Updates from the Lab

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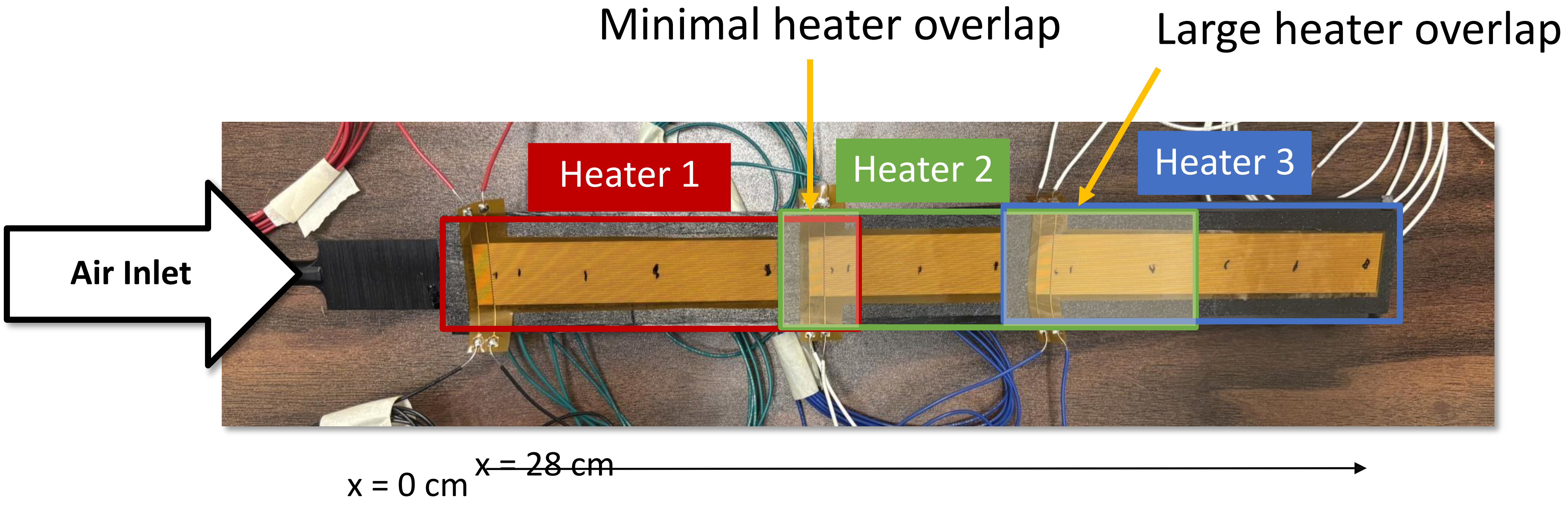
LBNL EIC meeting

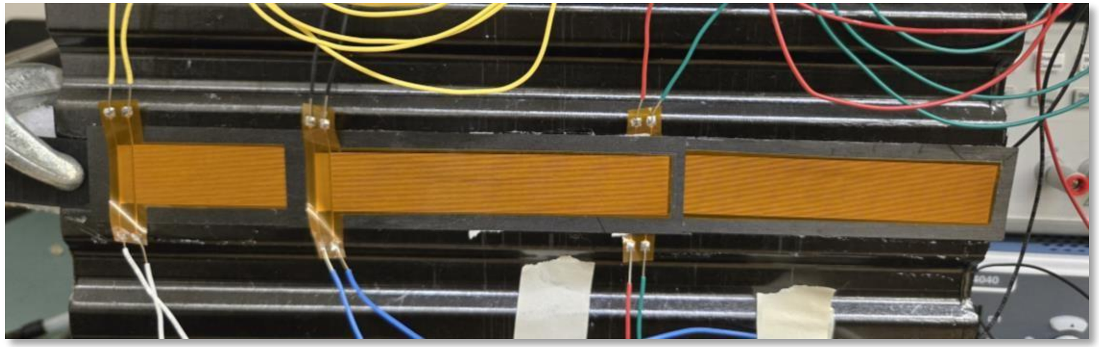
June 24, 2025

Testing Approach



- Temp measured at different x values along corrugation (0 – 28 cm)
  - One point taken at each LEC position
- Data taken at 4-5 different air velocity values
- Taken at MAX and NOM powers

Thermal test pieces



Large corrugated piece with one channel used

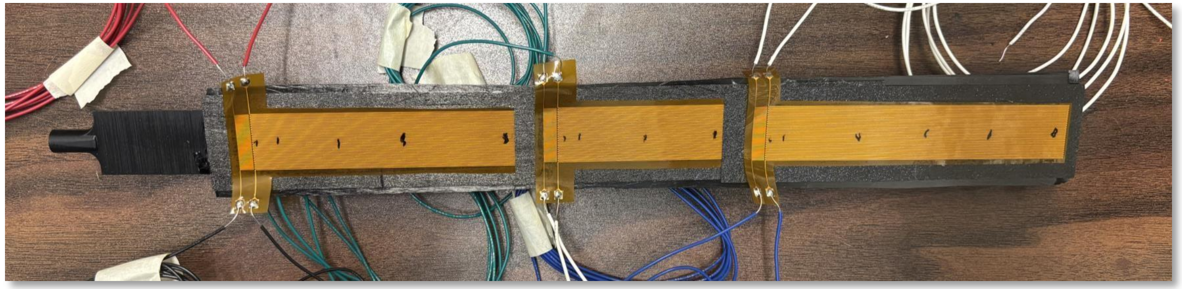
All heaters outward facing

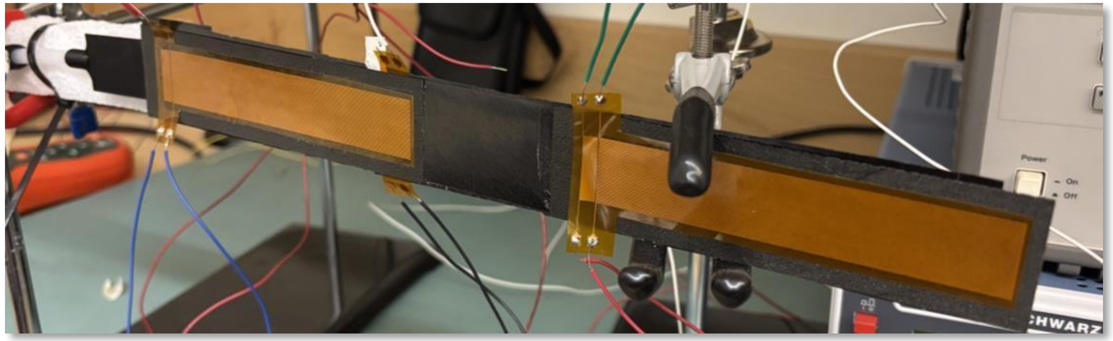
3rd LEC hidden

Single corrugation channel #1 & #2

All heaters facing

outward All LEC visible



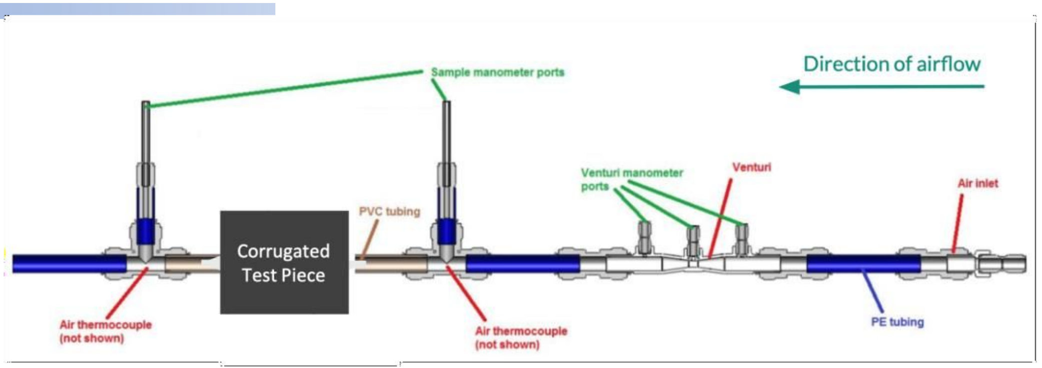


Single corrugation channel #3

One heater inward facing

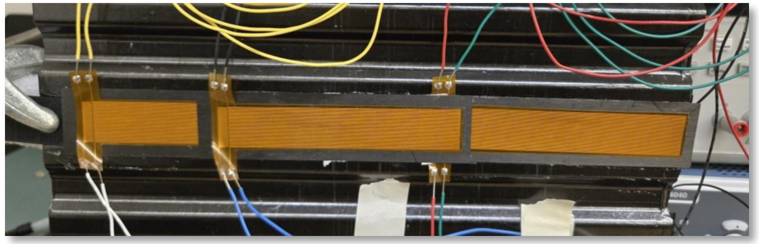
2nd heater hidden

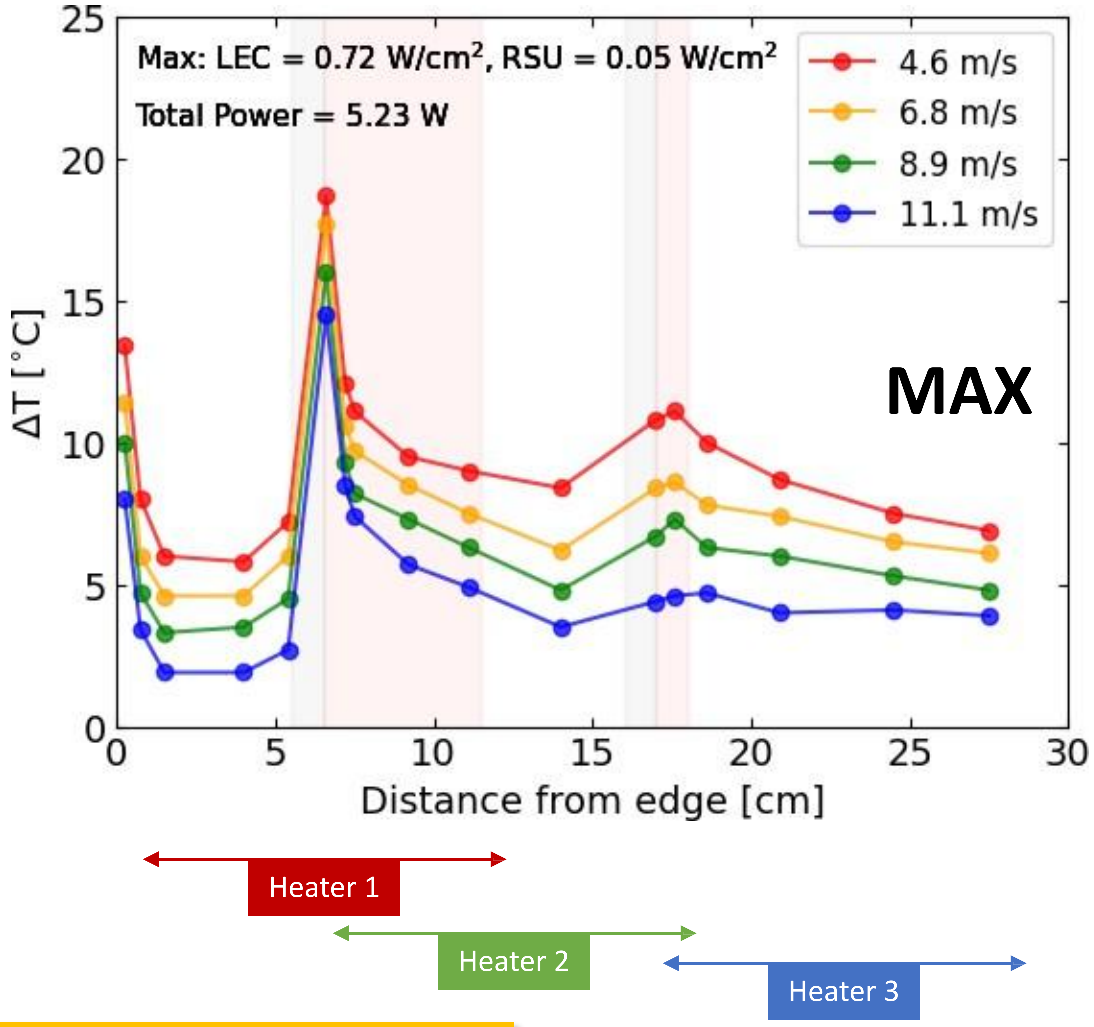
Test setup & caveats

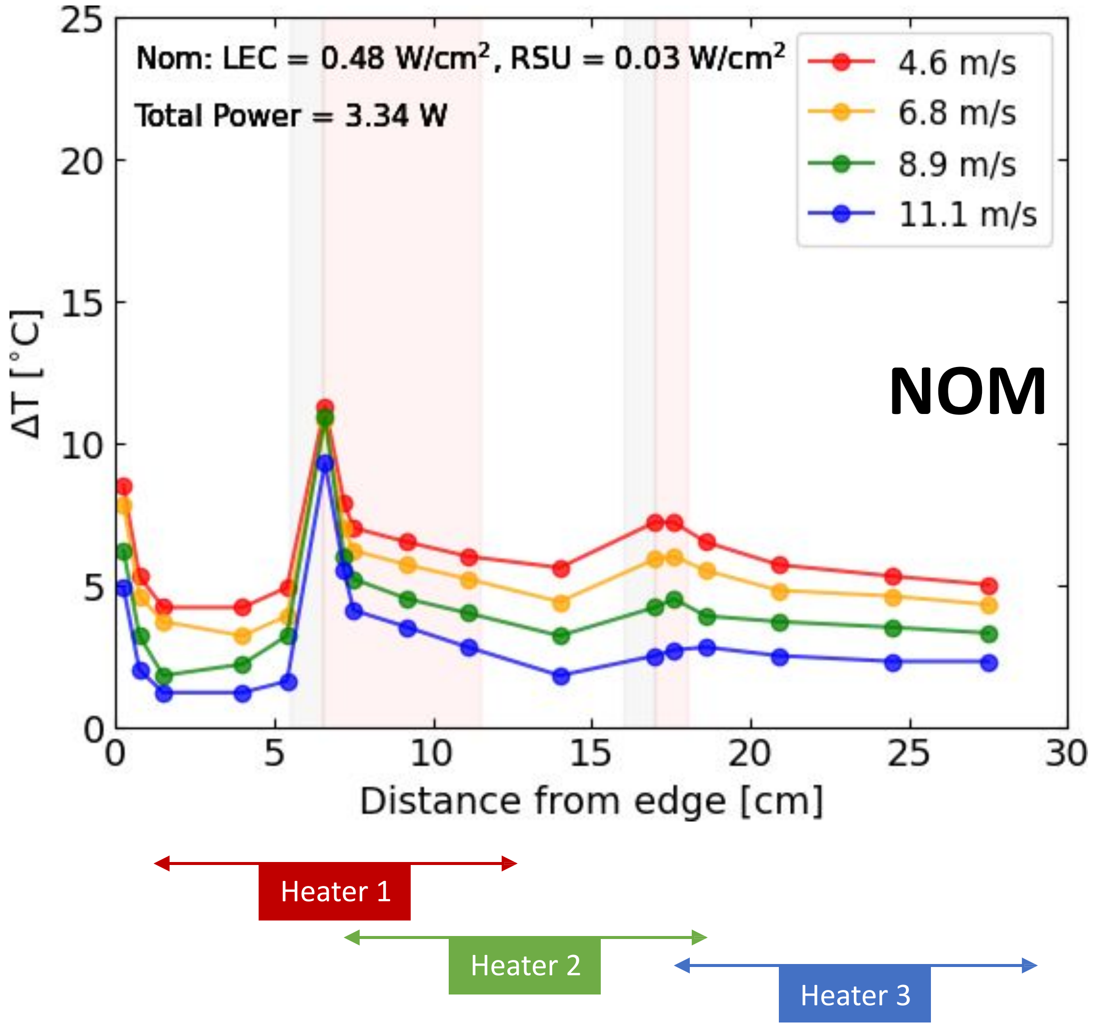


- Held in same orientation as planned in ePIC
- Using thermal camera ~0.5°C fluctuations
- $\Delta T = T_{BrightTemp} - T_{DarkTemp}$
  - Dark temp taken with air flowing, but no power
  - Bright temp taken with air flowing and power on
- Cannot measure ΔT of sections we cannot see, i.e. hidden behind overlap
- Air velocity limited by setup safety

Large corrugated test piece



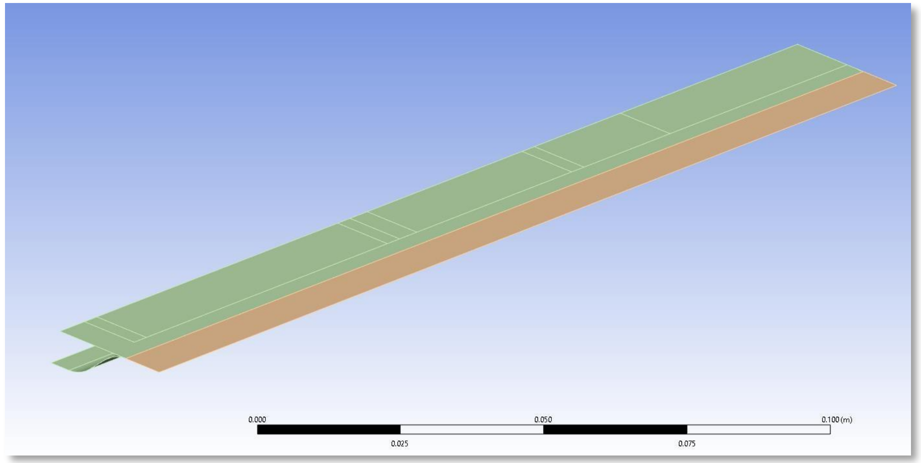


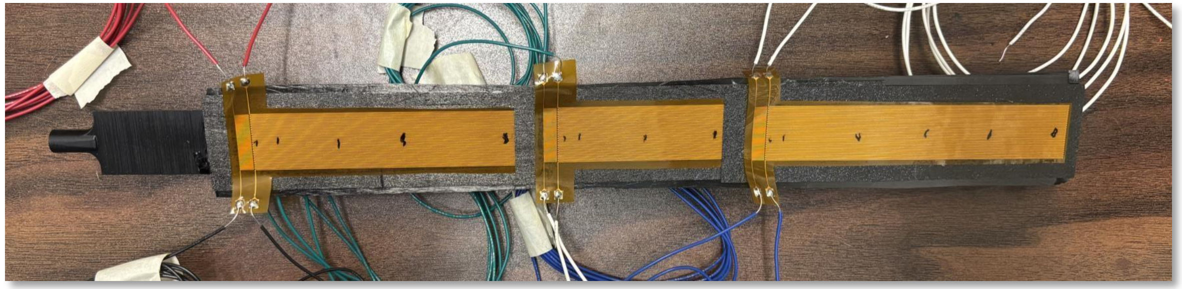


*LEC 3 cannot be directly measured

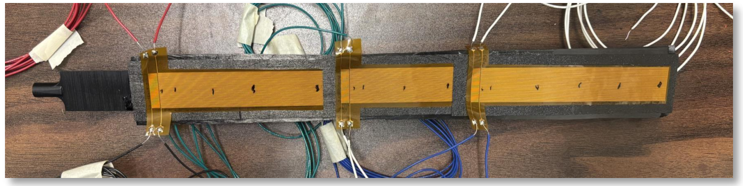
Single Corrugation Test Piece #1

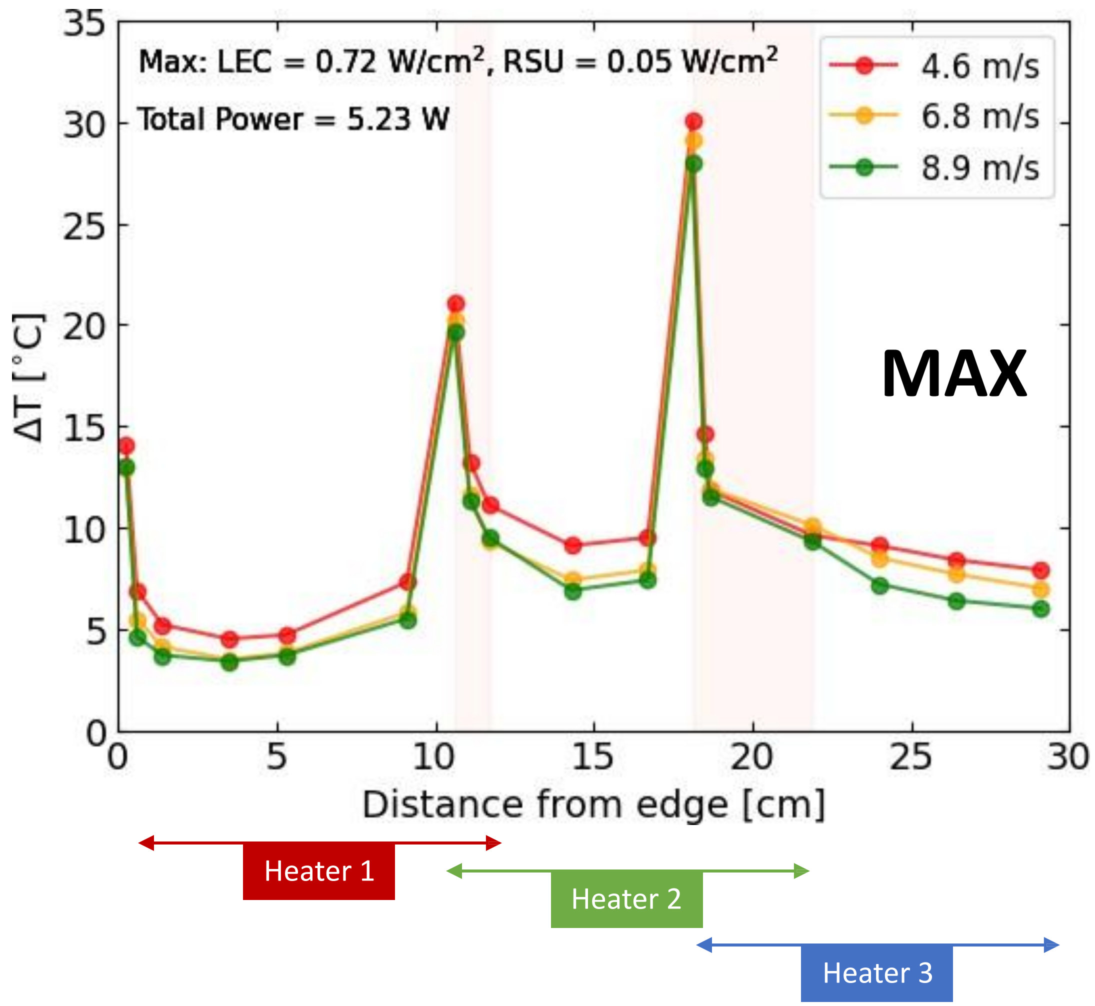
- Isolate natural convection & forced convection
- Minimize conduction through the corrugation
- Provide input to thermal model
- Expect T_{heater} to increase as T_{air} increases
  - T_{heater} should peak at the LECs (higher power density)

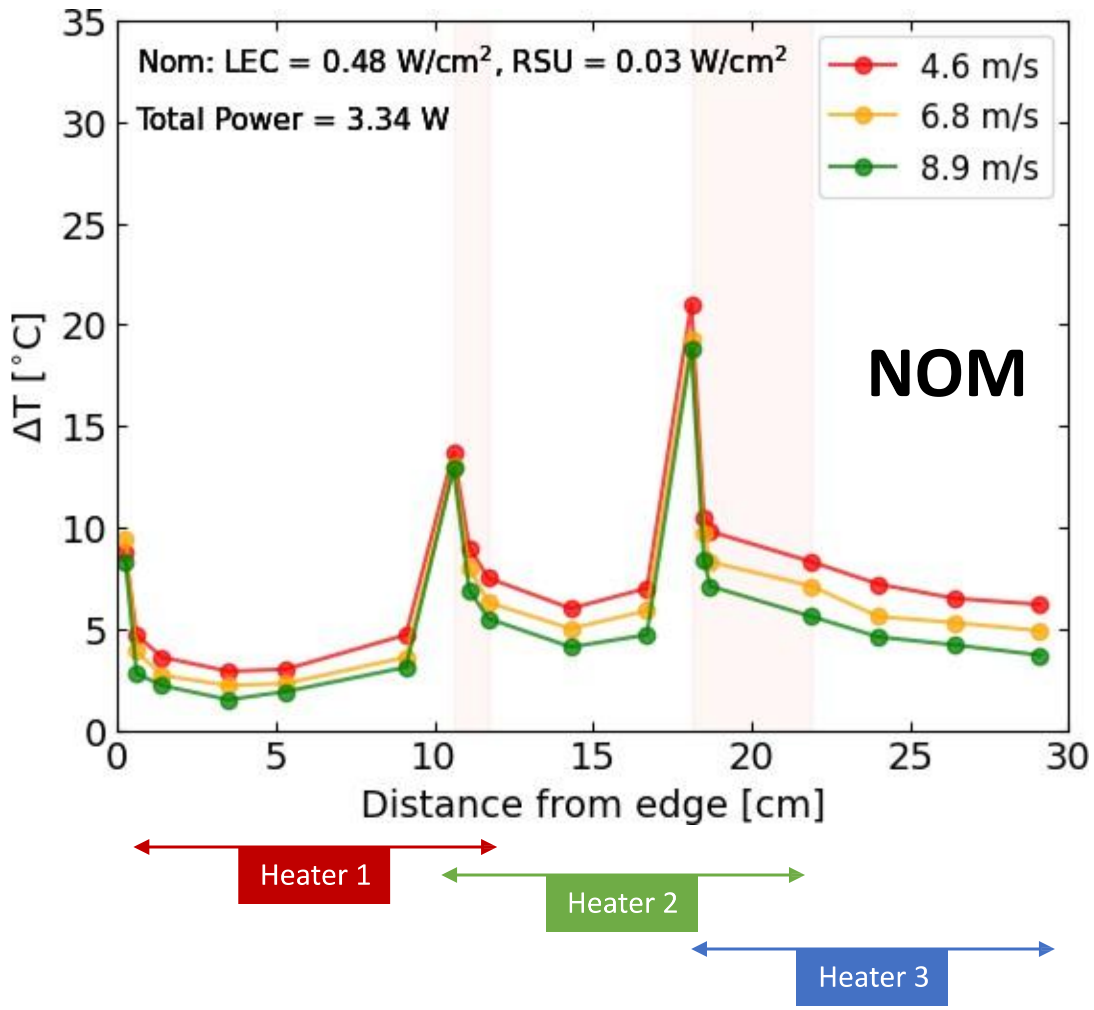




Thermal gradient



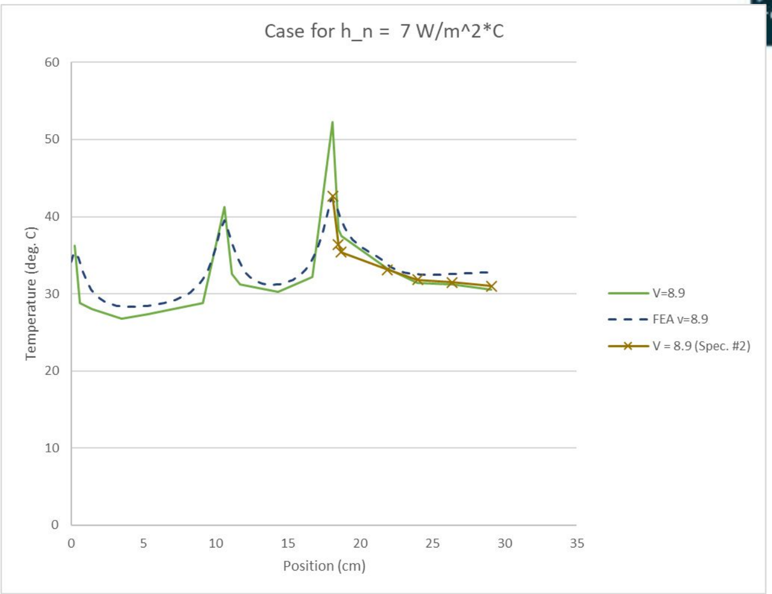


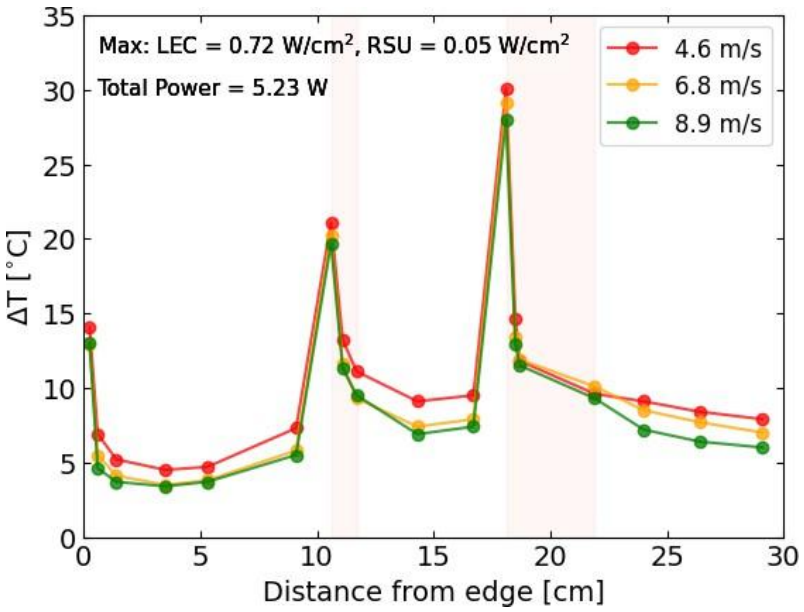


T does not vary much with air speed and significant T increase with each heater

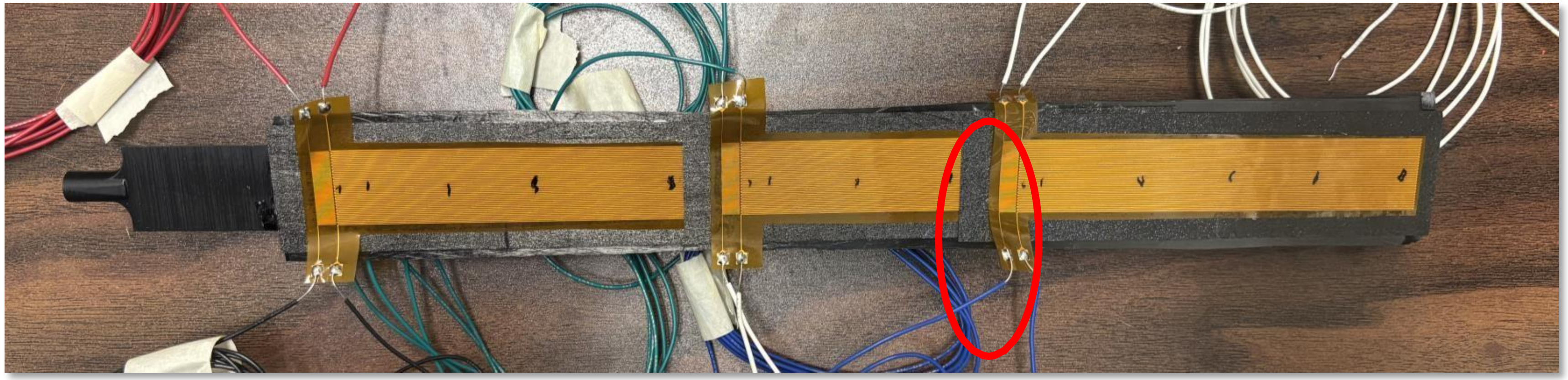
High ΔT investigation

- **Why is LEC 3 so much hotter than LEC 2?**
  - When individually powered, LEC 2 & 3 distributions should be the same. Both have overlap & are past the initial entrance zone region of the air flow
- Thermal model shows slight T increase per heater due to the increase in air temperature along the channel (1-2°C)
  - However, LEC 3 measures ~10°C greater than LEC 2
- **Why doesn't T vary with air speed?**
  - Previous results show ~1°C decrease per m/s increase
- Investigate this test piece and create a new one





Heater adhesion

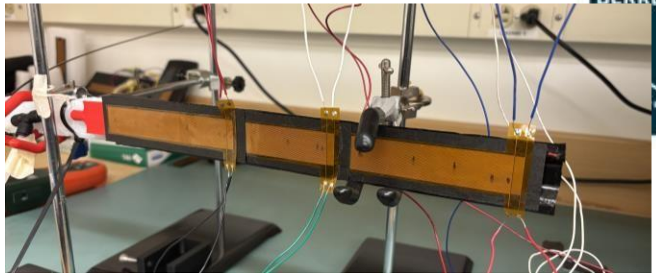


- Post inspection shows the delamination of the heater and larger than normal bonding material between layers was present.
- Without good adhesion, there is an air gap under the heater and the benefit of the CF conduction and the forced convection is lost.
- **Solution:** **Tighter control over adhesion procedure. Bonding under entire heater, not just copper traces**

Thermal camera: Max function

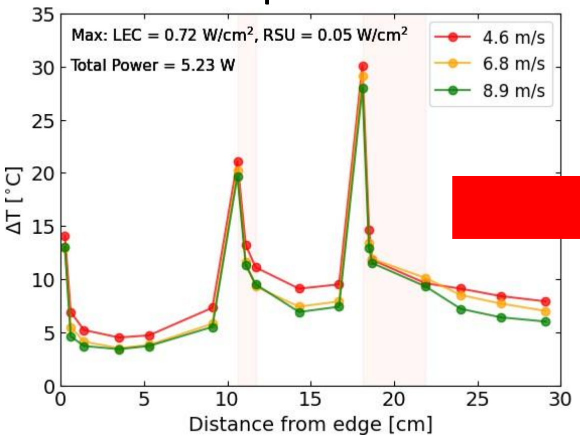
- Results shown used a different feature on the thermal camera: the **Max** function
- Will always find a hot spot and is not representative of the actual temperature
  - If hot spot is does not make contact with CF, it will never change with air velocity
- **Solution: Go back to taking average temperature along width of LEC**

Single Corrugation Test Piece #2

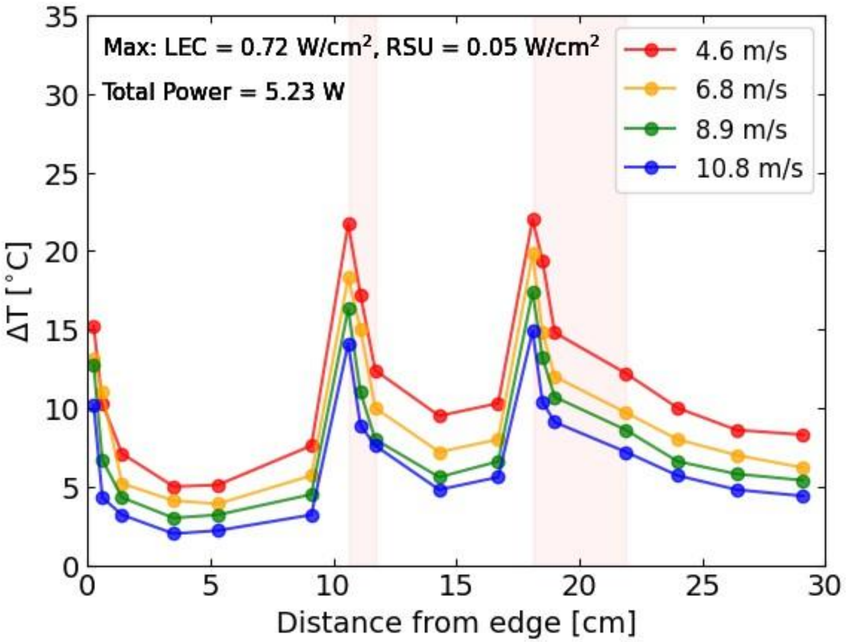


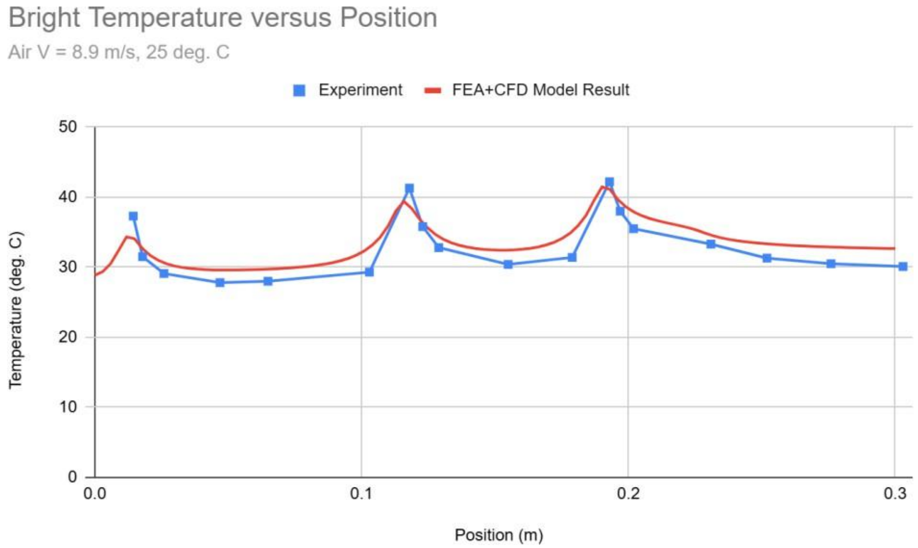
- Tighter control of bond thickness & adhesion under entire heater
- Measuring T directly (not Max function)
- Better agreement between LEC 2 & 3 and with model

Test piece #1

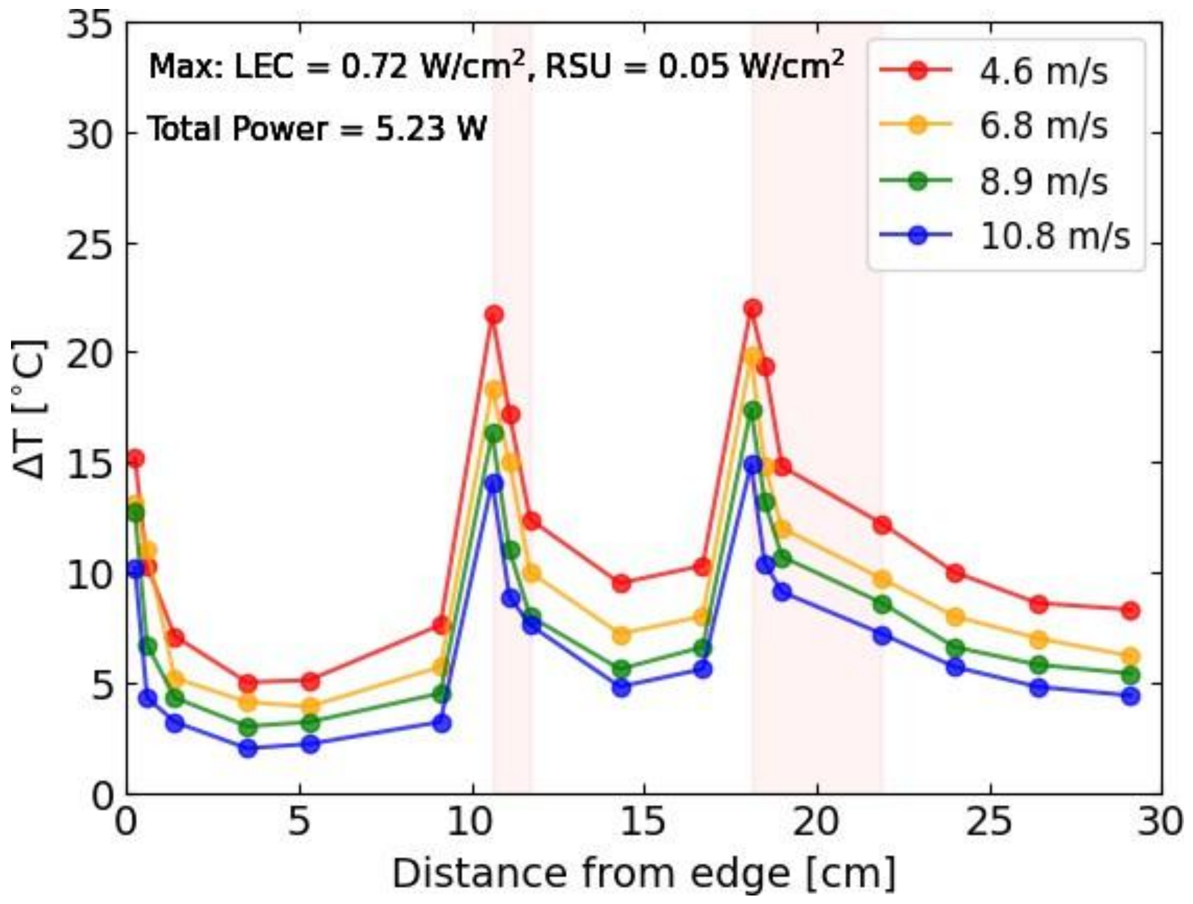


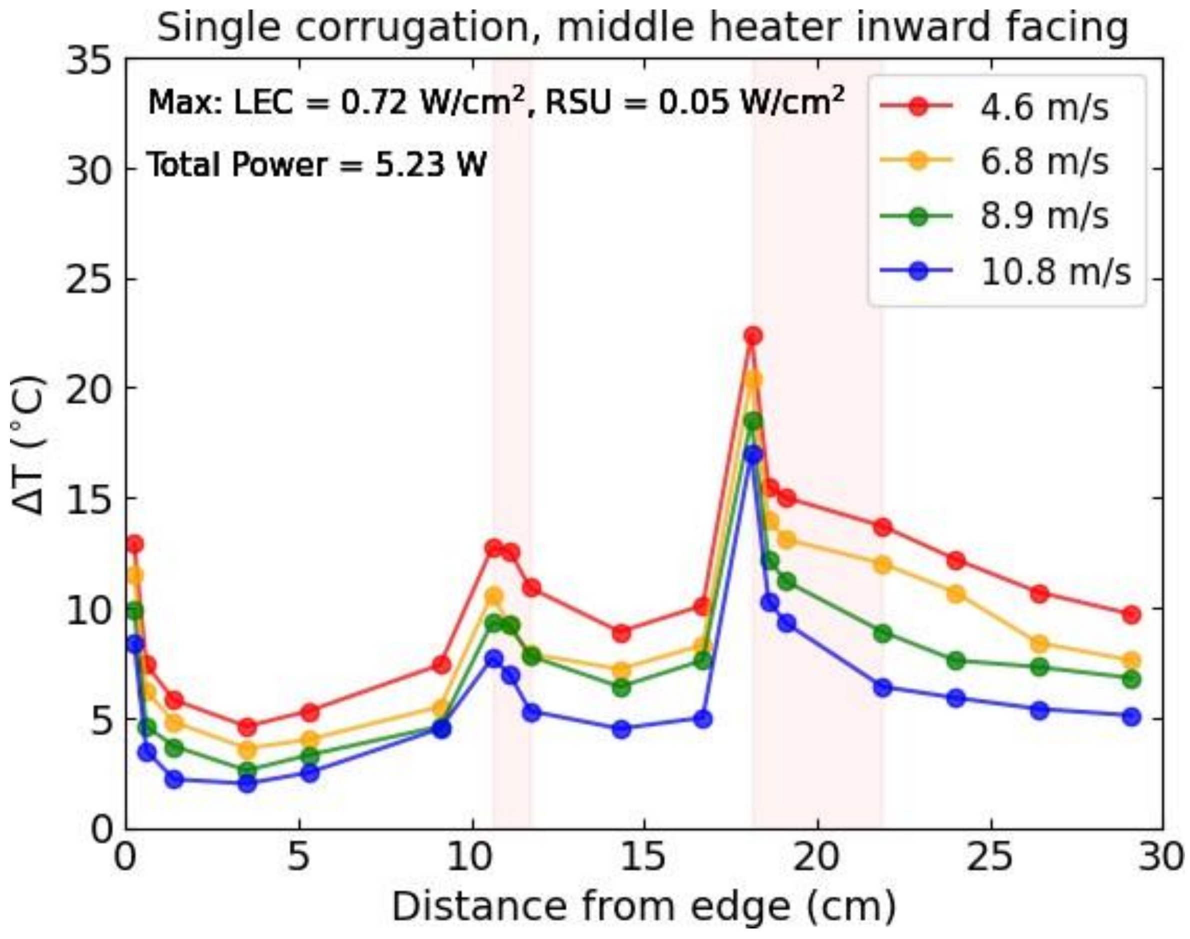
Test piece #2





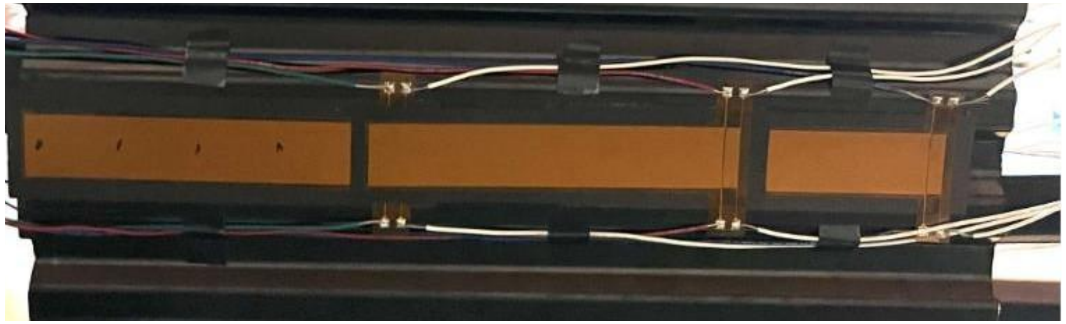
Comparison between #2 & #3

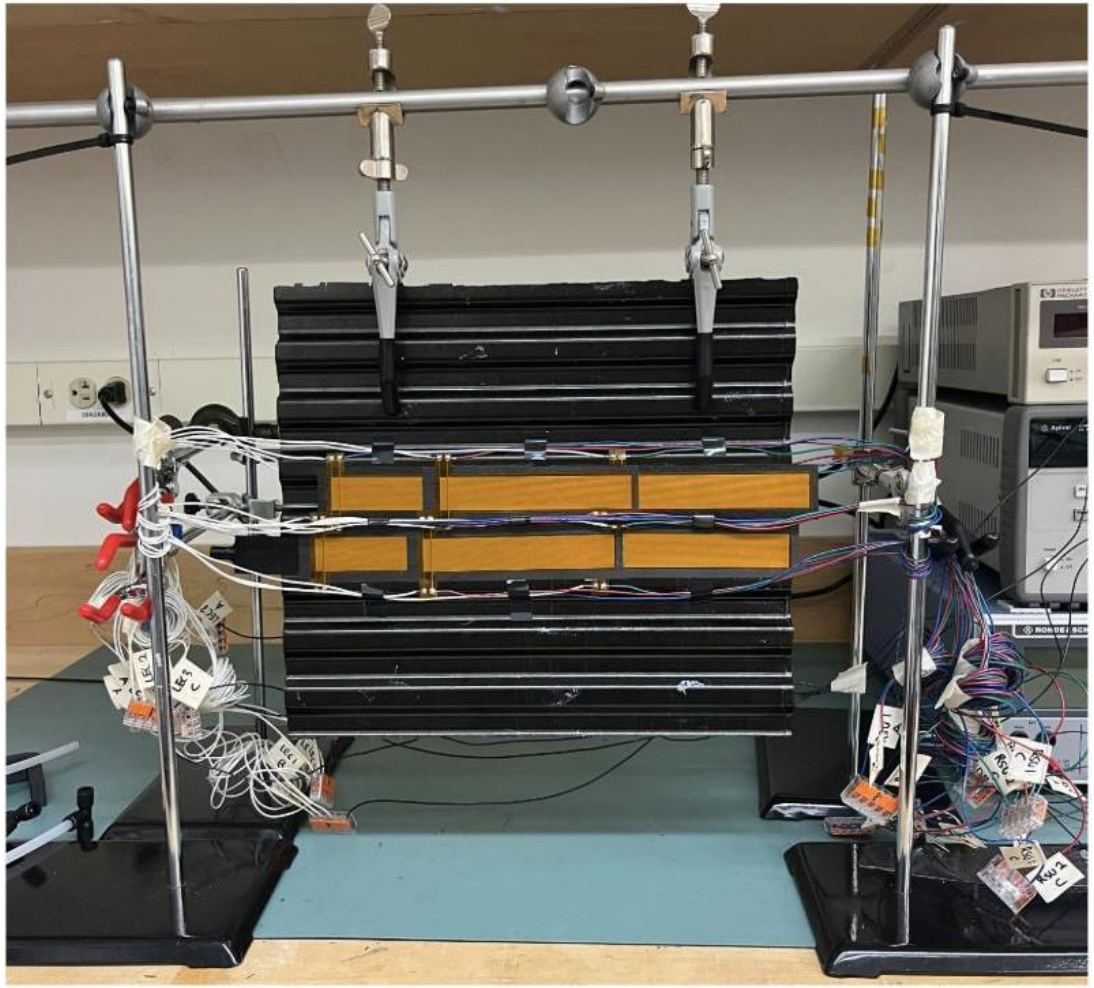




Large Thermal Test Piece

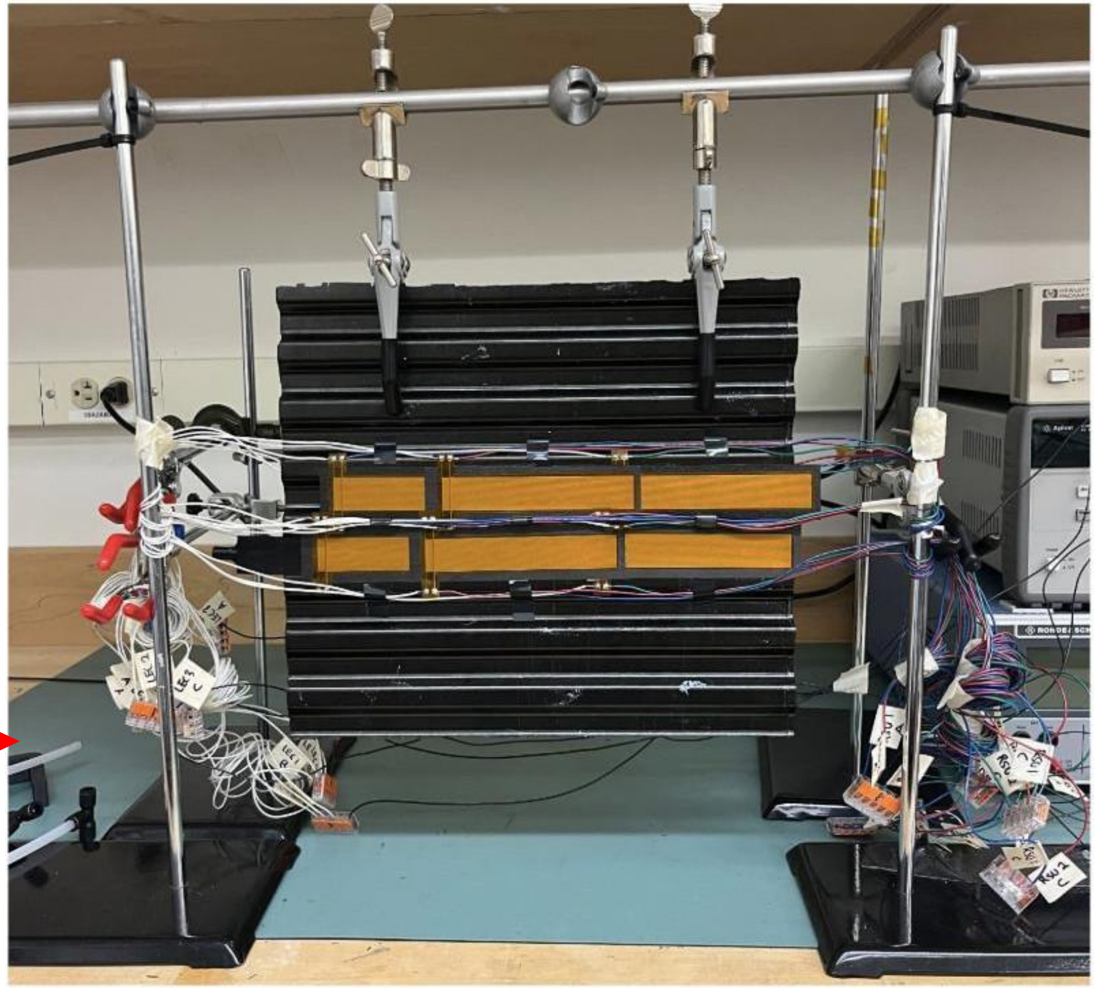
- Want to test now proximity to neighbors effects measurements
- Have two channels on the front, one on the back



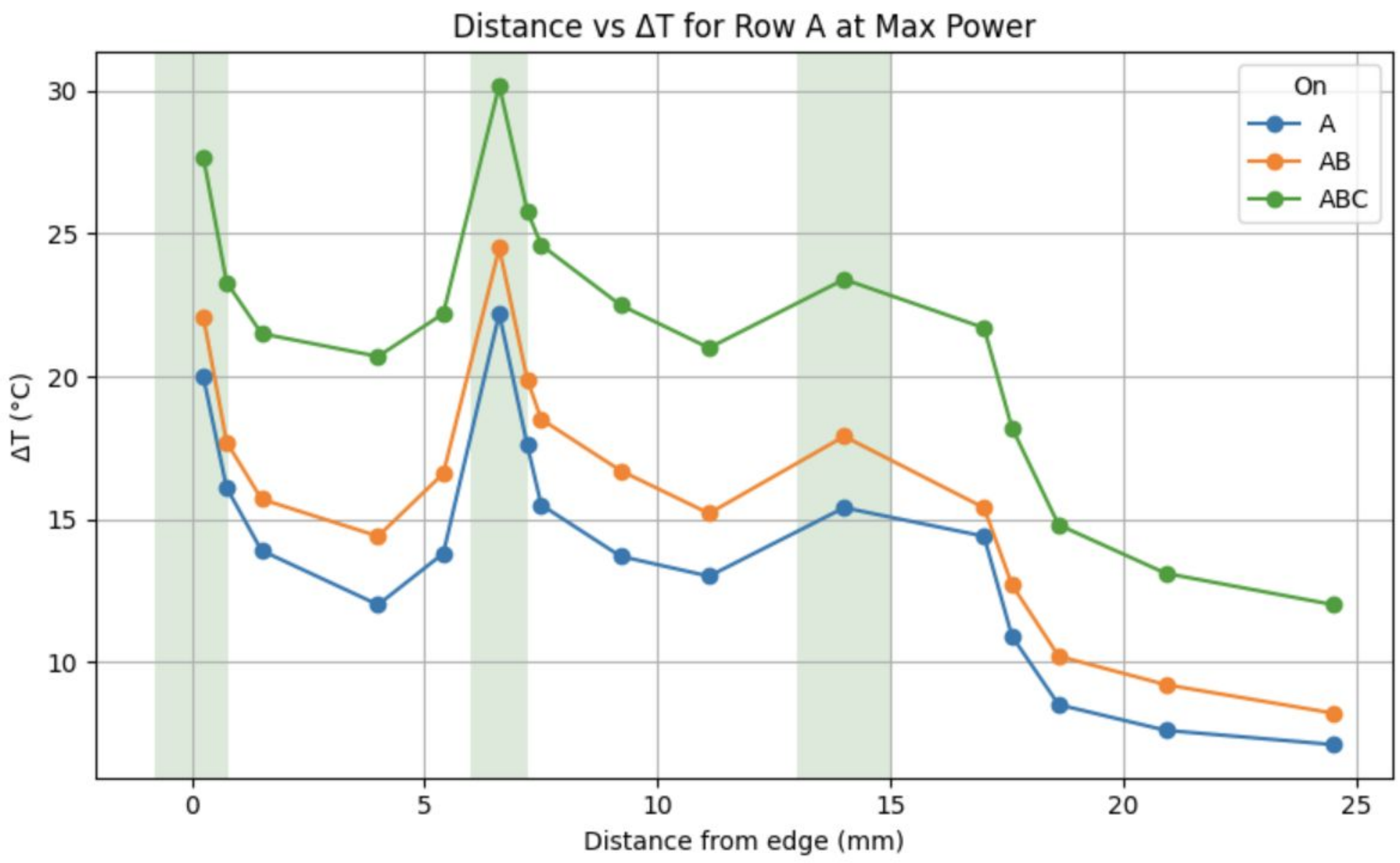


Large Thermal Test Piece

- With no air cooling, alternated which Rows were turned on and measured the front two rows (A & B)
- Alternated which rows were turned on and measured at Max and Nominal power



Thermal Gradient



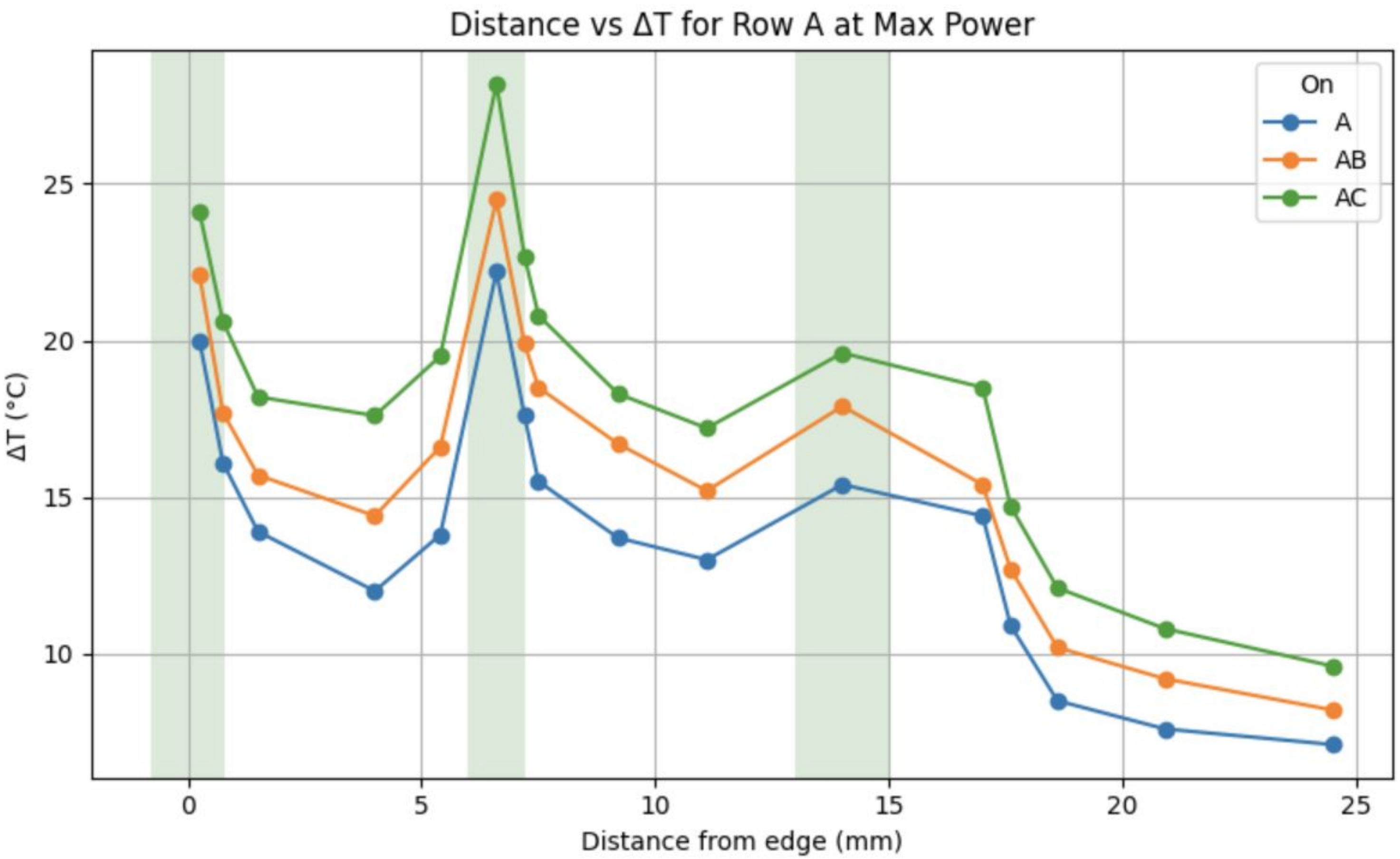
Legend

- Blue: Only Row A powered
- Orange: Rows A & B are powered
- Green: All Rows Powered

Notes

- We see a very large difference between all being powered and just row A
- Modest difference when adding only row B

A&C vs A&B Rows Powered



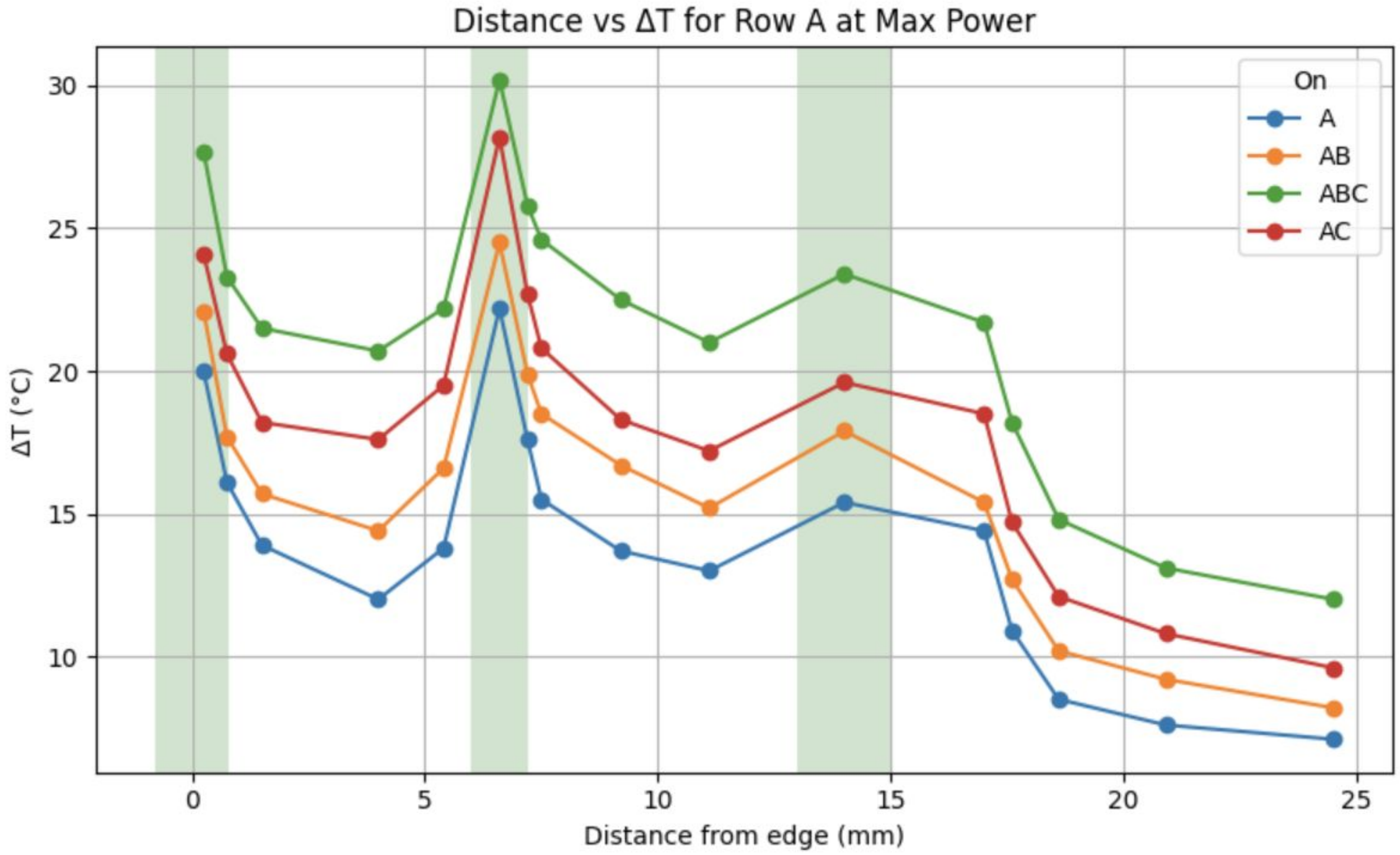
Look at only A and C powered

- The spike is much more than the addition of only row B

Notes

- Now examine with the inclusion of ALL rows being powered on

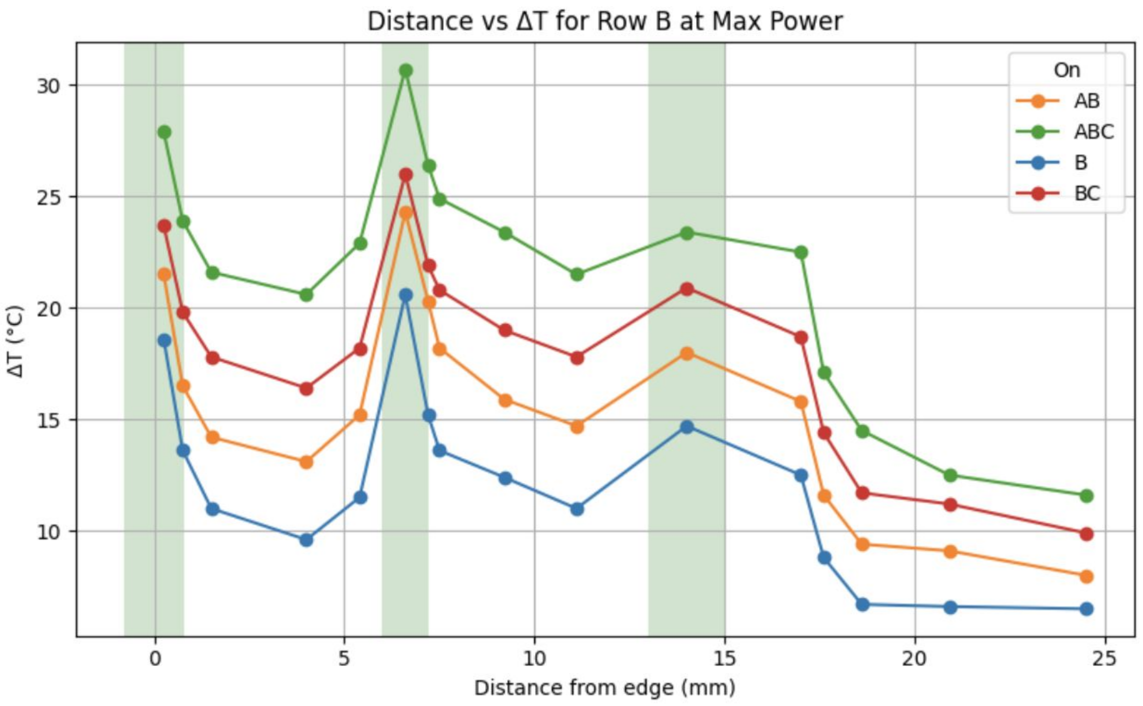
Impact of Row C

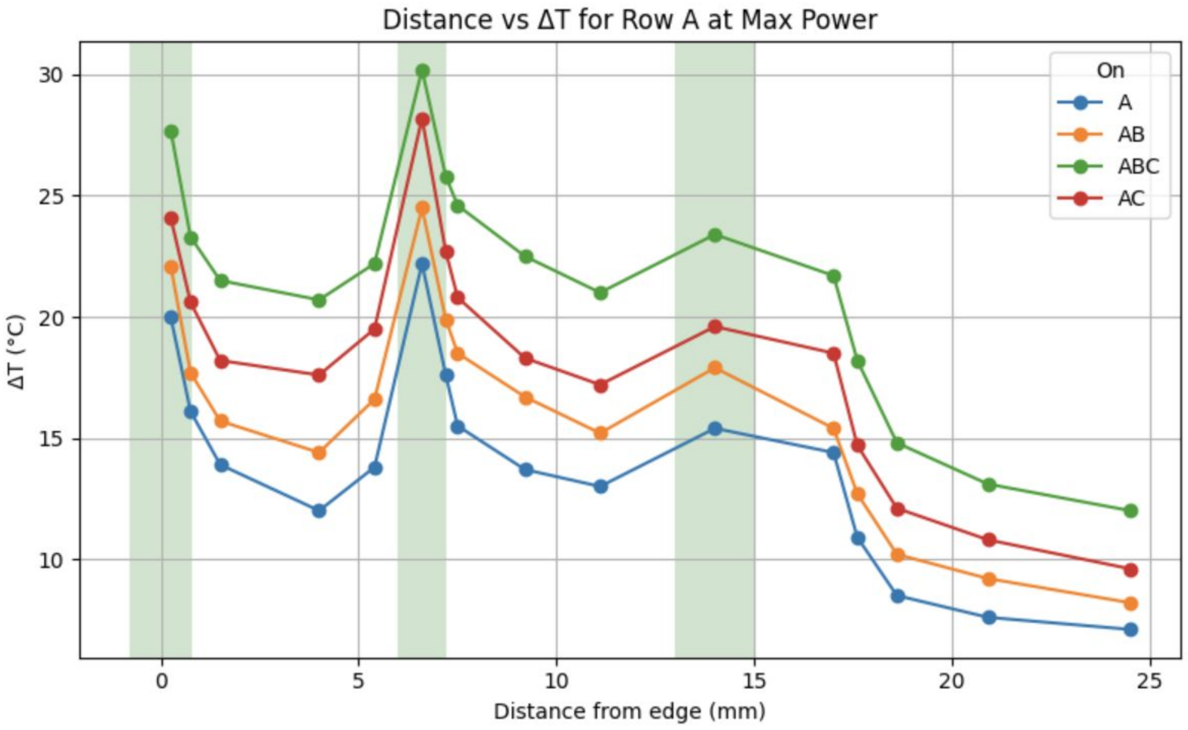


Findings

- There is a clear ordering
- Row C has a much greater impact
- Indicated temperature is more sensitive to this cross-carbon fiber conduction than laterally across rows

Gradient For Row B vs Row A



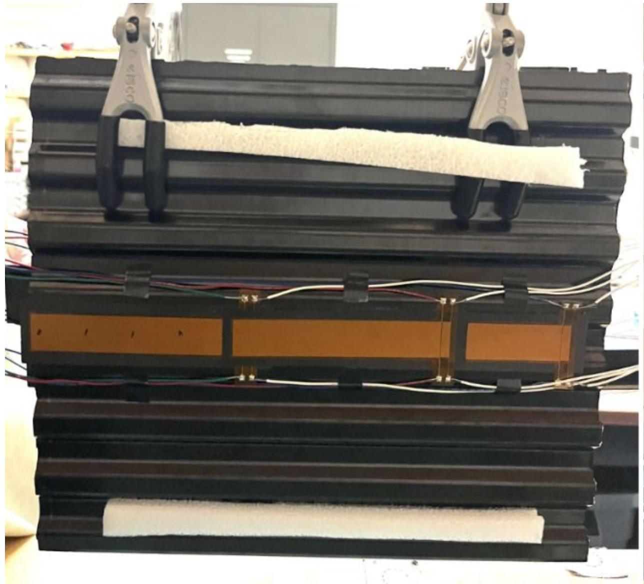


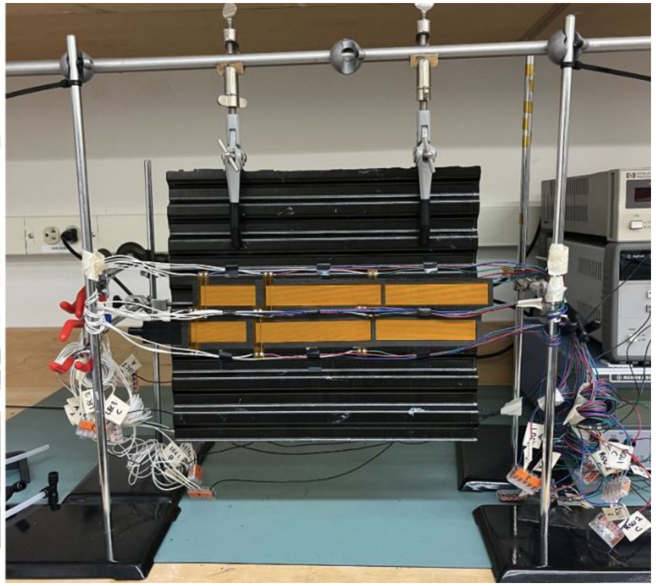
Notes

- Again we see Row C inclusion causes a greater spike.
- Behavior is the same

What’s Next?

- So far all measurements look at rows A&B, will flip around to take the same set of measurements along C
- Will pump air through two channels and measure with two rows powered

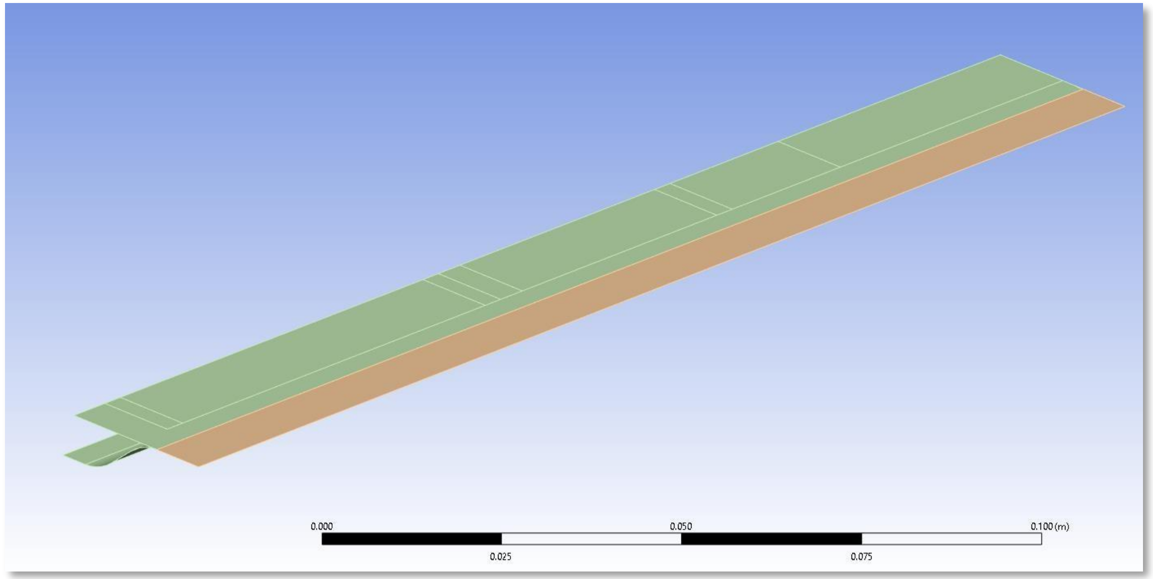




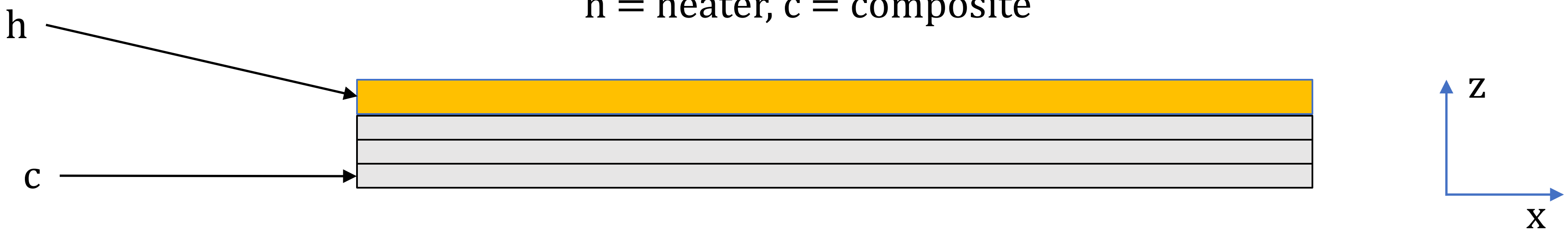
Backups

Modeling Approach

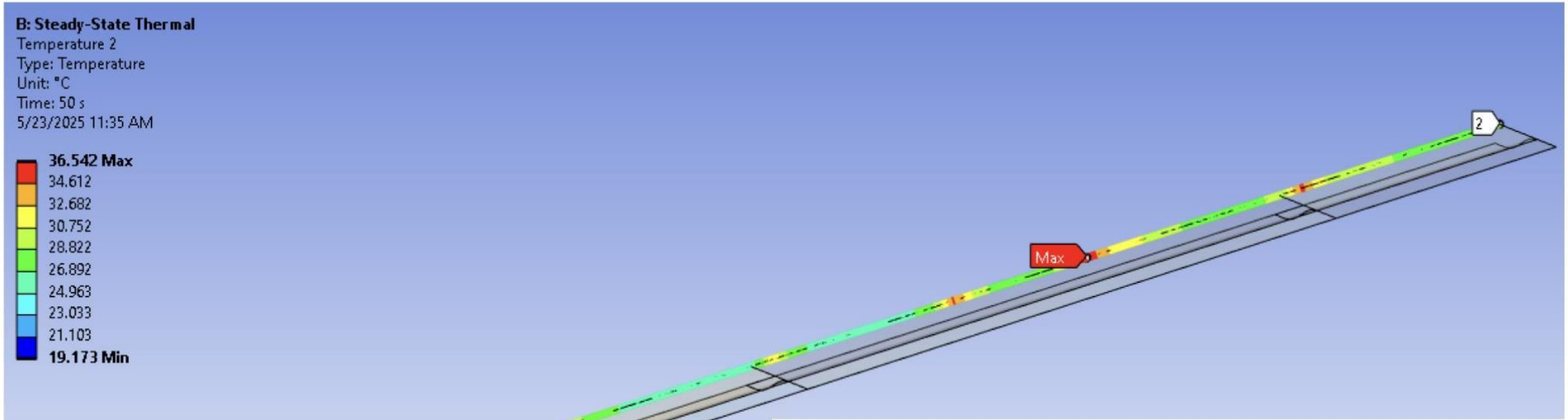
- Simplest model which captures thermal response.
- Shell model (2D) used instead of 3D components.
- Composite support and heaters homogenized into single part.

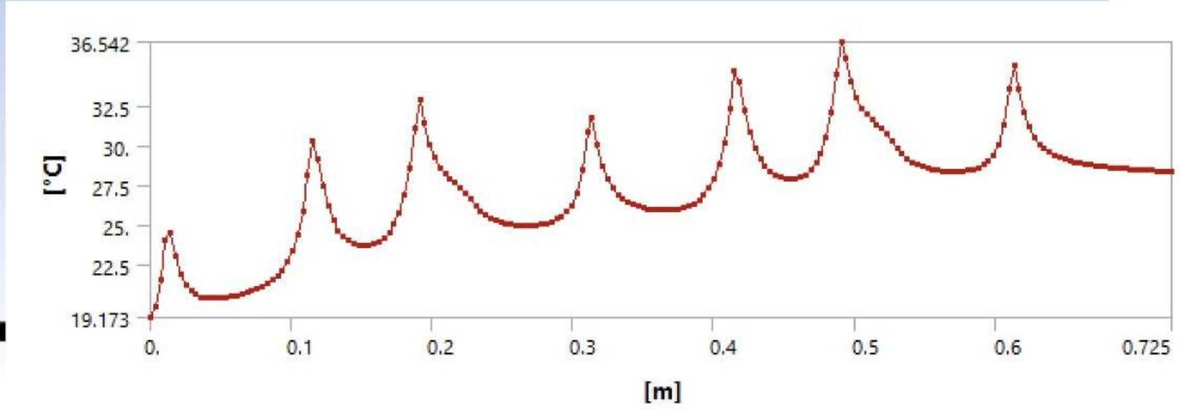


$$[0_h, 0_c, 90_c, 0_c]$$
h = heater, c = composite



Credit: Nick Payne





7 EIC-LAS in corrugation;
Temperature within req. range.

Forced Convection Model

- Using the Nusselt number to Gnielinski's correlation which is applicable to the transition flow region:

$$Nu_D = \frac{\left(\frac{f}{8}\right)(Re_D - 1000)Pr}{1 + 12.7\left(\frac{f}{8}\right)^{\frac{1}{2}}(Pr - 1)}$$

$$Re_D > 3000 \text{ and } Pr > 0.5$$

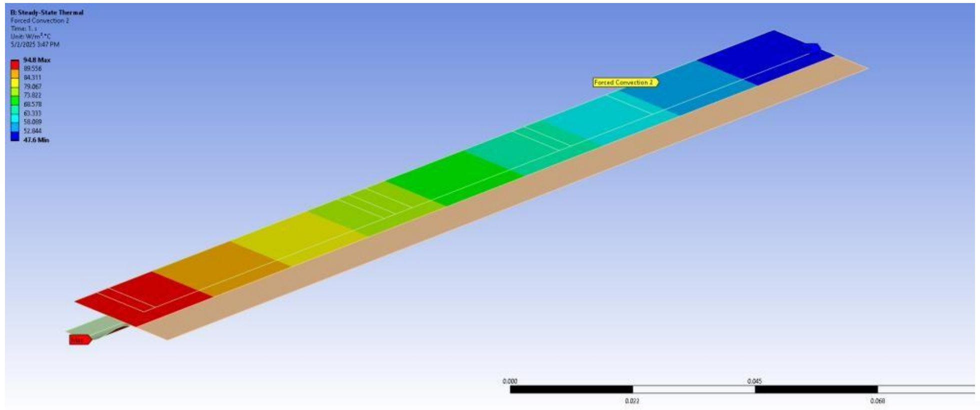
$$\boldsymbol{h_f = Nu_D \frac{\kappa}{D_H}}$$

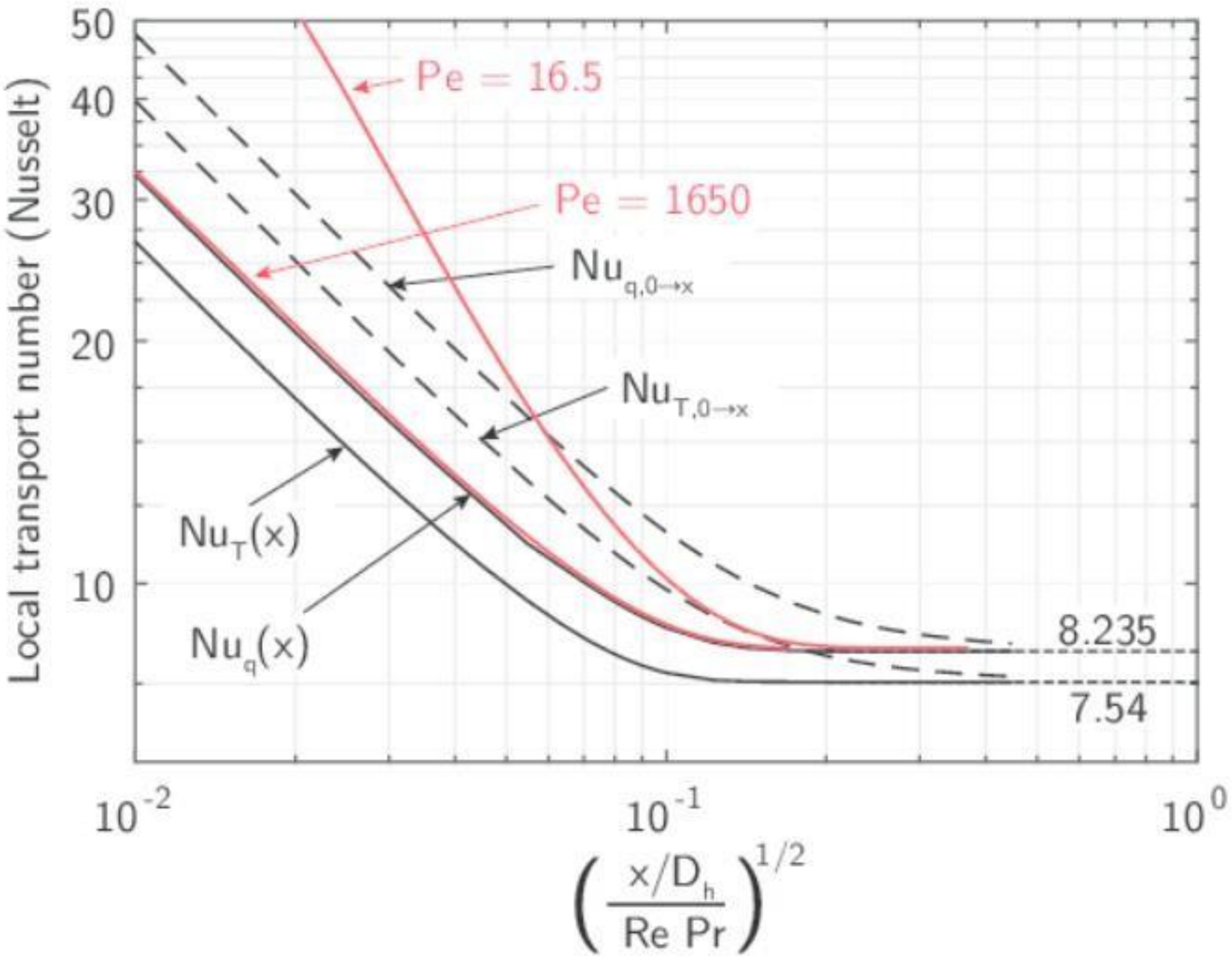
For cooling air flow at 8.9m/s and initial temperature of 25°C (heating of air taken into account),

$$Nu_D = 15.9; h_f = 47.52 \frac{W}{m{\cdot}K}$$

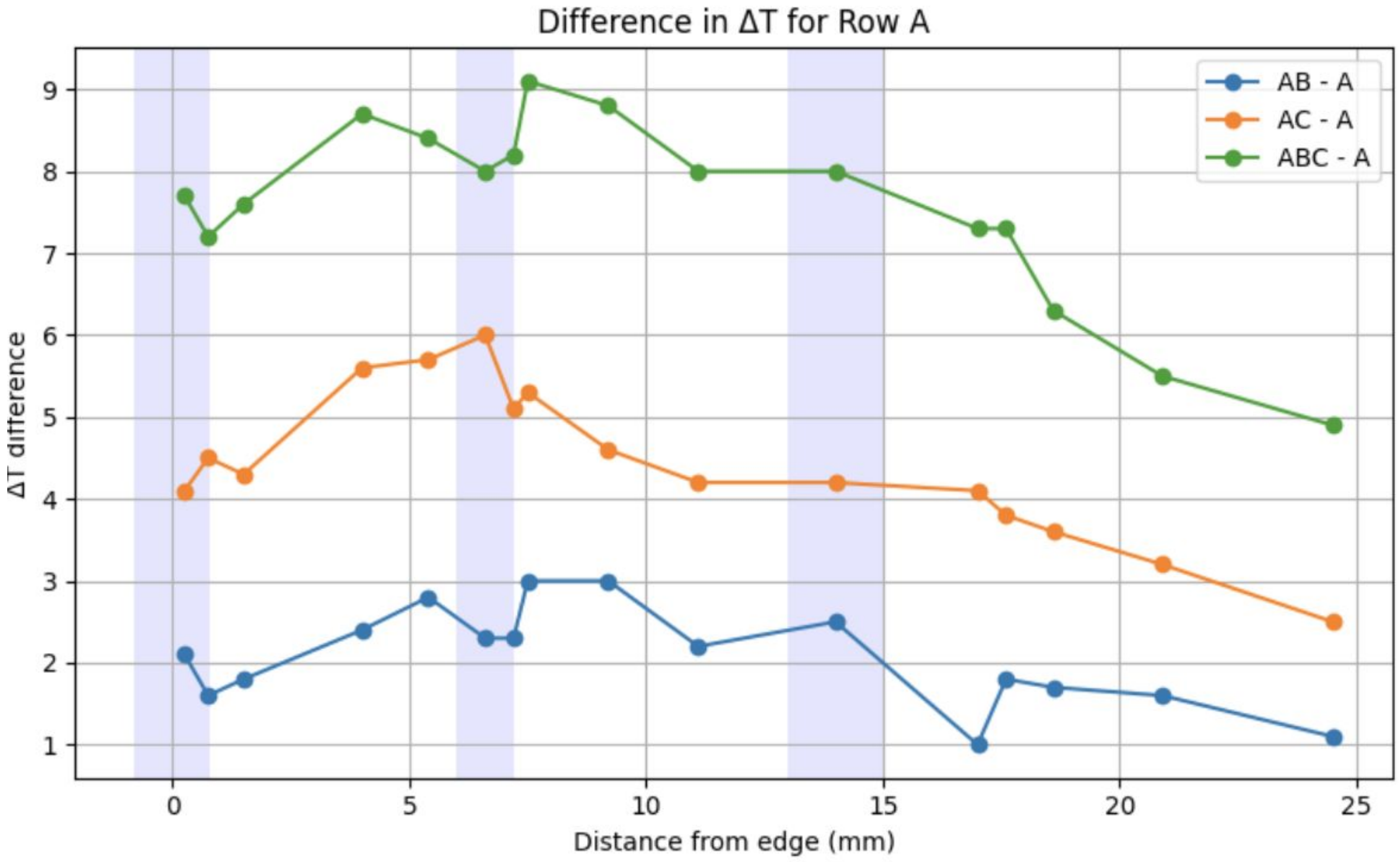
Entrance Region

- Nusselt number is inherently higher at the entrance of the duct.
- Analysis will use assumption that at inlet $Nu_D = 32$ and then scales to $Nu_D = 15.9$ at exit.
- Also temperature of air is at 25°C at inlet and scales to ≈30°C at outlet due to heating.





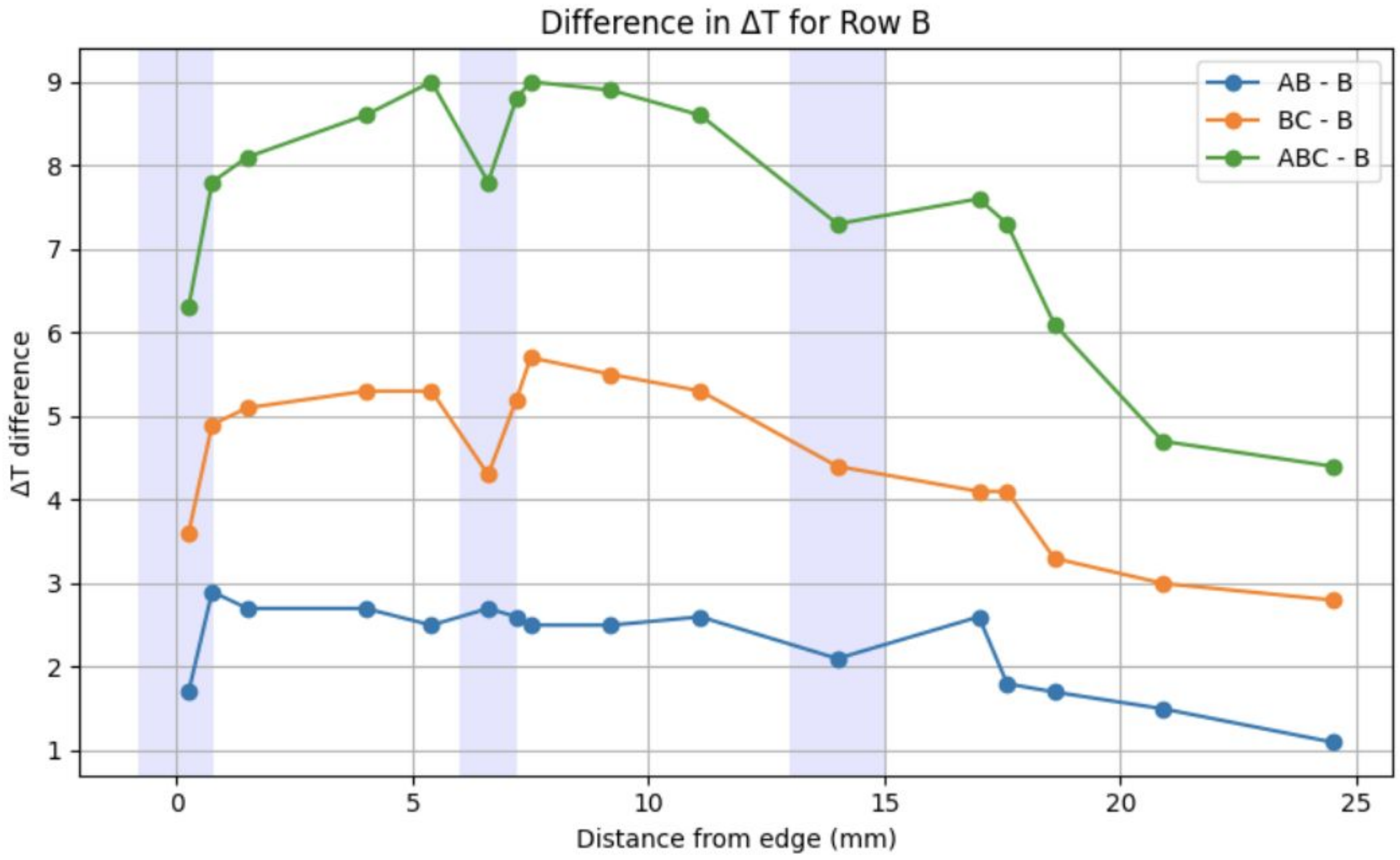
Subtracting Effects: Row A



Purpose

- Wanted to see where along the row the added heat from C or B contributes most
- LEC 3 is currently covered by an overlap of the heaters: uncovering it would likely produce a another “dip” shape

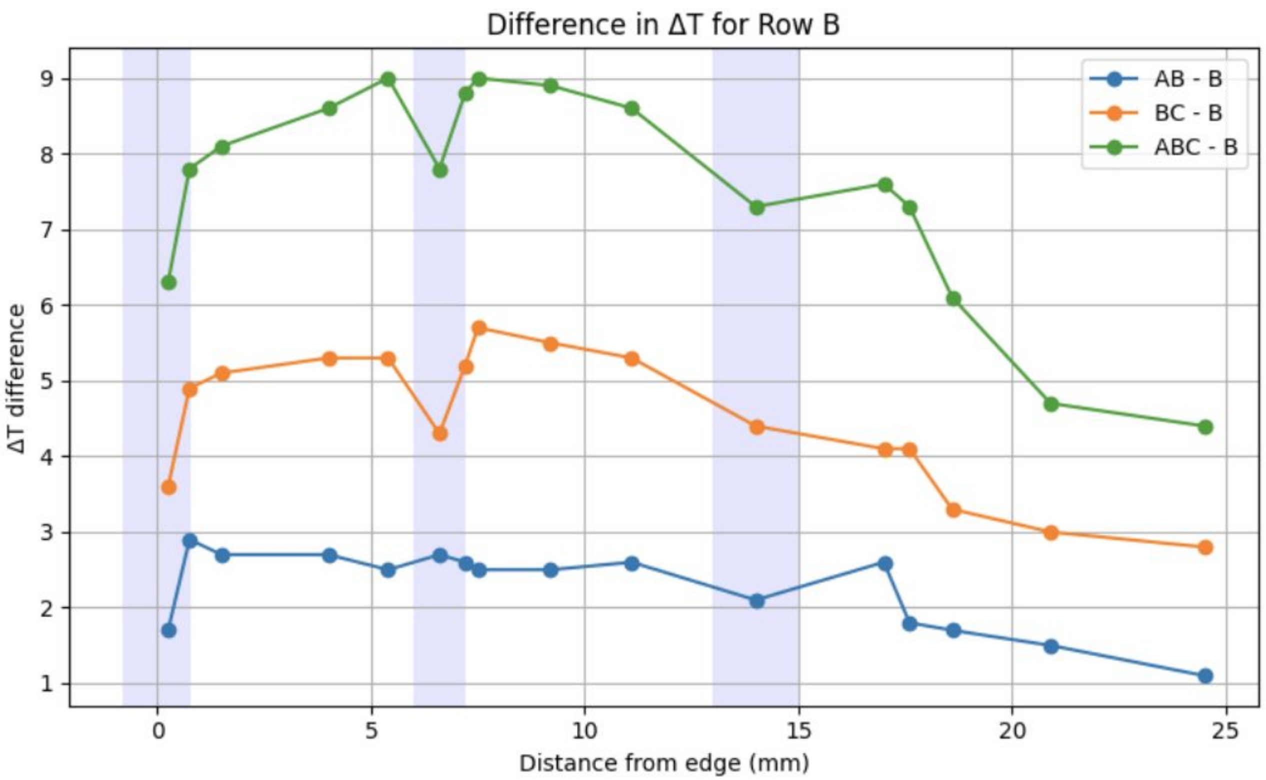
Subtracting Effects: Row B



Findings

- Same dip seem at LEC 2 for Row B at both Max and Nom power
- By subtracting the A-only profile (which contains LEC peaks) the LEC positions look relatively cooler in the difference plots, causing the “dip”

Subtracting Effects: Row B



"Dip" Cause

- Neighboring row heating raises the background temperature everywhere else, while the LEC dT remains more constant
- The baseline shifts upward, but the LEC regions are already saturated with heat from Row A
- Would this imply conduction from B or C preferentially warms the inter-LEC regions?