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

Zulkaida Akbar

University of Virginia

Outline

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

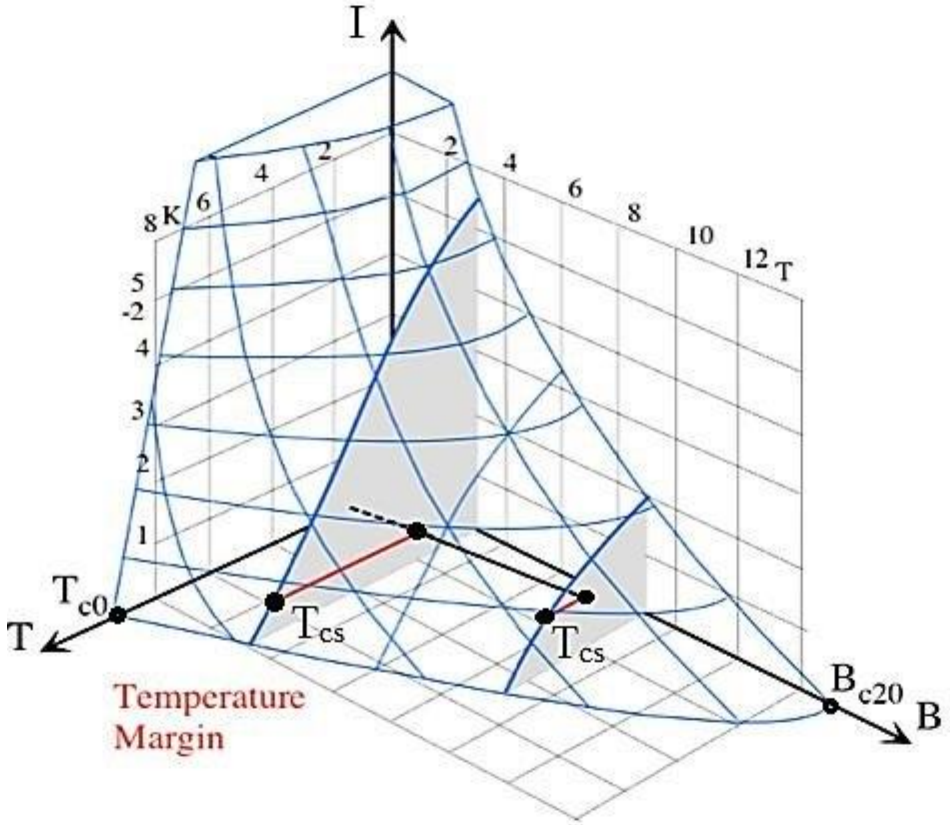
Introduction: SpinQuest Experiment at Fermilab

SpinQuest Physics:
- Sivers function for the sea quarks (main physics goal)
- Dark matter search
- Deuteron tensor function $b1$ (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 ≈ 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

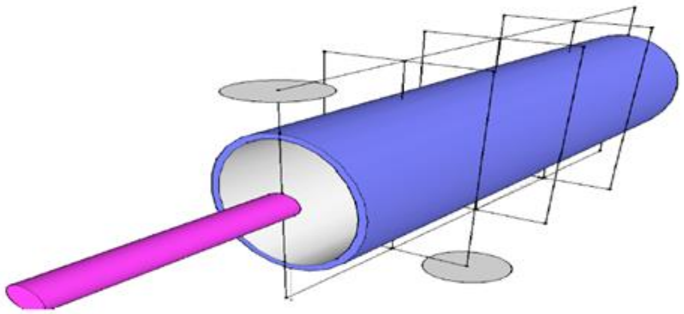
Main Questions:

- 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 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 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

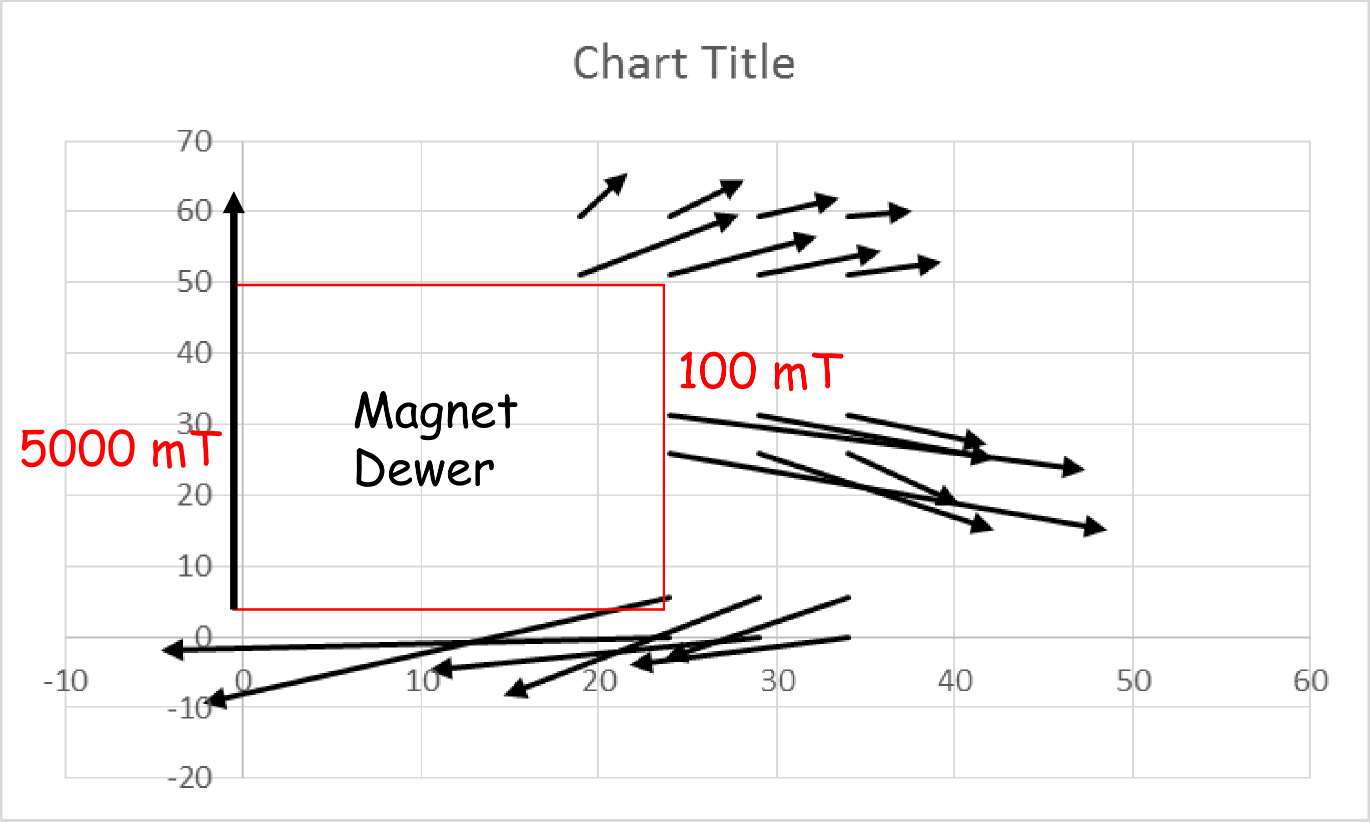
Measurement outside the dewar during the cooldown at UVA:

- 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

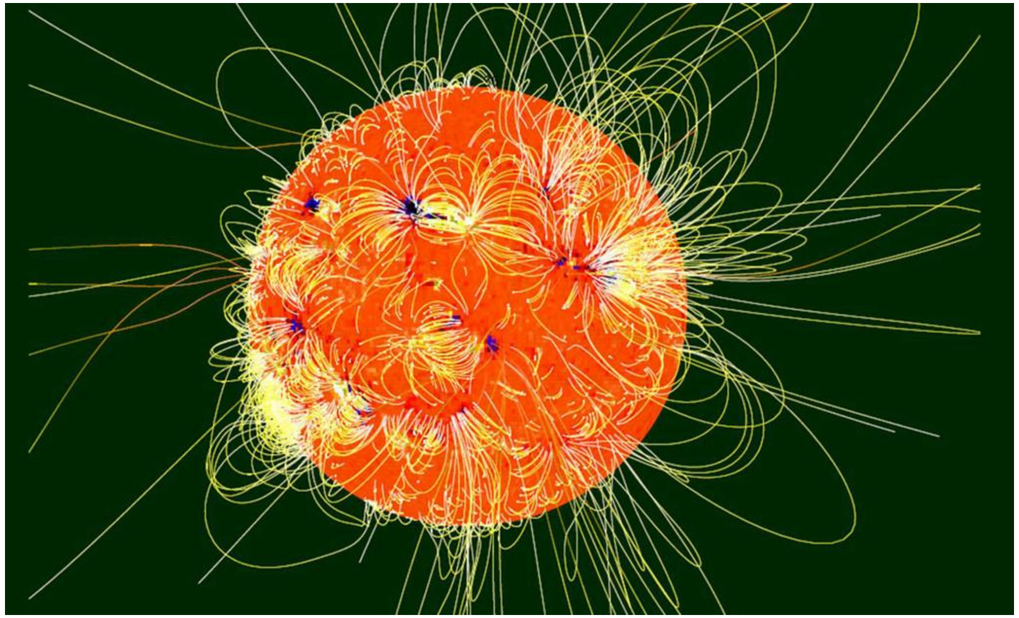


Sample of the measurements

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

Input:

- B measurement inside the target cup
- B measurement outside the dewar

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

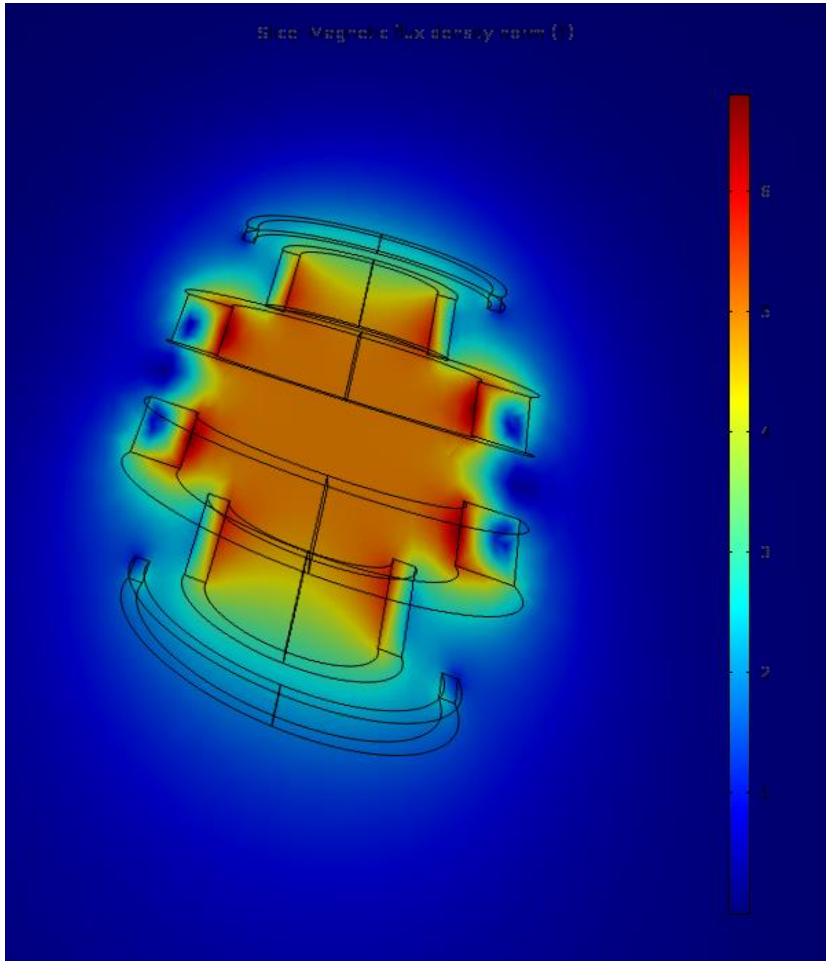
Outcome:

Put the B from the simulation into the Monte Carlo simulation

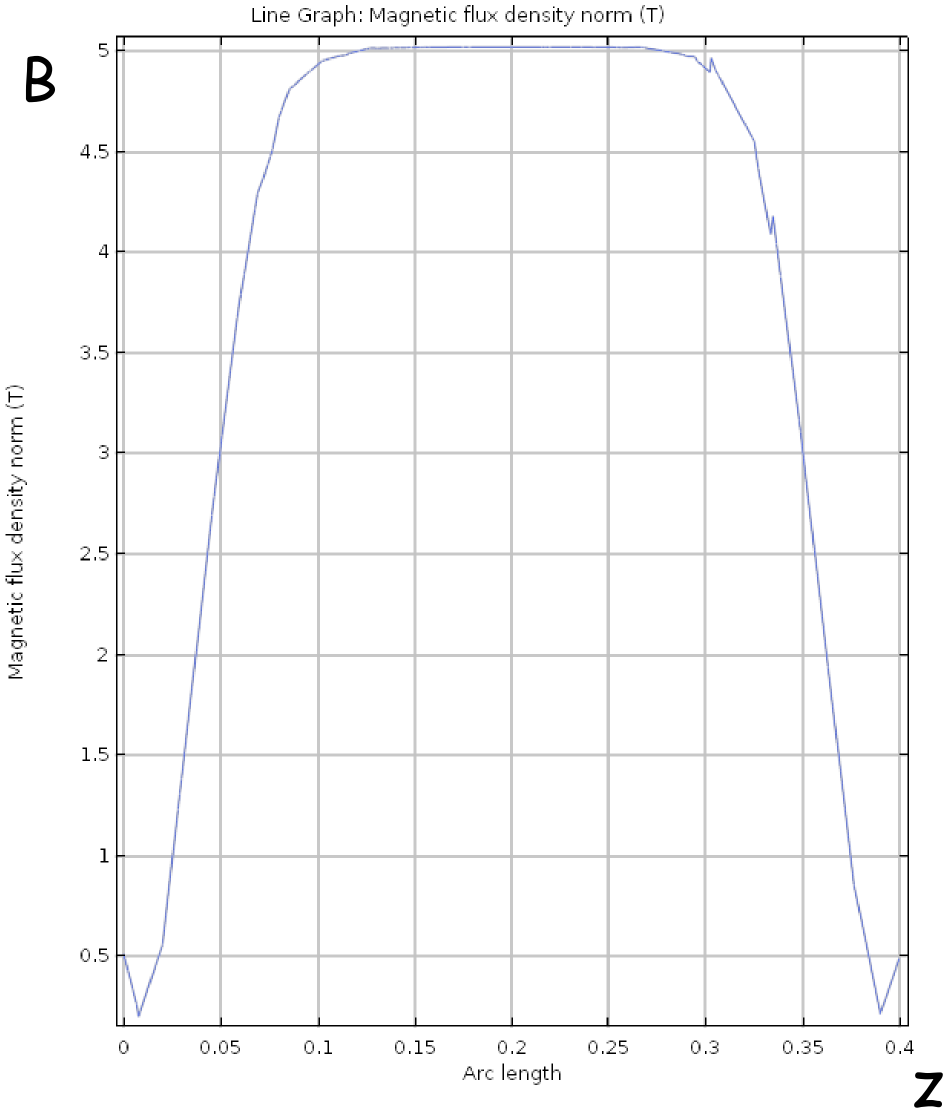
Notes: It is better to use the simulation results since the measurement outside the dewer use the hand probe gaussmeter which is not really accurate (the uncertainty is 20 mT)

Magnetic Field Measurement and Simulation

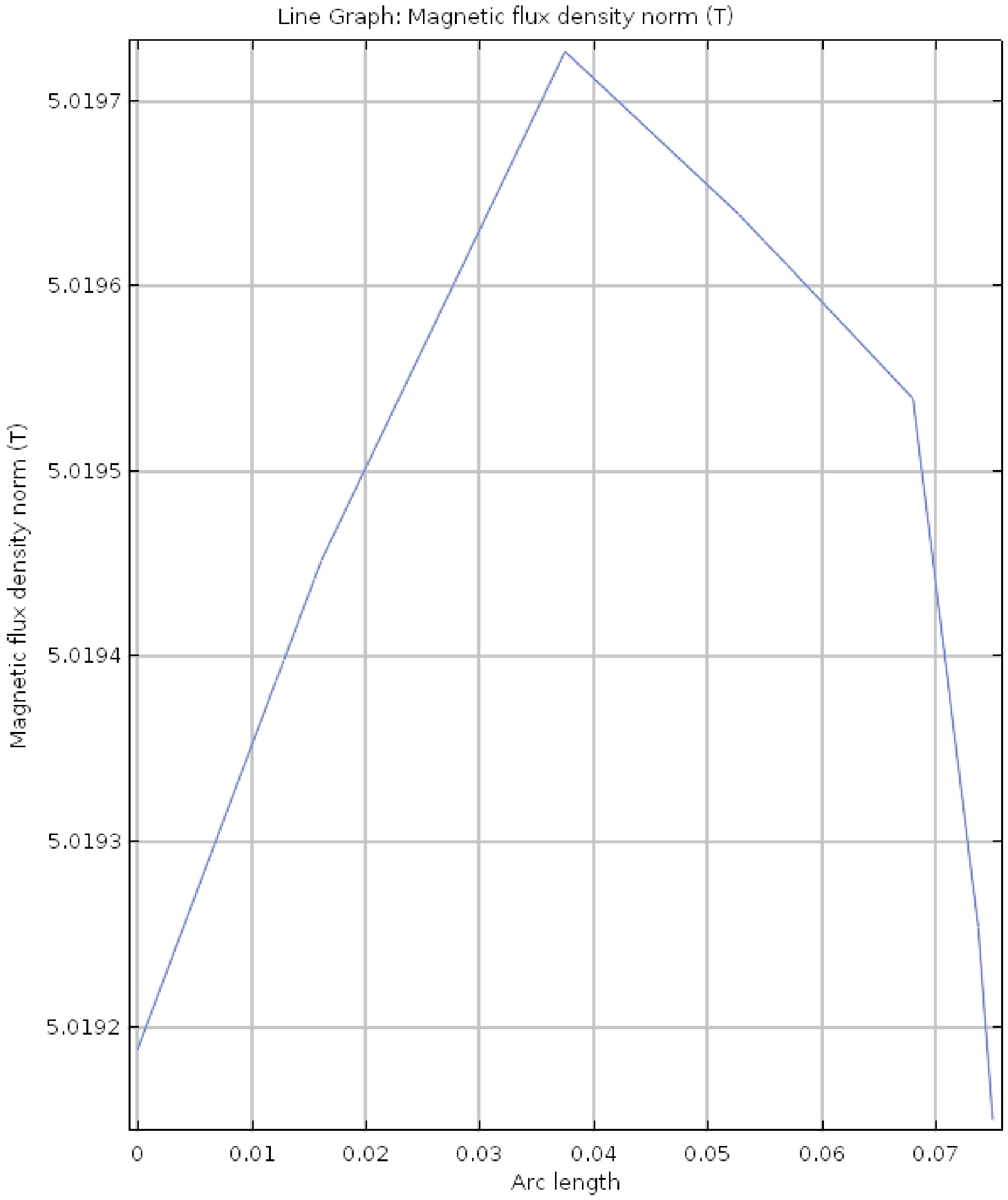
Simulation result: we achieve a high level of homogeneity around the target area & along the beam line:



High level of homogeneity in the target area



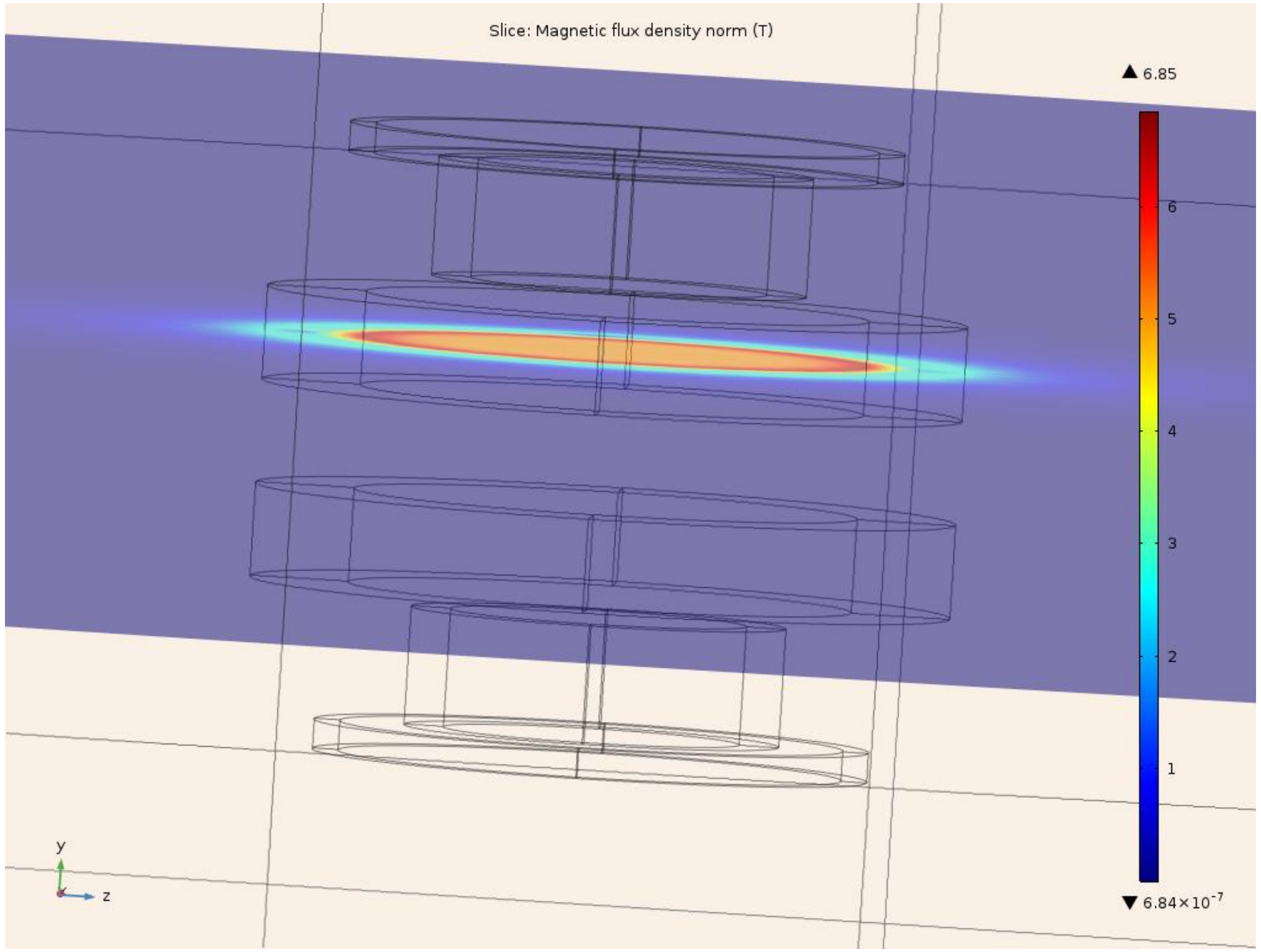
And if we zoom in:

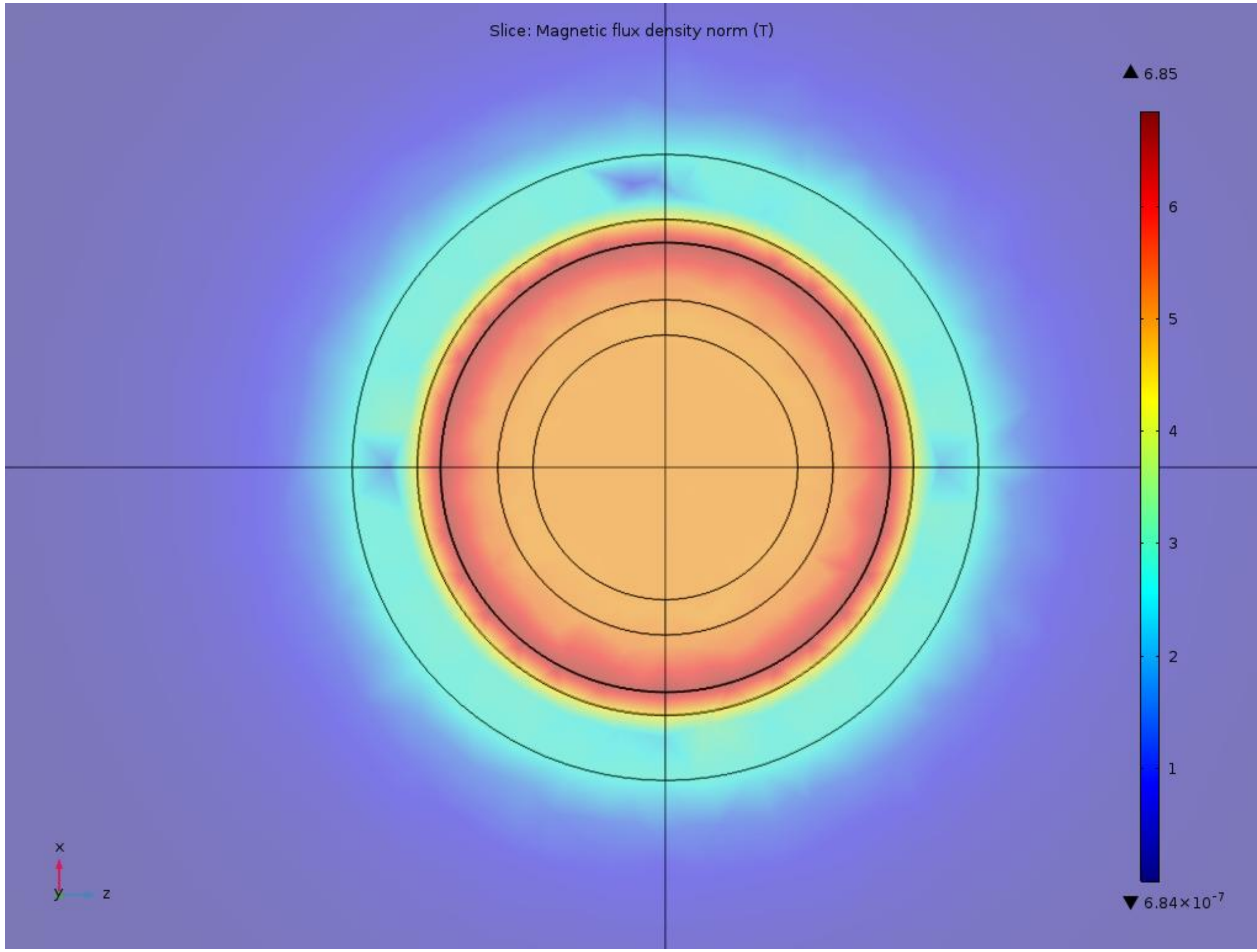


Z = [-3.75 cm;3.75 cm] , Y = 0 cm

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

Magnetic Field in the Magnet



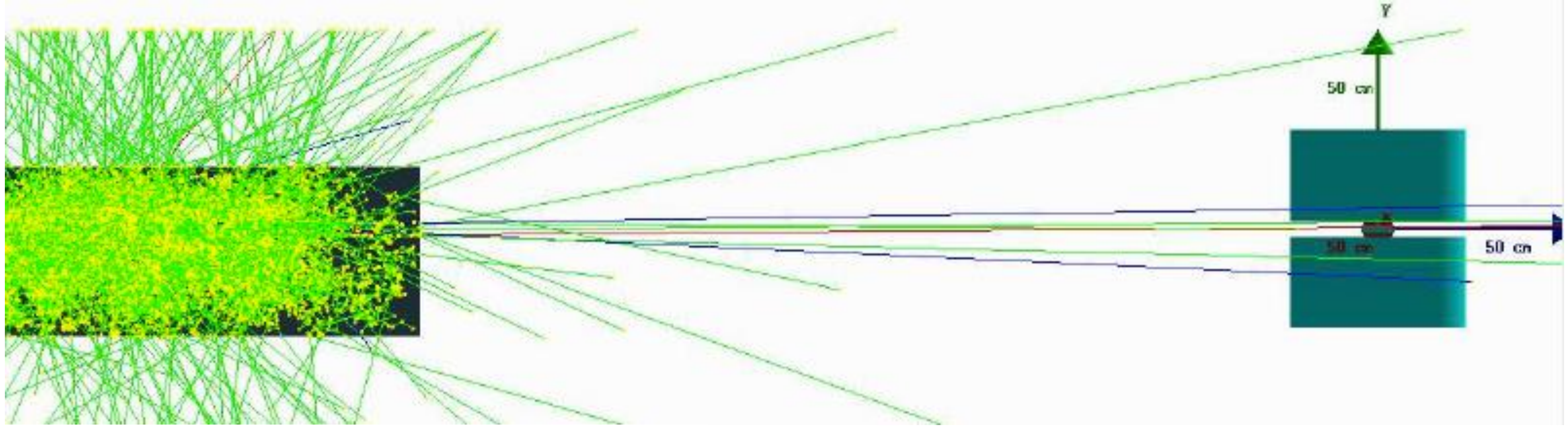


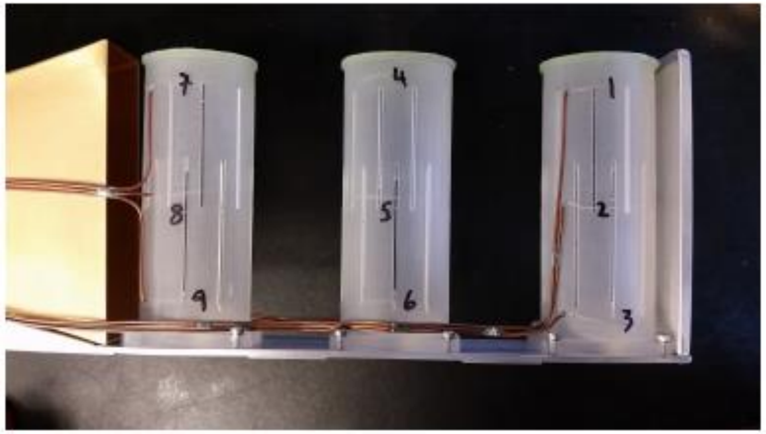
The magnetic field in the magnet is azimuthally symmetric (as expected) with the maximum field of 6.85 T at the inner surface of the coils. The Quench limit of the NbTi Superconductor for the B=6.85 T is ~ 6.35 K

Physics Processes

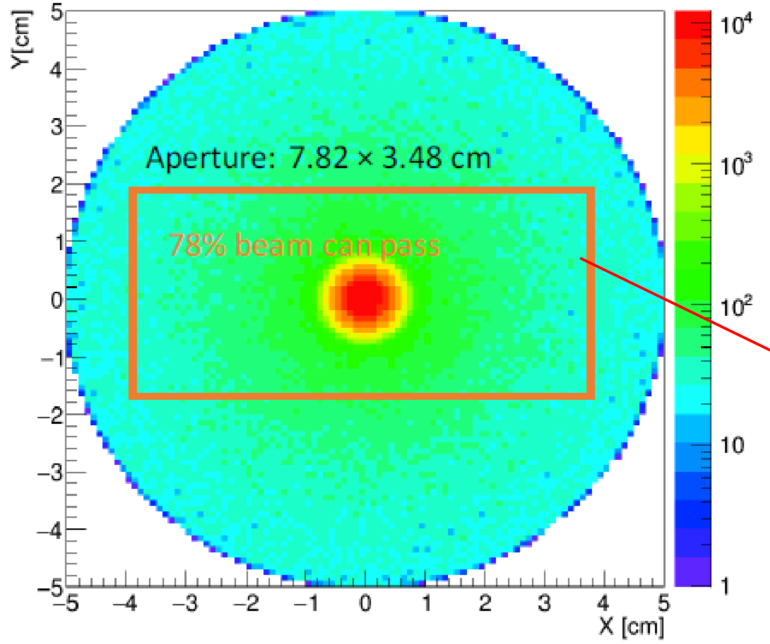
- Heat Load
- Cooling processes
- Approximation Strategy

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



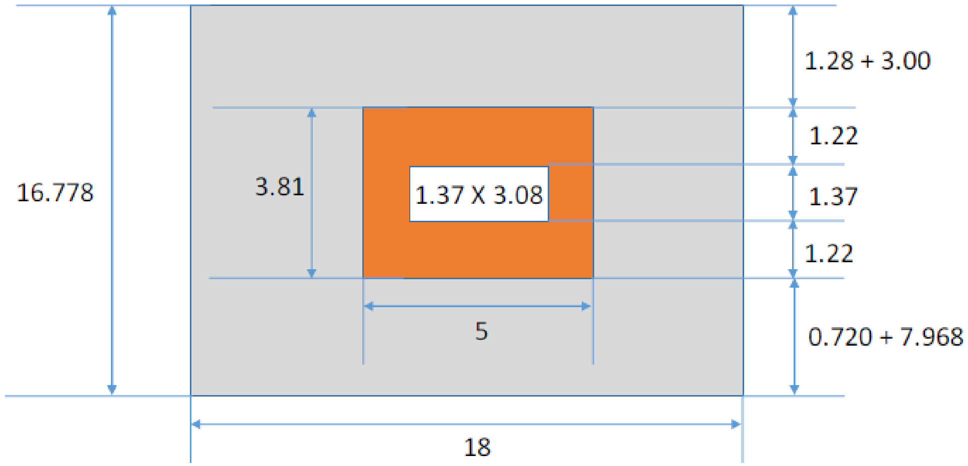


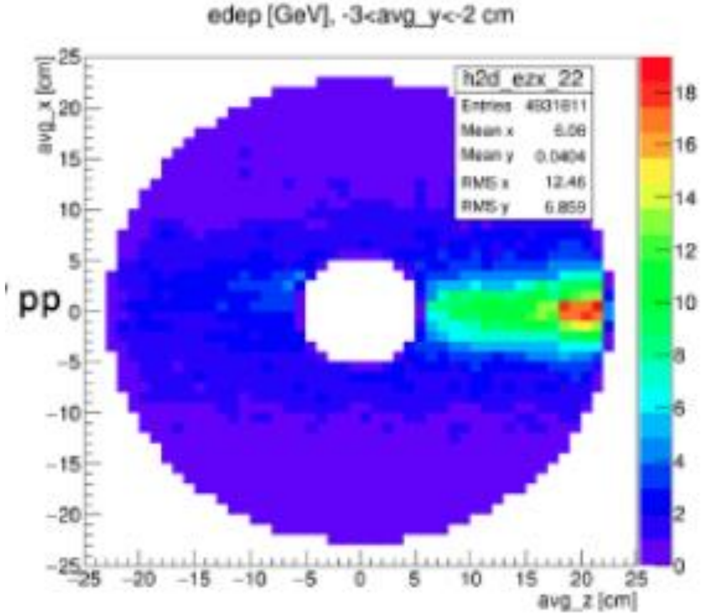
8 cm long target cells of solid NH_3/ND_3

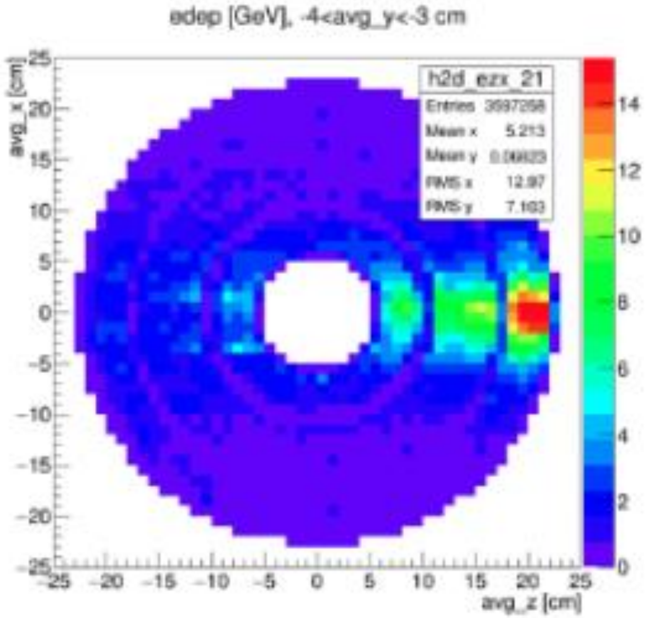


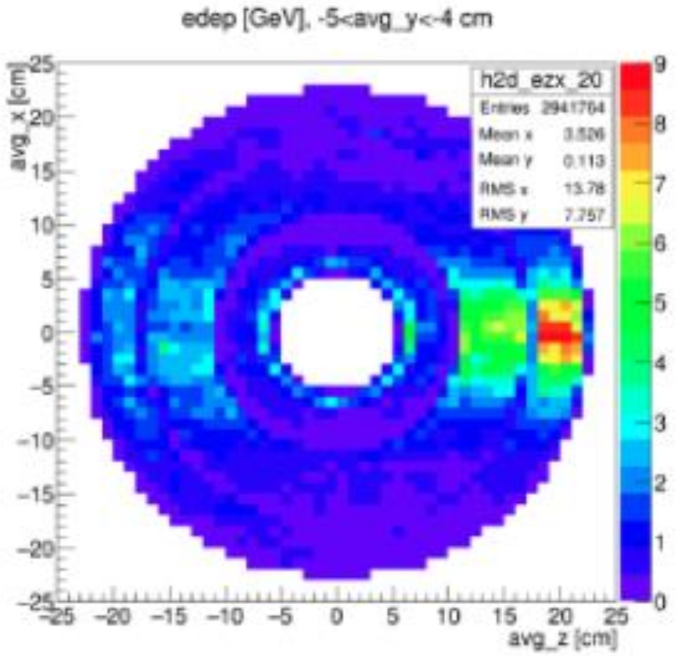
Beam profile: Gaussian + Tail

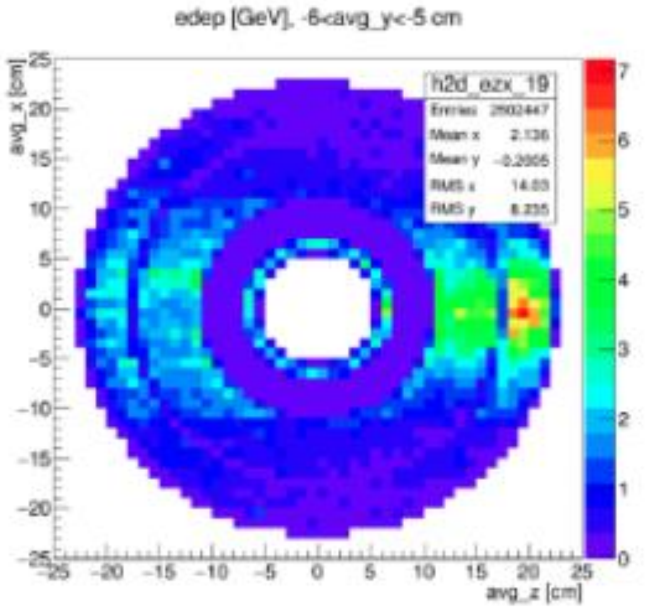
Collimator









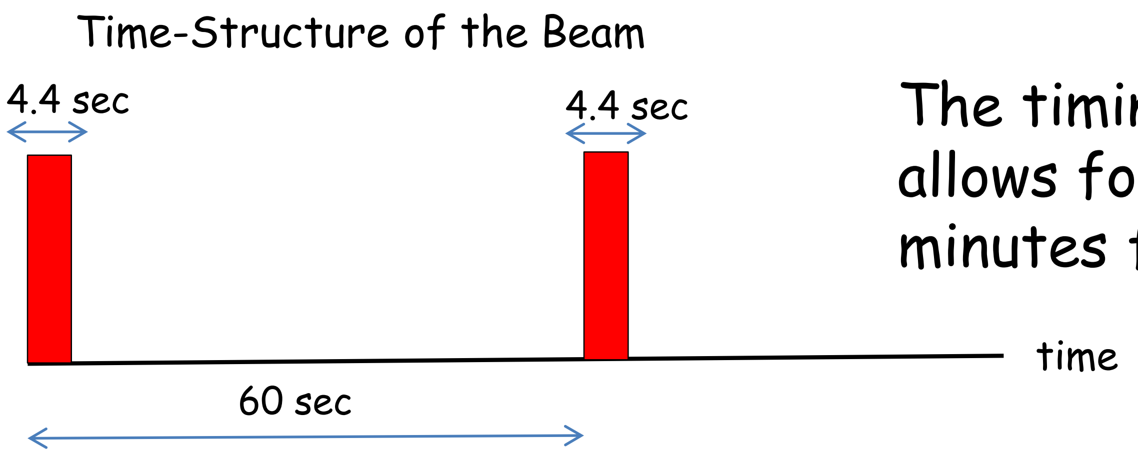


The heat load in the magnet are obtained from the Geant-Based MC simulations

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

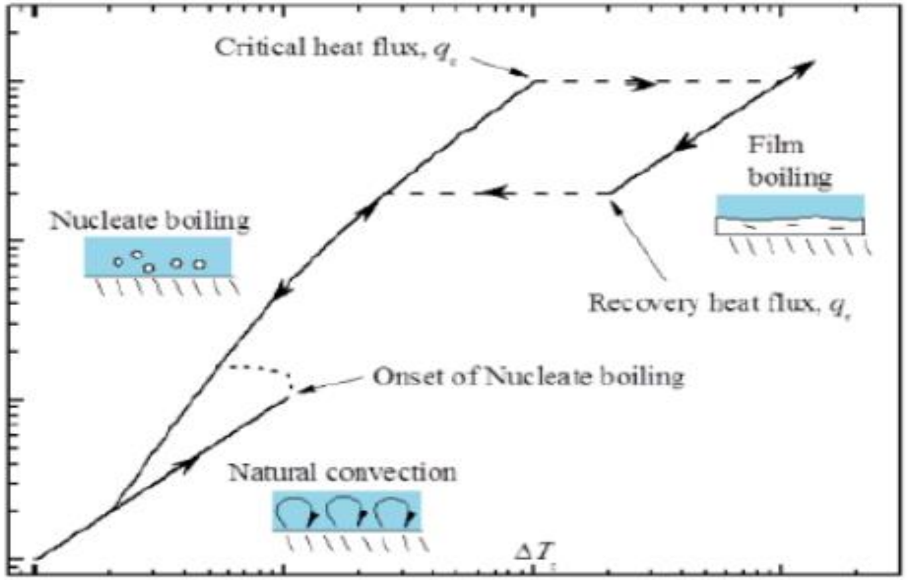
The hot spot in the upstream magnet comes from the beam-collimator interactions

Cooling Processes



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

LHe-Cooling processes diagram



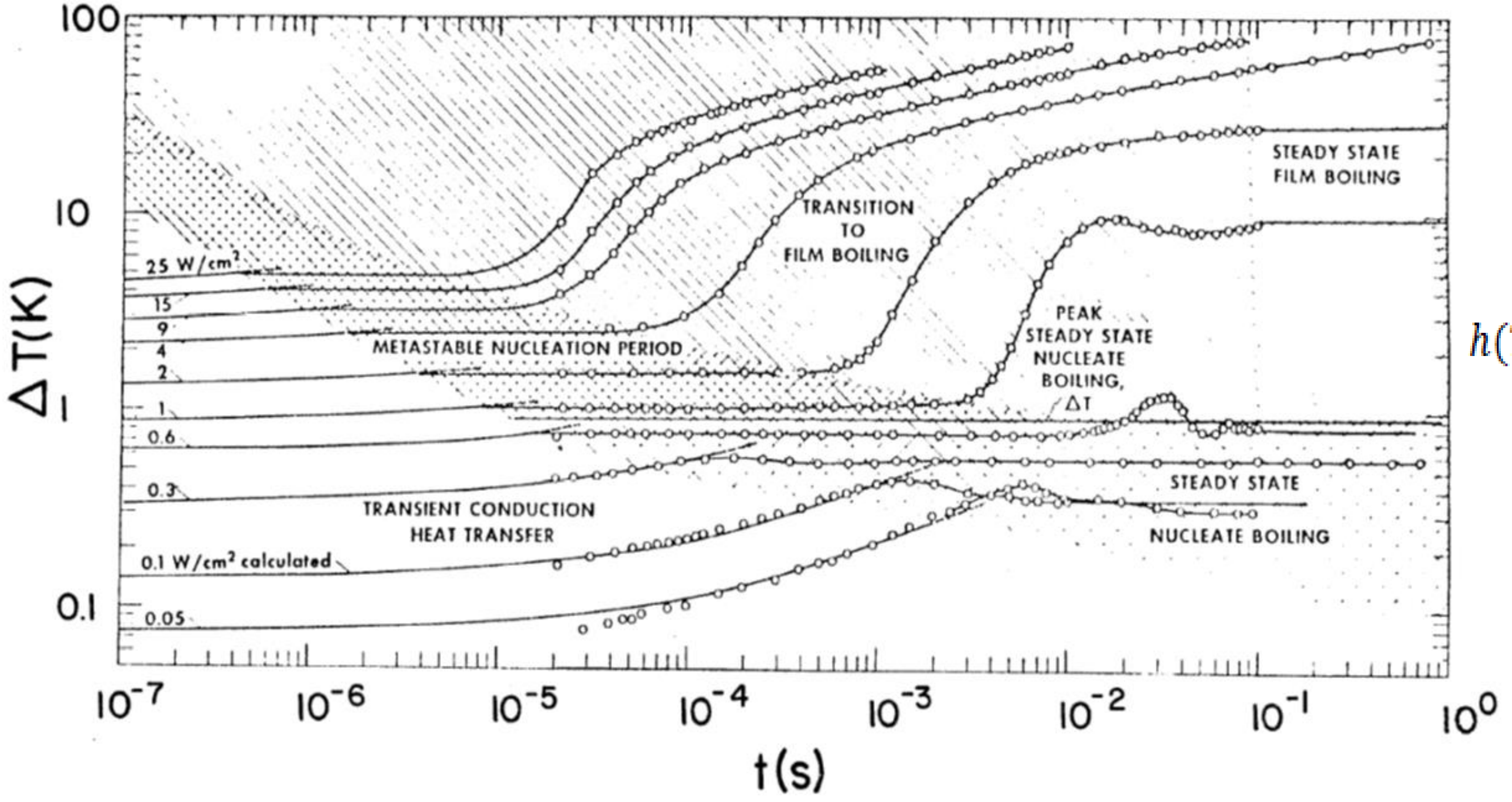
ΔT
The boiling regimes for a flat horizontal surface

Various cooling processes through LHe:

- Natural convection
- Nucleate boiling
- Film boiling

Approximation Strategy

Steady state is reached after ~ 0.1 s



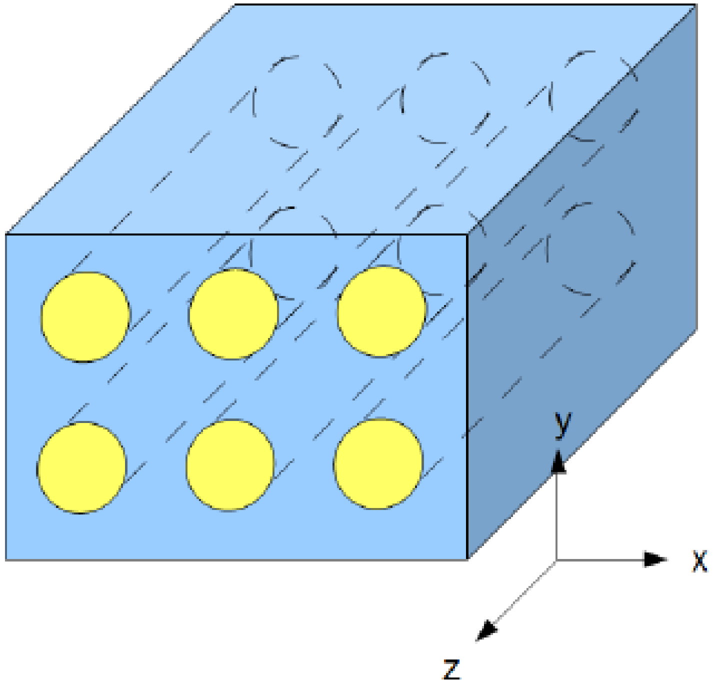
Various regimes of the heat transfer from solid to LHe

<u>First</u>, 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

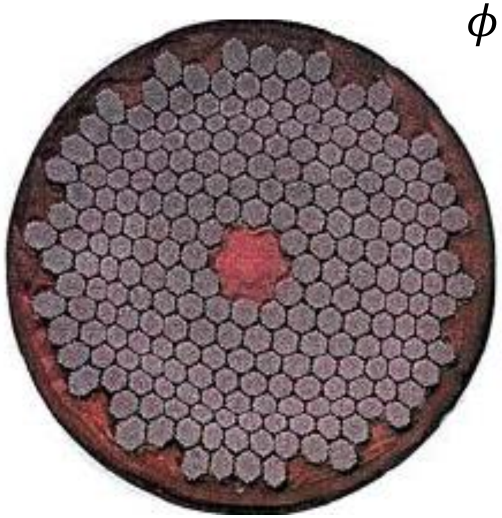


Rayleigh's model consist of parallel cylinders embedded in a continuous matrix

Rayleigh's formula for thermal conductivity

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

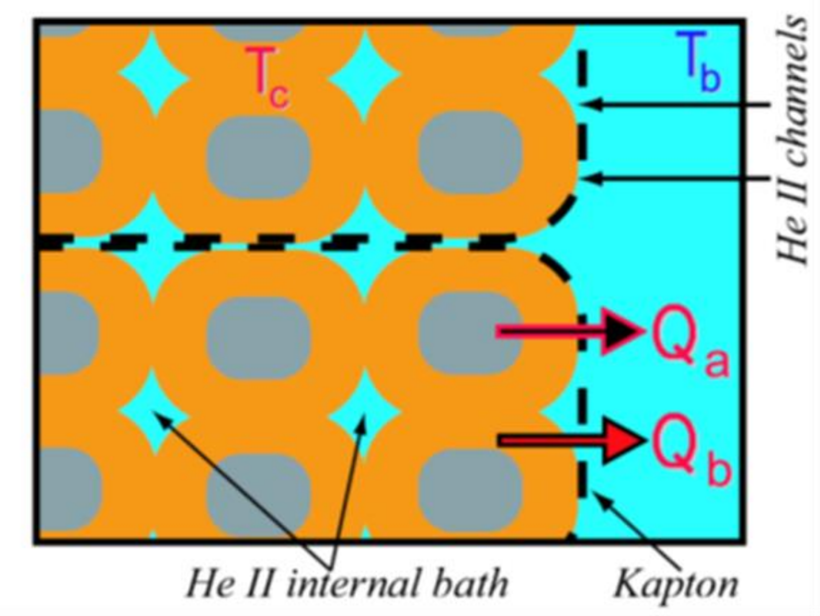
ϕ = Filling factor

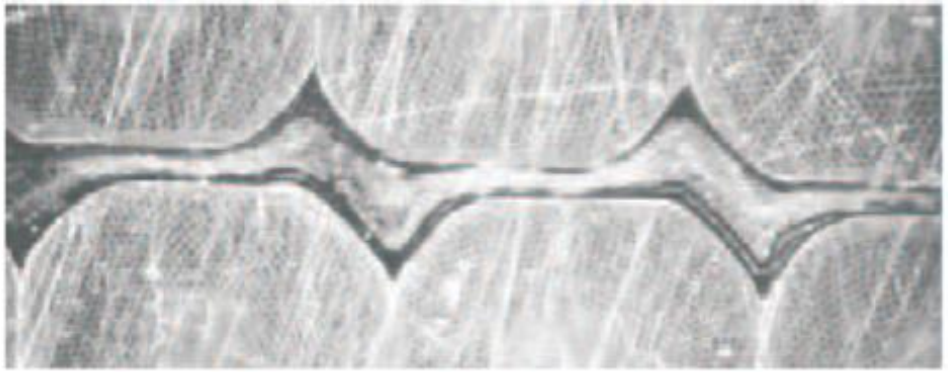


Approximation Strategy

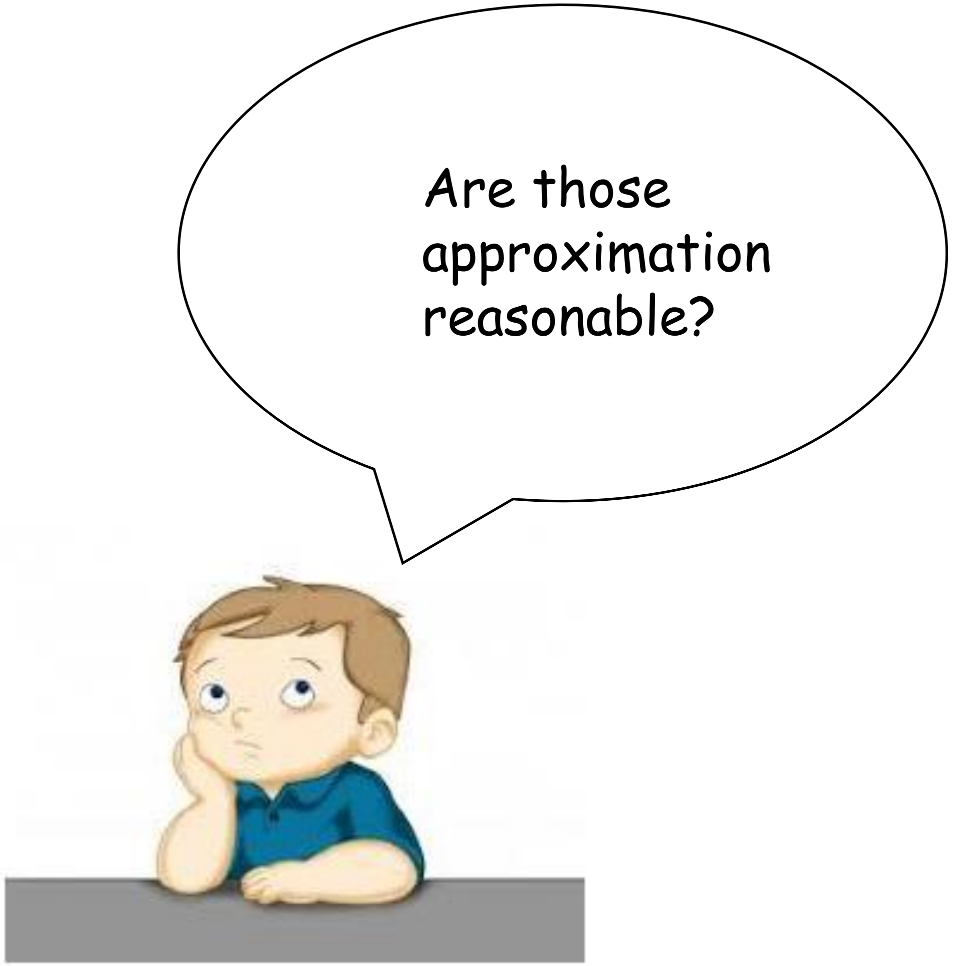
Third, we parameterize some of the unknown properties by the effective surfaces that are in direct contact with the LHe:

- Parameter of the He void
- Insulation
- Former





Microscopic view of the cable



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)

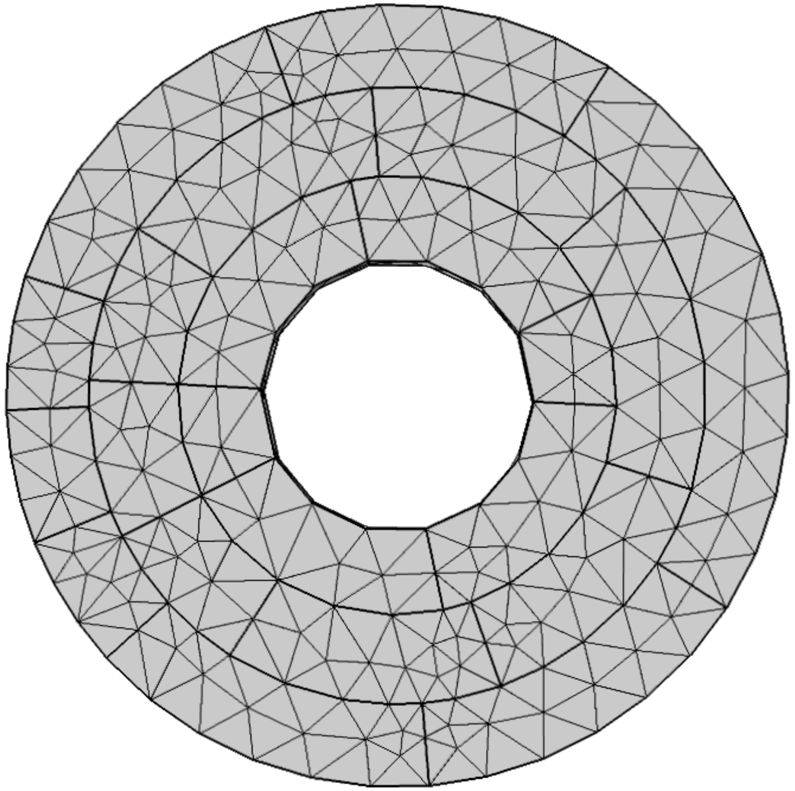
Some systems that require to be operated in the superfluid He phase have temperature margin less than 1K (even mK)

Simulation Method

Finite element analysis using COMSOL Multiphysics

<u>Input:</u>

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



<u>Proses:</u> Discretized element for the Finite Element calculation

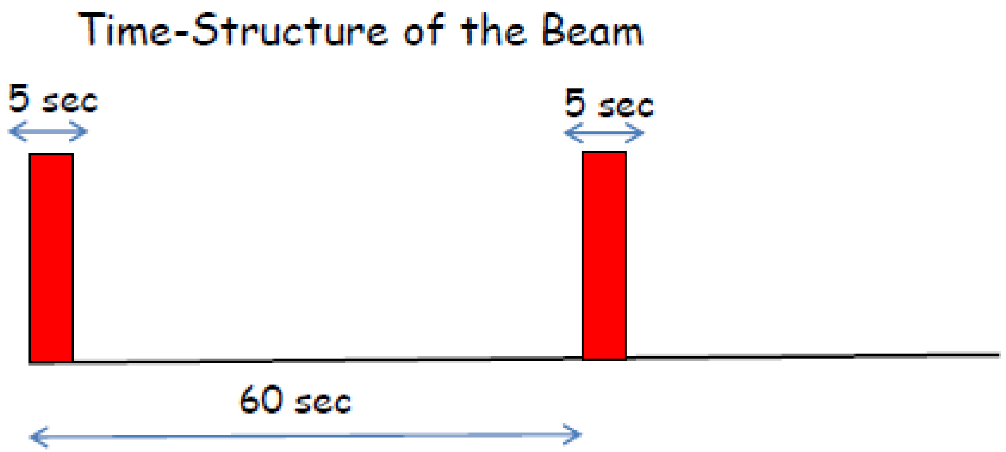
Results

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

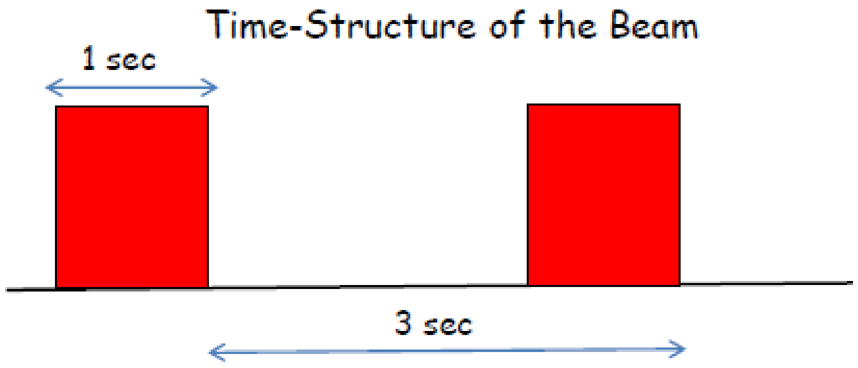
Result

SpinQuest VS BNL

SpinQuest



BNL



SpinQuest beam profile

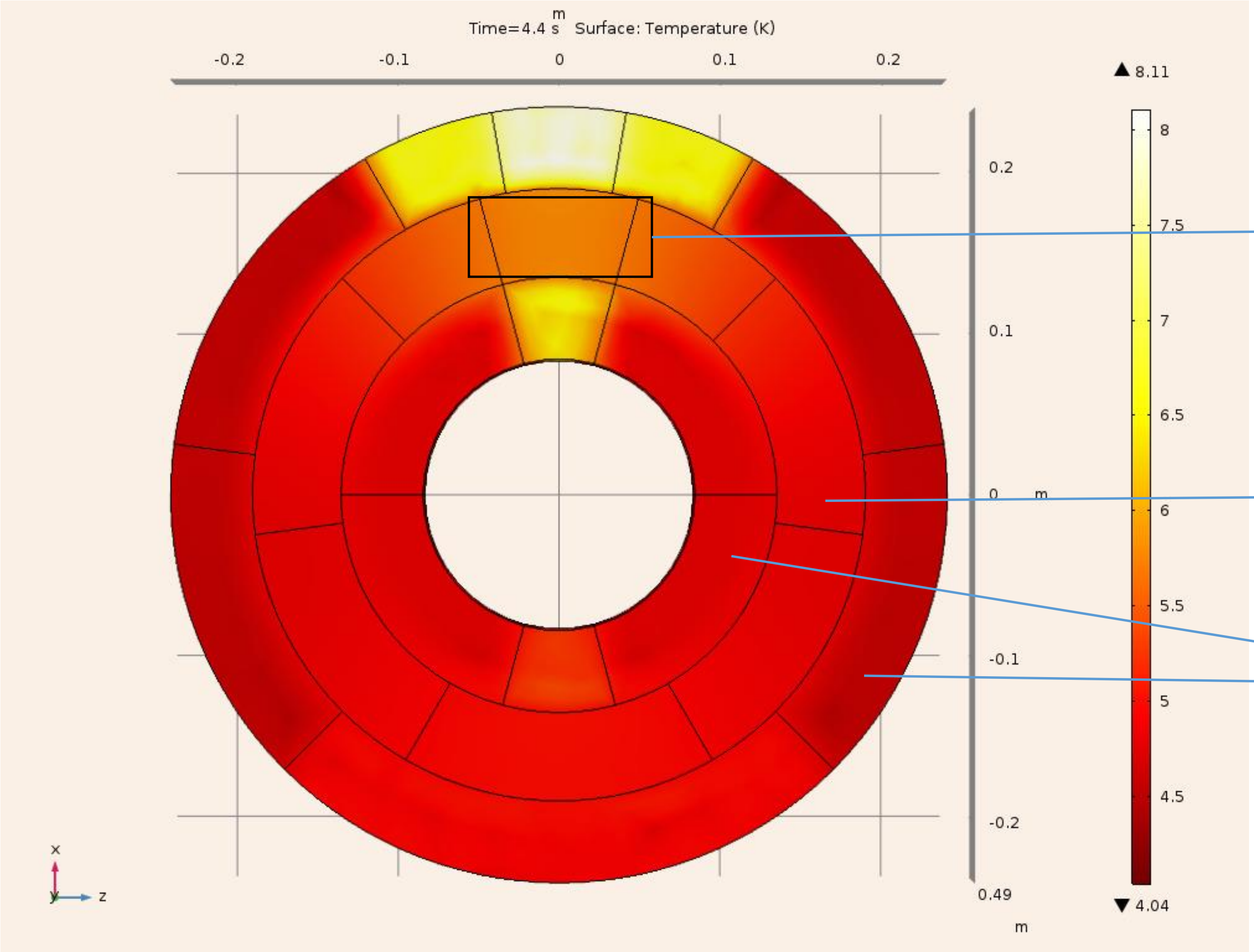
Energy	120 GeV
Cycle Time	60 s
Spill Length	4.4 s
Beam Intensity	1e12

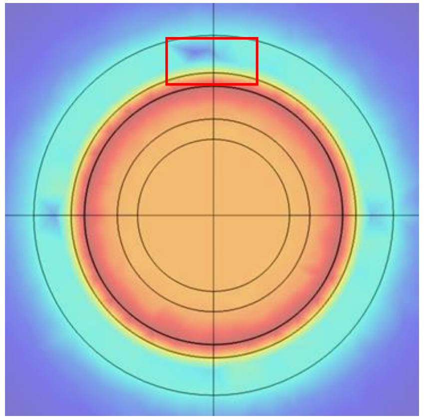
BNL beam profile

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





B-Profile of the magnet. The quench limit for the Bmax is 6.35 T

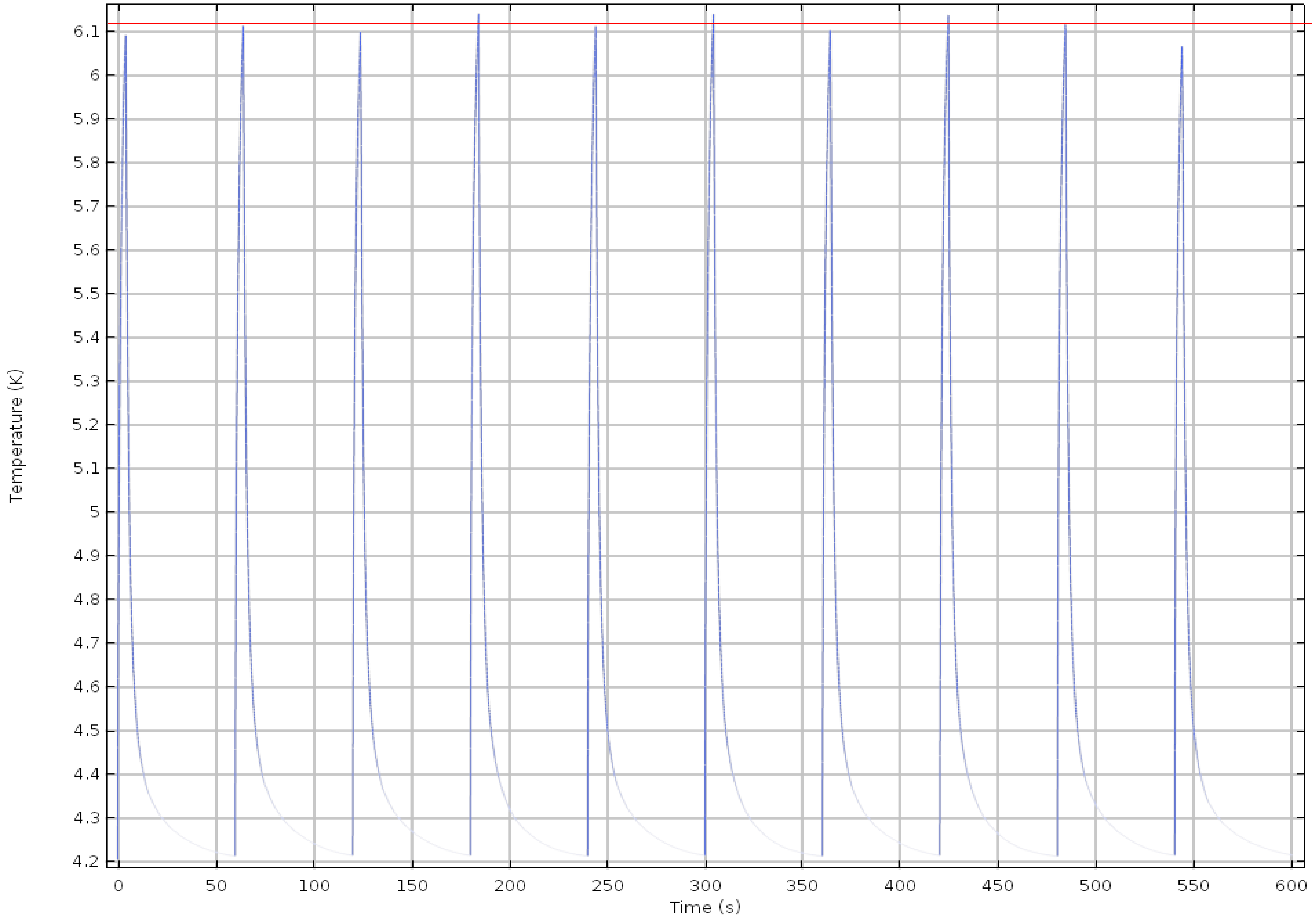
The hot spot spread uniformly due to the thermal conductivity of the copper matrix

Magnet coil

Stainless-steel former

Results: SpinQuest

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



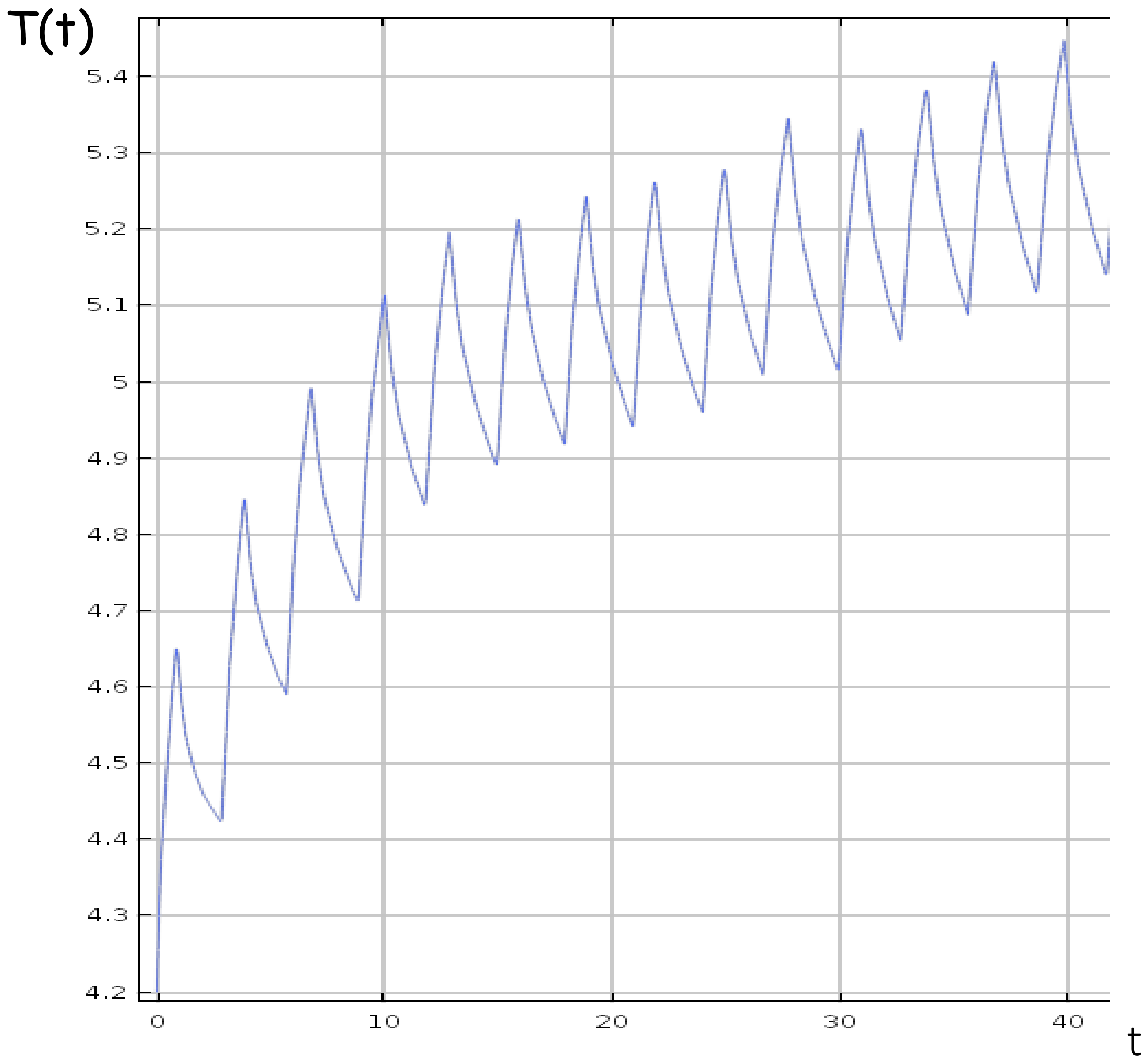
Maximum Temperature profile Tmax(t) for E1039:

- 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 Tmax(t) for BNL:

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

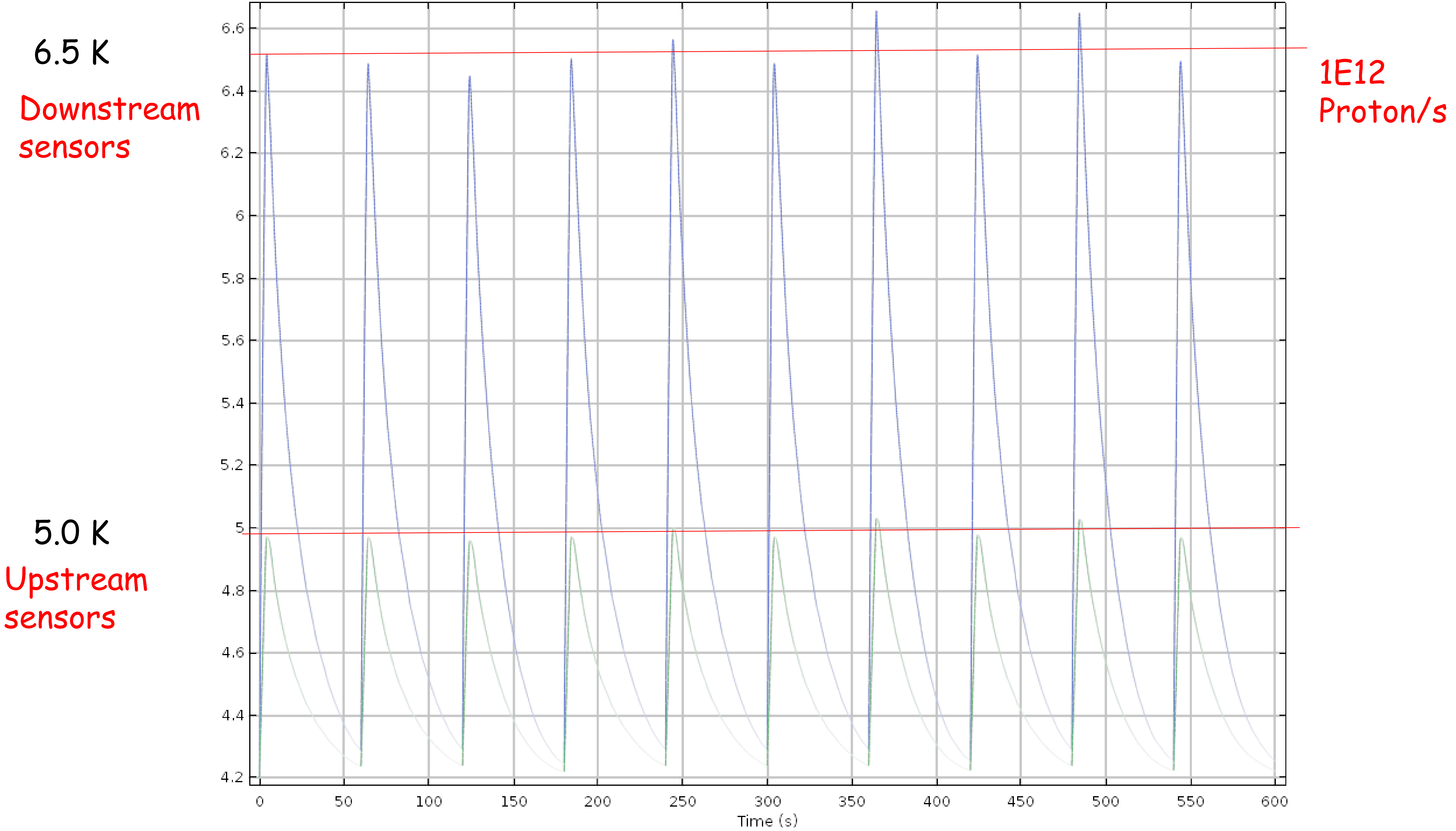
Notes:

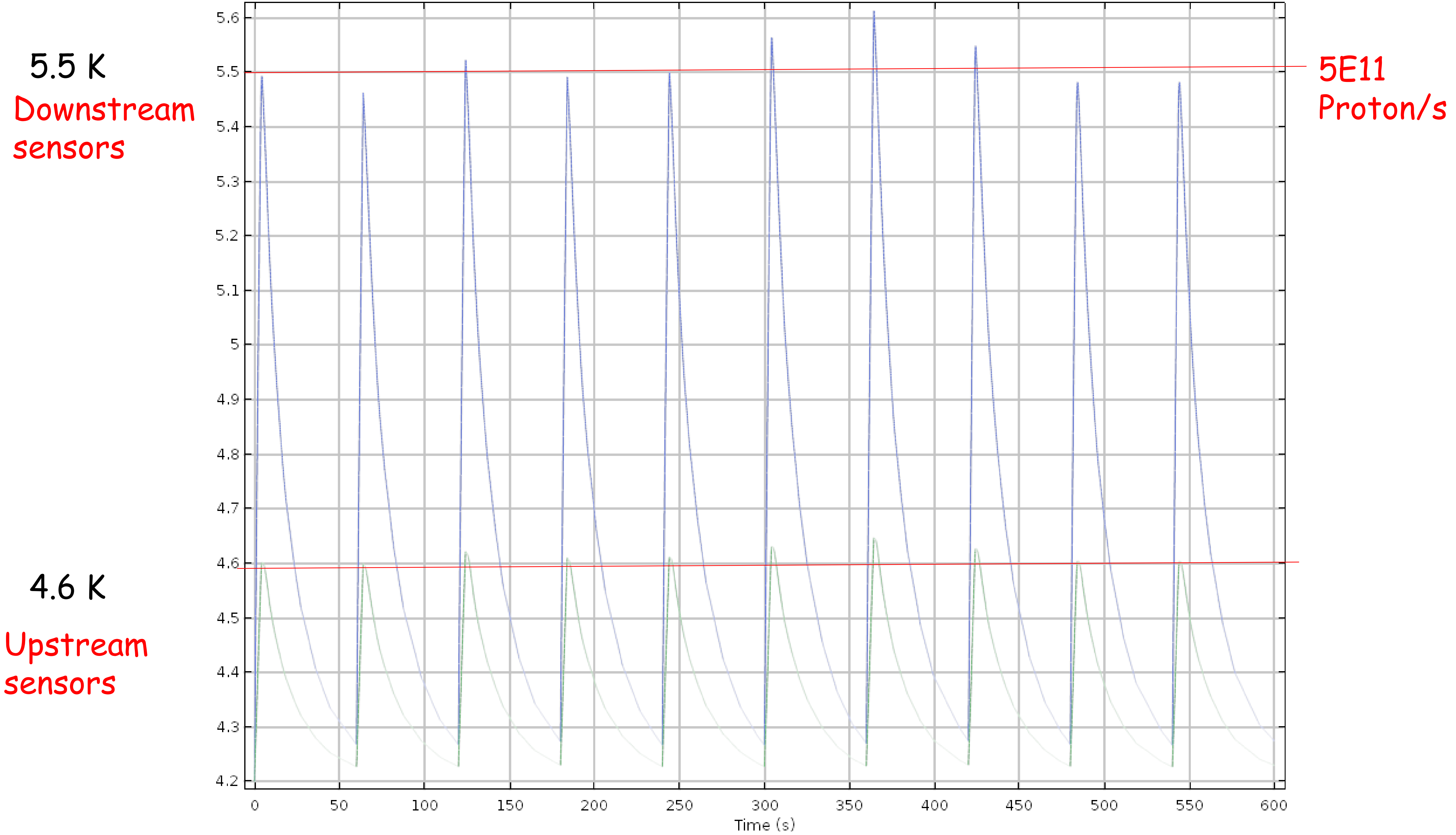
- The BNL magnet was quenched in this setup (Teflon target & 2e11 proton/s)
- The simulation results "indicate" quench -> The heat is accumulated over time

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
5.0 K
Upstream sensors
1E12 Proton/s
6.6
6.4
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)



5.5 K
Downstream sensors
4.6 K
Upstream sensors
5E11 Proton/s
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
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200
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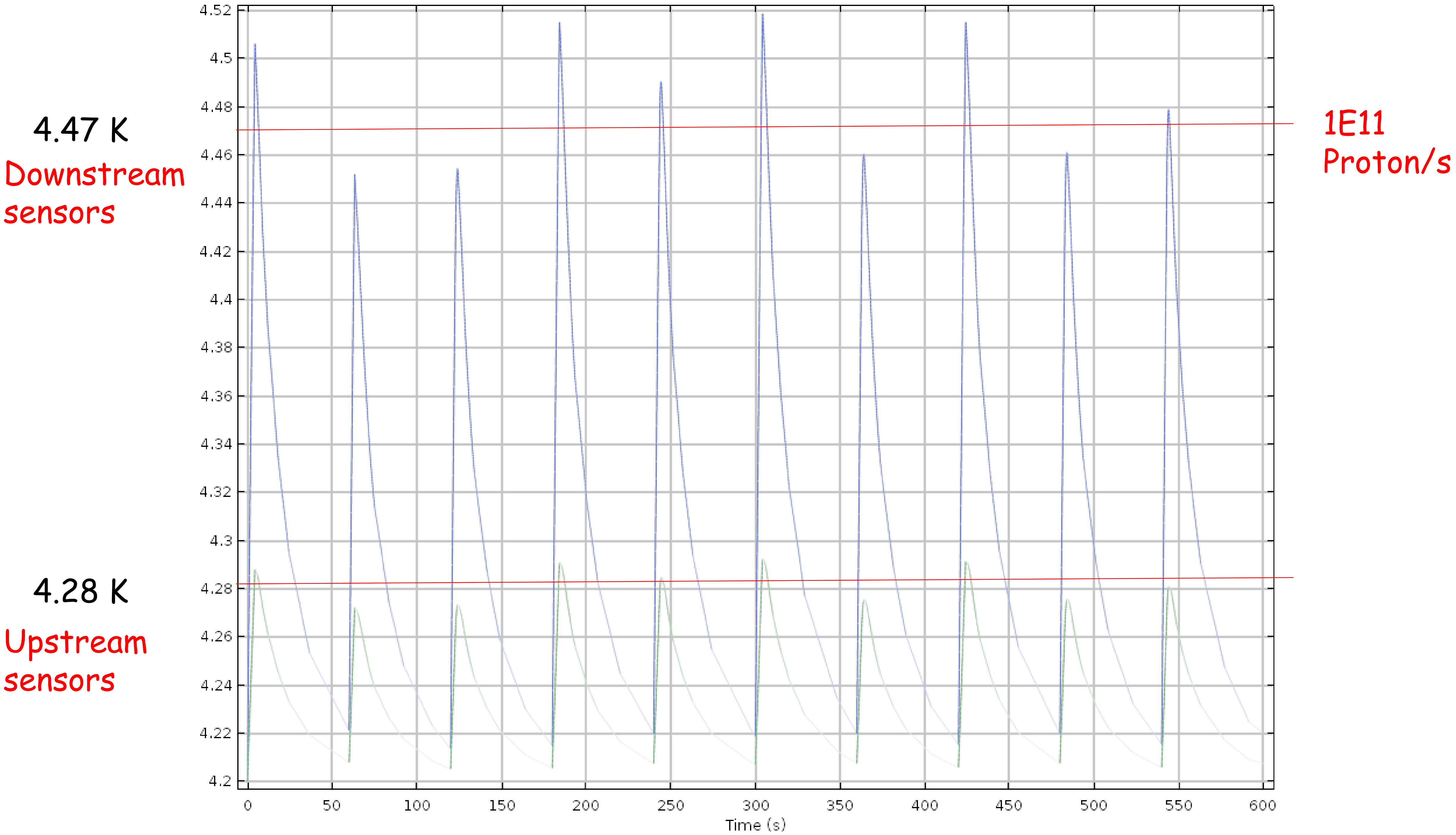
400
450
500
550
600
Time (s)



4.47 K
Downstream sensors
4.28 K
Upstream sensors
1E11 Proton/s
4.52
4.5
4.48
4.46
4.44
4.42
4.4
4.38
4.36
4.34
4.32
4.3
4.28
4.26
4.24
4.22
4.2
0
50
100
150
200
250
300
350
400
450
500
550
600
Time (s)

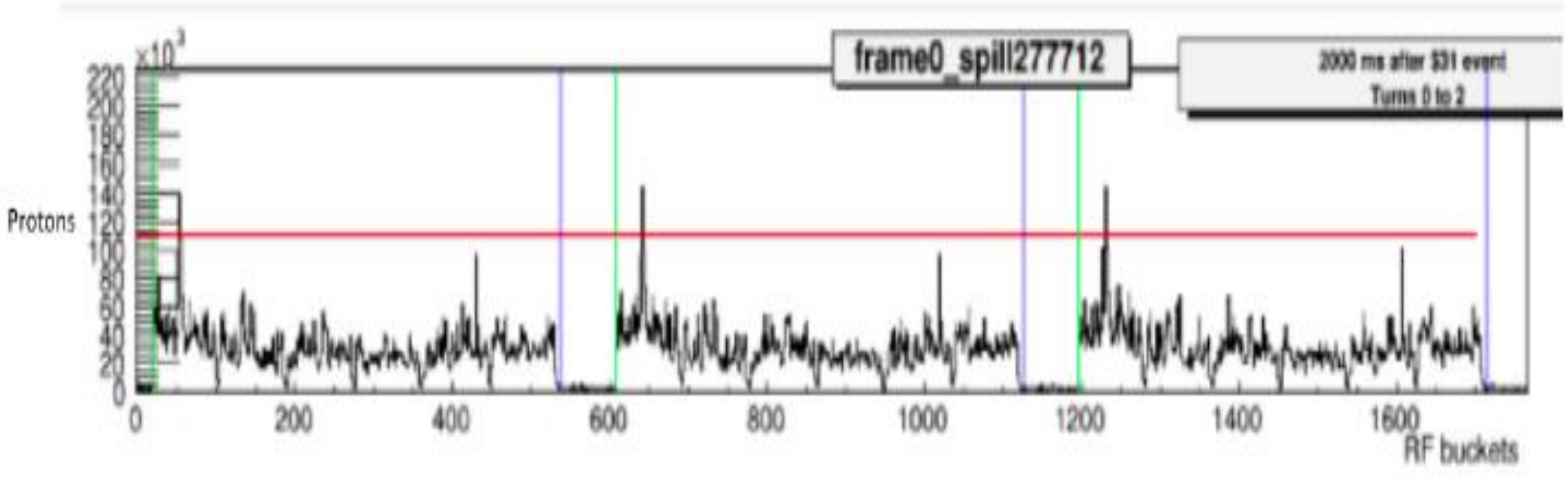
Thank You

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

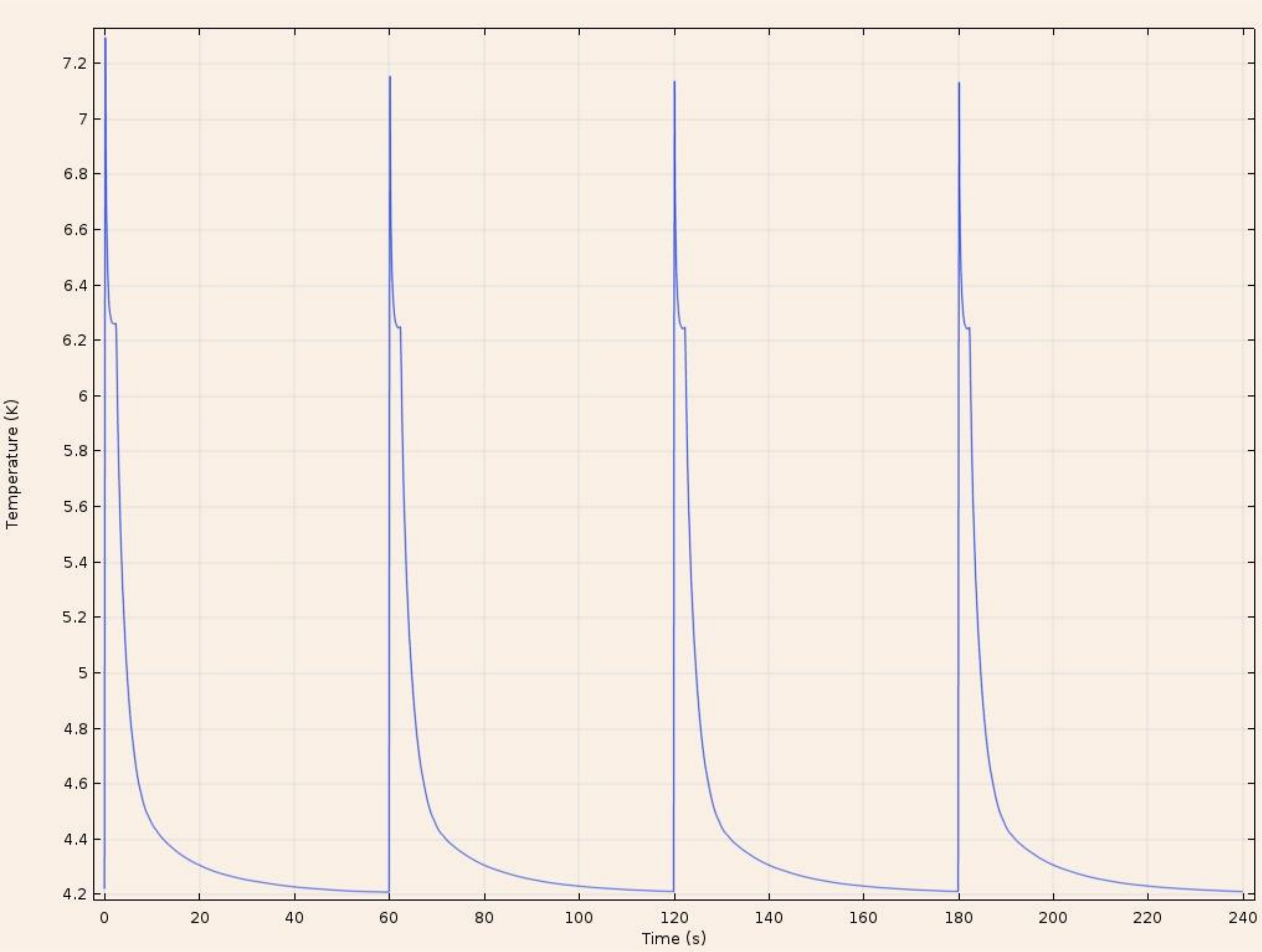
$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + \boxed{\dot{q} = \rho c_p \frac{\partial T}{\partial t}}$$

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

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

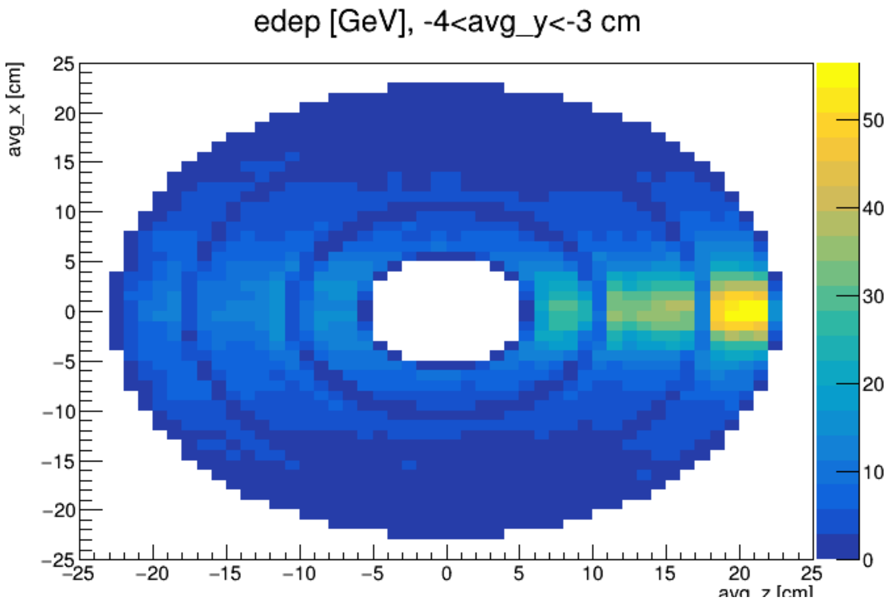
“Jump” intensity	Duration of the jump	Tmax Comsol (K)	Tmax Calculation (K)	Delta T
10 times	0.2	7.3	10.2	2.87
10 times	0.15	7	9.05	2.05
10 times	0.125	6.7	8.44	1.74
10 times	0.1	6.3	7.78	1.48

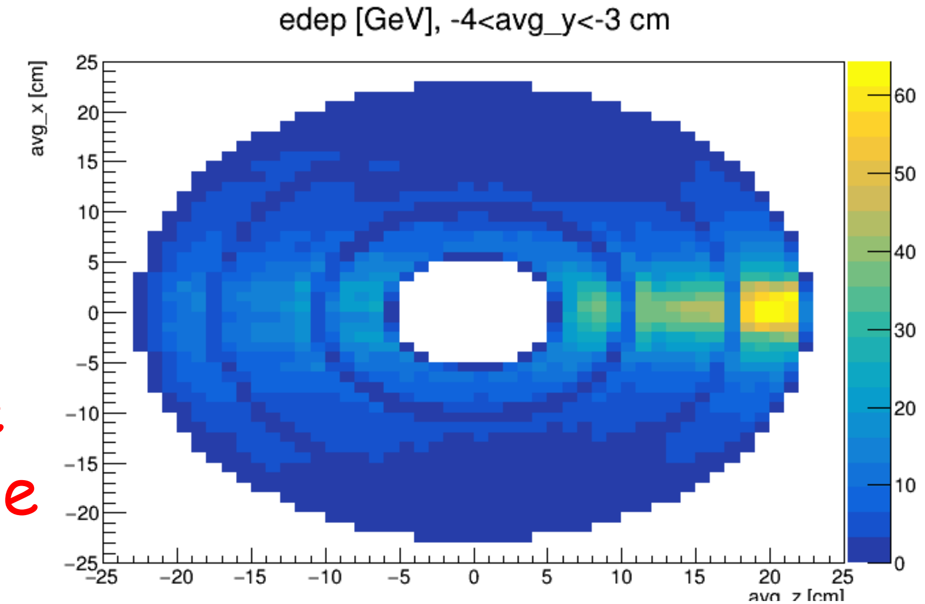
Since the Tmax calculation between simulation and calculation match as the time (duration of the jump) going smaller. We can trust the calculation. For the ns duration of the jump:

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

Perfect beam alignment

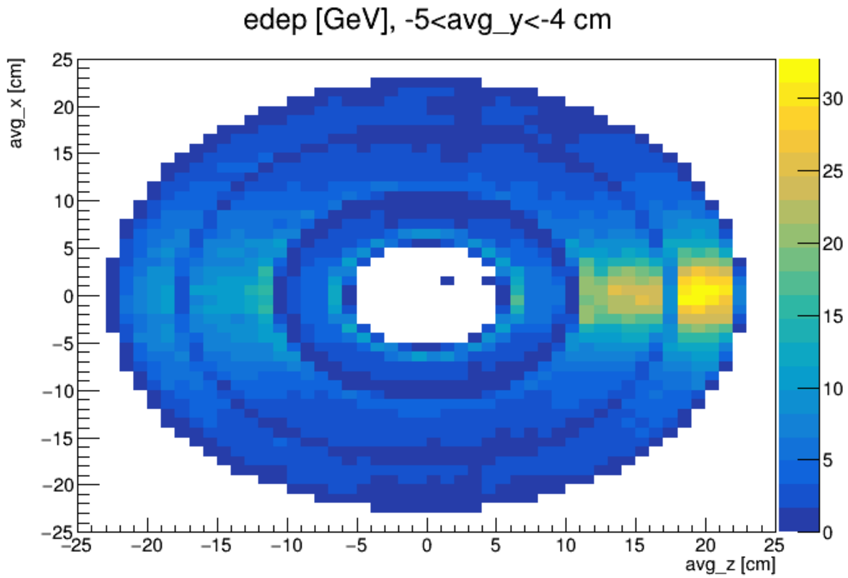
Beam drift or misalignment by 0.3 cm

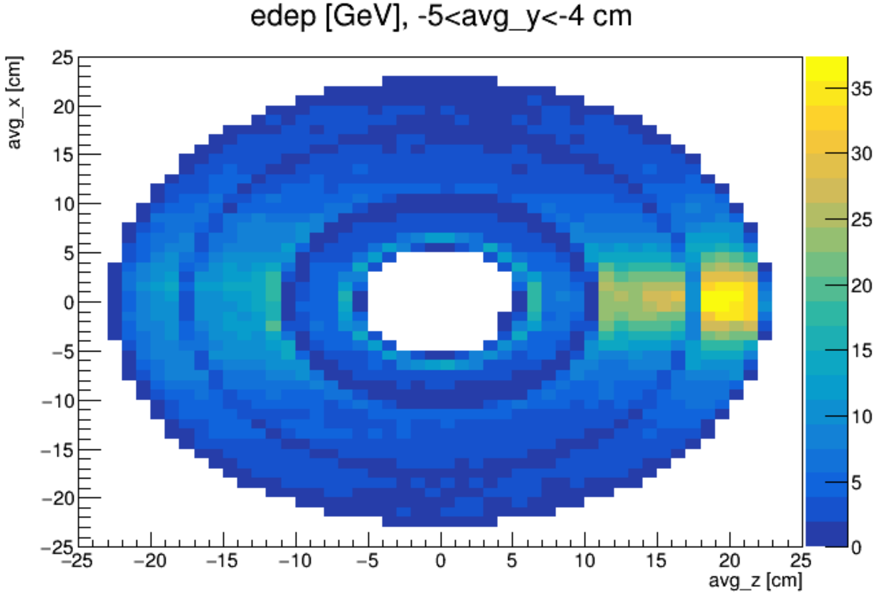




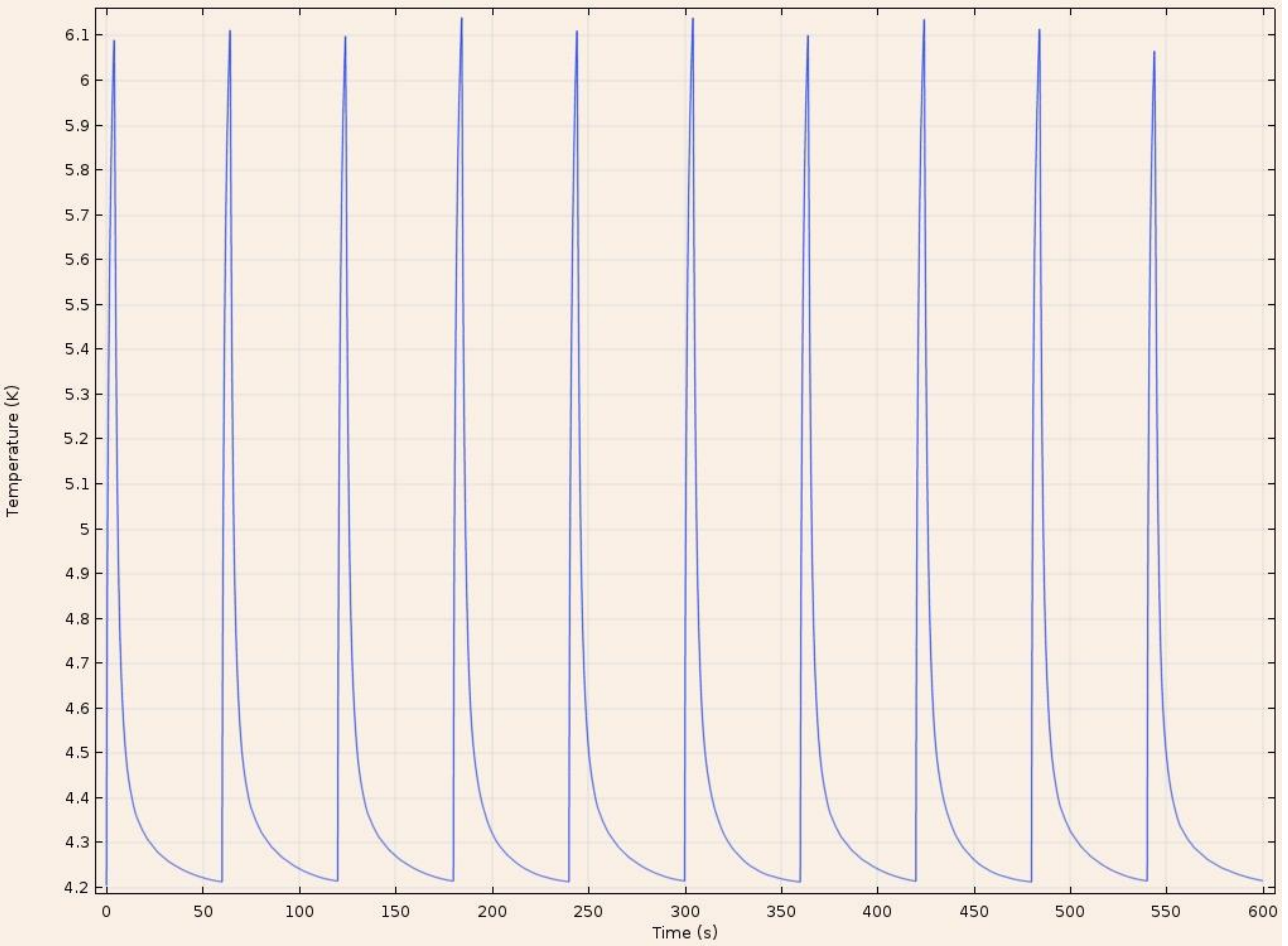
The energy deposited in the hot spot increase by ~ 15%

0.1 K of temperature increase

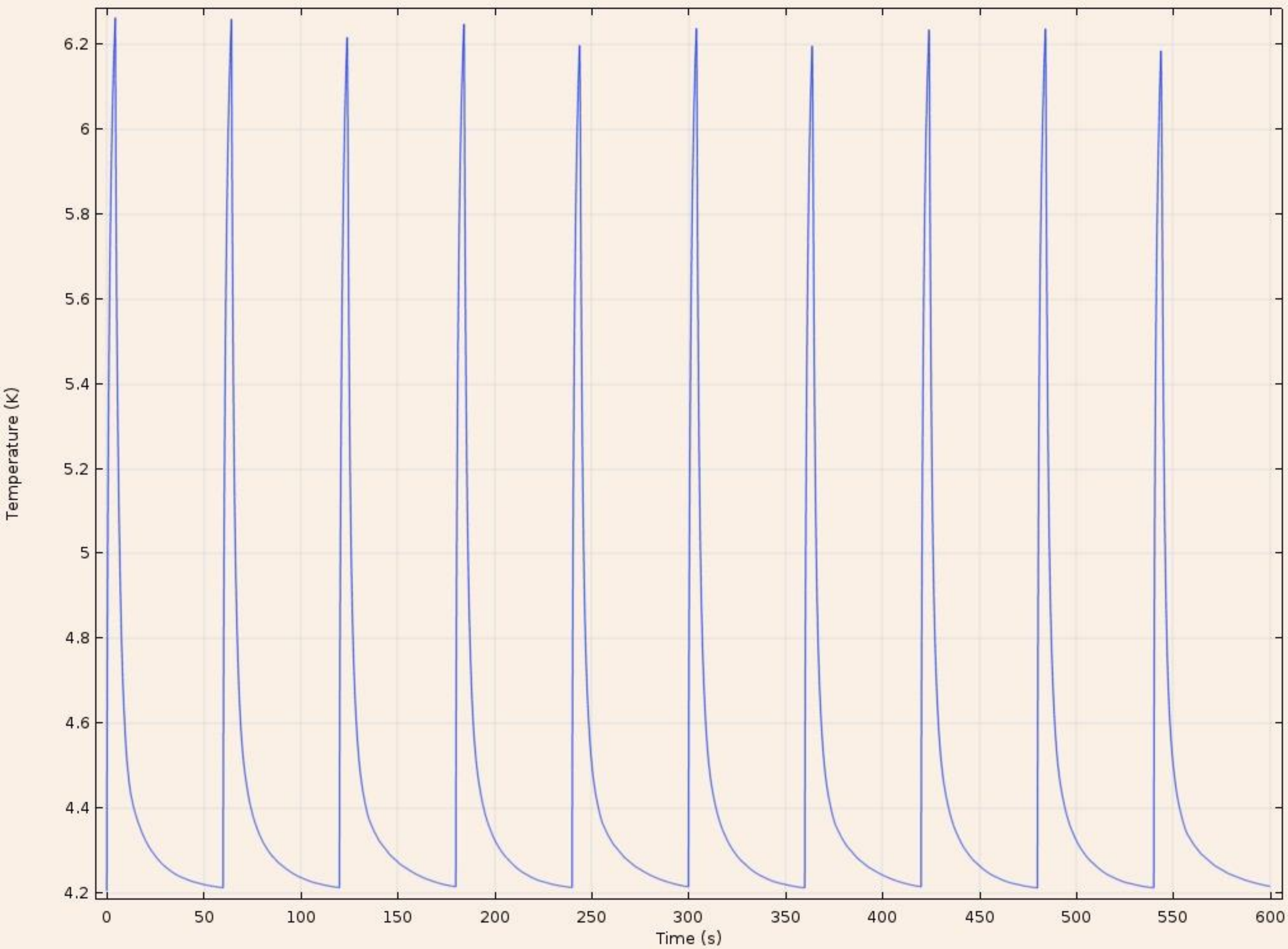




Temperature profile with a perfect alignment showing the maximum temperature of 6.1 T



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



Thank You