# ECal Design and Performance

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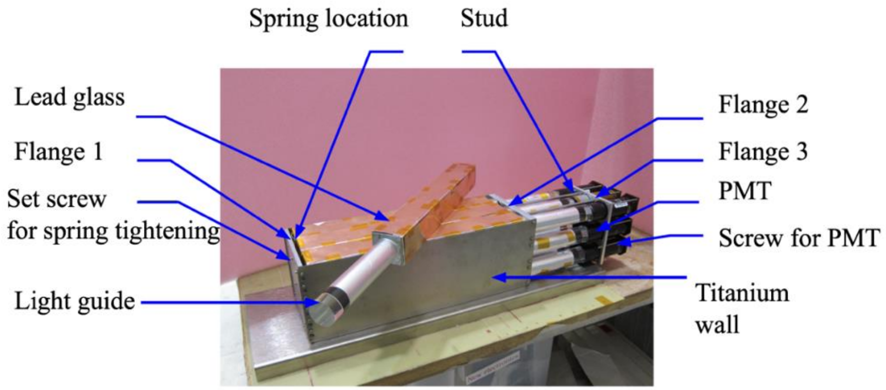
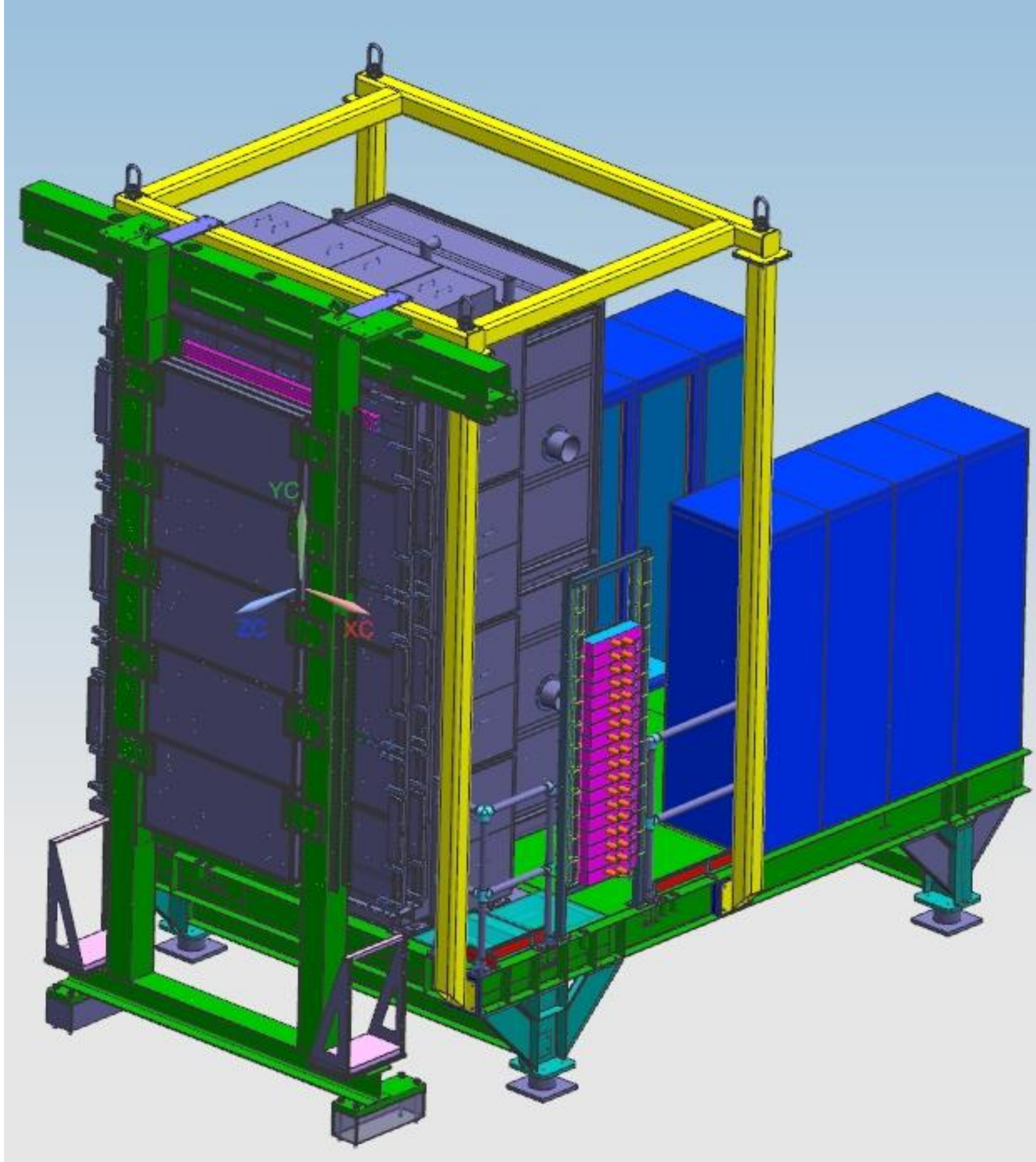
# ECal design highlights

- 1656 lead glass crystals:
  - 42.5mm square by 350mm long crystal size
  - 15 inch long 1.1” diameter glass light guides
- Crystals encased in 9x9 matrices called supermodules

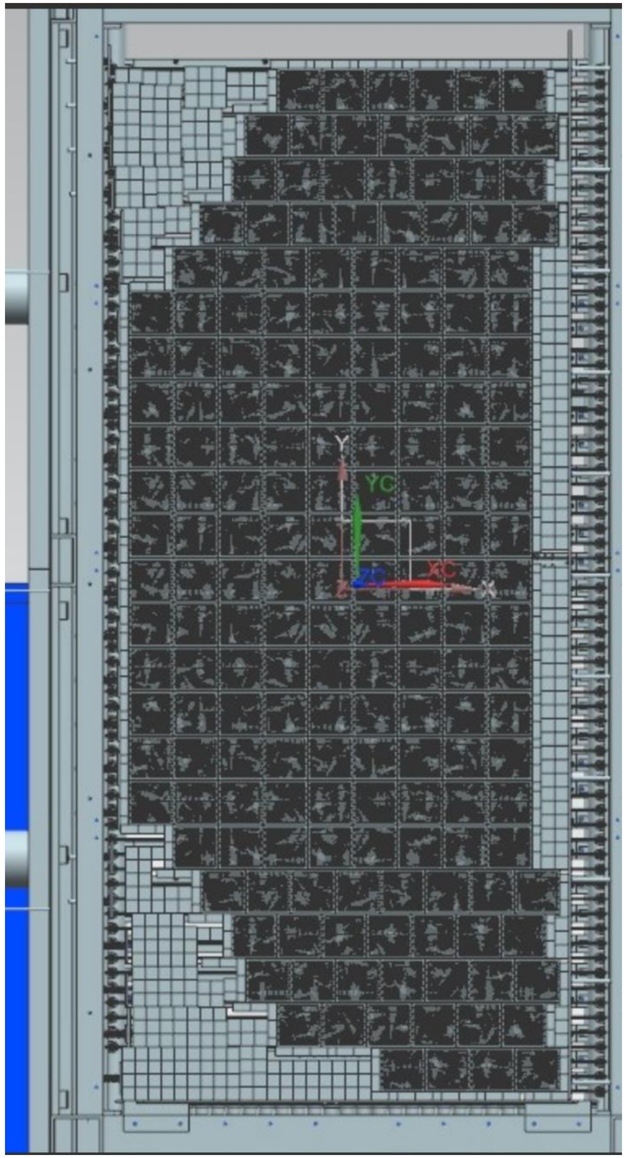


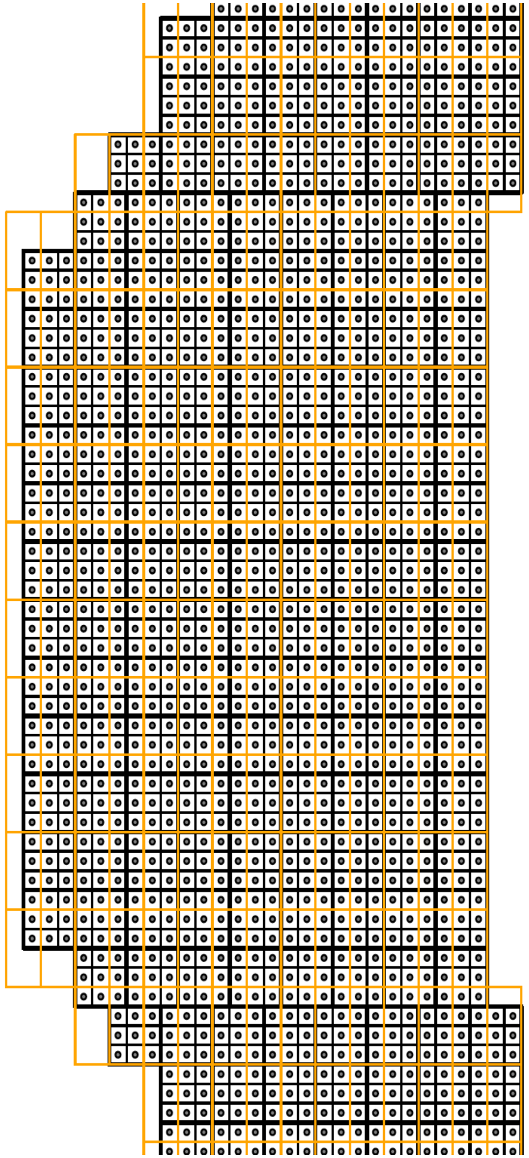

- Expected 5-6% energy resolution
- Detector crystals heated to >200 ℃ for continuous annealing
- Moveable to accommodate different kinematic points



# ECal design

- When I arrived in 2022 ECal became my primary focus alongside Iuliia Skorodumina and Albert Shahinyan
- We were tasked with ensuring all parts were designed, purchased, built/assembled
- At that time we were still going with a triple layer Fastbus readout with NIM formed sums of 8 and 32 going to the trigger
- The front end electronics were much more complex and the signals had to be discriminated before going to the DAQ
- In 2023 when we decided to go with an FADC-based DAQ, many of the parts and plans became obsolete.
- It also became obvious with Albert's involvement declining that the design of the heating and cooling systems design was immature

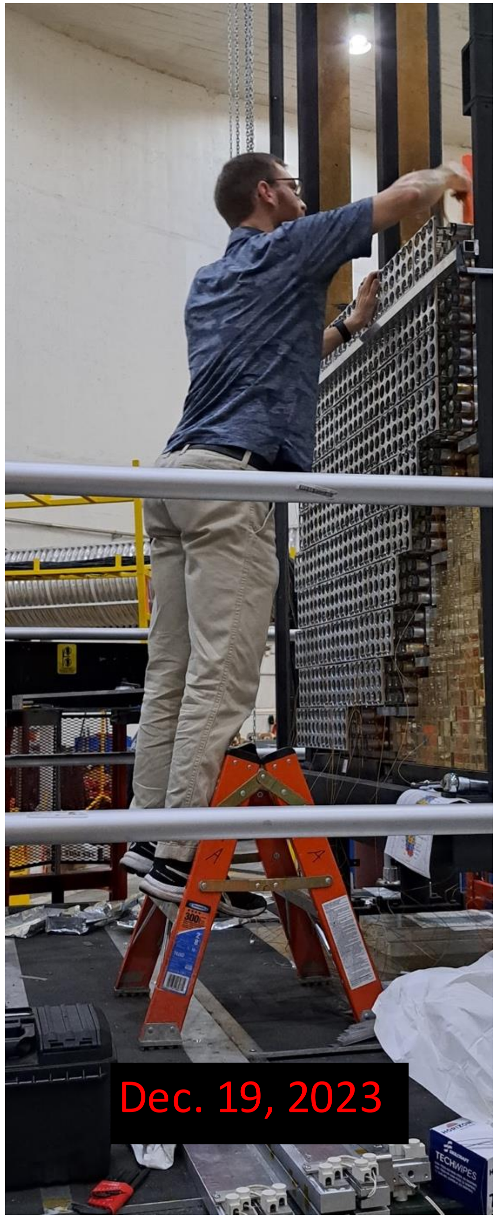


# Installation and assembly

- We began assembling the detector stack in Dec. 2024
- Took just over 2 months to complete the stack

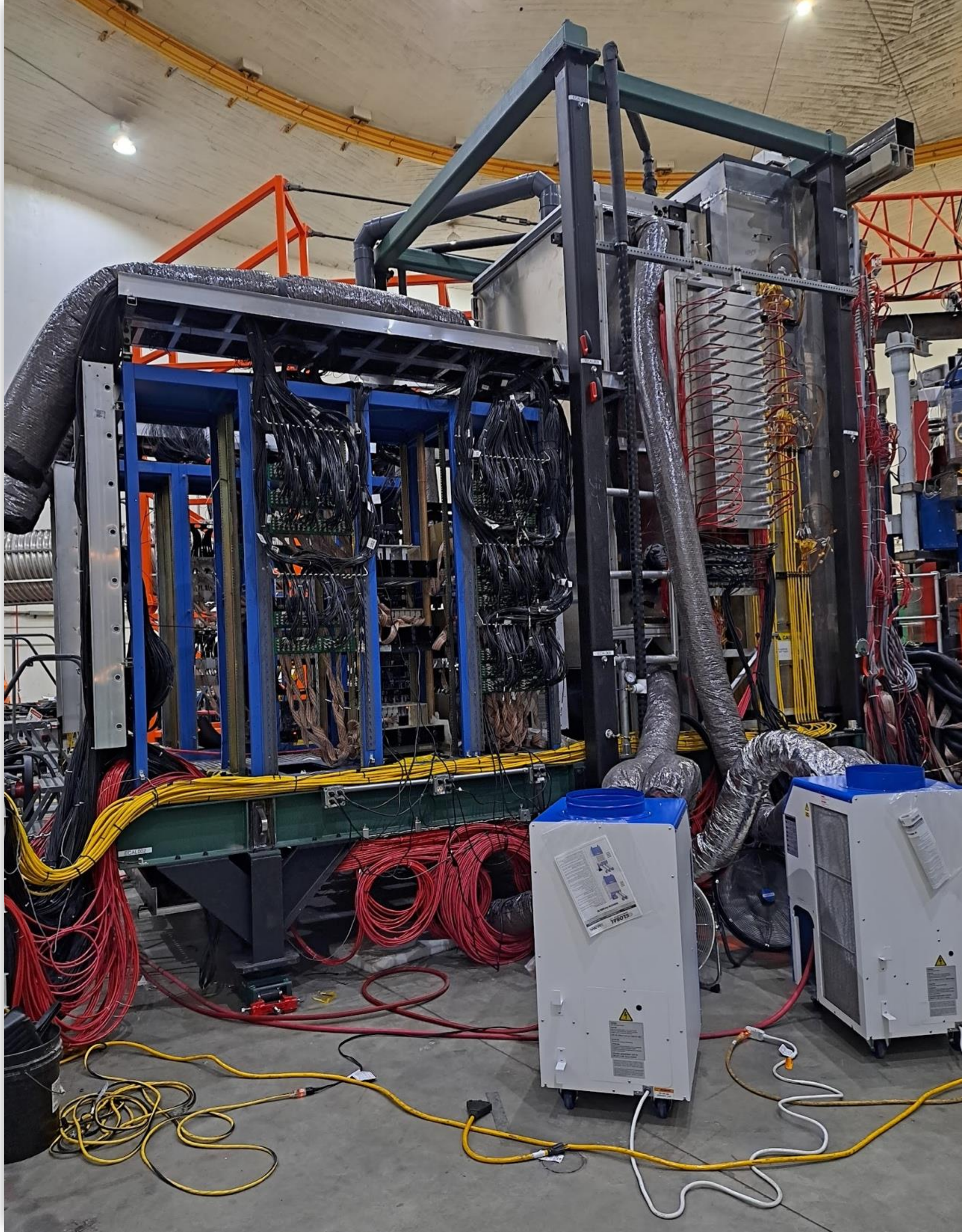





# Lots of work before we got to here->

- Install heater and cooling system and thermocouples
- Install insulated walls
- Install light-tight rear enclosure
- Install PMTs and bases
- Install PMT signal and HV patch panels
- Cable from PMTs to front end
- Cable from front end to DAQ bunker
- Install FADC DAQ
- Install HV supplies and remote control
- Cable from HV to detector

Small army of folks including staff, students and post docs to complete this installation on time.

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# Performance

- Old PMTs very noisy
  - Significantly added to difficulties with calibration and evolution of gain
  - Initial calibrations from cosmics then raw spectra endpoints after beam on
  - Final calibrations available after more mature analysis made cut on elastic electrons possible
- Bases had a loose plug connection and their design was not rubust—many broke during assembly
- 36 dead channels on start up and ~50 by the end
- Continuous monitoring and tweaking of individual channel high voltages by students Jhih-Ying and Kip throughout the several month run
- Light guide glue darkened and many failed where temperatures were hotter
- Heated crystals remained clear
- “Cookies” connecting between light guides and PMTs worked well
- Overall resolution ~11-12% (see Jhih-Ying’s talk tomorrow)
  - Unclear why the resolution is 2x expected

# Rate limitations

We were limited for most of the run to <20uA on a 30cm target

- Recall the original proposal was 75uA on a 40cm target 1.3m closer to the target
- Fortunately the phase space reduction from the trigger using the position correlation between HCal and ECal worked well.

**Contributing factors to rate limitations**

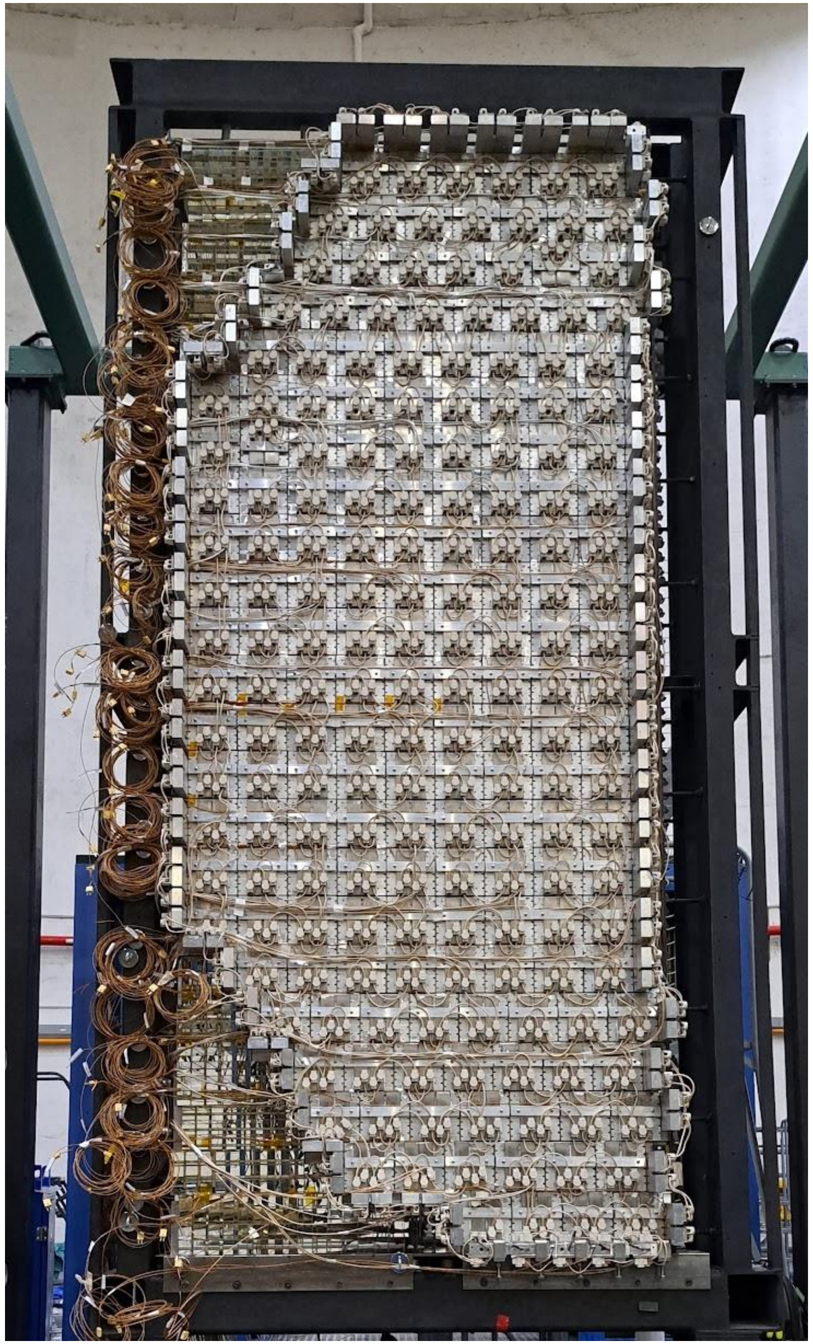
1. Difficulty calibrating ECal in real time—especially the top half (see more about this later)
2. Even with calibration ECal resolution only at 11%. Ran most of the time at 60% of elastic instead of the 80-85% we had hoped.
3. GEMs needed lower rates. Even below 20uA planes at 40% occupancy!
4. DAQ + data transfer/storage struggled with extreme rates from lower thresholds (approaching 2 GB/s at one point)

Ok…now let’s spend some time focusing on the novel aspect of this detector– it was heated.

Did it work well?
Is it worth doing again?
How might it be improved?

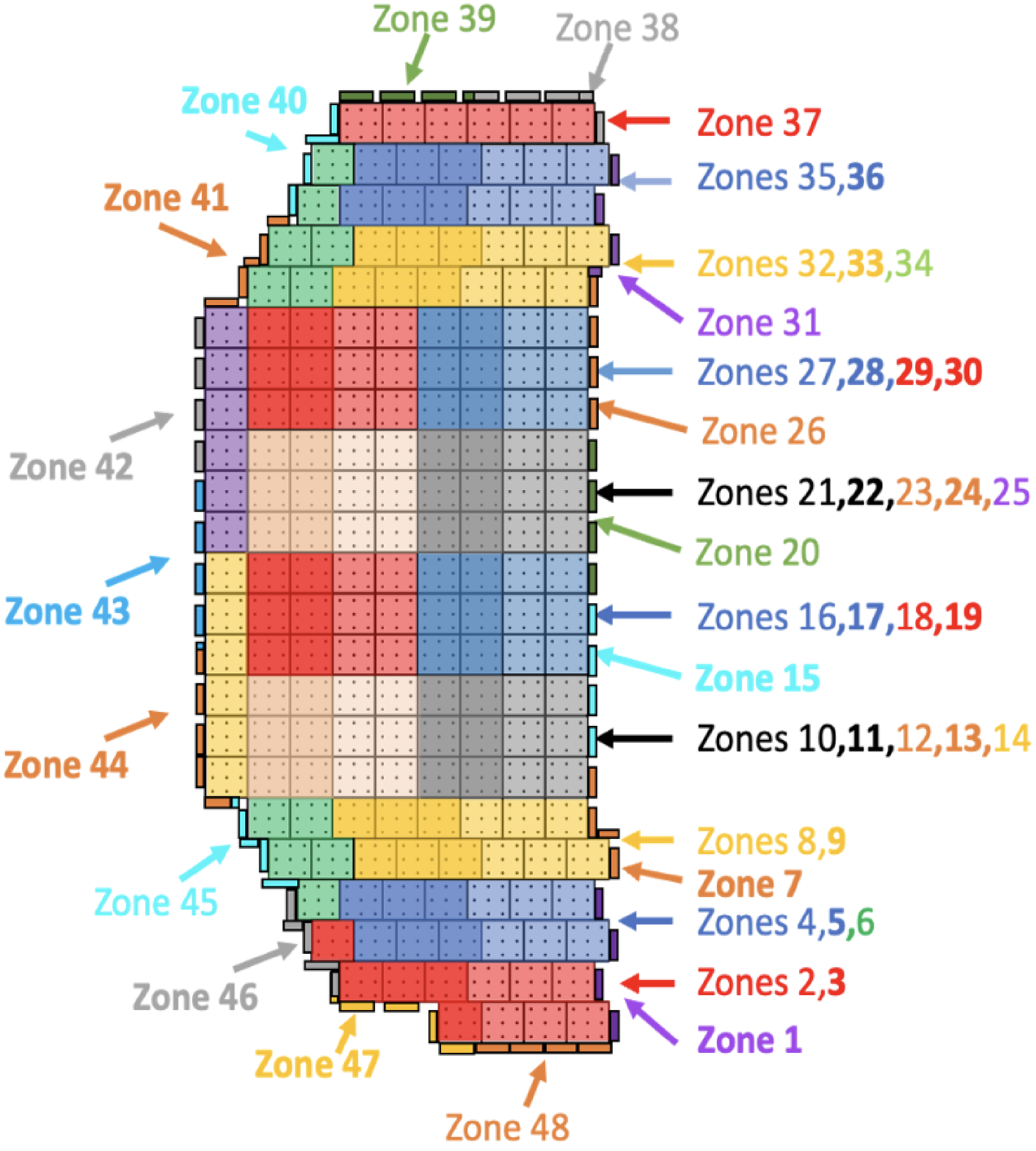
# Heated detector design

- Measurements from prototype C16 in 2017 demonstrated 225℃ sufficient to maintain crystal clarity.
  - Designed system to reach 225℃ on crystal front
  - 180 ℃ on back end of crystal
  - PMTs need to be <50℃
- Years of tests and measurements went into design of supermodules
  - Copper foils along length of each long crystal surface maintained heat profile
  - Titanium edge plates nearly matched to lead glass expansion.
  - BK7 glass for light guides better matched expansion so glue joint didn't fail
  - Springs to hold crystals in place inside supermodule units
- Heated aluminum bars along all edges to maintain profile at the boundary.
- Crystal frame designed to allow differential expansion
- Many tests and prototypes went into arriving at final heater system
  - Low voltage kept safety and fire hazard concerns low
  - Robust ceramic plate and cartridge heaters used
- Significant effort to ensure and document that all materials in the heated region rated for maximum termperatures



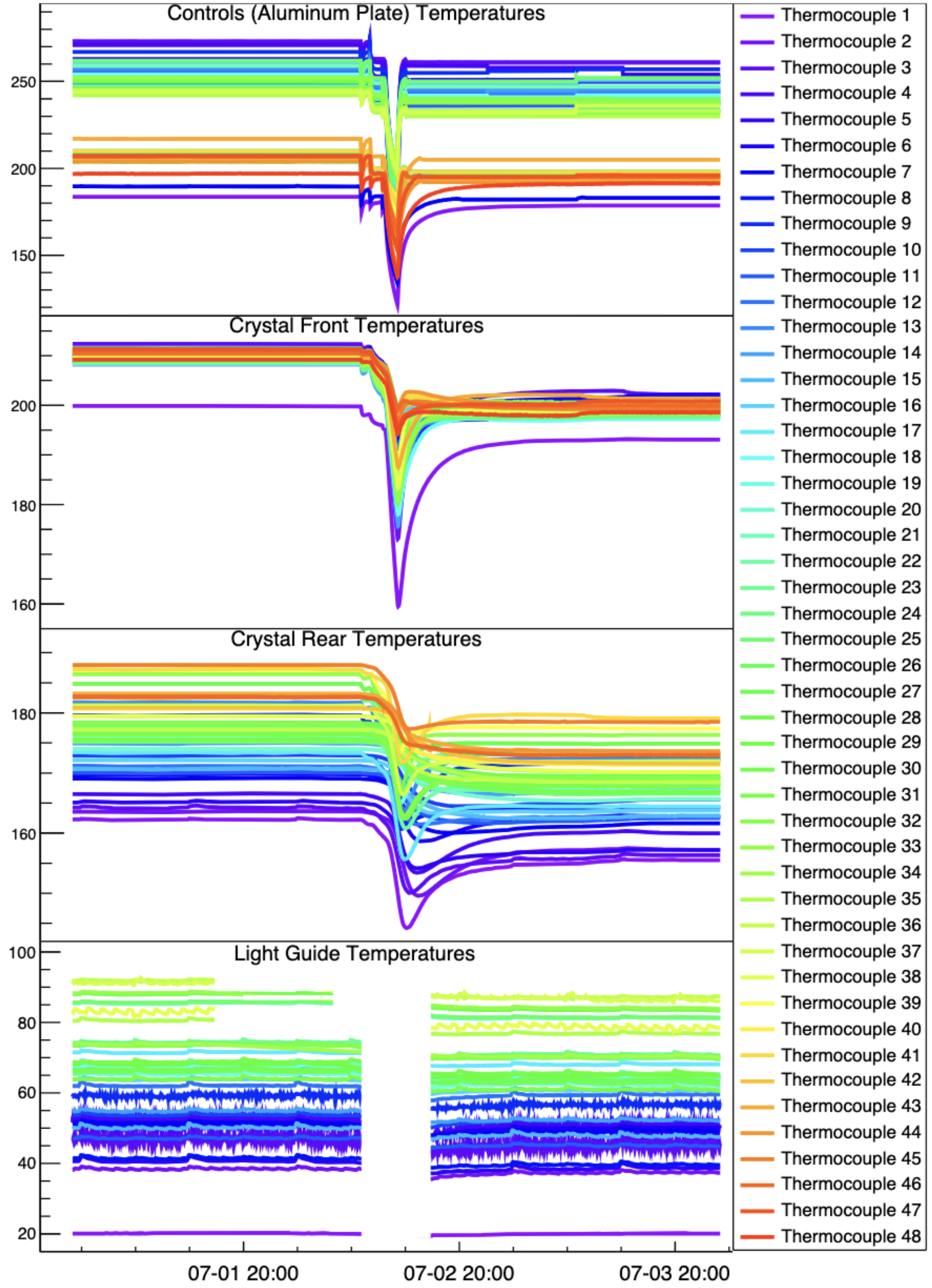
# ECal heater system

- Heater system designed to run on <50 VDC.
- 48 heater zones and >200 thermocouples gave flexibility for uniform temperature across detector
- Low cost DC supplies from industrial LED drivers
- DSG developed temperature controls and monitoring

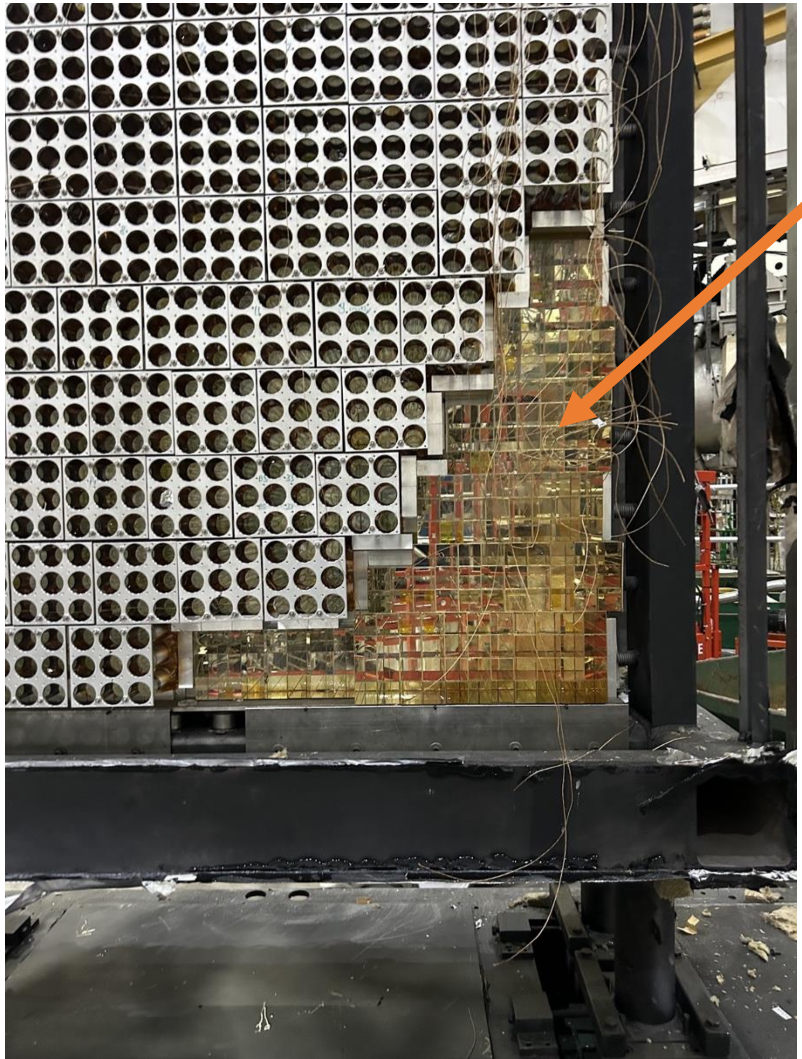



# What worked well?

- The LabVIEW-based controls and safety system worked very well and updated key parameters to EPICS
- Worked very well except for occasional radiation-induced hardware faults
- Temperatures on crystal front very stable and temperature spread of a few deg C.
- Started with average 210 °C crystal front then lowered to 200 °C. Plots on right show transition.
- Crystal clarity maintained

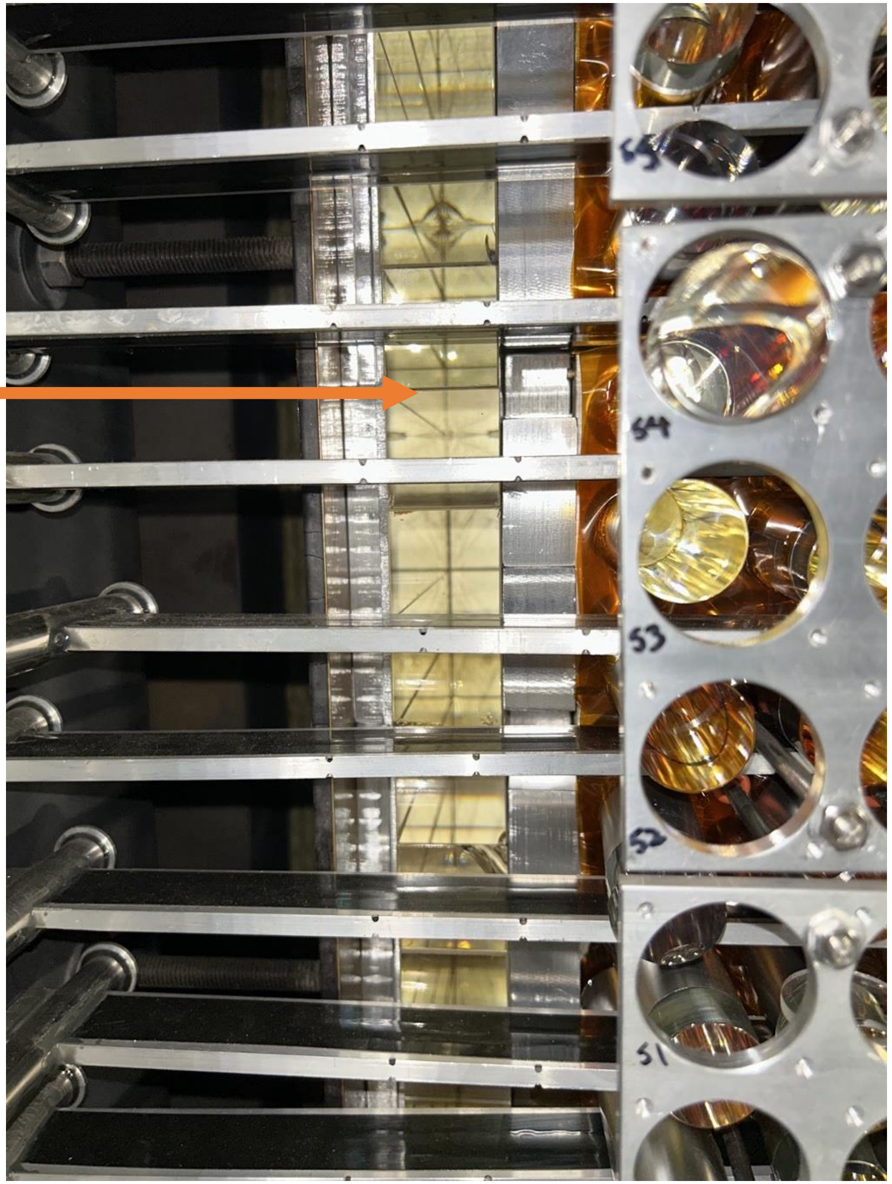


# Evidence lower temperatures were sufficient



Crystals not directly heated still show little evidence of darkening

No obvious correlation of lower trigger rate with beam on



# What didn’t work so well

- Software controls set to wrong thermocouple type on first heating test.
  - Resulted in overheating detector by tens of degrees
- Glue joints between crystals and light guides darkened and many failed.
  - May have been due to overheating incident
- Controls hardware should have been better shielded to prevent faults
- Cooling system inadequate
  - Rear enclosure had large temperature gradient
  - 20℃ on bottom, $> 50$℃ on top

# High temperature insulation failure

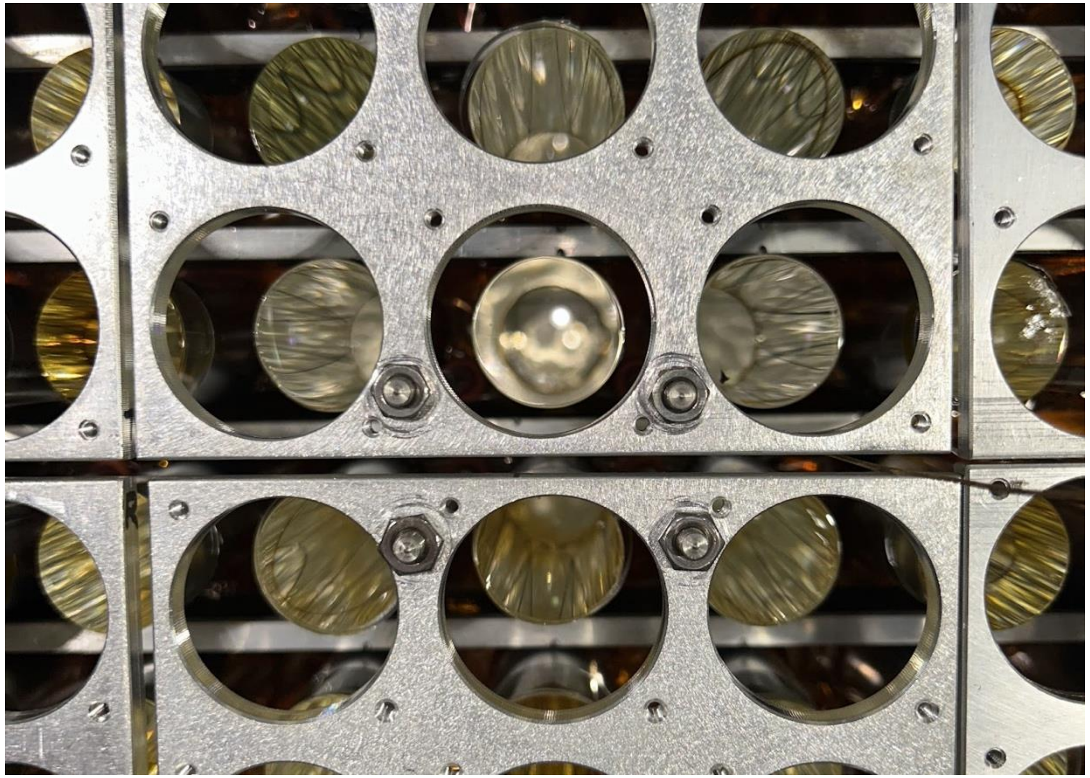
McMaster Carr claimed insulation rated to 650℃ but post-mortem showed foil failed well below 300℃

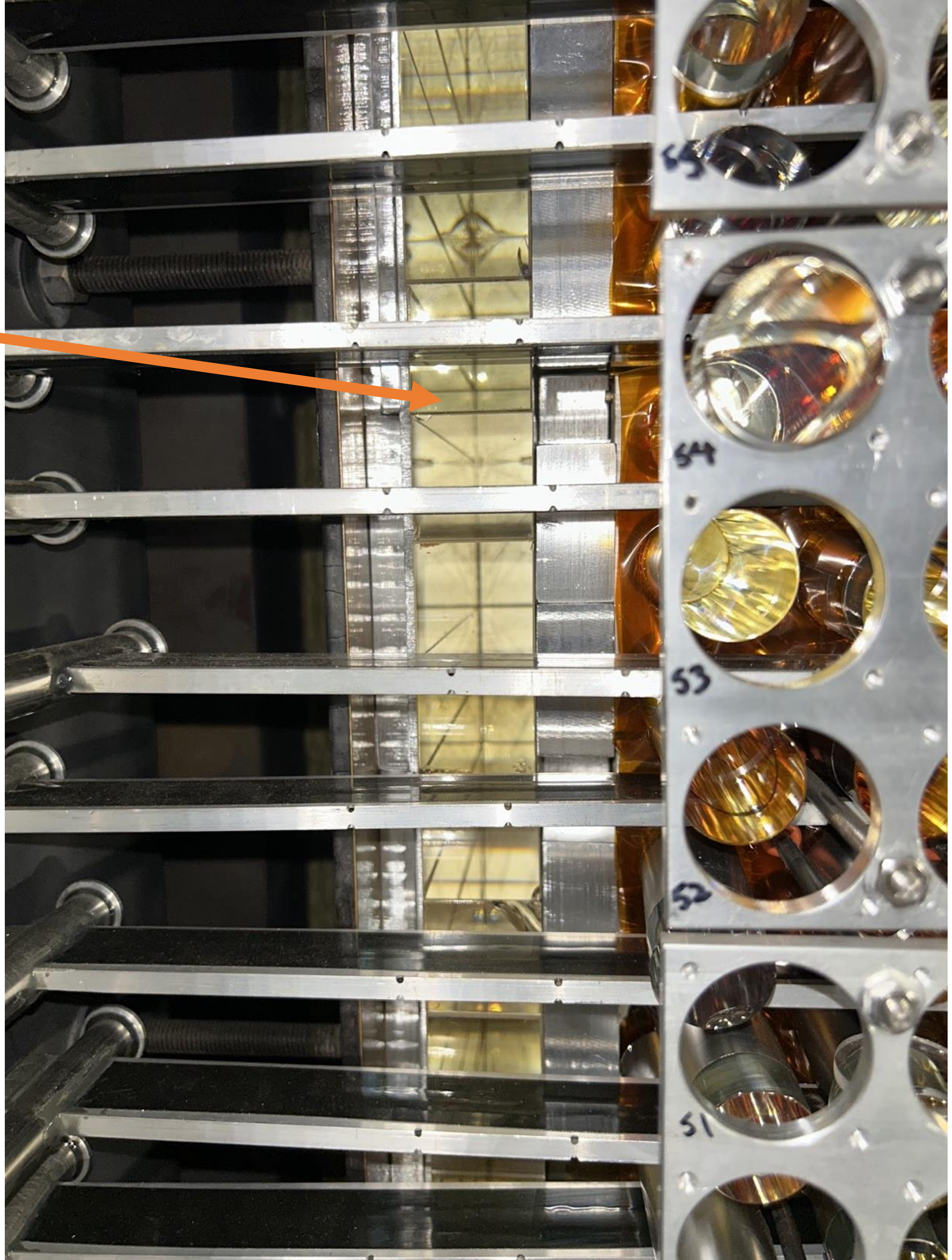
They admitted their mistake on follow up and told me the insulation was rated at 650℃ but the foil only to 150℃

Thankful that no safety issues arose after initial bake-off

# ECal crystals retained clarity

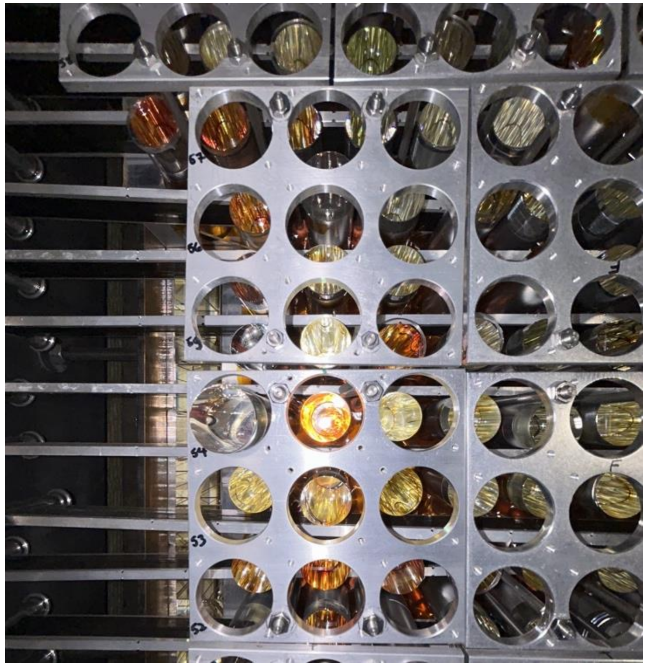
- The heated ECal crystals are still clear
- It is easiest to see in the bare crystals used for spacing
- It is also visible looking down some of the light guides





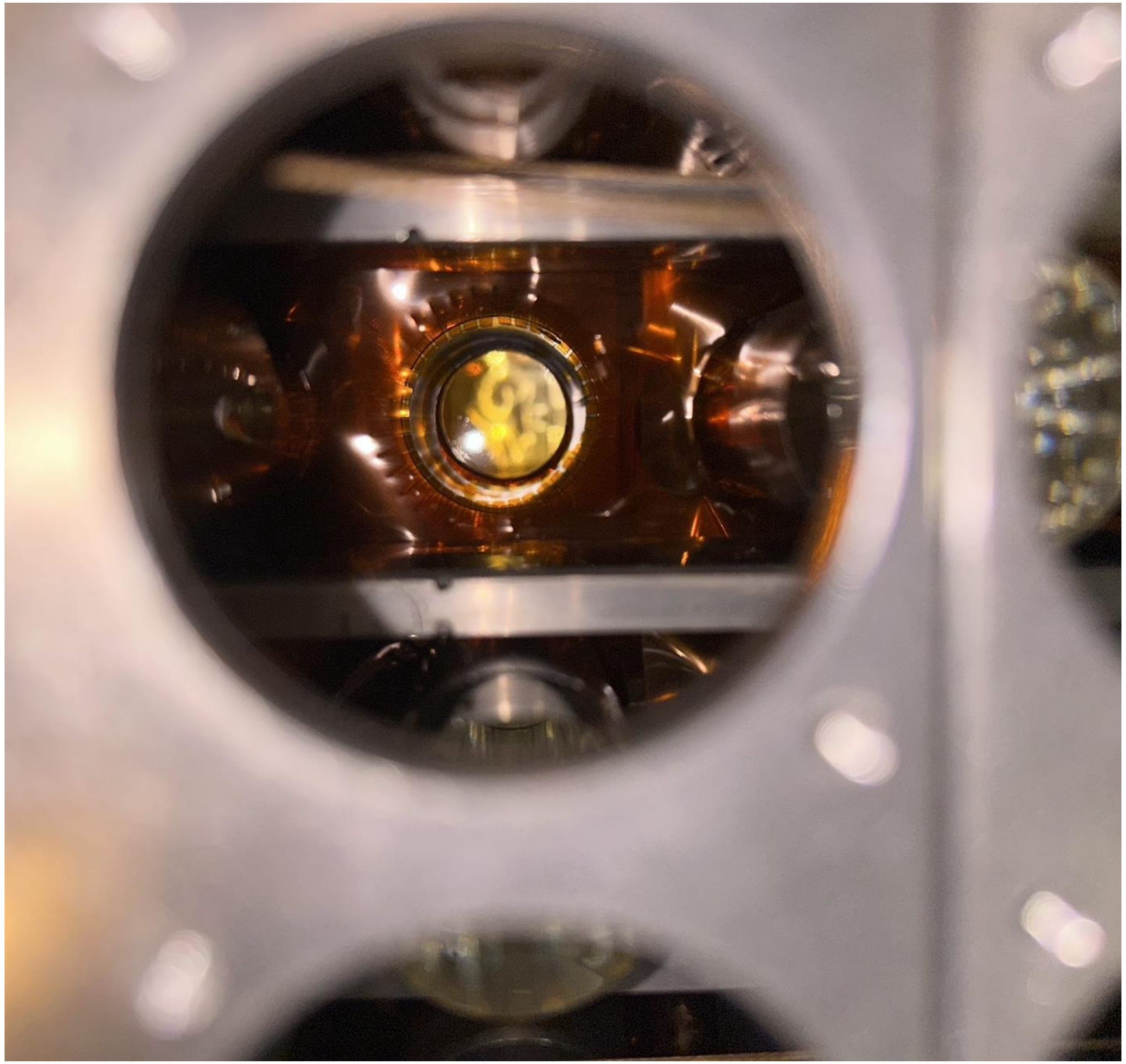
# Many look darkened

- A big picture of ECal shows a great deal of apparently darkened crystals
- Closer examination shows this darkening is the glue joining the light guide to the crystals
- Poorer quality joints especially those in the hotter regions show darkening
- Cookies retained full clarity!



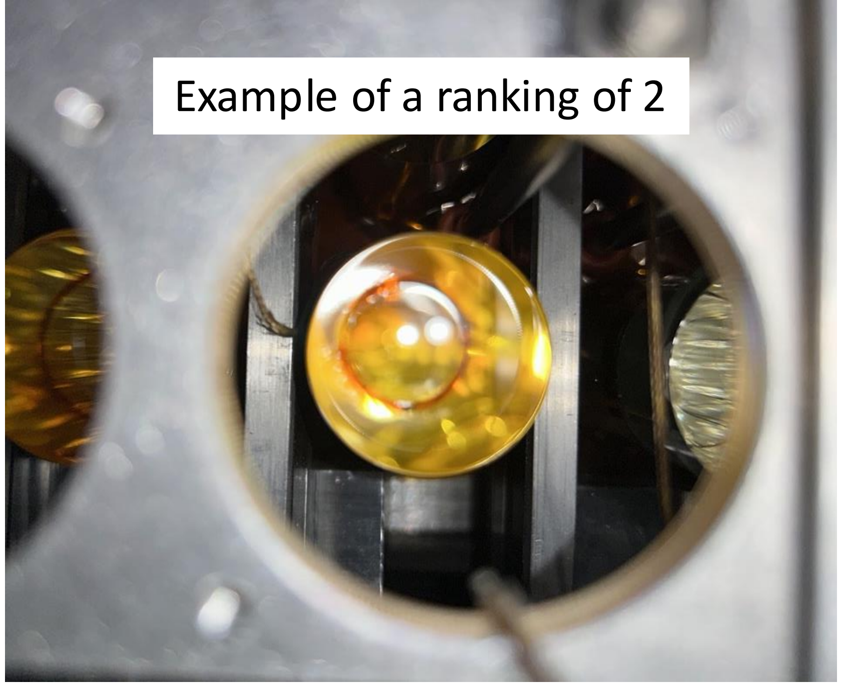
# Many loose light guides

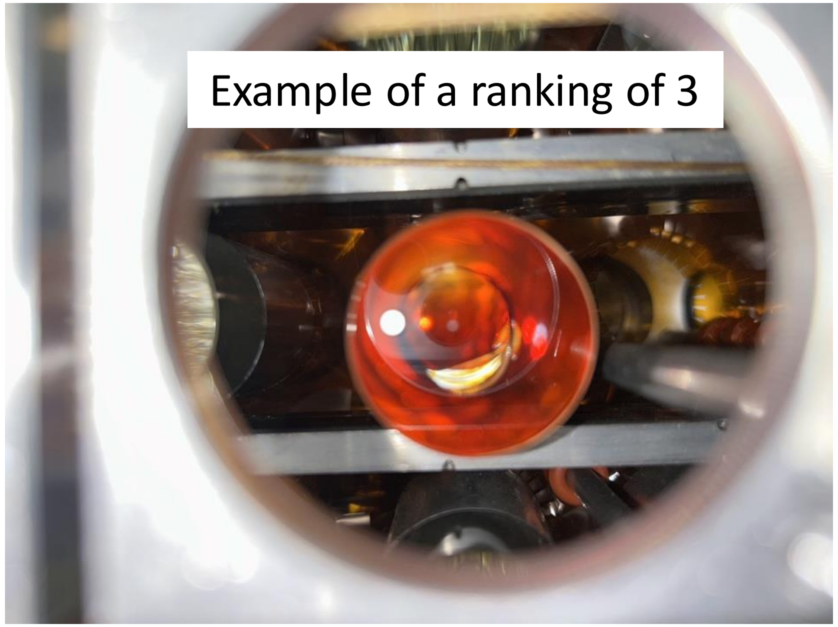
- After removing the PMTs we found many loose light guides
- Even though the glue joints in these cases had at least partially failed, the light guides were still held firmly in place and in contact with the crystals by the screw plates holding the PMTs
- Failed glue joints usually are accompanied by darkening suggesting it is a combination of air and heat that creates the darkening.
- The picture shows a crystal with the loose light guide removed and a yellowed glue film partially covering the crystal where the guide was



# Stark difference between top and bottom

- The top 1/3 of the detector (rows 43-69) showed much more darkening and many more loose light guides suggesting that the temperature in the upper region was too hot at least for a time
- The lower 2/3 (rows 1-42) had very few failures
- I went through and ranked the clarity of the glue joints qualitatively giving a ranking of 1,2,3,4 where 1 was mostly clear, 2 darkened to gold, 3 darkened to dark orange, 4 darkened to brown.
- Caveat: this was my qualitative judgment ranking
- There were only 2 ranked at 4

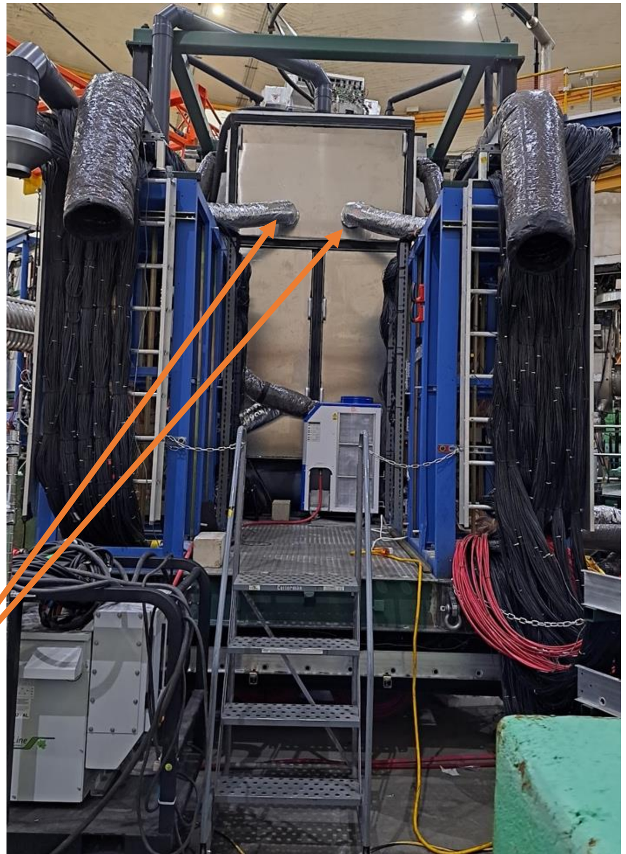


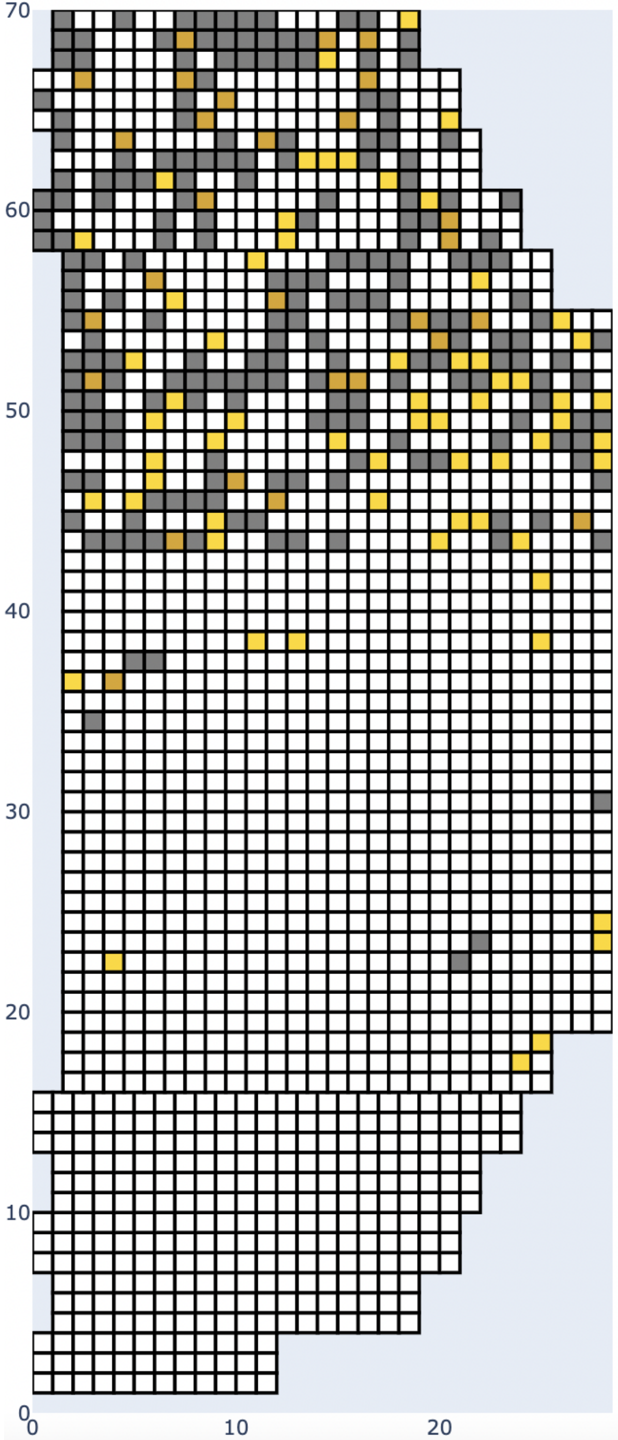



# Visualization of light guide performance

- Yellow and dark orange in diagram to left signify levels of crystal darkening.
- Gray signifies a loose light guide.
- Although the transmission of the loose light guides is not specified, they are generally associated with darkened glue in addition to being loose
- This helps explain why we had a lot of difficulty calibrating the top of ECal
- It is not clear if this was a slow process over time or if it was due to a single event

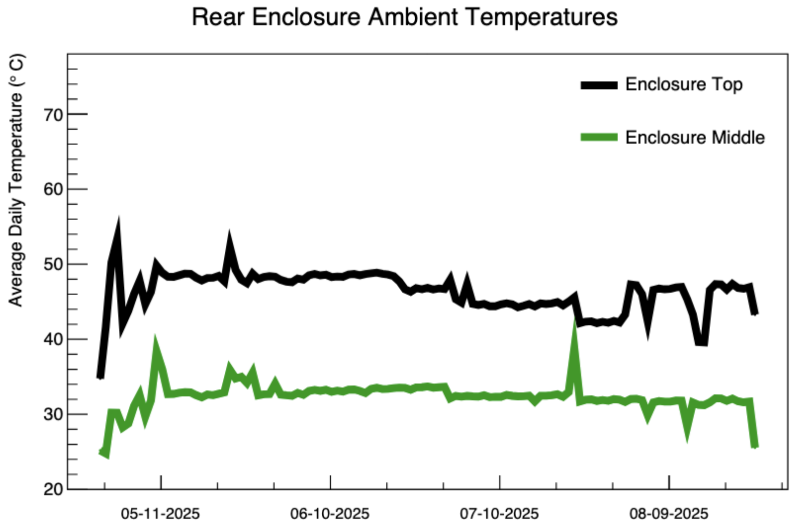
- The most severe overheating happened during a test Mar 11-12, before the beginning of the experiment when the controls program underreported the thermocouple temperatures (interpreting them as j-type instead of k-type)
- During this test I ran much of the detector at full power and could not reach the crystal target temperatures of 220degC and only later found out I was well above that.
- During this test only one air conditioner was active and it was blowing into the bottom half of the enclosure and exiting the top.
- After this test, I added two more air conditioners.
- It is likely that this event was partially to blame along with an underperforming cooling system.
- At end of 3-pass running more cooling exhaust vents added





# Cooling system

- A few weeks before GEP was starting I realized that the cooling system as designed would not accommodate both the heat generated by the hot crystals and the PMT bases.
- Retrofitted the rear enclosure to include pipes connected to an industrial air conditioner… then two air conditioners blowing air in the 1-5°C range
- Turned on detector and found dark current rate still extremely high with heater system on
- Biggest decrease in dark current happened when we added a 3rd air conditioner to feed cold air to pumps that shot jets of air at each PMT/light guide.
- Finally modification was adding more vents since inlets outnumbered outlets by a fair margin

# Suggested Improvements

- Put the controls and monitoring hardware in a better shielded area and add independent monitor of temperature in heated region
- Cooling system subject to large gradient which is nearly impossible to remove
  - Couldn’t seem to get rid of hot air pocket at the top even with cold air input near the top. Surprise--cold air falls.
  - Biggest gains were using cooled air directly as input to the cooling jet system
  - Recommend to introduce all cool air through the jet that are 2x radius (4x flow) so that the cool air is where you need it and you aren’t relying on difficult to predict flow patterns inside the enclosure.

# Conclusions

- ECal worked reliably throughout GEP albeit at reduced energy resolution
- ECal performance was limited by the noisy PMTs and decreased energy resolution (perhaps related)
- Heating system worked well modulo a few hiccups related to incorrect thermocouple assignments and radiation-induced errors.
- Cooling system worked OK but improvements to keep the PMTs in the $30-40°C$ range would be better

NIM paper already begun

Operation of a radiation-hard lead glass calorimeter during GEP at Jefferson Lab

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**Abstract**