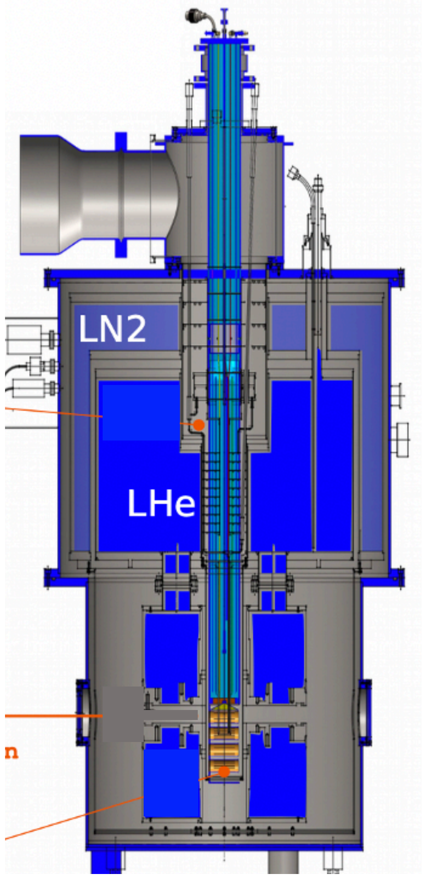
SpinQuest (E1039) Polarized Target : An Overview



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For the UVA Spin-Physics group

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Matsue, Shimane Prefecture, Japan

SPIN QUEST

Fermilab

University of Virginia

UVA - Spin
PHYSICS GROUP

U.S. DEPARTMENT OF ENERGY | Office of Science

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Outline

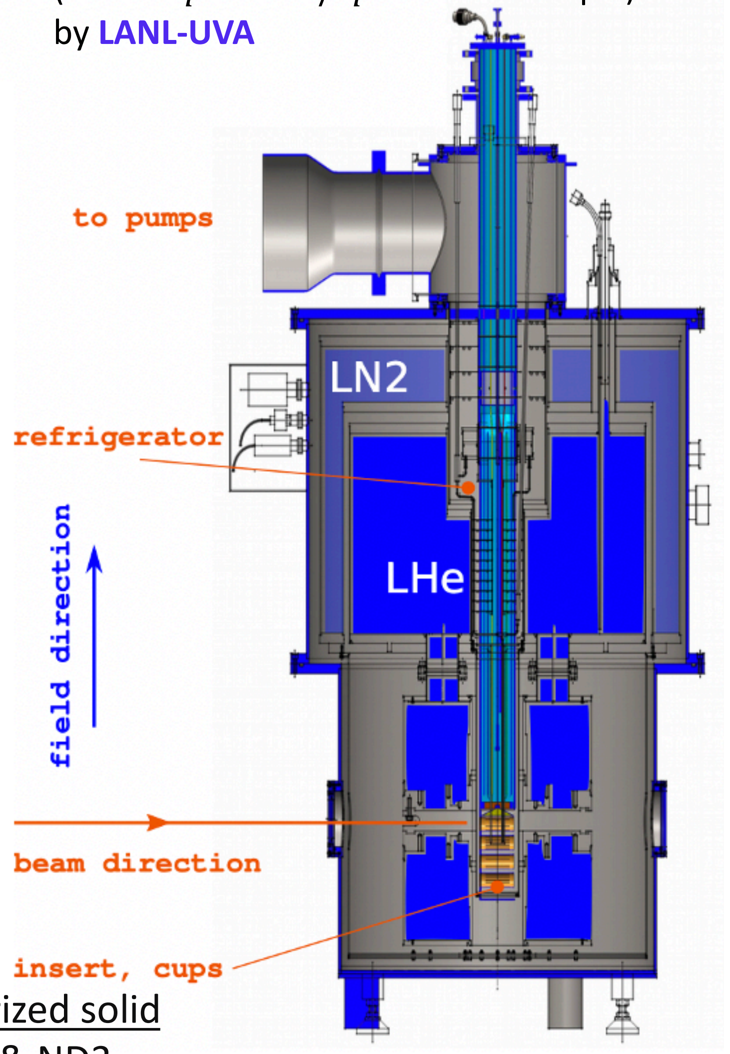
- Physics motivation
- SpinQuest (E1039) experiment setup at Fermilab
- Polarized Target setup at SpinQuest
- Dynamic Nuclear Polarization (DNP) method
- Microwave system
- Target Materials
- Superconducting magnet system
- Cryogenics
- Cryoplatform at NM4
- NMR
- Summary

Physics motivation

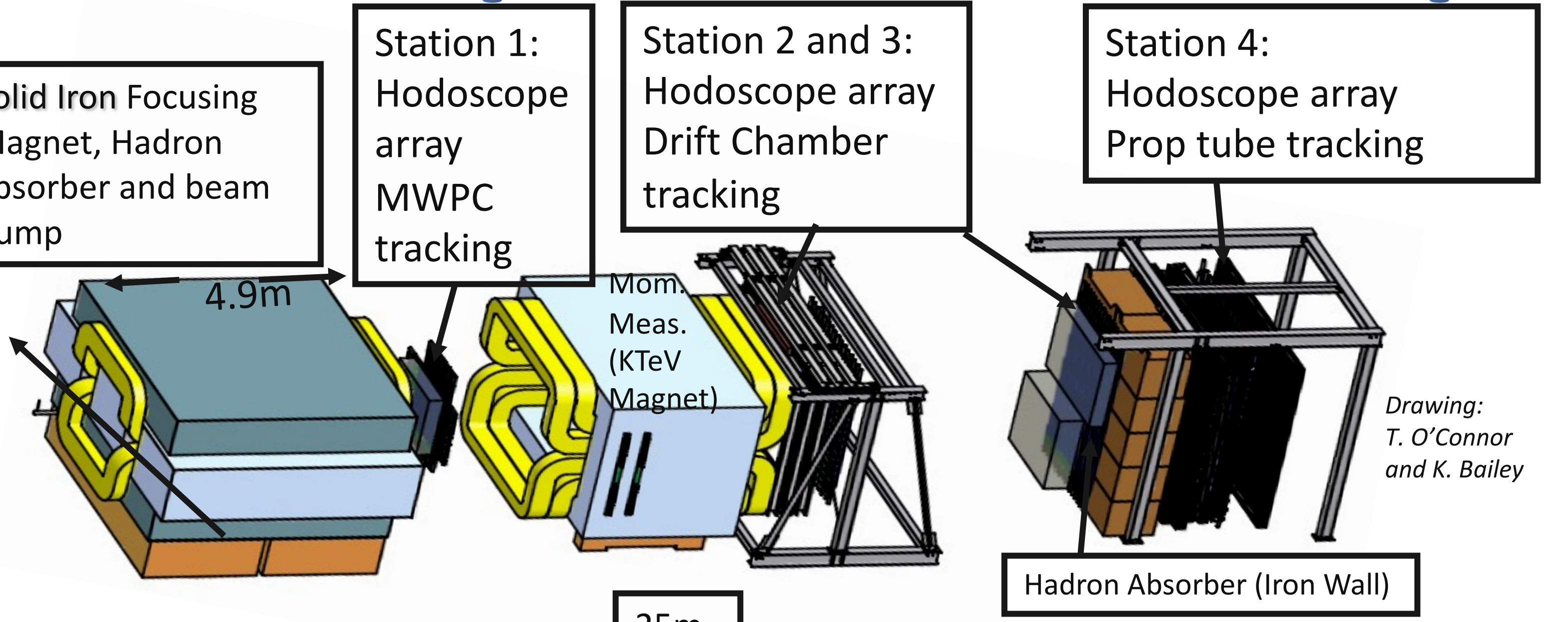
- ❑ SpinQuest will perform the first measurement of the Sivers asymmetry in Drell-Yan pp scattering from the sea quarks.
- ❑ A non-zero Sivers asymmetry from SpinQuest is "smoking gun" evidence for sea quark Orbital-Angular Momentum
- ❑ Require a transversely polarized target capable of both high polarization and integrated luminosity:
    - ➢ Attempt to push the proton intensity frontier on a solid polarized target
    - ➢ Use the longest (max. volume) target cell ever in 1K evaporation polarized target system
    - ➢ This is the highest cooling power DNP (Dynamic Nuclear Polarization) target in the world due to the high pumping rate and the refrigerator.

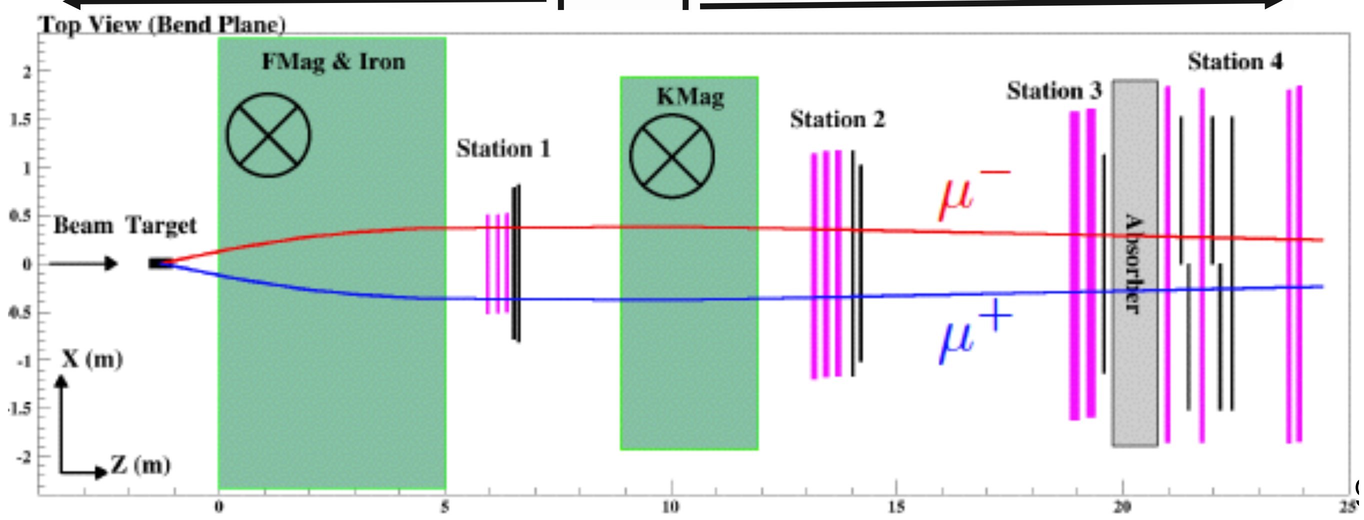
SpinQuest / E1039 Experiment Setup

- Designed for high intensity proton beam ($5\times10^{12} protons/spill$ with 4.4s spill) by **LANL-UVA**



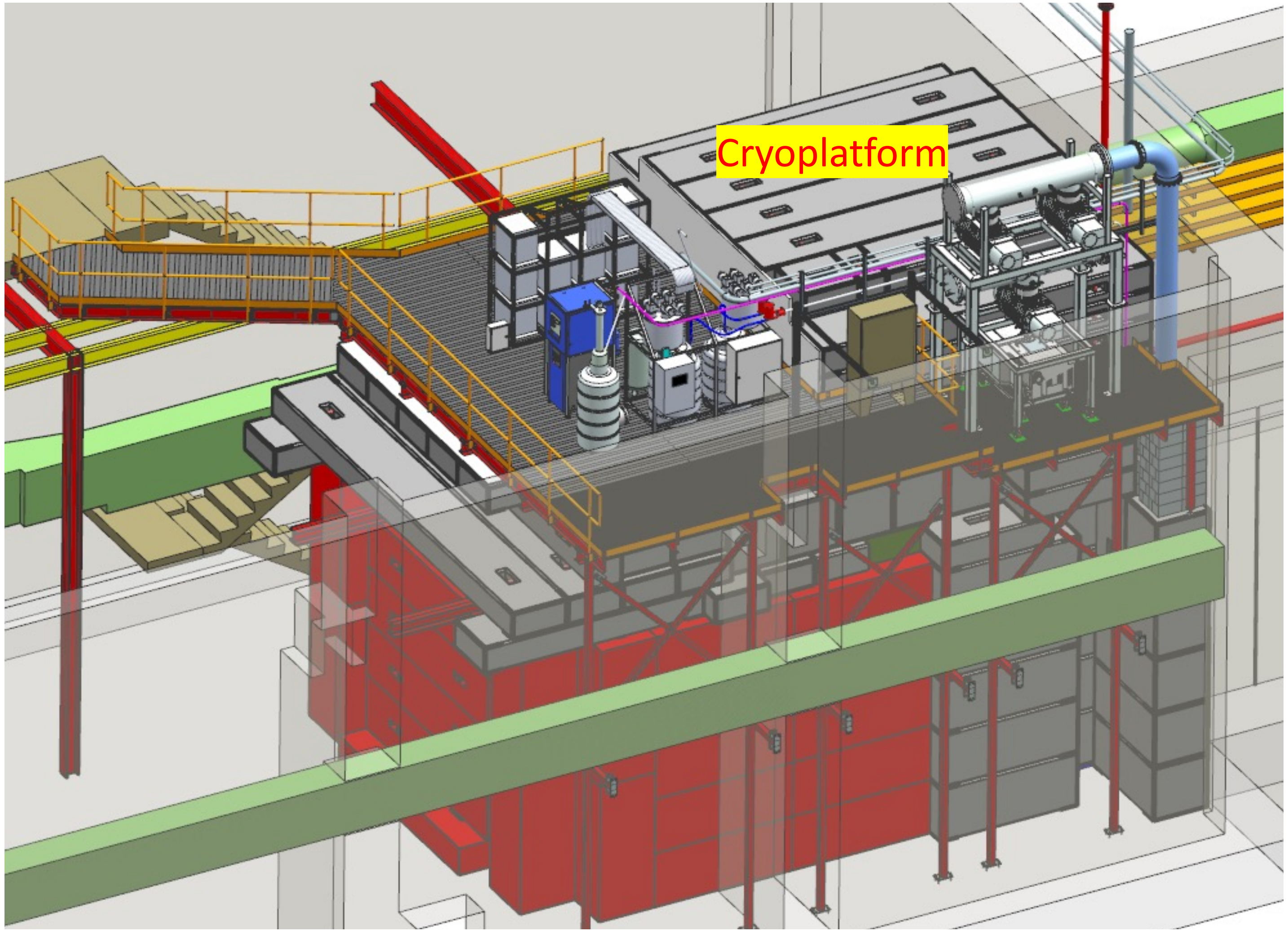
Polarized solid NH3 & ND3 target setup

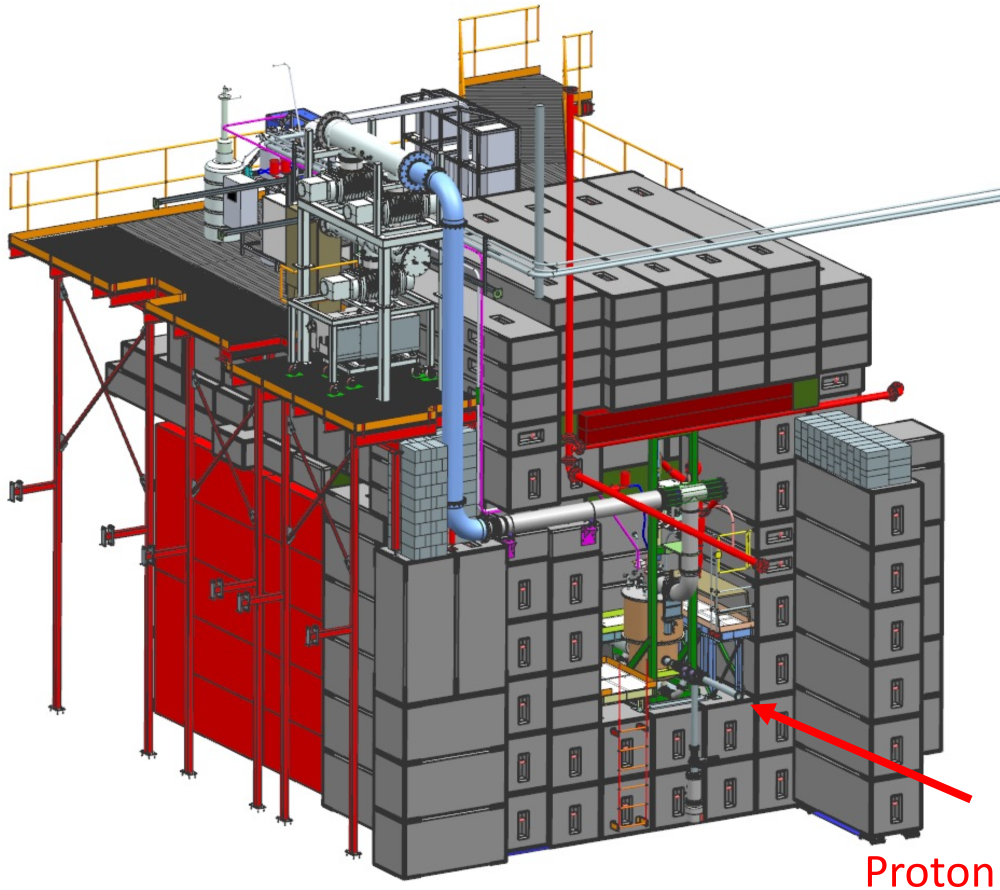




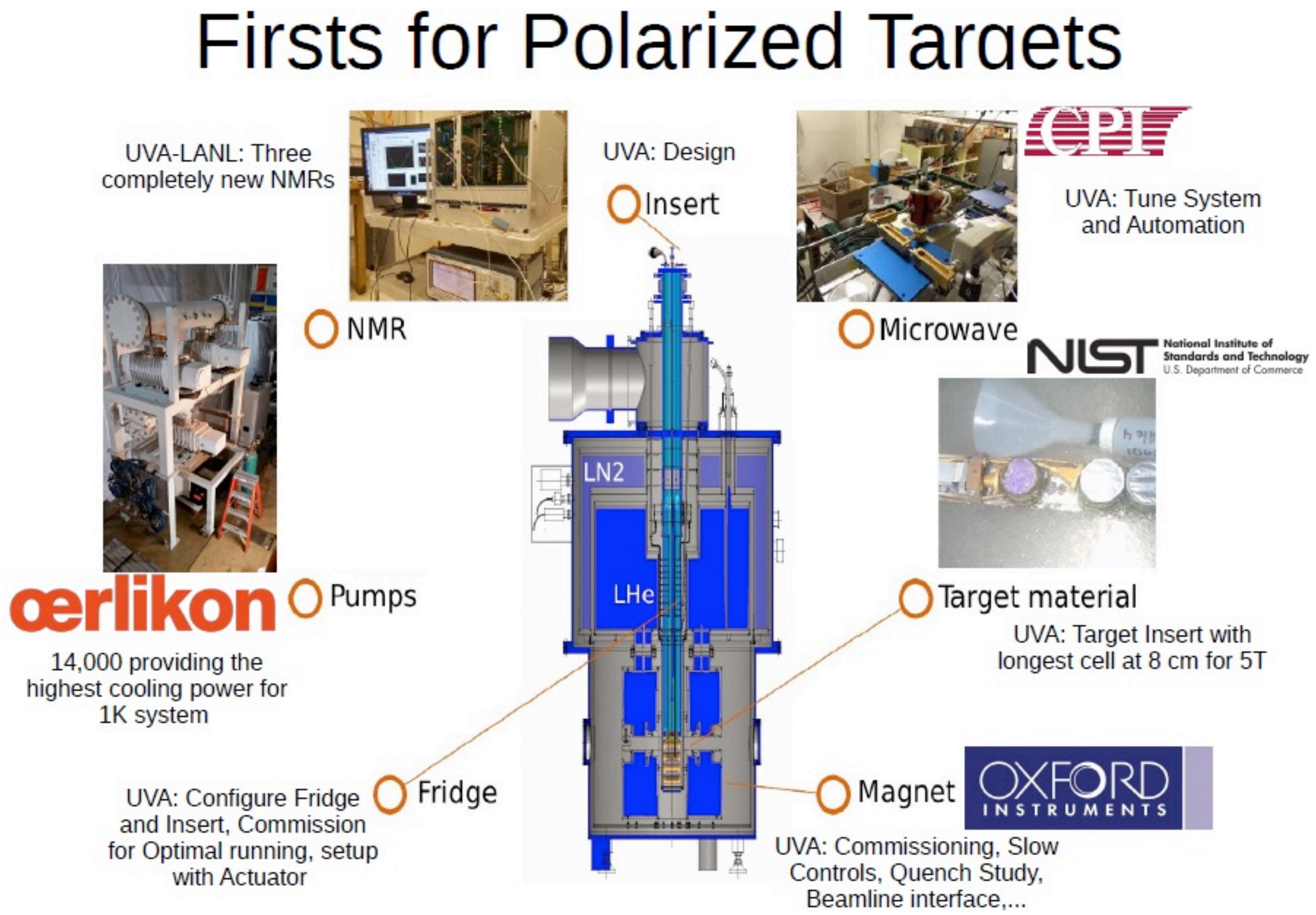
Please see the talks by Yoshiyuki Miyachi, Zulkaida Akbar, Anchit Arora, Catherine Ayuso & Arthur Conover

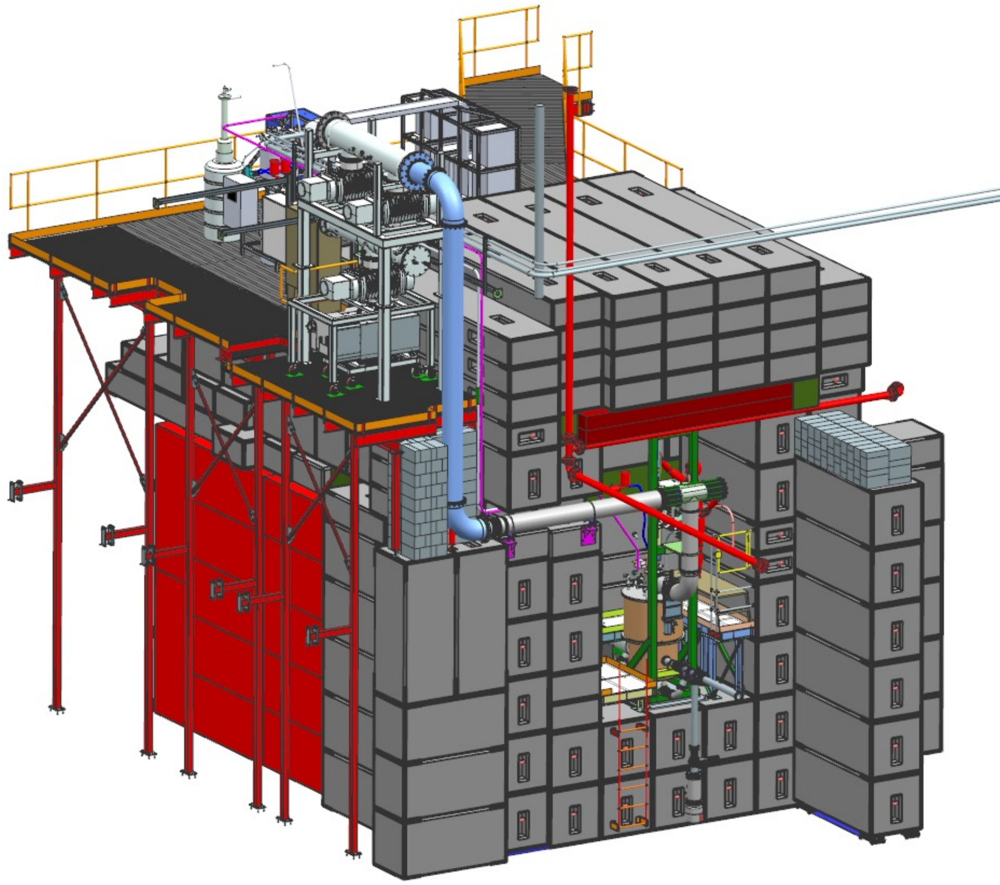
SpinQuest Polarized Target Setup



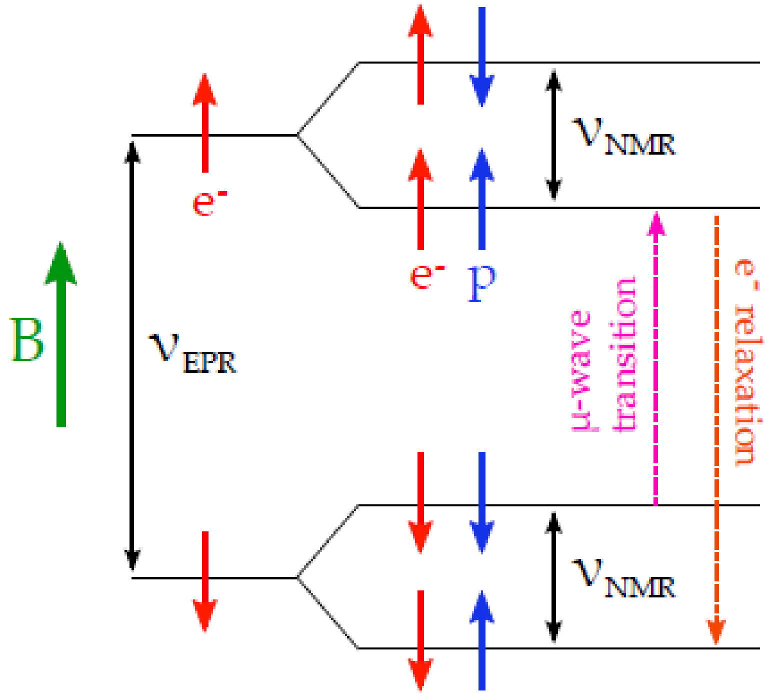


SpinQuest Polarized Target Setup



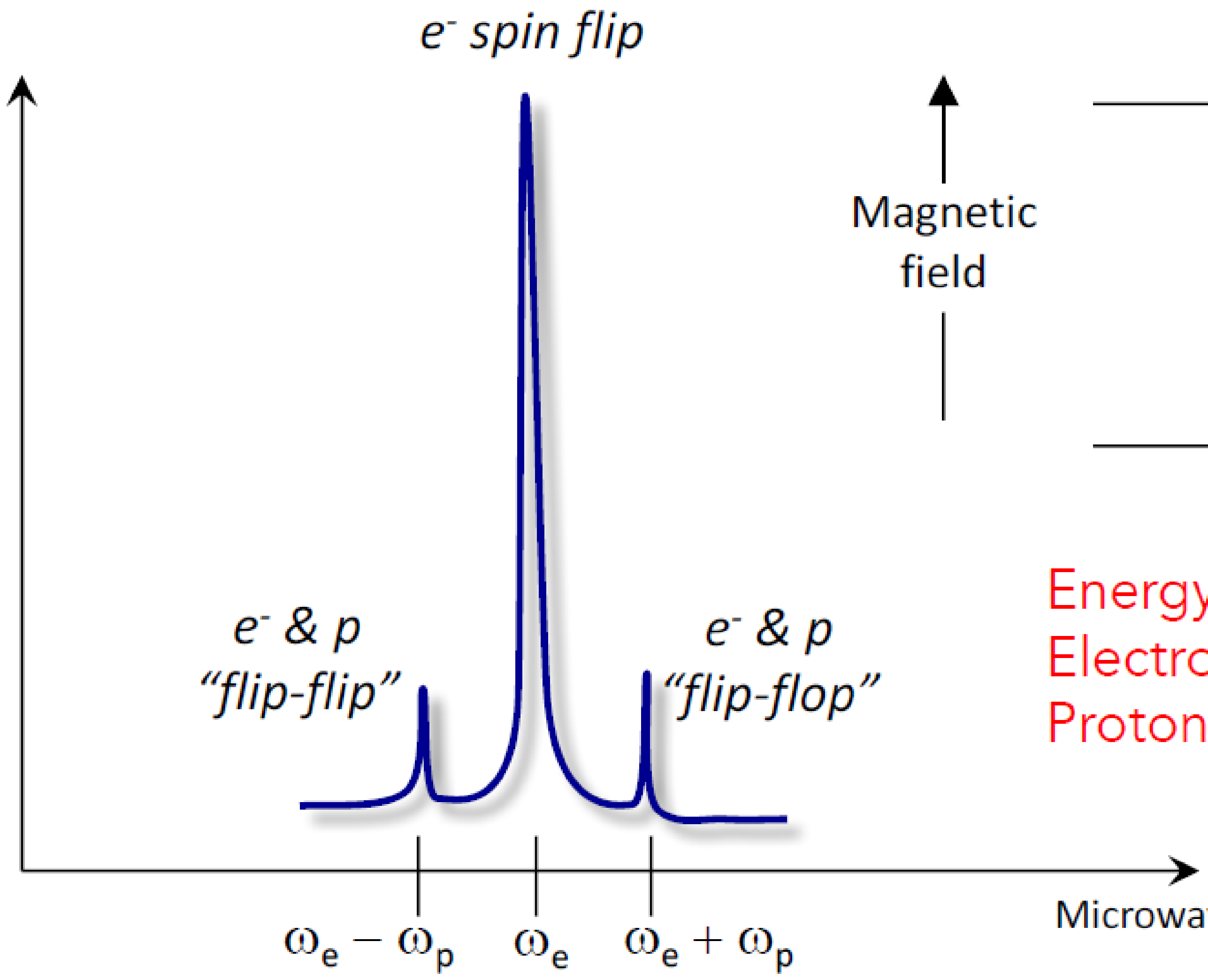


DYNAMIC NUCLEAR POLARIZATION (DNP) Method

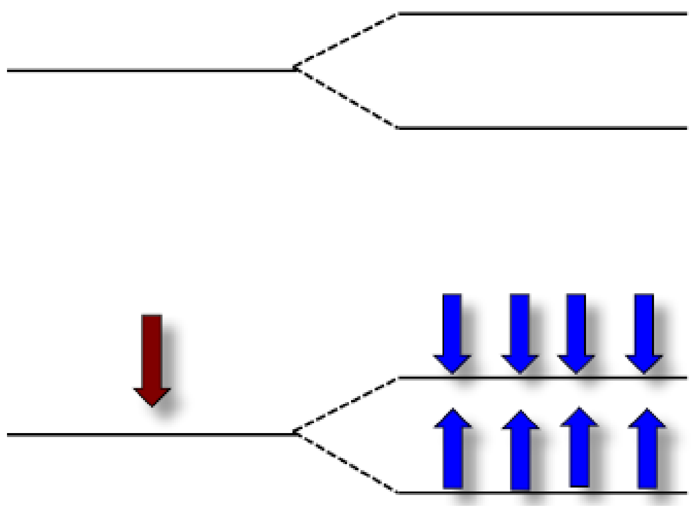


- The coupling between (unpaired) electron & proton introduces hyper-fine splitting $H = -\mu_e B - \mu_p B + H_{SS}$
- Applying an RF-field at the correct frequency, we can drive the proton state into desired spin-state
- The disparity in relaxation times between the electron (ms) and proton (tens of minutes) at 1K is crucial to continue proton polarization
- Allow to achieve proton polarization of > 90%

DNP Method



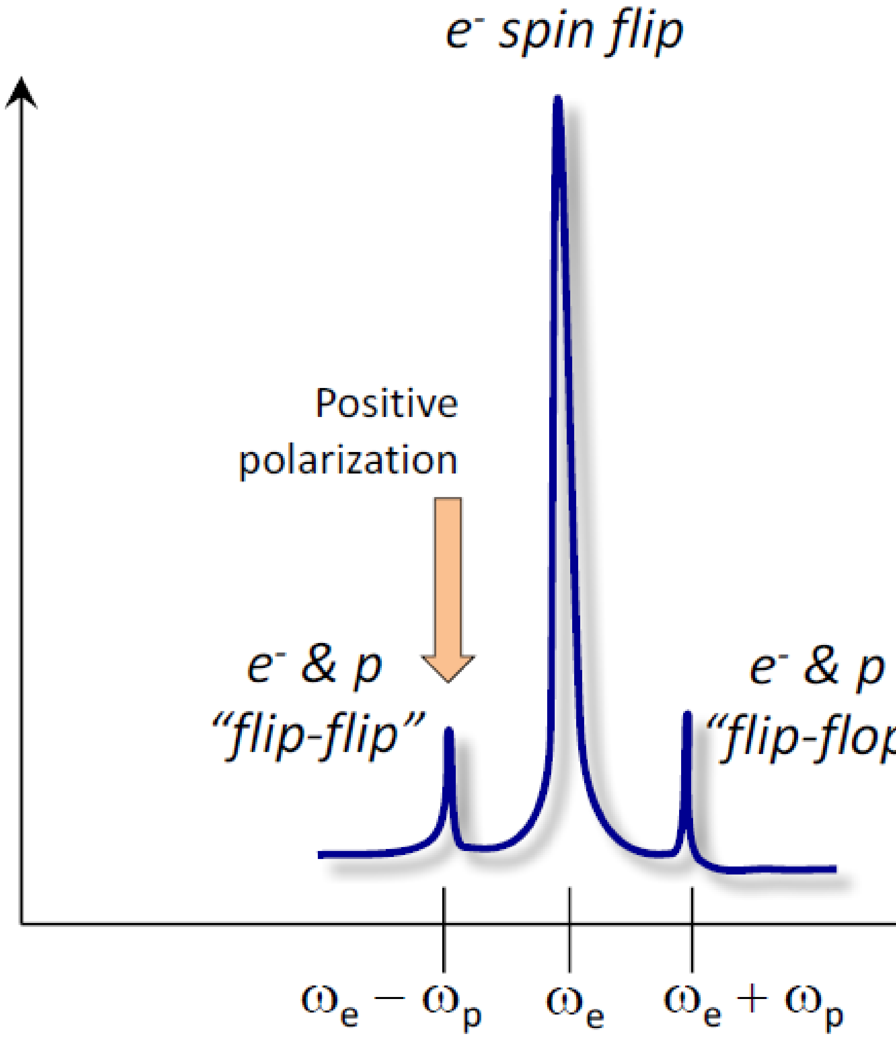
Courtesy of Chris Keith



Energy levels of a electron+ protons.
Electron is polarized.
Protons are not.

Based on the Solid-State model

DNP Method



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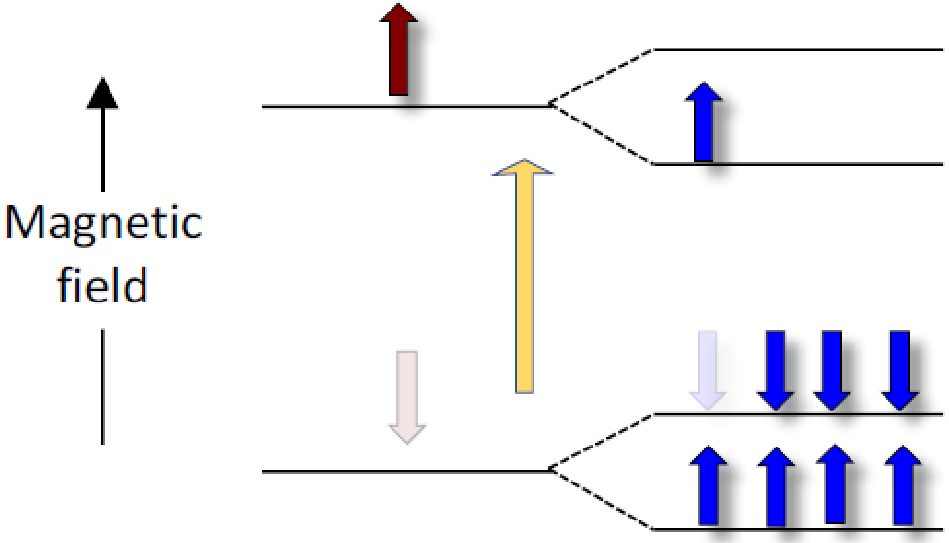
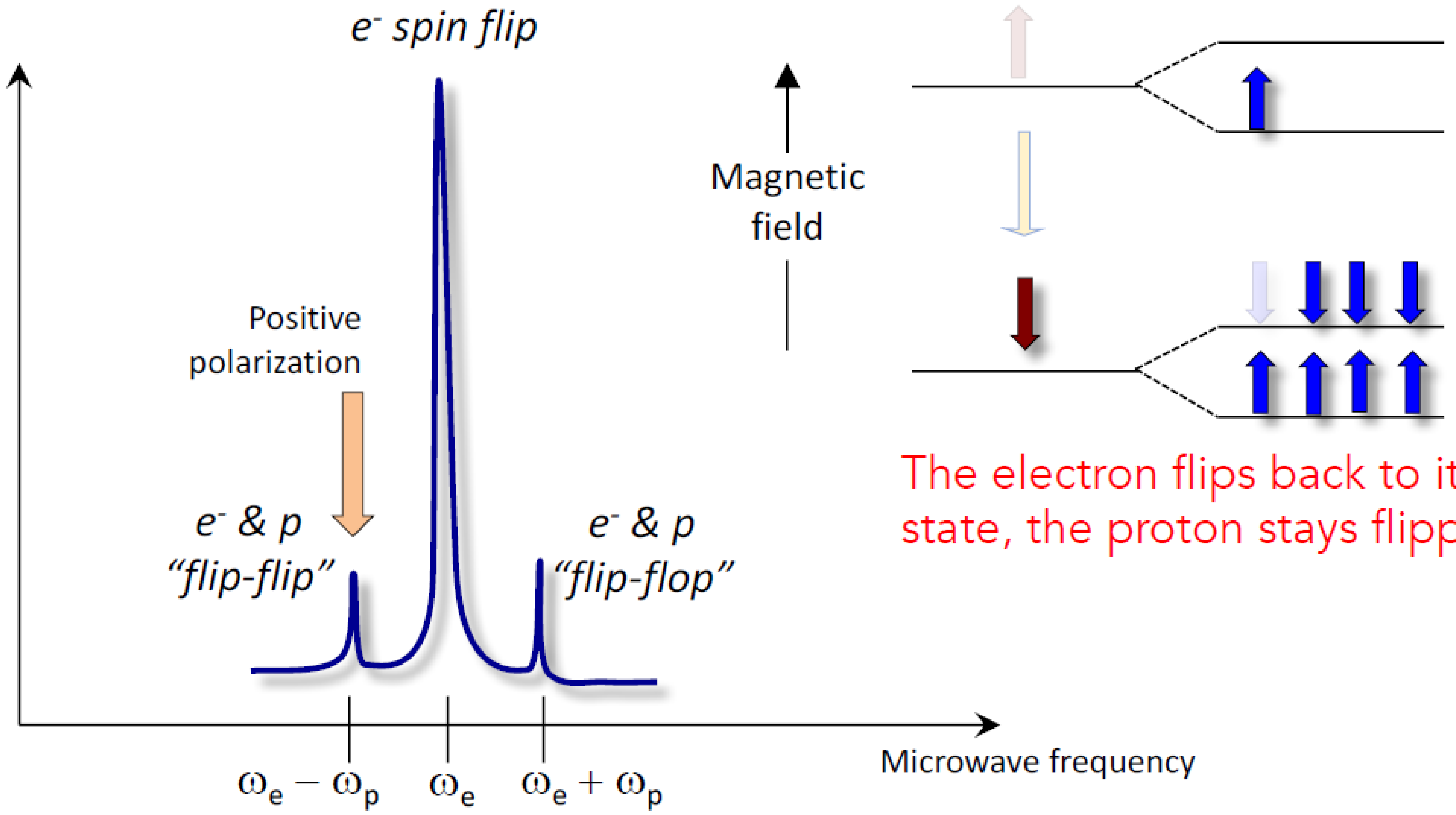


Microwaves at ω_e - ω_p flips both electron & proton spins.

DNP Method

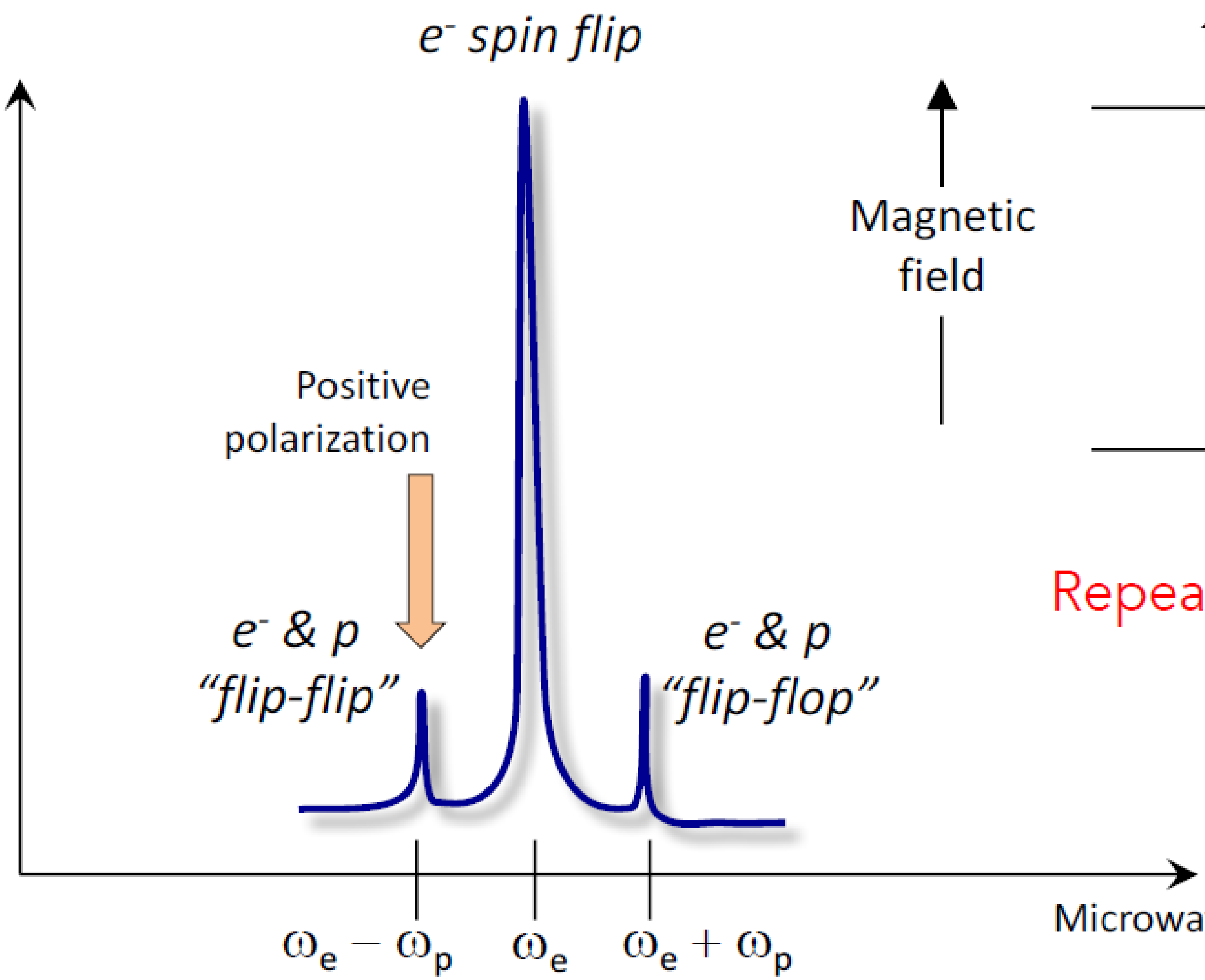


Courtesy of Chris Keith

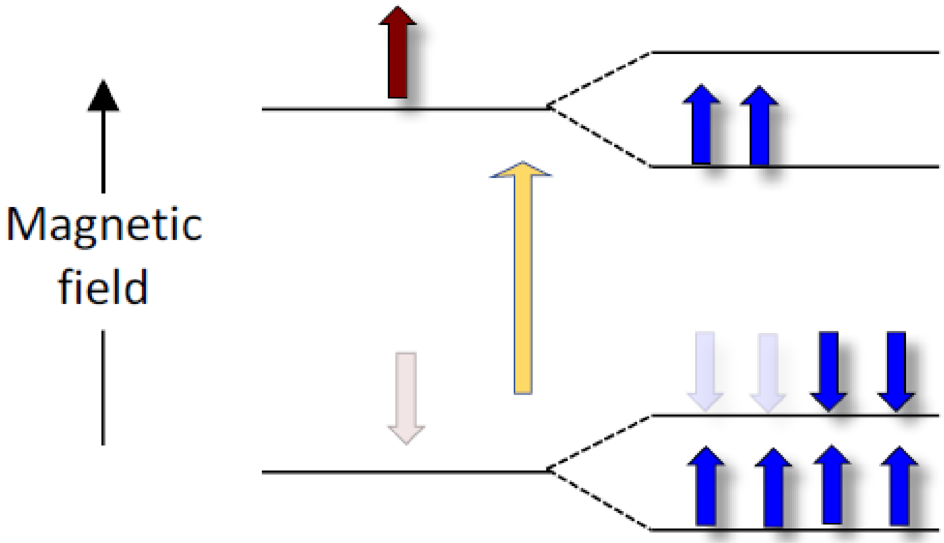
The electron flips back to its ground state, the proton stays flipped (long t_1).

Based on the Solid-State model

DNP Method



Courtesy of Chris Keith

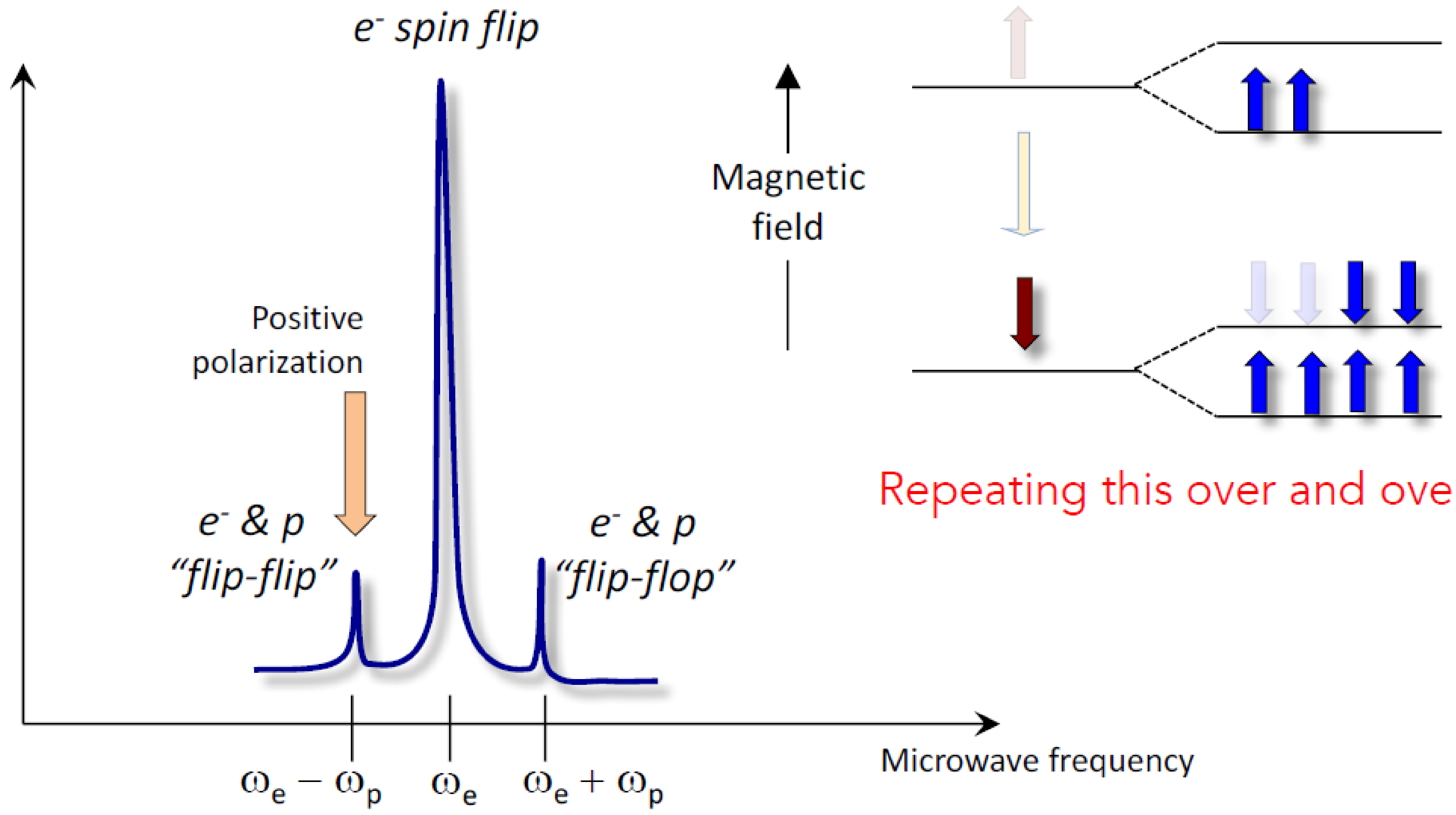


Microwave frequency

Repeating this over and over…

Based on the Solid-State model

DNP Method

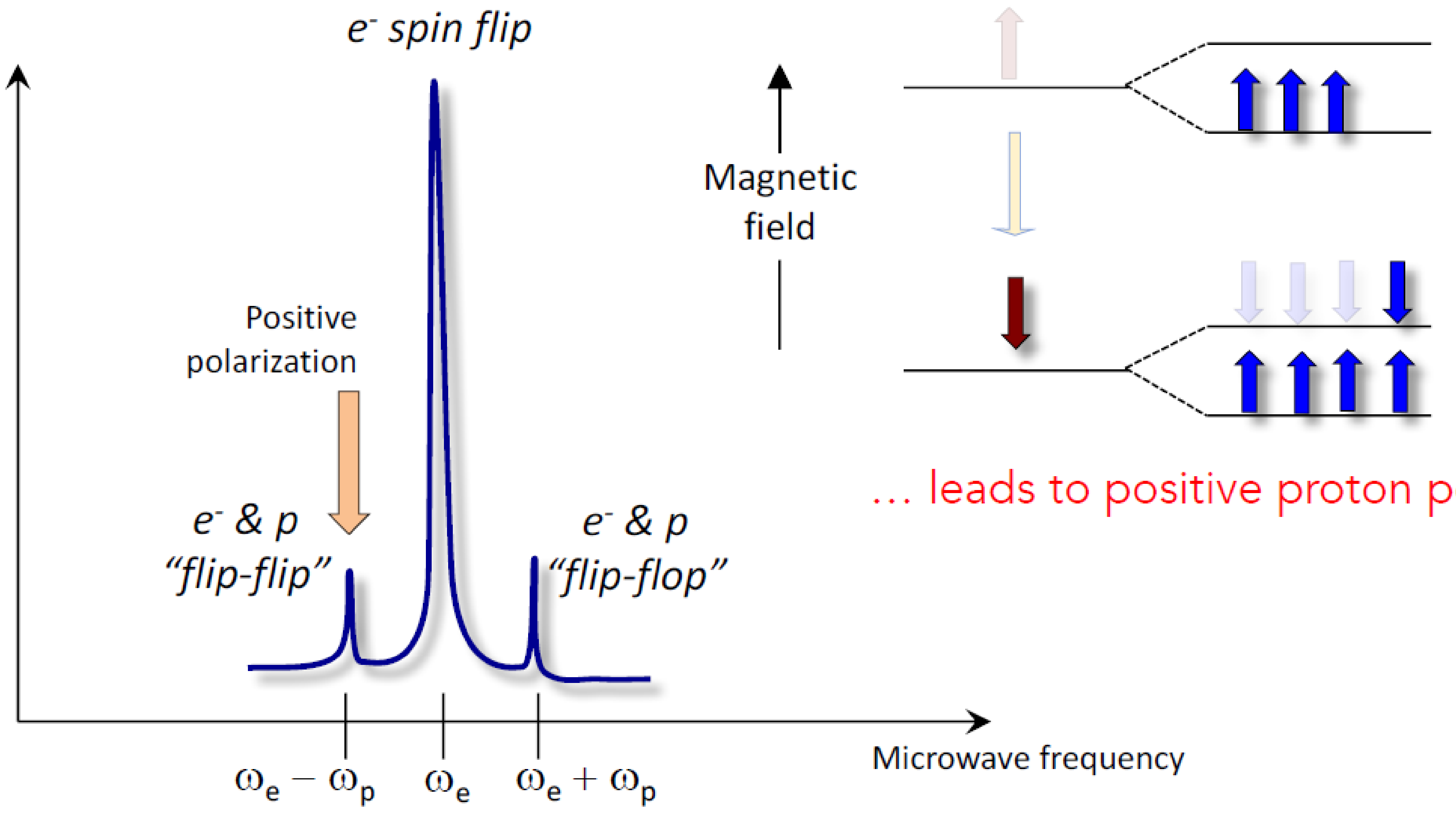


Courtesy of Chris Keith

Repeating this over and over…

Based on the Solid-State model

DNP Method



Courtesy of Chris Keith

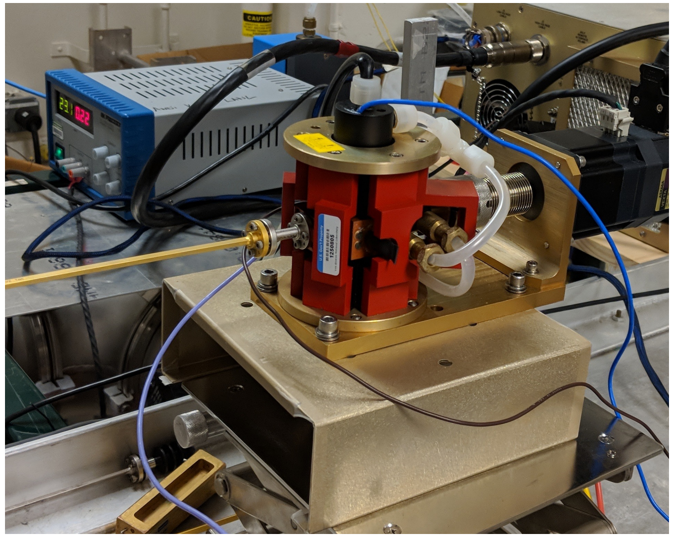
… leads to positive proton polarization.

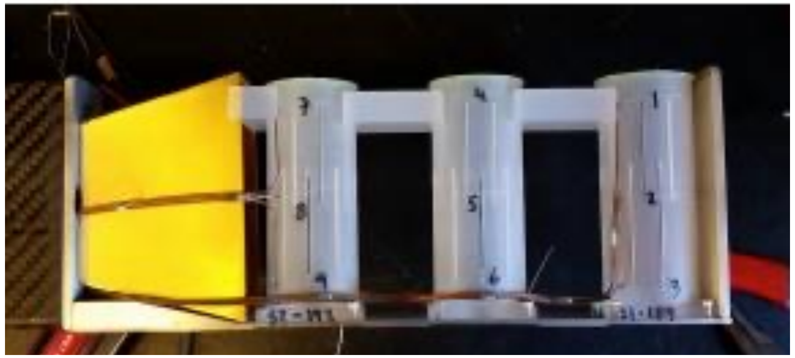
Based on the Solid-State model

Achieving a significant proton polarization using 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





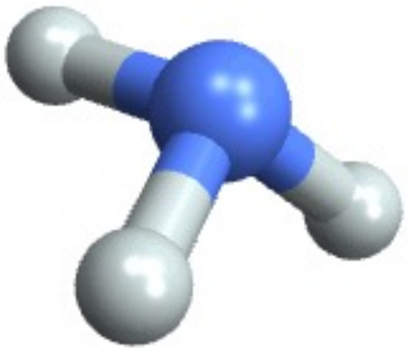
- 140 GHz RF signal is generated by Extended- Interaction Oscillator (EIO) through interaction between electron beam (produced from ~kV of cathode/anode) and resonant cavities

- The optimal frequency changes as we flip the spin direction.
  [freq change requiring the change in cavity size is to change polarization direction. Small freq changes can be made by adjusting the e beam velocity]
- The optimal frequency also 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)

- 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
- We will have 3 target cups so we can quickly replace the target when it is damaged due to the radiation

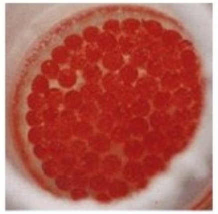
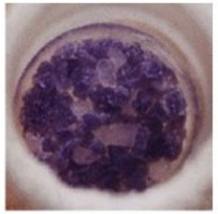
Target Materials



- A successful target material candidates for the DNP can be characterized by
  - Maximum achievable polarization
  - Dilution factor
  - Resistance to radiation damage

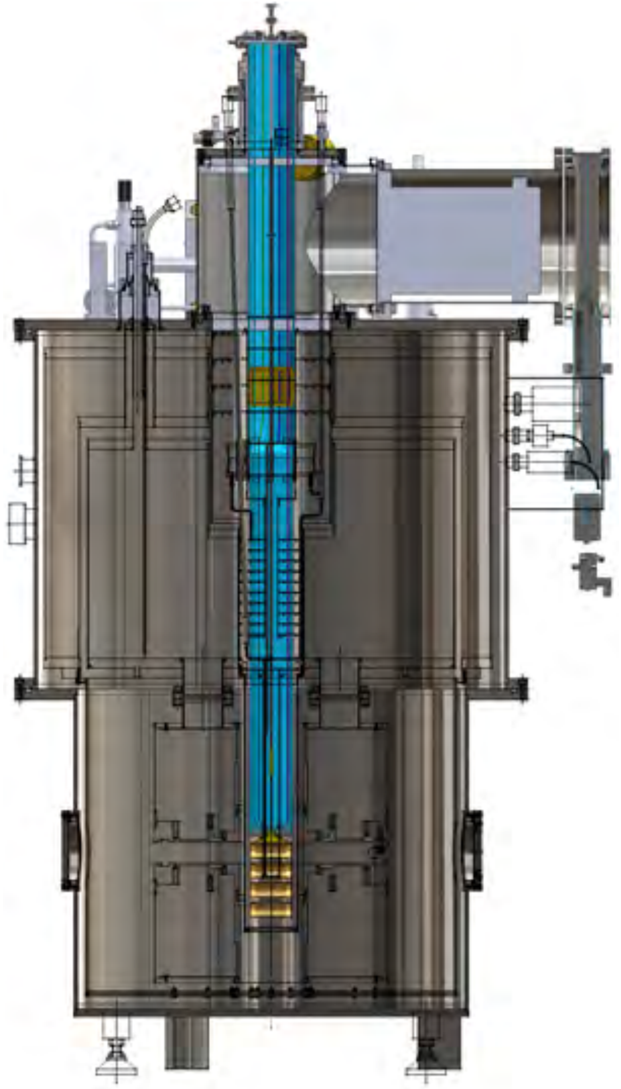
- SpinQuest experiment will use 8 cm of solid NH_3/ND_3 as target materials which are doped with paramagnetic free-radical by being irradiated at NIST (National Institute of Standard and Technology)

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


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*

Superconducting magnet system



- The superconducting magnet coils provide Magnetic Field (transverse to the beam):
  B = 5 T with uniformity $dB/B < 10^{-4}$ over 8 cm
  [^{4}He evaporation refrigerator (3 W of maximum cooling power) keeping the target at 1.0 K]

- The magnet consist of NbTi coils which are impregnated in epoxy to prevent them from moving during when the magnet is energized; and the coils are held in place by stainless steel (type: 316)

Superconducting magnet system:

Maximum proton beam intensity before Quenching ~6.3K @ ~5T target region

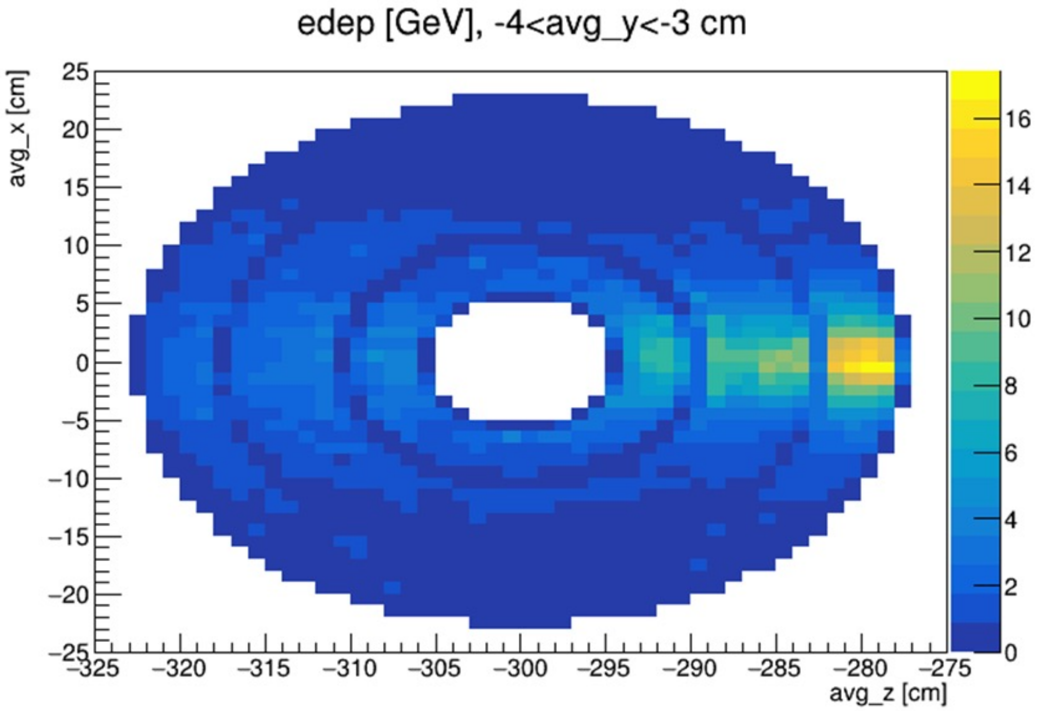
The Thermal processes within the magnet is described by a general heat transfer equation:

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

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:



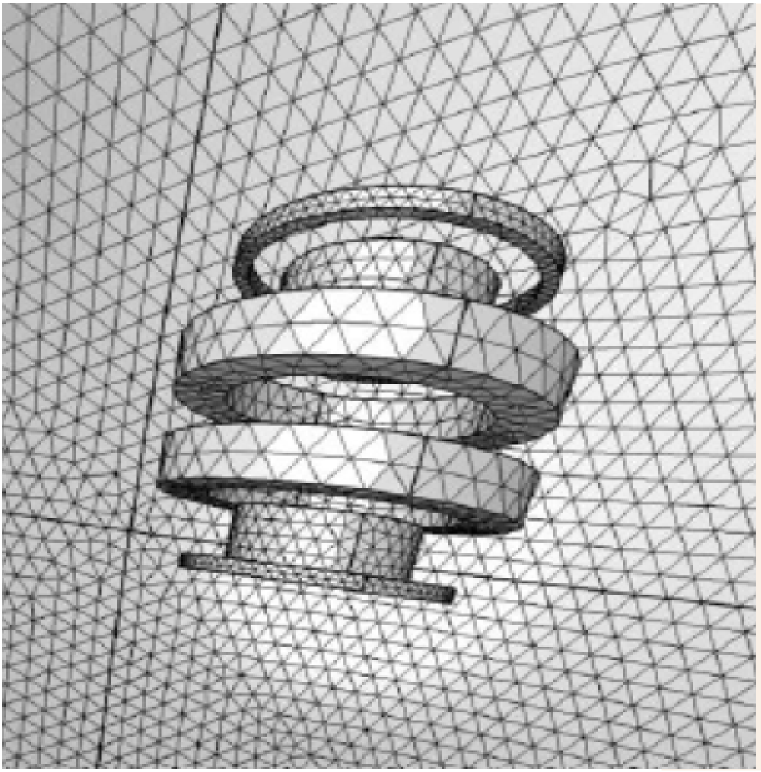
Superconducting magnet system:

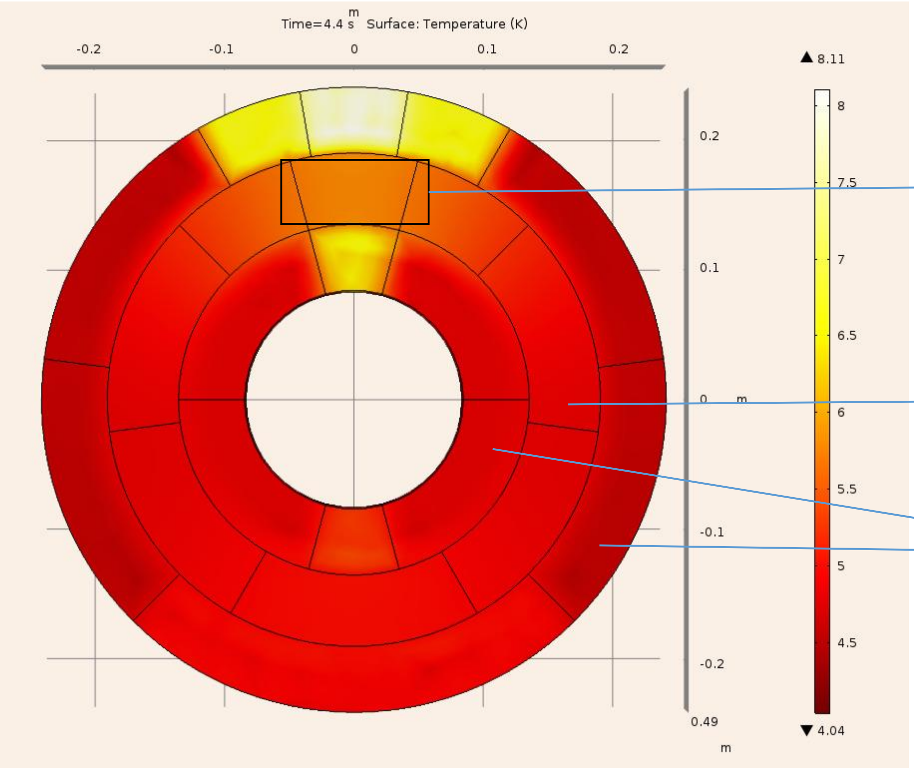
Maximum proton beam intensity before Quenching

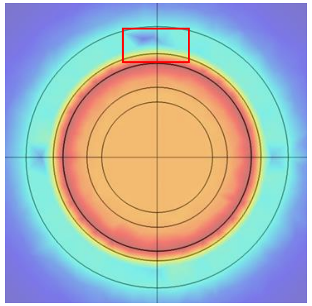
~6.3K @
~5T target region

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

The spatial & temporal profile of the temperature in the magnet







B-Profile of the magnet. The quench limit for the Bmax is

6.85 T

The hot spot spread uniformly due to the thermal conductivity of the copper matrix

Magnet coil

Stainless-steel former

Courtesy of Zulkaida Akbar

Based on this study the maximum intensity of the beam is 2.7×10^{12} proton/sec (with pumping on the He reservoir at 2.5 K with the rate of 100 SLPM)

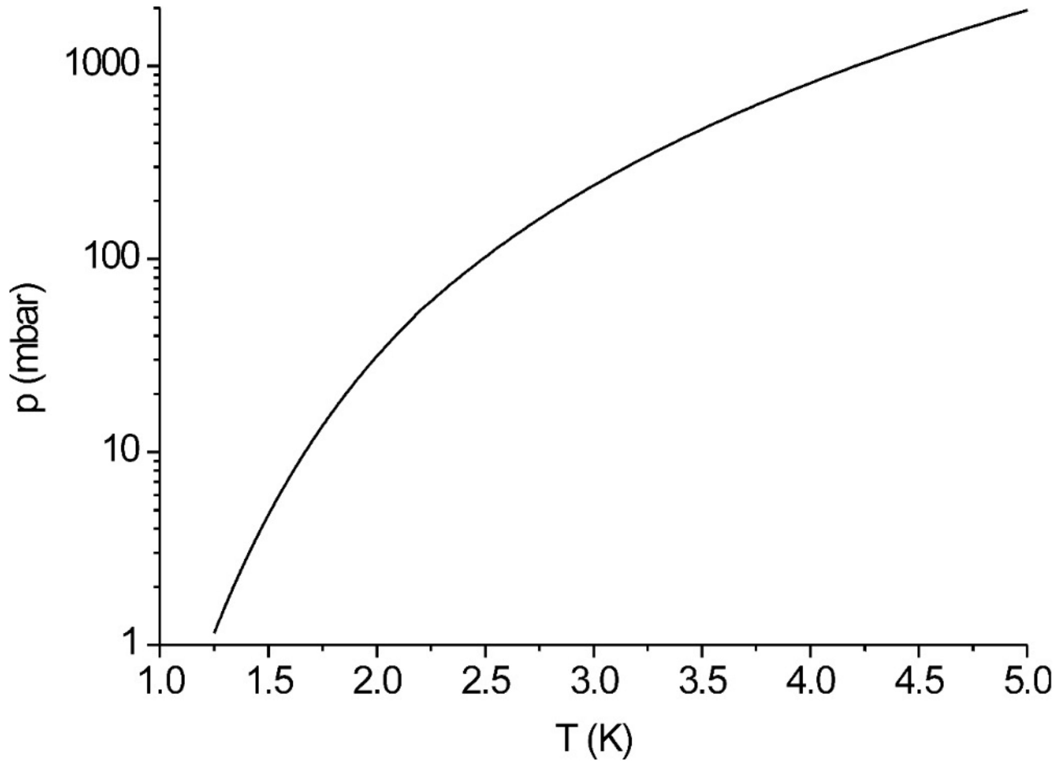
Cryogenics

Evaporated He from the target nose need to be pumped out by high powered pump to keep the temperature at 1 K at 0.12 Torr.

Critical components for high-cooling power refrigerator:

- ➢ High-power pump
- ➢ Sufficient supply of the liquid Helium
- ➢ Heat exchanger that bring the He temperature down from 4.2 K to 1 K
- ➢ Thermal shielding

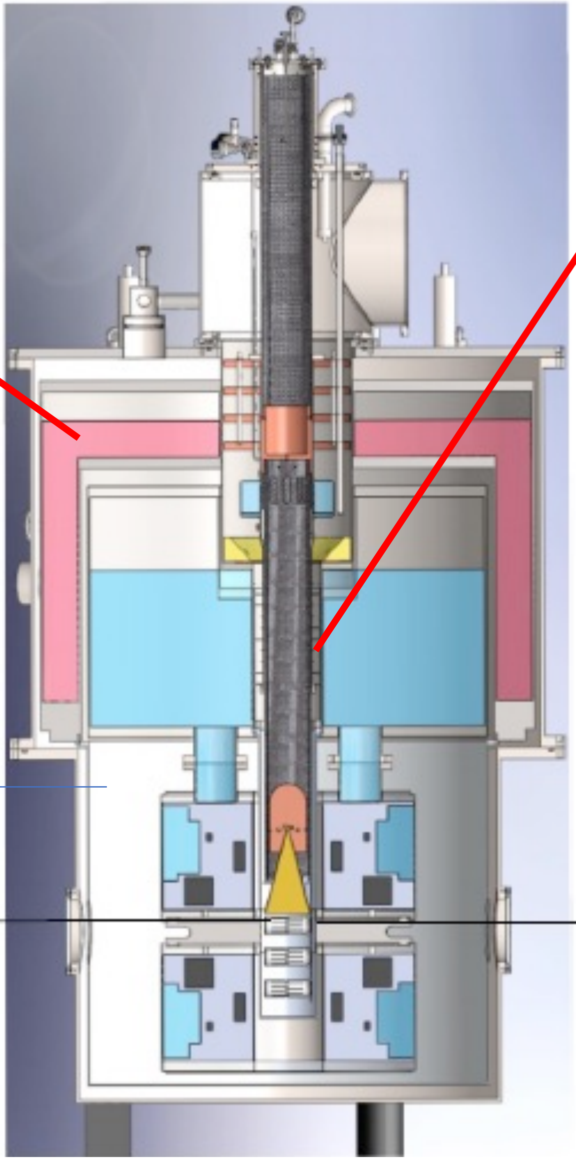
He-4 Pressure-Temperature diagram

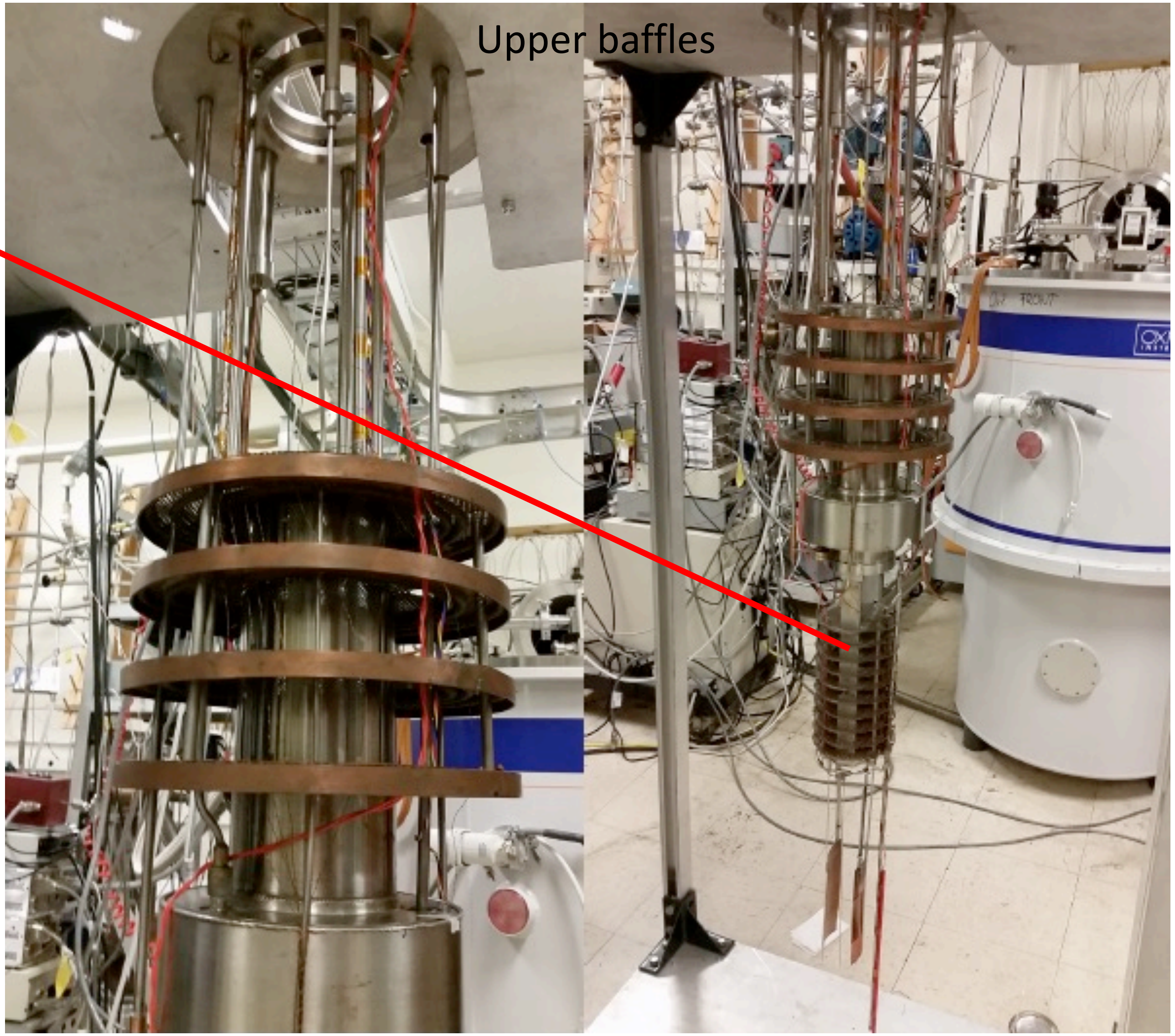


Cryogenics

Thermal shielding:
- Liquid Nitrogen
- Outer Vacuum

Turbo Molecular pump maintain the outer vacuum pressure at ~10^{-8} torr



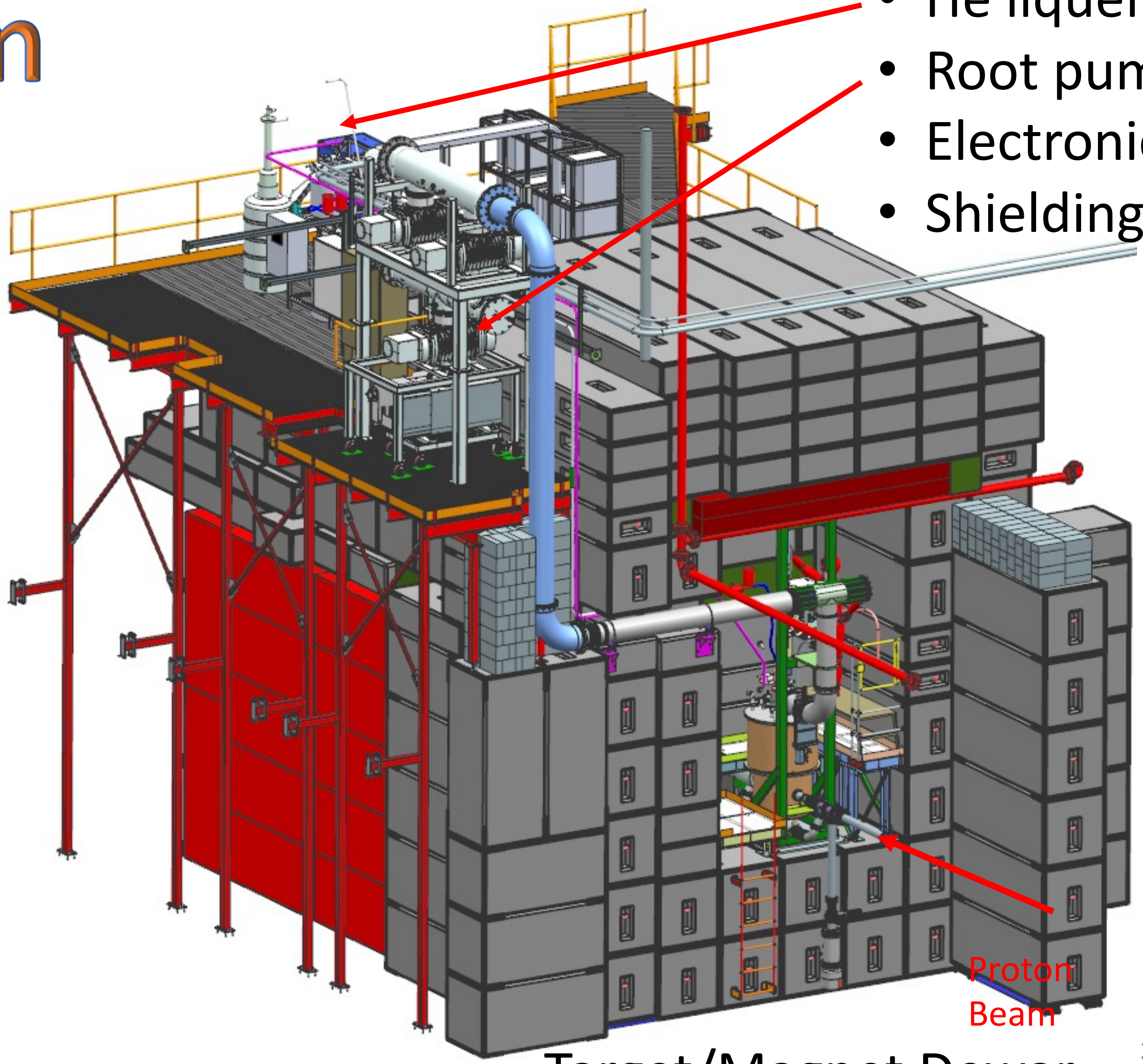


Cryoplatform

- Cryoplatform showing the He-liquefier and Roots pumps setup

- The liquefier is capable to supply 200 liter per day of liquid He

- Roots pump have the pumping capacity of ~ 16,800 m^3 per hour



Target/Magnet Dewar

Cryoplatform : Roots pumps setup

Cryoplatform

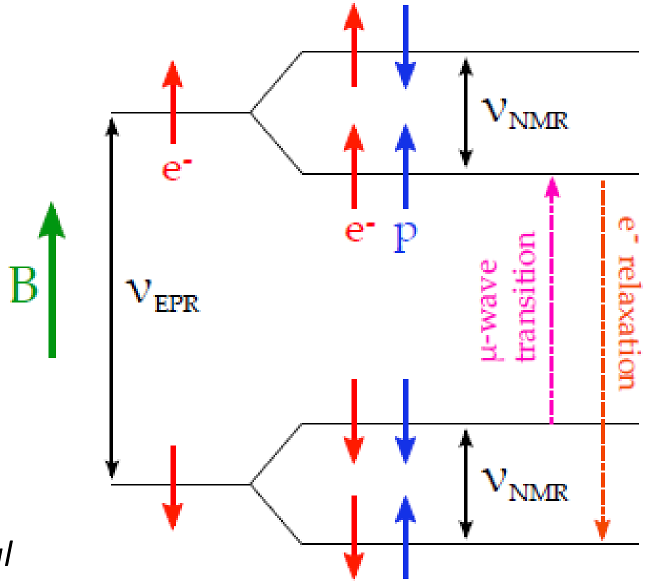
Helium Liquefier setup

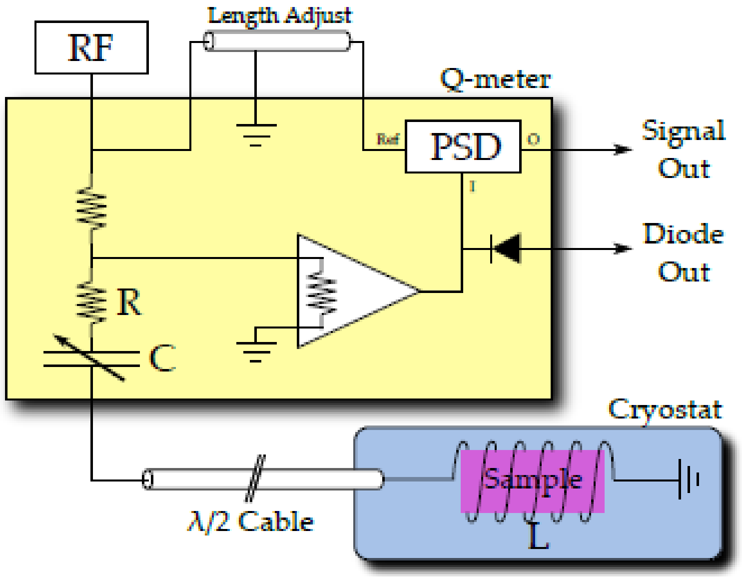
Nuclear Magnetic Resonance (NMR)

- 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 three NMR coils inside the target cup

- An LCR Circuit is tuned to the Larmor frequency of the target material
- The power generated or absorbed due to spin flip change → the circuit impedance that can be observed

UVA-NMR (PDP interface) with a sample crystal

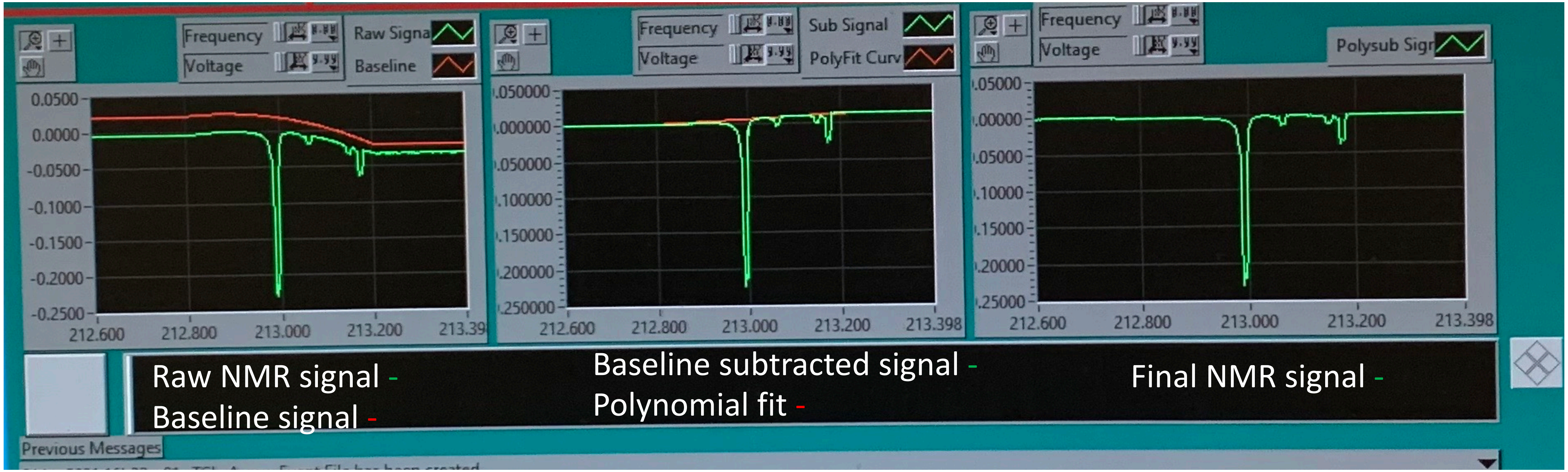




Courtesy of James Maxwell

Nuclear Magnetic Resonance (NMR)

UVA-NMR (PDP interface) with a sample crystal



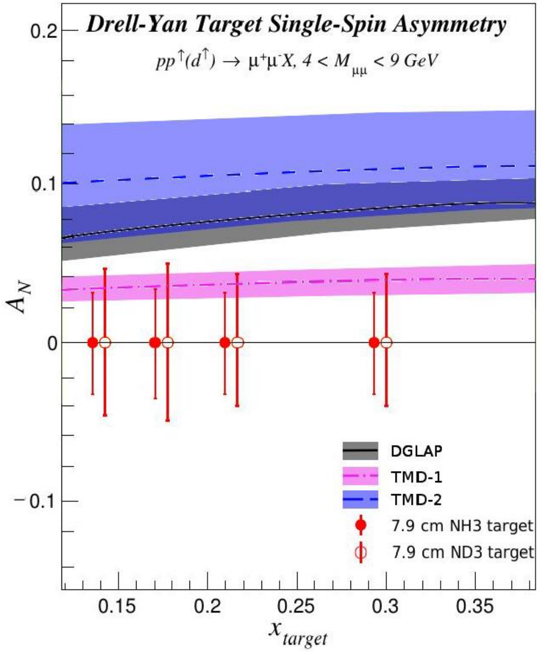
- Q-Curve is produced by sweeping the RF around the Larmor frequency
- The signal area after background subtraction is proportional to the polarization
- The proportional constant is obtained at Thermal-Equilibrium measurement

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

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

Predicted Uncertainties

- Beam (∽ 2.5%)
  - Relative luminosity (∽ 1%)
  - Drifts (< 2%)
  - Scraping (∽ 1%)
- Analysis sources (∽ 3.5%)
  - Tracking efficiency (∽ 1.5%)
  - Trigger & geometrical acceptance (<2%)
  - Mixed background (∽ 3%)
  - Shape of DY (∽ 1%)



DGLAP: M. Anselmino et al arXiv:1612.06413
TMD-1: M. G. Echevarria et al arXiv:1401.5078
TMD-2: P. Sun and F. Yuan arXiv:1308.5003
A. Prokudin et al (in progress)
I. Fernando, D. Keller (in progress)

$$A = \frac{2}{f|S_T|} \frac{\int d\phi_S d\phi \frac{dN(x_b, x_t, \phi_S, \phi)}{d\phi_S d\phi} sin(\phi_S)}{N(x_b, x_t)}$$

- Target (∽ 6-7 %)
  - TE calibration (proton ∽ 2.5%; deuteron ∽ 4.5%)
  - Polarization inhomogeneity (∽ 2%)
  - Density of target ($NH_{3(s)}$) (∽ 1%)
  - Uneven radiation damage (∽ 3%)
  - Beam-Target misalignment (∽ 0.5%)
  - Packing fraction (∽ 2%)
  - Dilution factor (∽ 3%)

Material	Density	Dilution factor	Packing fraction	Polarization	Interaction length
NH_3	0.867 g/cm^3	0.176	0.60	80%	5.3%
ND_3	1.007 g/cm^3	0.300	0.60	32%	5.7%

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 maximum proton polarization of 95% using Dynamic-Nuclear Polarization (DNP) technique

Welcome!

Please Join The Effort

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https://spinquest.fnal.gov/

http://twist.phys.virginia.edu/E1039/

Thank you

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