ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPRB108

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LBNF HADRON ABSORBER: UPDATED MECHANICAL DESIGN AND ANALYSIS FOR 2.4 MW OPERATION*

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Abstract

The Long-Baseline Neutrino Facility (LBNF) Hadron Absorber is located downstream of the decay pipe. It consists of actively cooled aluminum and steel blocks surrounded by steel and concrete shielding. Majority of the beam power is deposited in the absorber core which is water cooled. The surrounding steel and concrete shielding are air-cooled. The absorber provides radiation protection to personnel and keeps soil and ground activation levels below allowable limits. It is designed for 2.4 MW beam operations. The total heat load deposited into the absorber is approximately 400 kW. The current design considers the longer 4-interaction length target of the optimized beam design. In addition, the 'bafflette' around the target reduces the energy deposited into the absorber. For this reason, the sculpting in the aluminum core blocks, which was in the previous design, was removed, making the design uniform and less complicated. In addition, the uniformity of the absorber makes it easier to understand the muon monitor data. Steady state thermal, structural, and Computational Fluid Dynamics (CFD) analysis of critical absorber aluminum and steel components during steady state operations is discussed herein. A similar analysis for a 120 GeV, 10 µs pulse, accident condition is also discussed. A preliminary design for the accident pulse prevention system that protects the absorber is also described.

DESIGN OVERVIEW

The absorber consists of two major sections, as shown in Fig. 1. The core, a section consisting of replaceable water-cooled blocks, is shown inside the green box. It is enlarged in Fig. 2. The core consists of an aluminum spoiler block to initiate the particle shower, four aluminum mask blocks with air space in the center to allow the shower to spread, thirteen aluminum blocks to further distribute the heat load, and four solid low carbon steel blocks. All the aluminum in the core is 6061-T6. The beam power deposited into the core during 2.4 MW operation is approximately 280 kW, which is most of the incoming beam power into the absorber. Approximately, 120 kW is deposited into the surrounding steel and concrete shielding, which are air cooled.

ANALYSIS

Using MARS15 [1] energy deposition results as a basis for heat load on the absorber and its core blocks, many iterative simulations between MARS and ANSYS have been carried out to determine the final configuration of the absorber. The main driver of this optimization is reduction of temperature and stress to acceptable levels for the materials during both normal operation and accident scenarios. Creep and fatigue effects have been considered when applicable. Aluminum core blocks are all water cooled via four 1-inch diameter gun-drilled channels with 20 gallons per minute per channel (gpm) volumetric flow rate. The channels form four continuous loops. These loops are rotated by a 45-degree angle about the beam axis such that they form a diamond-shaped pattern at the center of each block. The spacing between each loop is 2.25-inch in the beam-direction. The diagonals of the loops present on the extremities of the block are 45-inch long, and those at the center of the block are 34-inch. The machining of continuous loops is facilitated by welding plugs at the ends of each gun-drilled path. Steel blocks are cooled via two 1-inch diameter stainless steel lines connected to the perimeter of the block with 20 gpm flow per line. Simulations were carried out with two different water temperatures: 10 ^{0}C and 25 ^{0}C. CFD simulations were carried out for the aluminum-steel core block and surrounding steel assembly to predict the worst-case steel temperatures. The air temperature and average velocity were 25 ^{0}C and 15 m/s, respectively.

Steady State Operation

Steady state temperatures and stresses predicted by ANSYS thermal/structural simulations at various locations are highlighted in Table 1 for 120 GeV operation.

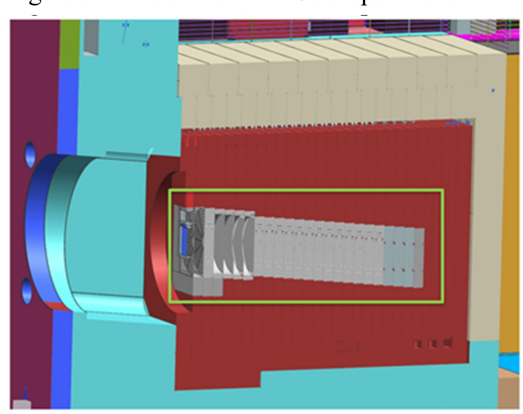

Figure 1: Cross-section of the absorber through the beam axis, the core is outlined by a green box.

Creep is a concern in aluminum when it is subjected to elevated temperatures under high stress. Temperatures and stresses predicted are well below the allowable values.

To determine the worst-case temperatures in the steel surrounding the core, CFD simulations were done. Air flowing through the 5 mm gaps separating each aluminum-

* This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics. FERMILAB-CONF-19-181-AD.
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steel assembly is used to cool the surrounding steel shielding. The total capacity of the air-cooling system is 25,000 CFM. This approximately corresponds to an average velocity of 15 m/s through each air gap. The highest energy deposition is realized in the steel surrounding the first aluminum core block. In these CFD simulations, the cooling water temperature inside the aluminum core blocks and the air inlet temperature were taken as 25 ^{0}C. Fig. 3 illustrates the temperature contours for the first aluminum core block and surrounding steel assembly.

Table 1: Maximum Temperature and Von-Mises Stress for Steady State Operation

Location	**Temp**	**Max. Von-Mises Stress**
Al. Spoiler	35 ^{0}C	25 MPa
Al. core block 1	28 ^{0}C	20 MPa
Al. core block 2	27 ^{0}C	16 MPa
Steel block 1	18 ^{0}C	12 MPa
Note: Cooling water inlet temperature is 10 ^{0}C.		

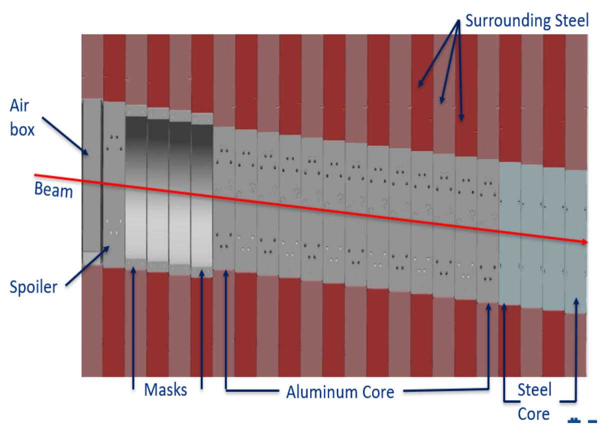

Figure 2: Cross-section of the absorber core with the red arrow indicating the central axis of the beam.

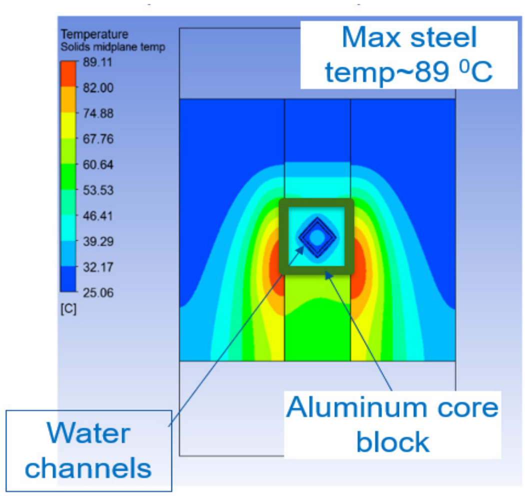

Figure 3: Temperature contours for the first aluminum core block (outlined by green box) and surrounding steel assembly. Maximum steel temperature is 89 ^{0}C.

Accident Condition

The absorber must be able to handle, without loss of function or damage, an accident condition where two pulses of the full proton beam hit it directly [2]. The accident condition is one where a full 120 GeV proton beam (2.88 MJ) misses the target and directly hits the upstream and downstream decay pipe windows, hadron monitors, spoiler, and ultimately the hadron absorber core after steady state operations. This is a very conservative scenario assumption. The peak energy depositions and temperatures in the updated version of the absorber design are similar to those determined for the previous design where the aluminum core was sculpted, that is, less dense. The peak energy is deposited in the second aluminum core block. CFD simulations predicted the maximum temperatures after 2 accident pulses. These are highlighted in Fig. 4 and Fig 5.

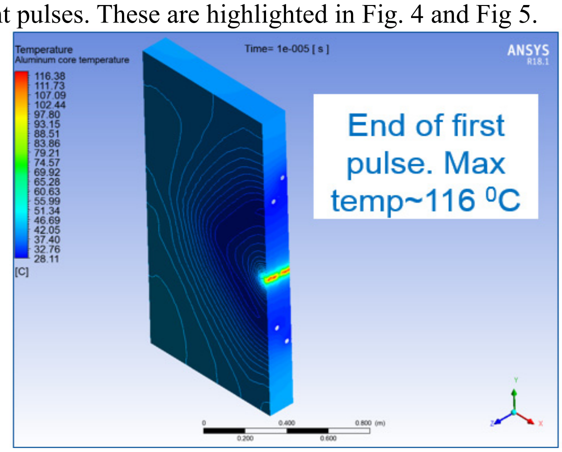

Figure 4: Temperature contours for the second aluminum core block after the first on-axis accident pulse.

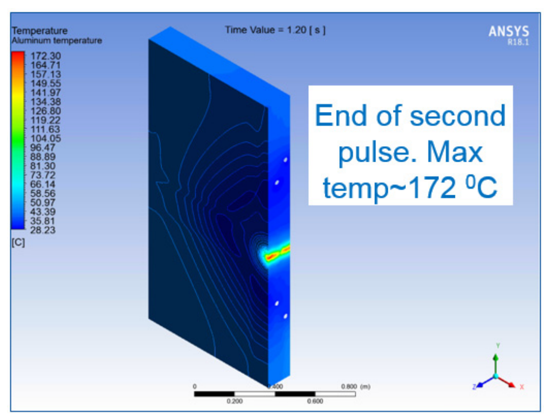

Figure 5: Temperature contours for the second aluminum core block after the second on-axis accident pulse.

The maximum temperature of 172 ^{0}C is reached. This temperature was very close to that realized for the previous absorber design, ~170 ^{0}C [2]. Tensile data at elevated temperature [3] shows no change in 6061-T6 mechanical properties after 0.5 hours at 177 ^{0}C. The induced stress exceeds the yield point of 6061-T6 aluminum after a single pulse, and a temperature dependent bilinear kinematic plasticity model was introduced to determine plastic strain. The maximum plastic strain achieved after two pulses is 0.7% while the plastic strain to failure for 6061-T6 aluminum is 16%.

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The volume of material with permanent deformation is very small. Thus, such an accident will not affect the functionality and operability of the absorber.

MECHANICAL DESIGN

The mechanical design of the absorber is based on the proven design of the NuMI target hall, utilizing remotely handled T-blocks to support the core. These T-blocks are supported by the steel shielding and are fully encapsulated by steel and concrete shielding for radiation protection. The T-blocks are removable via an overhead crane with a lifting fixture attached. Failed components can be stored in morgues integrated into the absorber design [2].

Active temperature monitoring of select core blocks will be necessary to protect the absorber from accident pulses and to aid in beam and target diagnostics. A thermocouple array in a solid Al block is designed with thermocouples spaced to allow the detection of an accident pulse. These thermocouples fit in removable bars that slide in T-slots on the T-block and core block to allow easy access for replacement as necessary. Jack screws are implemented on both sides of the bar to facilitate removal [2]. A T-block/aluminum core block assembly is highlighted in Fig. 6.

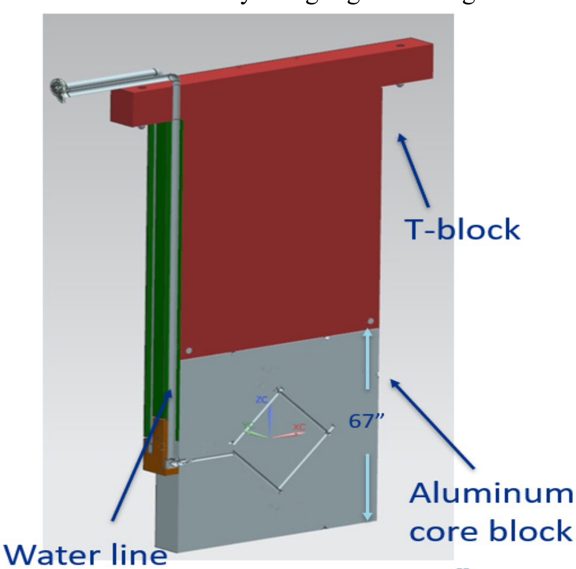

Figure 6: A standard T-block/aluminum core block assembly.

The absorber design incorporates different sized morgues to accommodate failed radioactive core blocks and hadron monitors. The design also incorporates a remote handling facility that can remotely insert, remove, and replace the hadron monitor [2].

ACKNOWLEDGEMENTS

MARS modeling, energy deposition results, and ideas to reduce absorber temperatures were provided by Igor Rakhno and Nikolai Mokhov of the Modeling/Energy Deposition/Theory group.

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