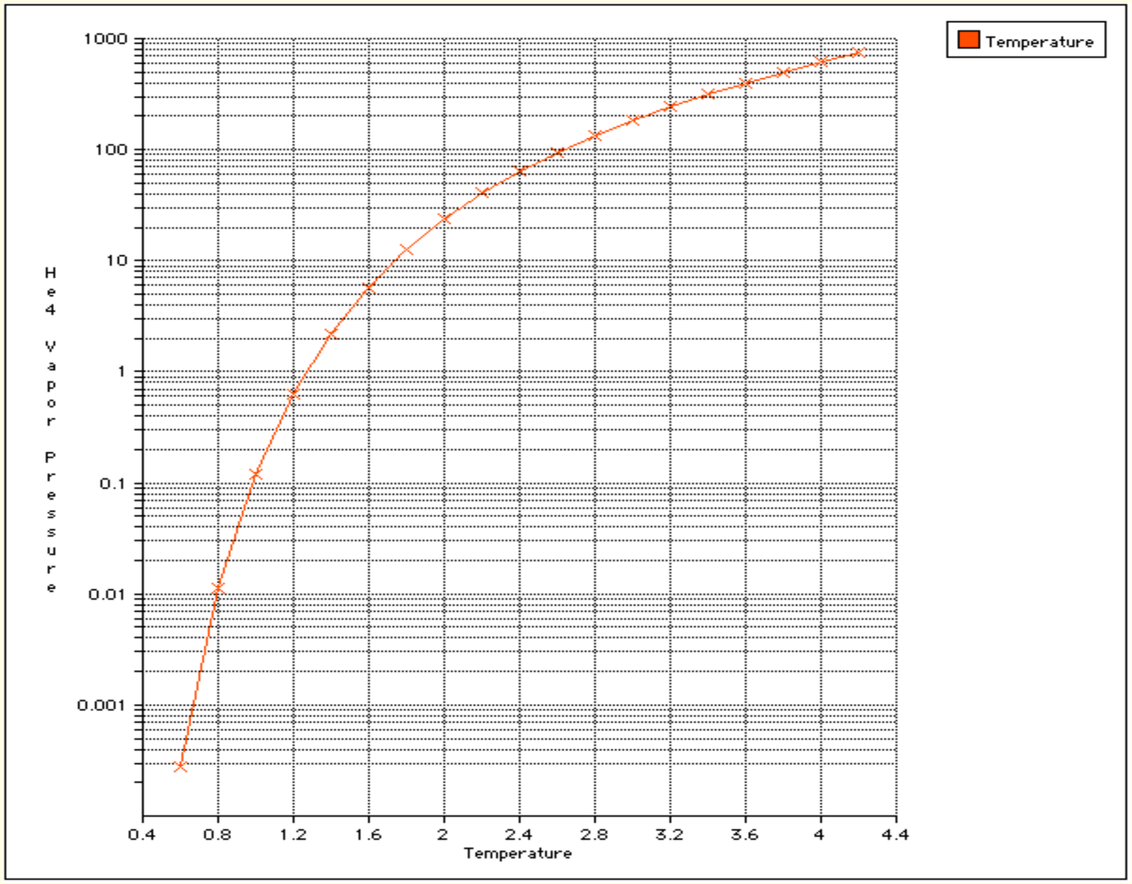
Refrigerator



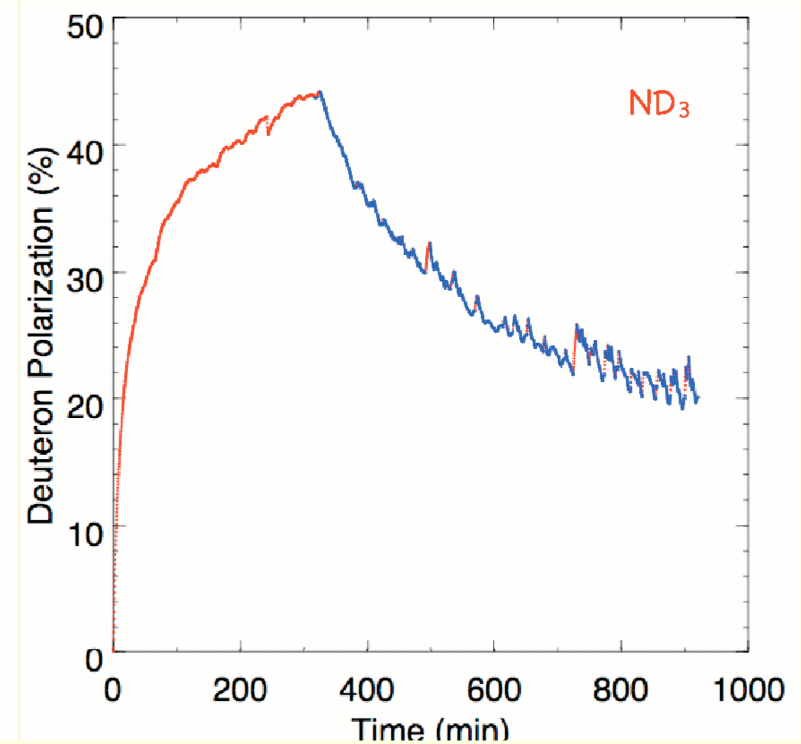
Microwave Setup

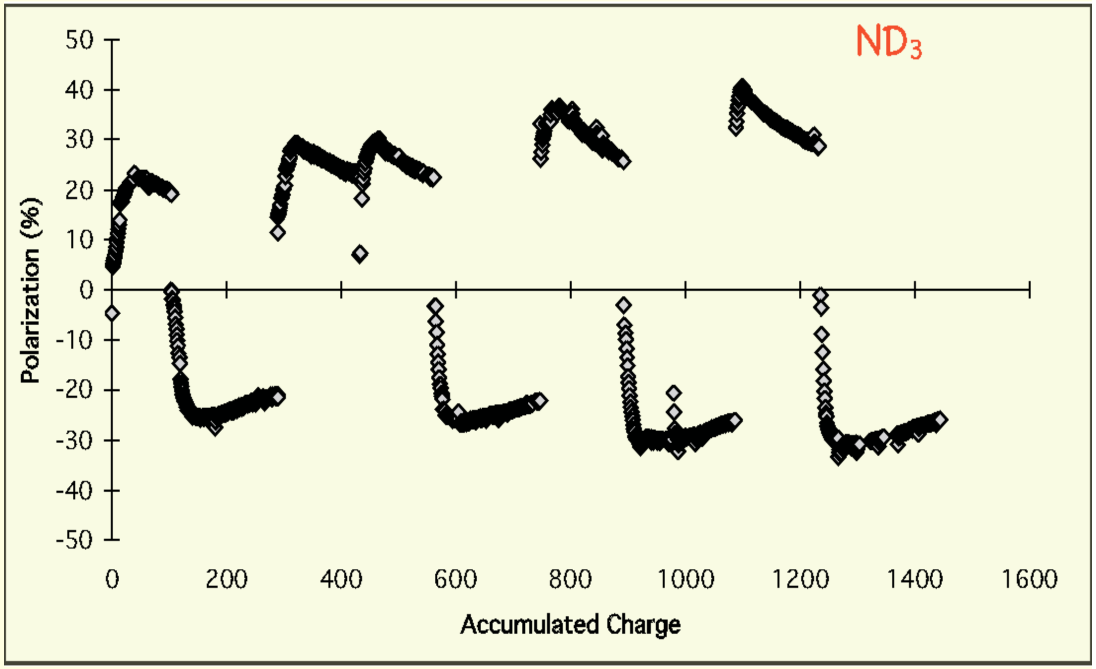


^{4}He vapor Pressure vs. Temperature

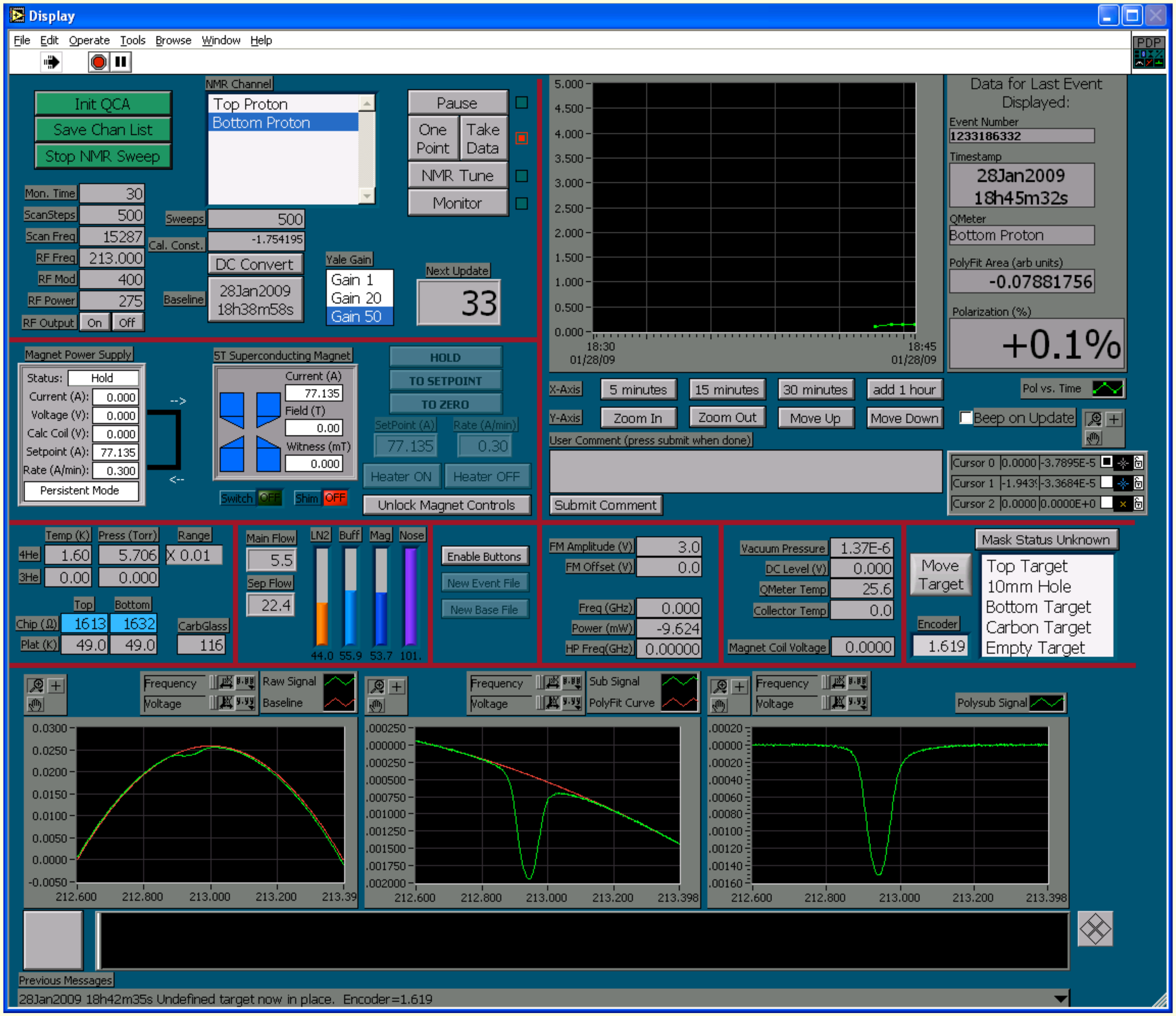


Performance and Experience





ND_3 material; Pol growth, Rad damage, anneal, reverse sign



NMR Channel: Top Proton, Bottom Proton

Mon. Time: 30
ScanSteps: 500
Scan Freq: 15287
RF Freq: 213.000
RF Mod: 400
RF Power: 275
RF Output: On Off
Sweeps: 500
Cal. Const.: -1.754195
Baseline: 28Jan2009 18h38m58s
Yale Gain: Gain 1, Gain 20, Gain 50
Next Update: 33

Data for Last Event Displayed:
Event Number: 1233186332
Timestamp: 28Jan2009 18h45m32s
QMeter: Bottom Proton
PolyFit Area (arb units): -0.07881756
Polarization (%): +0.1%

Magnet Power Supply
Status: Hold
Current (A): 0.000
Voltage (V): 0.000
Calc Coil (V): 0.000
Setpoint (A): 77.135
Rate (A/min): 0.300
Persistent Mode

5T Superconducting Magnet
Current (A): 77.135
Field (T): 0.00
Witness (mT): 0.000
SetPoint (A): 77.135
Rate (A/min): 0.30
Switch: OFF
Shim: OFF

User Comment (press submit when done)

	Cursor		
Cursor 0	0.0000	-3.7895E-5
Cursor 1	-1.943	-3.3684E-5
Cursor 2	0.0000	0.0000E+0

	Temp (K)	Press (Torr)	Range
4He	1.60	5.706	X 0.01
3He	0.00	0.000	

	Top	Bottom	CarbGlass
Chip (Ω)	1613	1632	
Plat (K)	49.0	49.0	116

Main Flow: 5.5
Sep Flow: 22.4

LN2	Buff	Mag	Nose
44.0	55.9	53.7	101.

FM Amplitude (V): 3.0
FM Offset (V): 0.0
Freq (GHz): 0.000
Power (mW): -9.624
HP Freq(GHz): 0.00000

Vacuum Pressure: 1.37E-6
DC Level (V): 0.000
QMeter Temp: 25.6
Collector Temp: 0.0
Magnet Coil Voltage: 0.0000

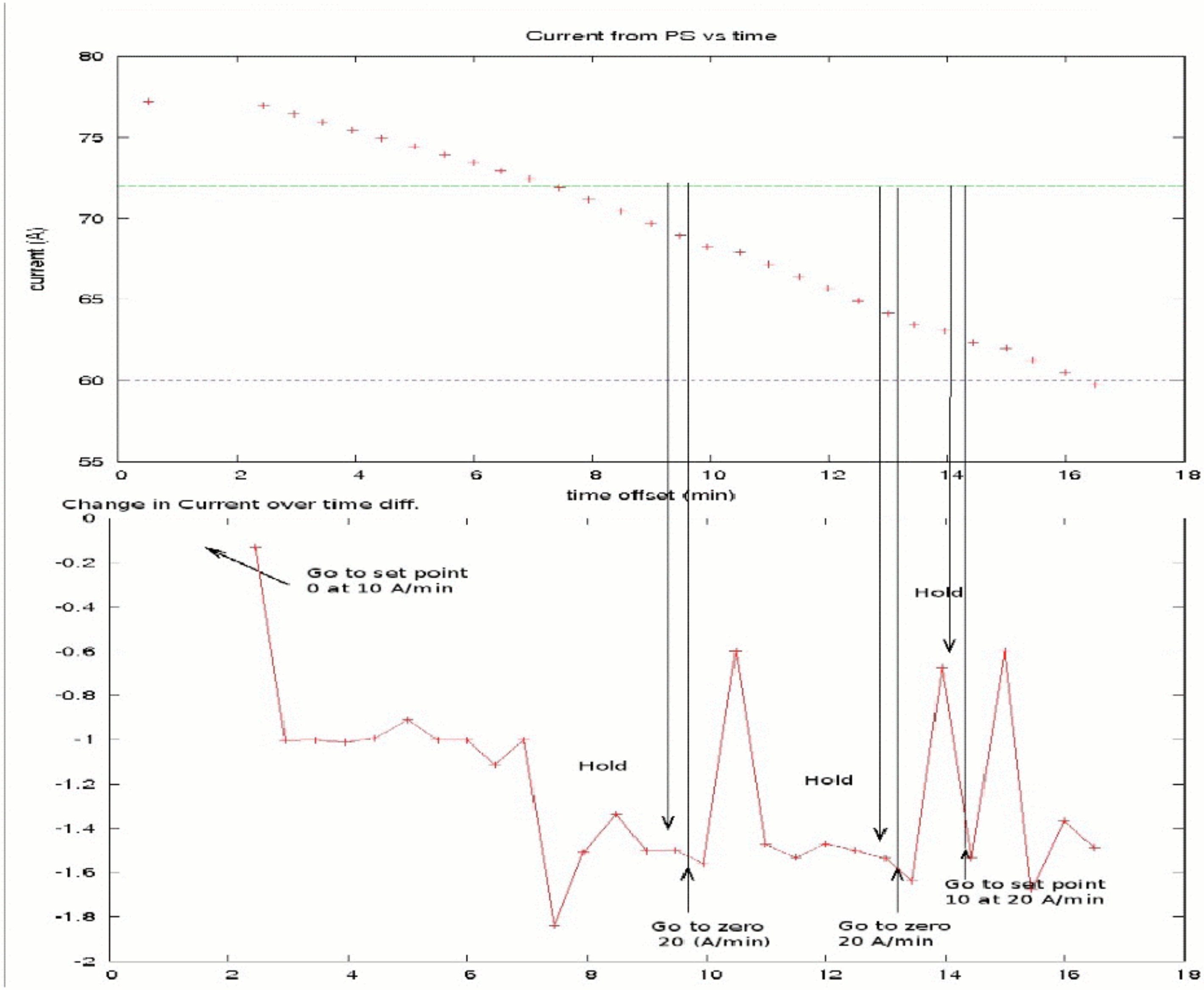
Encoder: 1.619

Top Target
10mm Hole
Bottom Target
Carbon Target
Empty Target

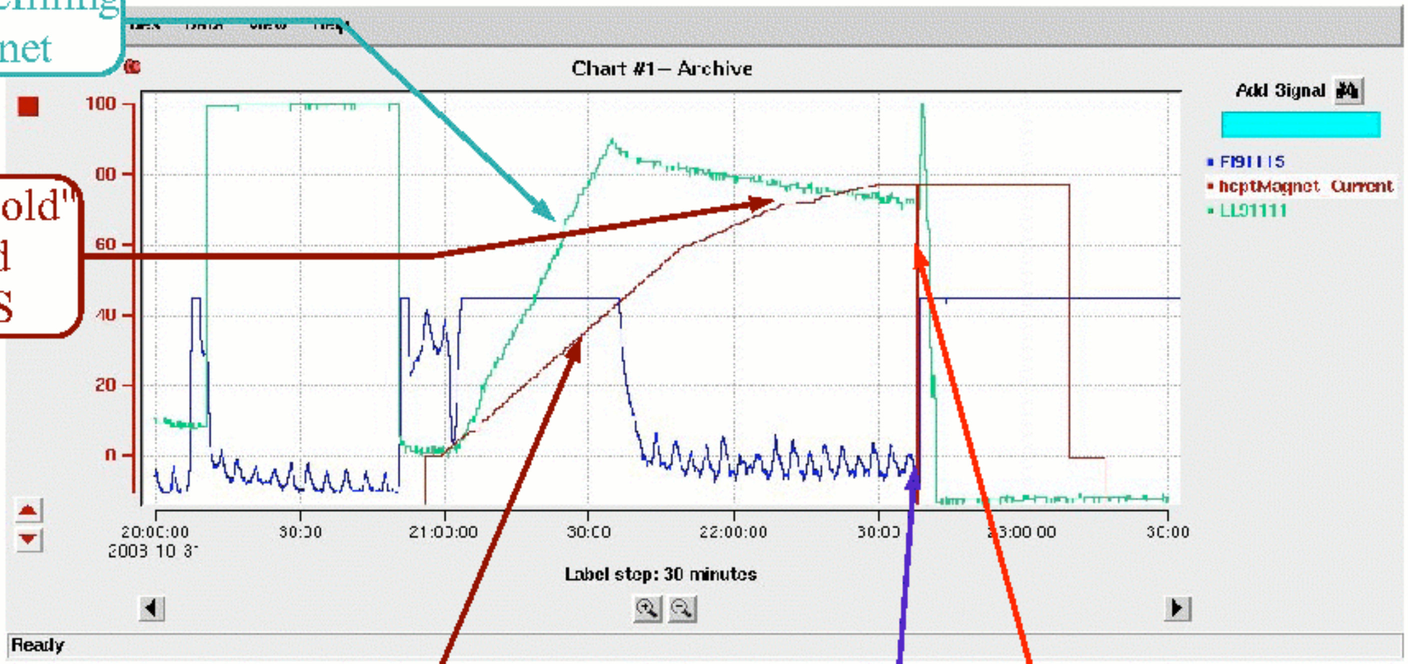
28Jan2009 18h42m35s Undefined target now in place. Encoder=1.619

TE scan of CH_2 target (January 28, 2009).

Quench of 11/3/08 AM (details)



Quench of 10/31/08



LHe refilling of magnet

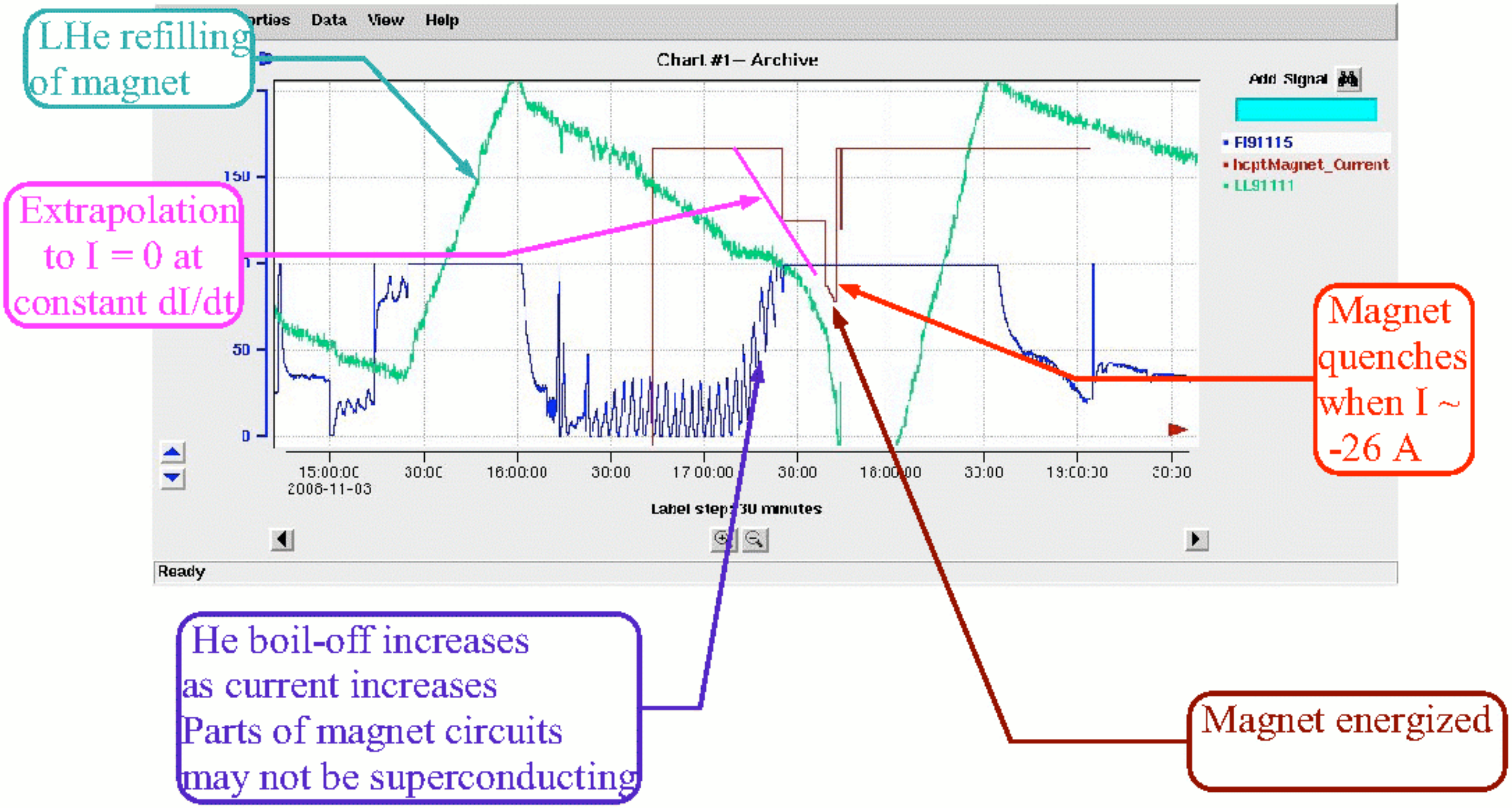
Brief "Hold" command sent to PS

Magnet energized at three rates:
1.2 A/min to 60 A
0.6 A/min to 72 A
0.3 A/min to 78 A

He boil-off jumps at time of quench (vertical scale not selected on plot)

Attemp to go to persistent mode before switch ready causes quench

Quench of 11/3/08 PM



LHe refilling of magnet

Extrapolation to I = 0 at constant dI/dt

Magnet quenches when I ~ -26 A

He boil-off increases as current increases
Parts of magnet circuits may not be superconducting

Magnet energized