LBNF Hadron Absorber

Preliminary Design Review

LBNF Hadron Absorber Core Blocks and Steel Shielding Energy Deposition and Thermal and Stress Analyses

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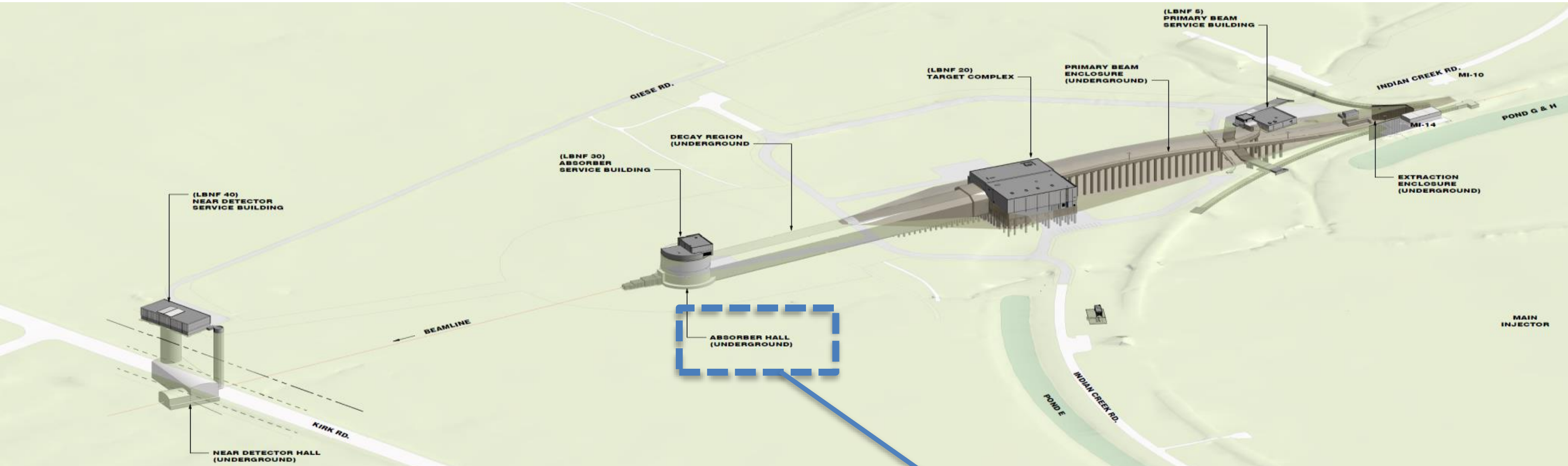
Fermilab CERN Sanford Underground Research Facility U.S. DEPARTMENT OF ENERGY Office of Science

Overview

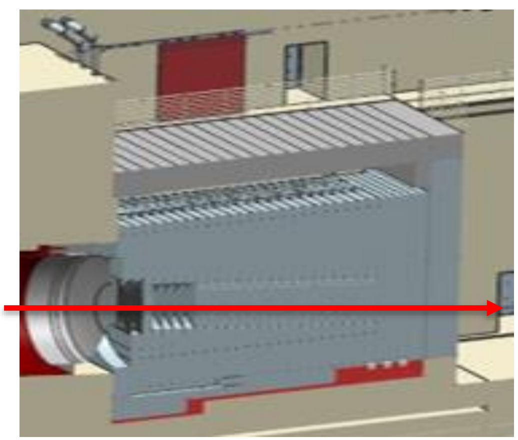
- Introduction
- Energy deposition, temperatures, and stresses in core
- Accident condition
- Beam interlock hardware system
- Surrounding steel temperatures
- Radiological protection
- Summary
- Questions and discussion

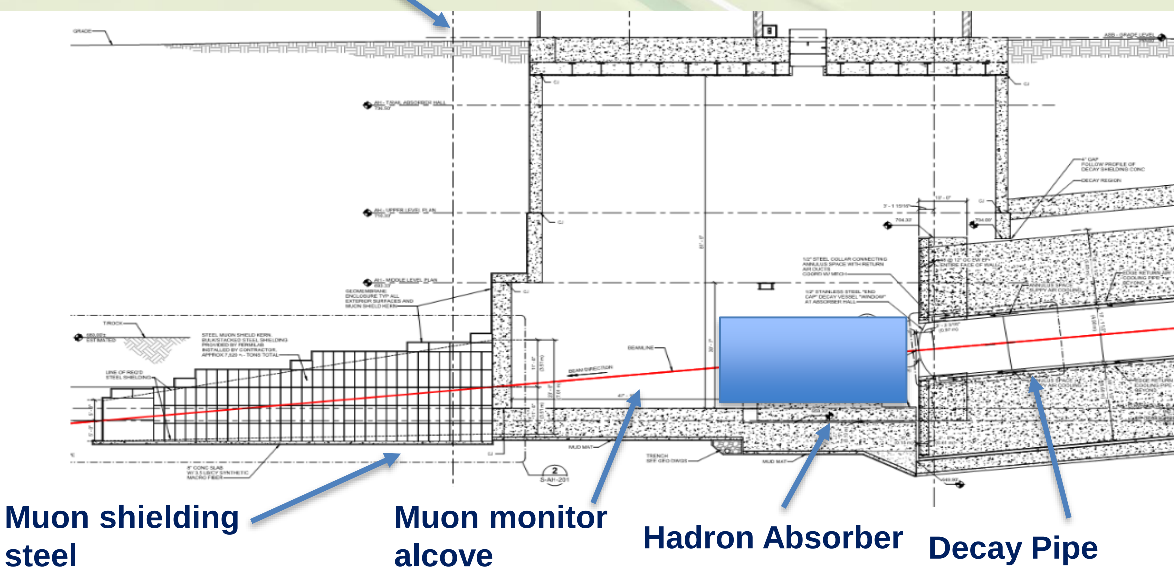
Introduction

Long-Baseline Neutrino Facility at Fermilab



Hadron Absorber Cross-section





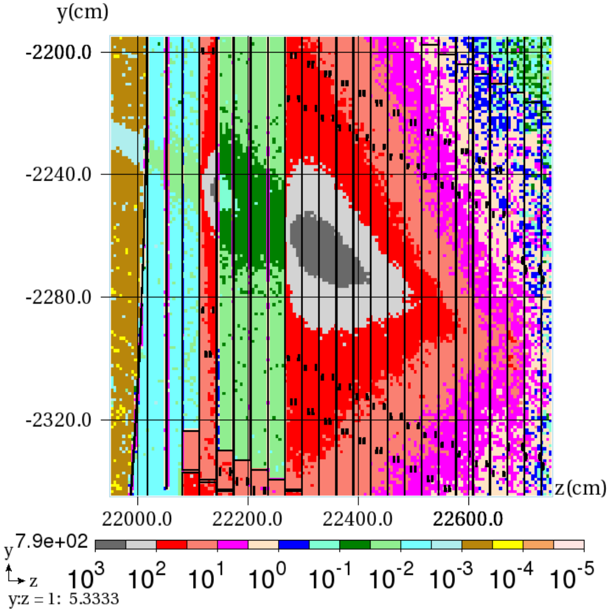
Introduction: Hadron Absorber

- Located directly downstream of the decay pipe –made up of actively cooled Aluminum and Steel blocks surrounded by concrete.
- Provides radiation protection to people and keeps soil/groundwater activation levels to below allowable limits.
- Designed for the worst case condition at 2.4 MW operation:
  - Shortest possible decay distance [221m from MCZero to end of decay pipe].
  - Helium filled decay pipe.
  - For a 1.5-m RAL style target.
  - Designed to sustain 2 successive beam accident pulses –interlock system limits the accident pulses to 1.

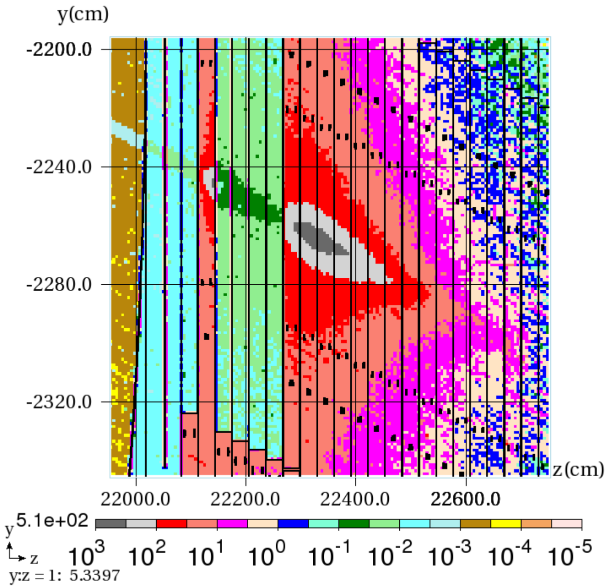
Energy deposition, temperatures, and stresses in the core

- The energy deposition in the Absorber strongly depends on the target design.
- Several target designs have been considered, the current target is the 1.5-m RAL target.

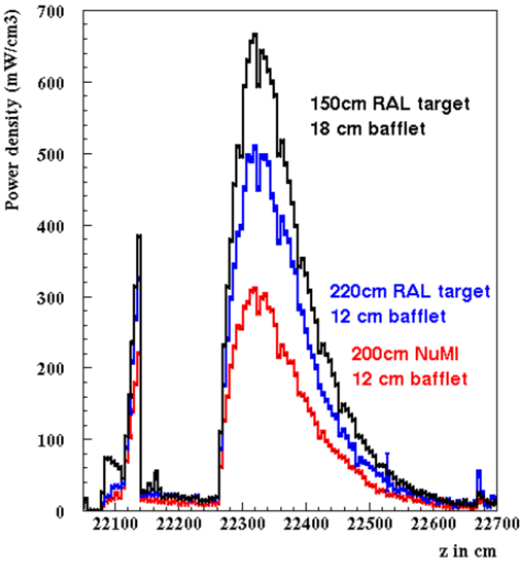
Sergi Striganov, Dune-doc-17064



150 cm RAL target



220 cm RAL target



Energy deposition, temperatures, and stresses in the core

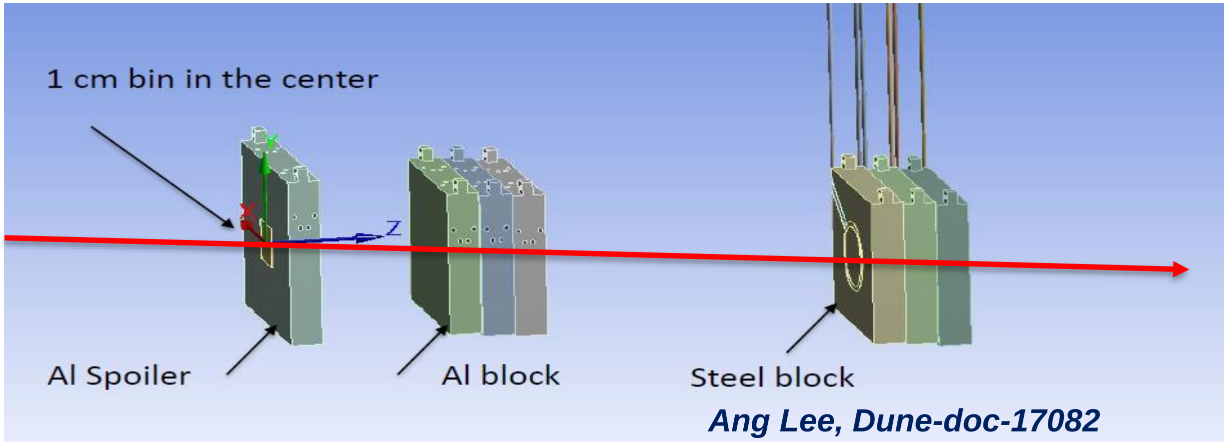
- The power deposited in individual Absorber components (kW):

	150 cm RAL target	220 cm RAL target	NuMI-type target
Al central	228.7	213.8	277.9
Steel core	4.0	2.9	3.3
Steel others	240	96.8	115.7
Concrete	3.0	2.4	3.0
Others	1.5	1.4	0.2
Total	**477.2**	**317.1**	**400.1**

Sergi Striganov, Dune-doc-17064

Energy deposition, temperatures, and stresses in the core

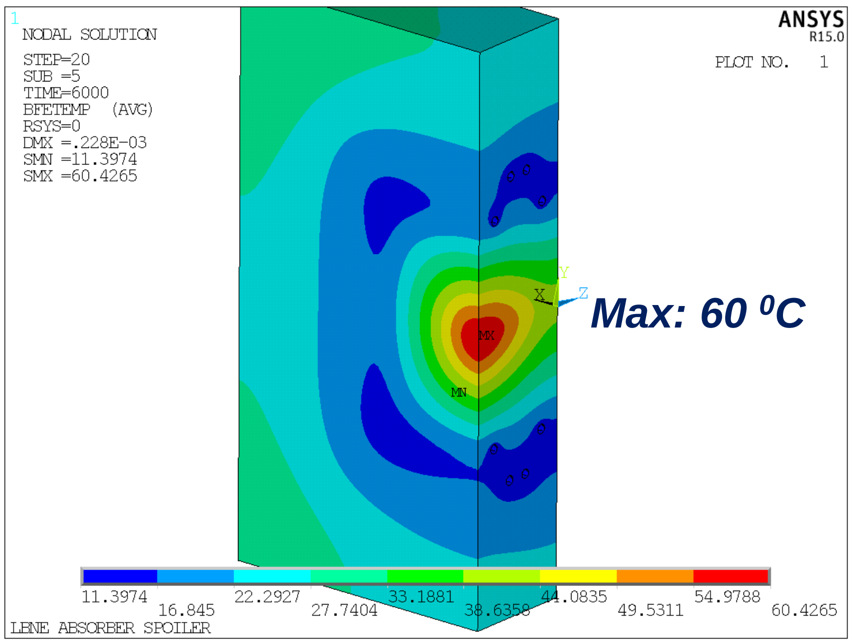
- One of the main considerations in an Al core design is keeping its components at temperatures below 100 ^{0}C.
- At elevated temperatures, 6061-T6 undergoes creep.
- Steady state thermal/structural analysis was done on:
  - Aluminum spoiler
  - First three Aluminum core blocks
  - First steel block
- Steady state energy deposition was for the 2.4-MW operations, 1.5-m RAL target case.



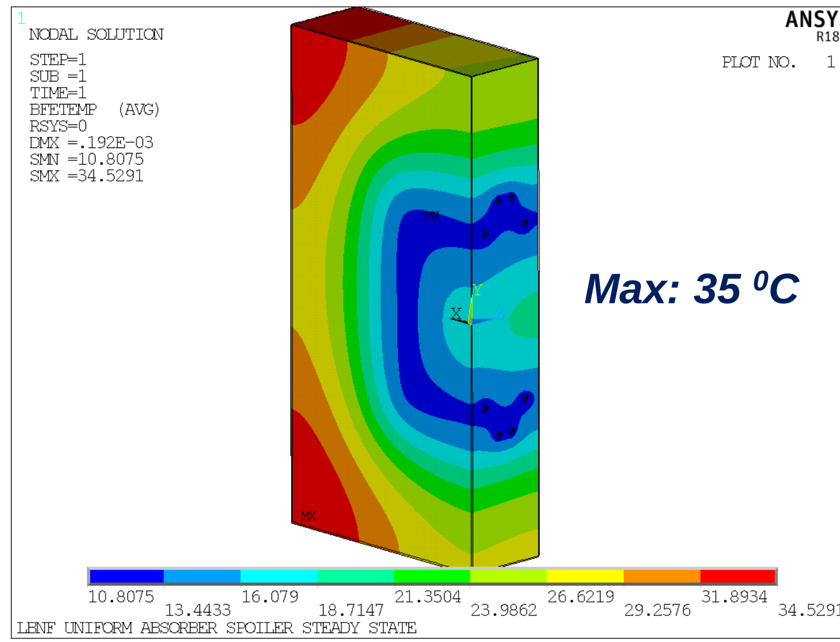
Energy deposition, temperatures, and stresses in the core

- Analyses done on previous designs.
- Spoiler temperatures below.
- Water inlet temperature is 10 ^{0}C.

Reference Design: 1-m Target



Optimized Design: 2-m Target

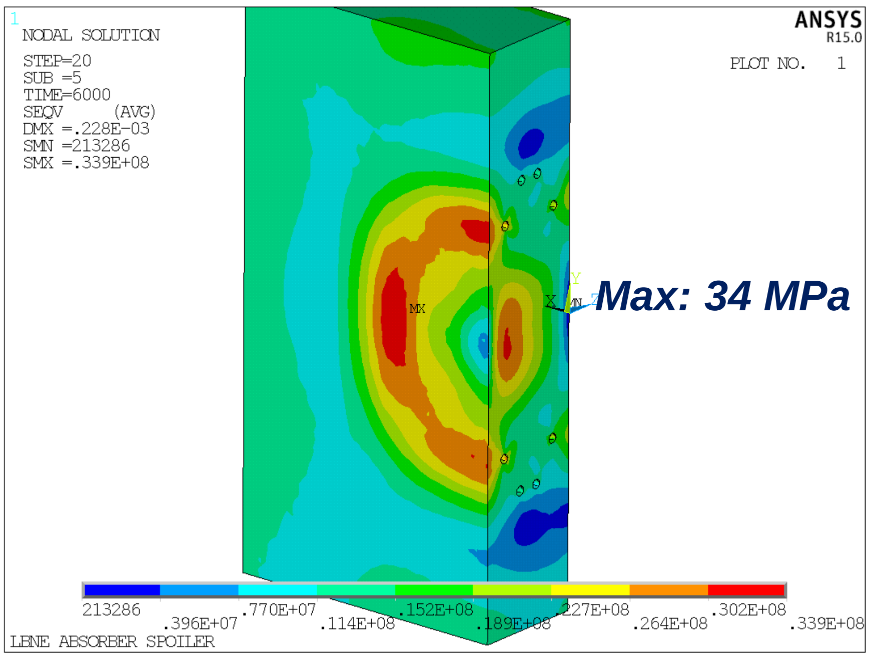


Brian Hartsell, Dune-doc-6602

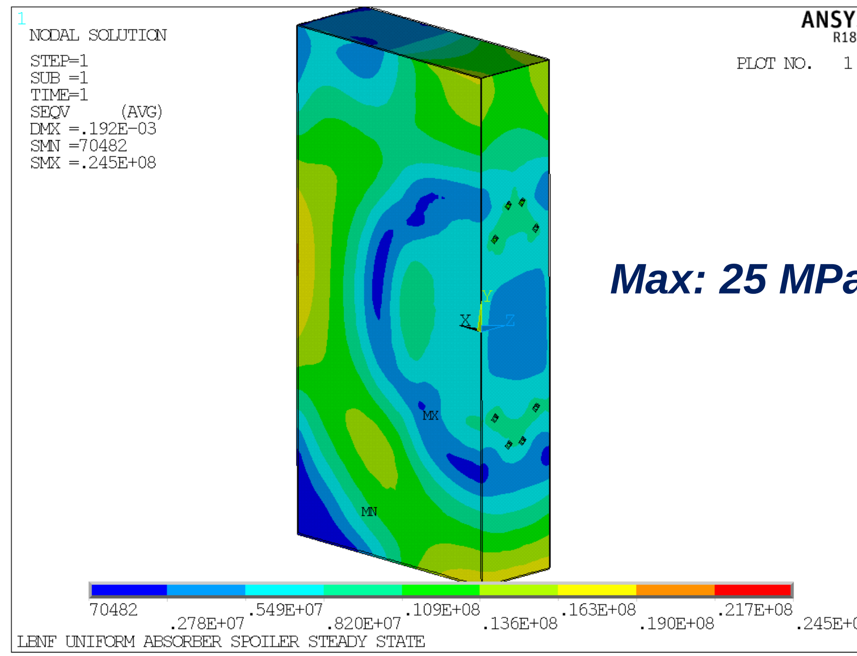
Energy deposition, temperatures, and stresses in the core

- Analyses done on previous designs.
- Spoiler stresses below.
- Water inlet temperature is 10 ^{0}C.

Reference Design: 1-m Target



Optimized Design: 2-m Target

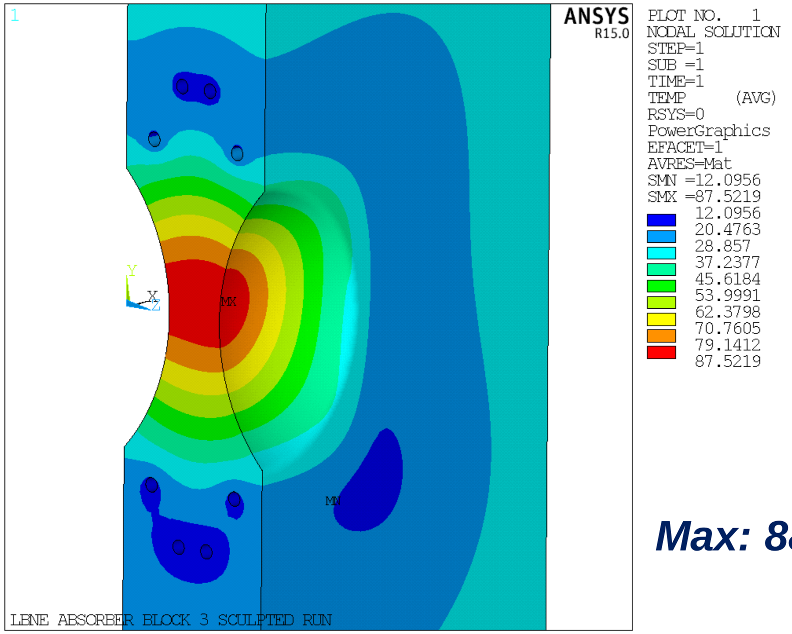


Brian Hartsell, Dune-doc-6602

Energy deposition, temperatures, and stresses in the core

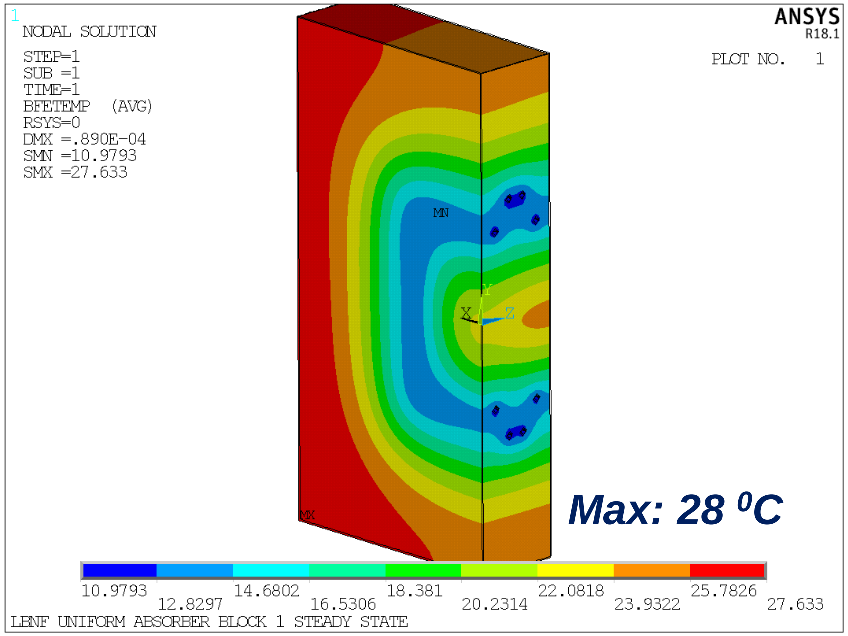
- Analyses done on previous designs.
- First Al core block temperatures below.
- Water inlet temperature is 10 ^{0}C.
- In the reference design, the core blocks were sculpted.

Reference Design: 1-m Target



Max: 88 ^{0}C

Optimized Design: 2-m Target



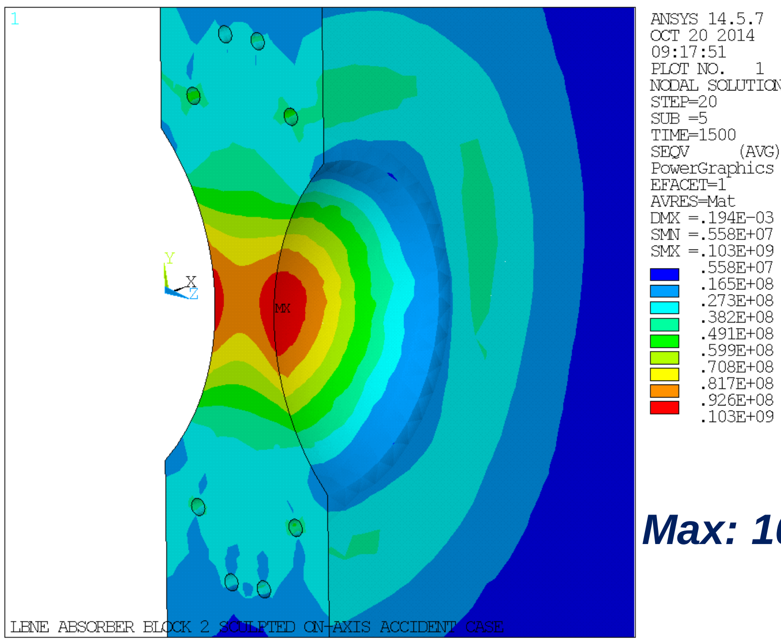
Max: 28 ^{0}C

Brian Hartsell, Dune-doc-6602

Energy deposition, temperatures, and stresses in the core

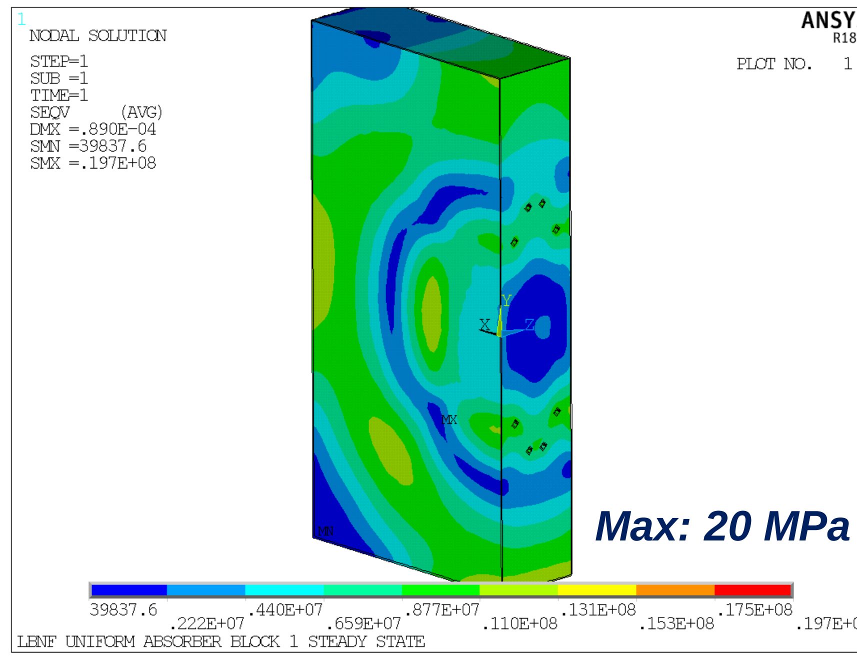
- Analyses done on previous designs.
- First Al core block stresses below.
- Water inlet temperature is 10 ^{0}C.

Reference Design: 1-m Target



Max: 103 MPa

Optimized Design: 2-m Target



Max: 20 MPa

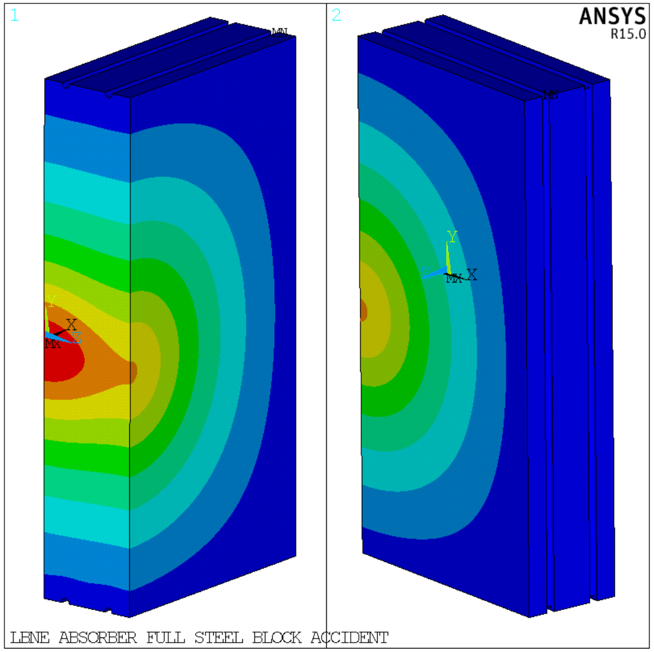
Brian Hartsell, Dune-doc-6602

Energy deposition, temperatures, and stresses in the core

- Analyses done on previous designs.
- First steel core block stresses below.
- Water inlet temperature is 10 ^{0}C.

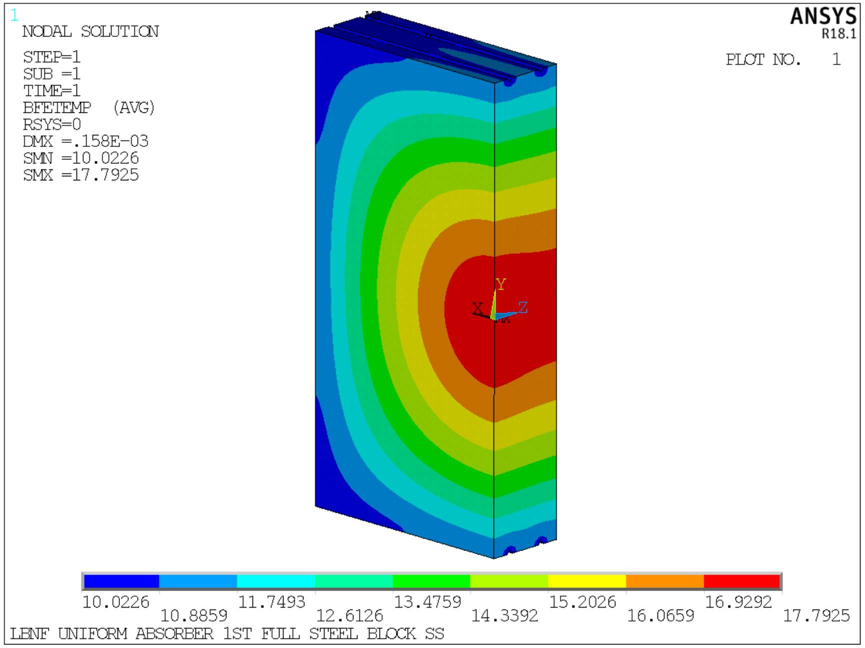
Brian Hartsell, Dune-doc-6602

Reference Design: 1-m Target



Max: 225 ^{0}C

Optimized Design: 2-m Target

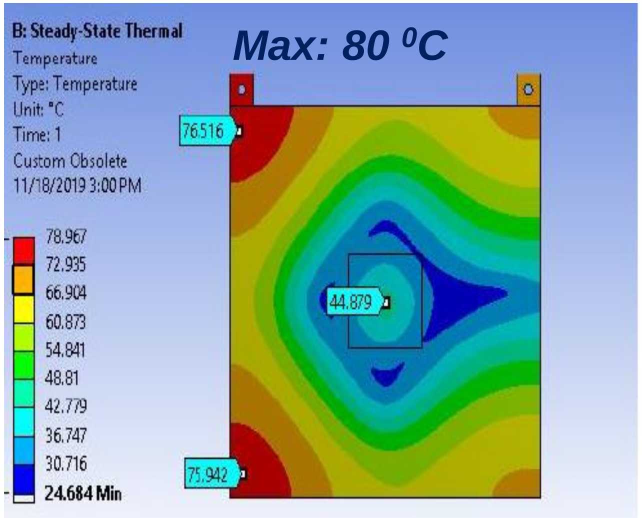


Max: 18 ^{0}C

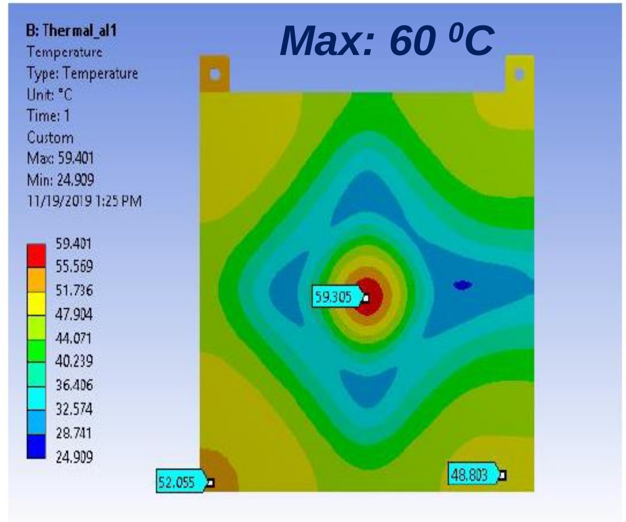
Energy deposition, temperatures, and stresses in the core

Temperatures for 1.5-m RAL Target, 2.4 MW operations

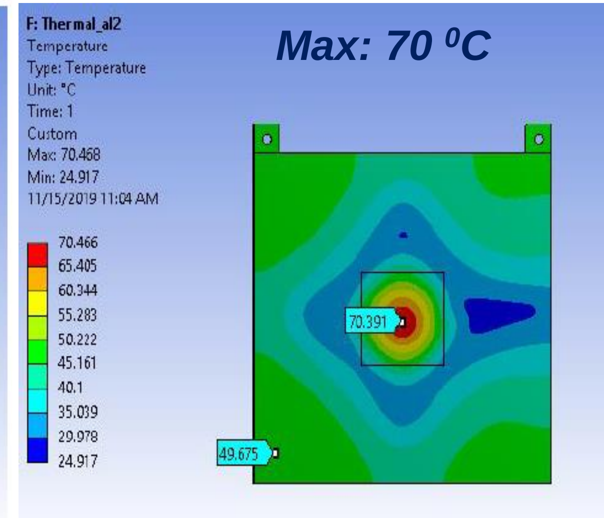
Al Spoiler



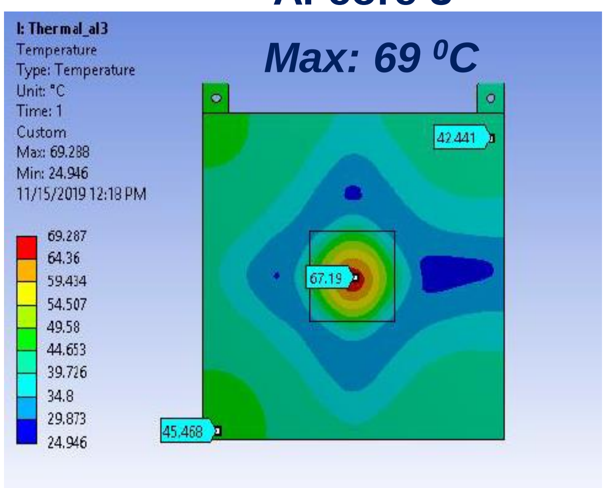
Al core 1



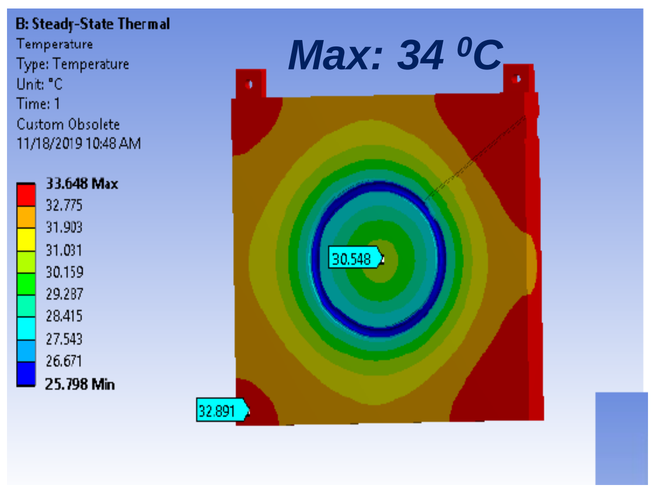
Al core 2



Al core 3



Steel core 1



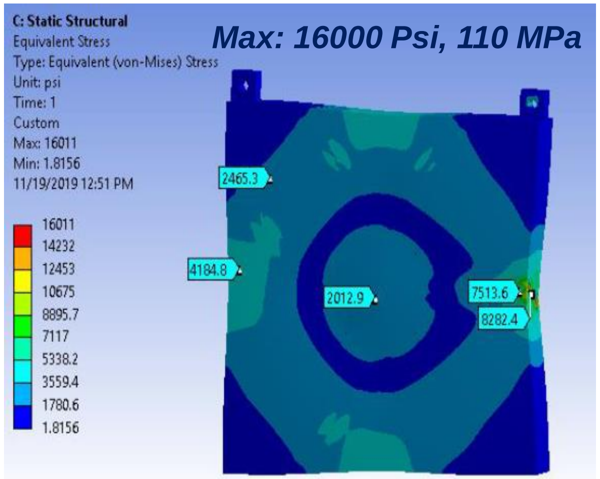
- **Cooling water inlet temperature: 25 ⁰C.**
- **Heat transfer coefficient of 7000 W/m²-K applied to all cooling channels.**
- **Cooling water flow per gun-drilled channel: 20 Gpm.**

Ang Lee, Dune-doc-17082

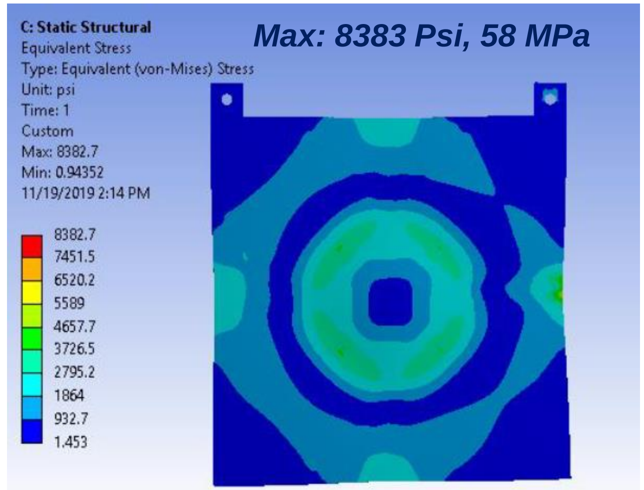
Energy deposition, temperatures, and stresses in the core

Stresses for 1.5-m RAL Target, 2.4 MW operations

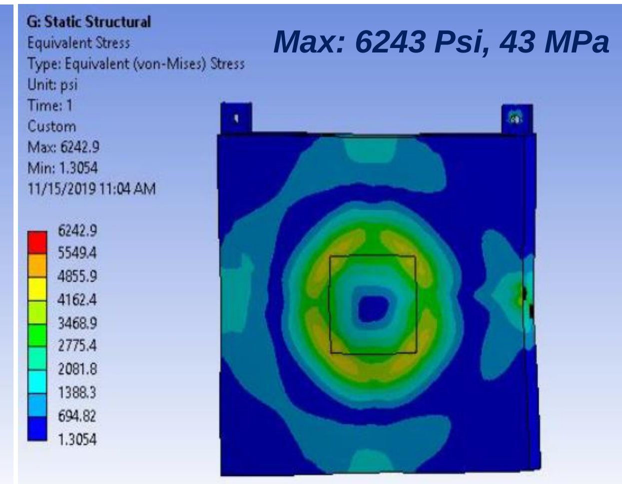
Al Spoiler



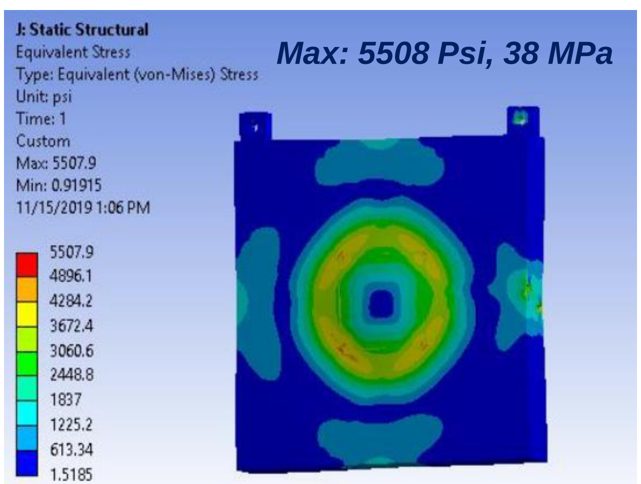
Al core 1



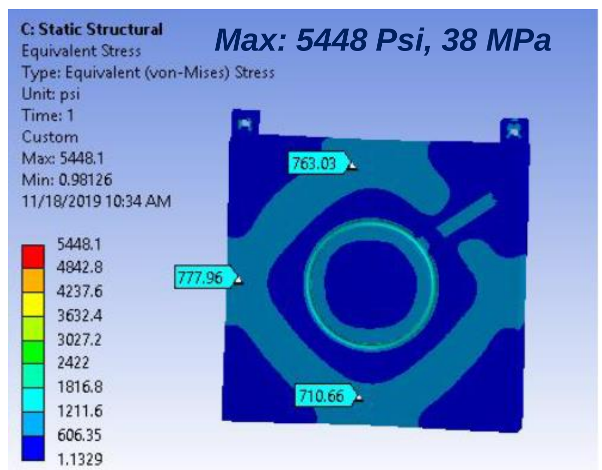
Al core 2



Al core 3



Steel core 1



- **Restrained at the pinned connections at the top.**
- **All other surfaces free to move.**
- **Yield of 6061-T6 at 92 ^{0}C is 232 MPa.**

Ang Lee, Dune-doc-17082

Energy deposition, temperatures, and stresses in the core

- Max Al temperatures and stresses simulated are 80 ^{0}C and 110 MPa for the current target case. It must be noted that the 110 MPa value is a stress concentration occurring in a small region at a sharp corner.
- Conservative operations predictions are that during a 20-year operation of the Absorber, there will be 5 cooldowns/day. This is 3.6x10^4 cycles.
- For 10^5 cycles, the fatigue strength of 6061-T6 is 165 MPa at 150 ^{0}C.

Cantilever-Beam Fatigue Strengths of Aluminum Alloys at Elevated Temperatures Following Stabilization at the Test Temperature

Cantilever-Beam Strengths at Elevated Temperatures (Stabilized) (continued)

Alloy	Temper	Product form	Testing temperature °F	Testing temperature °C	Holding time, days	No. of samples	Fatigue strengths at indicated cycles: 10^4 cycles ksi	10^4 cycles MPa	10^5 cycles ksi	10^5 cycles MPa	10^6 cycles ksi	10^6 cycles MPa	10^7 cycles ksi	10^7 cycles MPa
6061	T6	Rolled rod and shapes, plate, forgings, extrusions	75	25	...	18	44	305	31	215	23	160	17	115
		Rolled rod and shapes	300	150	300	1	...	...	24	165	18	125	14	95
			400	205	200	1	24	165	19	130	15	105	11	75
			500	260	100	1	8.5	59	7.5	52	6	41	5.5	38

Researched by Brian Hartsell, Properties of Aluminum Alloys, Kaufman (1999)

Energy deposition, temperatures, and stresses in the core

- Also, average stress to produce 1% creep at 100 ^{0}C over a 10-year period is 172 MPa.
- Also, the average stress necessary for a 0.1% creep at 100 ^{0}C over 1,000 hours is 250 MPa.

TABLE 13-4

Creep Factors for Aluminum Bus Conductors

(Average stress required during a 10-year period to produce 1.0% creep at 100°C, assuming well-designed bolted connections.)

Alloy and Temper	Estimated Average Stress PSI
1350-H111	2,500
1350-H12	5,000
1350-H17 and 6101-T61	6,500
6101-T6	18,000
6063-T6	24,000
6061-T6	25,000

172 MPa

Researched by Brian Hartsell, Aluminum Electrical Conductor Handbook, Kirkpatrick (1989)

6061-T6, -T651, -T6511 (Except for T6 Sheet and Rolled-and-Drawn Products): Creep and Stress-Relaxation Properties

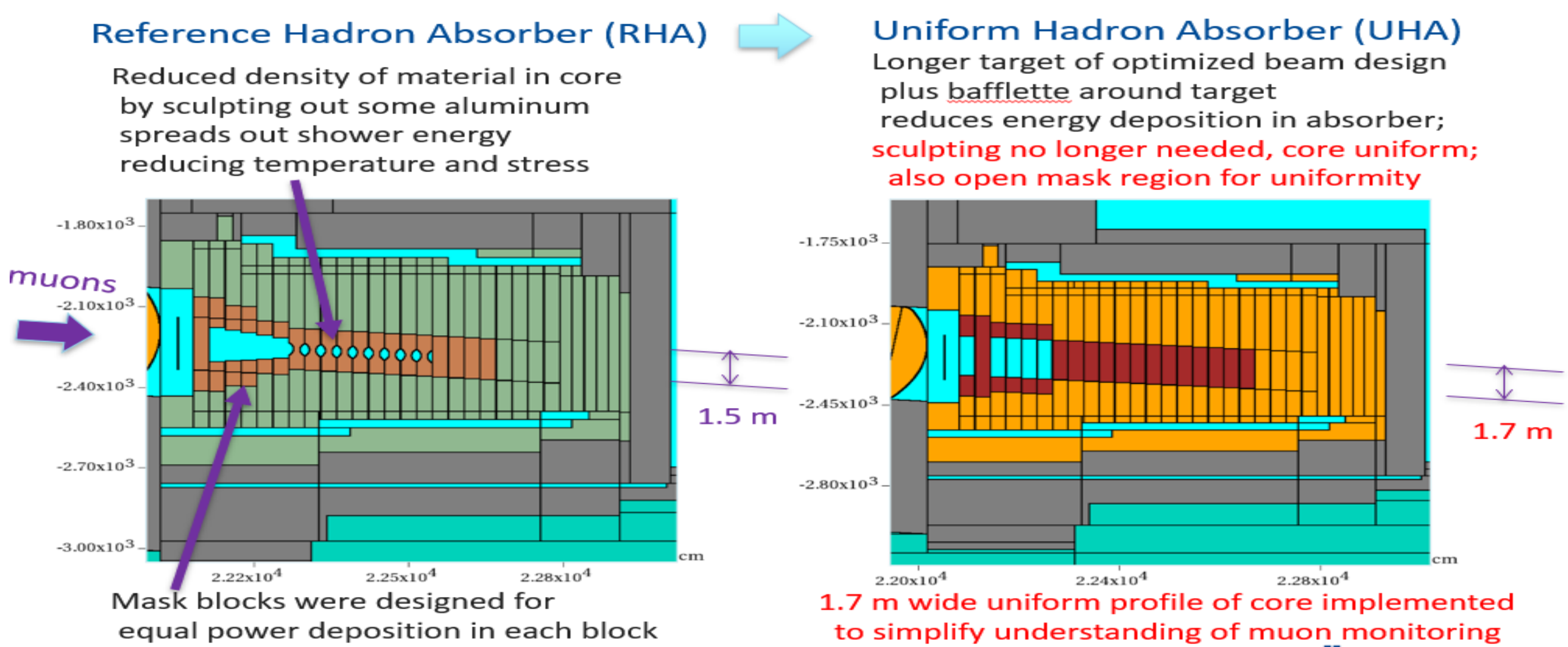
Temperature		Time under stress, h	Rupture stress		Stress at 1.0% creep		Stress at 0.5% creep		Stress at 0.2% creep		Stress at 0.1% creep	
°F	°C		ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
75	25	0.1	45	310	45	310	44	305	43	295	42	290
		1	45	310	45	310	43	295	42	290	42	290
		10	45	310	44	305	43	295	42	290	42	290
		100	45	310	44	305	42	290	42	290	41	285
		1,000	45	310	43	295	42	290	41	285	41	285
		...	...	...	...	...	...	...	...	...	...	...
212	100	0.1	41	285	40	275	40	275	39	270	38	260
		1	40	275	39	270	39	270	38	260	38	260
		10	39	270	38	260	38	260	38	260	37	255
		100	38	260	38	260	38	260	37	255	37	255
		1,000	37	255	37	255	37	255	37	255	36	250
		...	...	...	...	...	...	...	...	...	...	...

Researched by Brian Hartsell, Properties of Aluminum Alloys, Kaufman (1999)

Accident condition

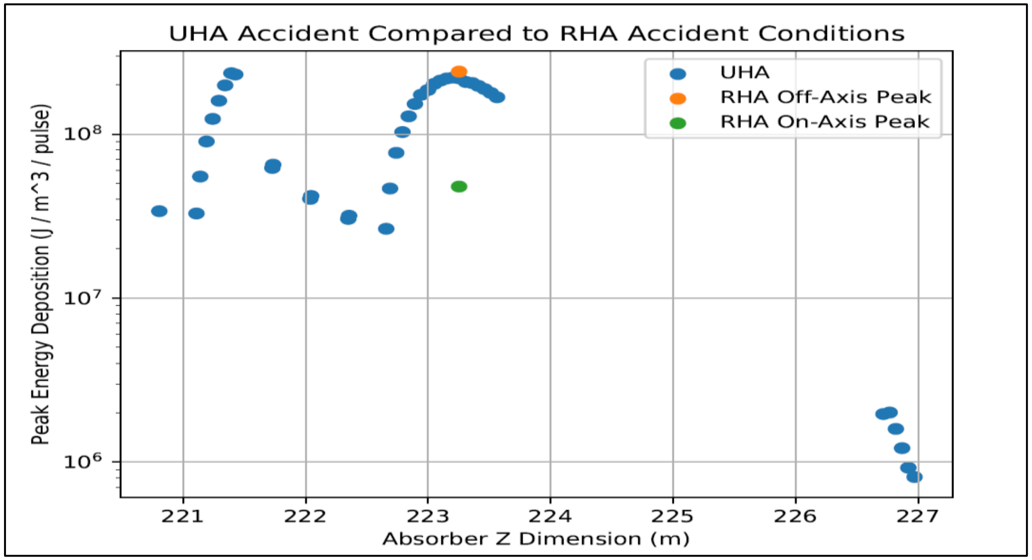
- The Absorber needs to survive 2-accident pulses.
- Two accident conditions that are evaluated: On-axis and Off-axis.
- An accident condition is when the beam hits the Absorber directly without interacting with the Target; a conservative assumption.
- The target is surrounded by the baffle and the bafflette; which make the accident conditions studied extremely unlikely; actual energy density will be much less.
- In order to understand these two conditions, an older design of the Absorber (RHA) will be discussed. A comparison between the two designs is below:

Jim Hylen, Dune-doc-10806



Accident condition

- Also, the RHA off-axis peak energy deposition value is higher than that of the UHA on-axis case:

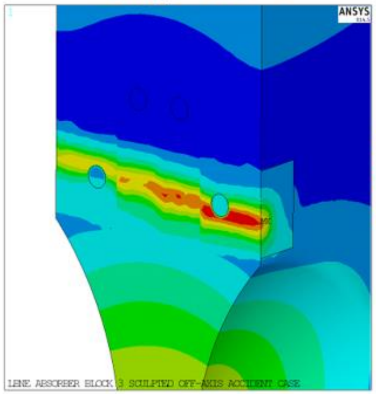


Jim Hylen, Dune-doc-10806

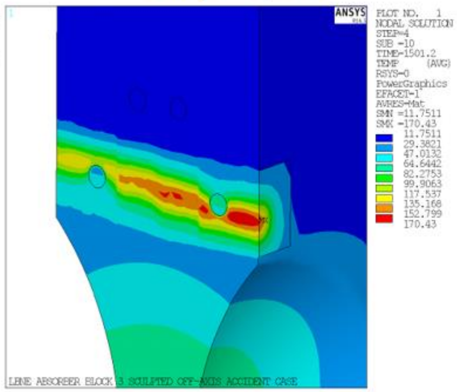
- RHA off-axis accident condition temperatures and stresses were shown (previous design review) to have no detrimental effects on the Aluminum blocks, Brian Hartsell, LBNE DocDB: 10992.

Accident condition, Off-axis, RHA

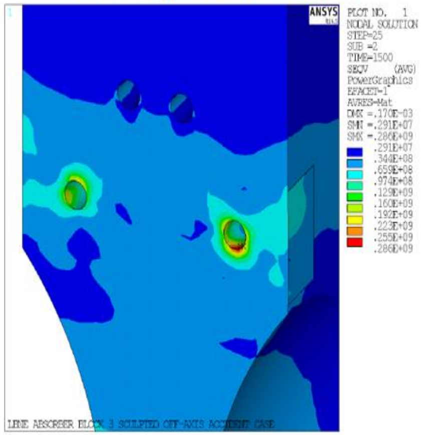
End of first pulse. Max temp~116 ^{0}C



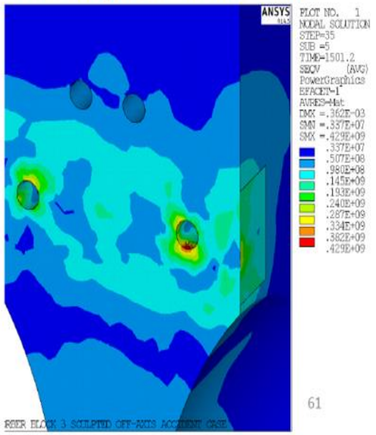
End of second pulse. Max temp~170 ^{0}C



After first pulse – 286MPa Max

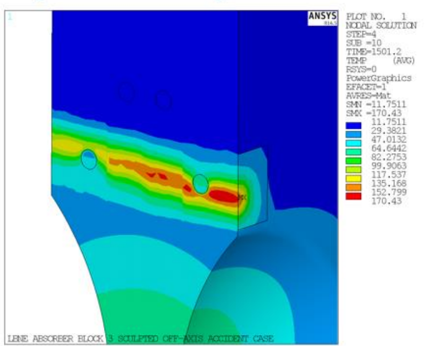


After two pulses – 429MPa Max

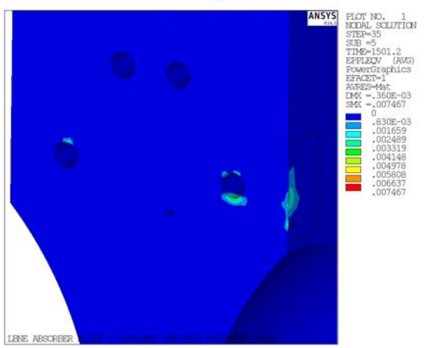


- The accident pulse happens at the end of steady state. 1.5e14 protons, 10 us pulse, 1.2 sec cycle time—a conservative assumption.
- Area of stress is limited to very small volume and is highly dependent on where the beam strikes.
- Heating material up to ~170 ^{0}C for a short time is not an issue.
- Maximum energy deposition in sculpted Al block 2. Some localized yielding occurs after two pulses, but plastic strain to failure is 16%--simulations predict 0.7%. No melting possible after 10 pulses with maximum temperature of 360 ^{0}C.

Temperature after 2 pulses – 170C Max



Plastic strain after 2 pulses – 0.7% Max

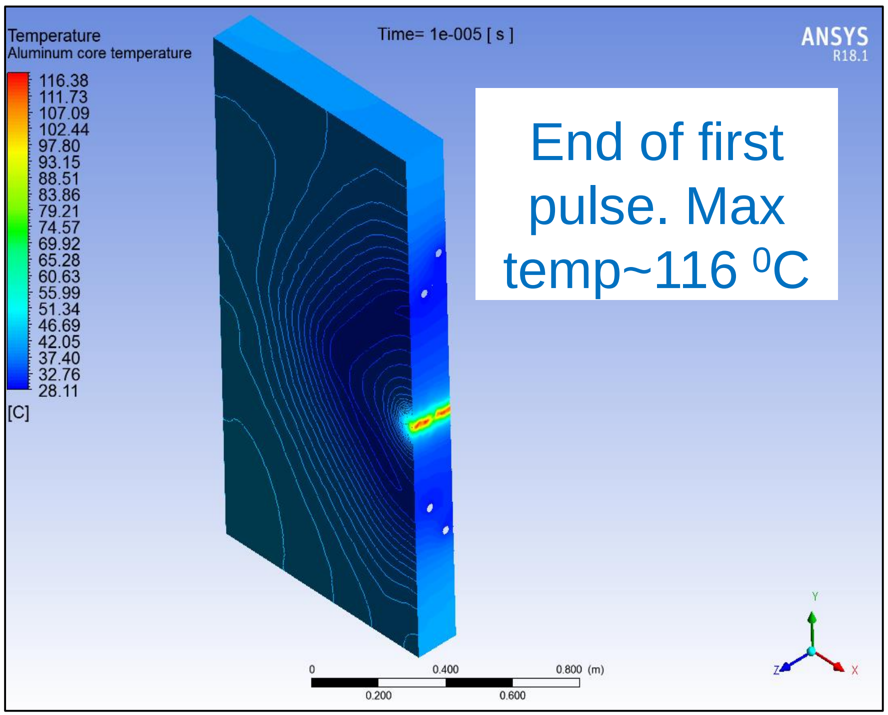


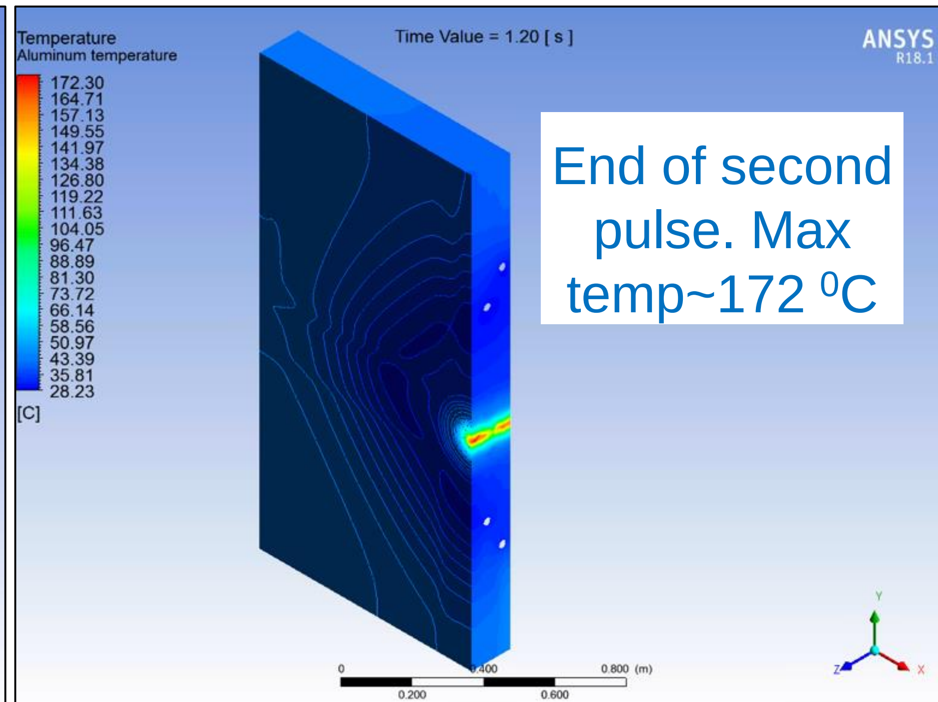
Jim Hylen, Dune-doc-10806, TechBoard 2018

Accident condition, On-axis, UHA (Current)

- CFD simulations were done to predict temperatures in the aluminum block for the on-axis accident condition.
- 120 GeV beam, 10 us pules, cycle time: 1.2 Sec, and total pulses: 2.
- Steady state energy deposition for block 1 and accident energy deposition for second Al core block was used—a conservative assumption. Water temp: 25 ^{0}C. HTC~7000 W/m2-K.

Abhishek Deshpande, Dune-doc-9670





Accident condition: Max temperature summary

Item#	Condition	[1]Maximum temperature in #2 UHA Al block, CFD simulation, ^0C	[2]Maximum temperature in #2 RHA Al block, ANSYS thermal simulation, ^0C	Ambient air and water temperature in CFD simulation, ^0C	Ambient water temperature in ANSYS simulation, ^0C
1	After first accident pulse	116.38	116.48	25	10
2	At the end of 1.2s cool down	91.33	80	25	10
3	After second accident pulse	172.3	170.43	25	10

Notes:

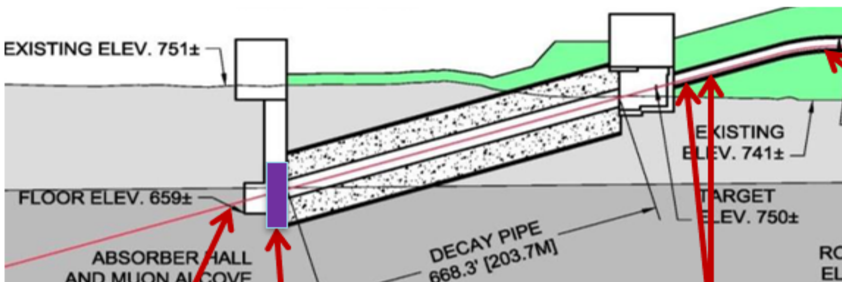
1. CFD simulation includes air flow on the Al surface at 15 m/s. This is a no-target, on-axis case for the UHA.
2. The ANSYS simulation probably did not include the air flow. This is a no-target, off-axis case for the RHA (sculpted). See Lbne-doc-10992.

Jim Hylen, Dune-doc-10806, TechBoard 2018

Beam interlock hardware system

- Three independent systems provide redundancy to pull beam permit quickly in non-normal condition .

Three independent systems provide redundancy to pull beam permit quickly in non-normal condition



Scope of this review

- **Beam position monitors** upstream of target
  - Pull beam permit after 1 beam spill if proton trajectory is off, missing target
- **Thermocouples** in absorber core
  - with thermocouple on-axis in shower, provides fast response (detect Energy deposition in thermocouple itself)
- **Muon monitor** after absorber combined with **Toroid proton monitor** before target
  - Can pull beam permit after 1 beam spill, if muon response is not proportional to number of protons in spill

Jim Hylen, Dune-doc-10806, TechBoard 2018

Beam interlock hardware system

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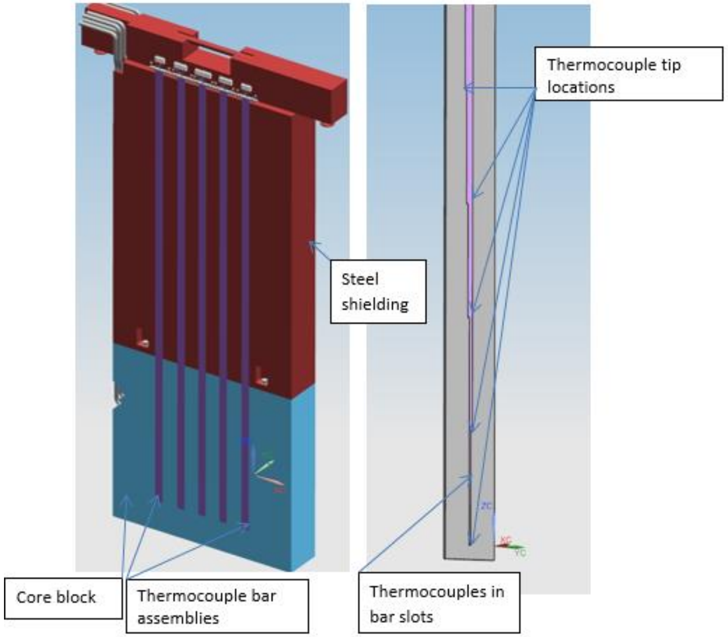
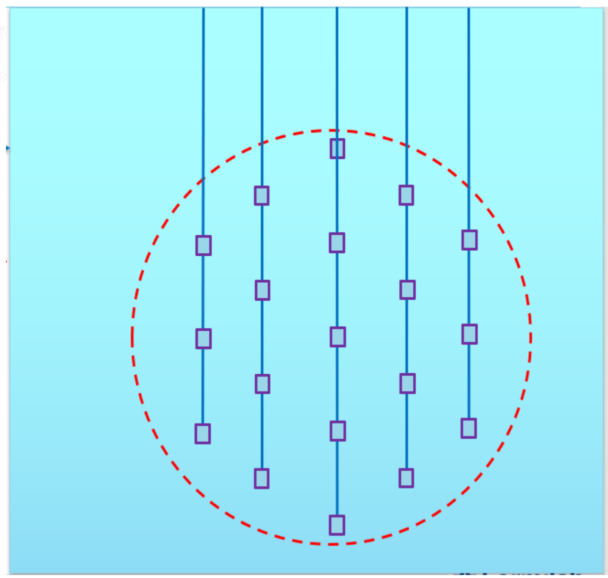
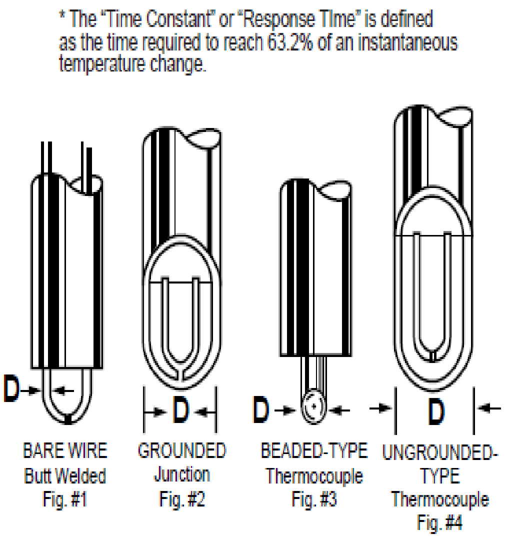
Thermocouple array



Thermocouple array-front view



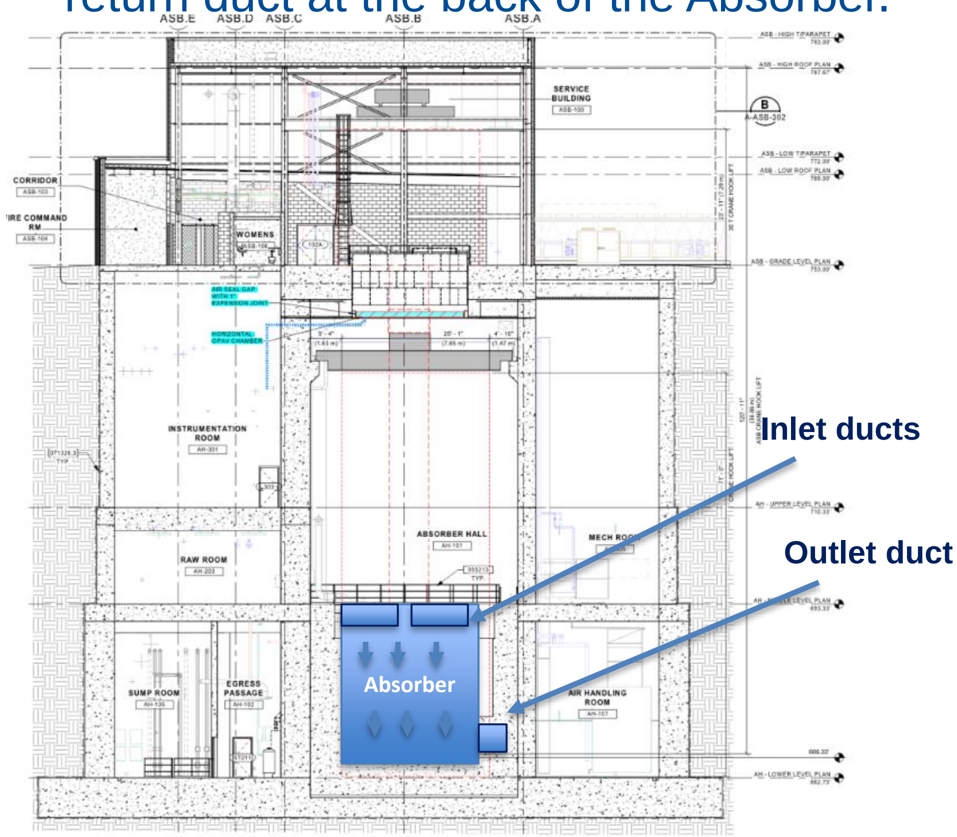
J-type thermocouples



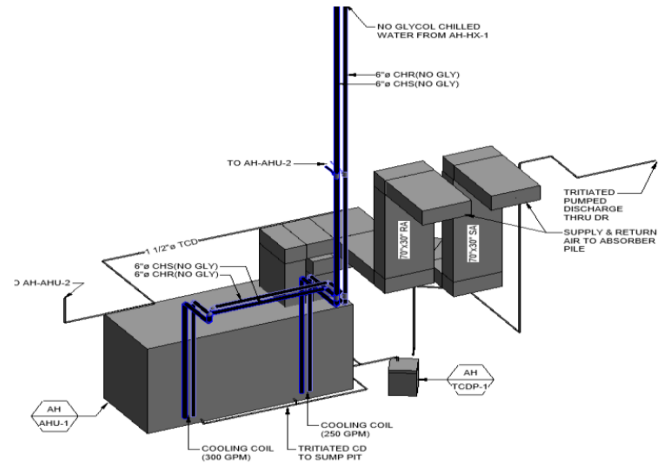
- Thermocouple array installed in Al core block 2, 3, and 4.
- Permit is pulled on absolute temperature limits and also on comparison of temperatures before and after two pulses.
- System designed to pull the beam permit after 1 accident pulse.
- Ungrounded, 1/16", J-type thermocouples used in NuMI will be specified. They have a 0.3 sec response to dT in surrounding material.

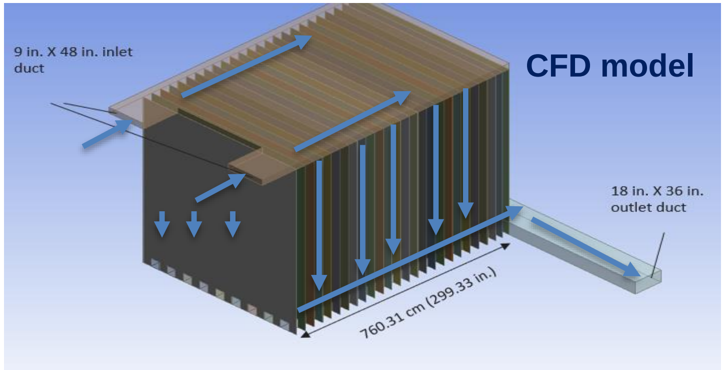
Surrounding steel cooling

- The surrounding steel is air-cooled. The air cooling system is a closed-loop system.
- An air cooling system, designed by CF, delivers 25,000 CFM of air which blows in on top of the absorber blocks and passes through the 5-mm gaps between the blocks. Collects in the air channels at the bottom and enters the return duct at the back of the Absorber.



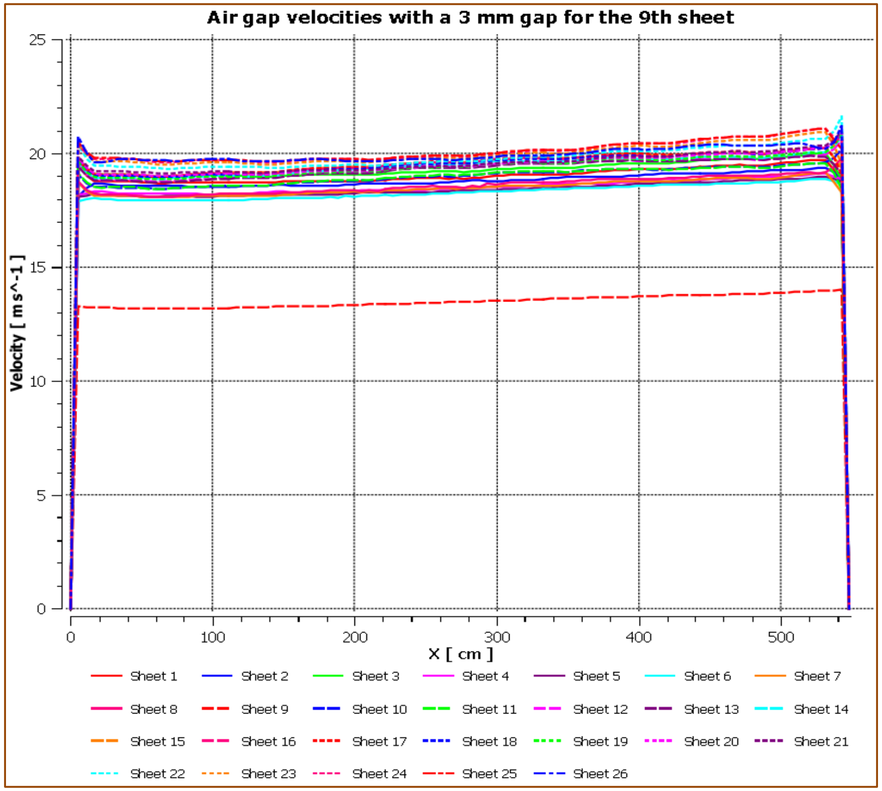
Air handling unit

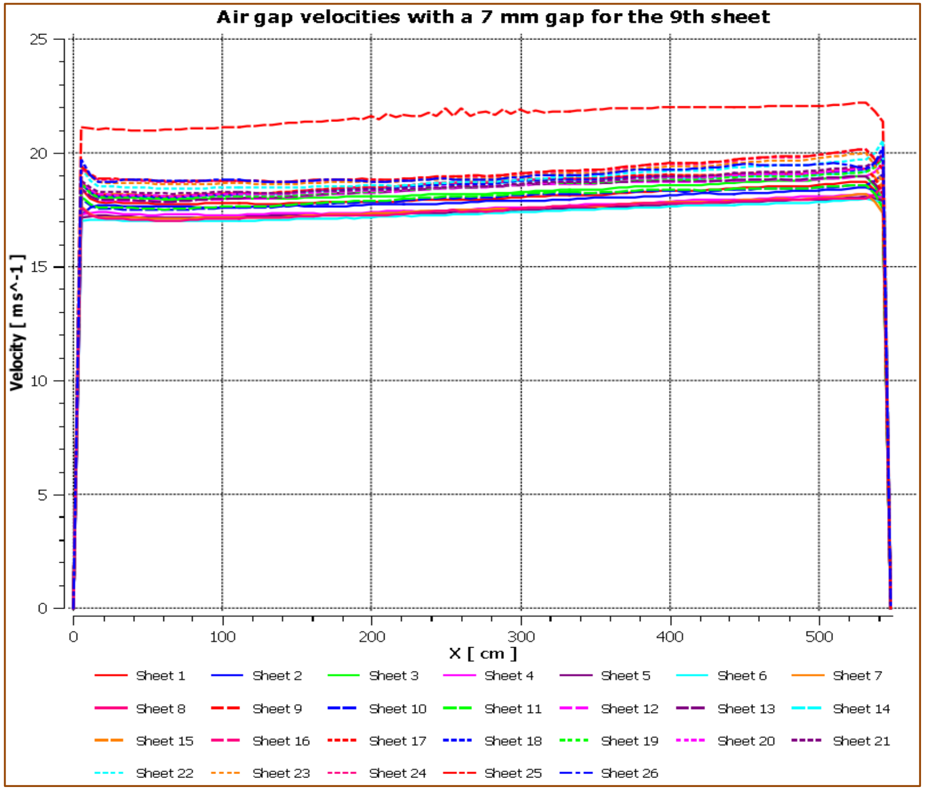




Surrounding steel cooling

- CFD simulations show the velocity profiles in the 5-mm gaps between Absorber components are uniform.
- Sensitivity analyses to show that air velocity is adequate if the air gap sizes become non-uniform were also done.





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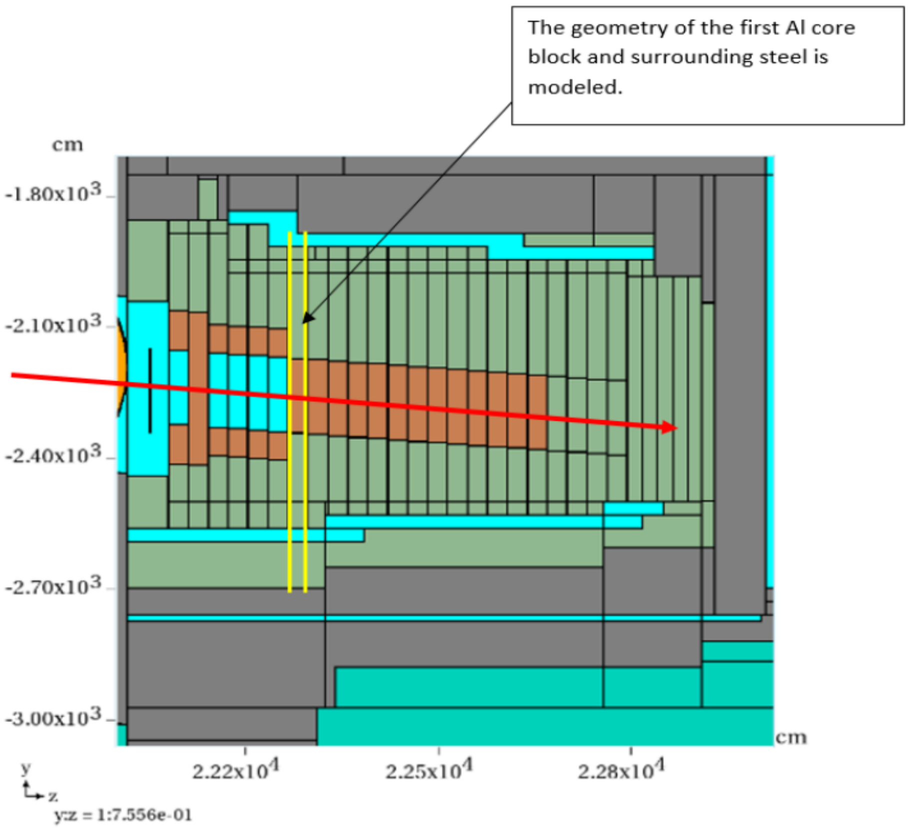
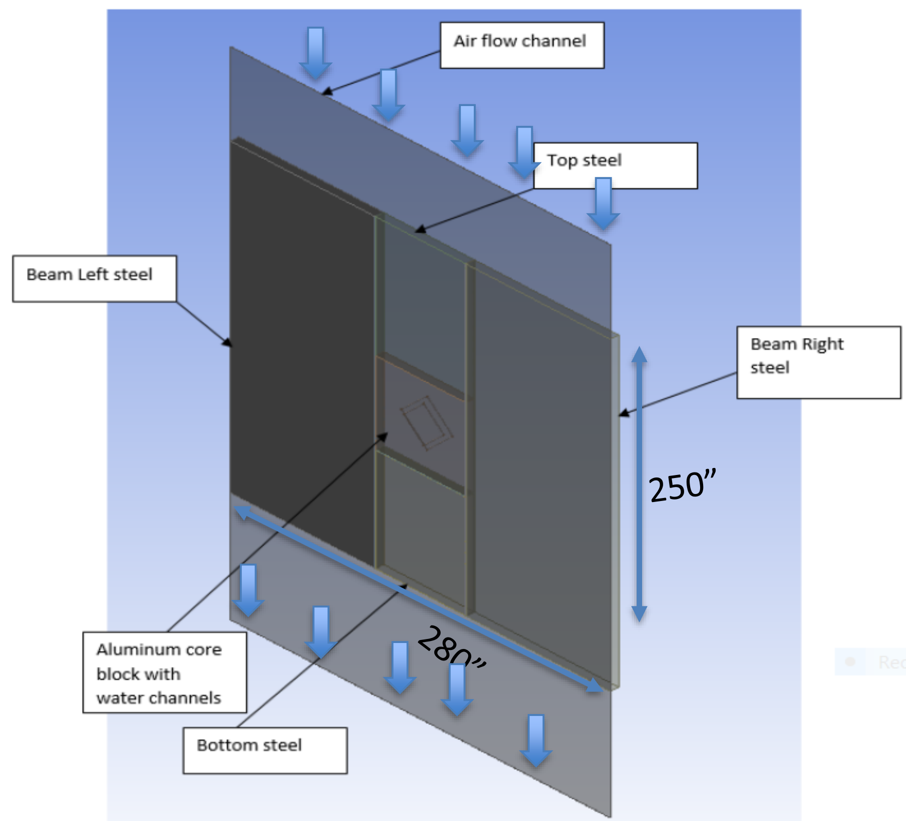
Surrounding steel cooling

- MARS simulations show that the steel surrounding the first Al core block gets the maximum energy deposition.
- CFD simulations predict the maximum steel temperatures for the 1.5-m RAL target case and other cases.

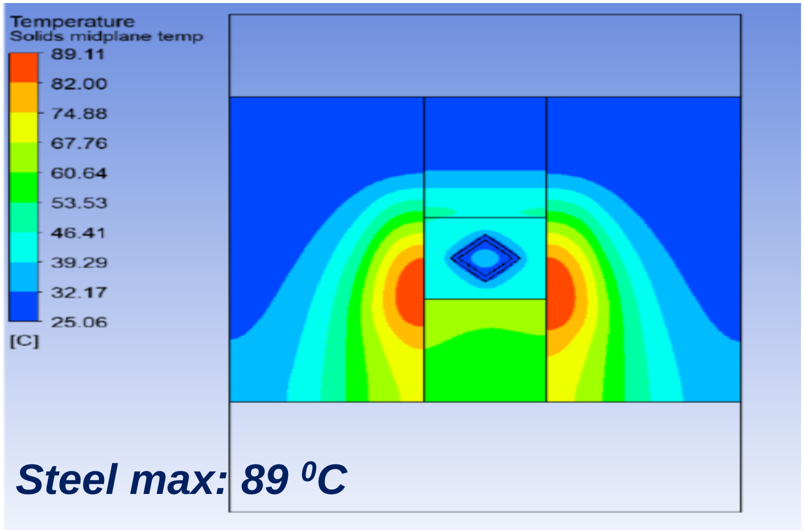


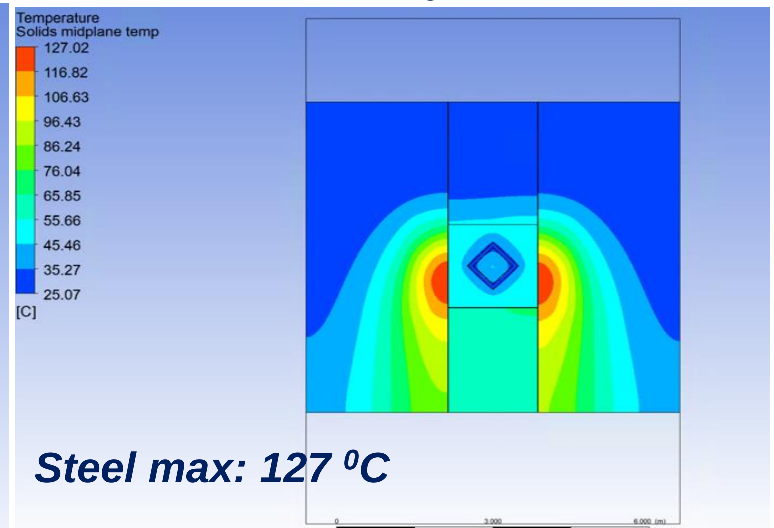


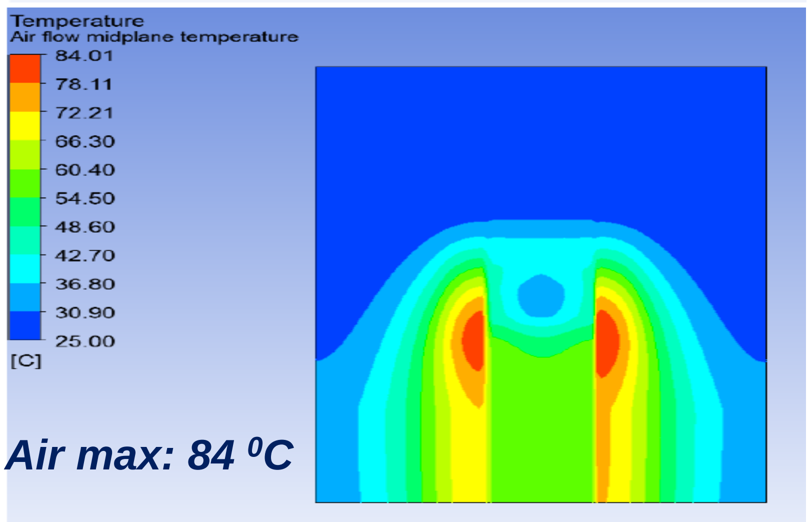
Surrounding steel cooling

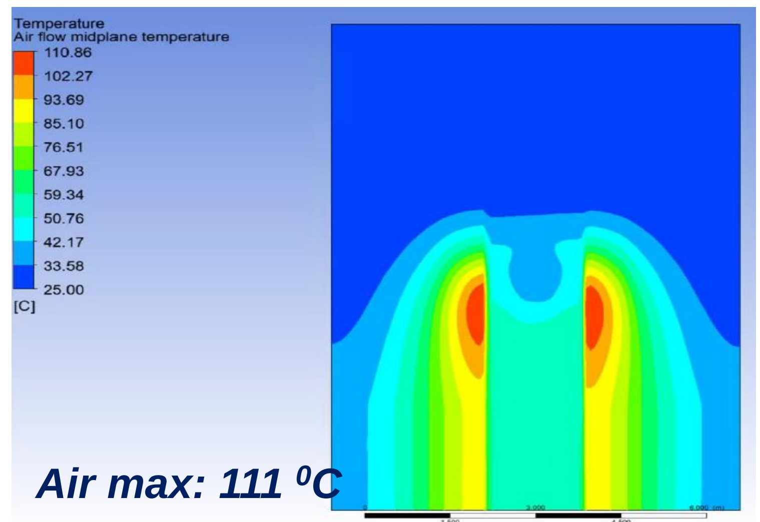
2-m NuMI Target @ 2.4 MW

1.5-m RAL Target @ 2.4 MW









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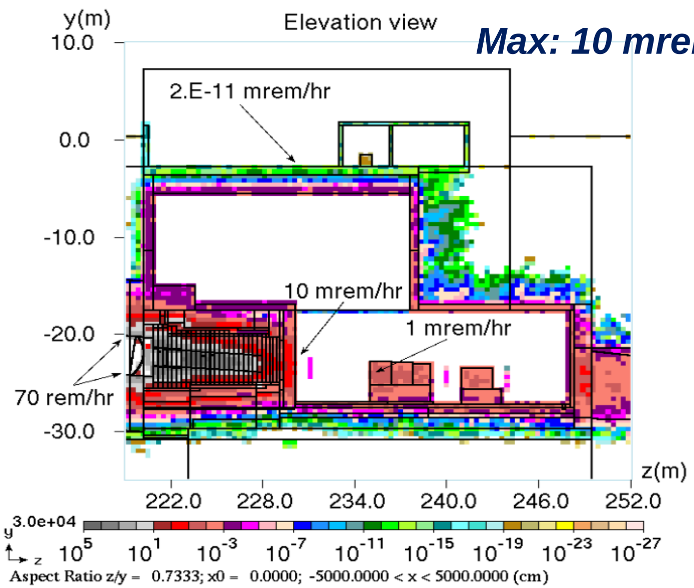
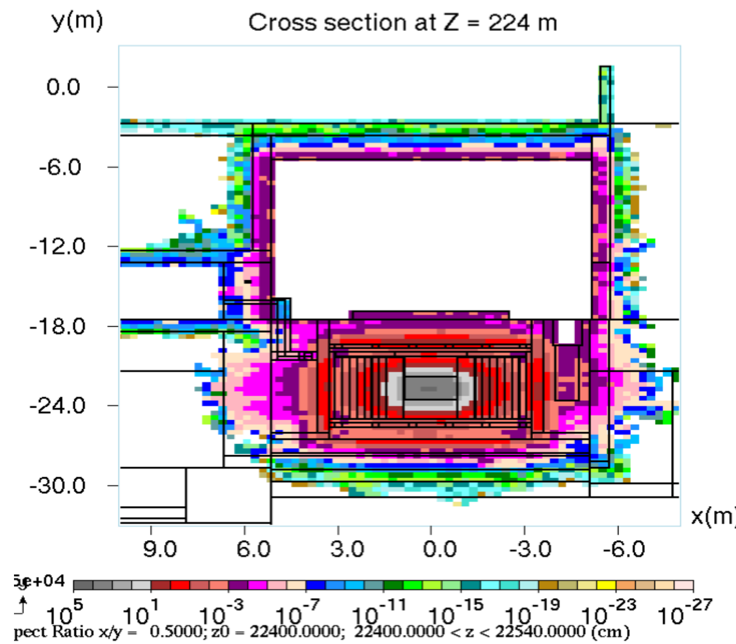
Maximum allowable steel and anti-rust paint temperature is 260 ^{0}C.

Radiological protection

- One of the requirements of the Absorber is to provide radiation protection to people in compliance with FRCM.
- Residual dose rates in Beam OFF areas need to be less than 20 mrem/hr. Max is 10 mrem/hr as shown below.

Max: 10 mrem/hr





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- Beam ON prompt dose rates in the Absorber service building do not exceed 5 x 10^{-5} mrem/hr—the facility is designed for 0.25 mrem/hr.

Summary

- The design of the absorber for the most conservative case, 2.4 MW beam and 1.5-m RAL Target, is well understood.
- Aluminum temperatures, stresses, and deformations are within allowable limits.
- The effect of fatigue loading (20-years of continuous operation) and creep on Al components have been addressed.
- The accident condition simulations reveal that it will not have a detrimental effect on Absorber operations.
- The accident pulse interlock system has been developed.
- The water cooling system for the core is over-sized—there is room for value engineering to reduce costs.
- The installation of the stainless steel pan that will capture RAW water from a catastrophic leak in the core has been addressed.

Summary

- The surrounding steel air cooling system's feasibility has been addressed—this is actually CF's scope.
- The air cooling system design flow rate, temperature, and heat load have been established.
- The maximum operating temperature for the surrounding steel has also been determined.
- Absorber provides adequate radiological protection to public in beam ON areas.
- The residual and prompt dose rates in the Absorber complex are within the limits specified by FRCM.

Questions and discussion