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

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2019 Workshop on Polarized Sources, Targets, and Polarimetry

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Outline

- Introduction
- Magnetic Field Measurement & Simulation
- Physics Processes
- Simulation Methods
- Results
- Beam Stability Issue
- Outlook

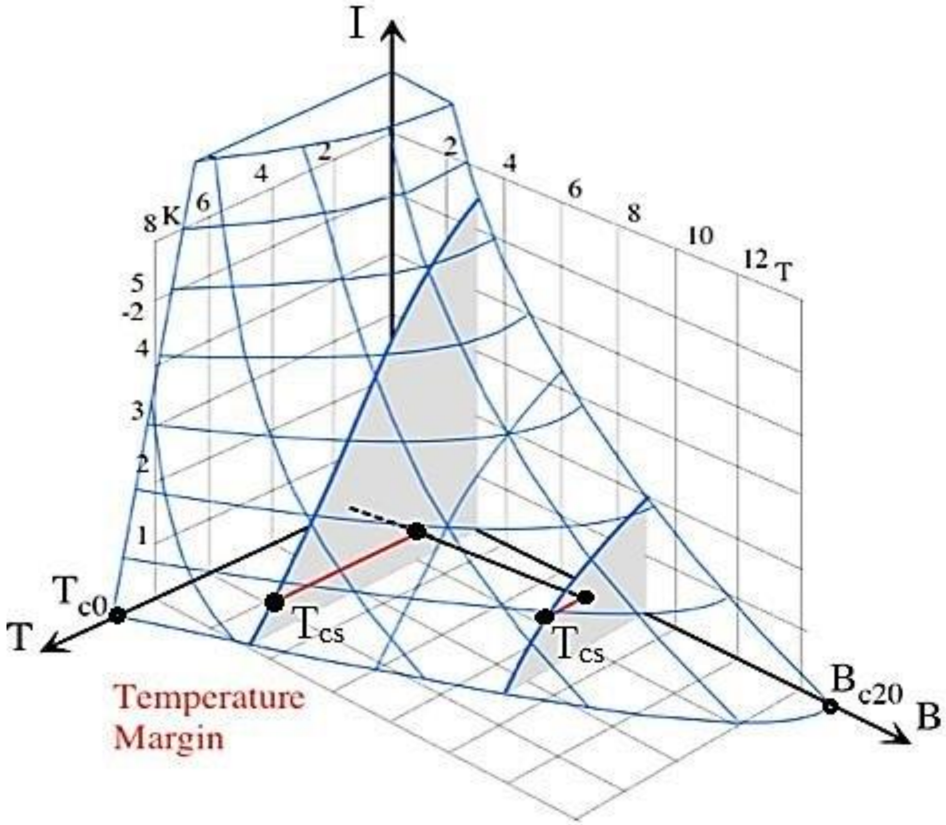
Introduction: SpinQuest Experiment at Fermilab

SpinQuest Physics:
- Sivers function for the sea quarks (main physics goal)
- Dark matter search
- Deuteron tensor function $b1$
- 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 ≈ 4.5 seconds
- a 5T of NbTi-Superconducting split coil magnet
- Polarized NH_3 and ND_3 targets

UVA/LANL Target system

Introduction: Superconducting-magnet Quench



Critical surface for NbTi superconductor

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

Magnet become normal conductor (quench) if the T, B or J 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

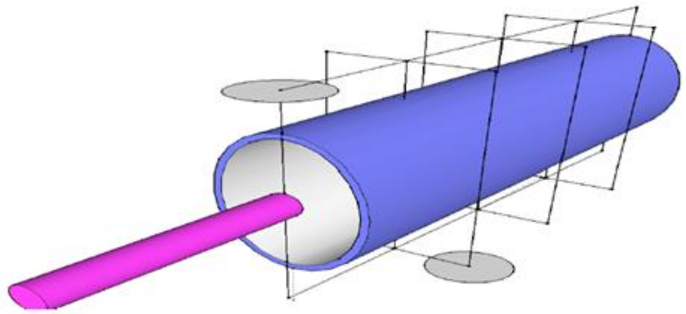
Main Questions:

- How to determine the strength of the magnetic field in the magnet?
- What is the maximum intensity for the proton beam 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 Δz = 7.5 cm and Δy = 3 cm)
- We need to measure the magnetic field outside the dewar: requires an extrapolation method into the region inside the dewar but 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

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

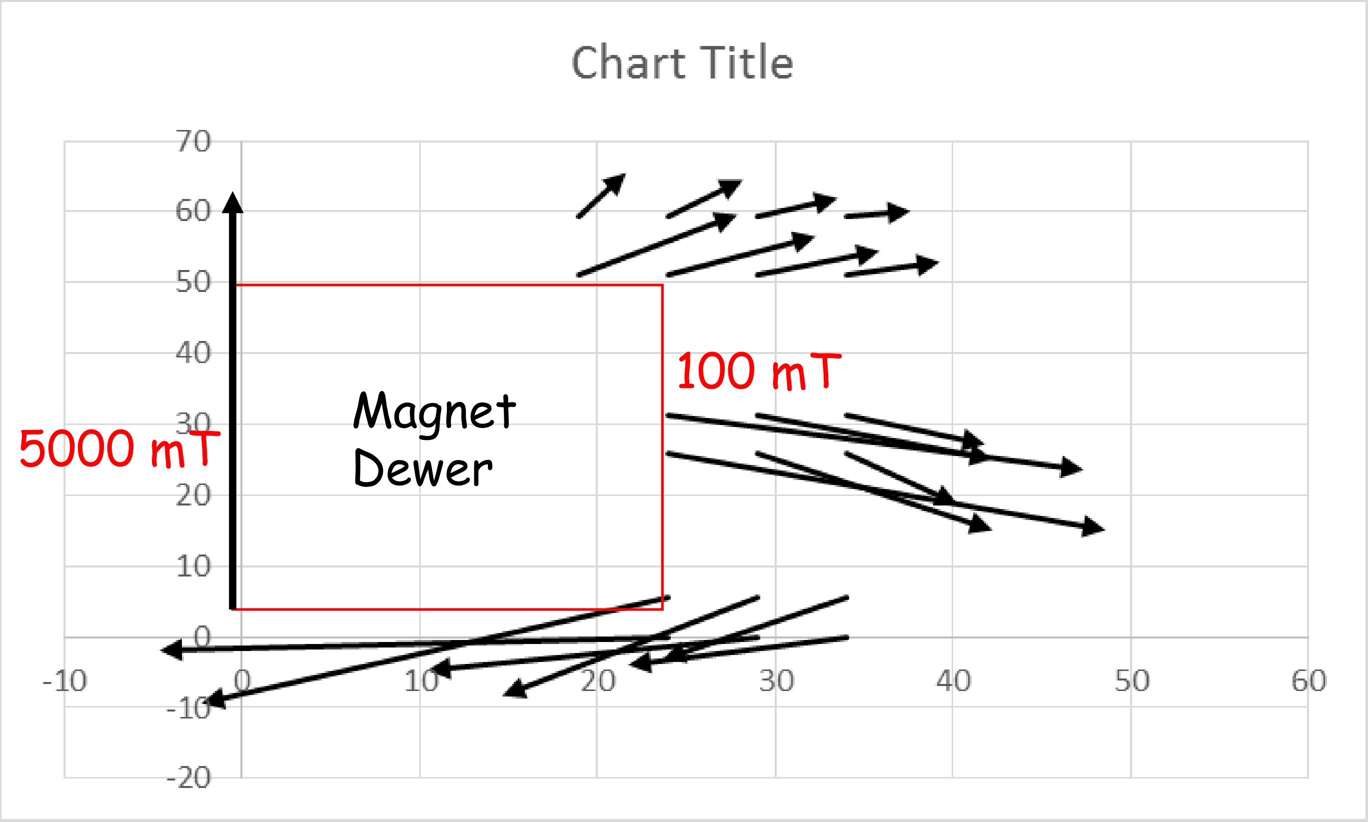
Covering 60 inch distance from the surface

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 get the Magnetic field inside the dewar

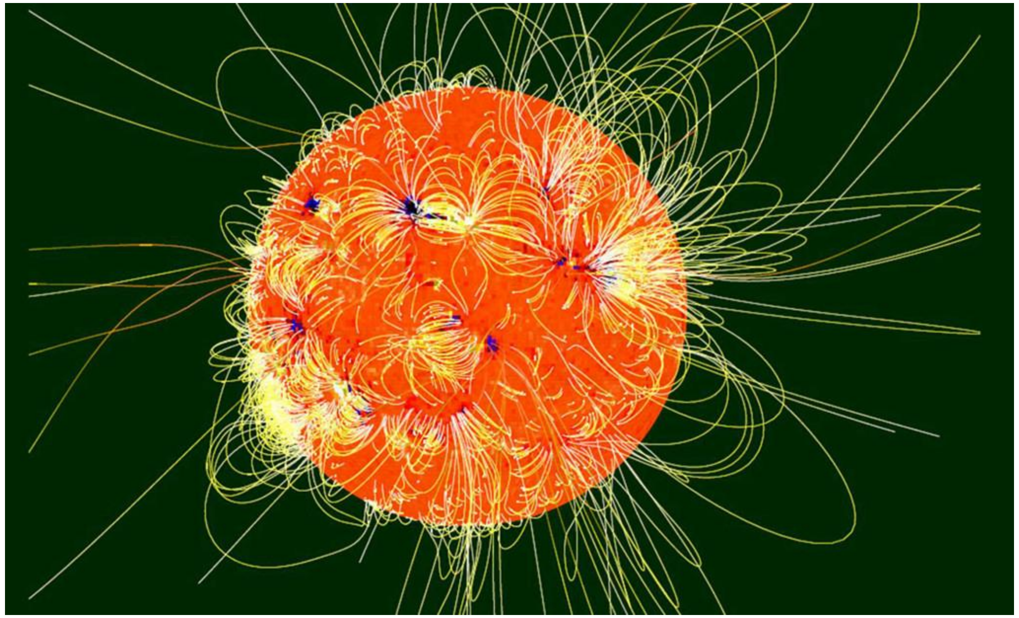


Sample of the measurements

Magnetic Field Measurement and Simulation

Two options:

First, solving a set of Maxwell equation with 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 coild

We chose this method

Magnetic Field Measurement and Simulation

Input:
- B measurement inside the target cup
- B measurement outside the dewer

→

Process:
Magnetic field simulation of the superconducting coil using Finite Element Methods & COMSOL multiphysics software

↓

Output:
Simulation that matched the measurement results inside the target cup and outside the dewer

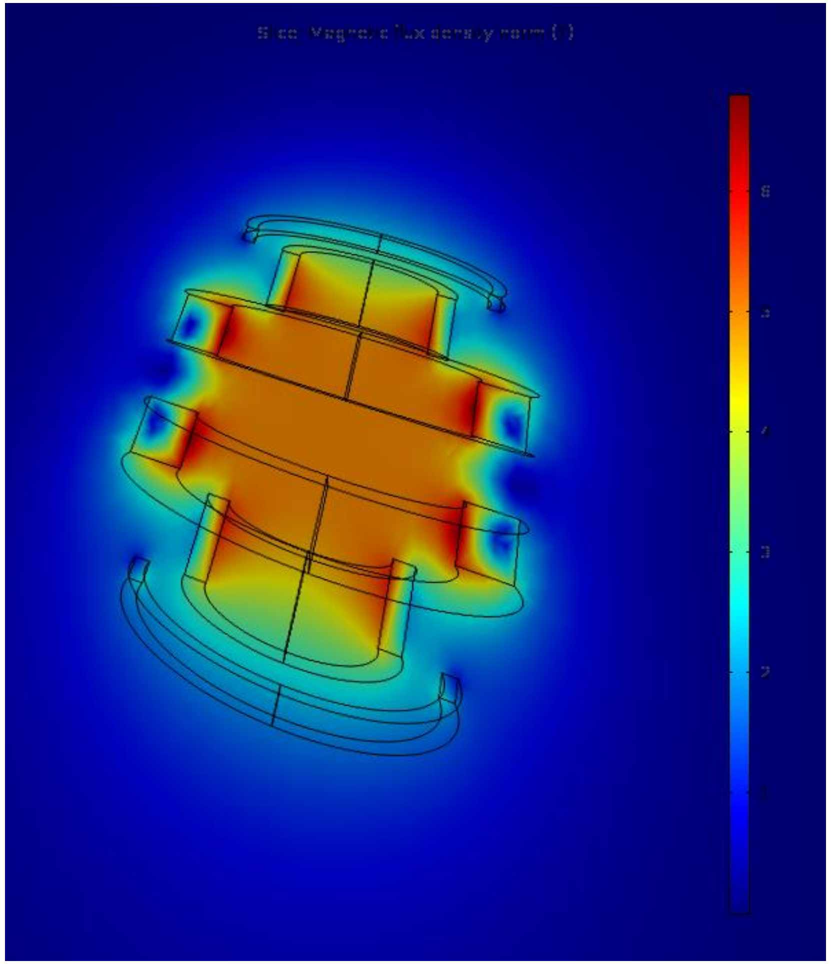
←

Outcome:
Put the B from the simulation into the Monte Carlo simulation

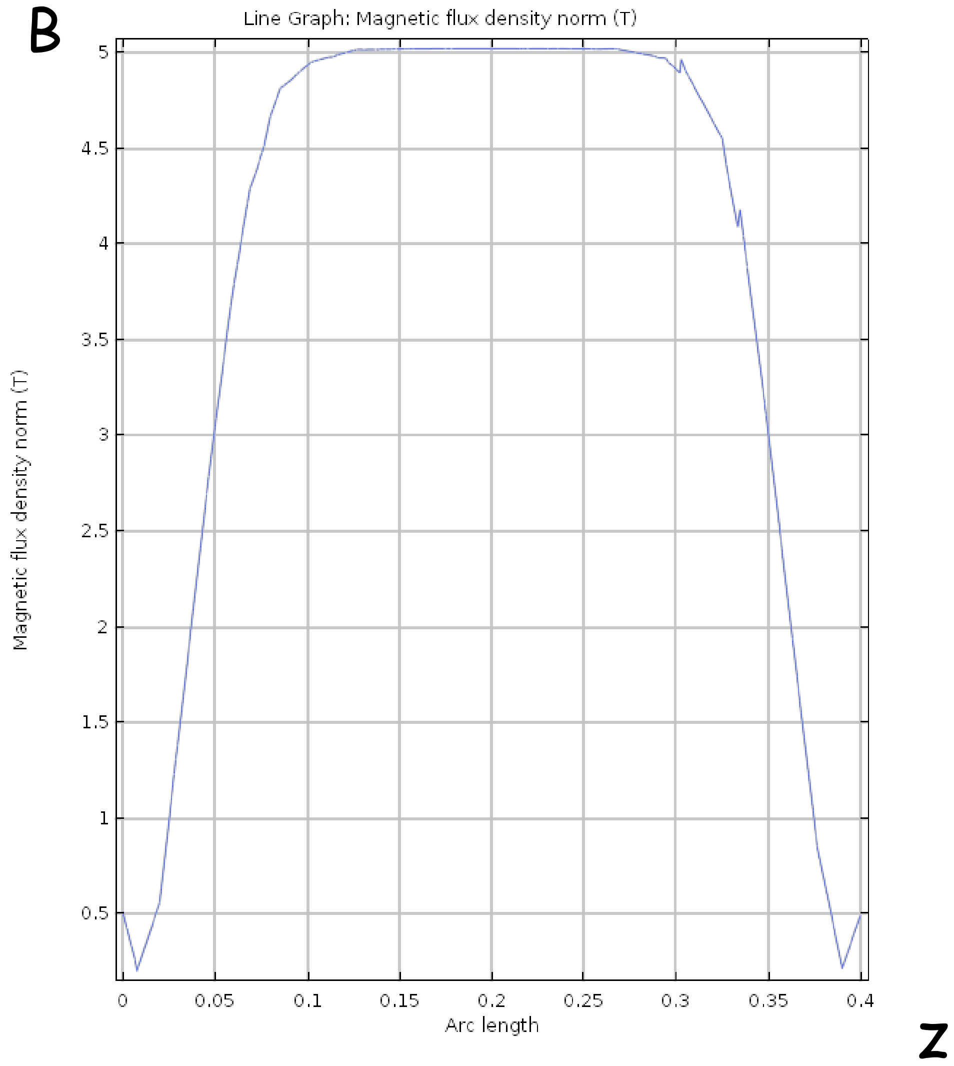
Notes: It is better to use the simulation results since the measurement outside the dewer use the hand probe gaussmeter which is not really accurate (the uncertainty is 20 mT)

Magnetic Field Measurement and Simulation

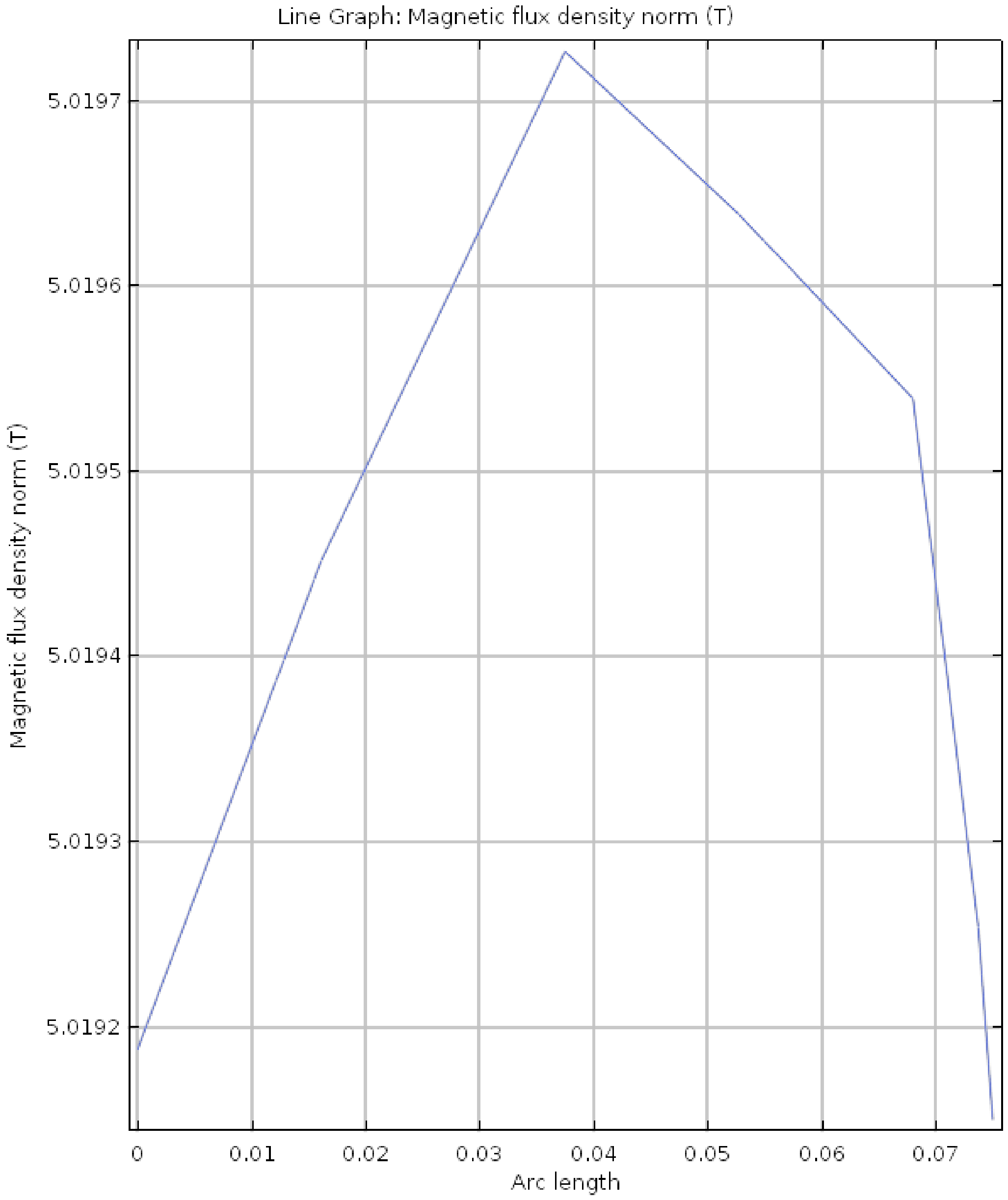
We achieve a high level of homogeneity around the target area & along the beam line:



High level of homogeneity in the target area



And if we zoom in:



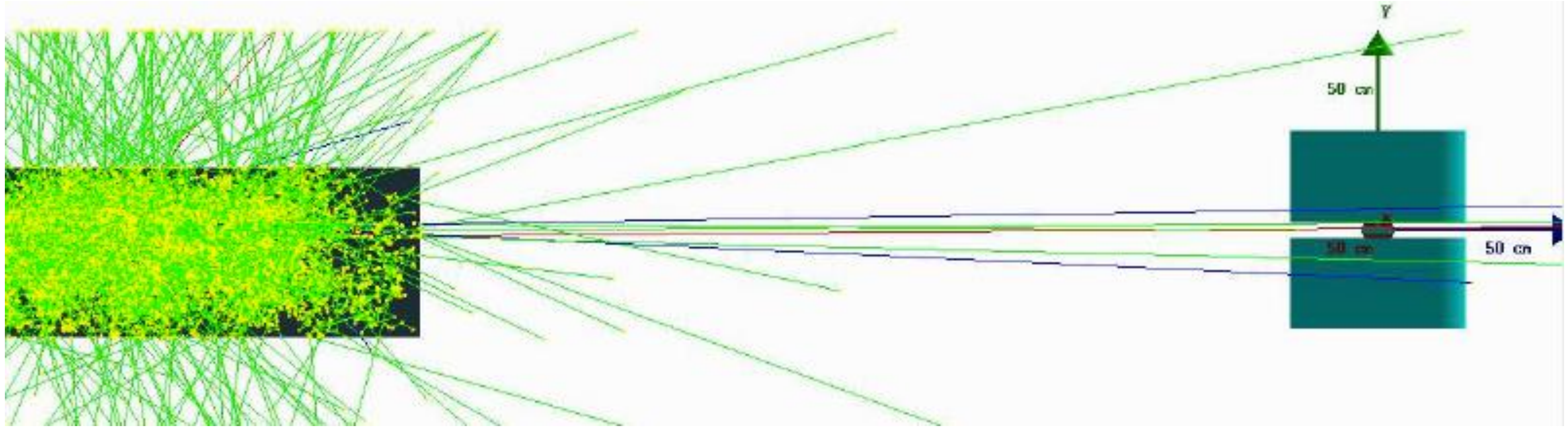
Z = [-3.75 cm;3.75 cm] , Y = 0 cm

Simulation	Measurement
B = [5.0192 T ; 5.0197 T]	B = [5.0195 T ; 5.0199 T]

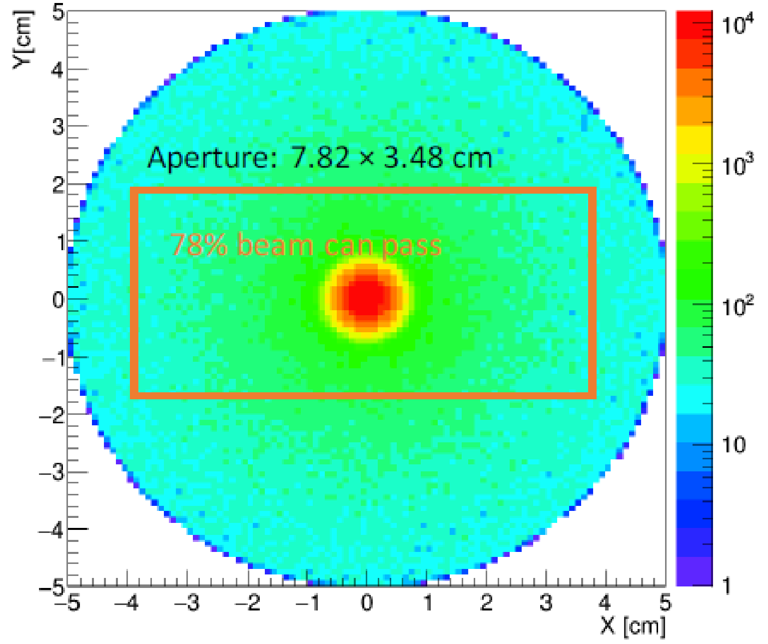
Physics Processes

- Heat Load
- Cooling processes
- Approximation Strategy

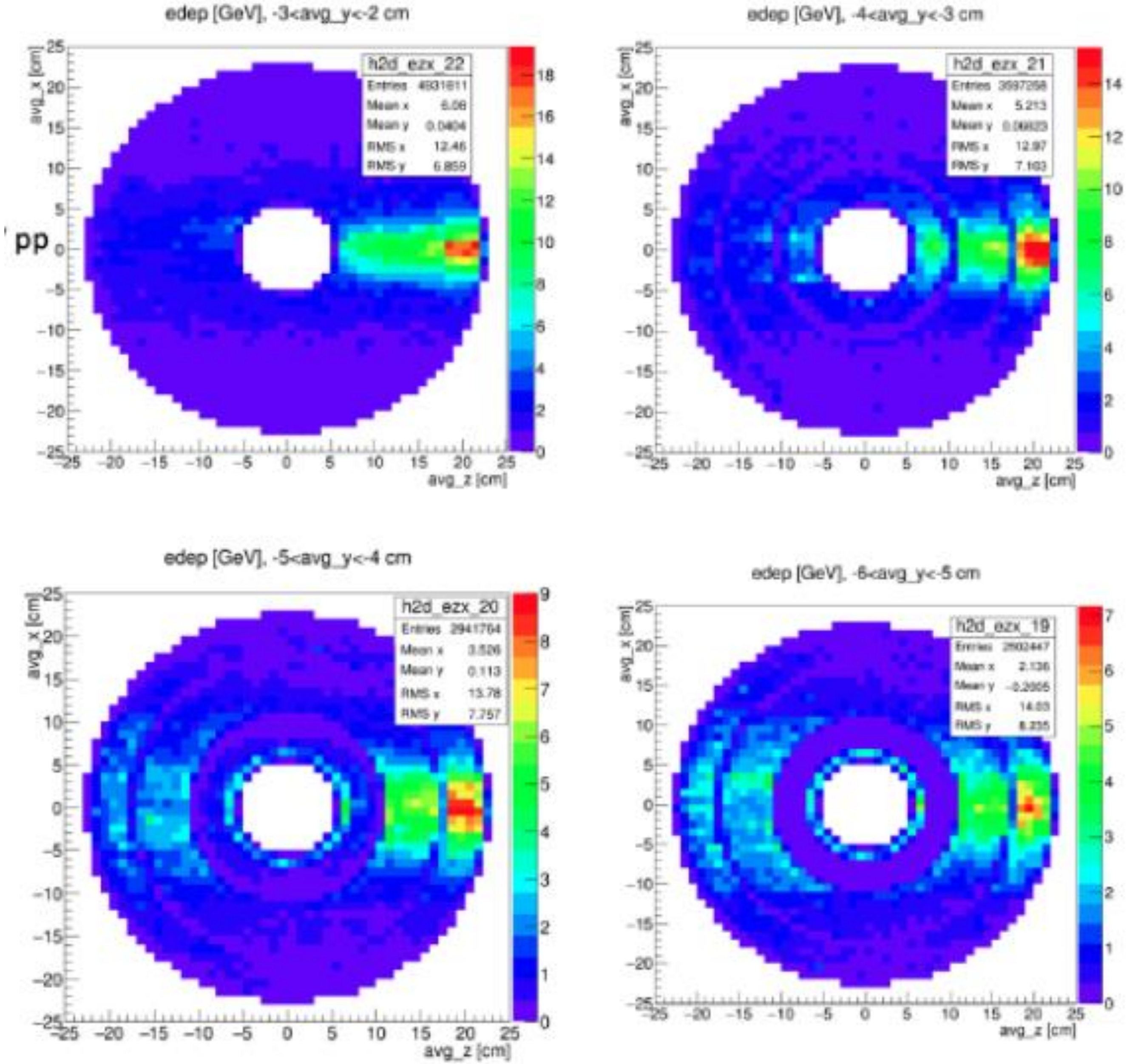
The heat load mainly come from the target and collimator interactions



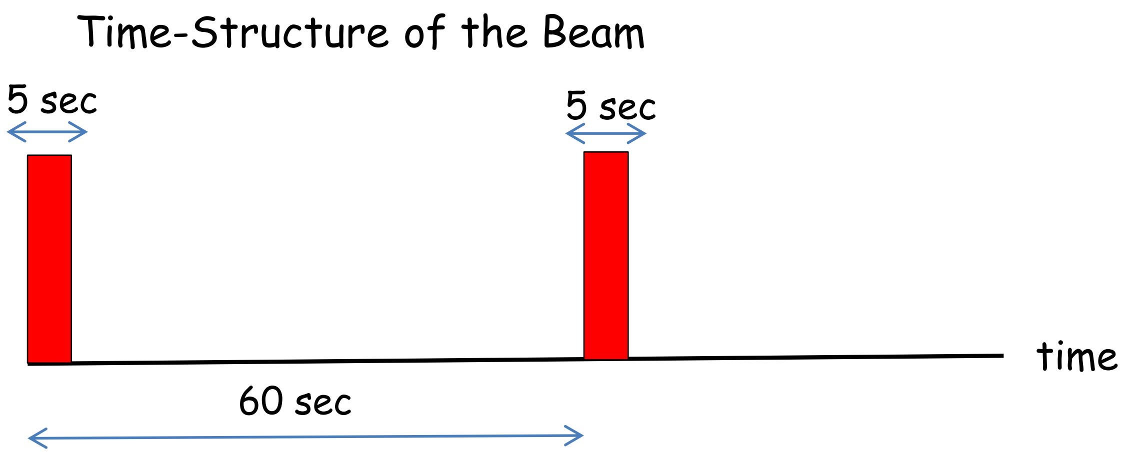
Beam profile:
Gaussian + Tail

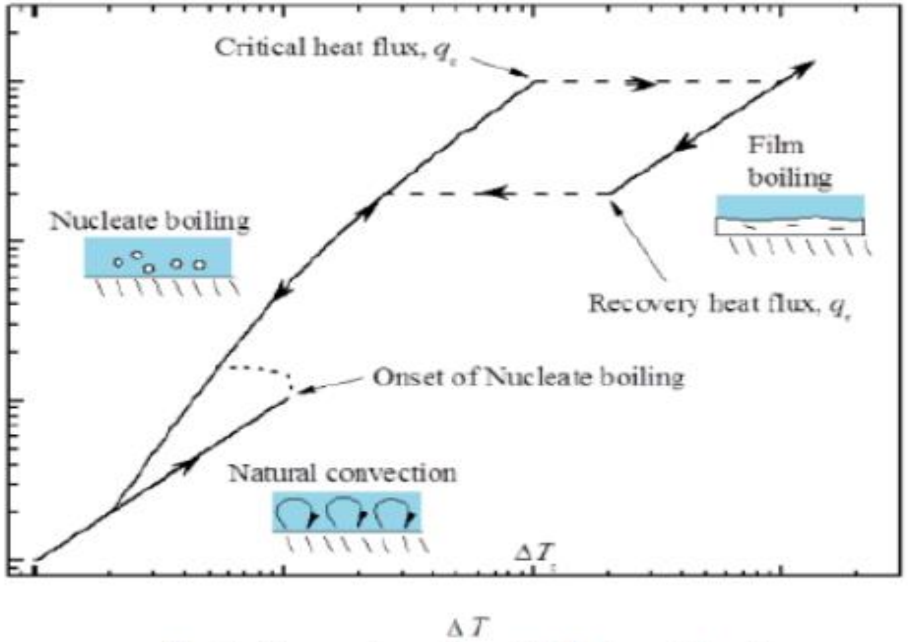


The heat map are obtained from the Geant-Based MC simulations



Cooling Processes

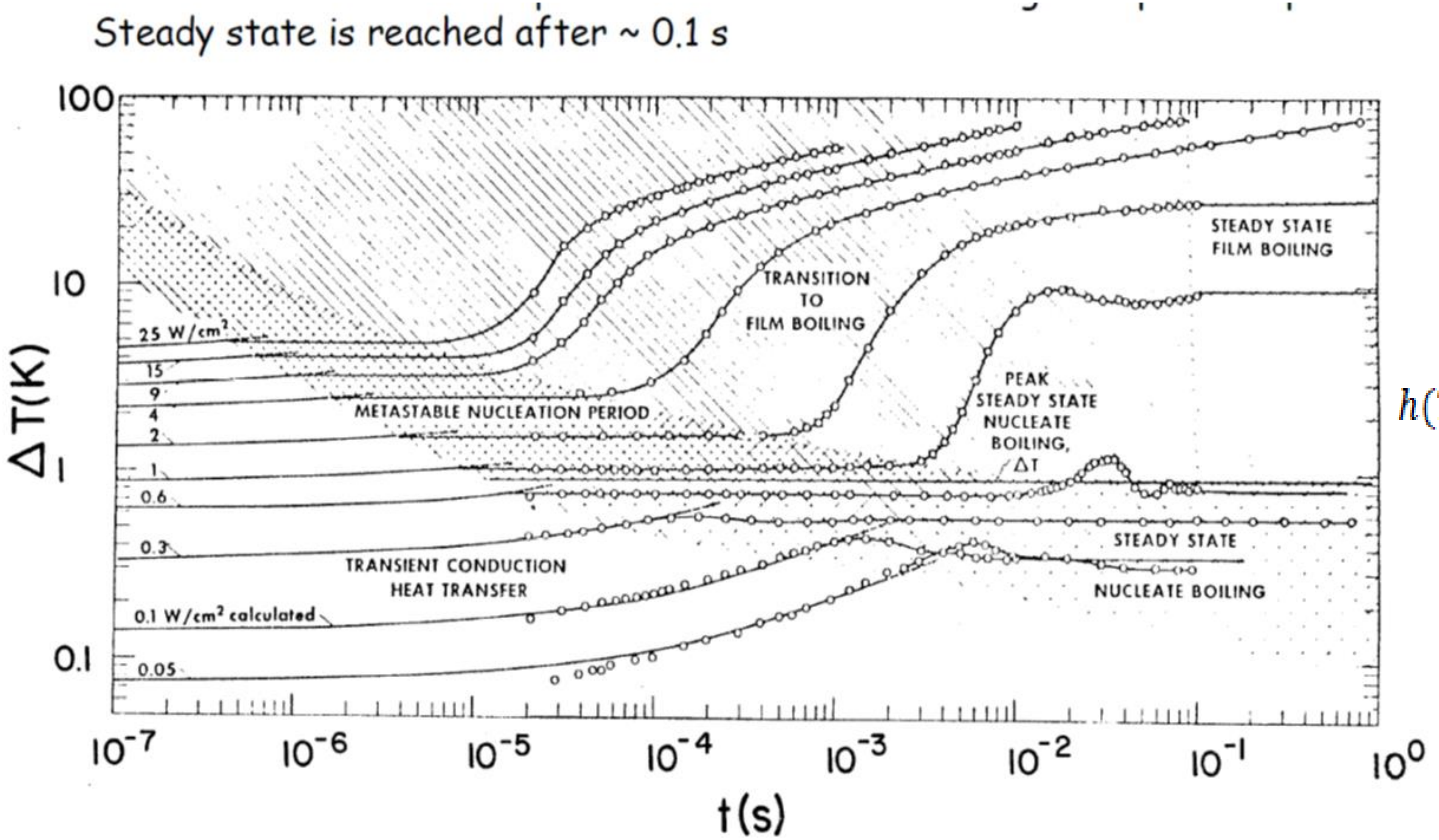




The boiling regimes for a flat horizontal surface

Lhe-Cooling processes

Approximation Strategy



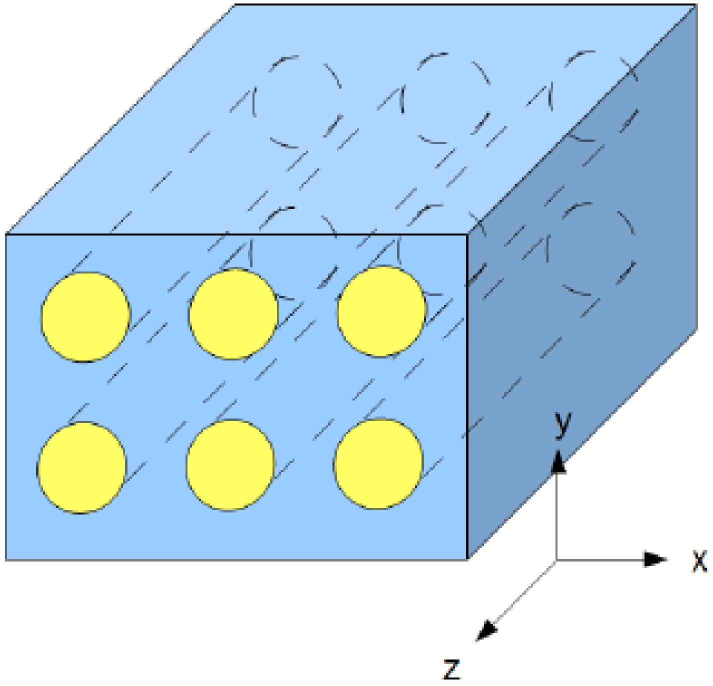
Various regimes of the heat transfer from solid to LHe

First, Steady state Film boiling regime is applied

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

Approximation Strategy

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



Rayleigh's formula

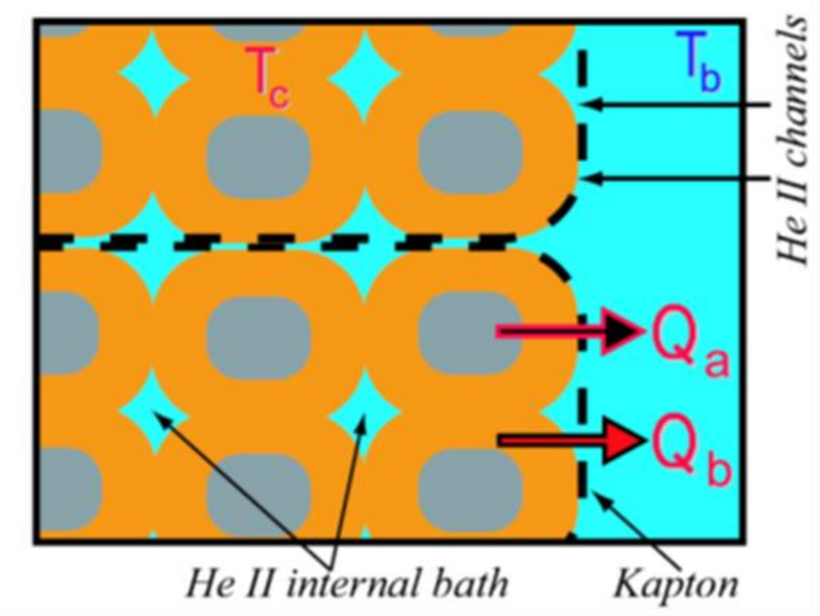
$$\frac{k_{eff}}{k_m} = 1 + \frac{3\phi}{\left(\frac{k_1-2k_m}{k_1-k_m}\right) - \phi + 1.569\left(\frac{k_1-k_m}{3k_1-4k_m}\right)\phi^{\frac{10}{3}} + \ldots}$$

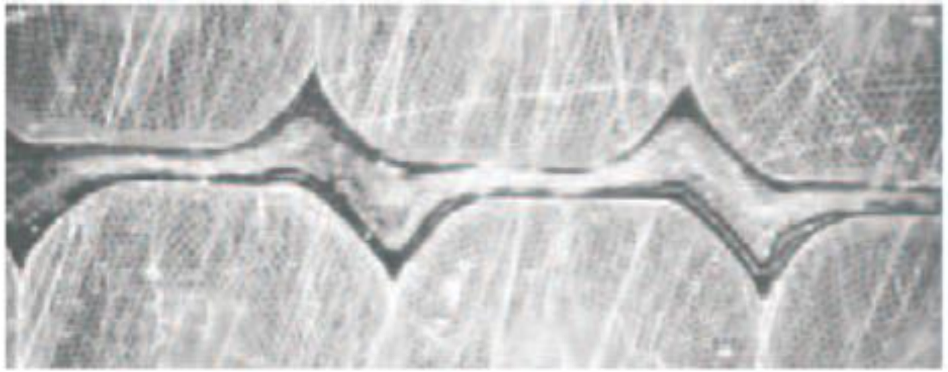
Rayleigh's model consist of parallel cylinders embedded in a continuous matrix

Approximation Strategy

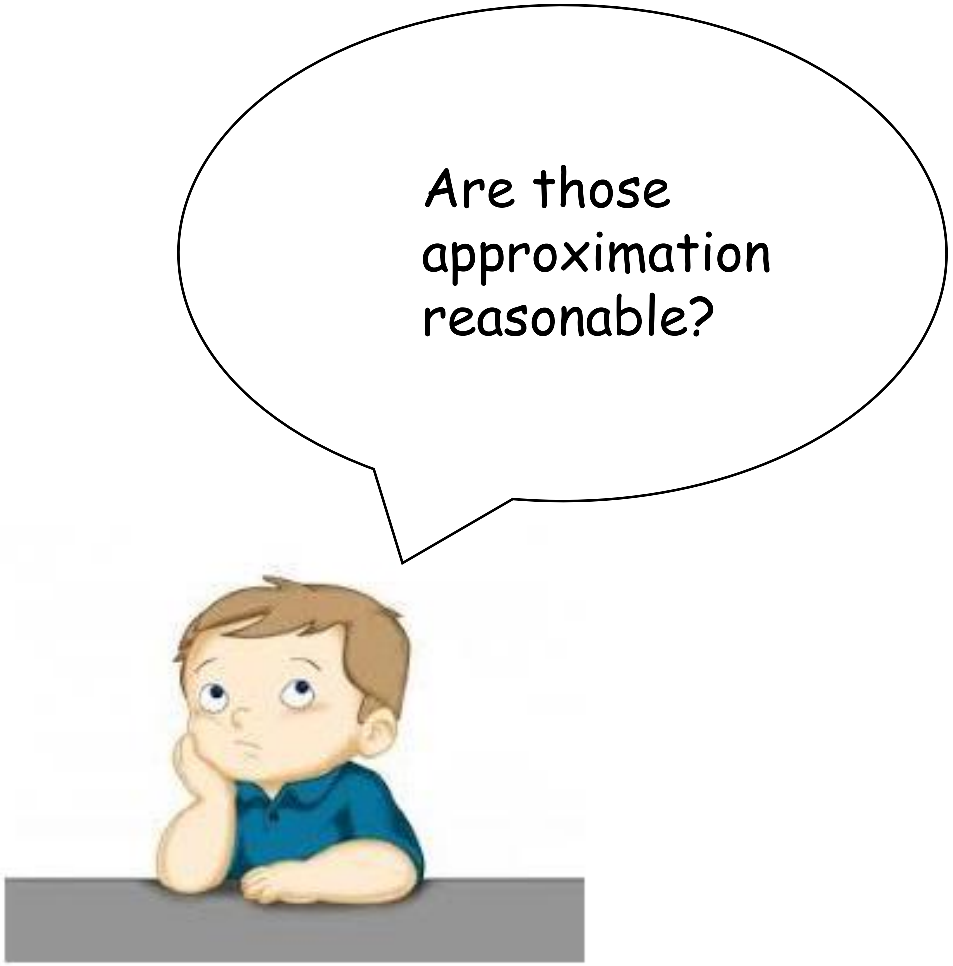
Third, we parameterize some of the unknown properties by the effective surfaces that are in direct contact with the LHe:

- Perimeter of the He void
- Insulation
- Former





Microscopic view of the cable



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

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

Where the coefficient is in $Wm^{-2}K^{-1}$. Therefore the effective surface contact can be absorbed into this coefficient

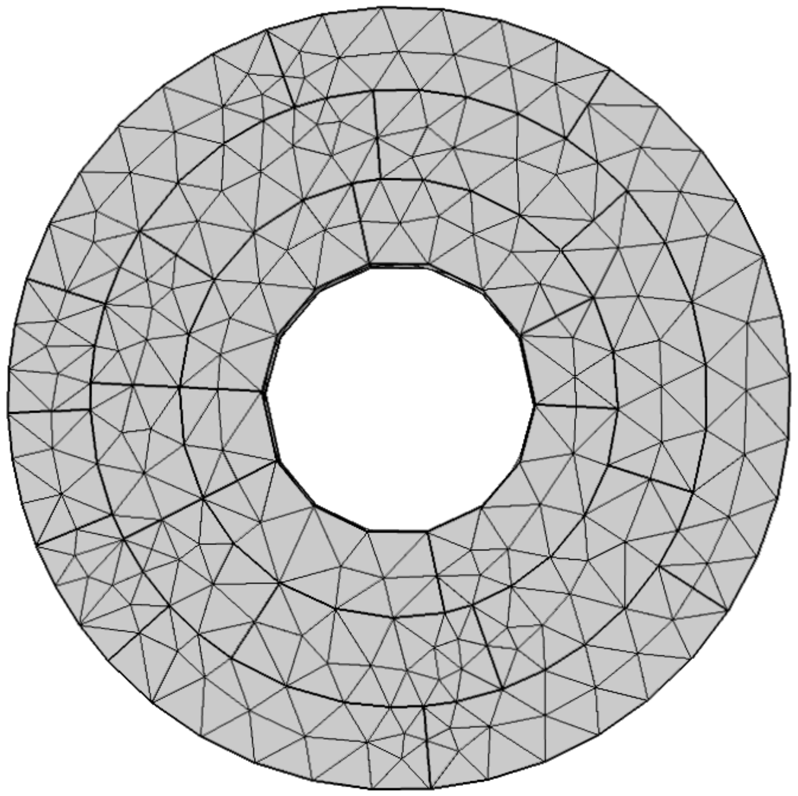
We have quite large temperature margin (4K) since we operate in the normal phase of He (evaporation fridge)

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

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



Discretized element

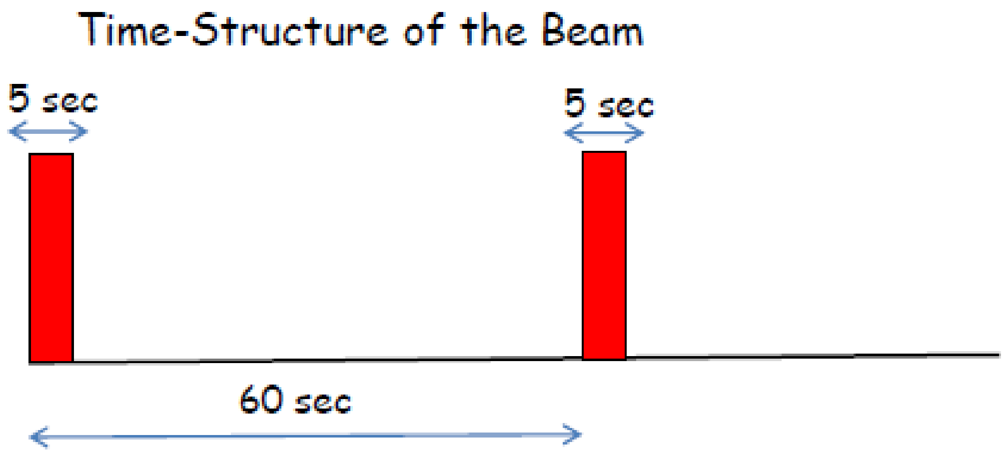
Results

- BNL VS SpinQuest
- Temperature profile T(x)
- Temperature profile Tmax(t)

Results

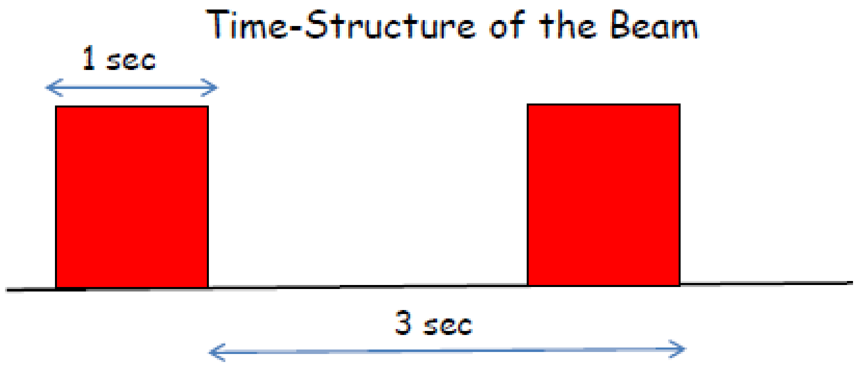
SpinQuest VS BNL

SpinQuest



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

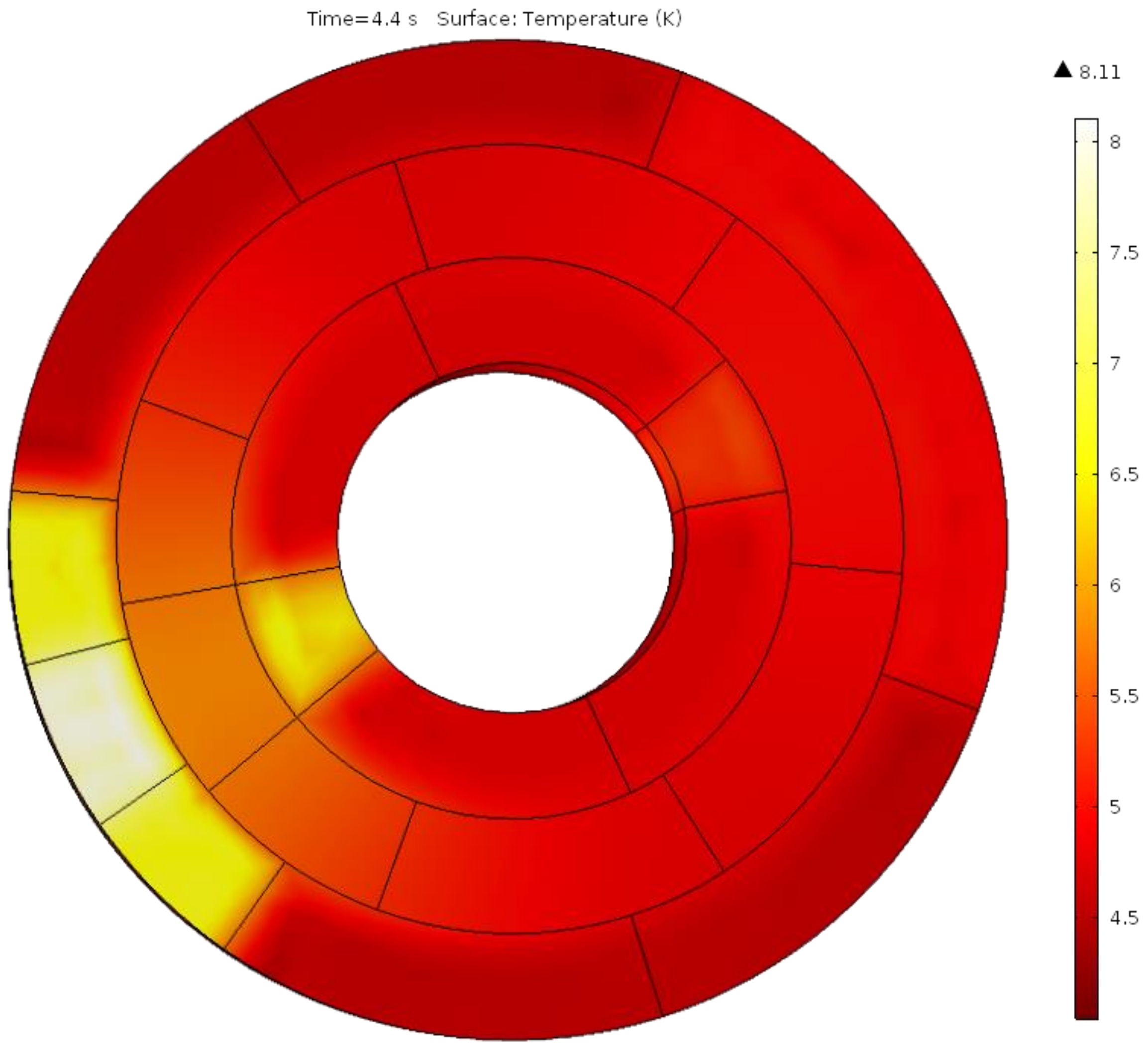
BNL



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

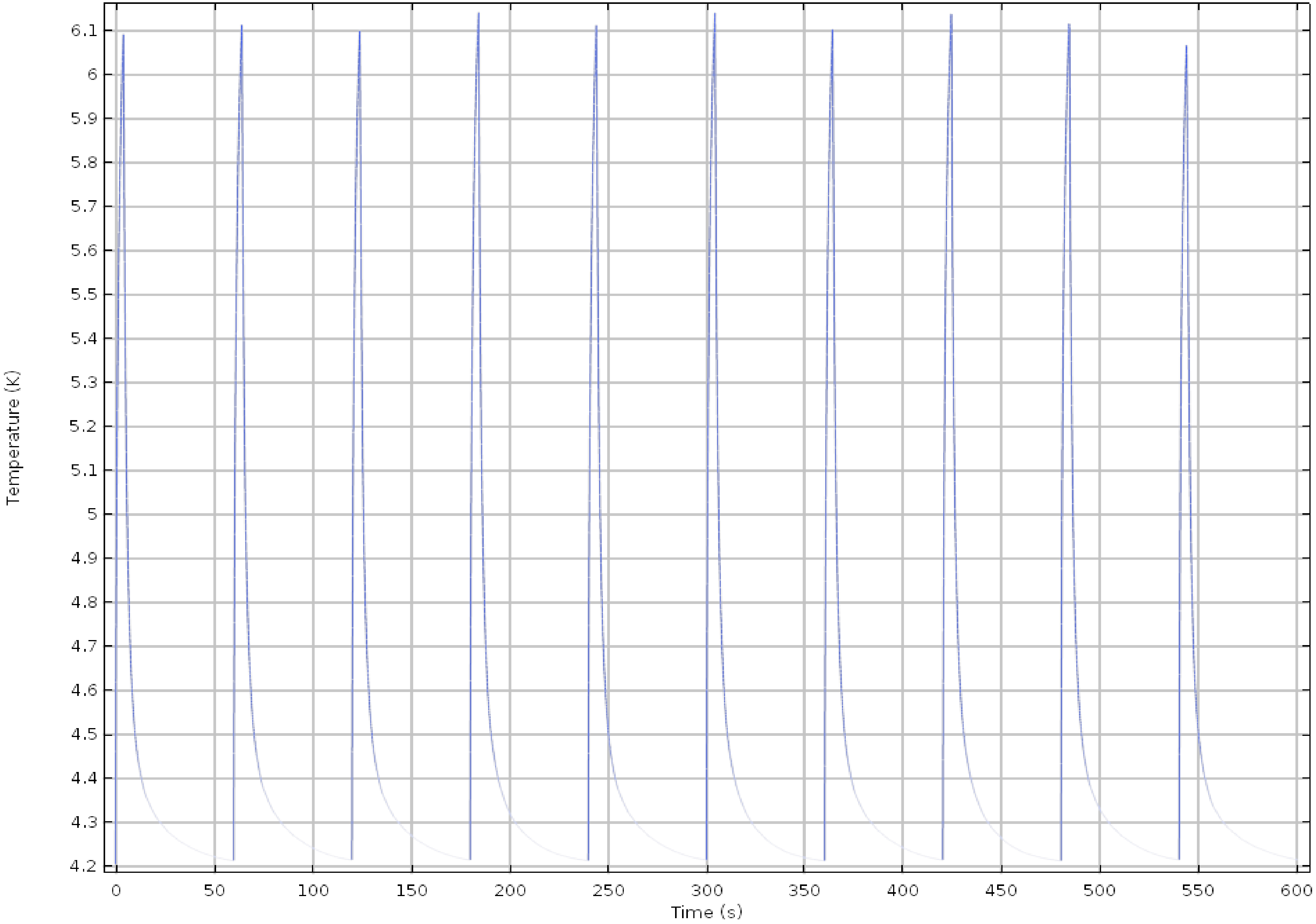
Results

The temperature profile for a particular time



Results

The maximum temperature of the coil as a function of time



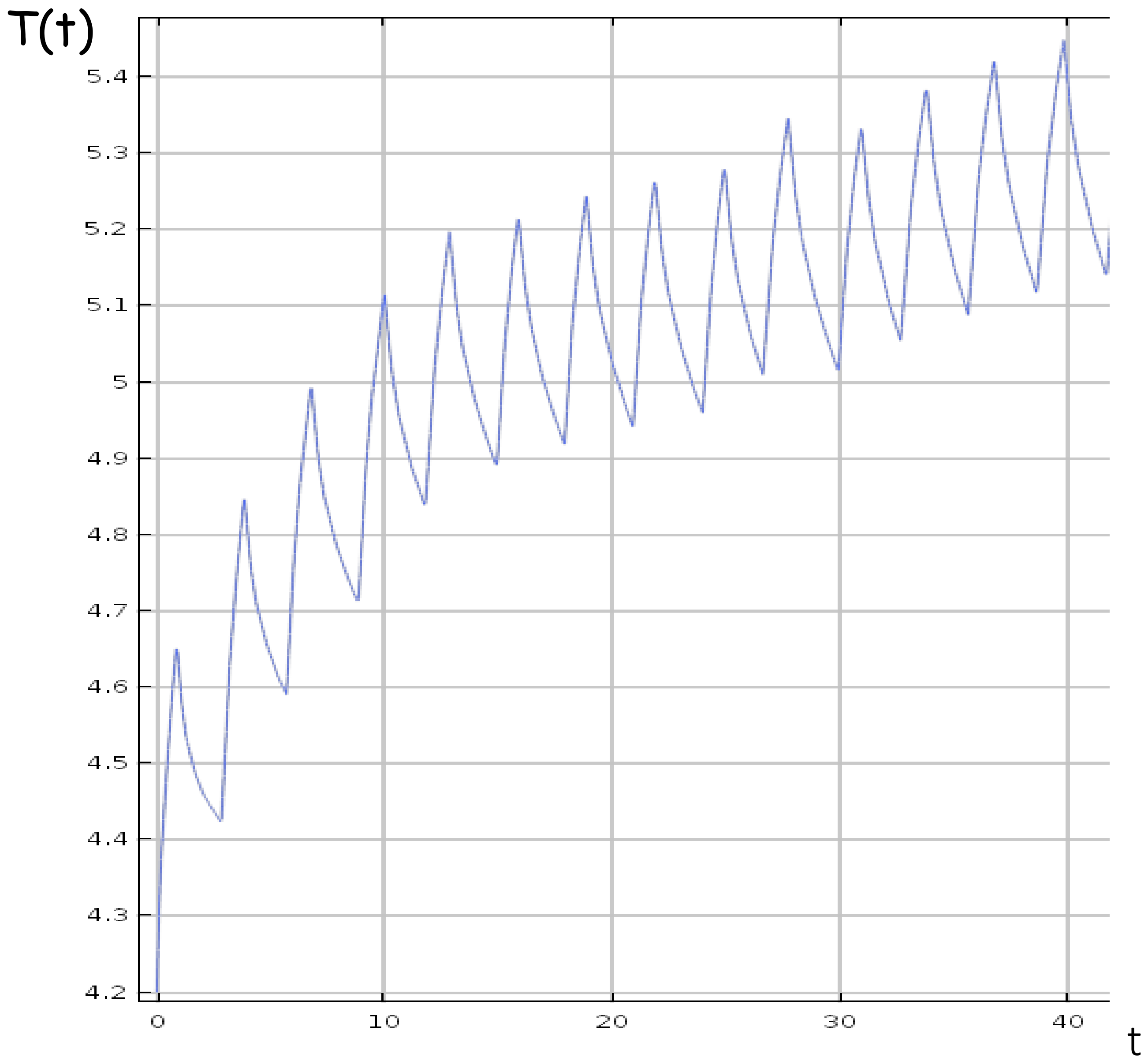
Maximum Temperature profile Tmax(t) for E1039:

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

Conclusion: It is save to run at 1e12 proton/s but I recommend this intensity to be considered as the upper limit

Results

The maximum temperature of the coil as a function of time



Maximum Temperature profile Tmax(t) for BNL:

- 240 GeV proton
- 2e11 proton/s
- Teflon Target

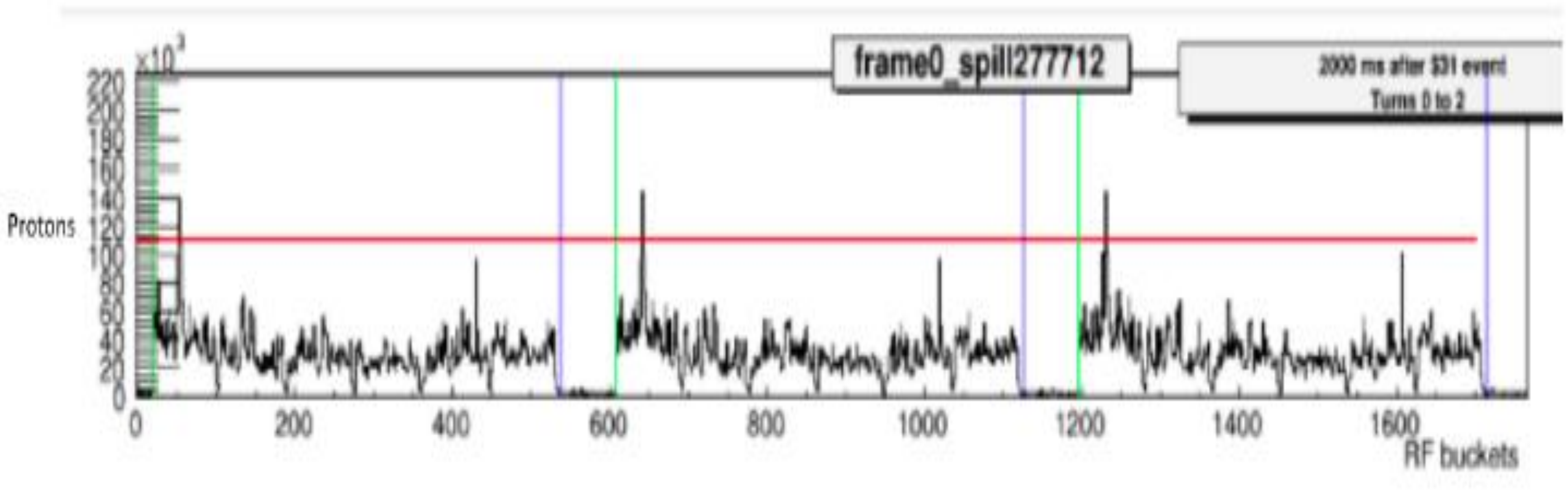
Notes:

- The BNL magnet was quenched in this setup (Teflon target & 2e11 proton/s)
- The simulation results "indicate" quench -> The heat is accumulated over time
- There is an issue about numerical convergence issue for longer run that need to be fixed -> require extremely fine Mesh and time step

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

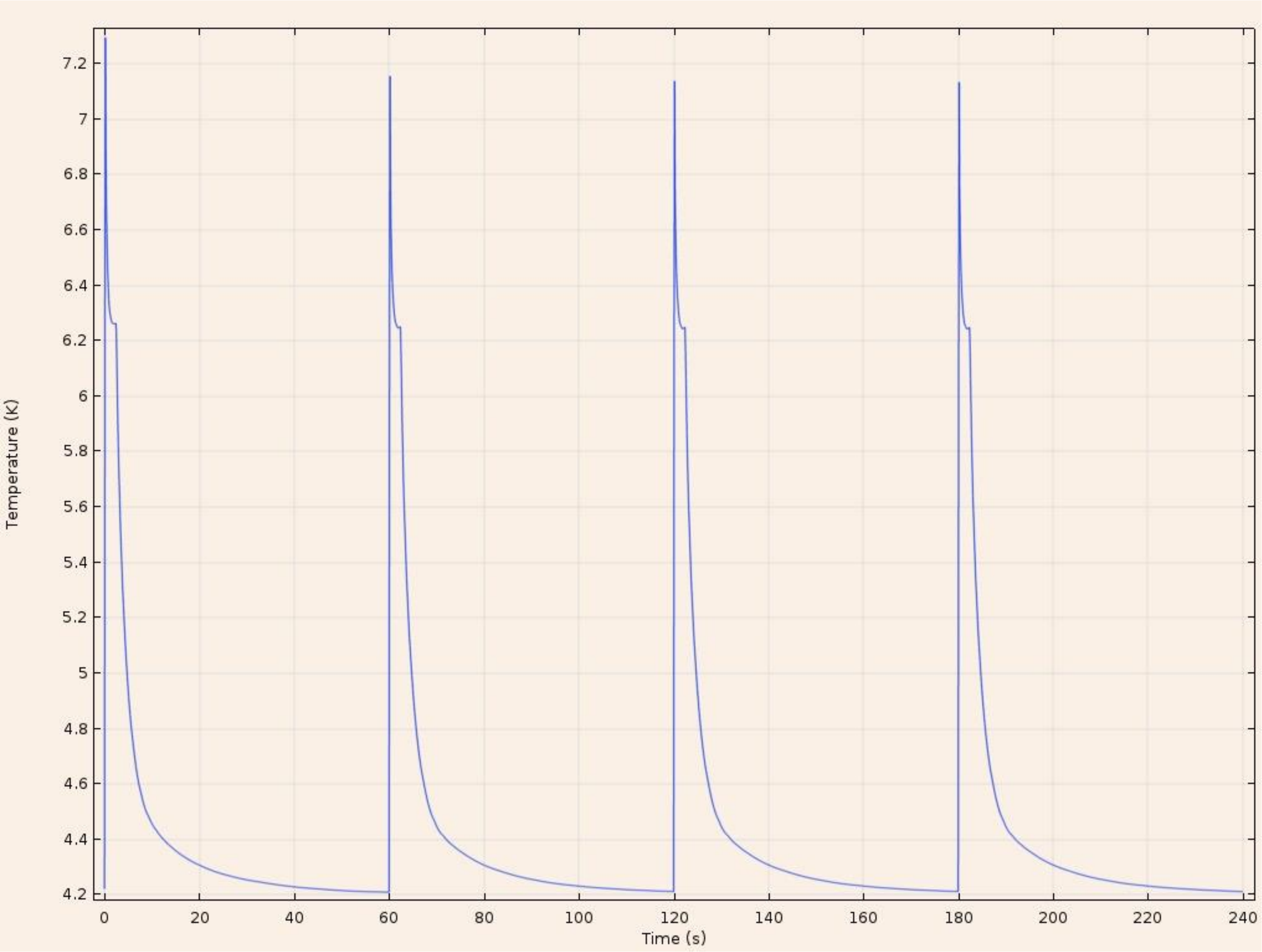
$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+\boxed{\dot{q}=\rho c_p\frac{\partial T}{\partial t}}$$

Assumption for the upper limit of Temperature approximation: In a very short period of time, the Heat are localized -> 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 s



Calculation for t = 0.2 s

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

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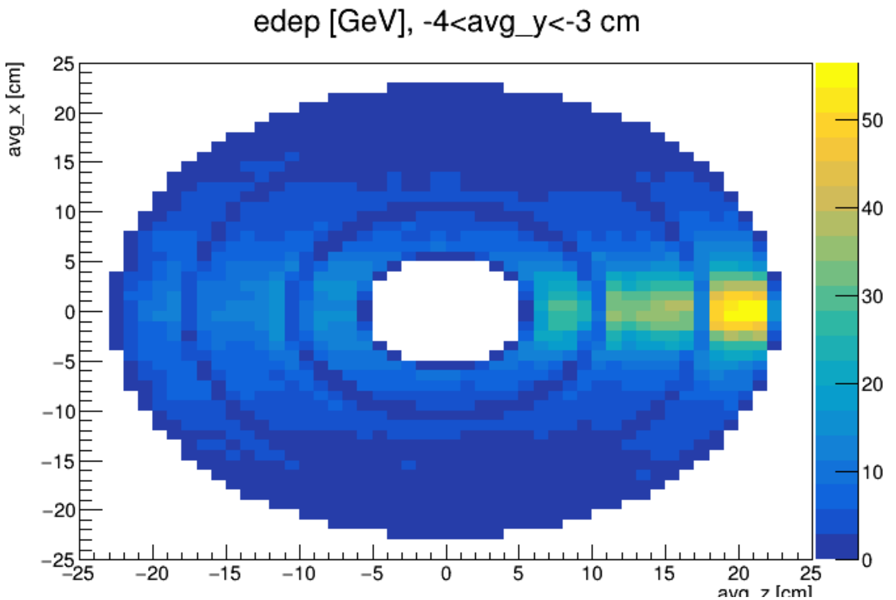
10 times	0.15	7	9.05	2.05
10 times	0.125	6.7	8.44	1.74
10 times	0.1	6.3	7.78	1.48

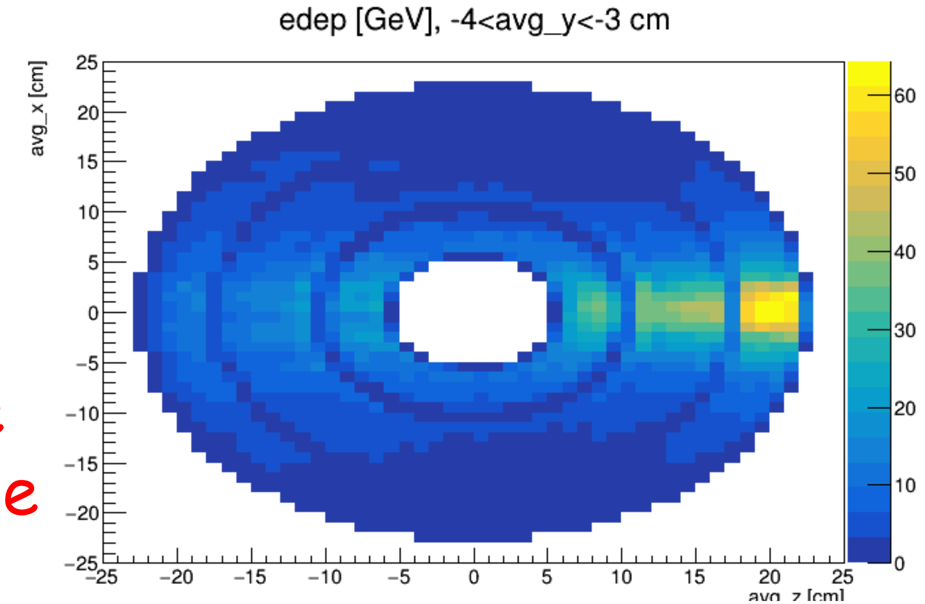
Since the Tmax calculation between simulation and calculation match as the time (duration of the jump) going smaller. We can trust the calculation. For the ns duration of the jump:

$$T = \sqrt{42.868 \times I \times t + 17.64} \\ \sim 4.2\ K$$

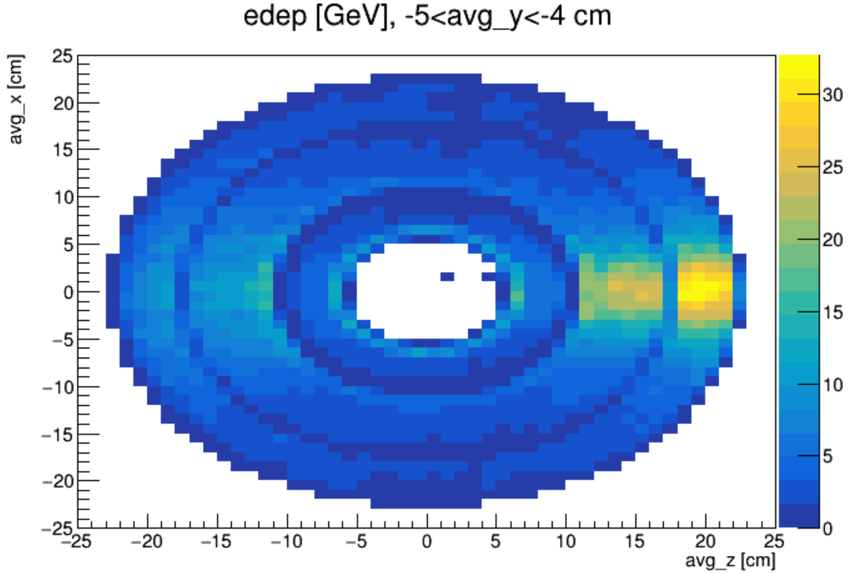
Perfect beam alignment

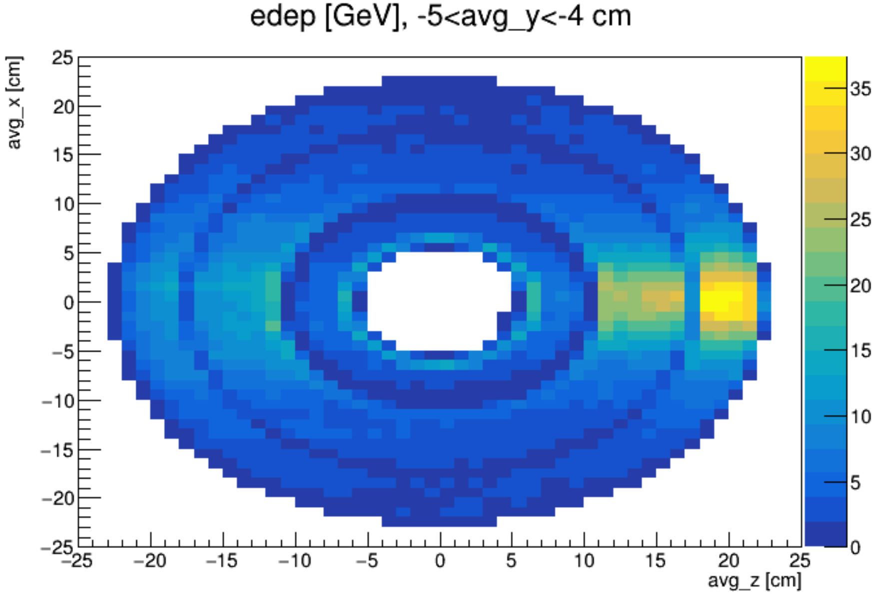
Beam drift or misalignment by 0.3 cm





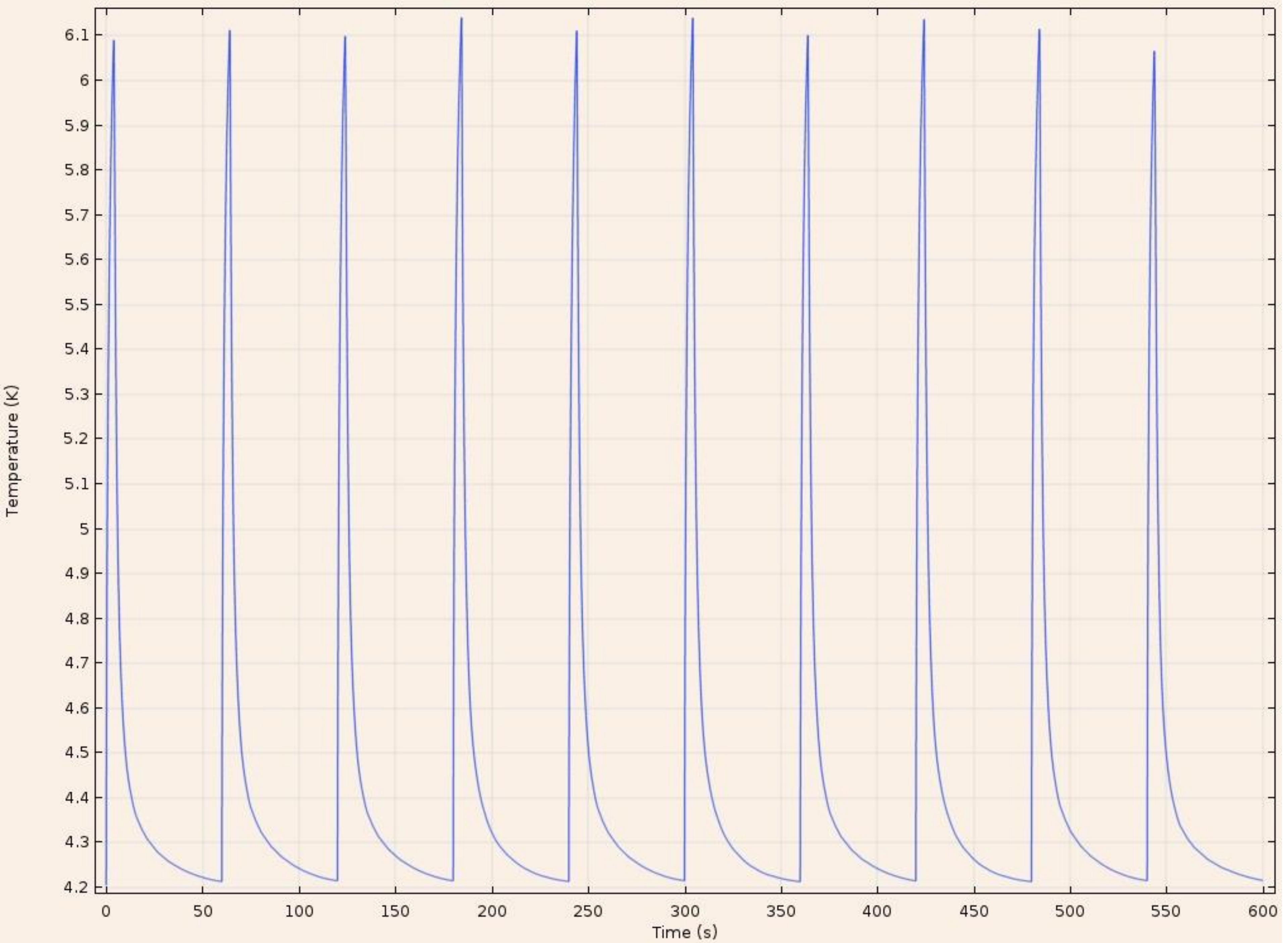
The energy deposited in the hot spot increase by ~ 15%





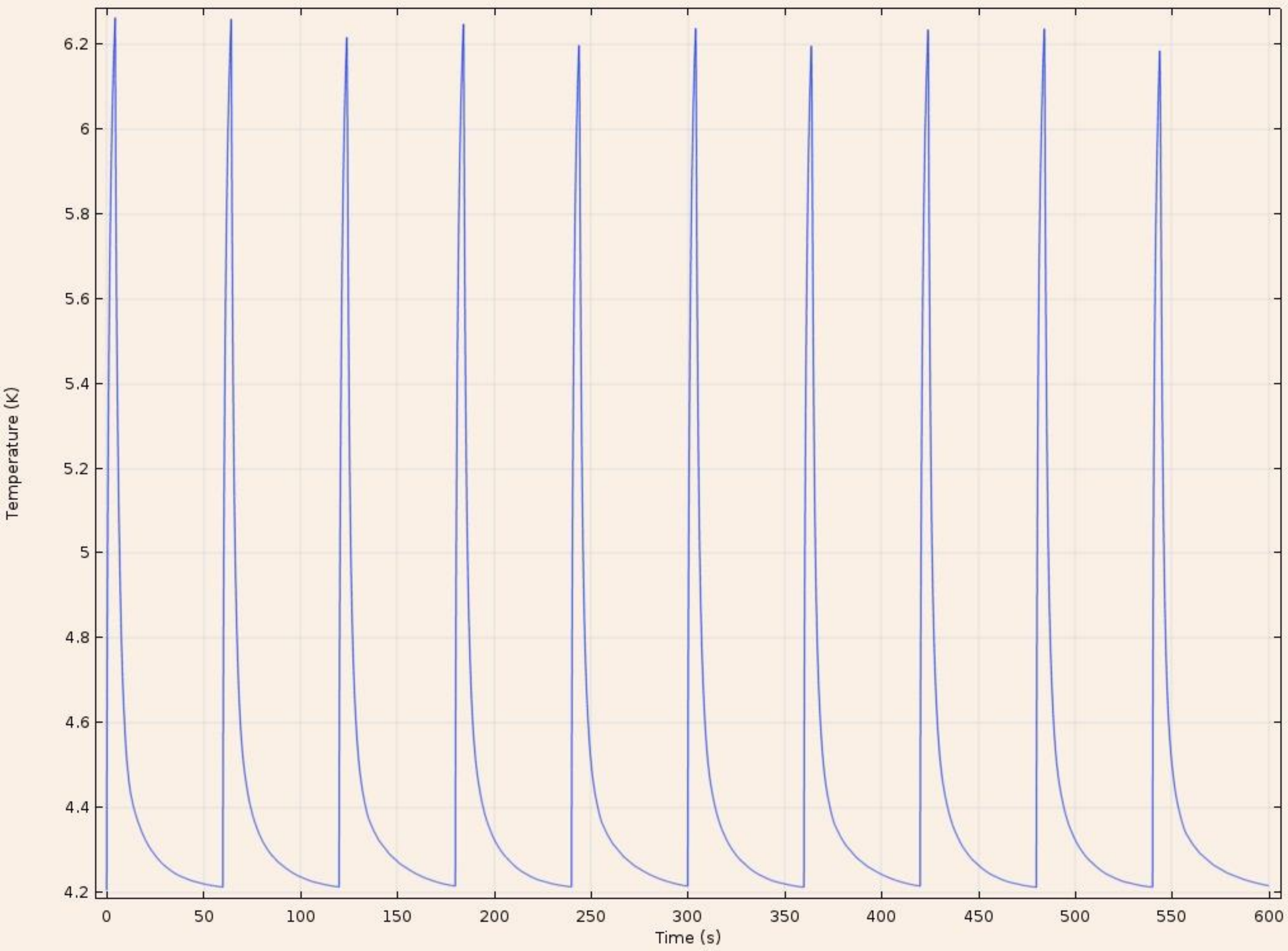
0.1 K of temperature increase

Benchmark



Temperature (K)
6.1
6
5.9
5.8
5.7
5.6
5.5
5.4
5.3
5.2
5.1
5
4.9
4.8
4.7
4.6
4.5
4.4
4.3
4.2
0
50
100
150
200
250
300
350
400
450
500
550
600
Time (s)

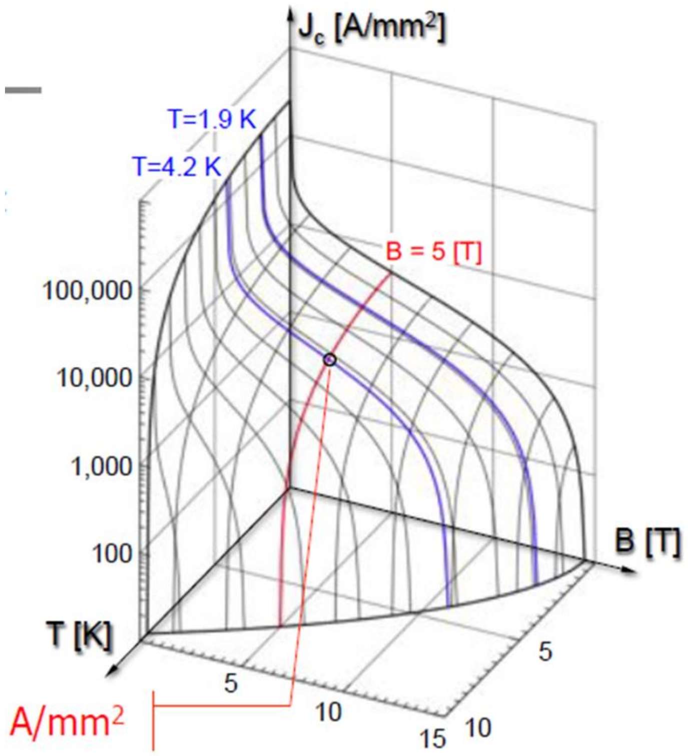
Drift

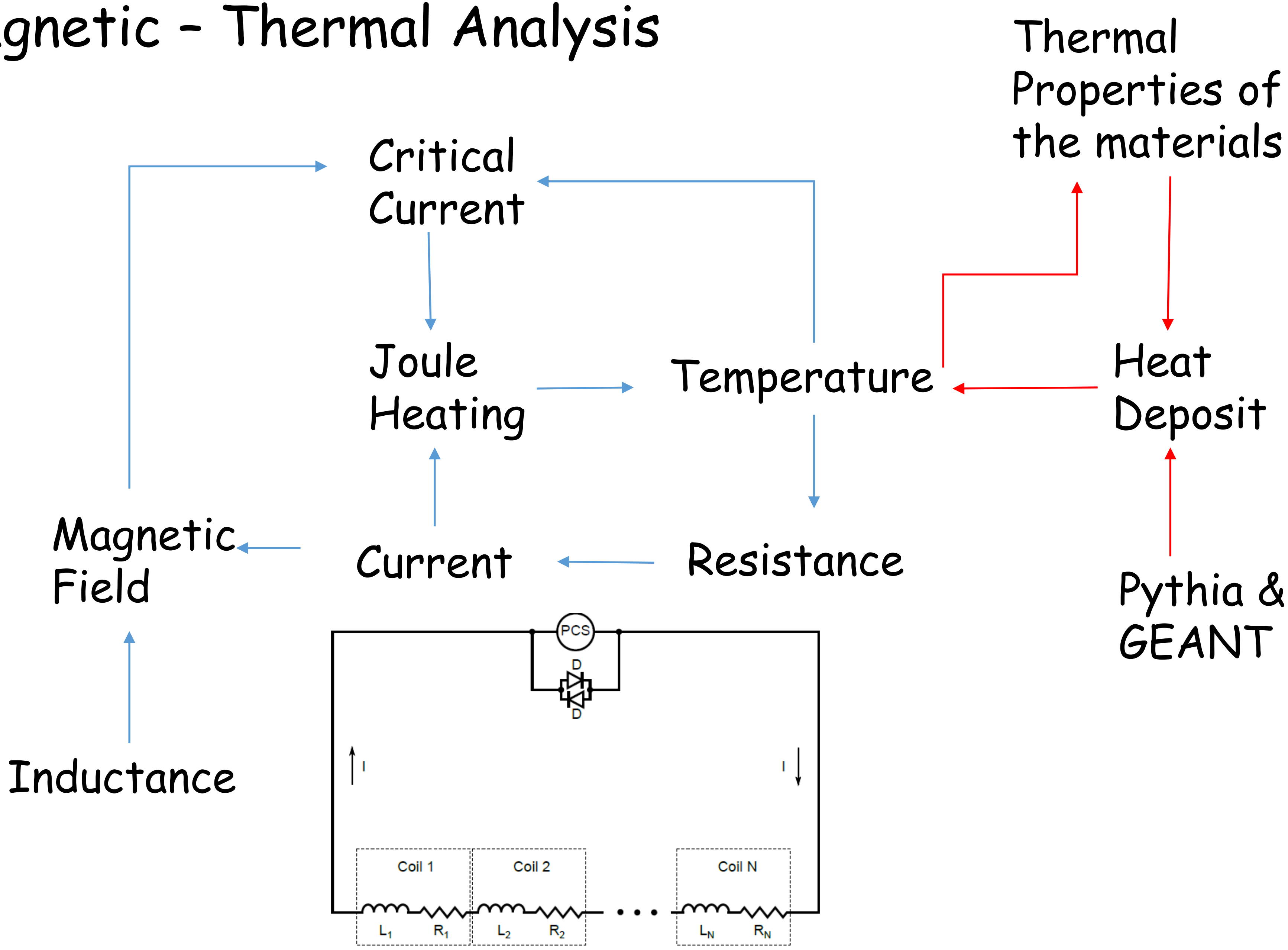


Temperature (K)
6.2
6
5.8
5.6
5.4
5.2
5
4.8
4.6
4.4
4.2
0
50
100
150
200
250
300
350
400
450
500
550
600
Time (s)

Outlook: Electromagnetic – Thermal Analysis

Critical surface of a LHC NbTi wire





Thank You