Thermal Analysis and Simulation of the Superconducting Magnet for the SpinQuest Experiment at FermiLab

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Outline

- Introduction
- Magnetic Field Measurement & Simulation
- Physics Processes
- Simulation Methods
- Results
- Outlook: Quench Commissioning Plan
- Backup Slide: Beam Stability Issue

Introduction: SpinQuest Experiment at Fermilab

SpinQuest Physics:

- **Sivers function for the sea quarks (main physics goal)**
- Dark matter search
- Deuteron tensor function b_1 (longitudinal polarization)
- Gluon TMD/Twist-3 correlation function
- QCD dynamics with heavy quarks

SpinQuest as intensity frontier for the polarized-target experiment:

- 120 GeV of proton beam
- 5×10^{12} proton/spill. 1 spill $\approx$ 4.4 seconds
- a 5 T of Nb-Ti Superconducting split coil magnet
- Transversely-Polarized NH_3 and ND_3 targets

UVA/LANL Target system

Introduction: Superconducting-magnet Quench

Critical surface for Nb-Ti superconductor (courtesy of Deepak Paudel)

Critical surface for a superconductor is defined from the temperature (T), magnetic field (B), and the current (I)

Magnet becomes normal conductor (quench) if the T, B or I lie outside the critical surface

The magnetic field (B) in the target area between the coils is 5T

But we do not have the information about the magnetic field in the magnet itself

Main Questions:

- How to determine the strength of the magnetic field in the conductor?
- What is the maximum intensity of the proton beam for the SpinQuest experiment before the magnet quench?

Magnetic Field Measurement and Simulation

Motivation:

- We need to know the magnetic field in the magnet to determine the quench limit
- But Oxford instrument only provides the magnetic field measurement inside the target cup (Along $\Delta z = 7.5$ cm and $\Delta y = 3$ cm)
- We need to measure the magnetic field outside the dewar: **requires an extrapolation method into the region inside the dewar and outside the target region**
- Goal: **A complete 3D picture of the magnetic field inside/outside the magnet dewar**

Oxford's measurements in the target area using NMR probe

Magnetic Field Measurement and Simulation

Measurement outside the dewar during the cooldown at UVA:

Over 300 points measurement

Measure the radial and vertical component of the field

Covering 60 inch distance from the surface

Covering 5 horizontal plane and 4 different azimuthal angle

Lakeshore Gaussmeter
(Uncertainty: 20mT)

Magnetic Field Measurement and Simulation

Challenge: There is no trivial way to fit and extrapolate the data to obtain the Magnetic field inside the dewar

Sample of the measurements

Magnetic Field Measurement and Simulation

Two options to address this challenge:

First, solving a set of Maxwell equation with a very complicated boundary conditions. This technique is applied by astrophysicist to extrapolate the magnetic field in solar corona from the photosphere.

Solar corona magnetic field

Second, using COMSOL Multiphysics to simulate the Magnet coil

We chose this method

Magnetic Field Measurement and Simulation

Notes: It is better to use the simulation results since the measurement outside the dewar use the hand probe gaussmeter which is not really accurate (the uncertainty is 20 mT)

Magnetic Field Measurement and Simulation

Simulation result: we achieve a high level of homogeneity around the target area & along the beam line:

High level of homogeneity in the target area

And if we zoom in:

$Z = [-3.75 \text{ cm}; 3.75 \text{ cm}] , Y = 0 \text{ cm}$

Simulation	Measurement
$B = [5.0192 \text{ T} ; 5.0197 \text{ T}]$	$B = [5.0195 \text{ T} ; 5.0199 \text{ T}]$

Magnetic Field in the Magnet

The magnetic field in the magnet is azimuthally symmetric (as expected) with the maximum field of 6.85 T at the inner surface of the coils. **The Quench limit of the NbTi Superconductor for the $B=6.85$ T is ~ 6.35 K**

Physics Processes

- Heat Load
- Cooling processes
- Approximation Strategy

The heat deposited in the magnet mainly come from the beam-target and the beam-collimator interactions

Beam profile:
Gaussian + Tail

Collimator

8 cm long target cells of
solid NH3/ND3

The heat load in the magnet are obtained from the *Geant-Based MC* simulations

The hot spot in the downstream magnet comes from the beam-target interactions

The hot spot in the upstream magnet comes from the beam-collimator interactions

Cooling Processes

Time-Structure of the Beam

The timing structure of the beam allows for ~ 55 seconds cooling every minutes for the magnet coils

LHe-Cooling processes diagram

Various cooling processes through LHe:

- Natural convection
- Nucleate boiling
- Film boiling

Approximation Strategy

Steady state is reached after ~ 0.1 s

First, Steady state
Film boiling regime
is applied

$$h(T_s, T_{\text{He}}) = a_{\text{FB-I}}(T_s - T_{\text{He}}). \quad [\text{Wm}^{-2}]$$

Various regimes of the heat transfer from solid to LHe

Approximation Strategy

Second, we consider the superconducting magnet as a composite material with the effective thermal parameter

Rayleigh's model consist of parallel cylinders embedded in a continuous matrix

Rayleigh's formula for thermal conductivity

$$\frac{k_{eff}}{k_m} = 1 + \frac{3\phi}{\left(\frac{k_1 - 2k_m}{k_1 - k_m}\right) - \phi + 1.569 \left(\frac{k_1 - k_m}{3k_1 - 4k_m}\right) \phi^{\frac{10}{3}} + \dots}$$

ϕ = Filling factor

Approximation Strategy

Third, we parameterize some of the unknown properties by the effective surfaces that are in direct contact with the LHe:

- Parameter of the He void
- Insulation
- Former

Microscopic view of the cable

Are those
approximation
reasonable?

The time scale is large enough to take film boiling regime as an approximation

The film boiling heat transfer equation is linear $h(T_s, T_{\text{He}}) = a_{\text{FB-I}}(T_s - T_{\text{He}})$. $[\text{Wm}^{-2}]$

Where the coefficient is in $\text{Wm}^{-2}\text{K}^{-1}$.

Therefore the effective surface contact can be absorbed into this coefficient

We have quite large temperature margin (4K) since we operate in the normal phase of He (evaporation fridge)

Some systems that require to be operated in the superfluid He phase have temperature margin less than 1K (even mK)

Simulation Method

Finite element analysis using COMSOL Multiphysics

Input:

- Volumetric heat source (Heat Map)
- Thermal properties of the material
- Heat transfer in solid and heat flux to the LHe
- Beam profile

Proses: Discretized element for the Finite Element calculation

Results

- BNL VS SpinQuest
- Temperature profile $T(x)$
- Temperature profile $T_{\max}(t)$

Result

SpinQuest VS BNL

SpinQuest

BNL

SpinQuest beam profile

Energy	120 GeV
Cycle Time	60 s
Spill Length	4.4 s
Beam Intensity	1e12

BNL beam profile

Energy	24 GeV
Cycle Time	3 seconds
Spill Length	1 second
Beam Intensity	2×10^{11} protons/pulse

Results

The temperature profile at 4.4 s

The quench limit for the B_{max} is 6.35 T

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

Magnet coil

Stainless-steel former

Results: SpinQuest

The maximum temperature of the coil as a function of time ~ 6.1 K

Maximum Temperature profile $T_{\max}(t)$ for E1039:

- 120 GeV proton
- $1e12$ proton/s
- NH3 Target

Conclusion: It is safe to run at $1e12$ proton/s but this intensity is considered as the upper limit (maximum) for the NH3 target

Results: BNL

The maximum temperature of the coil as a function of time

Maximum Temperature profile $T_{\max}(t)$ for BNL:

- 24 GeV proton
- $2e11$ proton/s
- Teflon Target

Notes:

- The BNL magnet was quenched in this setup (Teflon target & $2e11$ proton/s)
- The simulation results "indicate" quench $\rightarrow$ The heat is accumulated over time

Outlook: Quench commissioning plan

- 8 Type-T Thermocouple sensors are installed in the surface of the stainless-steel former
- 4 sensors are installed upstream of the magnet and 4 sensors are installed downstream of the magnet
- The next 3 slides show the temperature prediction of the sensors for various beam intensities as indirect way to validate the simulation

Type-T Thermocouple sensors are installed upstream/downstream of the magnet

6.5 K

Downstream
sensors

1E12
Proton/s

5.0 K

Upstream
sensors

5.5 K
Downstream
sensors

5E11
Proton/s

4.6 K
Upstream
sensors

4.47 K
Downstream
sensors

4.28 K
Upstream
sensors

1E11
Proton/s

Thank You

Backup Slide

Beam Stability Issue

- Intensity instability
- Beam drift

The beam intensity “jump” in a very short period of time (ns)

E906 temporal beam profile

Challenge: The simulation could not handle time scale of ns

Solution: Analytic calculation with some approximation

$$\frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) + \dot{q} = \rho c_p \frac{\partial T}{\partial t}$$

Assumption for the upper limit of Temperature approximation: In a very short period of time, the Heat are localized $\rightarrow k = 0$

If this assumption is correct, the difference between the calculation and real simulation should going smaller (match) as the time become smaller

"Jump" intensity	Duration of the jump	Tmax Comsol (K)	Tmax Calculation (K)	Delta T
10 times	0.2	7.3	10.2	2.87
10 times	0.15	7	9.05	2.05
10 times	0.125	6.7	8.44	1.74
10 times	0.1	6.3	7.78	1.48

Simulation for $t = 0.2 \text{ s}$

Calculation for $t = 0.2 \text{ s}$

$$T = \sqrt{42.868 \times I \times t + 17.64}$$
$$= 10.2 \text{ K}$$

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10 times	0.125	6.7	8.44	1.74
10 times	0.1	6.3	7.78	1.48

Since the Tmax calculation between simulation and calculation match as the time (duration of the jump) going smaller. We can trust the calculation. For the ns duration of the jump:

$$T = \sqrt{42.868 \times I \times t + 17.64}$$

$$\sim 4.2 \text{ K}$$

Perfect beam alignment

The energy deposited in the hot spot increase by $\sim 15\%$

0.1 K of temperature increase

Beam drift or misalignment by 0.3 cm

Temperature profile
with a perfect
alignment showing
the maximum
temperature of 6.1 T

Temperature profile with
the 0.3 cm of beam
drift/misalignment
showing the maximum
temperature of 6.2 T

Thank You