Thermal Analysis of the Bus Bars for the 800MeV Injection Era

Silvia Picchi, Victor Grzelak
Italian Summer School, final presentation
09/27/2023

Presentation Outline

- ☐ Introduction
- ☐ COMSOL thermal simulations for present conditions
  - Results
  - Validation
- ☐ COMSOL thermal simulations for PIP-II conditions
- ☐ Proposed changes
  - New busbars section
  - Results
- ☐ Peak temperature tables
- ☐ Conclusions

Proton Improvement Plan II

PIP-II is the plan to upgrade Fermilab's present accelerator complex:

- Building a new linear accelerator
- **Improvement of the Booster**

	Present	PIP-II
Booster injection KE	400 MeV	800 MeV
Machine frequency	15Hz	20Hz
RF frequency range	37.9-52.8 MHz	44.7-52.8 MHz
RMS bias current (tuning circuit)	1354 A	1695 A

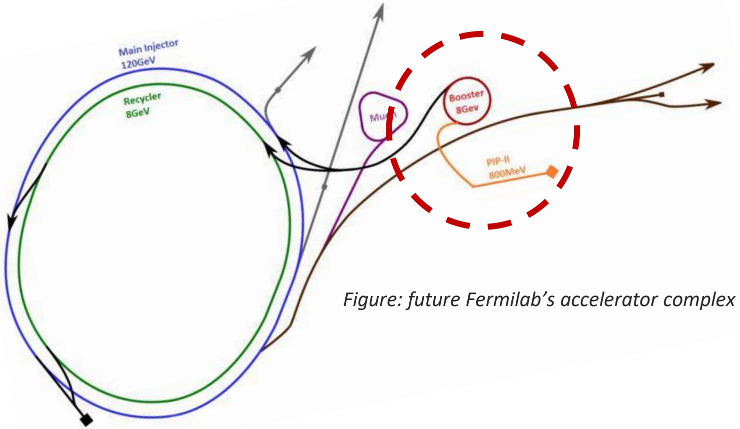
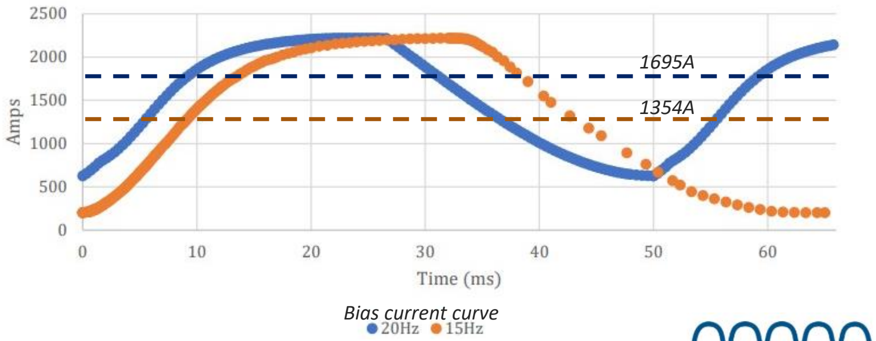


Figure: future Fermilab's accelerator complex



Bias current curve

In the previous episode…

The components of the stations heat up due to these possible reasons:

- Driver input 4 kW RF
- High voltage from anode modulator
- High current bus for cavity tuning

The goal of this work is to investigate the heating caused by the bias supply line in the new operational conditions.

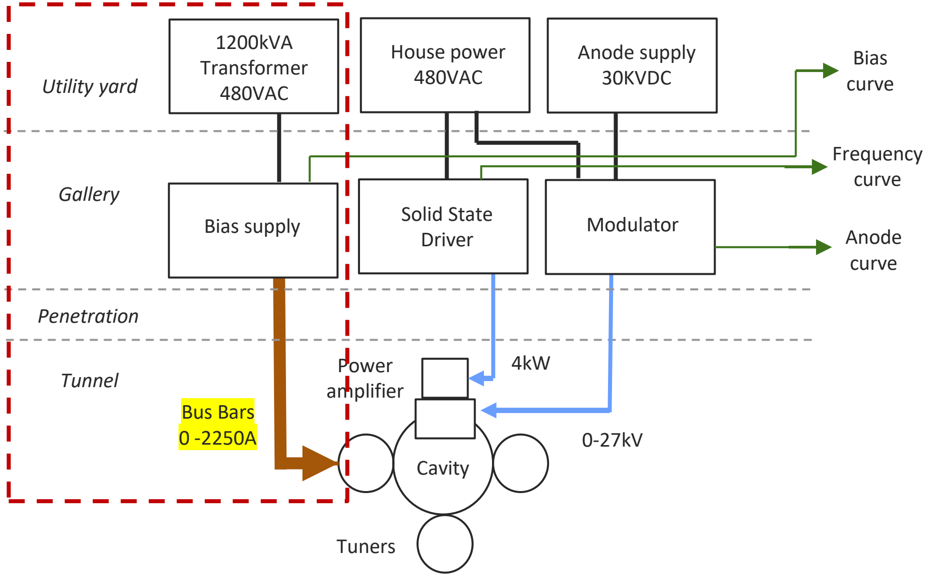
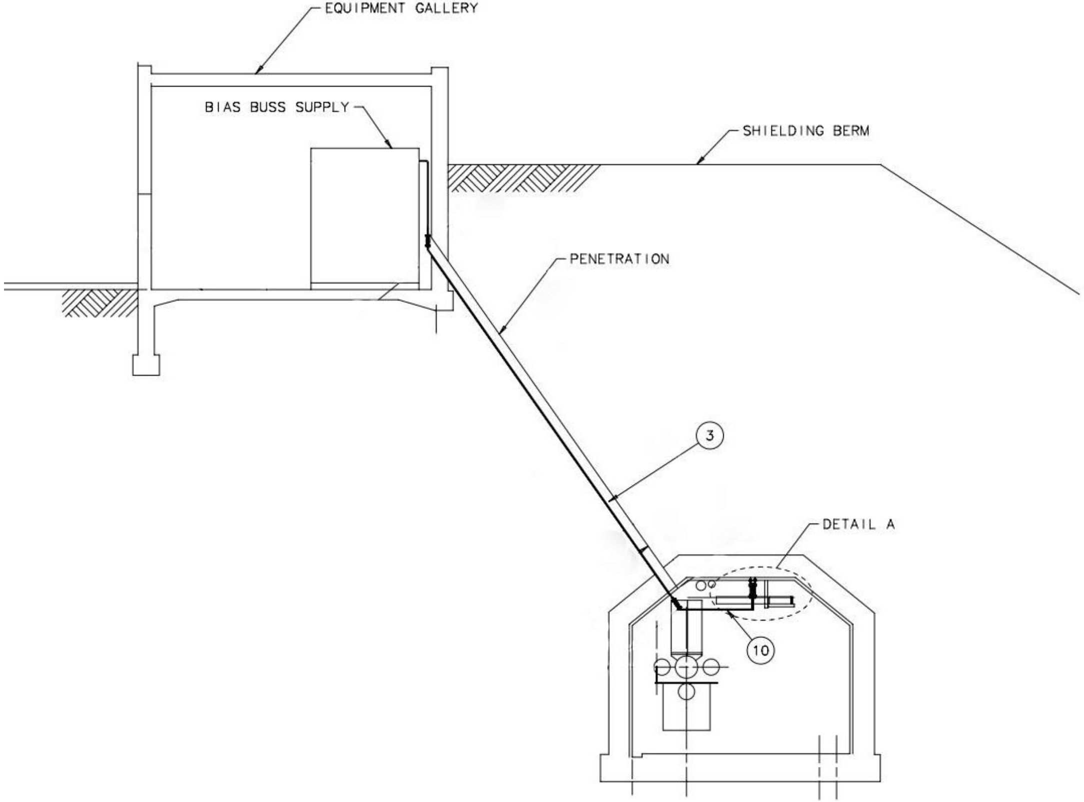


Figure: simplified system block diagram of a single station

Booster station layout

The layout of each station of the Booster is composed by:

- The gallery, where the bias supplies are placed
- The penetration, which connects the gallery and the tunnel
- The tunnel, where the RF accelerating cavities are placed.



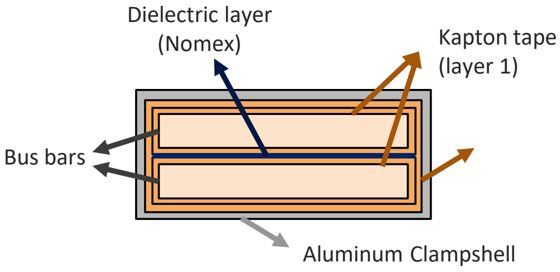
The bus bars

The devices that bring bias current to the ferrite tuners through the penetration are called **bus bars**.

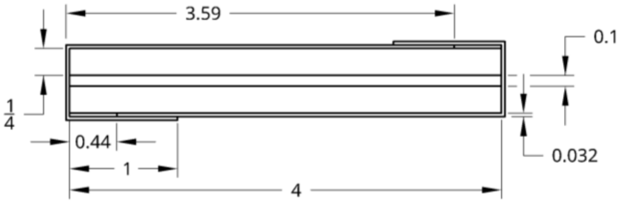
Along the penetration, a fraction on their total length is exposed to air while the other fraction is wrapped in the neutron shield (poly-ethylene). This fraction is variable for each station.

During operation, bur bars heat up due to **Joule effect**. The heat generation and the lack of appropriate cooling could cause the overheat of the neutron shield.

$$\dot{Q}_{Joule} = I^2 R$$

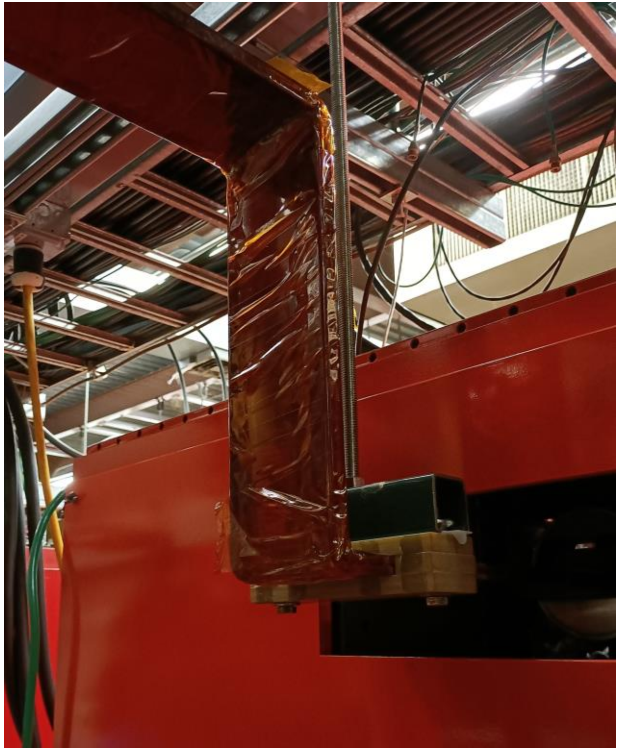


Bus bars assembly



Bus bars assembly, technical drawing (measurements in inches)

The bus bars



Bus bars behind the bias supply

Bus bars as seen from the gallery

Bus bars as seen from the tunnel

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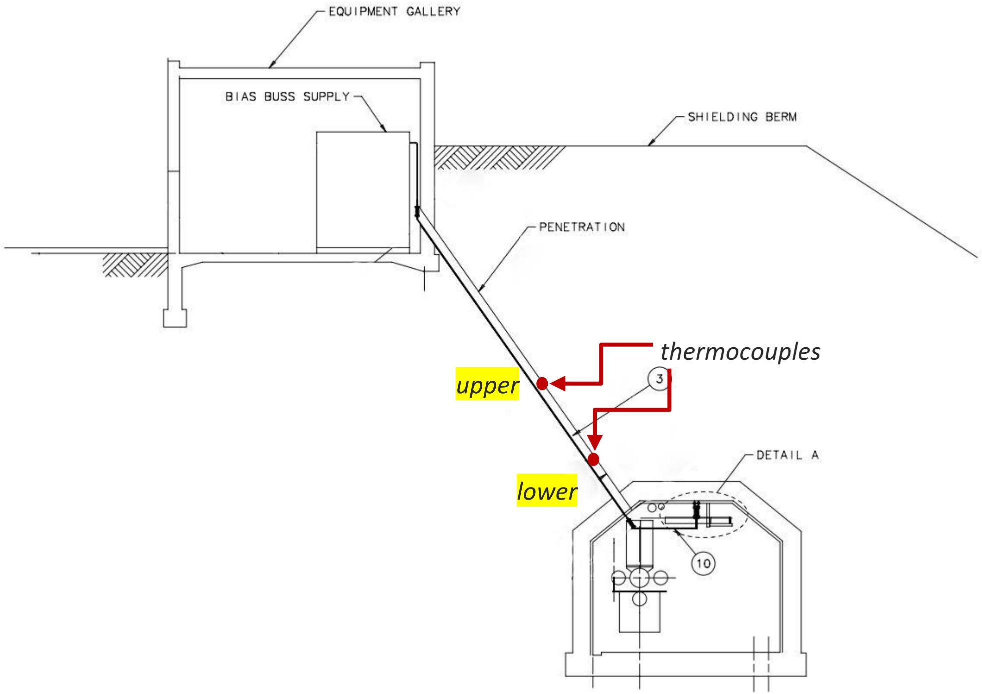
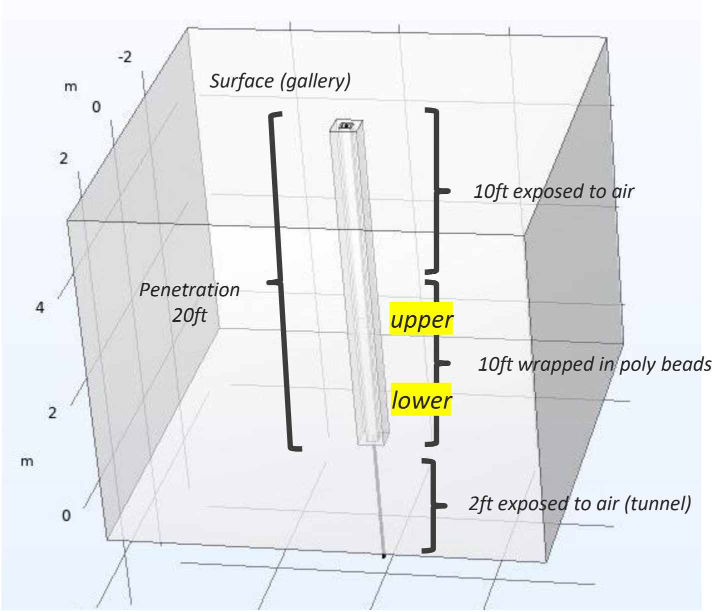
COMSOL 3D simulation – geometry



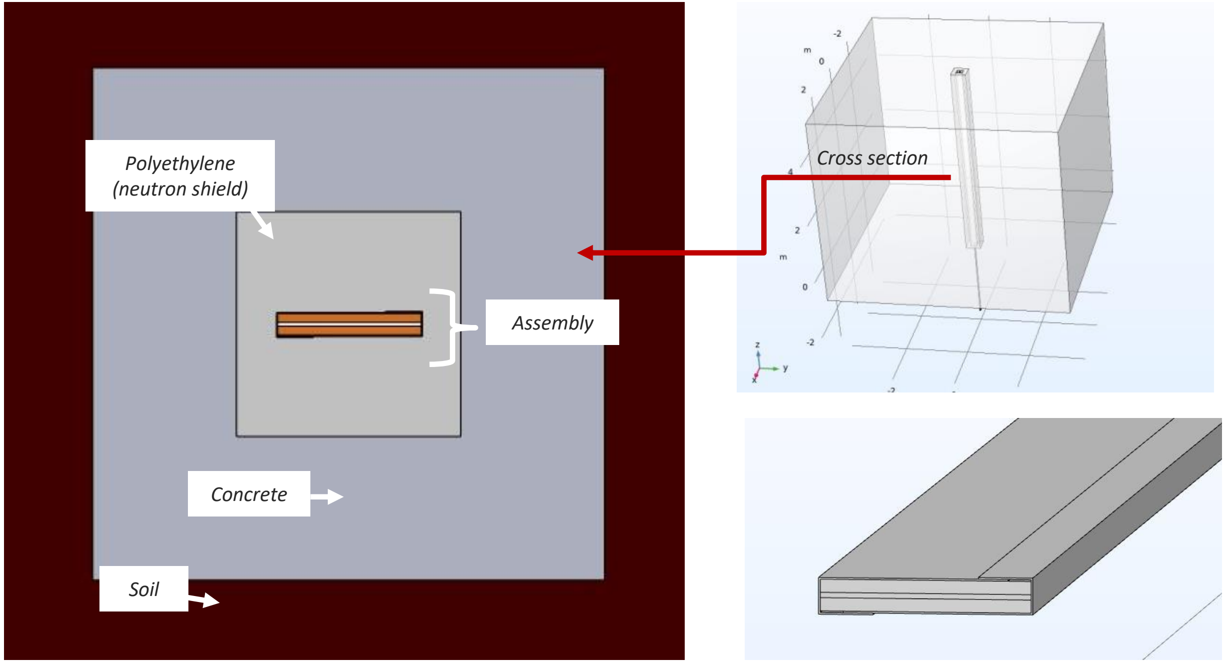
Booster station layout



Simulation geometry

COMSOL 3D simulation – boundary conditions and materials

- Electric Currents *(ec)*
  - Current Conservation 1
  - Electric Insulation 1
  - Initial Values 1
  - Terminal 1
  - Ground 1
  - Terminal 2
  - Ground 2
- Heat Transfer in Solids *(ht)*
  - Solid 1
  - Initial Values 1
  - Thermal Insulation 1
  - Surface-to-Ambient Radiation 1
  - Heat Flux busbars
  - Heat Flux (soil)
  - Heat Flux 3 (forced convection)
  - Temperature (soil)
  - Temperature (heat sink)
- Multiphysics
  - Electromagnetic Heating 1 *(emh1)*

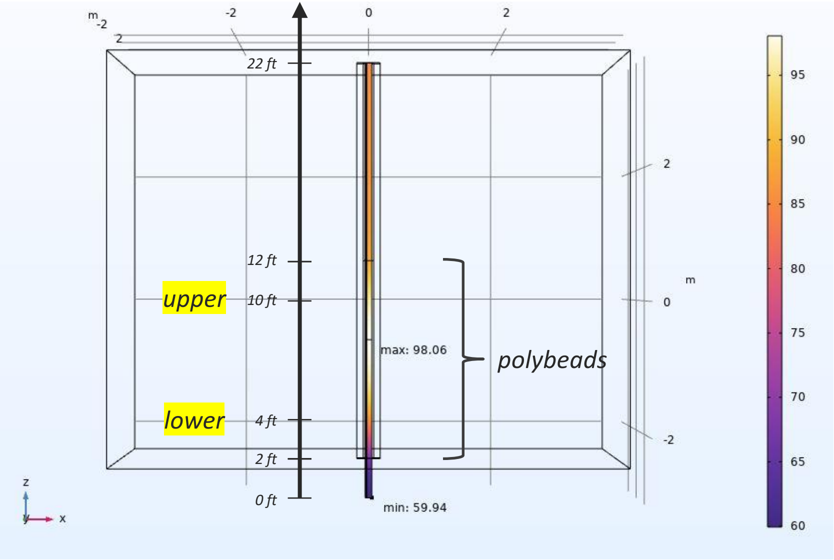


Boundary conditions

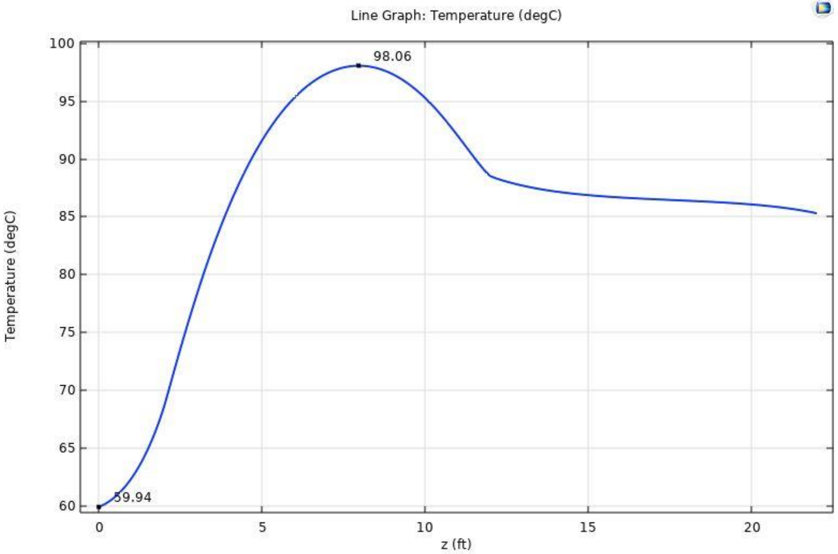
Materials

COMSOL 3D simulation – present conditions

Simulations results for 15Hz, 1354A RMS



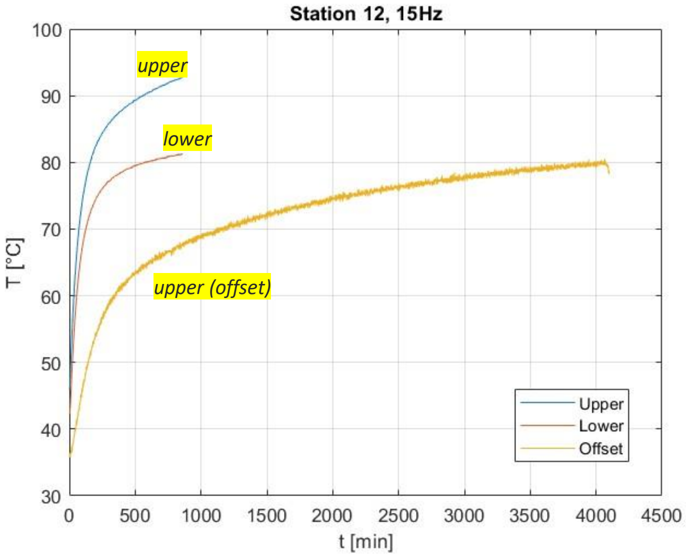
Temperature gradient of the assembly



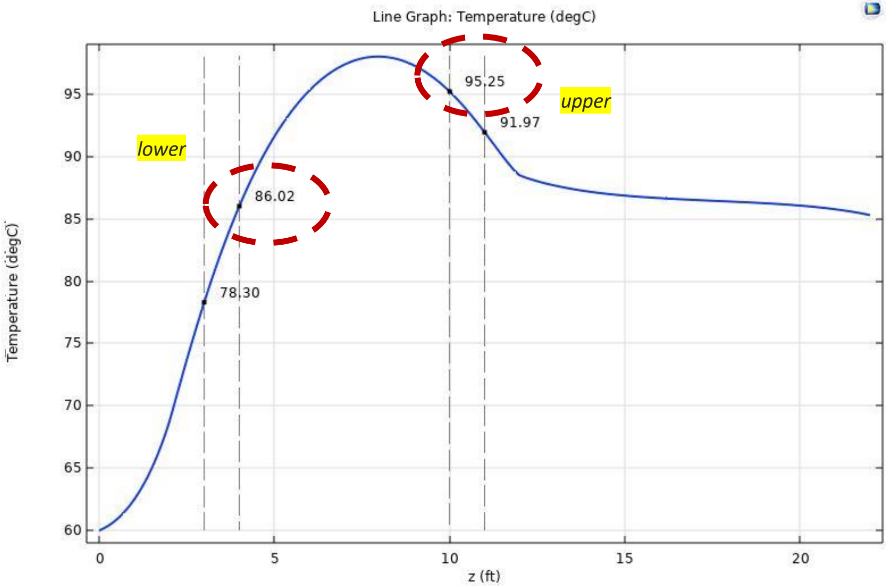
Temperature along the surface of a clampshell

COMSOL 3D simulation – present conditions

Validation of the results: comparison with thermocouples readings



Experimental data



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COMSOL 3D simulation – present conditions

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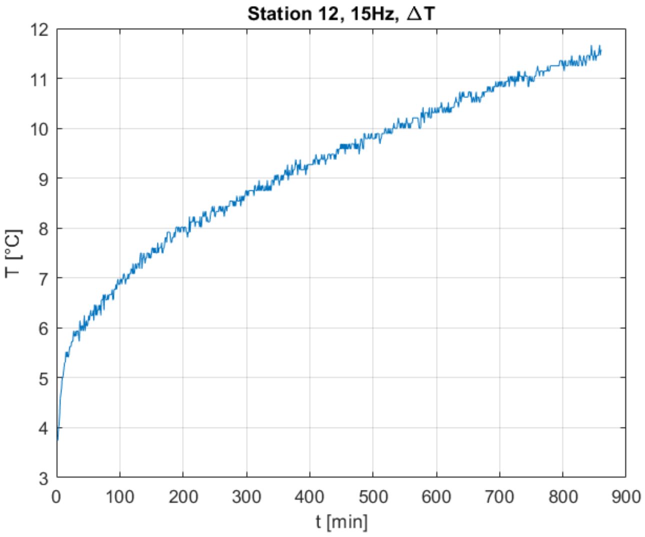

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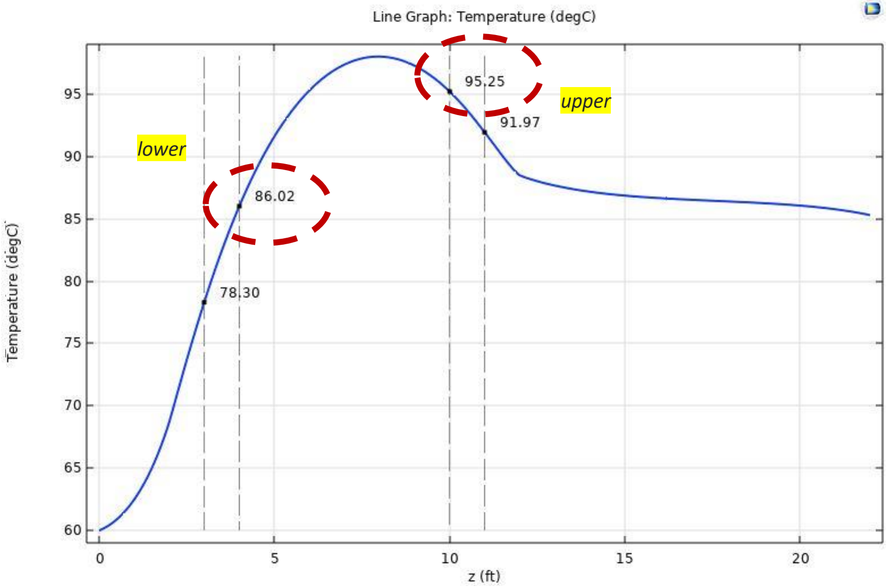
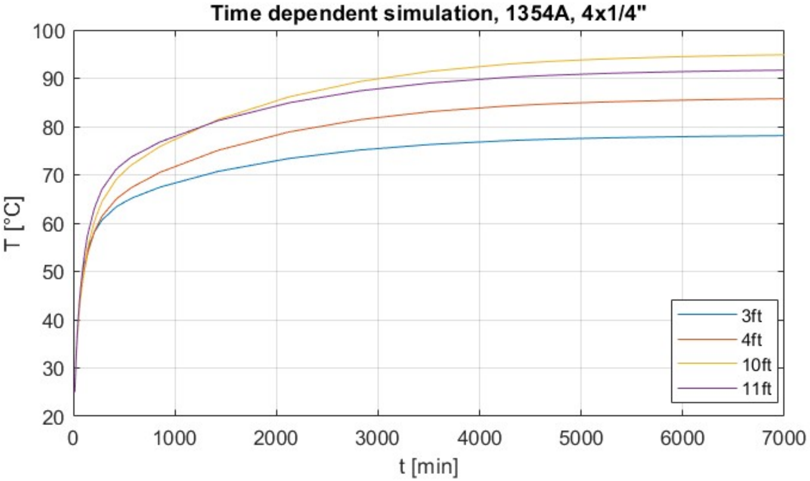


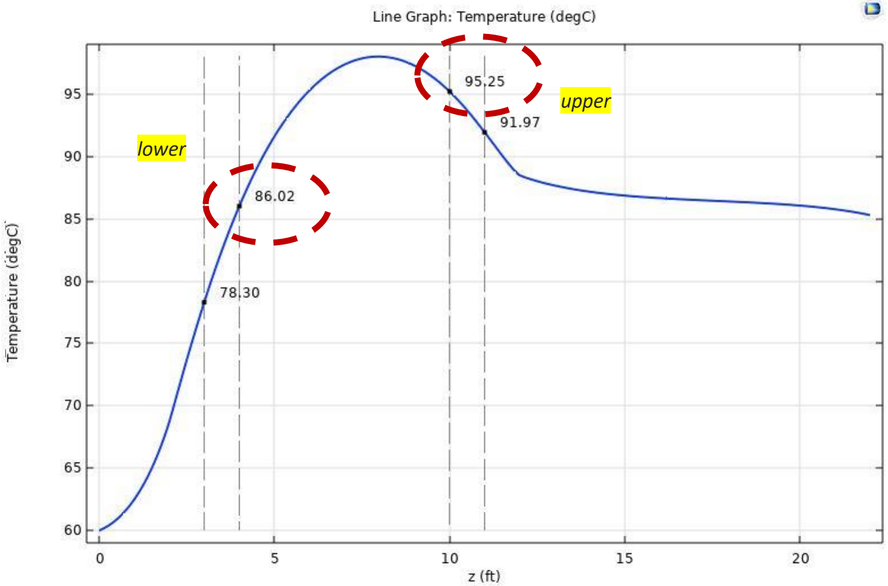
Temperature along the surface of a clampshell

COMSOL 3D simulation – present conditions

Transient simulation



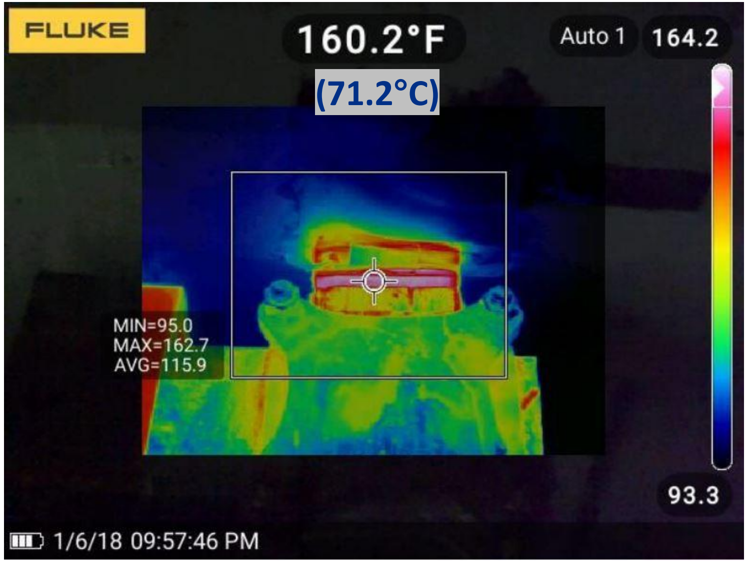
Experimental data



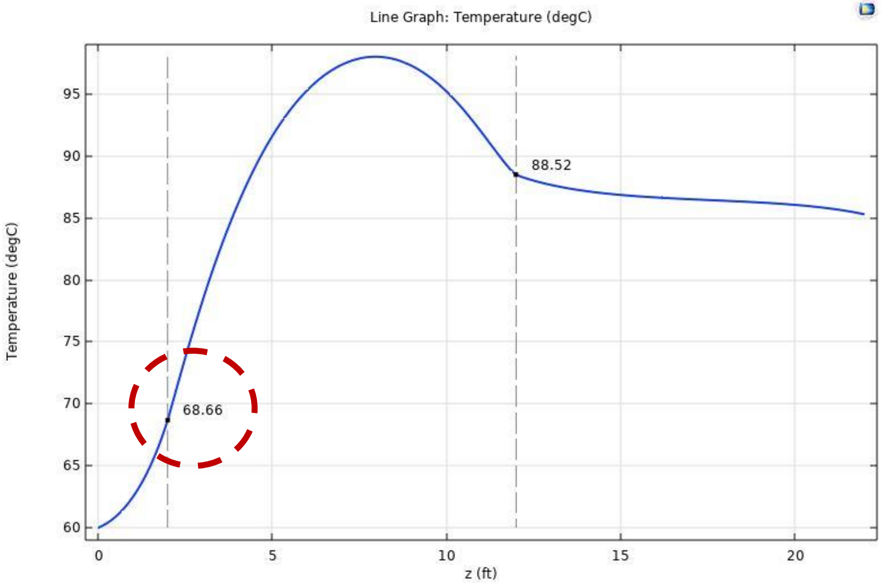
Temperature along the surface of a clampshell

COMSOL 3D simulation – present conditions

Validation of the results: comparison with IR camera images



IR camera image of the bottom of the penetration



Temperature simulated value at the bottom of the penetration

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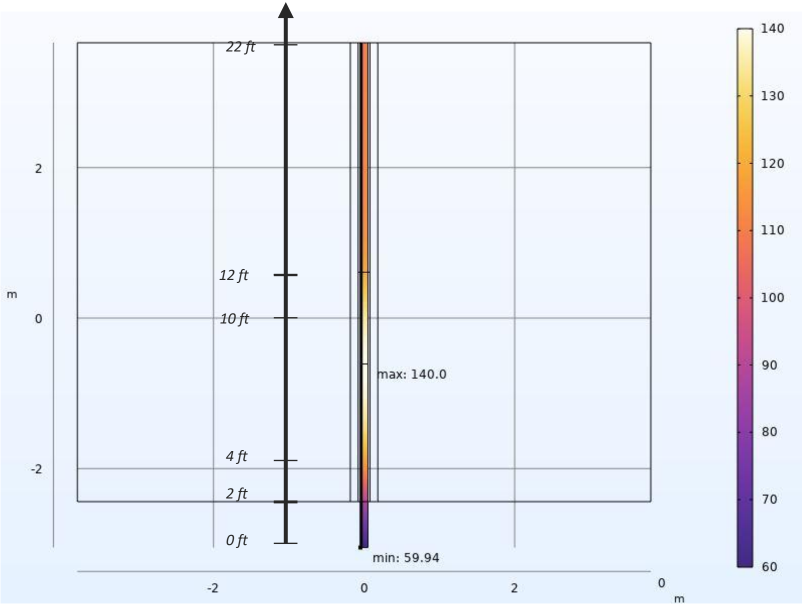
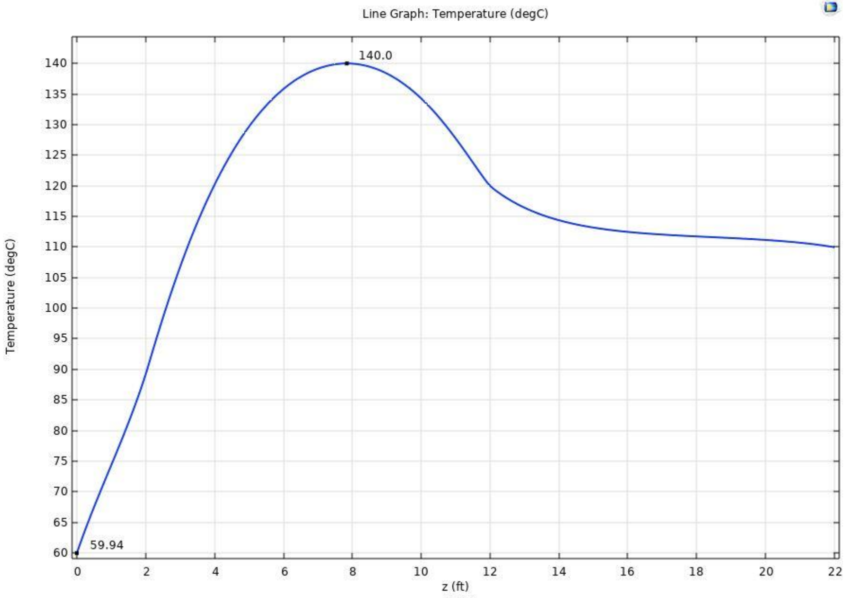
COMSOL 3D simulation – PIP-II conditions

Simulations results for 20Hz, 1695A RMS



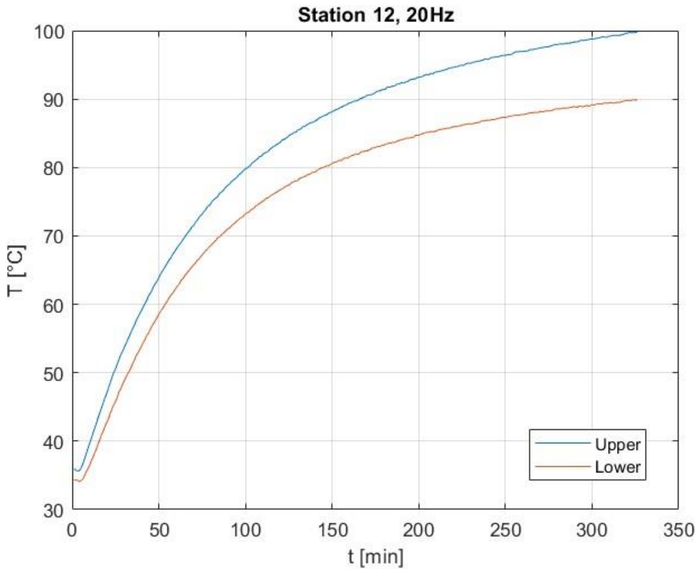
Temperature gradient of the assembly



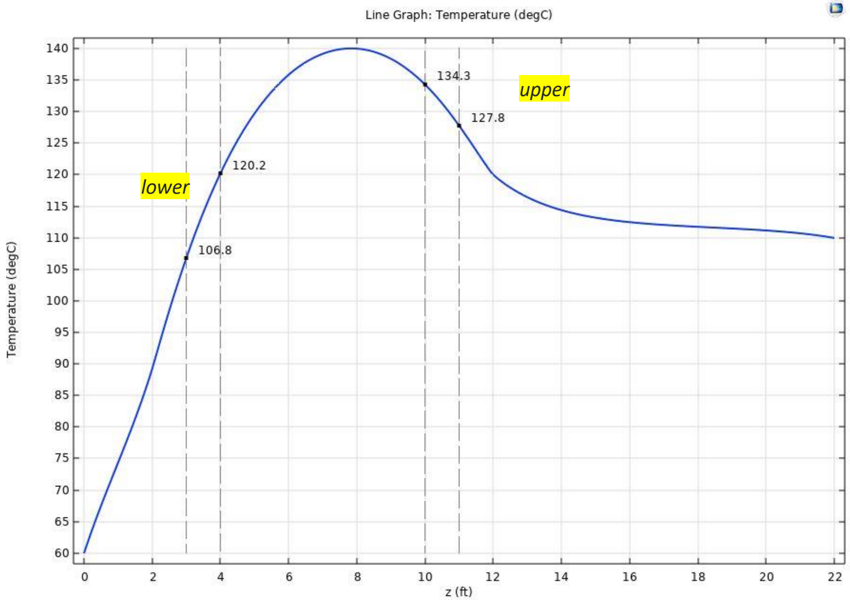
Temperature along the surface of a clampshell

COMSOL 3D simulation – PIP-II conditions

Comparison with experimental data (steady-state)



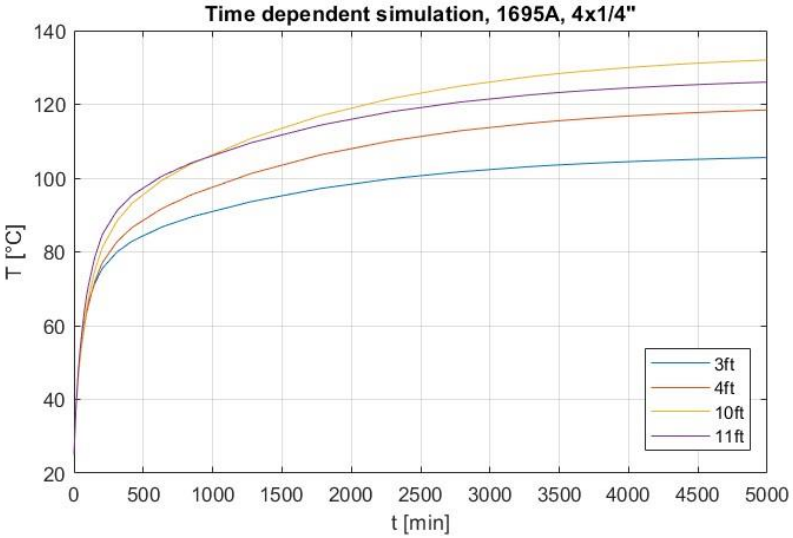
Experimental data



Temperature along the surface of a clampshell

COMSOL 3D simulation – PIP-II conditions

Transient simulation



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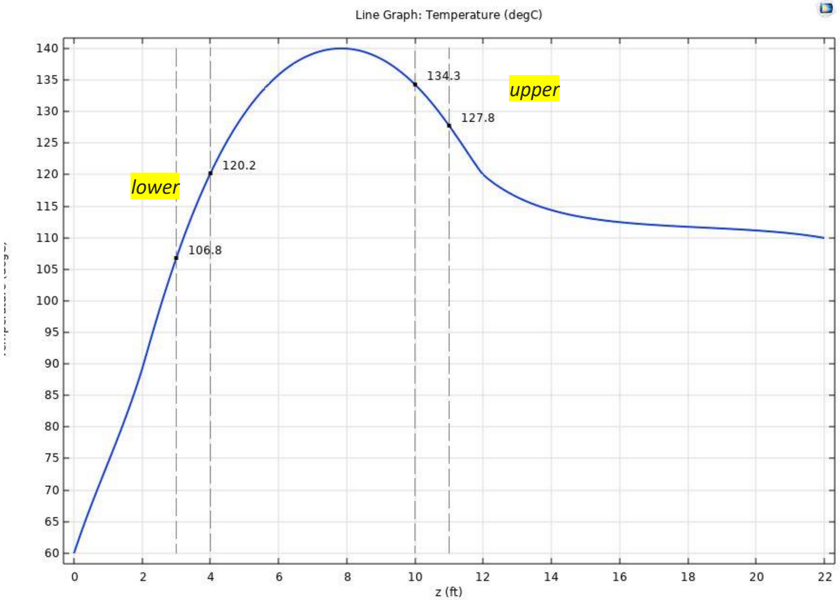

Temperature along the surface of a clampshell

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Proposed change: increasing the cross section

One of the many possible solutions to the thermal problem would be increasing the cross section of the bus bars. A bigger cross section would mean:

- Smaller resistance: $R = \rho \frac{L}{A}$, hence less power generation
- Bigger heat capacity, hence more heat stored in the mass of the bars

Taking into consideration a simple, lumped parameter equation that could describe the system:

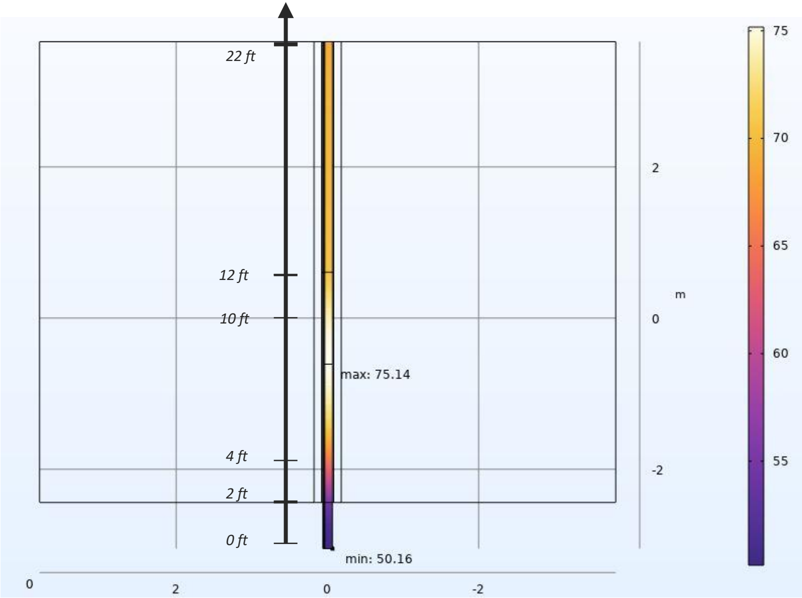
$$-hA(T - T_\infty) - \varepsilon\sigma A(T^4 - T_\infty^4) + \dot{Q}_{joule} = \rho c V \frac{dT}{dt}$$

Decrease in power generation
(about -50% power generation)

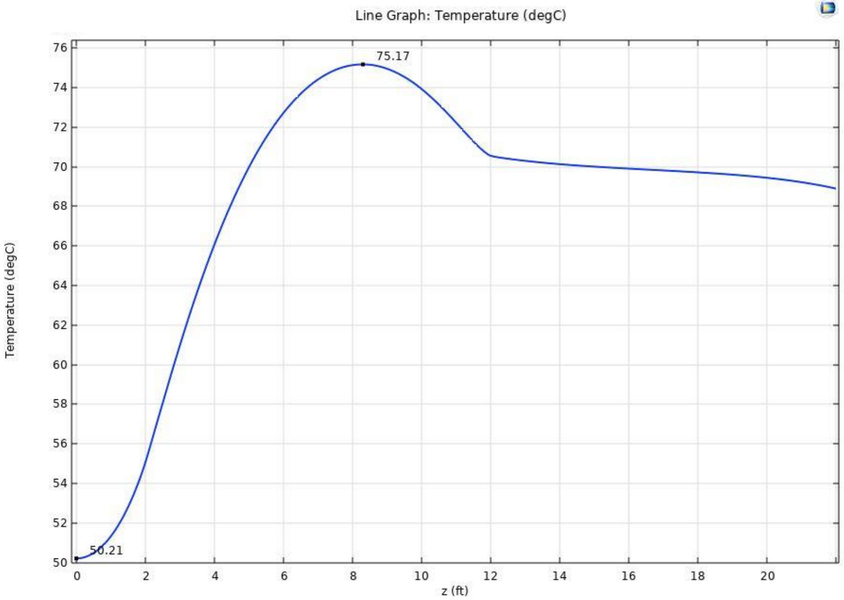
Increase in heat capacity
(about +85% volume)

COMSOL 3D simulation – PIP-II conditions + new assembly

Simulations results for 20Hz, 1695A RMS, 5x3/8’’ cross section



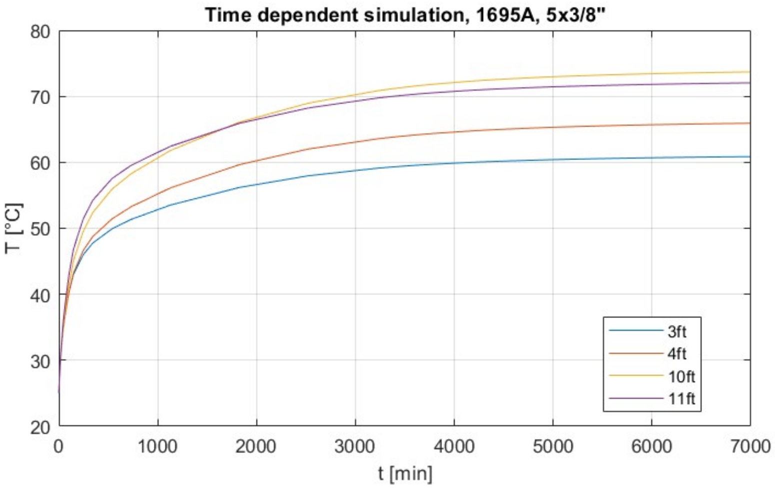
Temperature gradient of the assembly



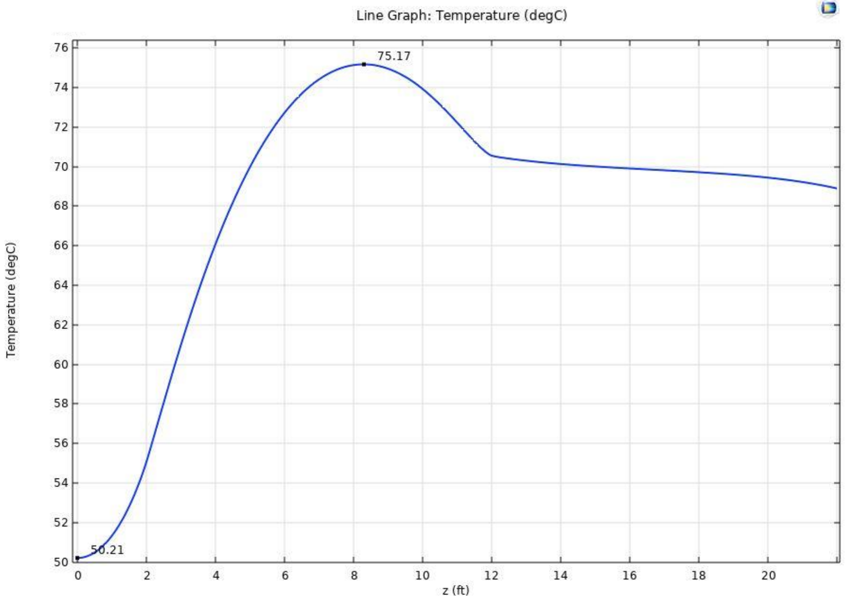
Temperature along the surface of a clampshell

COMSOL 3D simulation – PIP-II conditions + new assembly

Simulations results for 20Hz, 1695A RMS, 5x3/8'' cross section



Temperature gradient of the assembly



Temperature along the surface of a clampshell

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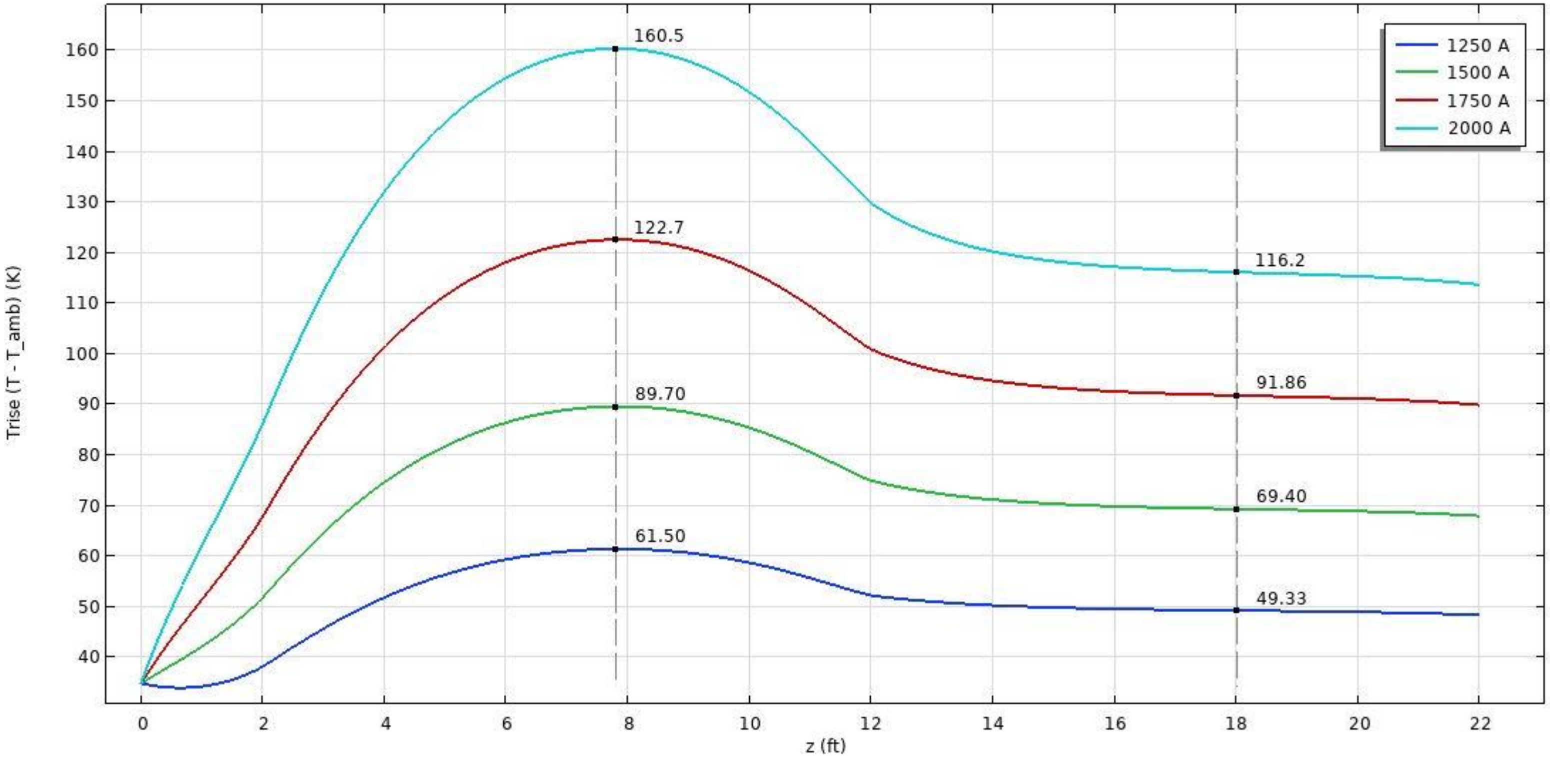
Data evaluation – current sweep



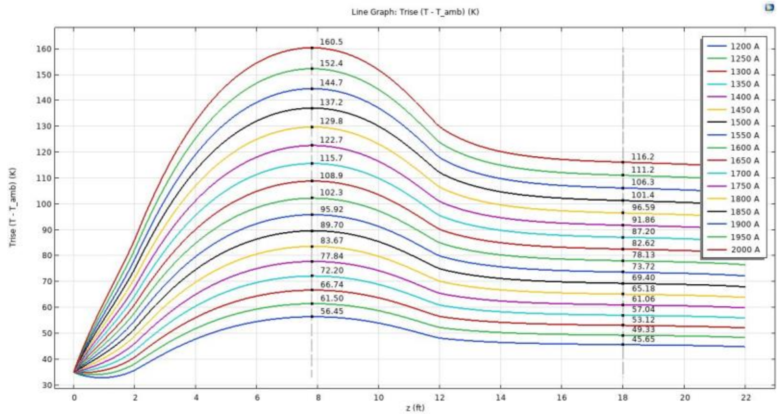
Data evaluation – current sweep

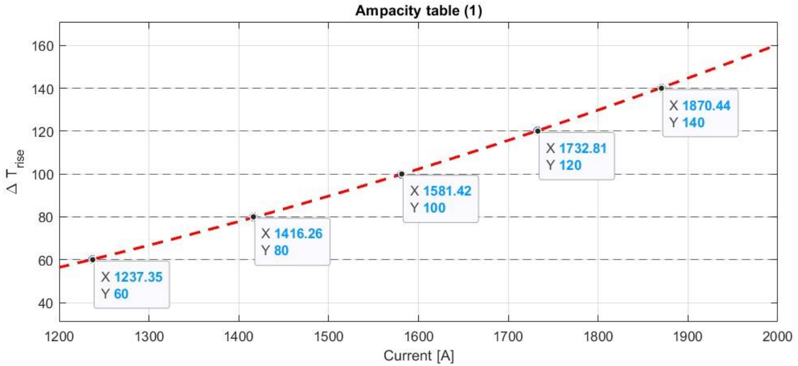
In order to gather the data to build a reference table, the simulation has been computed for several different RMS values of the bias current.

The goal is to be able to evaluate the **temperature rise** as a function of the amount of RMS current carried by the bus bar.

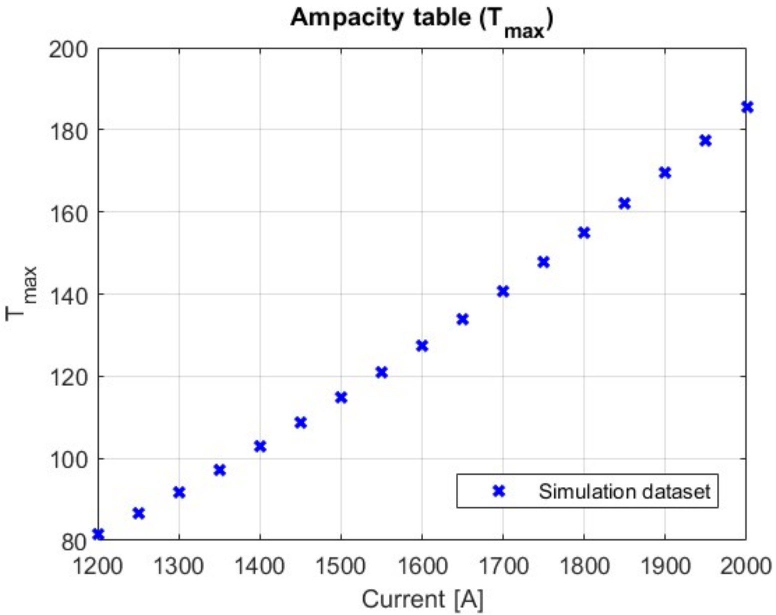
The ΔT_{rise} is defined as the difference between the maximum temperature and the ambient temperature, since for this kind of problem the maximum temperature is the most significant data:

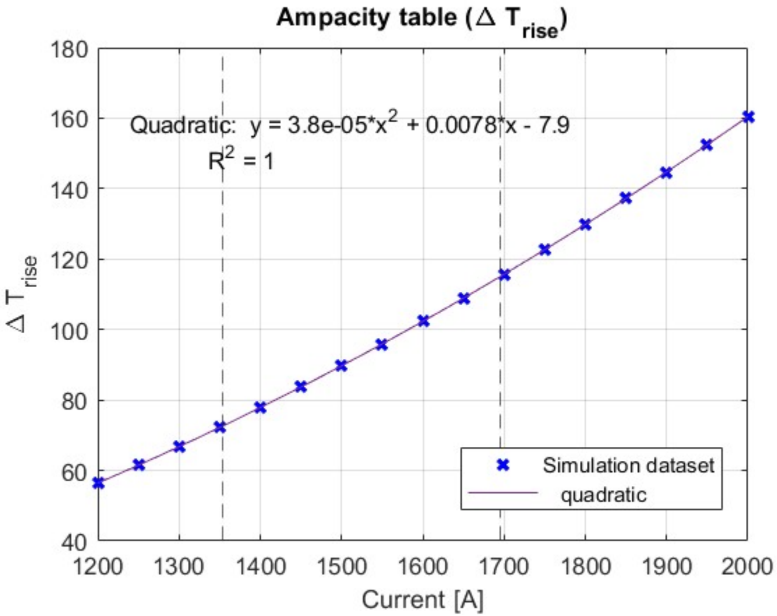
$$\Delta T_{rise} = T_{max} - T_{amb}$$





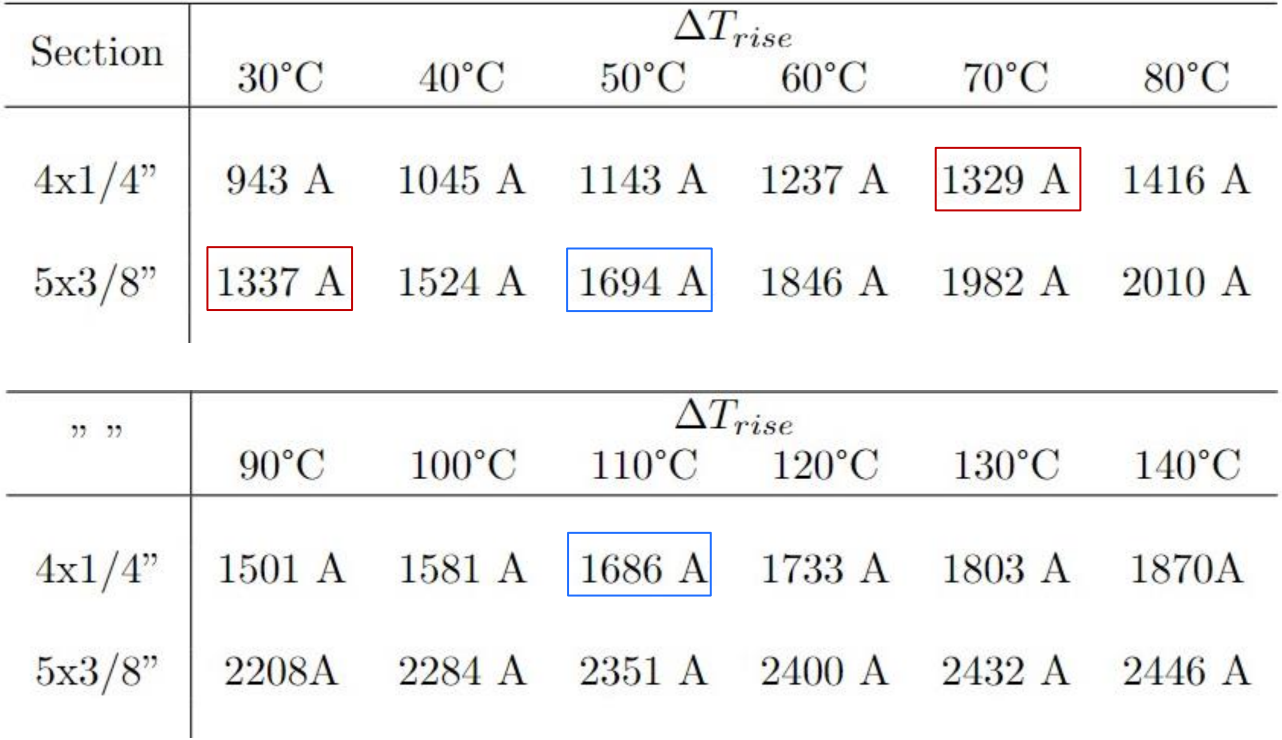
Data evaluation





After gathering a discrete number of $(I, \Delta T_{rise})$ points it is possible to fit the data and obtain the necessary RMS current to get a specific temperature rise.

Peak temperatures table



Section	ΔT_{rise}					
	30°C	40°C	50°C	60°C	70°C	80°C
4x1/4”	943 A	1045 A	1143 A	1237 A	1329 A	1416 A
5x3/8”	1337 A	1524 A	1694 A	1846 A	1982 A	2010 A

” ”	ΔT_{rise}					
	90°C	100°C	110°C	120°C	130°C	140°C
4x1/4”	1501 A	1581 A	1686 A	1733 A	1803 A	1870A
5x3/8”	2208A	2284 A	2351 A	2400 A	2432 A	2446 A

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Conclusions

- It has been proved that in the new working conditions the polyethylene shield will melt
- It has been obtained a reliable model of the assembly, that can be useful for future evaluations prior to experiments/tests
- An ampacity table has been made for quick consultation in case of future change in operational conditions
- A solution to the problem has been proposed

References

- Victor Grzelak, “THE FERMILAB BOOSTER RF MODIFICATIONS FOR THE 800MEV INJECTION ERA”
- Fermilab Accelerator Division. “Concepts book
- Matther Domeier. “Booster Bus Bar Replacement”
- Taylor Electronics Services. “Ampacity table for copper busbars”
- Engineering toolbox
- John H. Lienhard IV and John H. Lienhard V. “A heat transfer textbook”.

Figure: me and Victor during a visual inspection

Thank you for your attention!

Silvia Picchi, Victor Grzelak
Thermal Analysis of the Bus Bars
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Backup

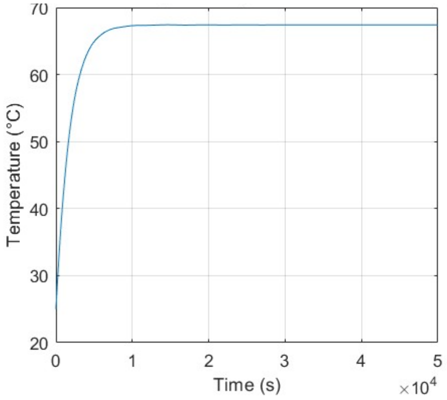
Lumped capacity analysis

Hypothesis: the temperature gradients are small, $T(\vec{x},t) = T(t)$ *(true if* $Bi = \frac{hL}{k} \ll 1$*)*

Energy balance:

$$-hA(T - T_\infty) - \varepsilon\sigma A(T^4 - T_\infty^4) + Q_{joule} = \rho c V \frac{dT}{dt}$$

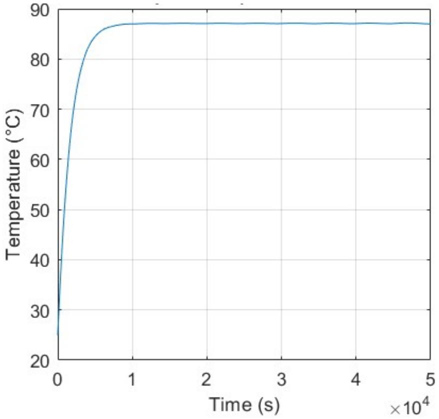
Solving this non-linear equation gives an approximation of the temperature variation of the busbars, from ambient temperature to steady-state.



Temperature T(t) for the 4x1/4” cross section, in open air.

I_{RMS} = 1354A (current operating conditions)

Tsteady = 67.4°C



Temperature T(t) for the 4x1/4” cross section, in open air.

I_{RMS} = 1695A (PIP-II operating conditions)

Tsteady = 87.9°C

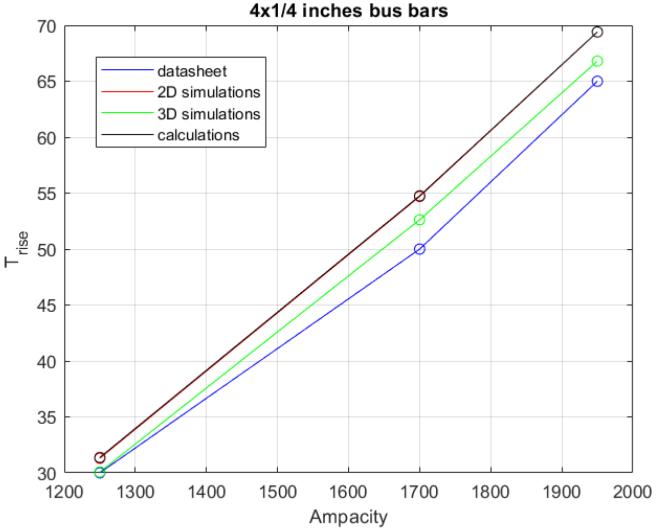
Preliminary analysis

Preliminary evaluations have been made:

- Investigating possible solutions to the problem
- Analytical lumped model of the busbars assembly

$$-hA(T-T_\infty)-\varepsilon\sigma A(T^4-T_\infty^4)+\dot{Q}_{joule}=\rho c V\frac{dT}{dt}$$

- 2D COMSOL simulations of single bus bars
- 3D COMSOL simulations of single bus bars



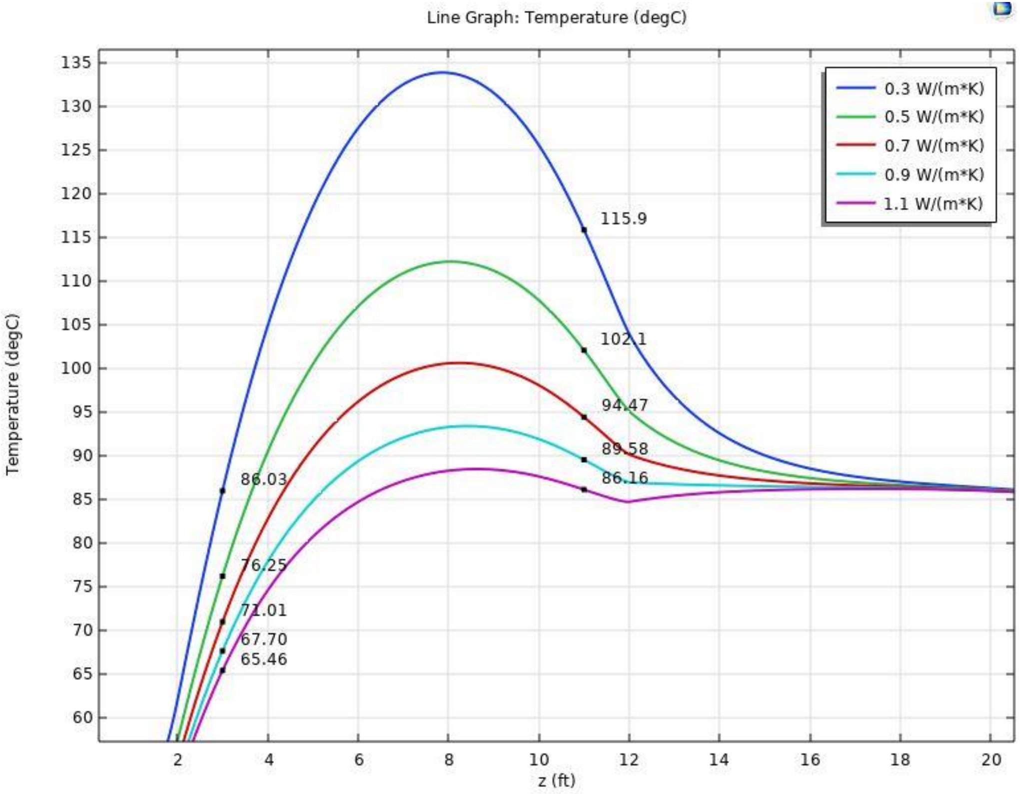
Comparison of different datasets

Parametric sweep

Soil thermal conductivity

- Changes with the time of the years and the weather conditions
- Affects greatly the results of the simulations

Finally, a value of 0.7W/mK has been chosen.

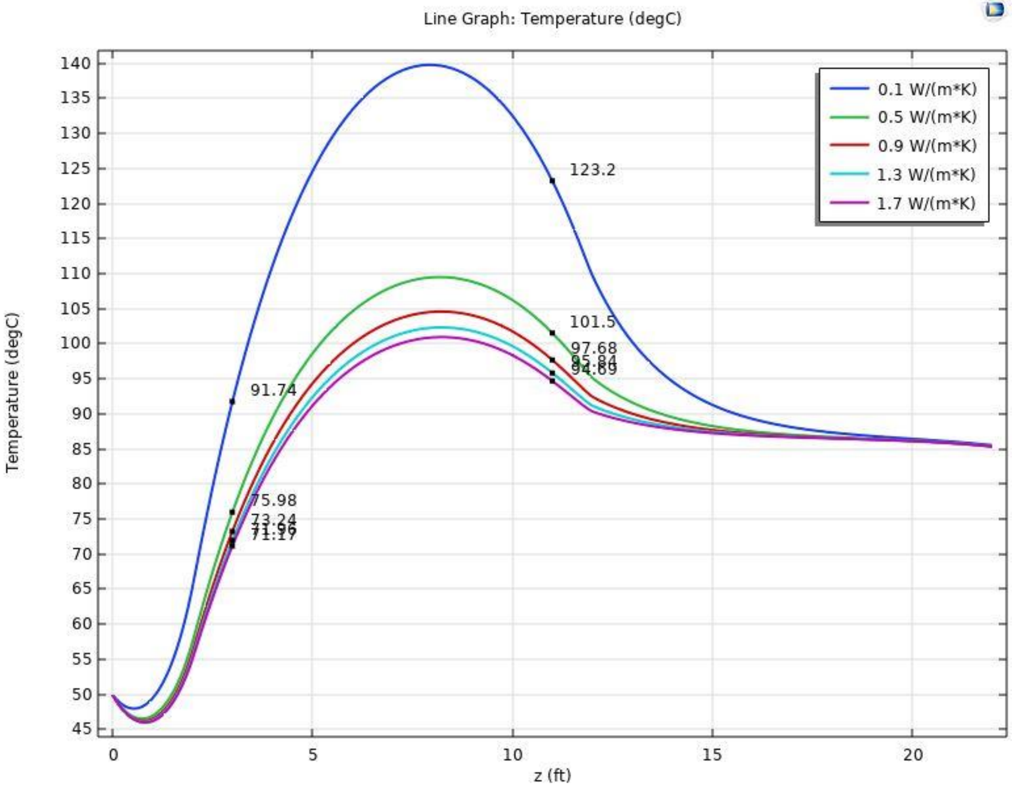


Parametric sweep

Concrete thermal conductivity

- Not specified in literature
- Affects greatly the results of the simulations

Finally, a value of 1.7W/mK has been chosen.



Natural convection calculations

Natural convection coefficient h can be evaluated from adimensional number of Nusselt, $Nu = h\delta/k$.

Grashof number:

$$Gr = \frac{g\,\Delta T\,\beta\delta^3}{\nu^3}$$

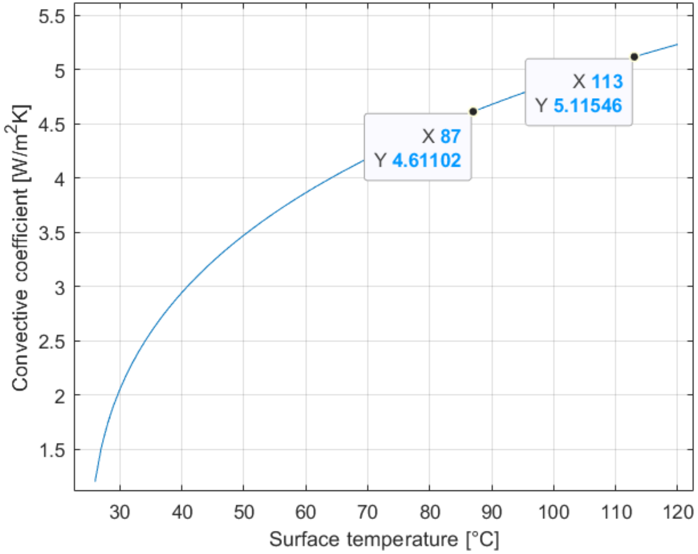
Prandtl number:

$$\mathrm{Pr} = \frac{\alpha}{\nu}$$

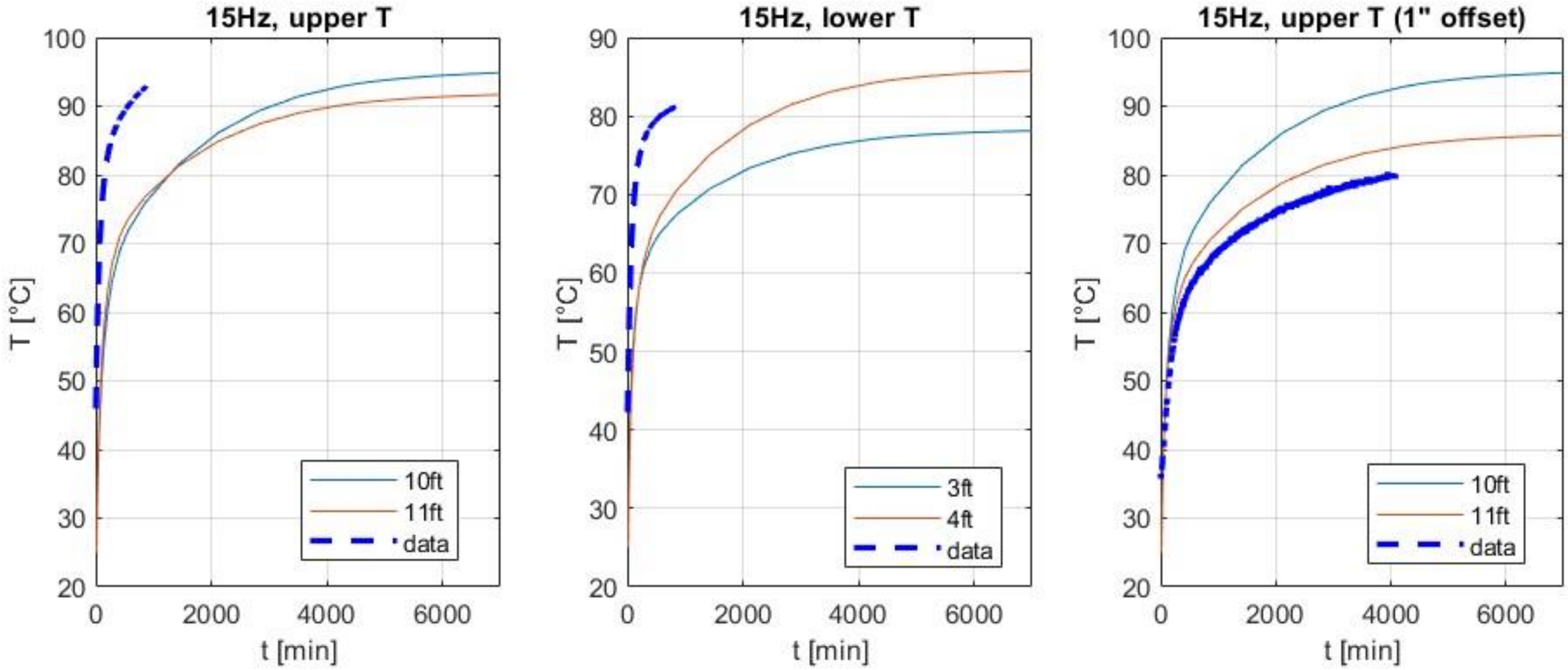
Rayleigh number:

$$Ra = \mathrm{Pr}\cdot Gr$$

And from the Ra number it is possible to use experimental correlations to calculate Nu.



Transient comparison (4x1/4”, present conditions)



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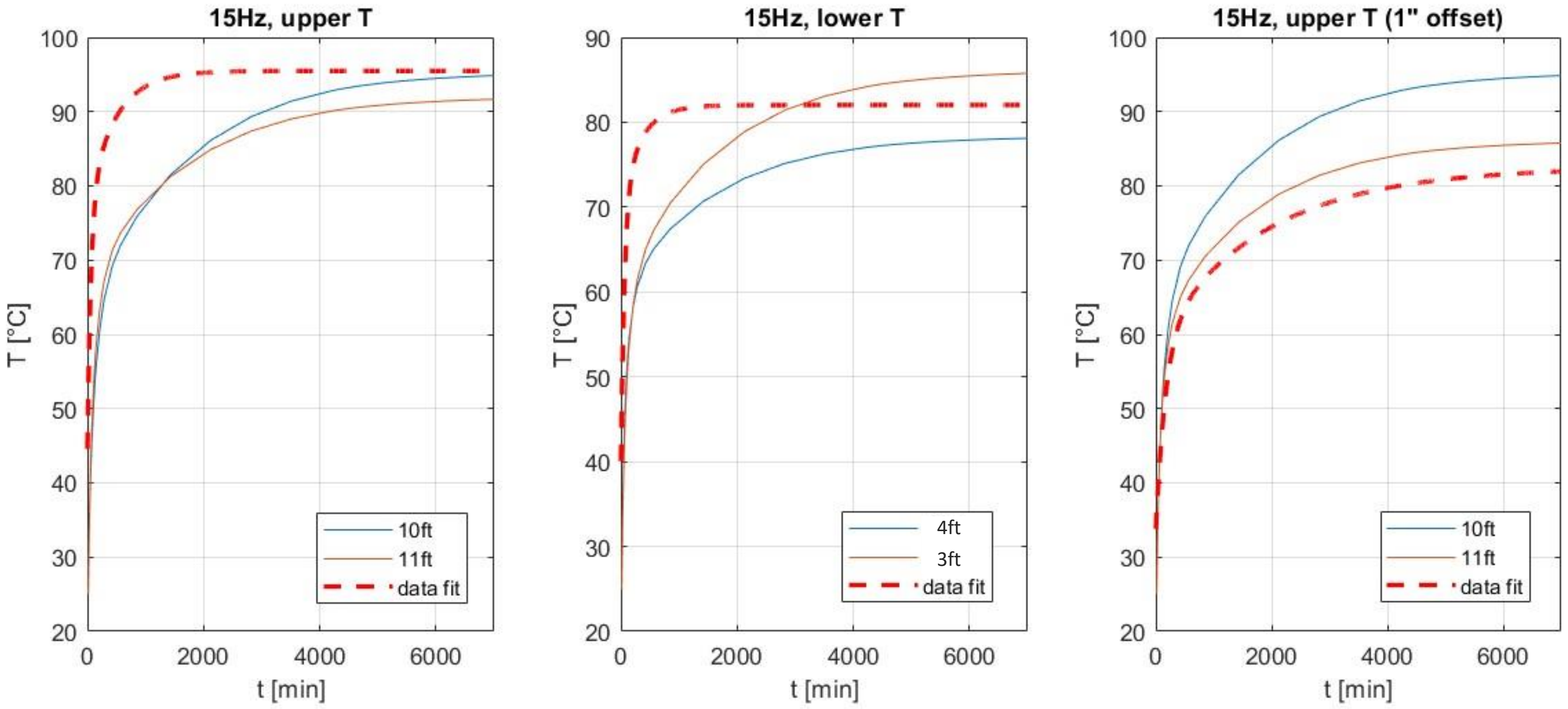
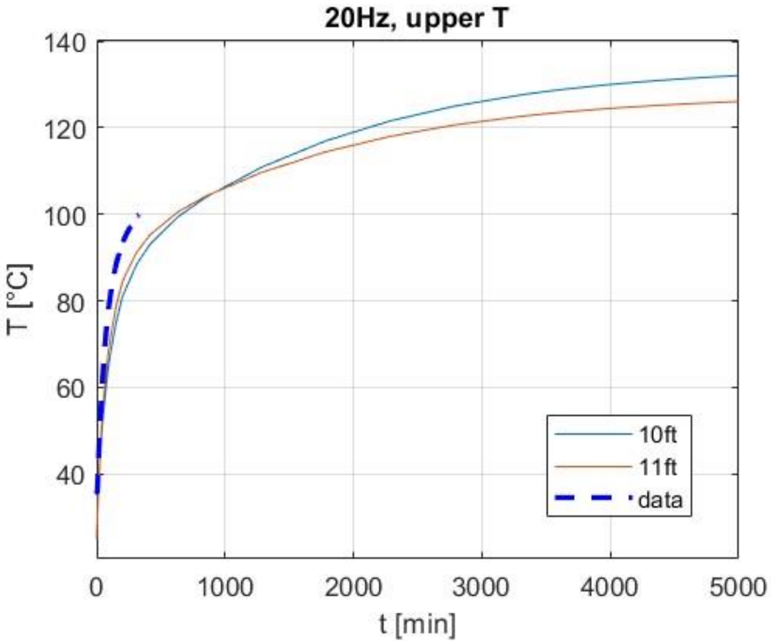
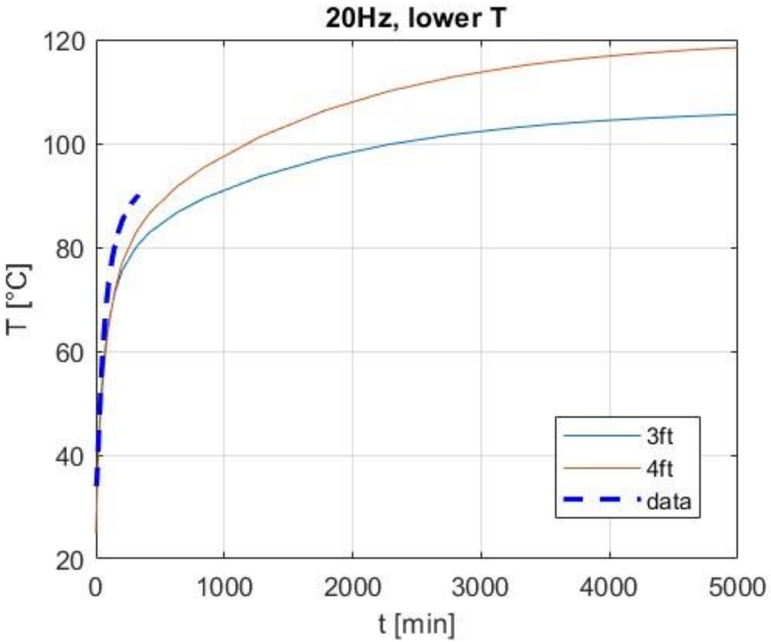
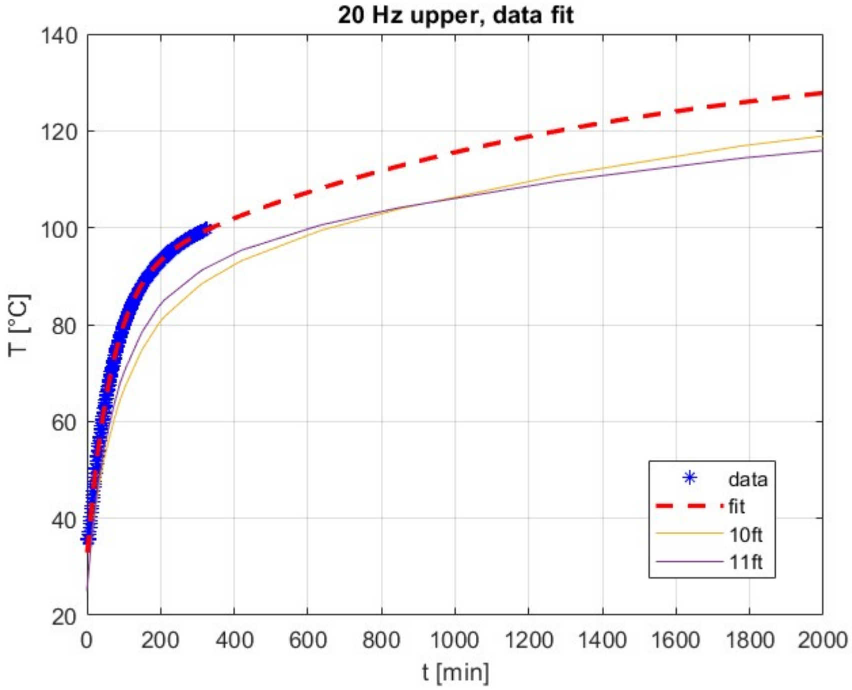


Transient comparison (4x1/4”, PIP-II conditions)





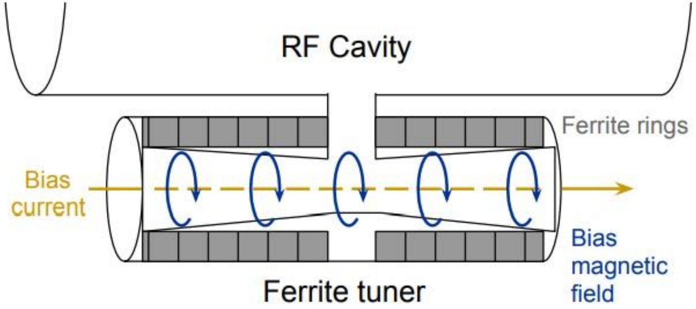
Transient comparison (4x1/4”, PIP-II conditions)



Biasing ferrite tuners

- Modern high-energy accelerators use conducting structures known as **RF cavities**
- RF cavities are **electromagnetically resonant**
- Synchrotrons require the RF frequency to increase with the beam energy- so the resonant frequency of the cavities must be changed. This is accomplished using **ferrite tuners**.

- The ferrite of the tuners changes the inductance of the system, thus altering the resonant frequency of the cavity. This happens when a **large amount of current** is applied to the tuner- it creates a biasing field that **changes the magnetic permeability** of the tuner itself.
- Applying a large current causes a decrease in magnetic permeability.



RF cavity with ferrite tuner

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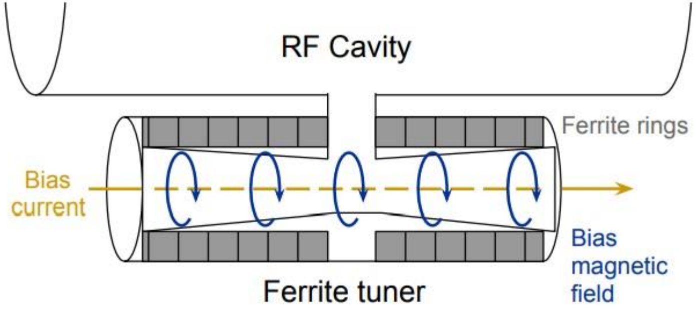
Another way around the problem

Instead of focusing on reducing the temperature, another effective way to solve the problem would be **reducing the current** needed by the ferrite tuners.

This can be done in different ways, such as **changing the harmonic number** of the accelerator or **redesigning the ferrite tuners**.

- The harmonic number is defined as $h = \frac{f_{RF}}{f_{rev}}$. It is the number of RF oscillations completed in the time it takes a particle to traverse one orbit.
- RF cavities resonate in a range of frequencies, as the current changes the magnetic permeability of the ferrite tuners (and therefore the resonant frequency).



RF cavity with ferrite tuner

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Calculating RF frequency curves

Momentum curves

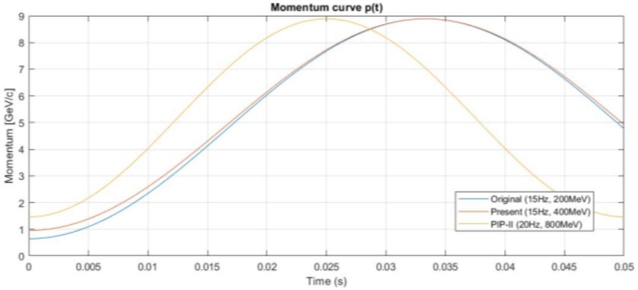
$$p(t) = \frac{p_f + p_i}{2} - \frac{p_f - p_i}{2}\cos(\omega t)$$

$$\omega = 2\pi f$$

$f \rightarrow$ *machine frequency*

$$p_i = \sqrt{\left(\frac{KEi + m_p c^2}{c}\right)^2 - m_p^2 c^4}$$

$$p_f = \sqrt{\left(\frac{KE_f + m_p c^2}{c}\right)^2 - m_p^2 c^4}$$



Total energy

$$E_{TOT}(t) = m_p^2 c^4 + p^2(t)c^2$$

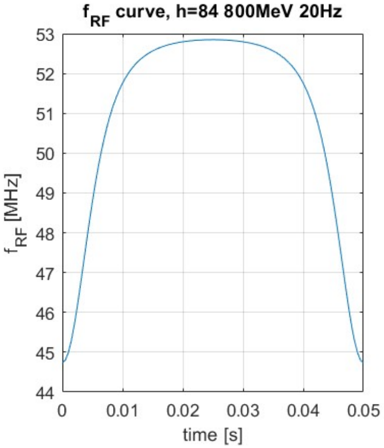
$$\gamma(t) = \frac{E_{TOT}(t)}{m_p}$$

$$\beta(t) = \sqrt{1 - 1/\gamma^2(t)}$$

Revolution frequency

$$f_{rev}(t) = \frac{\beta c}{C}$$

$C \rightarrow$ *Booster circumference*

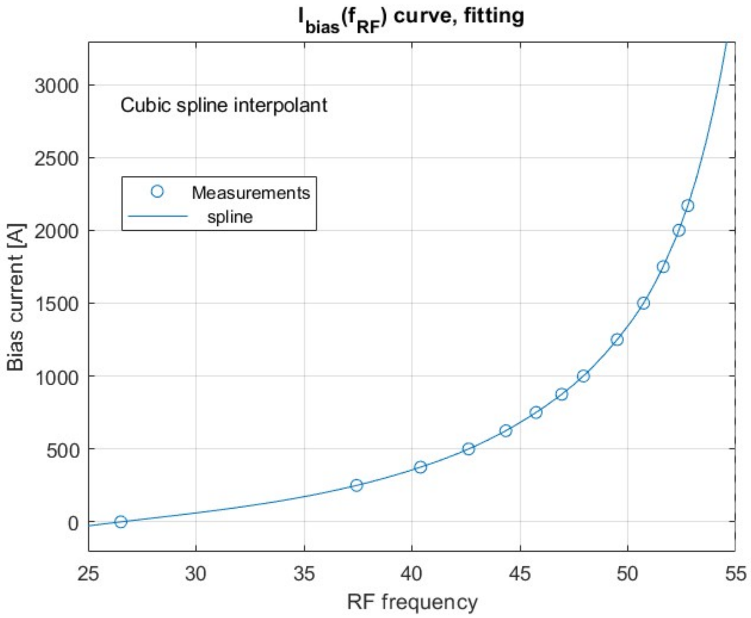


RF frequency

$$f_{RF}(t) = h \cdot f_{rev}(t)$$

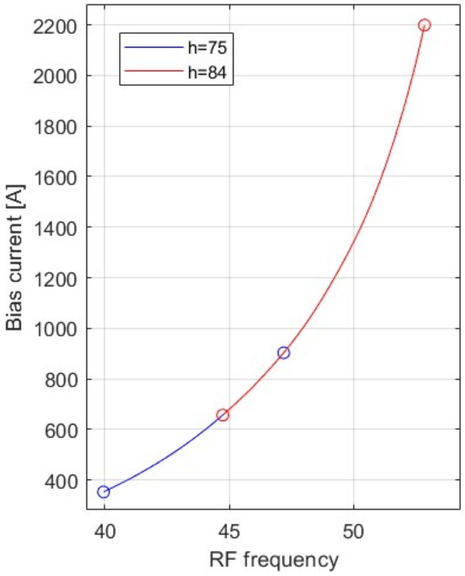
RF frequency – Bias current transfer function

Fitting experimental data:



Spline interpolation of experimental data

Calculating new I_{RMS}:



Current ranges for different h

Harmonic number
h = 84
RMS current
I_{RMS} = 1695A

h = 75
I_{RMS} = 770.1A