NuMI AIP 1 MW Target Analysis

TSD Topical Meeting

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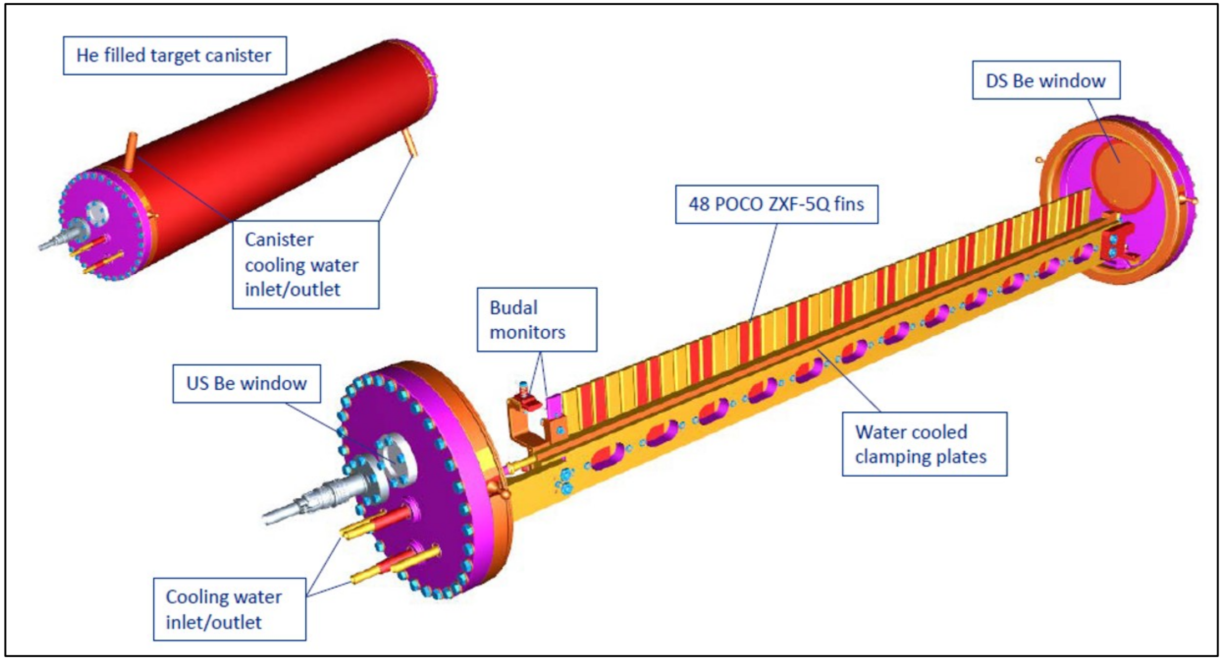
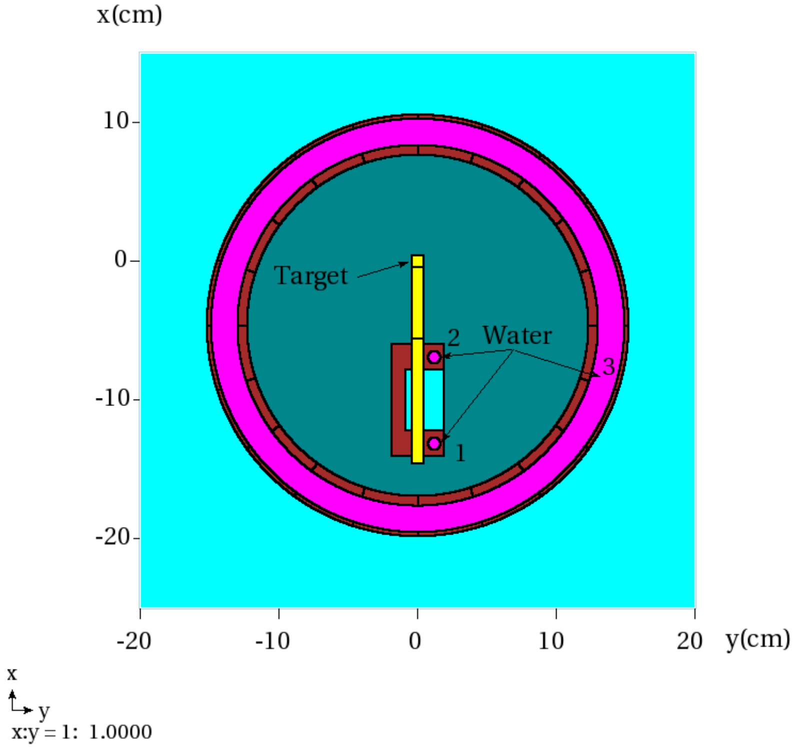
12.13.2018

Introduction

- NuMI AIP to accelerate physics goals by increasing number of protons on target
- Higher beam power of ~<u>1 MW</u>
  - Beam spot size: 1.5 mm
  - Graphite fin width: 9 mm
- Evaluate thermal/structural performance of NOvA target design at 1 MW



MARS energy deposition data
(I. Rakhno)



NuMI AIP 1 MW beam parameters

Energy: 120 GeV
Power: 1 MW
σ = 1.5 mm
Repetition rate: 1.2 s
Pulse length: 10 μs

Protons/pulse = 6.25e13
Protons/s = 5.21e13

MARS geometry and binning

48 fins: 24 mm x 9 mm x 150 mm

x-y direction:

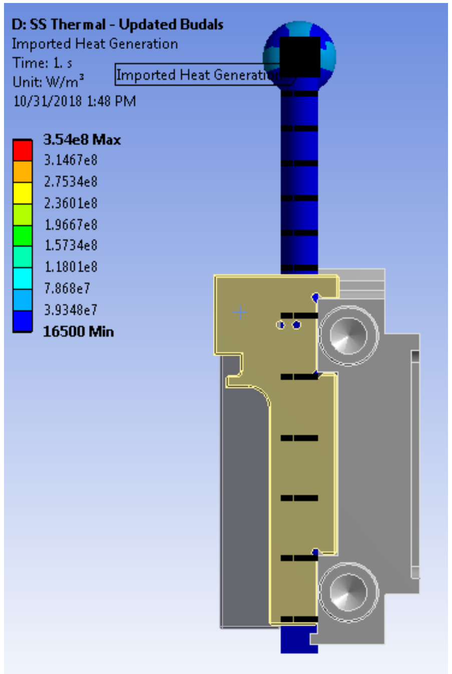
18 x 18 bins: x from 4.25 mm to -4.25 mm, y from -4.25 mm to 4.25 mm (0.5 mm x 0.5 mm bins)
6 x 6 bins: x from 3.75 mm to -3.75 mm, y from -51.7083 mm to -8.79167 mm (1.5 mm x 8.6 mm bins)
6 x 6 bins: x from 3.75 mm to -3.75 mm, y from -138.042 mm to -63.4583 mm (1.5 mm x 14.9 mm bins)

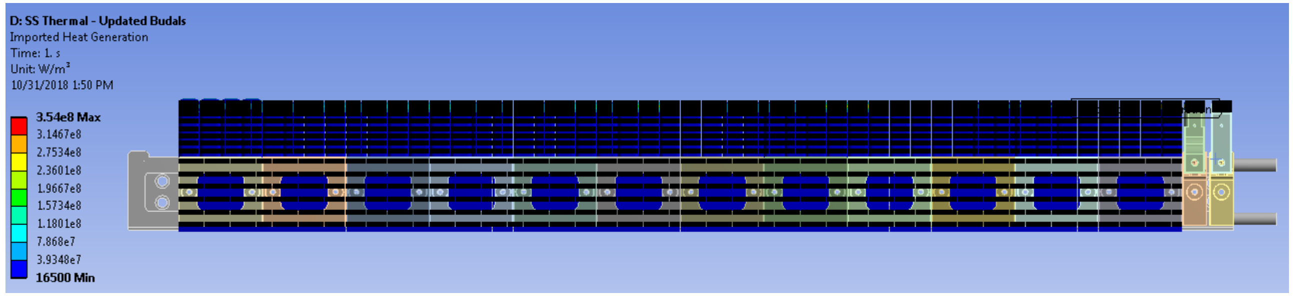
z-direction:

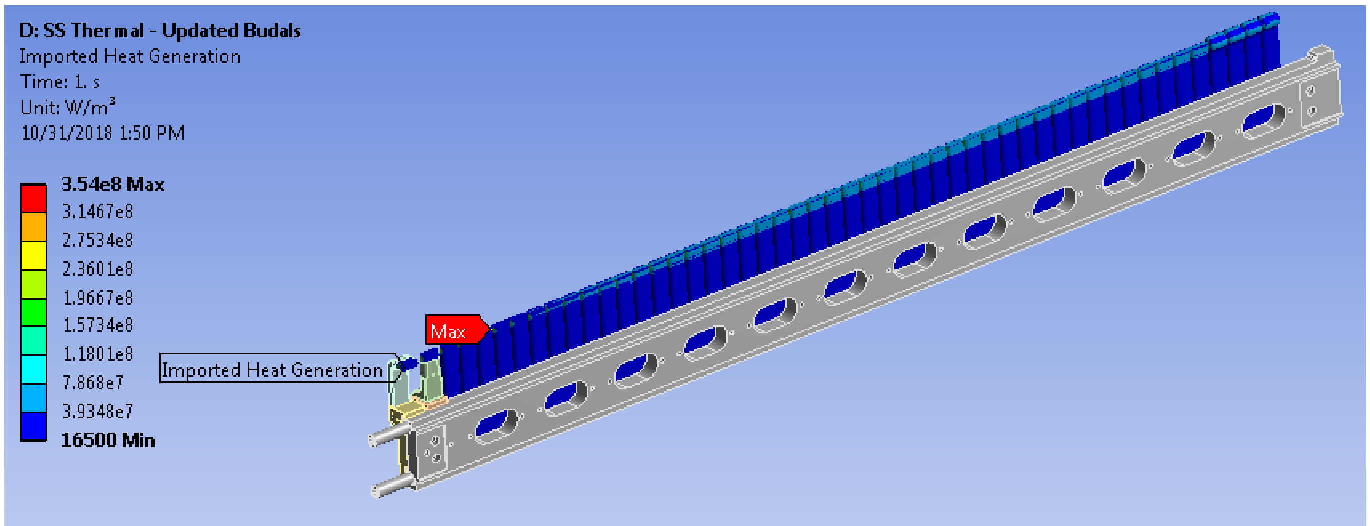
4 x-y data sets per fin for 48 fins

[(18 x 18 x 4) + (6 x 6 x 4) + (6 x 6 x 4)] x 48 = *76032 data points*

MARS energy deposition data mapping in ANSYS







- Max energy deposition at downstream end of fin 3

ANSYS Workbench FEA

- 3D analysis of target assembly
  - Steady state thermal and static structural analysis of target fin assembly
  - Transient thermal and structural analysis of single fin (dynamic analysis)
    - Standard fin (max. energy deposition in fin number 3)
    - Winged fin (at DS end)

- Temperature dependent material properties for Al6061[1] and POCO ZXF-5Q[2]
  - Thermal conductivity (transient/steady-state thermal)
  - Specific heat capacity (transient thermal)
  - Coefficient of thermal expansion (transient/static structural)
  - Elastic modulus (transient/static structural)

[1]Summers et al., "Overview of aluminum alloy mechanical properties during and after fires", Fire Sci Rev (2015), 4, 3. https://doi.org/10.1186/s40038-015-0007-5
[2]POCO Graphite - An Entegris Company, "Properties and characteristics of graphite", January 2015.

FEA boundary conditions

1. Cooling water heat transfer coefficient calculation (applied to inner surface of tube)

- Tube inner diameter: 9 mm
- Flow rate: 5.5 GPM
- Inlet T: 31 °C
- Outlet T: 35 °C
- Using friction factor for smooth surface (conservative)

$$f = (0.790 \ln Re_D - 1.64)^{-2} \qquad 3000 \lesssim Re_D \lesssim 5 \times 10^6$$

- **Nusselt number = 353**

$$Nu_D = \frac{(f/8)(Re_D - 1000)Pr}{1 + 12.7(f/8)^{1/2}(Pr^{2/3} - 1)}$$

h = 24500 W/m^2.K

Eq. 8.21 and 8.62 from Incropera & DeWitt, "Fundamentals of Heat and Mass Transfer", 5th edition, Wiley.

FEA boundary conditions

2. Free convection on graphite fin and Al surfaces: **5 $W/m^2.K$**
   - Ambient He temperature: 100 °C (scaled NOvA 700 kW CFD results by ~35%)

3. Radiation on graphite fin surfaces
   - **Emissivity: 0.75***
   - Ambient He temperature: 100 °C (scaled NOvA 700 kW CFD results by ~35%)

4. Al cooling rail and pressing plates volumetric heat generation
   - MARS data: 0.132 GeV/proton
   - **Internal heat generation: 4.30e5 W/m^3** (time-averaged)

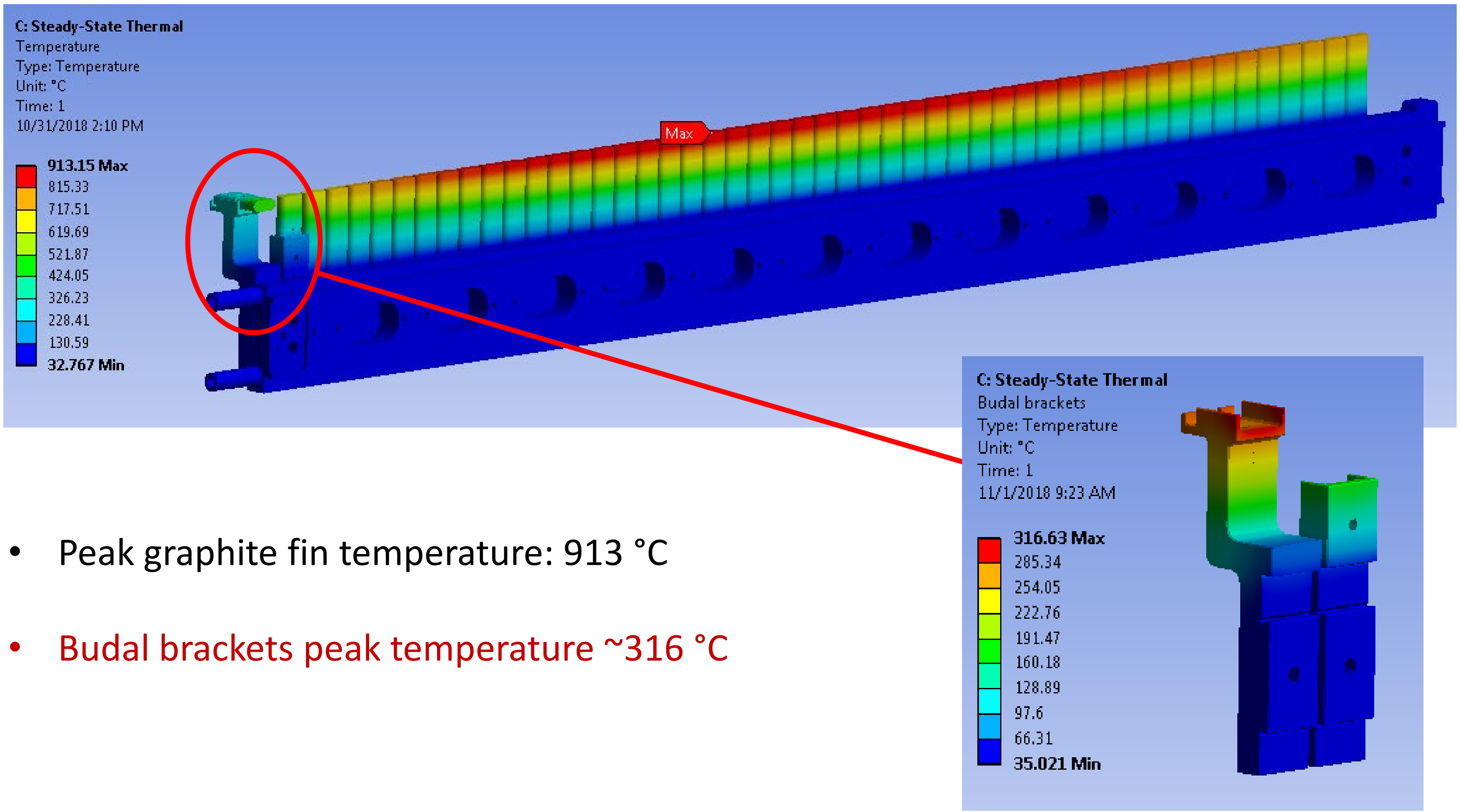
5. Assumed perfect thermal contact conductance between graphite fins and Aluminum pressing plates

*Mikron, "Table of emissivity of various surfaces for infrared thermometry", emissivity of graphite: 0.7 – 0.8 (0 – 3600 °C)
http://www-eng.lbl.gov/~dw/projects/DW4229_LHC_detector_analysis/calculations/emissivity2.pdf

Steady-state thermal analysis

Initial analysis

- 9 mm wide fins
- No winged fins

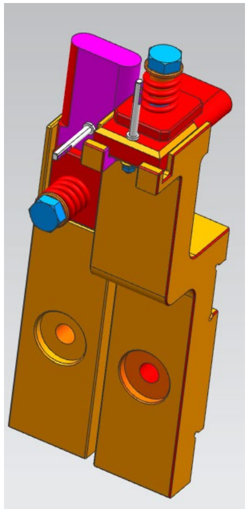


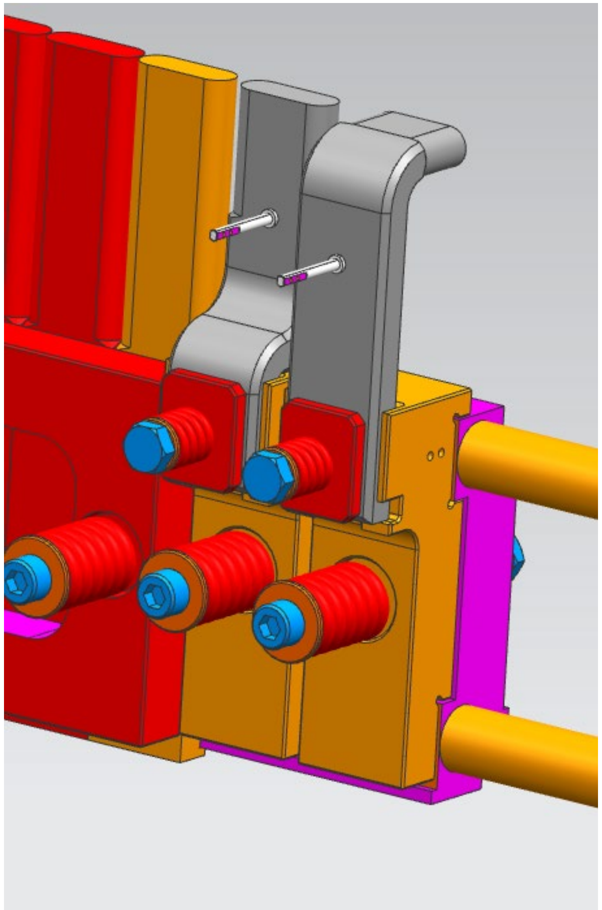
- Peak graphite fin temperature: 913 °C
- Budal brackets peak temperature ~316 °C

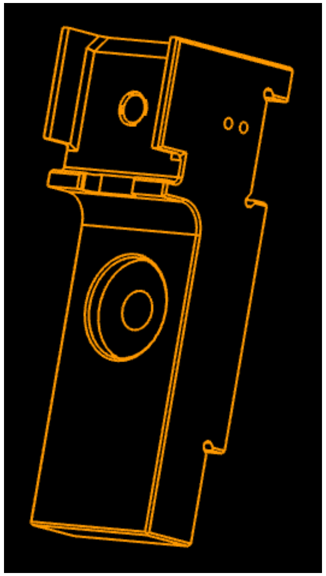
Updated Budal fins and brackets design

- Reduce conduction path length in Aluminum
  - Shorten and keep Al brackets closer to cooling rail
  - Longer graphite fins extending towards cooling rail

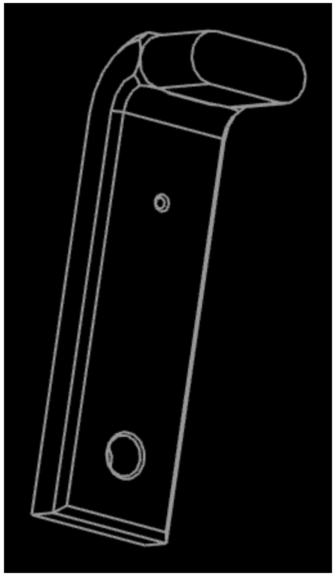
Original Budal fins/brackets design



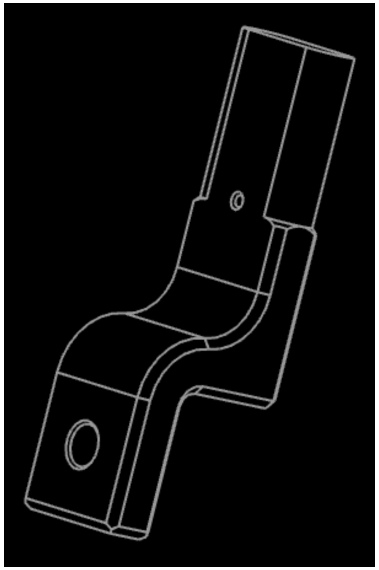




Aluminum bracket



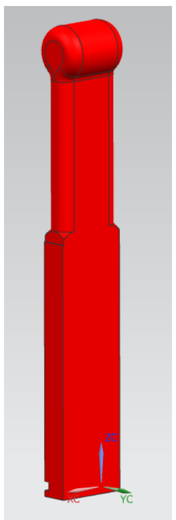
US Budal fin

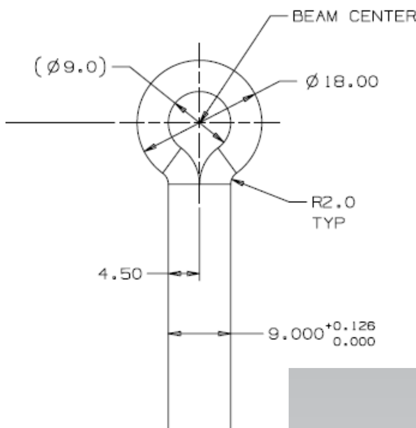


DS Budal fin

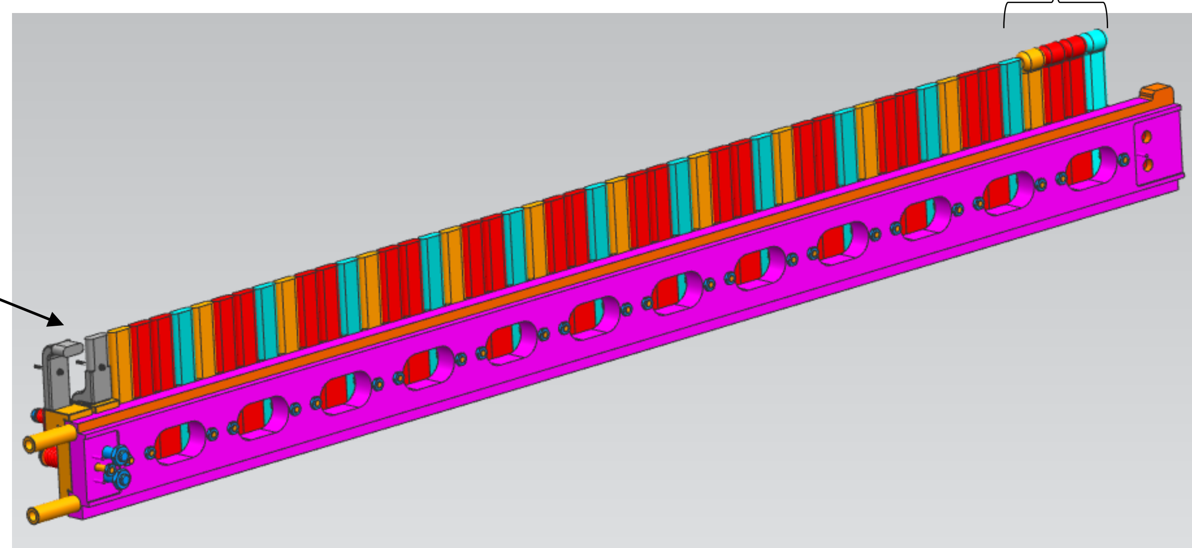
Graphite winged fins

- Addition of four winged fins at downstream end of target
- Provides protection for decay pipe window and Horn 1 neck in the event of completely mis-steered beam





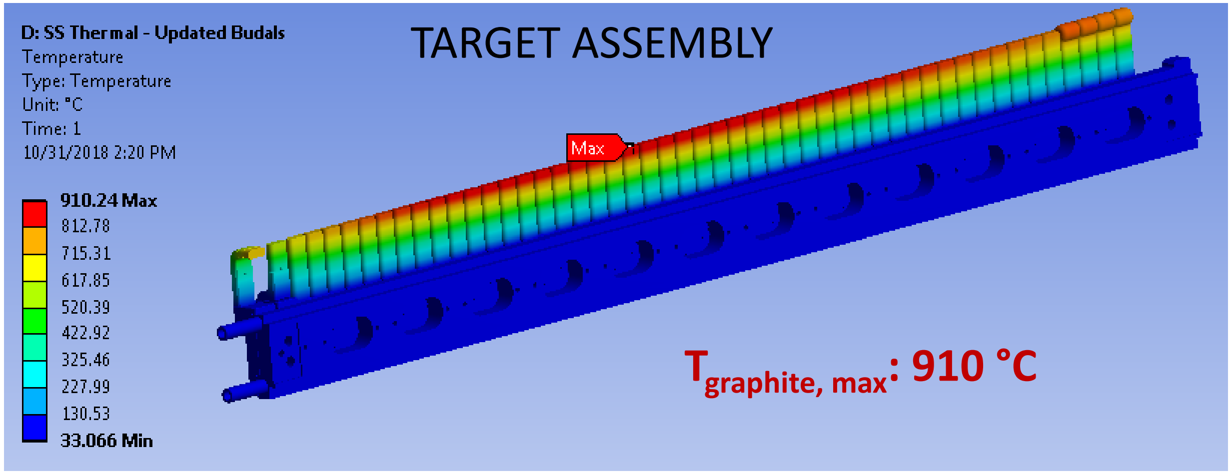
Winged fins



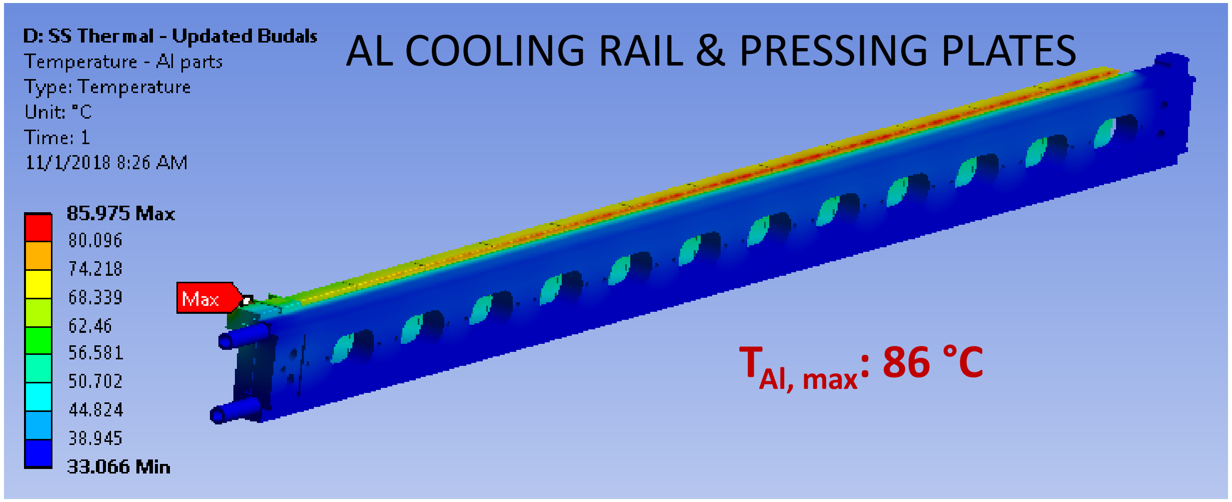
Updated Budal fins/brackets

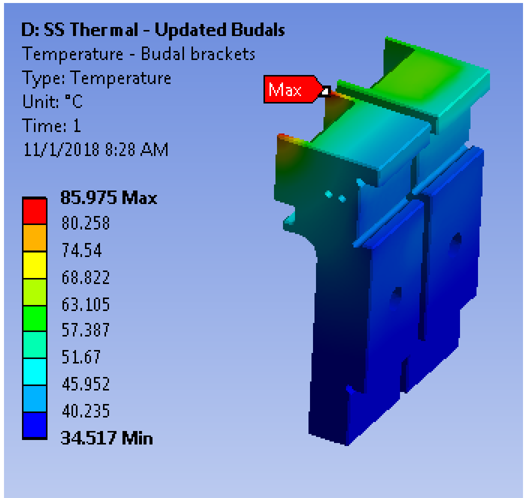
Steady-state thermal analysis

Updated assembly – **F10109309**



BUDAL FIN BRACKETS



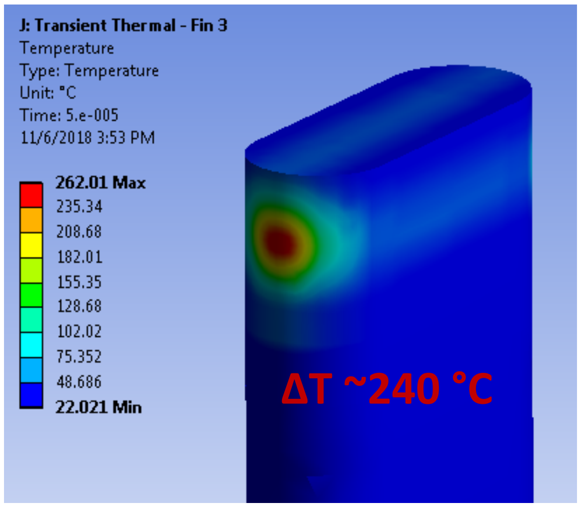


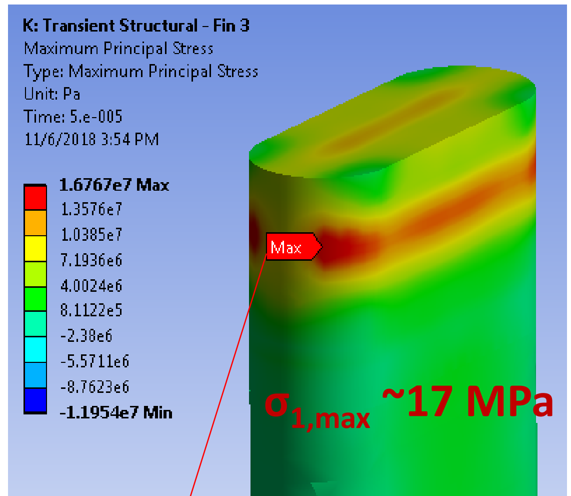
Transient structural analysis

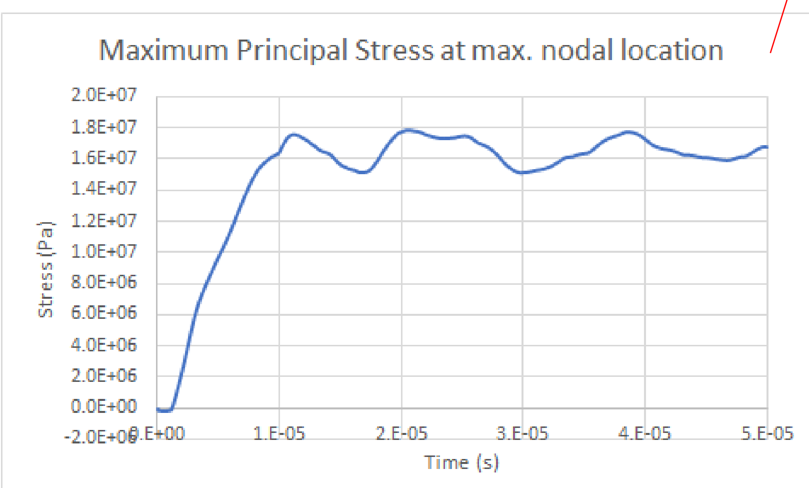
Dynamic stresses

POCO ZXF-5Q
Tensile strength: 79 MPa
Compressive strength: 175 MPa

- Analysis of Fin 3 (highest energy deposition)
- Single beam pulse starting at room temperature (22 °C)

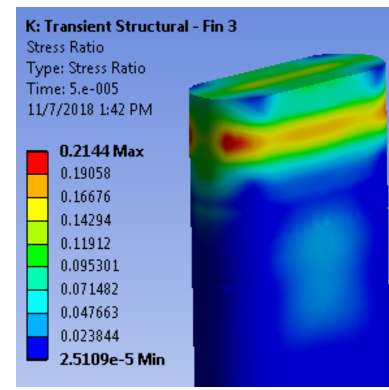


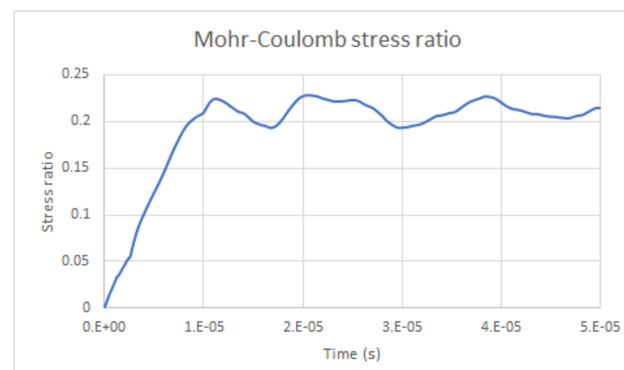




Mohr-Coulomb stress ratio design criterion

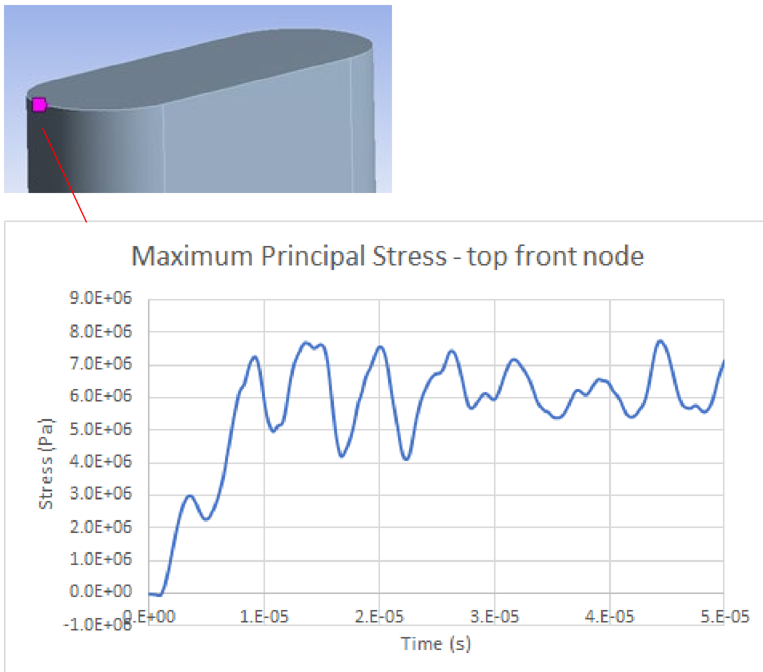
$$\frac{\sigma_1}{S_{tensile}} + \frac{\sigma_3}{S_{compressive}} < 1$$

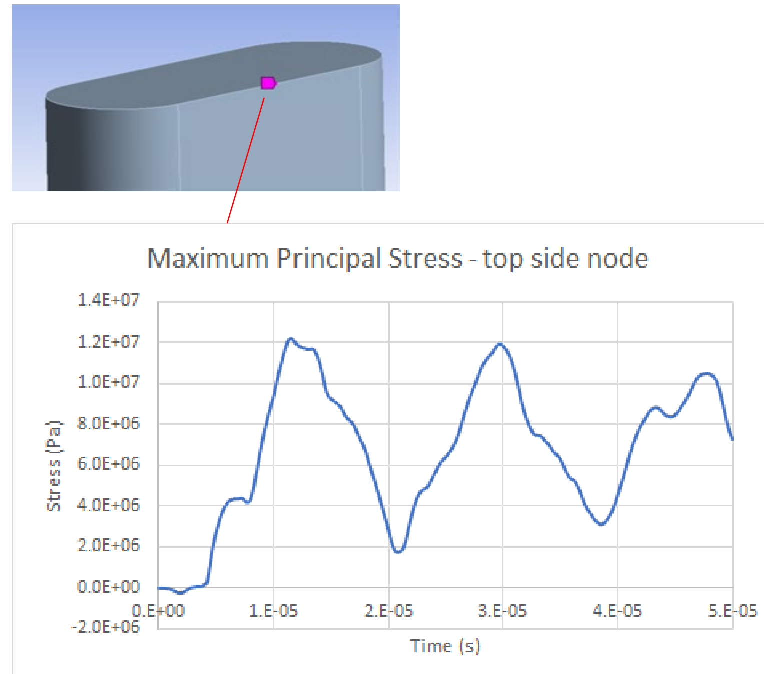




Transient structural analysis

Dynamic stresses at fin corner nodes



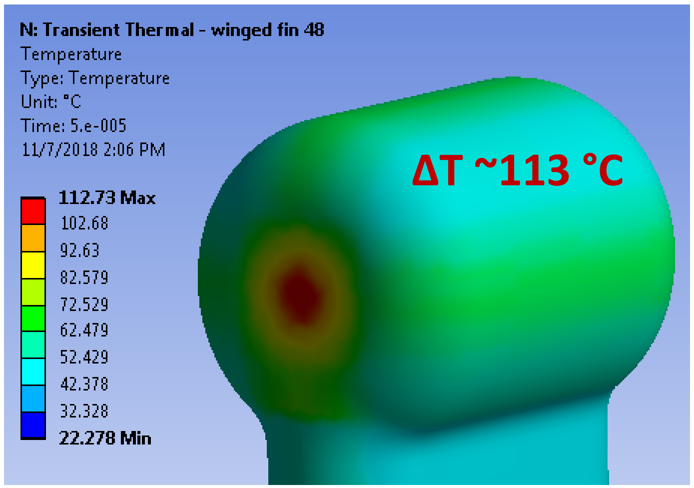


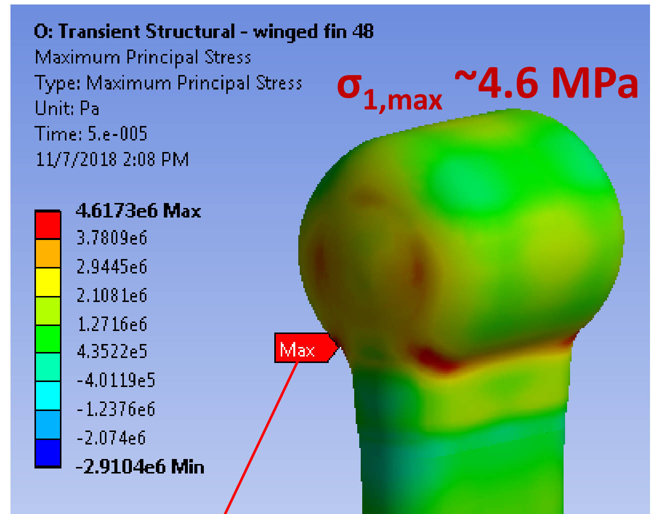
Transient structural analysis (winged fin)

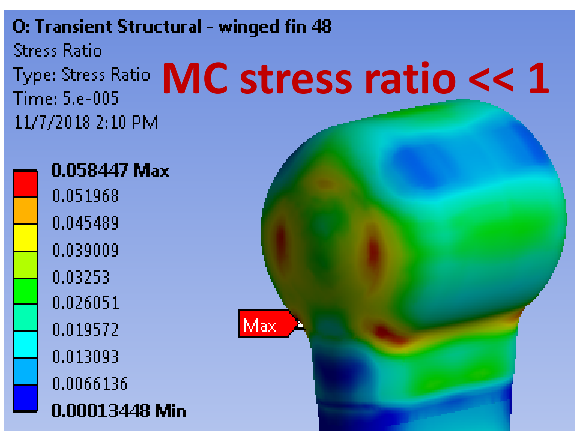
Dynamic stresses

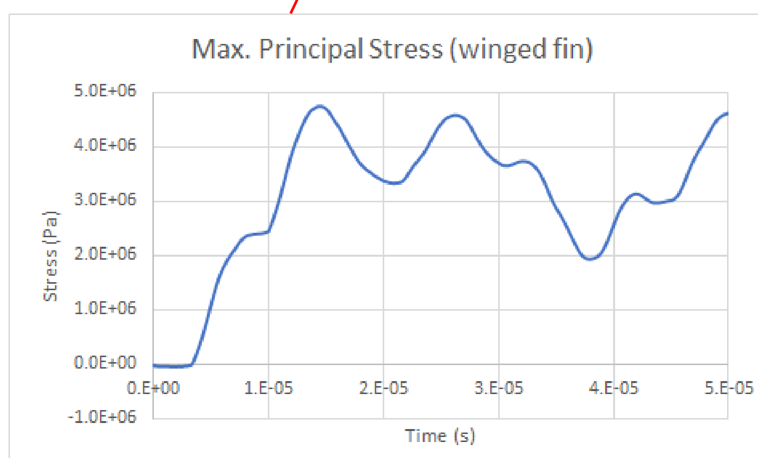
POCO ZXF-5Q
Tensile strength: 79 MPa
Compressive strength: 175 MPa

- Analysis of **winged** fin (Fin 48)
- Single pulse starting from room temperature (22 °C)





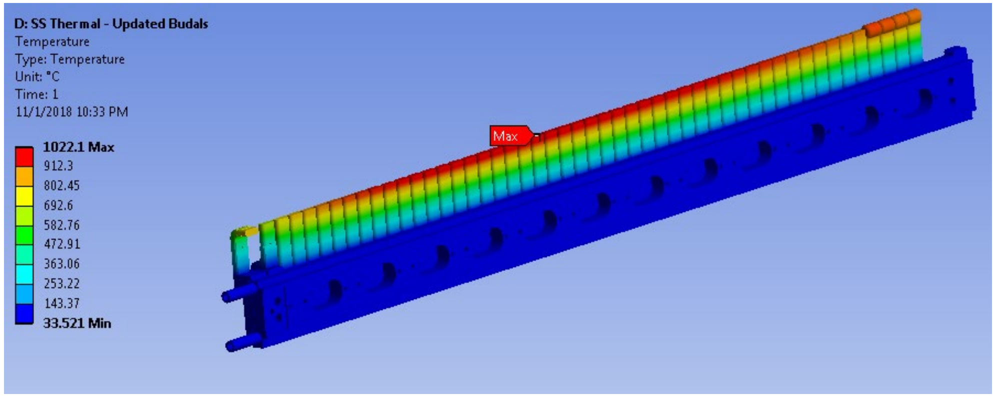




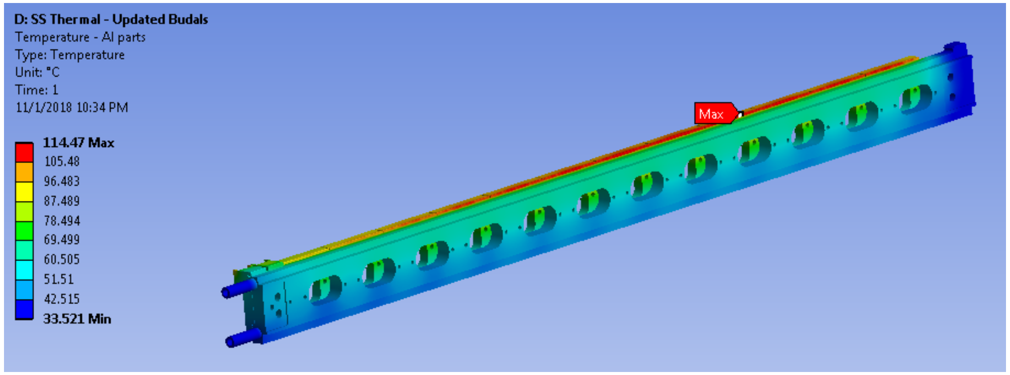
Steady-state thermal analysis

BCs sensitivity analysis

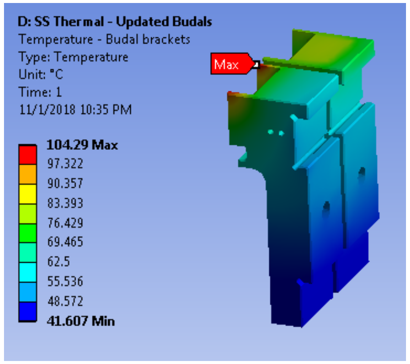
- Cooling water HTC: 5000 W/m^2.K (instead of 24500 W/m^2.K)
- Radiation emissivity: 0.5 (instead of 0.75)
- Free convection HTC: 2 W/m^2.K (instead of 5 W/m^2.K)



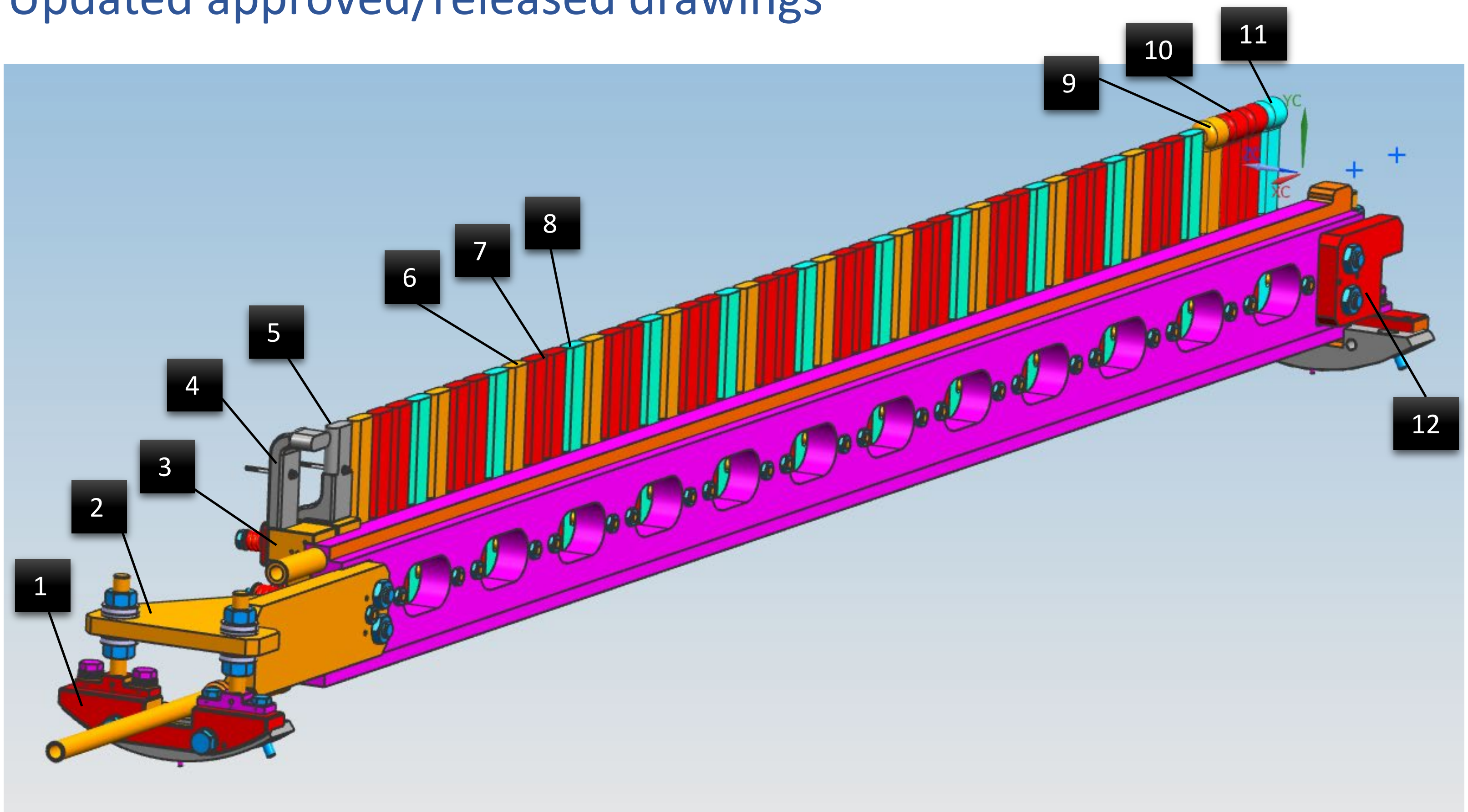
Peak graphite fin temperature
1022 °C



Peak Aluminum temperature
114 °C



Updated approved/released drawings



1. F10108227: Cooling rail support base plate
2. F10107744: Cooling rail upstream bracket
3. F10108973: Budal brackets
4. F10108968: NOVA 1 MW vertical Budal fin
5. F10110482: NOVA 1 MW horizontal Budal fin
6. F10107571: NOVA 1 MW upstream target fin
7. F10107446: NOVA 1 MW target fin
8. F10107571: NOVA 1 MW downstream target fin
9. F10108485: NOVA 1 MW upstream winged fin
10. F10108487: NOVA 1 MW winged fin
11. F10108486: NOVA 1 MW downstream winged fin
12. F10107743: Cooling rail downstream bracket

Next steps

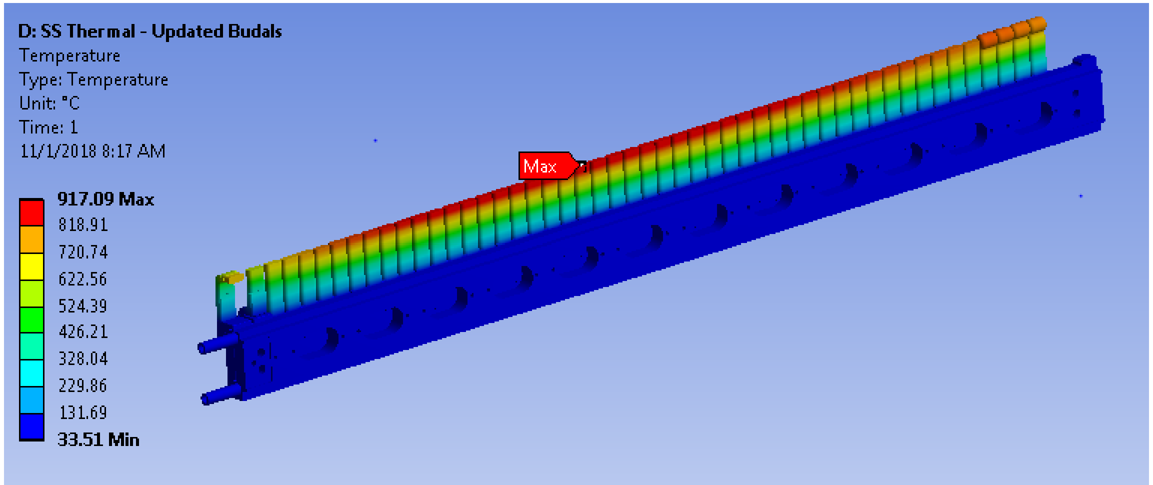
- Static structural analysis
  - Expansion and displacement along cooling rail
- Off-axis beam condition analysis
- Transient analysis of winged fins when positioned in upstream location
- Target canister downstream beryllium window analysis
- Fins procurement and new parts fabrication/modification
  - Plan to install 1 MW target during 2019 shutdown

Back-up slides

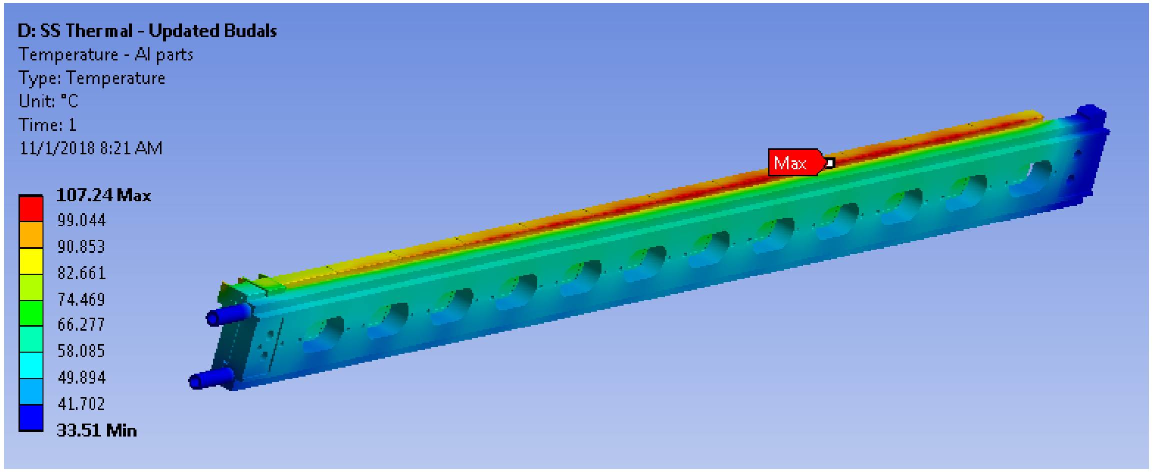
Steady-state thermal analysis

BCs sensitivity analysis

- Cooling water HTC: 5000 W/m^2.K (instead of 24500 W/m^2.K)



Peak graphite fin temperature
917 °C

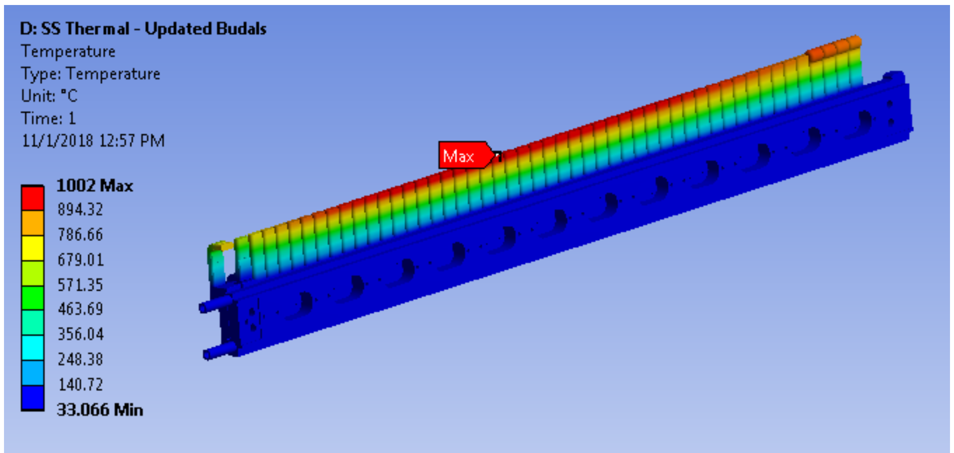


Peak Aluminum temperature
107 °C

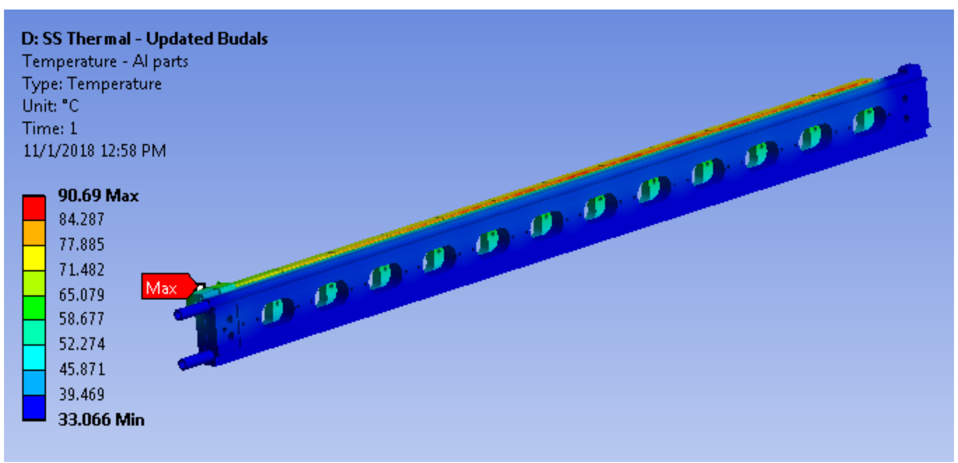
Steady-state thermal analysis

BCs sensitivity analysis

- Graphite emissivity: 0.5 (instead of 0.75)
- Ambient He temperature: 100 °C



Peak graphite fin temperature
1002 °C

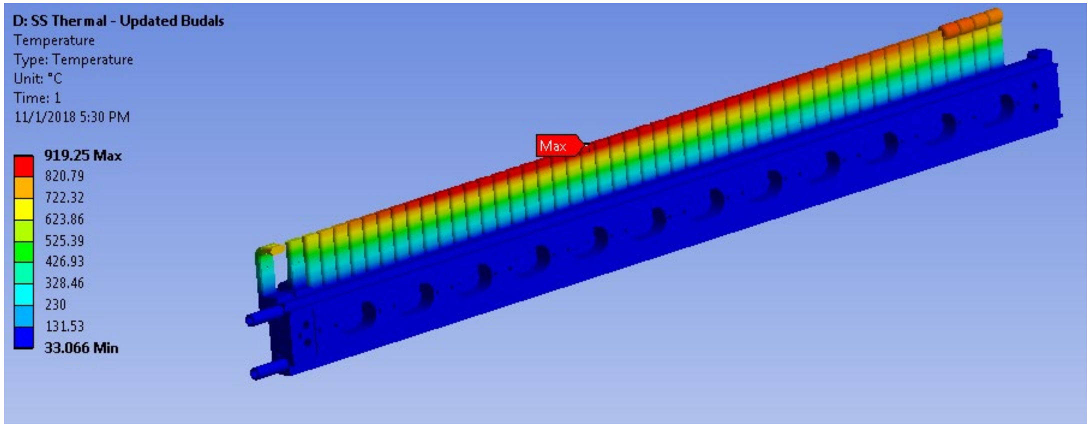


Peak Aluminum temperature
91 °C

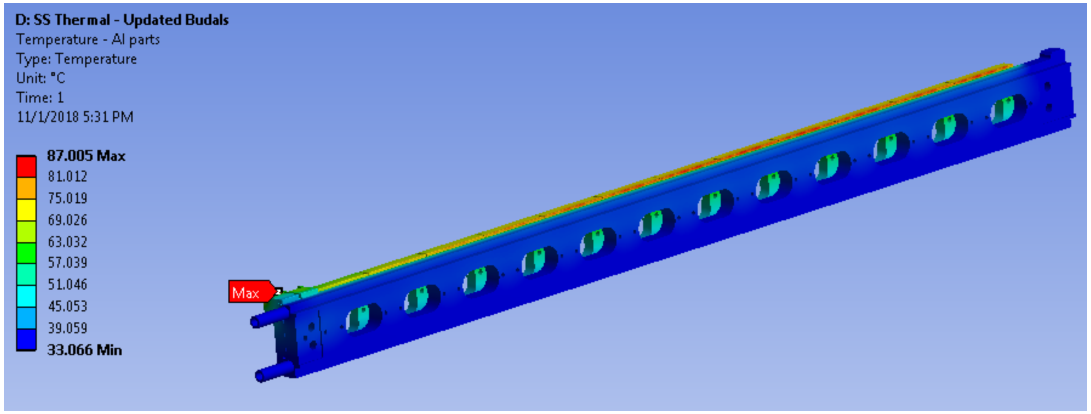
Steady-state thermal analysis

BCs sensitivity analysis

- Free convection HTC: 2 W/m^2.K (instead of 5 W/m^2.K)
- Ambient He temperature: 100 °C



Peak graphite fin temperature
919 °C

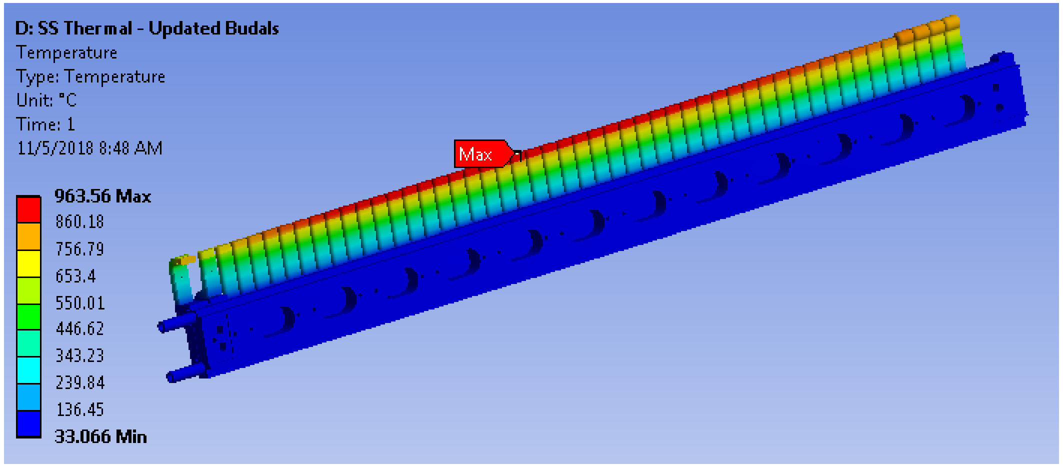


Peak Aluminum temperature
87 °C

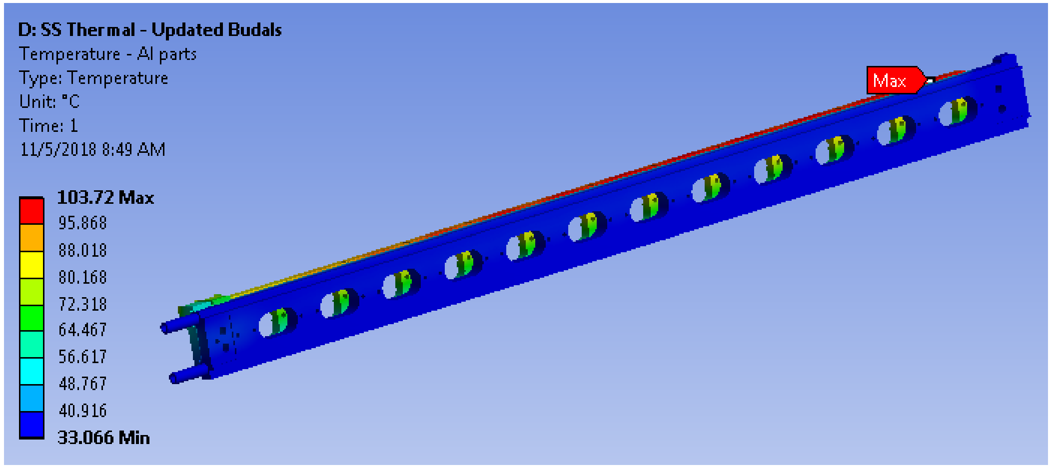
Steady-state thermal analysis

BCs sensitivity analysis

- Non-perfect thermal contact conductance
  - Assume at 25 µm He gap between contacts
    - Gap conductance: 7240 W/m^2.K (k_{He} @ 100 °C = 0.181 W/m.K)



Peak graphite fin temperature
964 °C



Peak Aluminum temperature
104 °C

Boundary conditions sensitivity analysis summary

Steady-state temperature

Boundary conditions sensitivity analysis		**Case 1**	**Case 2**	**Case 3**	**Case 4**
Emissivity	**0.75**	0.75	0.5	0.75	0.5
Free conv. HTC ($W/m^2.K$)	**5**	5	5	2	2
Water cooling HTC ($W/m^2.K$)	**24500**	5000	24500	24500	5000
Peak Graphite Temperature (°C)	**910**	917	1002	919	1022
Peak Aluminum Temperature (°C)	**86**	107	91	87	114

Graphite material properties