The Polarized-Target System for the SpinQuest Experiment at Fermilab

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New Perspective 2.0

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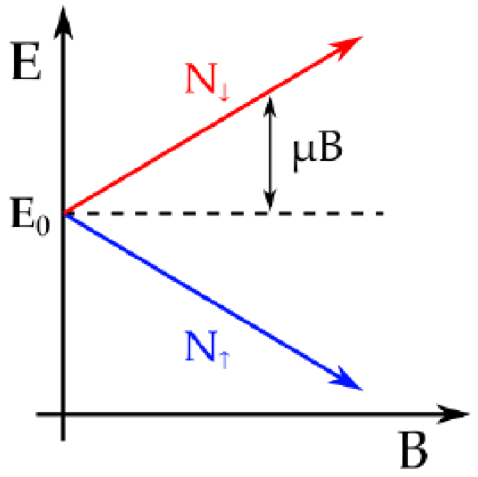
Outline

- Introduction
- Microwave System
- Target Materials
- Superconducting-Magnet System
- Cryogenics
- Nuclear-Magnetic Resonances (NMR) system
- Summary

Introduction:
How do we obtain significant nucleon polarization?

Brute-Force Method:

- Use high-B at low-T via zeeman-splitting mechanism



- Degree of polarization at thermal equilibrium

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

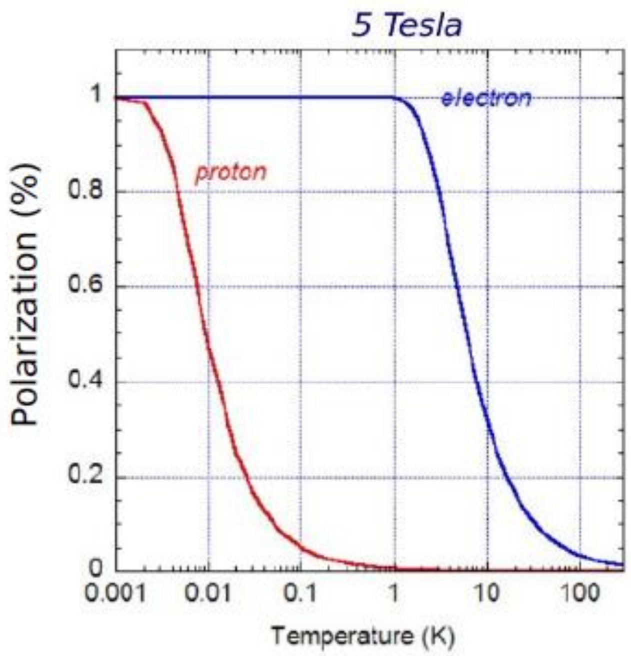
- Proton has small magnetic moment

$$\mu_e \approx 660\mu_p$$

- At B = 5 Tesla & T = 1 K

$$P_e = \sim 98\%,\ P_p = 0.51\%$$

- We need a better method!



Introduction:
How do we obtain significant nucleon polarization?

Dynamic-Nuclear Polarization (DNP):

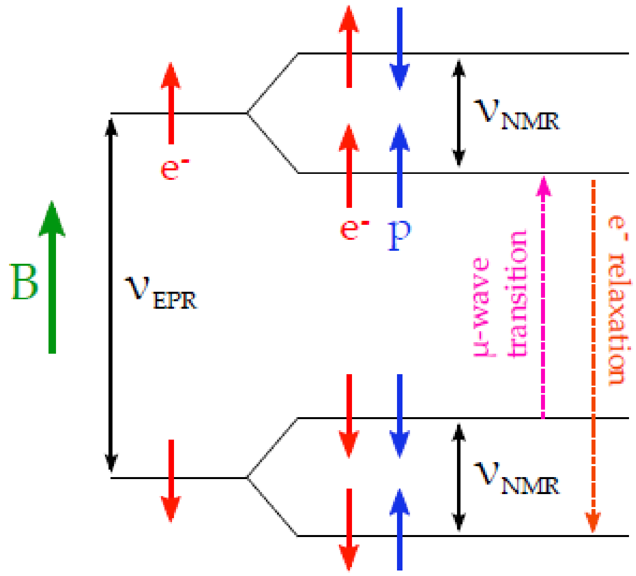
- The coupling between (unpaired) electron & proton introduces hyper-fine splitting

  $$H = \mu_e B + \mu_p B + H_{SS}$$

- Applying an RF-field at the correct frequency, we can drive the nucleons state into desired proton-state

- The disparity in relaxation times between the electron (ms) and proton (tens of minutes) at 1K is crucial to continue proton polarization

- Allow to achieve proton polarization of > 90%

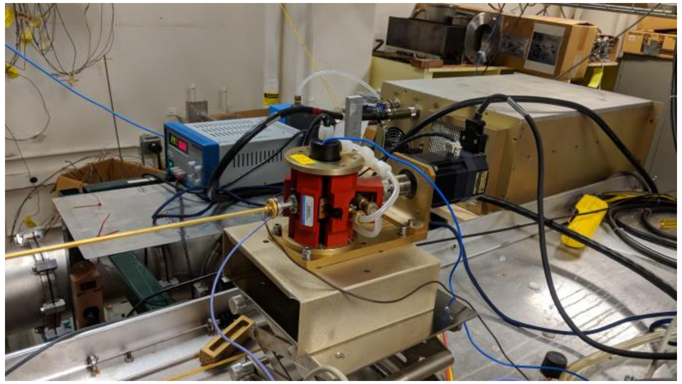


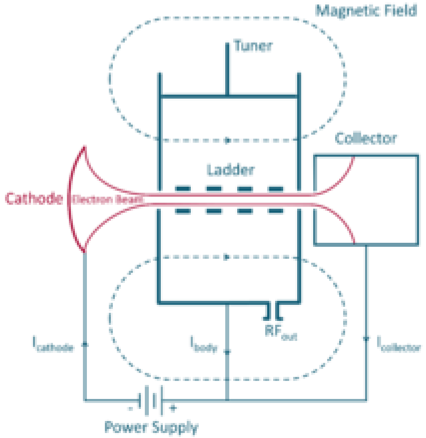
What do we need to achieve significant proton polarization using the DNP Method?

- Continuous microwaves generator
- Target material with a suitable number of unpaired electrons, resistance to radiation and reasonable dilution factor
- Superconducting magnet with homogenous fields in the target region
- Cryogenics system with high cooling power
- Reliable Nuclear-Magnetic Resonance (NMR) system for polarization measurement

Microwave system

140 GHz RF signal is generated by Extended-Interaction Oscillator (EIO) through interaction between electron beam (produced from ~kV of cathode/anode) and resonant cavities

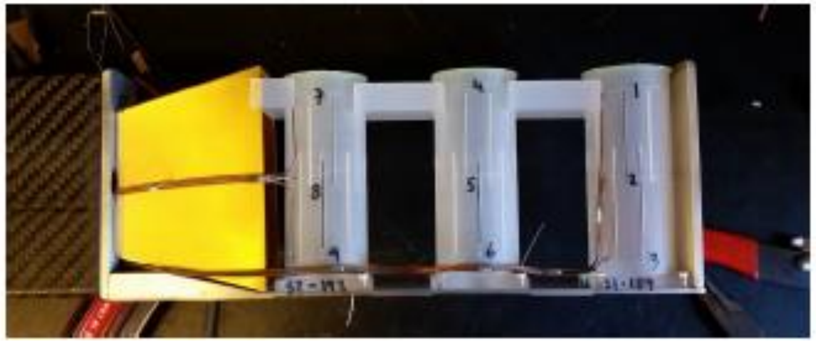




The optimal frequency changes as the target accumulate radiation damage from the beam. Therefore, the frequency is adjusted by adjusting the cavity size using a stepper motor (~2% adjustment)

Microwave system

The EIO is coupled to the target cups via a wave-guide which send the microwave through the target stick terminating at a gold plate copper horn



Other subsystems: Power supply, EIP frequency counter and cooler.

Target materials

Target material for DNP characterized by

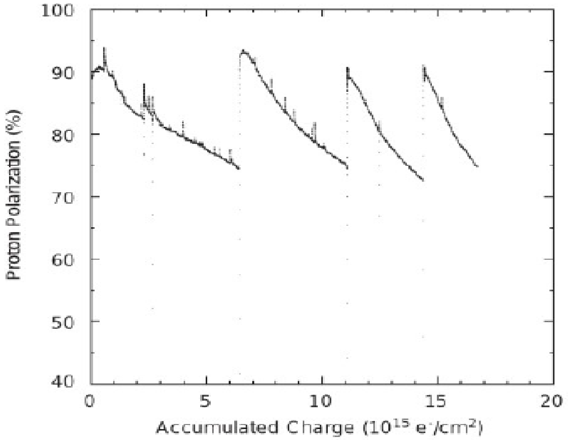
- Maximum achievable polarization
- Dilution factor
- Resistance to radiation damage



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

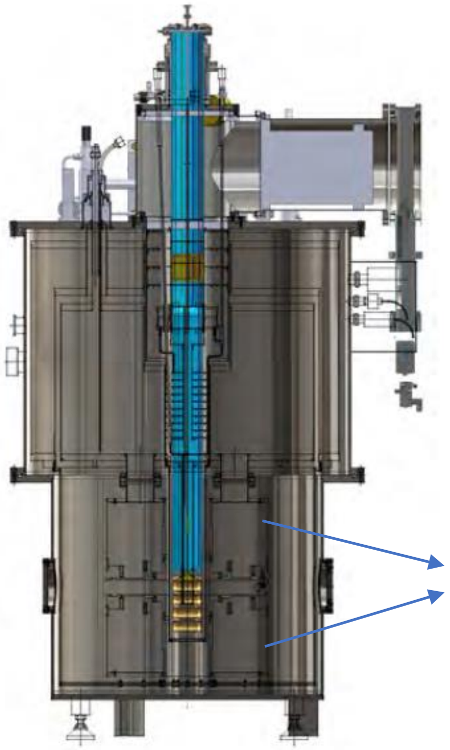
SpinQuest experiment will use 8 cm of solid NH_3/ND_3 as target materials which are doped with paramagnetic free-radical by being irradiated at NIST

The polarization decays over time due to the radiation damage and restored temporarily by annealing process (target is heated at 70-100 K).

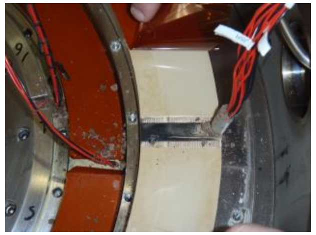


Superconducting-magnet system

The superconducting magnet coils provide 5 T of transverse field in the target area with the homogeneity level of 10^{-4}



The NbTi coils are impregnated in epoxy to prevent them from moving during when the magnet is energized



The coils are formed by 316 stainless steel

Superconducting-magnet system

What is the maximum intensity of the proton beam before quenching the superconducting magnet?

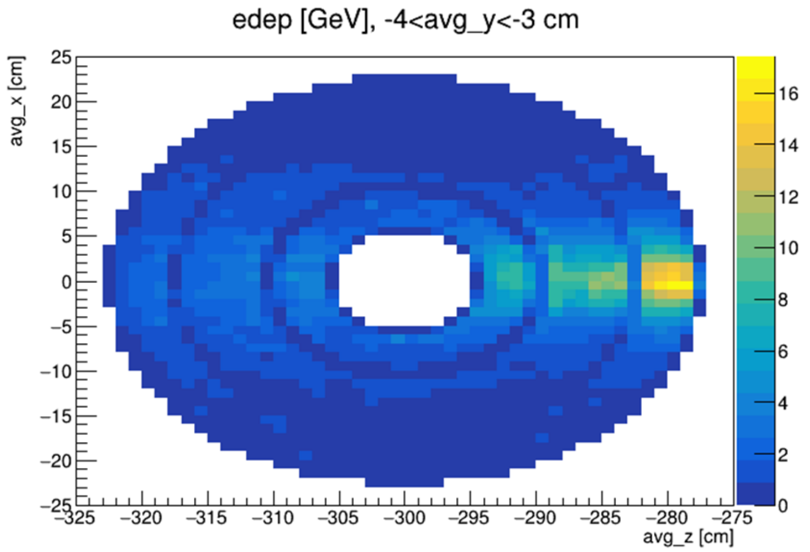
The Thermal processes within the magnet is described by a general heat transfer equation:

$$c\frac{\partial T}{\partial t} = \nabla(\kappa\nabla T) + P_{ext} + P_{He}$$

P_{ext} is the external-heat sources coming mainly from the beam-target interactions

P_{He} is the heat transferred to the liquid Helium

The heat deposited to the magnet (P_{ext}) is simulated using Geant:

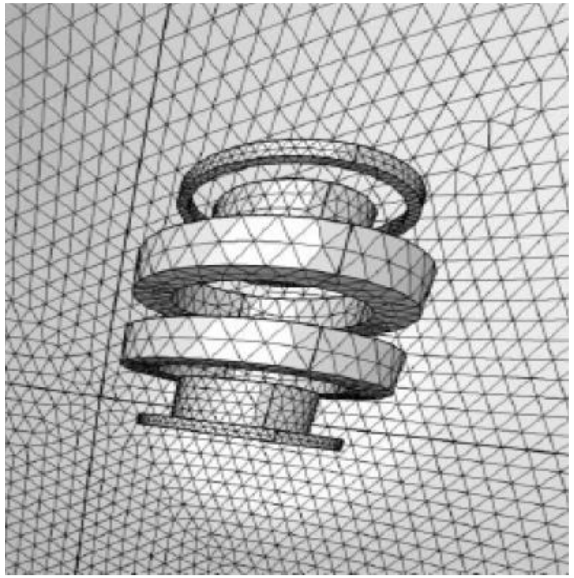


We will run at the highest instantaneous intensity for the polarized target with proton beam

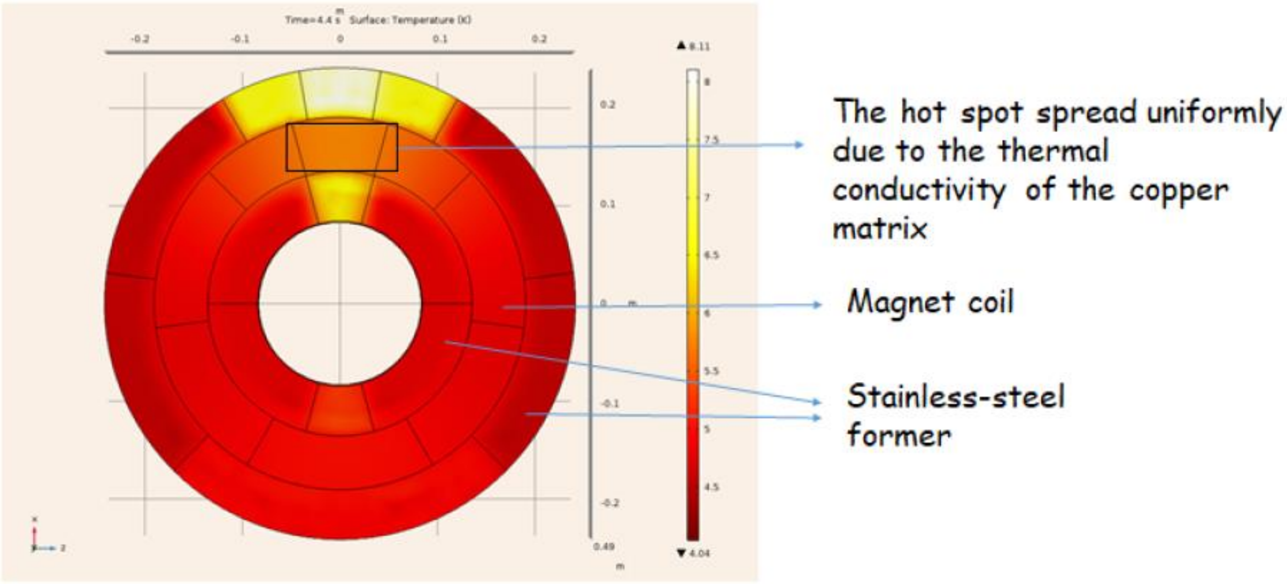
Superconducting-magnet system

What is the maximum intensity of the proton beam before quenching the superconducting magnet?

The simulation was done using COMSOL by applying Finite-Element Method



We obtained the spatial & temporal profile of the temperature in the magnet



Based on this study the maximum intensity of the beam is 2.7×10^{12} proton/sec (with pumping on the He reservoir)

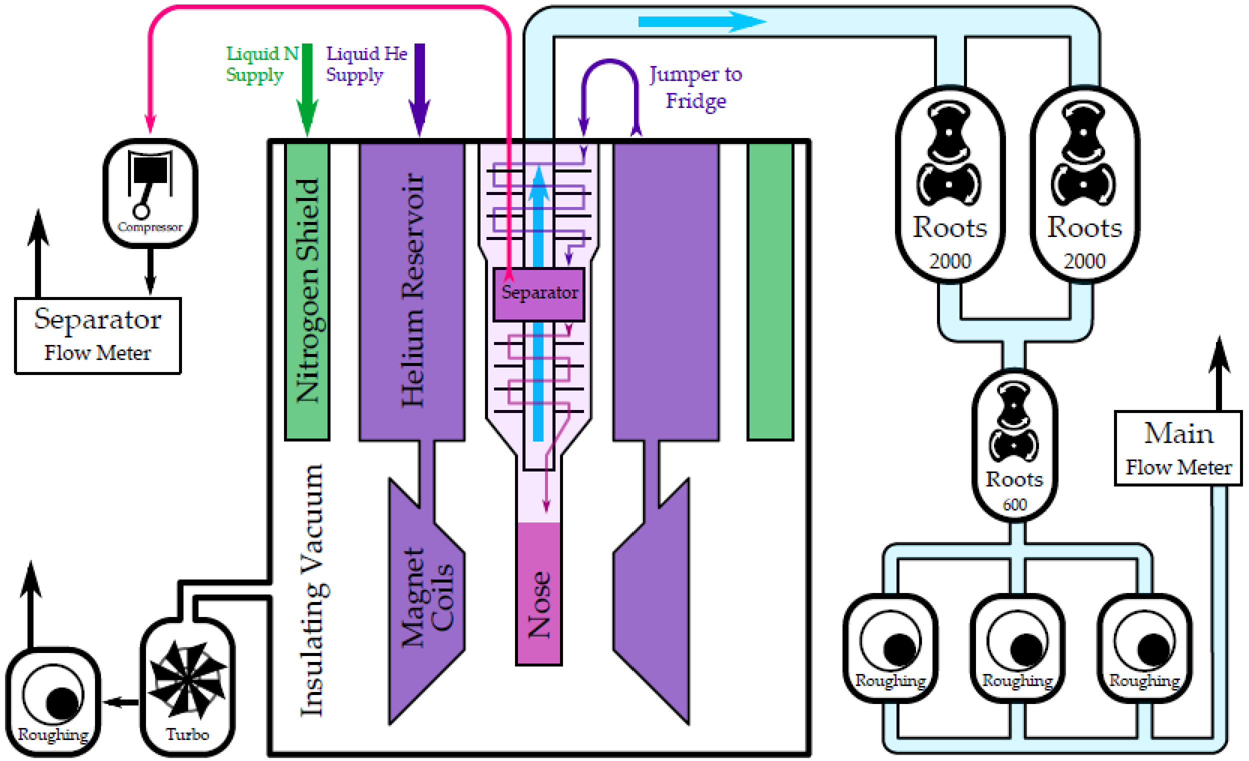
Cryogenics: Evaporation Refrigerator with 1 W of Cooling Power

The target ladder sits in the nose of the refrigerator and cooled by 1 K liquid helium bath

Liquid helium at 4.2 K is drawn from the magnet reservoir through insulated jumper into the separator

The separator is pumped on using KNF pump. The He temperature in separator is lower than 4.2 K

The lHe is supplied from the liquefier with the capacity of ~ 160 liter/day



Courtesy of James Maxwell

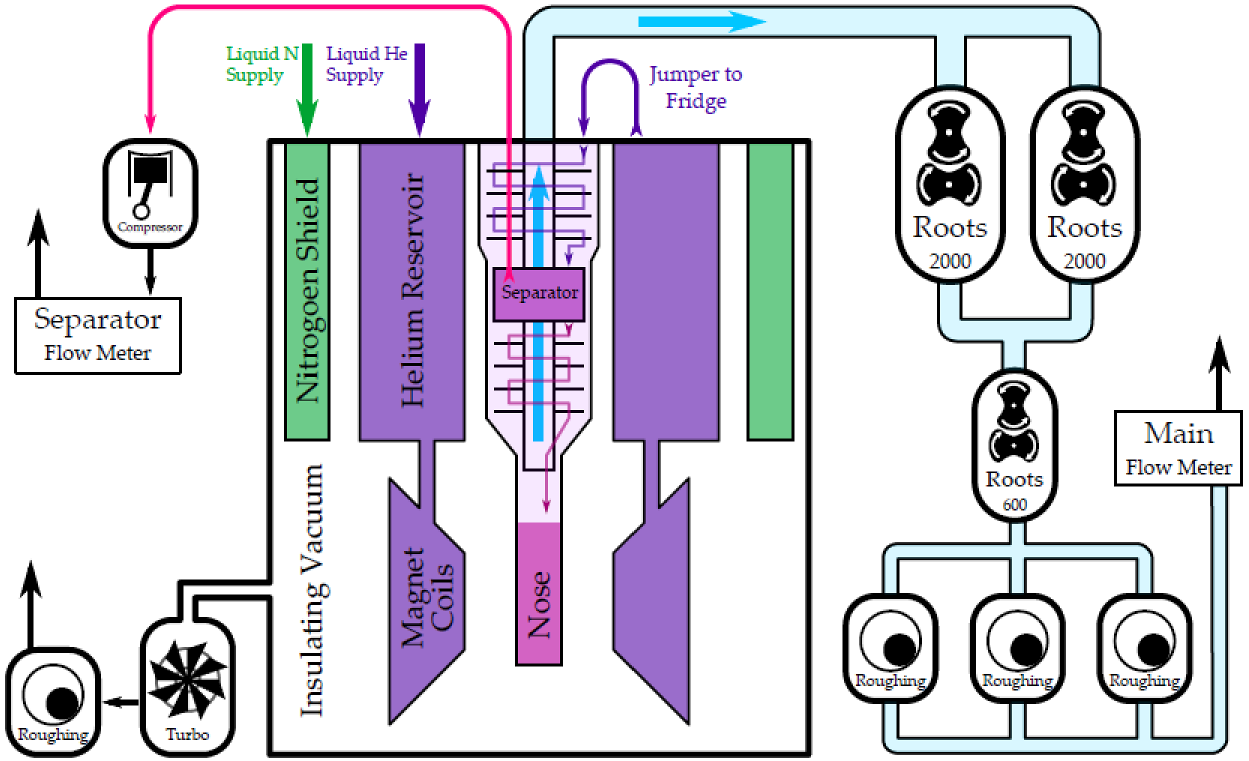
Cryogenics:
Evaporation Refrigerator with 1 W of Cooling Power

The He reaches the nose through bypass valve or run valve

The bypass valve directly down to the nose, used to start the evaporation process

The run valve is thermally coupled to heat exchanger which serve to cool the He further

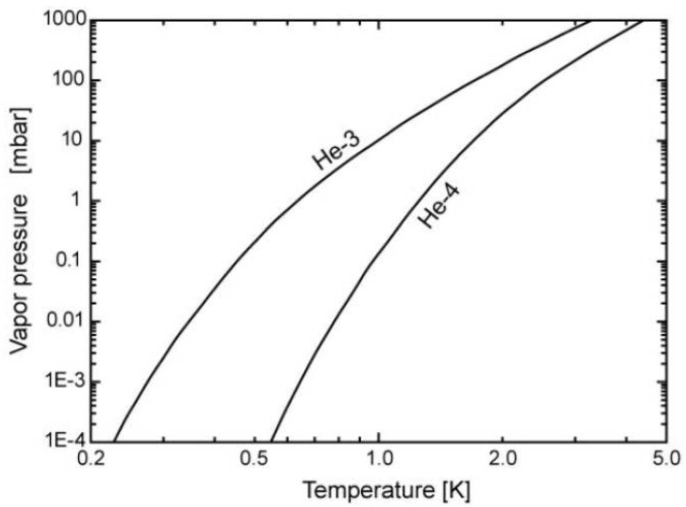
The outer-vacuum system consist of insulating vacuum (~10^{-8} torr) and Nitrogen shield

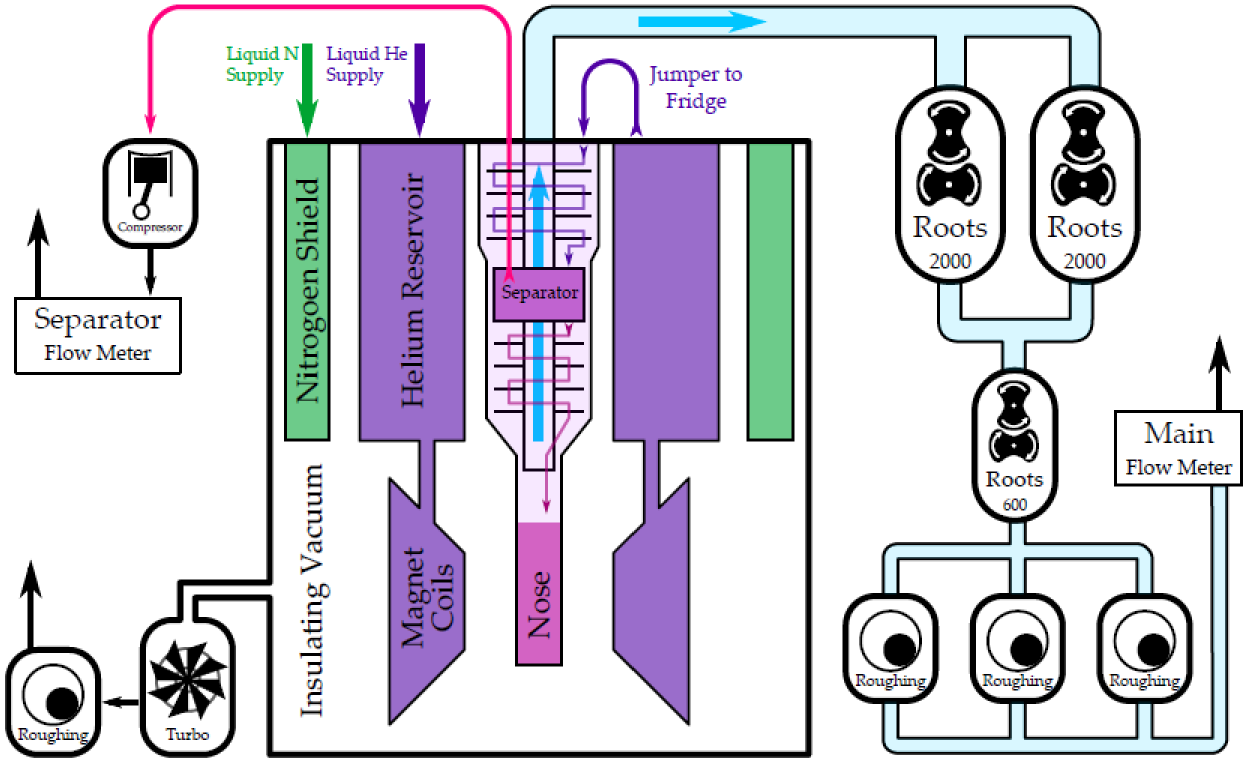


Courtesy of James Maxwell

Cryogenics:
Evaporation Refrigerator with 1 W of Cooling Power

Evaporated He from the nose cools the refrigerator as it is pumped out by high powered pump to keep the temperature at 1 K at 0.12 Torr





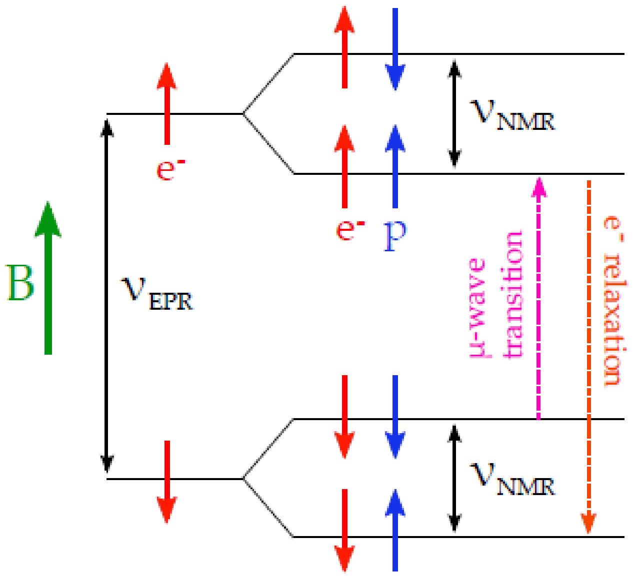
Courtesy of James Maxwell

Nuclear Magnetic Resonances (NMR)

Polarization of the proton is measured using NMR technique

An RF field at the Larmor frequency of the proton (213 MHz at 5 T) can cause a flip of the spin

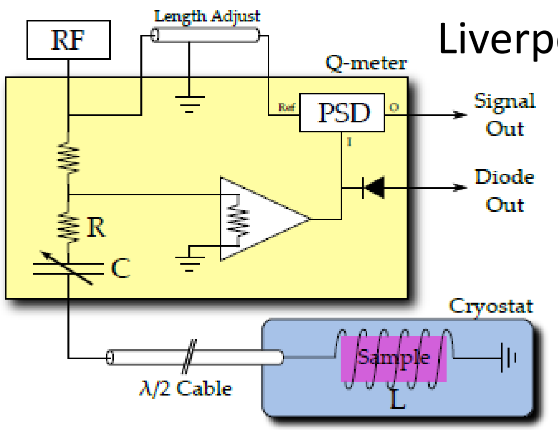
The RF field is produced by 3 NMR coils inside the target cup



An RLC Circuit is tuned to the Larmor frequency of the target materials

The power generated or absorbed due to spin flip change the circuit impedance that can be observed

Liverpool Q-Meter



Courtesy of James Maxwell

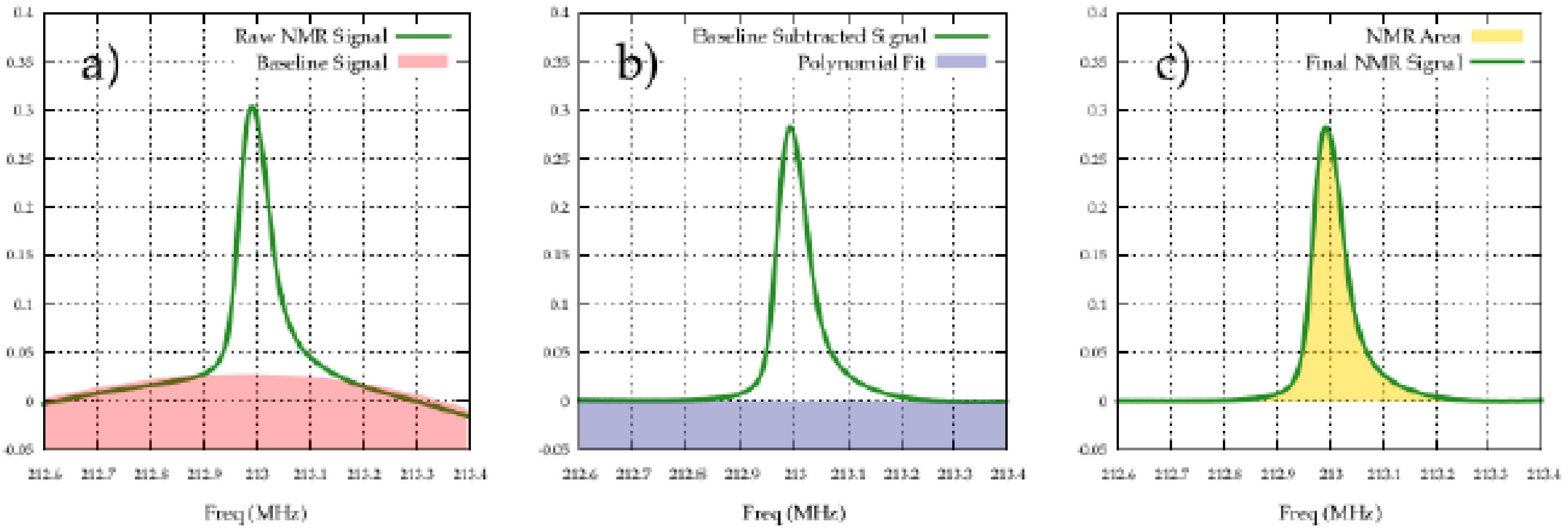
Nuclear Magnetic Resonances (NMR)

Q-Curve is produced by sweeping the RF around the Larmor frequency

The signal area after background subtraction is proportional to the polarization

The proportional constant is obtained at Thermal-Equilibrium measurement

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



Courtesy of James Maxwell

Notes: SpinQuest experiment will use a new NMR system developed by LANL-UVA based on the original Liverpool Q-meter design

Summary

The main polarized-target system for the SpinQuest experiment consist of a 5T superconducting-split magnet, 140 GHz RF generator, 8 cm of solid NH_3/ND_3 target, evaporation refrigerator and LANL/UVA-NMR system

During cooldowns at University of Virginia, The SpinQuest-polarized target achieved proton polarization of 95% using Dynamic-Nuclear Polarization (DNP) technique

Thank You