FCAL2 Lead Tungstate Crystal Cooling Analysis

Jefferson Lab
Thomas Jefferson National Accelerator Facility

U.S. DEPARTMENT OF ENERGY | Office of Science

ODU

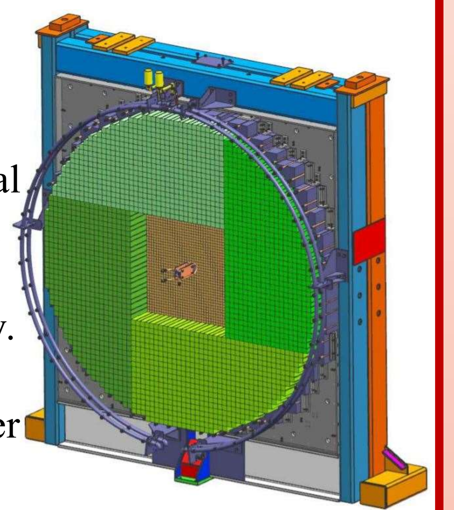
Nathan Merten - Old Dominion University
Timothy Whitlatch – Thomas Jefferson National Accelerator Facility

Abstract

Hall D's current calorimeter (FCAL), which is used to detect neutrals and measure electron energy from the photon shower created when the photon enters the calorimeter, is being updated with a large lead tungstate crystal insert to replace a middle portion of the current lead glass crystals that will be capable of better resolution when viewing the collected data. The crystals the calorimeter uses are very sensitive to temperature regarding achieving the most clear and concise results through the attached Photomultiplier tubes (PMTs), and it is necessary to keep the crystals as close to 10 degrees Celsius as possible. To achieve this there are water cooled aluminum blocks all around the crystals as well as one in the center each maintained at 10 degrees Celsius. In addition, the whole system is operating in a temperature controlled dark room through a heat exchanger and fans set at an air temperature of 10 degrees Celsius. All this cooling is needed as a result of the electronics for the PMTs to transfer and read the collected data. The purpose of this project was to verify that the current layout and assumptions for the crystal PMT setup would be enough to keep the temperature variation in the crystals under 1.5 degrees Celsius between each crystal and under 0.5 degrees Celsius within each crystal itself. The methods used to obtain this verification revolved around a three-step approach. Within each crystal setup there are several components each relevant in deterring the heat transfer from the electronics to the crystal, and through a set of one-dimensional analytical calculations of basic heat transfer the heat flux into the crystal was found. These results were inputted into Excel's iterative calculation feature generating a two-dimensional display of heat transfer between each crystal. To formalize and compare all the data in a more detailed fashion a three-dimensional thermal analysis of the system was also created using ANSYS, which is a finite element analysis software containing analysis from structural to the thermal analysis. The analysis showed the ΔT of the system to be just below 8 degrees C with an internal crystal ΔT of about 3.4 degrees C. Both numbers are in a range that can be accepted for functionality but not best clarity of results. Since the goal is to have both numbers as close to the desired values of 1.5 degrees C and 0.5 degrees C and both are over, two additional measures were tested in ANSYS to find the best option for additional cooling. These tests found that cooling the electronics directly would yield the best results for lowest system and crystal ΔT. Knowing this vital information will help guide the finalization of the design process to fit the desired temperature parameters needed by the equipment on this device for maximum data resolution. Information like this will also be an asset for any future calorimeter work or design in the lab for years to come.

Overview

- Hall D currently contains a forward calorimeter (FCAL) which is being upgraded to FCAL2. This upgrade involves replacing an inner portion of the FCAL's current lead glass crystals with an insert of lead tungstate crystals. This insert will provide much better resolution of data when detecting neutrals and measuring electron energy.



- Each crystal module is fitted with a Photomultiplier tube or PMT, along with some other materials to assist with heat conduction or mounting for electronics. Outside of the crystal is wrapped in a layer each of ESR foil and tedlar which both act as anti-reflectance for the crystal providing improved resolution while also having a very low thermal conductivity. The crystals are cooled through an outer layer and one inner stack of aluminum cooling blocks as well as a heat exchanger and fans.
- For the system to operate at peak level the temperature variation of the system is needed to stay below an assumed 8 degrees C from its hottest to coldest and have a ΔT within each crystal as low as possible. To begin this project, a max system temperature difference of 1.5 degrees C and ΔT in each crystal of 0.5 degrees C were targeted to ensure the actual values be in the needed range.

Methods

- Individual crystal setup Heat flux from the PMT electronics through structural material and into the lead tungstate crystal was found on paper using one-dimensional heat transfer calculations for combined materials.
- $$\Delta T = \frac{Q}{A\left(\frac{\left[0.037\left(\frac{VL}{\nu}\right)Pr^{0.33}\right]K}{L}\right)} \qquad \Phi_q = \frac{\left[\Delta T\left(\frac{1}{\left[\frac{L_1}{K_1A_1}+\frac{L_2}{K_2A_2}+\cdots\frac{L_n}{K_nA_n}\right]}\right)\right]}{A}$$
- One-dimensional calculations were then expanded in excel to show range of heat flux with differing cooling fans air speed values.
- A smaller system test was created using Excel's iterative calculation feature generating a two-dimensional display of heat transfer between each crystal with cooling block boundaries and center cooling tube in place.
- Using ANSYS, a finite element analysis solver, three-dimensional thermal analysis models were created showing the heat flow of the entire system under multiple heat conditions.

1D Results

- Initial calculations done on paper with the fan air velocity of 2 m/s were expanded to show an air speed range of 1–10 m/s.

Air Velocity	Renolds #	Nusselt #	Convective heat transfer coeficient (h)	ΔT From fan	ΔT including crystal temp	Q up to crystal	Q through insulation to crystal	ΔT in crystal (Q1-Q2)	ΔT in crystal (Q1)	Added heat for crystal
1	1402.525	10.99845	13.40145227	237.19374	232.1937398	0.215744491	0.002912	26.60406143	26.96806143	539.3612285
2	2805.049	19.14942	23.33328364	136.232029	131.2320294	0.121935189	0.002912	14.87789856	15.24189856	304.8379713
3	4207.574	26.48675	32.27370817	98.4931935	93.49319347	0.086869876	0.002912	10.49473455	10.85873455	217.1746909
4	5610.098	33.34108	40.62560644	78.244754	73.24475403	0.068055893	0.002912	8.142986567	8.506986567	170.1397313
5	7012.623	39.85728	48.56550034	65.4526477	60.45264768	0.056170014	0.002912	6.657251809	7.021251809	140.4250362
6	8415.147	46.11611	56.19178966	56.5694847	51.56948466	0.047916159	0.002912	5.62551992	5.98951992	119.7903984
7	9817.672	52.16871	63.56679219	50.0063079	45.00630791	0.041817936	0.002912	4.863242031	5.227242031	104.5448406
8	11220.2	58.05019	70.73328914	44.9398101	39.93981012	0.037110363	0.002912	4.274795402	4.638795402	92.77590803
9	12622.72	63.78605	77.72234071	40.8986728	35.89867282	0.033355511	0.002912	3.80543891	4.16943891	83.38877820
10	14025.25	69.39556	84.55744736	37.5926744	32.59267436	0.030283719	0.002912	3.421464865	3.785464865	75.70929731
m/s	N/A	N/A	W/m^2 K	Degrees C	Degrees C	W	W	Degrees C	Degrees C	W/m^2

- With expanded range the heat flux going into the crystal found a significant drop off as the airspeed increased by each m/s.
- The heat flux value of 75 W/m^2 was found to be most applicable to current system assumptions and selected for use in next testing stage.

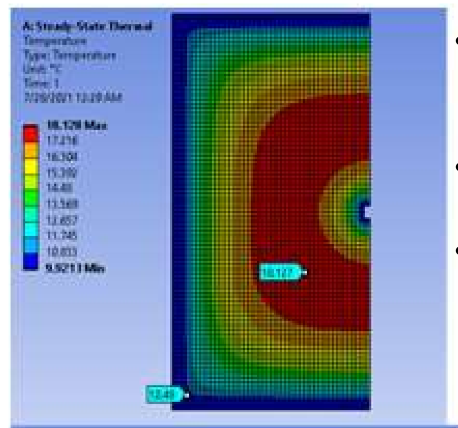
2D Results

- The size of the system was limited by the number of equations Excel's iterative solver feature can solve at once, which is 100 equations.
- With an added heat flux of 75 W/m^2 the max temperature came to 12.9 degrees C and a min of 10.8 degrees C which gives a ΔT of 2.1 degrees C.
- System limited by equations lack of reference to the heat flow within each crystal causing all the heat being transferred from crystal to crystal when in reality heat will also flow though the crystals themselves and into insulation on upstream side.

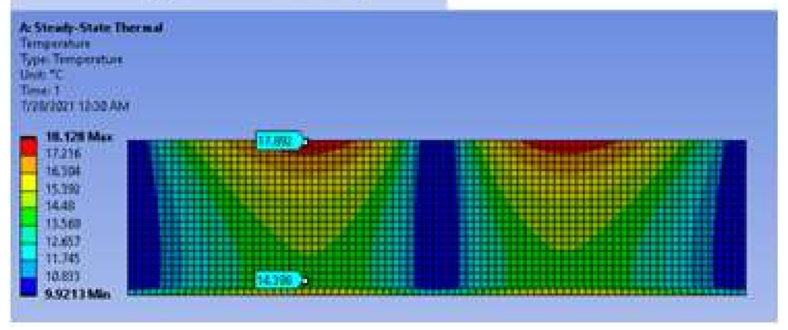
	10	10	10	10	10	10	10	10	10	10	
10	10.8	11.3	11.5	11.6	11.7	11.7	11.6	11.5	11.3	10.8	10
10	11.3	12.1	12.4	12.6	12.6	12.6	12.6	12.4	12.1	11.3	10
10	11.5	12.4	12.9	12.9	12.8	12.8	12.9	12.9	12.4	11.5	10
10	11.6	12.6	12.9	12.7	12.1	12.1	12.7	12.9	12.6	11.6	10
10	11.7	12.6	12.8	12.1	10	10	12.1	12.8	12.6	11.7	10
10	11.7	12.6	12.8	12.1	10	10	12.1	12.8	12.6	11.7	10
10	11.6	12.6	12.9	12.7	12.1	12.1	12.7	12.9	12.6	11.6	10
10	11.5	12.4	12.9	12.9	12.8	12.8	12.9	12.9	12.4	11.5	10
10	11.3	12.1	12.4	12.6	12.6	12.6	12.6	12.4	12.1	11.3	10
10	10.8	11.3	11.5	11.6	11.7	11.7	11.6	11.5	11.3	10.8	10
	10	10	10	10	10	10	10	10	10	10	

ANSYS Results

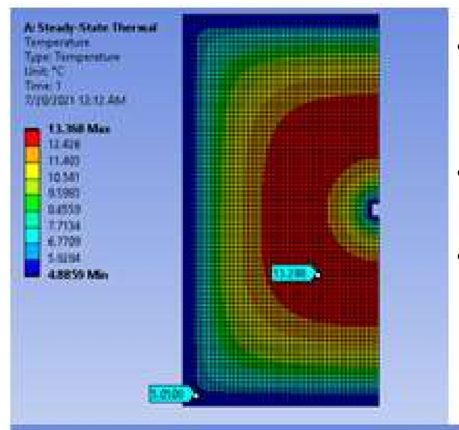
Current System setup



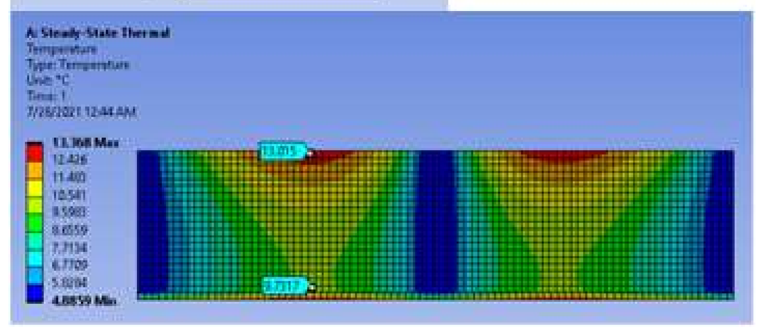
- System high temperature shown at 18.12 degrees C.
- ΔT of system at 7.6 degrees C
- ΔT of individual crystal found to max at 3.4 degrees C



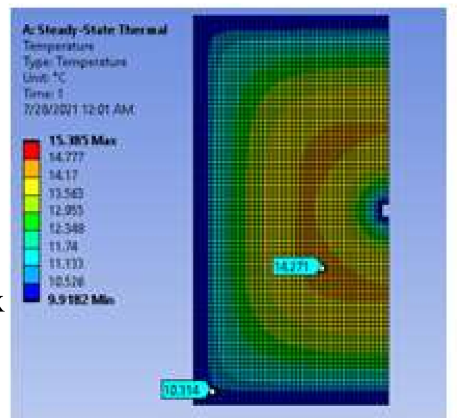
Additional cooling option one



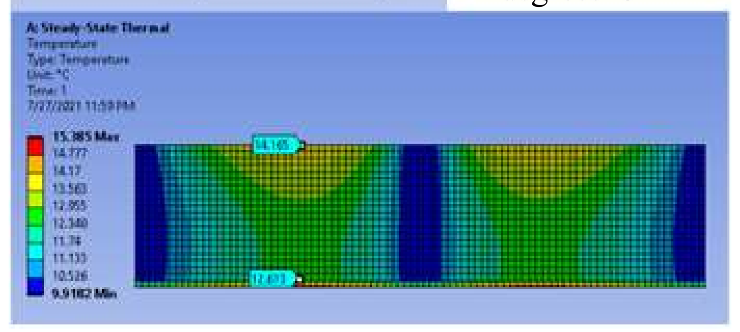
- System high temperature shown at 13.3 degrees C.
- ΔT of system at 8.247 degrees C
- ΔT of individual crystal found to max at 3.28 degrees C



Additional cooling option two



- System high temperature shown at 14.27 degrees C.
- ΔT of system at 3.957 degrees C
- ΔT of individual crystal found to max at 1.55 degrees C



- ANSYS model made in half to help processing time since the system is symmetric about its mid axis.
- Option one compared to the current system has the outer and inner cooling blocks/tube reduced from 10 degrees C to 5 degrees C.
- Option two compared to the current system sees the heat flux going into each crystal reduced from 75 W/m^2 to 37.5 W/m^2.

Conclusions

- Values present in one/two dimensional calculations correlate to ANSYS model but vary slightly due to constraints of the calculations not being able to consider all variables in the system in just a 1D or 2D setting as much as the 3D.
- As shown the temperature values in ANSYS are within the acceptable range but right on the fringe so additional cooling is highly recommended
- Between the two cooling options as shown the best course of action would be option 2 as in that scenario the overall system ΔT is greatly reduced from 18.2 degrees C to 14.3 degrees C, and the ΔT inside the crystals at most was shown to go down from 3.4 degrees C to 1.55 degrees C.
- Option one reduces the highest overall temperature of the system but, the overall ΔT is found to be much higher than option one or the current setup. The internal crystal ΔT is lower than the current system but just slightly and compared to option two is double.

References / Acknowledgements

National Center for Biotechnology Information. "PubChem Compound Summary for CID 24464, Lead tungstate

eFunda, Inc. "Steady State 1-Dimensional Heat Conduction." *1D Conduction Theory in Heat Transfer*, https://www.efunda.com/formulae/heat_transfer/condition/conduction_1d.cfm

Edwards, Robert, and Michael Lobaugh. "Using Excel to Implement the Finite Difference Method For 2-D Heat Transfer in a Mechanical Engineering Technology Course." *2014 ASEE Annual Conference & Exposition Proceedings*, 15 June 2014, doi:10.18260/1-2--23261.

Çengel Yunus A., and Afshin J. Ghajar. *Heat and Mass Transfer: Fundamentals and Applications*. McGraw-Hill Education, 2020.

I would like to extend my most sincere thank you to my mentor Tim Whitlatch for his constant guidance and support though this project. I would also like to thank Stephanie Worthington, Jalyn Dio, Lisa Surles-Law and Steve Gagnon. A final thank you to the Department of Energy and Jefferson Labs for giving me this most amazing opportunity for the summer that will help guide me for years to come