Ansys Steady-State Analysis of the Hall C Lead Tungstate Crystals of the Neutral Particle Spectrometer

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November 4, 2022

In a previous note [1], the results of the Ansys Steady-State overall simulation and analysis were presented. In this note, the results of the Ansys analysis performed to determine the heat flux ϕ and the temperature differential ΔT of single lead tungstate ($PbWO_4$) crystals of the Hall C Neutral Particle Spectrometer (NPS) are presented.

The NPS crystal array is an arrangement of 36 rows by 30 columns of $PbWO_4$ blocks, each measuring 200 mm x 20 mm x 20 mm and each connected to a Hamamatsu photomultiplier tube (PMT) (R41253355027), which in turn is connected to a divider base.

At the front and the rear of the array, the crystals are separated from each other by dividers, carbon fiber and mu-metal. The dividers, carbon fiber (20 mm wide and 0.5 mm thick) and mu-metal (67.5 mm wide and 0.5 mm thick), run the height (738.5 mm) and the width (615.5 mm) of the crystal array, which is wrapped with a copper cooling shell (165 mm wide and 12 mm thick), Fig. 1.

A Kodiak chiller (RC006G03BE3) pumps coolant water, the temperature which can be as low as 10°C, through the copper tubes embedded in the copper shell, Fig. 2.

For the simulations, Ansys DesignModeler was used to generate the crystal array model. Simulation parameter values, such as thermal conductivities of the materials, and the ambient and cooling shell temperatures are given in ref [1]. A natural convection rate of 5 W/m^2°C was set for the dividers, the copper cooling shell, and the crystals.

Based on the expected operating high voltage of 605 V and low voltage of 4.5 V, with operating currents of 405 µA and 18 mA per PMT channel, respectively, a heat load of 0.3 W was applied to the rear face of each crystal.

Python programs heatFluxPlotGenerator.py and temperaturePlotGenerator.py were developed to plot ϕ and the temperatures, respectively. Analysis shows that the maximum heat flux is ~7 mW/mm^2 at the mu-metal, Fig. 3.

FIG. 2. Copper cooling shell with tubes.

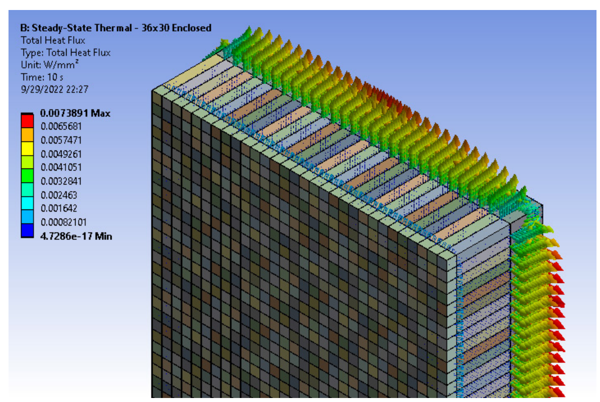

FIG. 3. Isometric view of heat flux through crystal array; the copper cooling shell has been hidden.

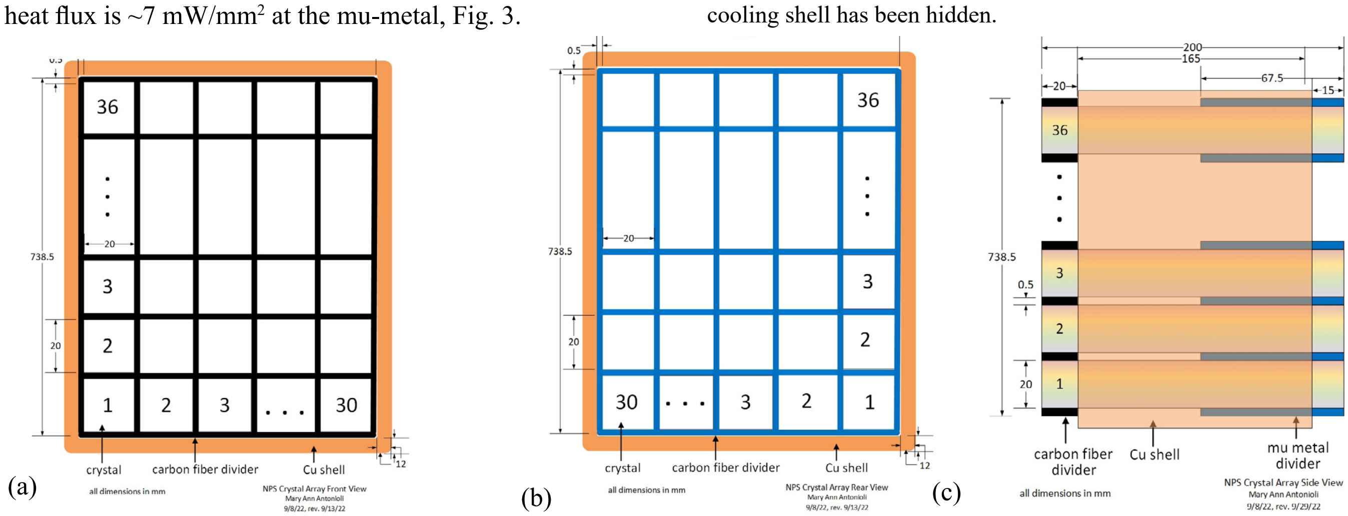

FIG. 1. NPS crystal array views (a) front, (b) rear, and (c) side.

To investigate ϕ and the temperature profile of peripheral crystal (36, 15), 41 probes were placed along the length of the crystal side facing the copper cooling shell (there is a 0.5 mm gap between the crystal and the copper cooling shell) and 41 on the opposite side, one every 5 mm from 0 mm to 200 mm.

Figure 4 shows the average temperatures along the length of peripheral crystal (36,15) of the four zones—carbon fiber, copper cooling shell, copper cooling shell and mu-metal, and mu-metal—for the copper cooling shell side and the opposite side.

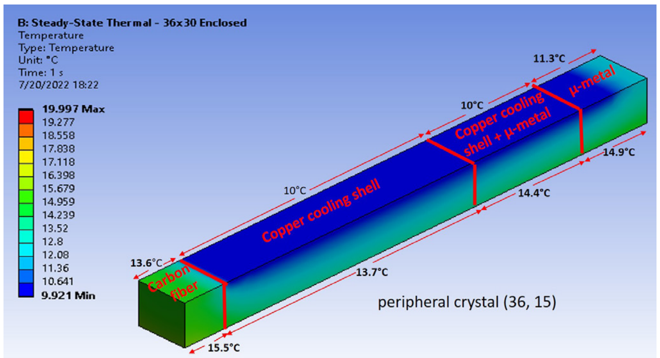

FIG. 4. The average temperatures of the side facing the copper cooling shell and the opposite side of the four regions are displayed. The rear region's temperature is lower because mu-metal is a better heat conductor than carbon fiber.

ΔT of the four regions are 1.9°C, 3.7°C, 4.4°C, and 3.6°C, respectively. Since, the light yield sensitivity of $PbWO_4$ is about 2–2.5%/°C [2], the peripheral crystals could have light yield issues.

For crystal (18, 15) in the center of the array, the probes were placed on two opposite faces along the length of the crystal. The crystal temperature was found to be ~20°C, the ambient temperature, Fig. 5.

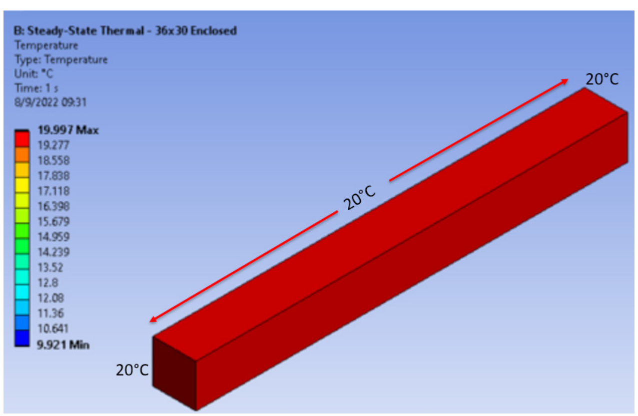

FIG. 5. Temperature profile of a single central crystal.

Figure 6, a surface temperature plot, shows the temperature measured on the front face of the crystal, and Fig. 7 shows the associated histogram. Four hundred and eighty crystals are between 19.5°C and 20.5°C. Crystals are cooler the closer they are to the copper cooling shell.

Figure 8 shows a histogram of ΔT between the front and rear faces of the crystals. In bins #1, #2, and #3, there are 956, 113, and 11 crystals, respectively.

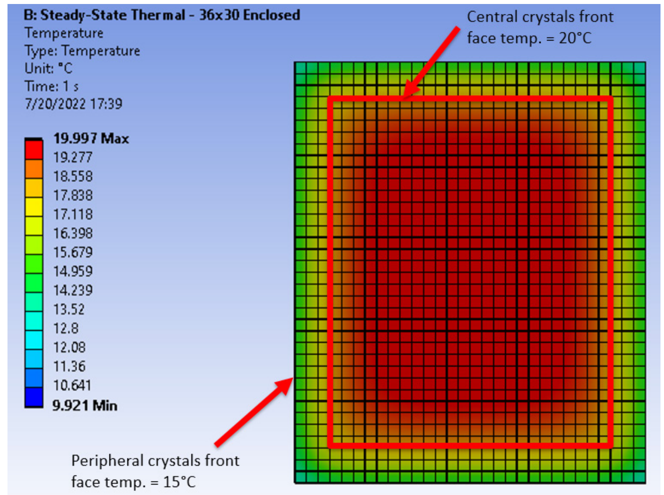

FIG. 6. Temperature profile of front faces of crystal array; the central region temperature is between 19.5°C and 20.5°C.

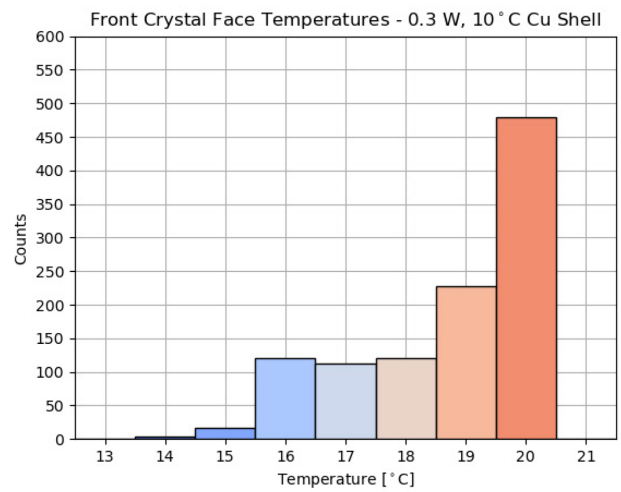

FIG. 7. Histogram plot of front crystal faces.

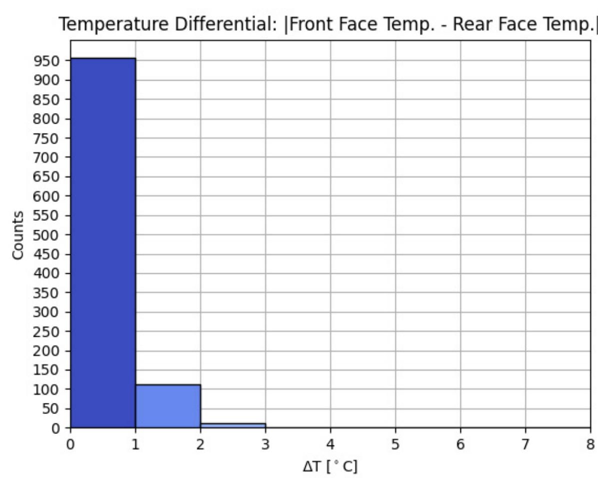

FIG. 8. Histogram of ΔT between the front and rear face of crystals.

Figure 9 shows ϕ, indicated by the blue halo around the peripheral crystals. ϕ was measured on the cross-sectional surface halfway along the length of the crystal (100 mm). On each of the four sides of the crystal array, ϕ decreases towards the corners. The four corner crystals enclosed by the green boxes have the lowest ϕ. Crystals next to the corner crystals, enclosed by the white boxes, have a higher ϕ than that of the corner crystals. Crystals enclosed by the red boxes have the highest ϕ.

Figure 10 shows the ΔT histogram of the peripheral crystals. ΔT between the copper cooling side and the opposite side was measured on the same surface as ϕ, halfway along the length of the crystal (100 mm). In bin #1, there are four crystals, the corner crystals—these crystals are cooled from two sides. In bin #2's temperature range, there are no crystals. In bin #3, there are 16 crystals (four per side)—these crystals are adjacent to the four corner crystals. In bin #4, there are 108 crystals.

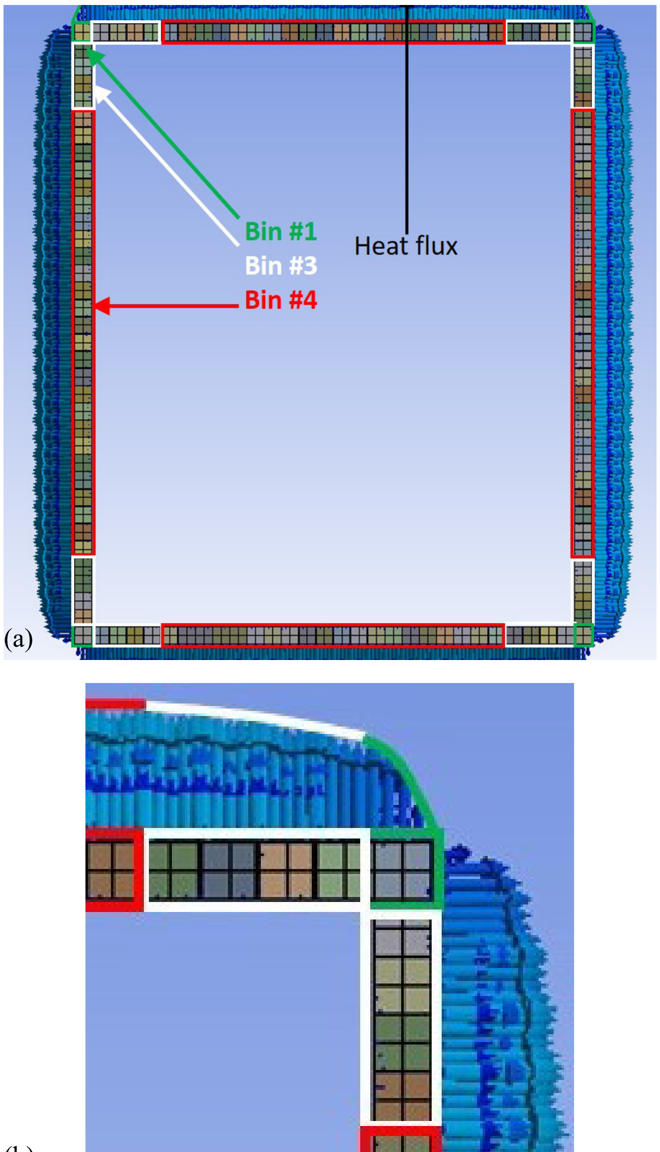

FIG. 9(a). ϕ of the peripheral crystals. (b) Zoom of the bottom right corner. The black squares are the Ansys mesh. Each of the 128 peripheral crystals has a grid of four squares.

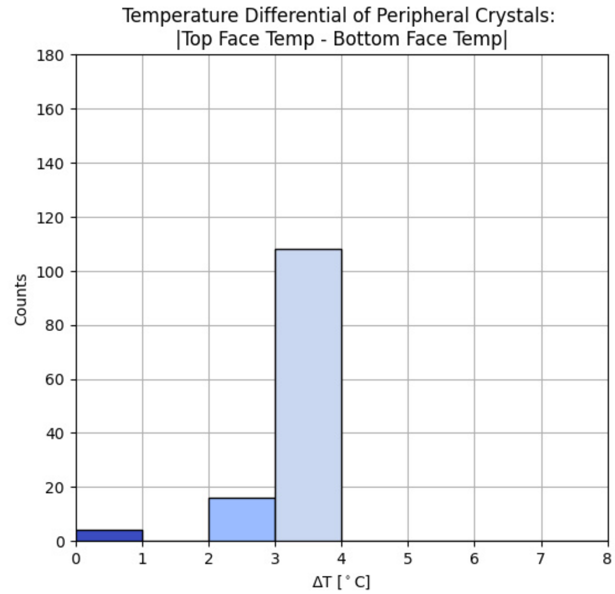

FIG. 10. ΔT between the copper cooling side and the opposite side of the peripheral crystals.

To conclude, peripheral crystals are cooler than those in the interior of the crystal array. However, most of them have a ΔT > 1°C, which implies that there could be light yield issues with the peripheral crystals. About 50% of the crystals are close to the ambient temperature. All crystals could have the same temperature if the ambient and the coolant temperatures are set to be the same.

[1] A. Brown et al., *Ansys Steady-State Thermal Analysis of the Engineered Cooling Design for the Hall C Lead Tungstate Crystals of the Neutral Particle Spectrometer*, DSG Note 2022-02, 2022.

[2] E. Aschenauer and R. Ent, *Backward Detector Integration*, Presented at ePIC GD/I Meeting, September 19, 2022.