The Polarized-Target System for the SpinQuest Experiment at Fermilab

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Outline

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

Introduction:
SpinQuest Experiment at Fermilab

Physics goal:

- ❑ 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

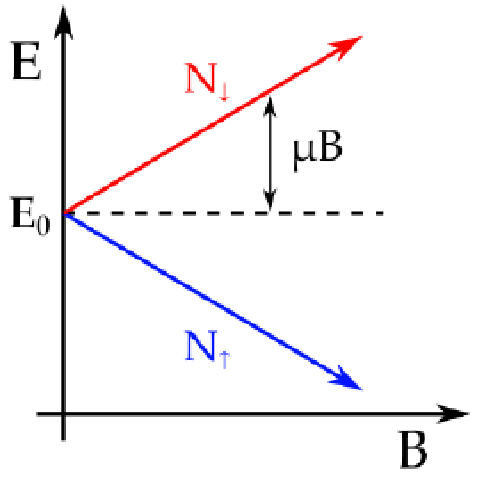
Require a transversely polarized target capable of both high polarization and integrated luminosity:

- ❑ Push the 120 GeV-proton-beam intensity frontier on a solid polarized target
- ❑ Use the longest target cell (and most volume) ever ran in a 1 K evaporation polarized target system
- ❑ Utilize Highest cooling power DNP (Dynamic Nuclear Polarization) target in the world due to the high pumping rate and the refrigerator.

Introduction:
How do we obtain significant nucleon polarization?

Brute-Force Method:

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



Courtesy of James Maxwell

- Degree of polarization at thermal equilibrium

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

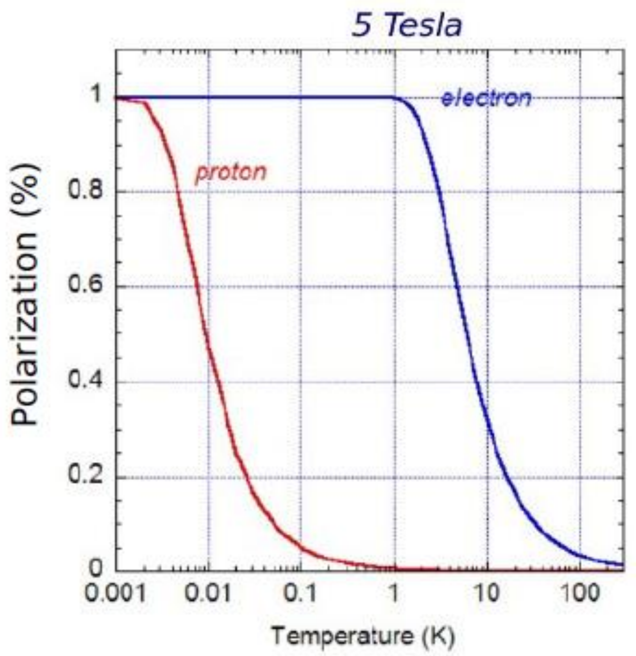
- Proton has small magnetic moment

$$\mu_e \approx 660\mu_p$$

- 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):

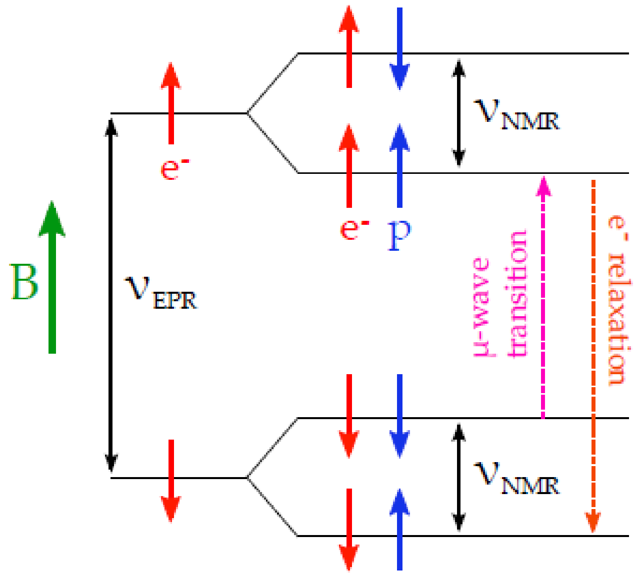
- The coupling between (unpaired) electron & proton introduces hyper-fine splitting H_{SS}

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

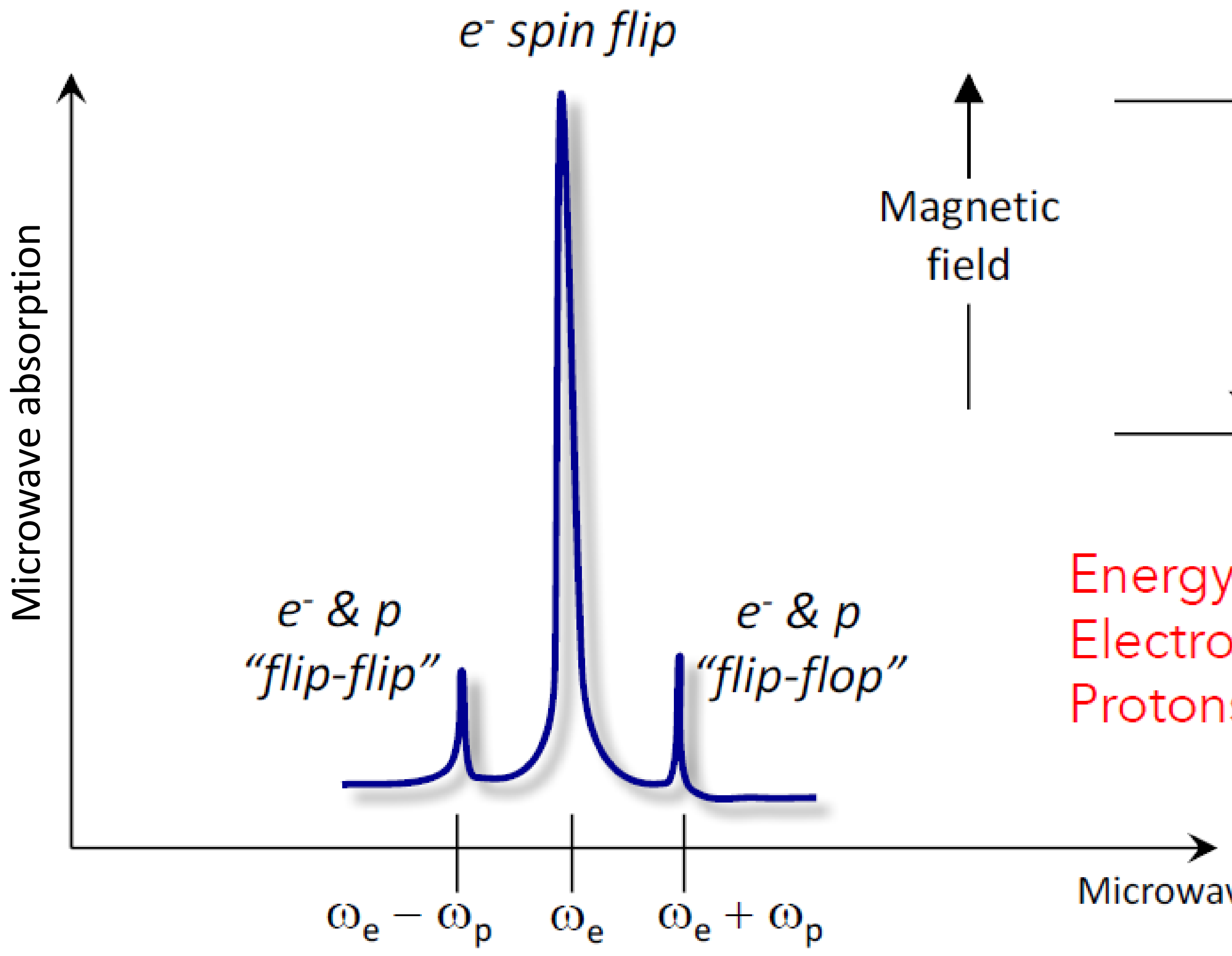
- Applying an RF-field at the correct frequency, we can drive the nucleons state into desired proton-state

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

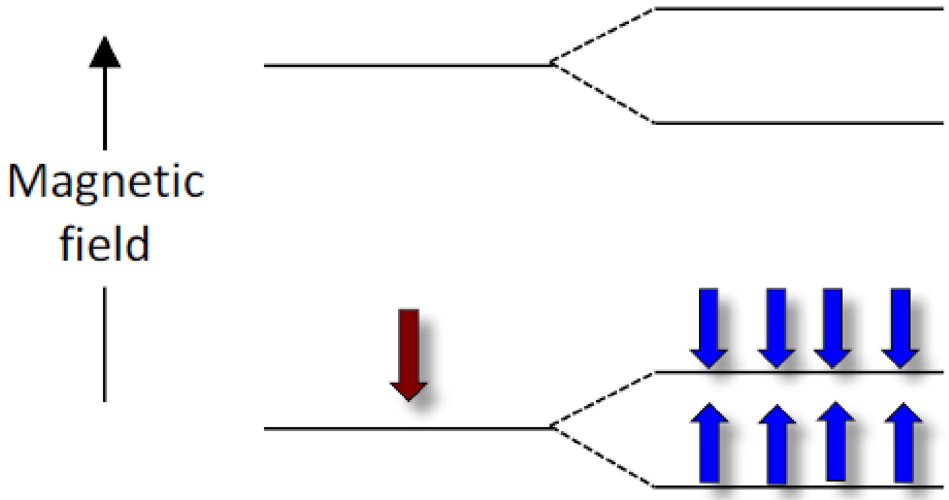
- Allow to achieve proton polarization of > 90%
- During a cooldown at UVA, we achieve 95% of proton polarization



DNP (Pumping Mechanism) for Spin $^1/_2$

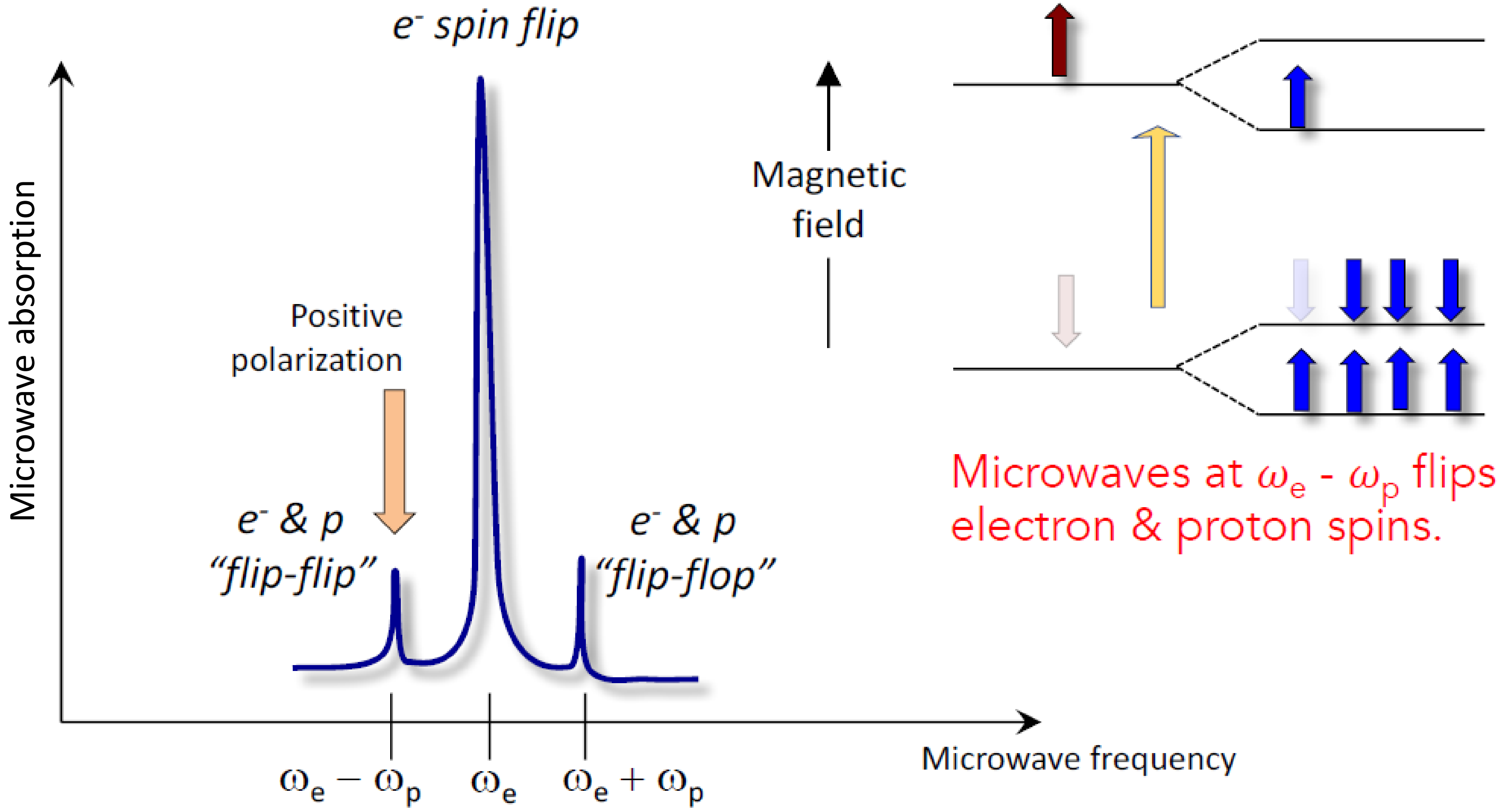


Courtesy of Chris Keith



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

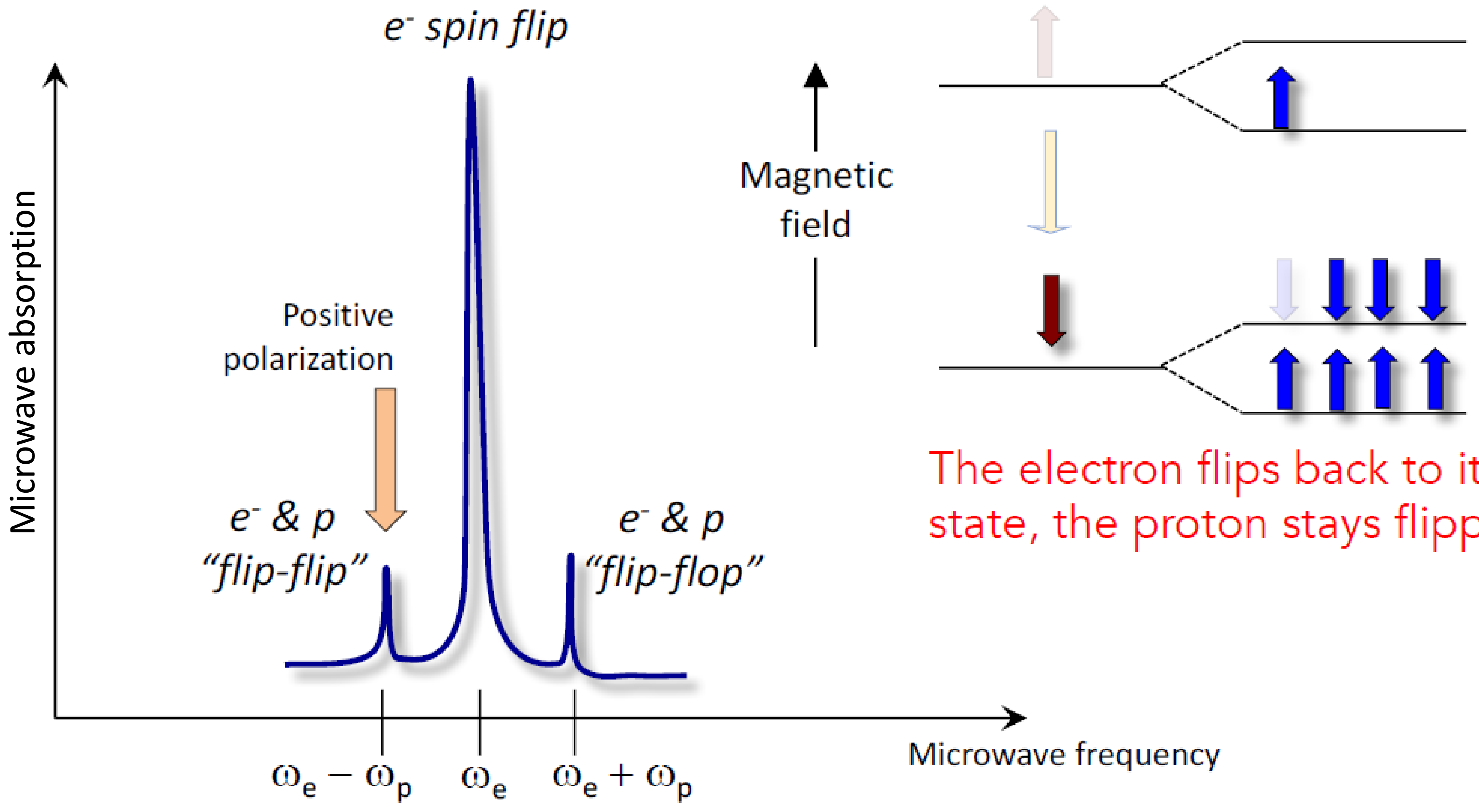
DNP (Pumping Mechanism) for Spin $^1/_2$



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

Courtesy of Chris Keith

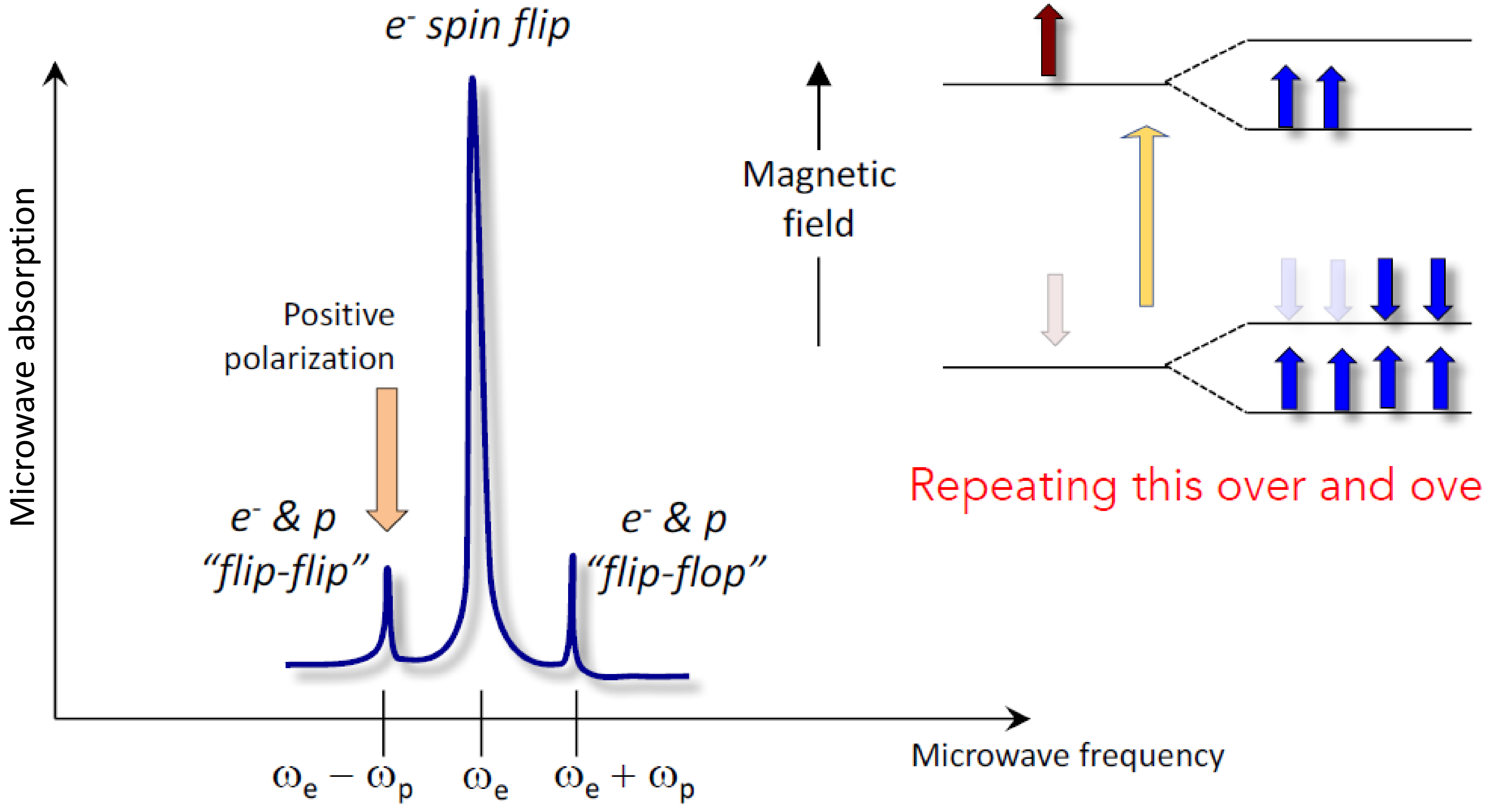
DNP (Pumping Mechanism) for Spin $^1/_2$



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

Courtesy of Chris Keith

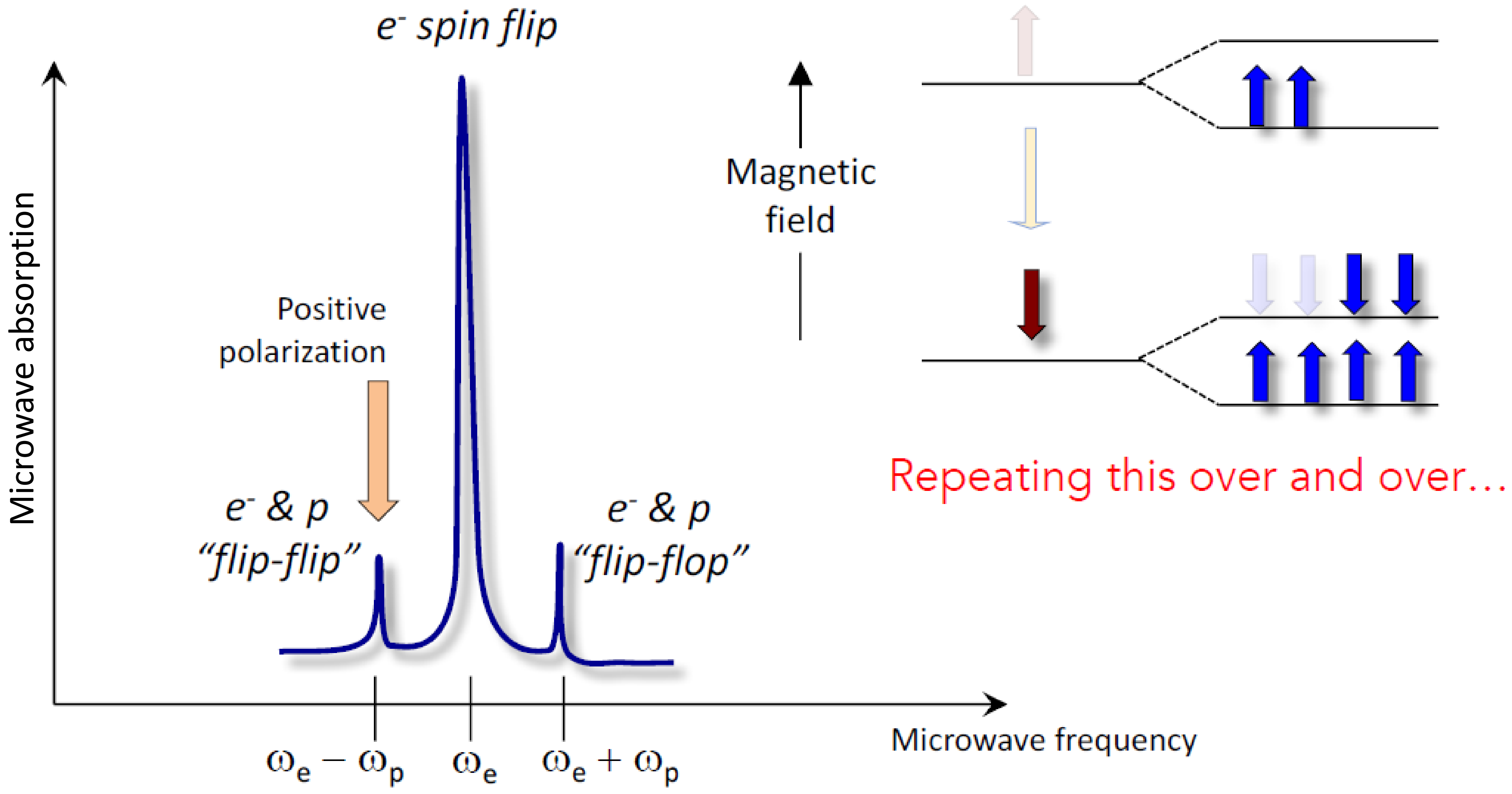
DNP (Pumping Mechanism) for Spin $^1/_2$



Repeating this over and over…

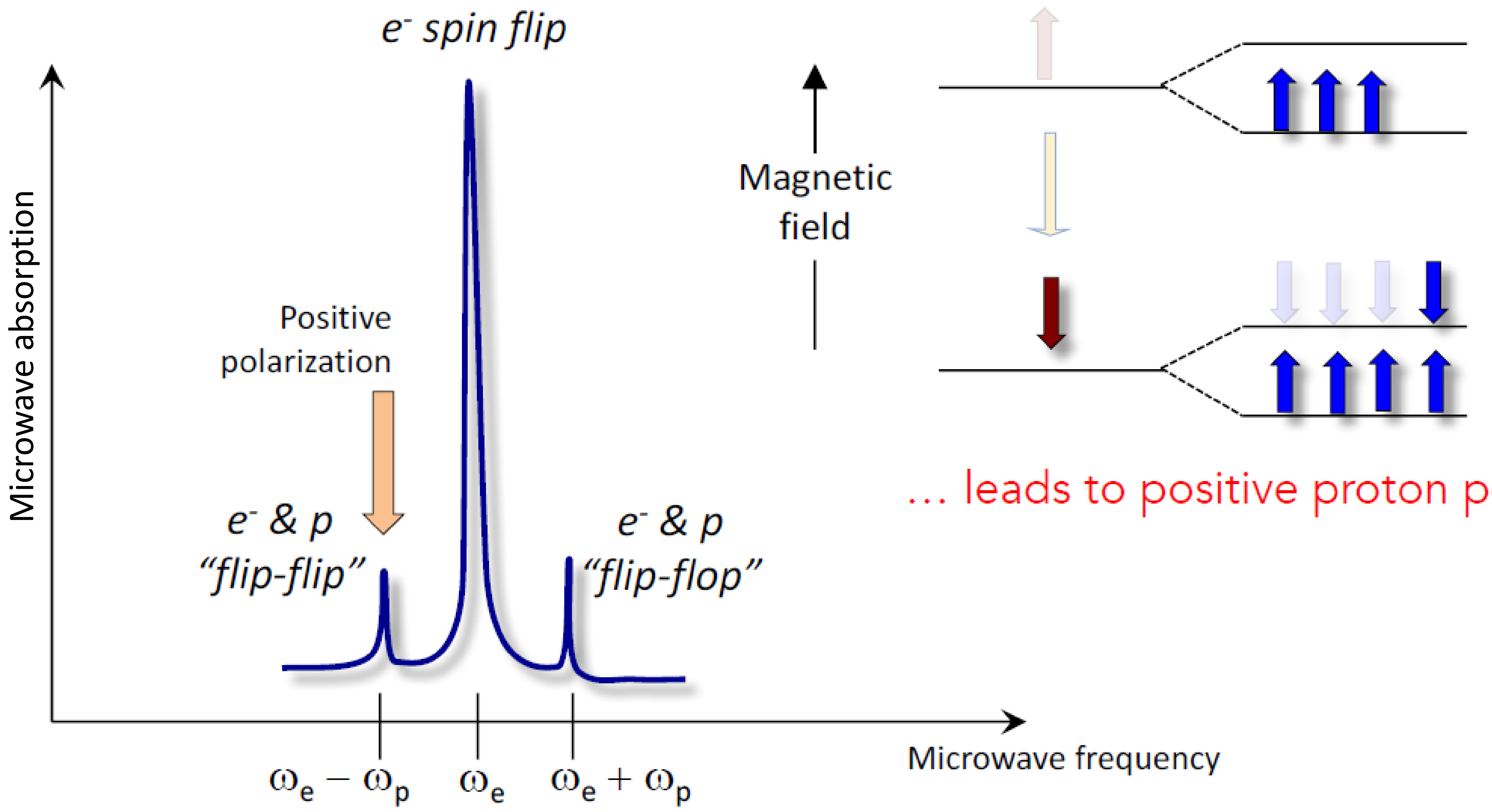
Courtesy of Chris Keith

DNP (Pumping Mechanism) for Spin $^1/_2$



Courtesy of Chris Keith

DNP (Pumping Mechanism) for Spin $^1/_2$



… leads to positive proton polarization.

Courtesy of Chris Keith

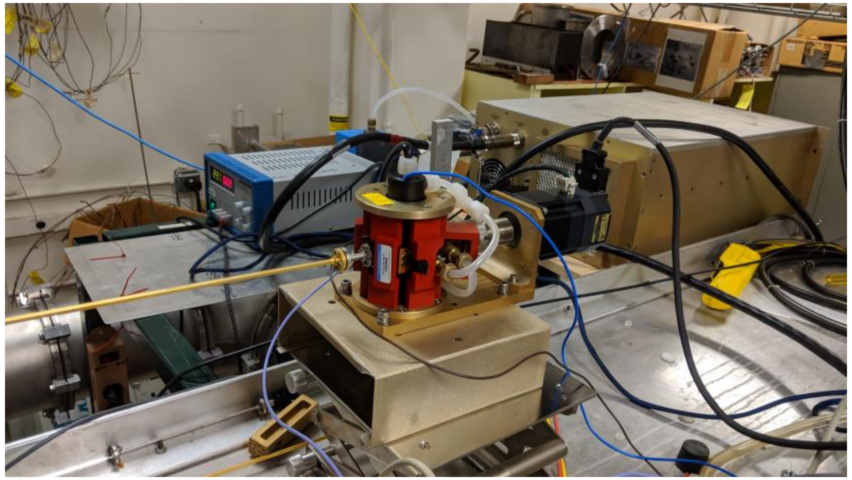
What do we need to achieve significant proton polarization using the DNP Method?

- ❑ 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

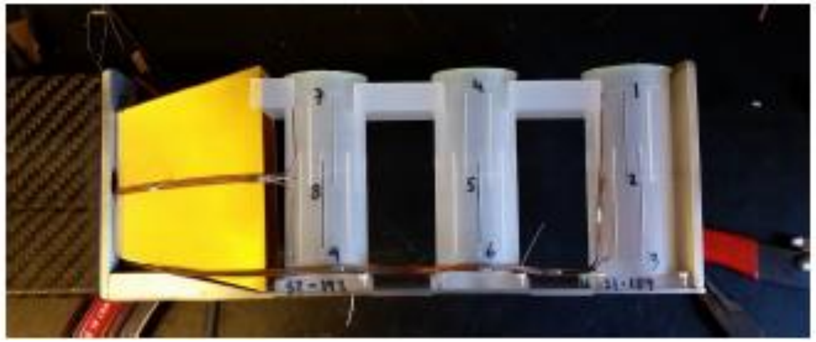
- 140 GHz RF signal is generated by Extended-Interaction Oscillator (EIO) through interaction between electron beam (produced from ~kV of cathode/anode) and resonant cavities
- The optimal frequency changes as we flip the spin direction

- 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)



❑ 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



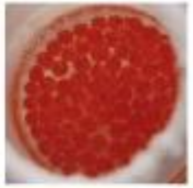
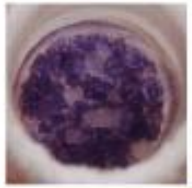
We will have 3 target cups so we can quickly replace the target when it is damaged due to the radiation

❑ Target materials

Target material for DNP 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).

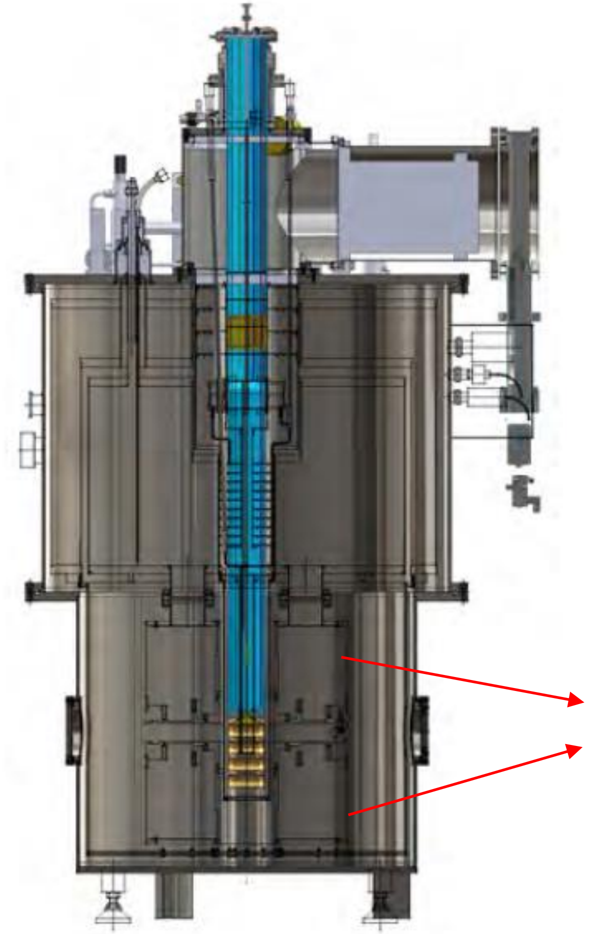

Material	Butanol	Ammonia, NH_3	Lithium Hydride, ^7LiH
Dopant	Chemical	Irradiation	Irradiation
Dil. Factor (%)	13.5	17.6	25.0
Polarization (%)	90-95	90-95	90
Material	D-Butanol	D-Ammonia, ND_3	Lithium Deuteride, ^6LiH
Dil. Factor (%)	23.8	30.0	50.0
Polarization (%)	40	50	55
Rad. Resistance	moderate	high	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 5 T of transverse field in the target area with the homogeneity level of 10^{-4} over the target region

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

- The coils are held in place by 316 stainless steel



Superconducting-magnet system

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

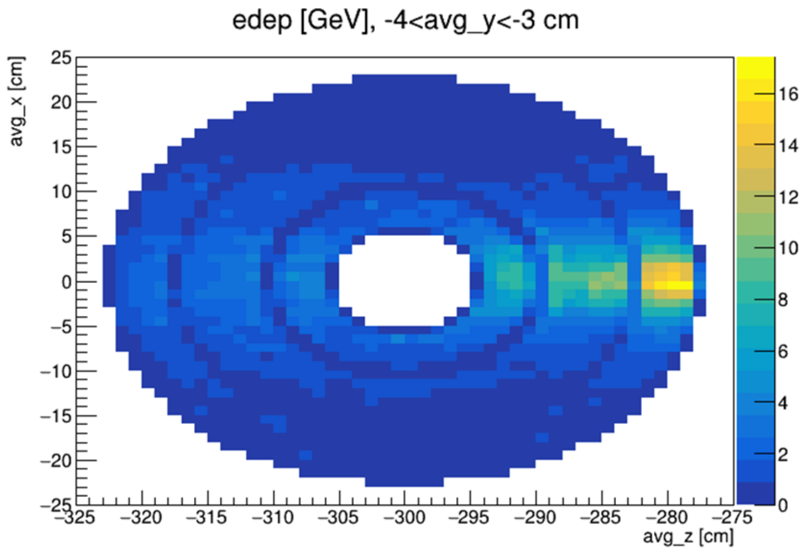
The Thermal processes within the magnet is described by a general heat transfer equation:

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

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:

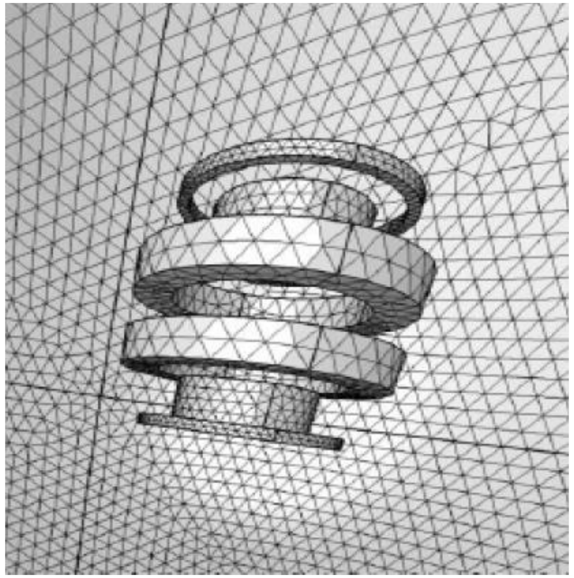


We will run at the highest instantaneous intensity for the polarized target with proton beam

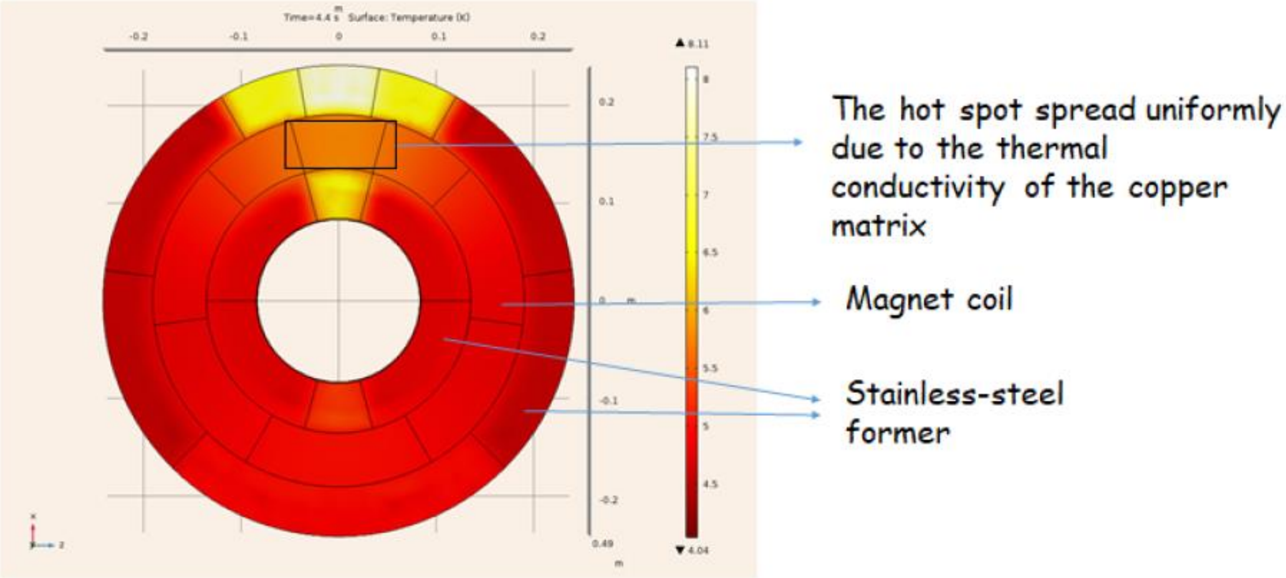
❑ Superconducting-magnet system

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 instantaneous 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)

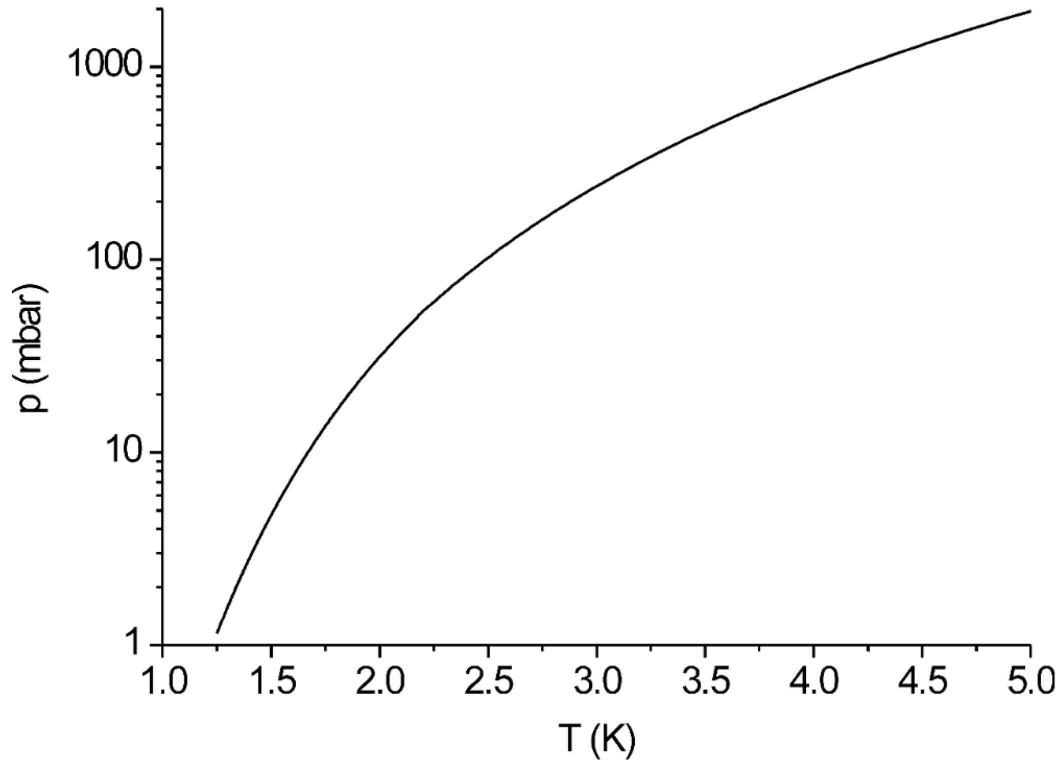
Cryogenics:
Evaporation Refrigerator with 3 W of Maximum Cooling Power

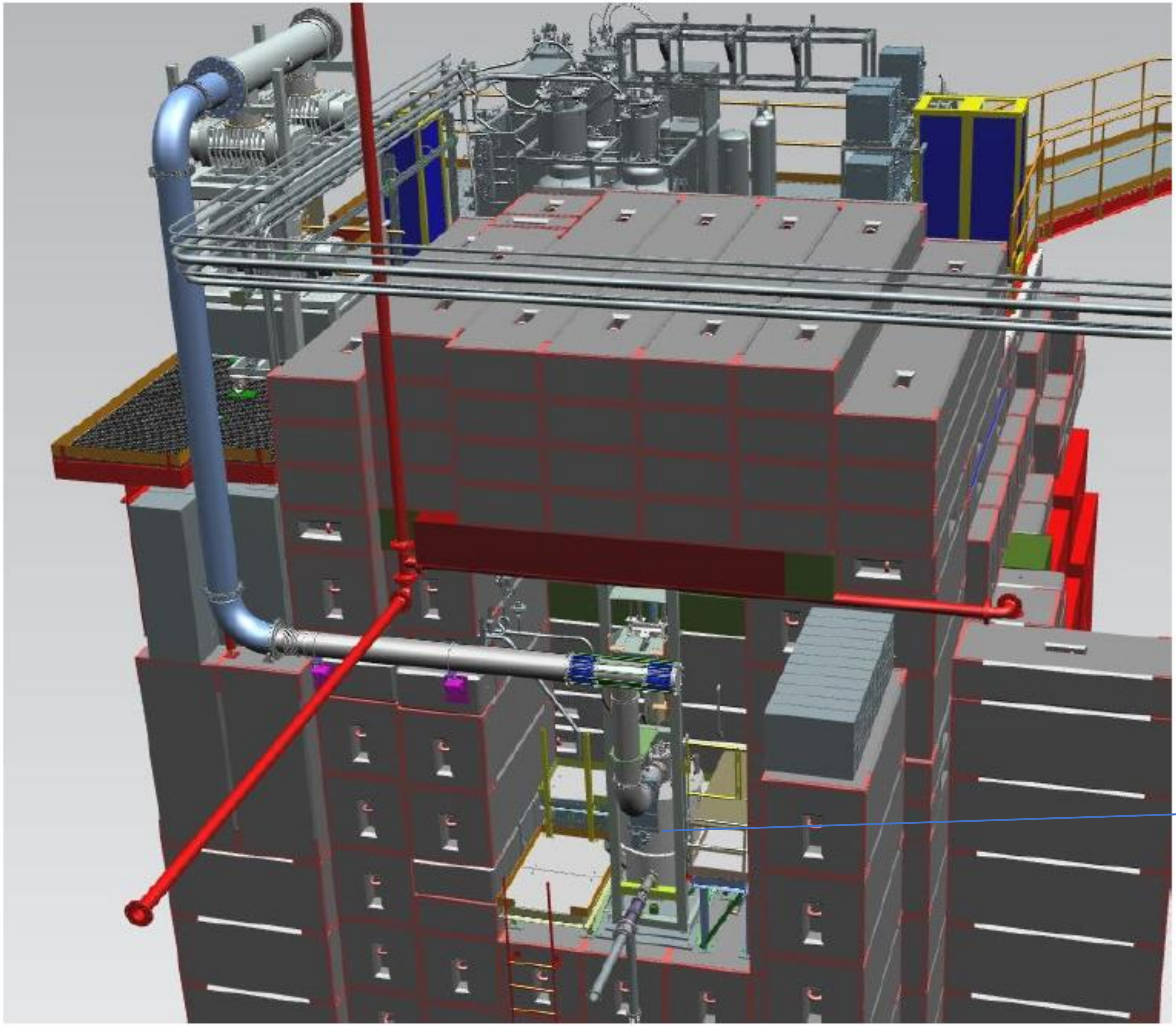
Evaporated He from the target nose need to be pumped out by high powered pump to keep the temperature at 1 K at 0.12 Torr

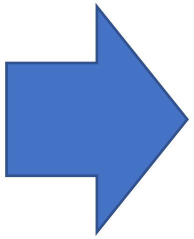
Critical components for high-cooling power refrigerator:

- 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



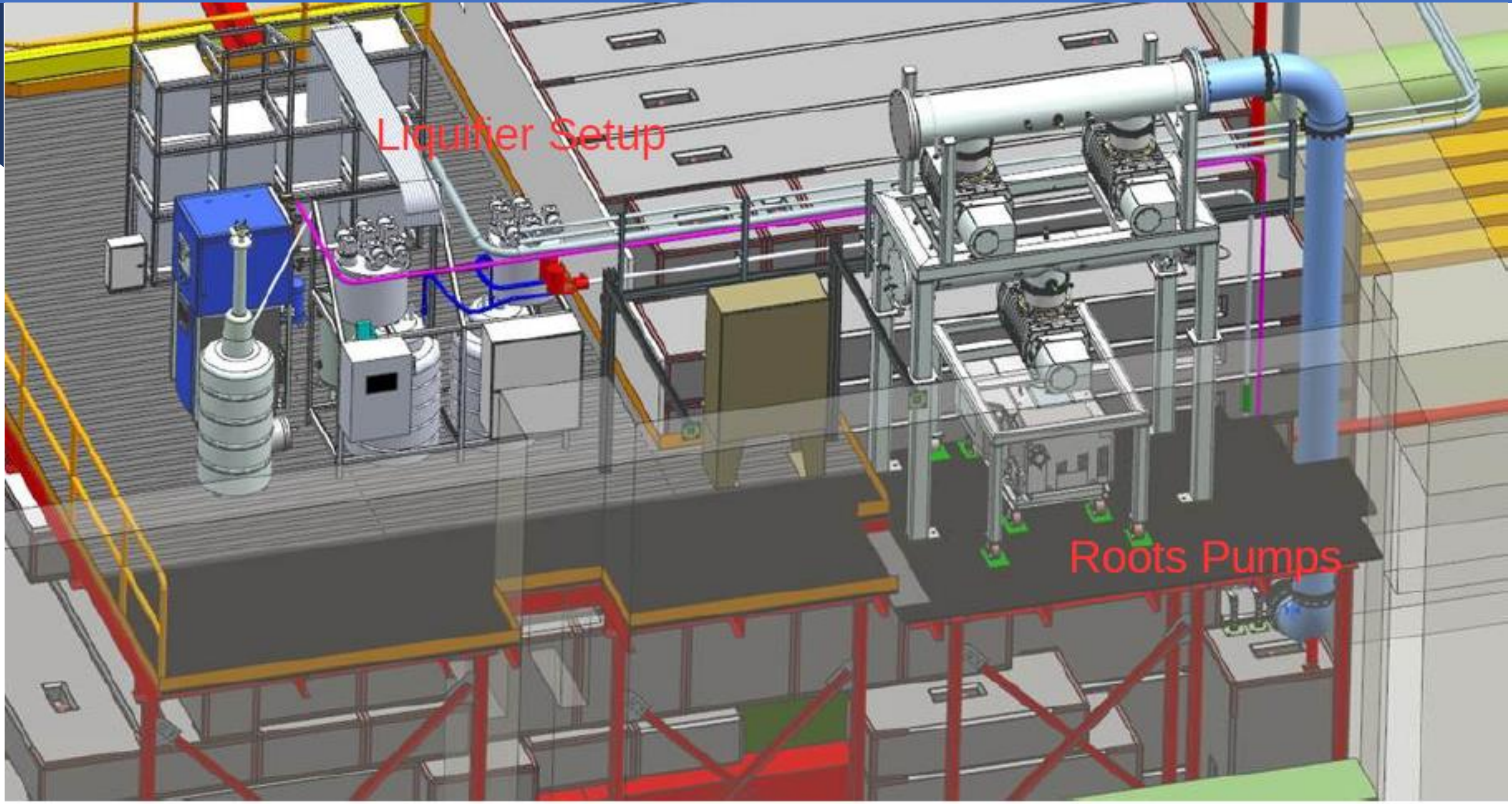




Cryo Platform:
- He liquefier
- Root pumps
- Electronic rack
- Shielding

Target/Magnet dewar

❑ Cryogenics:
Evaporation Refrigerator with 3 W of Maximum Cooling Power



Cryo platform showing the He-liquefier and Roots pumps setup

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

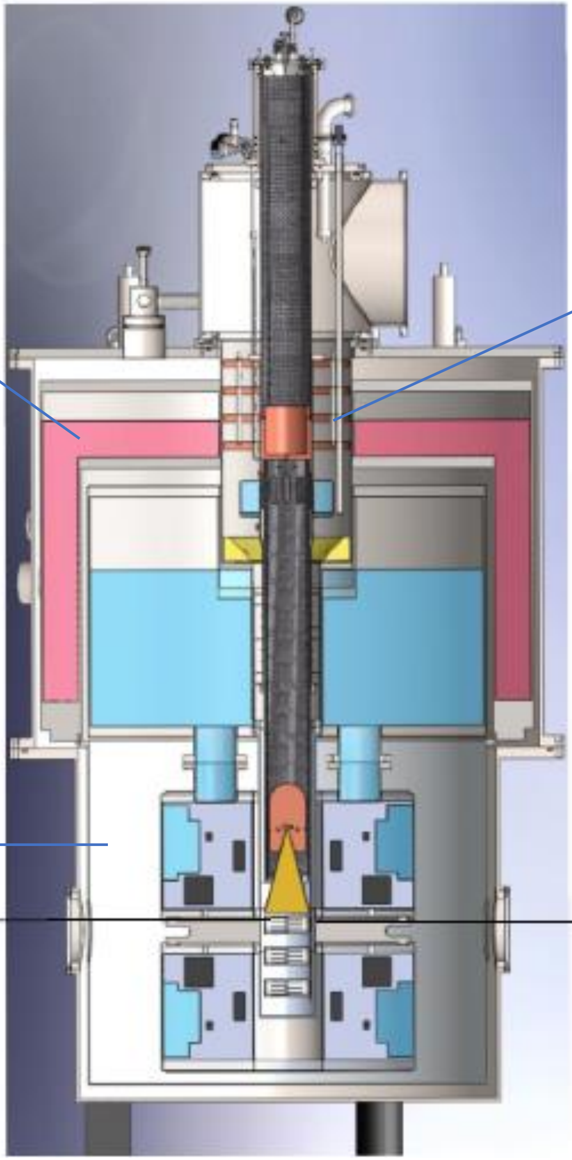
Roots pump have the pumping capacity of ~ 17,000 m^3 per hour

Thermal shielding:

- Liquid Nitrogen
- Outer Vacuum

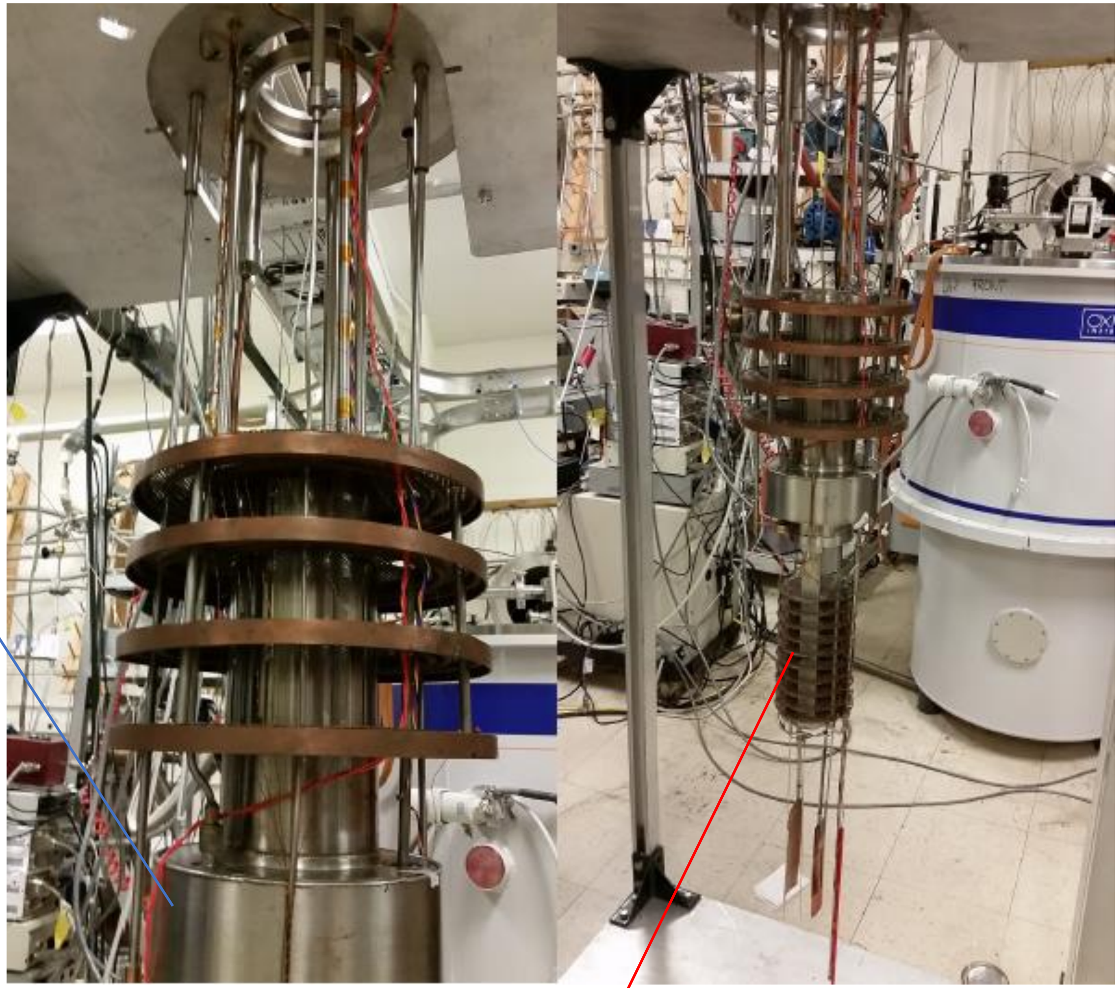
Turbo Molecular pump maintain the outer vacuum pressure at ~10^{-8} torr

Outer vacuum



Separator

Beam



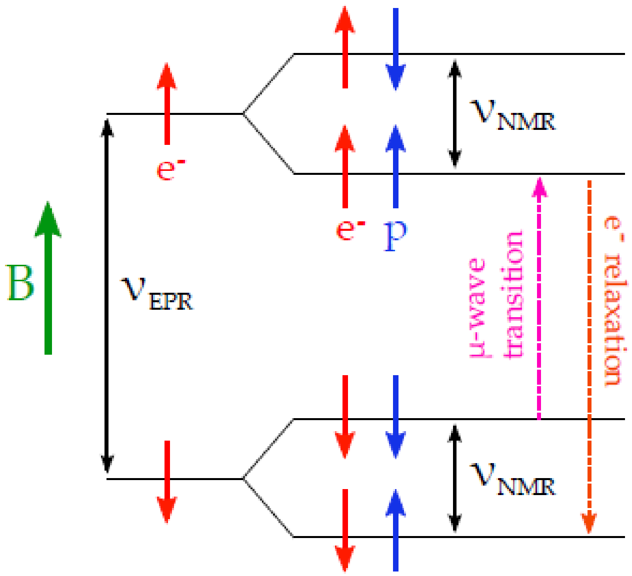
Heat exchanger

❑ 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

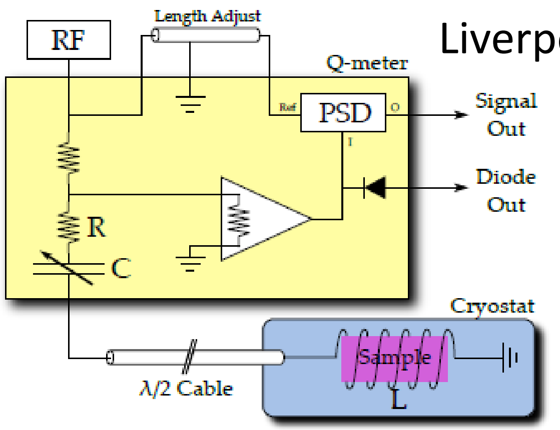
The RF field is produced by 3 NMR coils inside the target cup



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

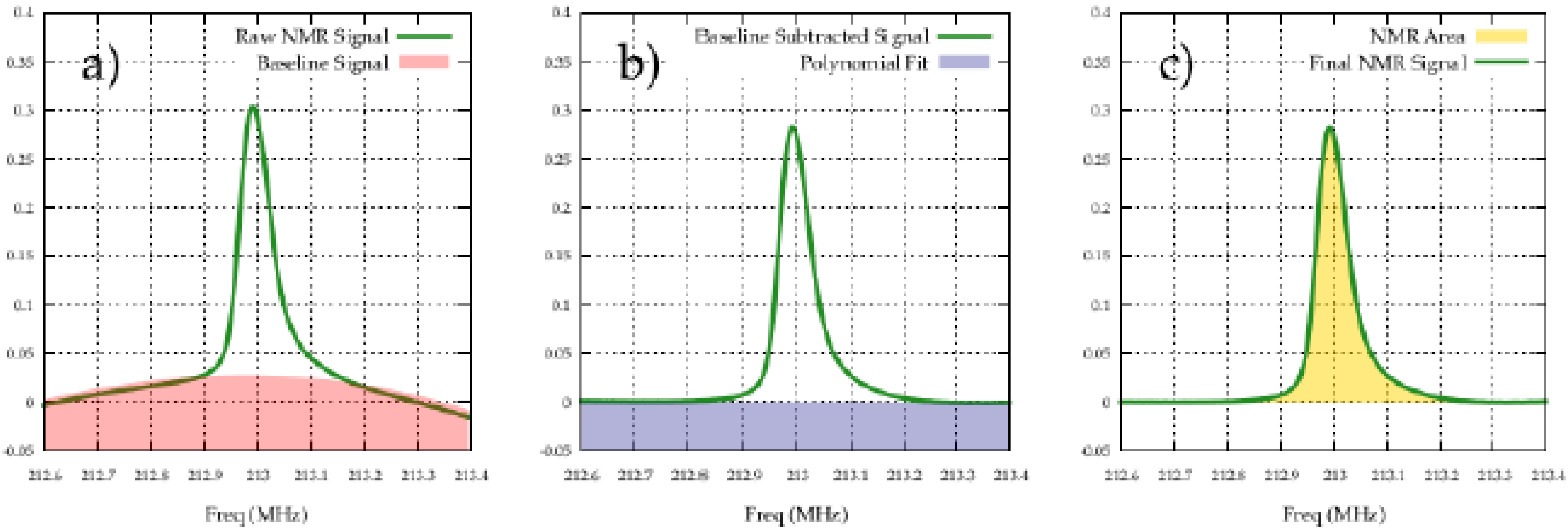
❑ Nuclear Magnetic Resonances (NMR)

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

Acknowledgement:

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