TFPX Dee Thermal Validation

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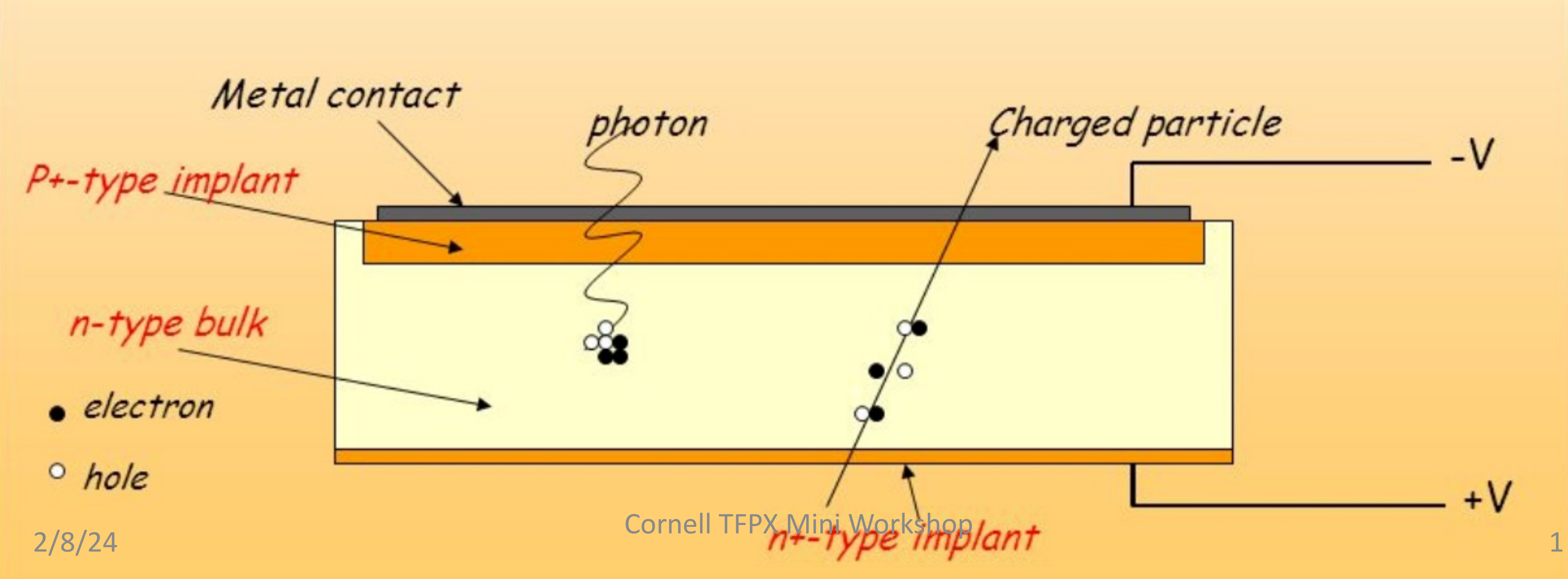
Silicon Particle Detectors

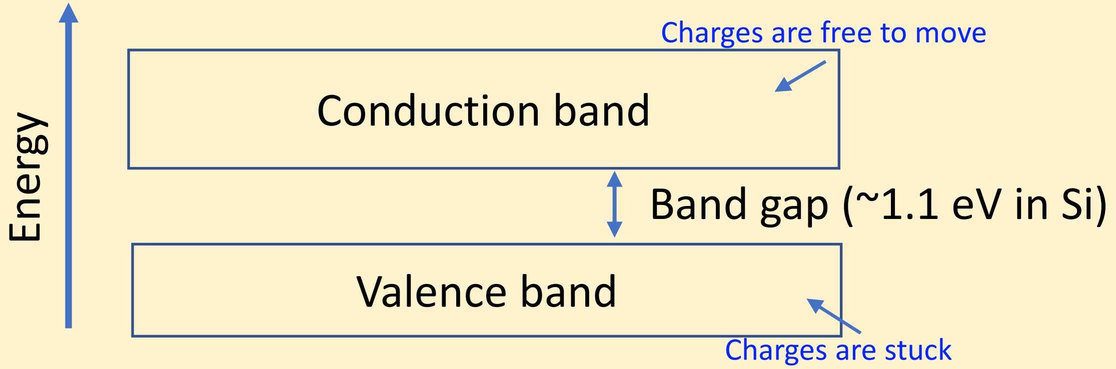
- Thin (150um), planar structures
- diode structure between top and bottom (pin diode)
- (Reverse) bias voltage provides electric field to move signal charges up to collection electrode.
- Plus, thermally-generated reverse current: dark current. Normally *very small*: hence Power = I_{dark} V_{bias} = *small*.



Dark Current – Thermally Generated

Fresh silicon

Quantum states in semiconductor



Energy

Charges are free to move

Conduction band

Band gap (~1.1 eV in Si)

Valence band

Charges are stuck

Thermal energy kT can kick e- into conduction band. But 1/40eV << 1.1 eV

After radiation damage

Quantum states in semiconductor

Energy

Conduction band

Valence band

Damage to crystal, Si atoms out of place.
New quantum states appear in bandgap
→Stepping stone path to conduction band
→Dark Current increases!!

Dark Current is temperature Dependent

$$I(T) = \text{const} \times T^2 e^{-(T_A/T)}$$

We don’t know the constant, but can “calibrate”:

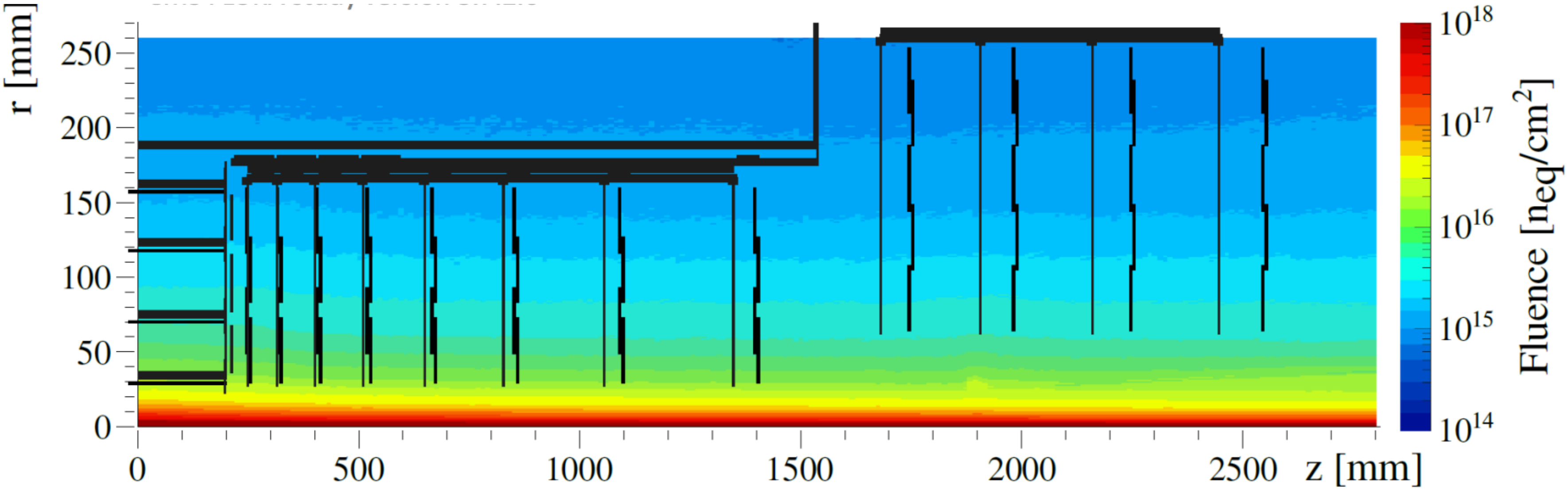
$$I(T_{\text{ref}}) = \text{const} \times T_{\text{ref}}^2 e^{-(T_A/T_{\text{ref}})}$$

$$\rightarrow \qquad I(T) = I(T_{\text{ref}}) \left(\frac{T}{T_{\text{ref}}}\right)^2 e^{-T_A\left(\frac{1}{T} - \frac{1}{T_{\text{ref}}}\right)}$$

$$Q(T) = I(T_{\text{ref}}) V_{\text{bias}} \left(\frac{T}{T_{\text{ref}}}\right)^2 e^{-T_A\left(\frac{1}{T} - \frac{1}{T_{\text{ref}}}\right)}$$

Heat generated by dark current grows ~exponentially: doubles every 6.5 ºC

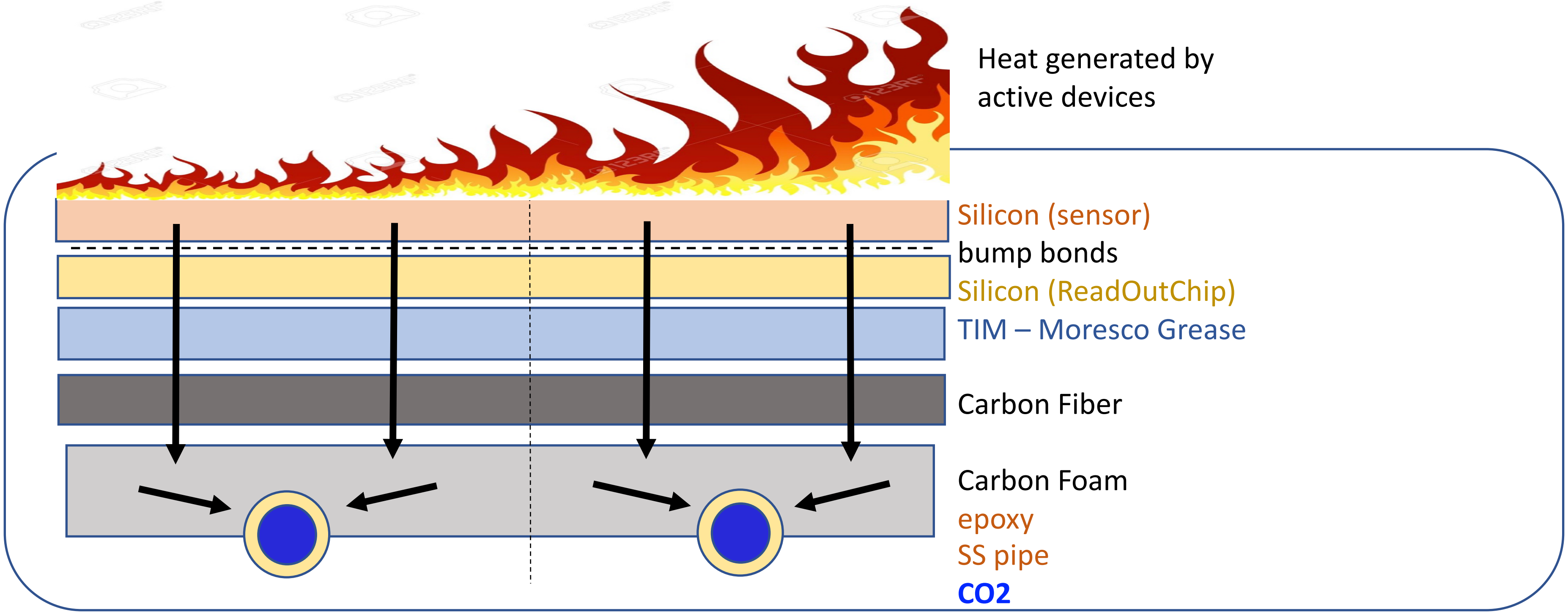
Fluence



Most damage at inner radius – closest to beam

The Problem: Heat and Temperature

TFPX simplified model (cross section)



Heat generated by active devices

Silicon (sensor)

bump bonds

Silicon (ReadOutChip)

TIM – Moresco Grease

Carbon Fiber

Carbon Foam

epoxy

SS pipe

CO2

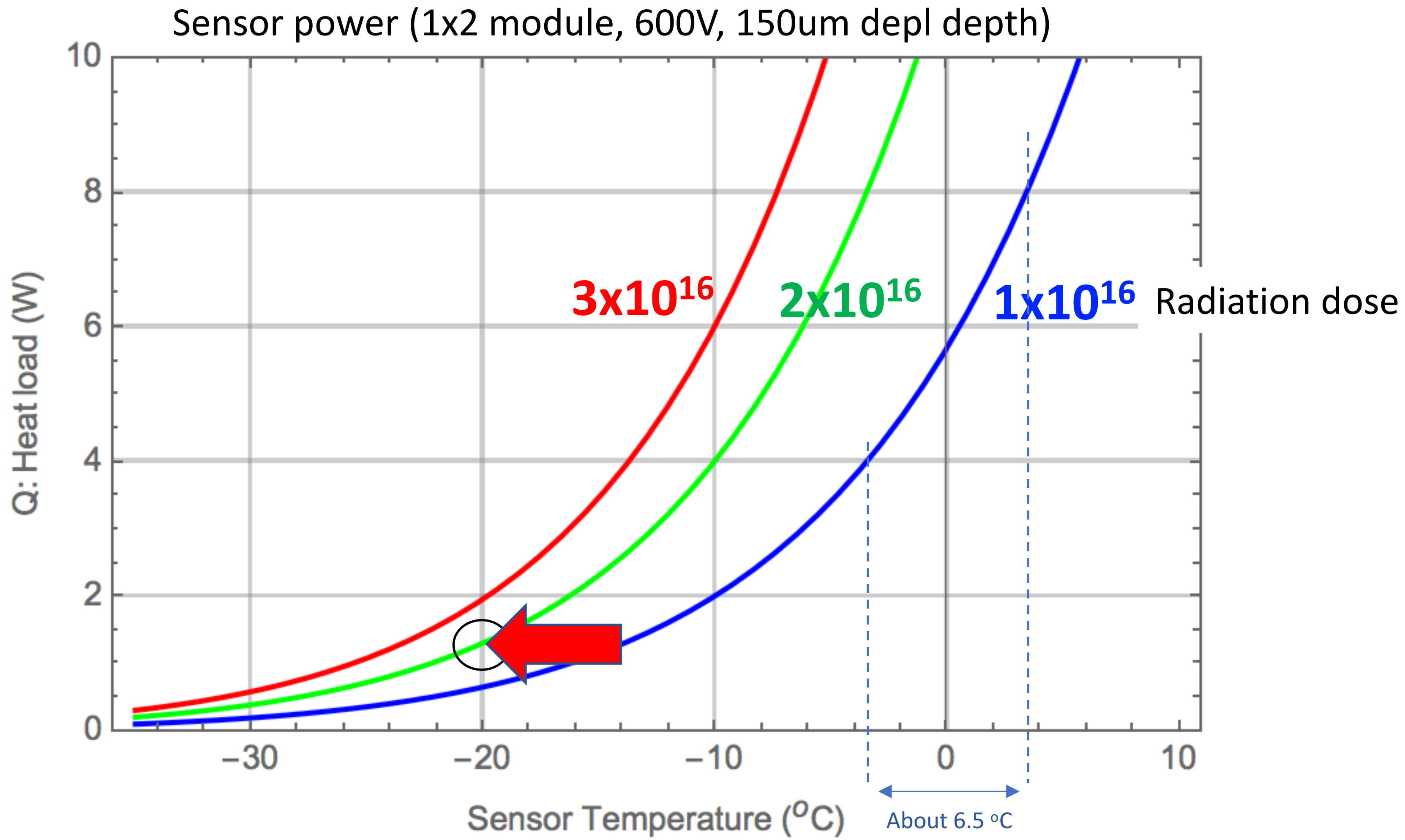
Black arrows show cartoon version of heat flow.

CO_2 is cold! approximately $T = -33^{o}C$

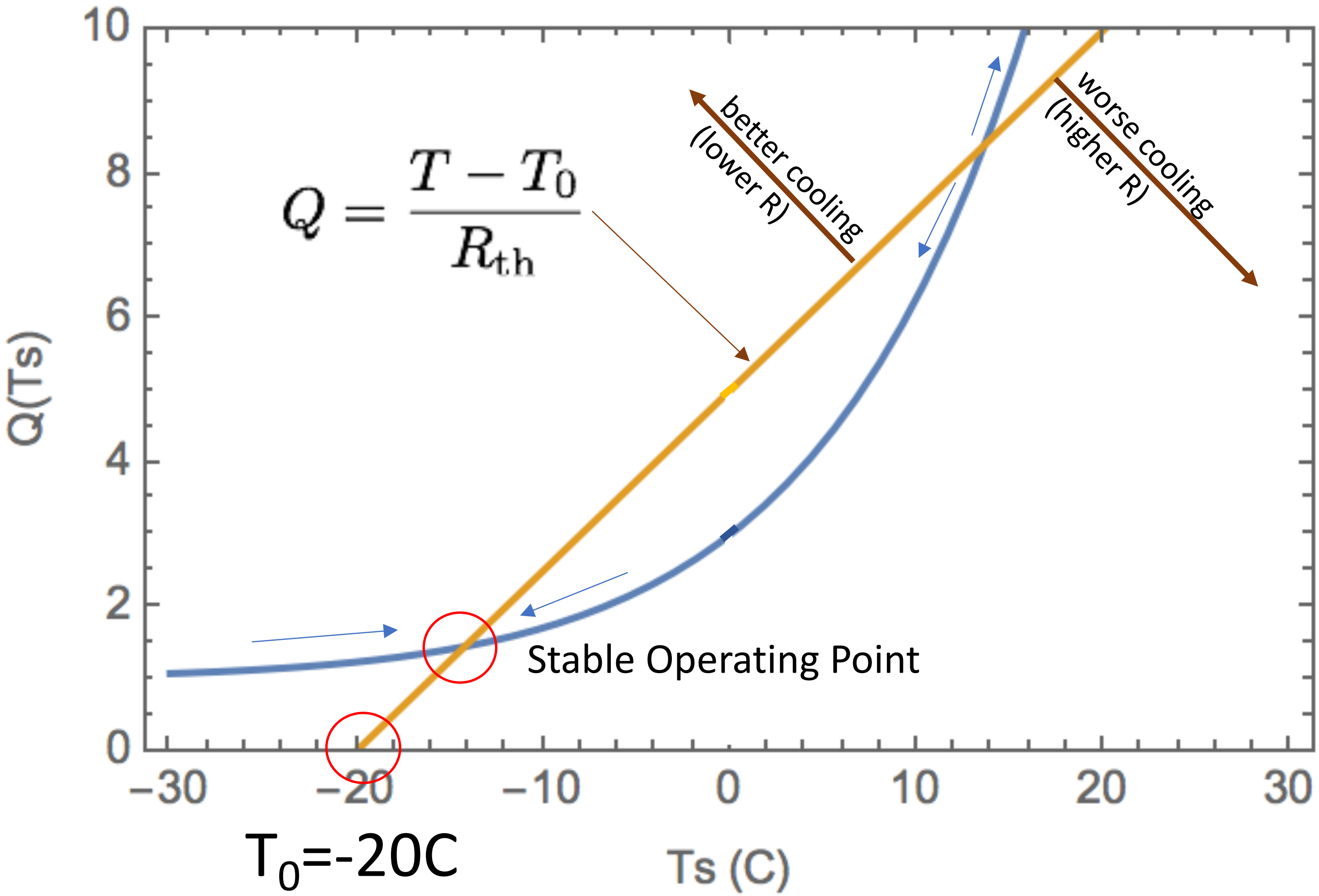
Where Does the Heat Come From

- Electronics for reading out the silicon sensor:
  - Amplifiers, digitization, memory, communication, etc etc.
  - Must be *very fast*:
    - 25ns between proton collisions
    - Extremely large amounts of data to be moved
    - transmission times ~ tens of GigaBits per second → 0.1 ns per bit
  - Fast electronics is hot electronics:
    - changing voltages (eg on transistor gates) requires $\Delta Q/C = \Delta V$.
    - fast change → dV/dt is large. → dQ/dt == I is large. → IV = dissipated power, is also large.
    - voltages are low (~1.2V) because transistors are small! (65nm). But still…
  - In addition: The ReadOutChip has components that generate lots of heat: Shunt LDOs. These are along side of chip. (hence flames were asymmetric in previous diagram)
- And the silicon sensors also generate some heat.

Exponential Heat Load (Q vs T)



Cooling is a Linear Process



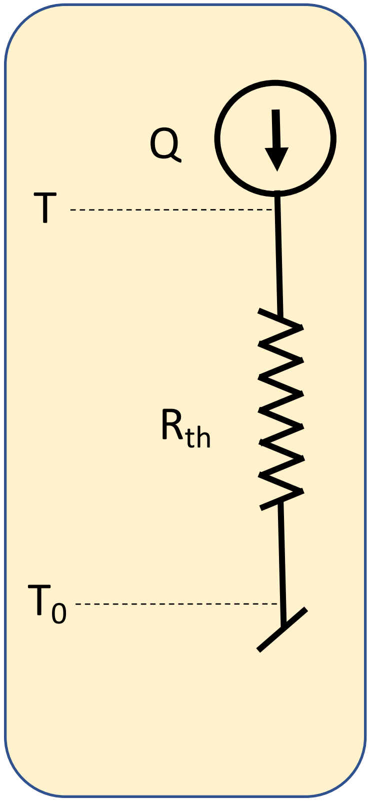
$$Q = \frac{T - T_0}{R_{th}}$$

better cooling (lower R)

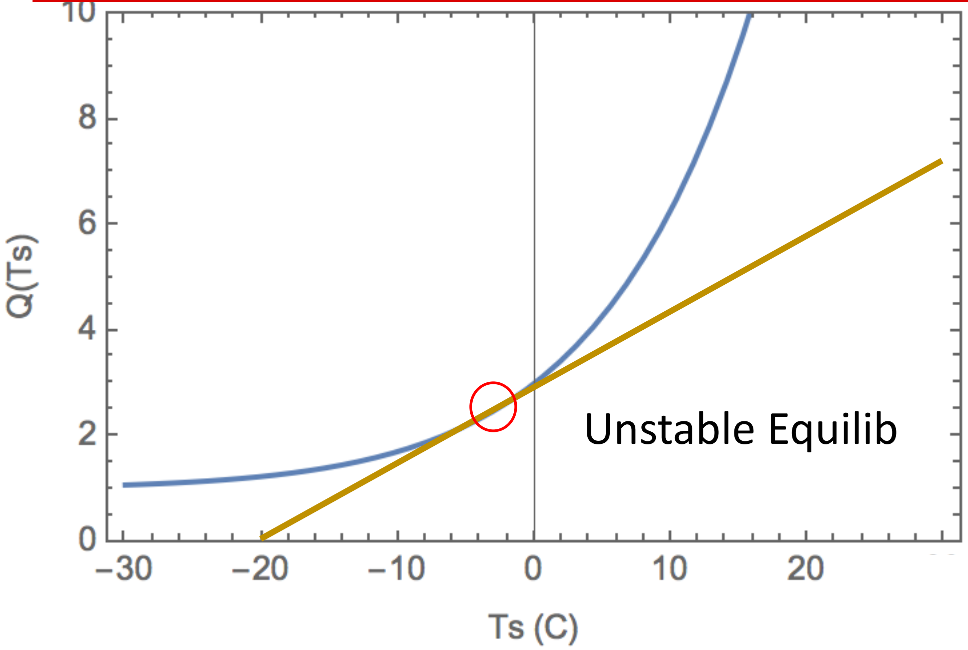
worse cooling (higher R)

Stable Operating Point

T_0=-20C

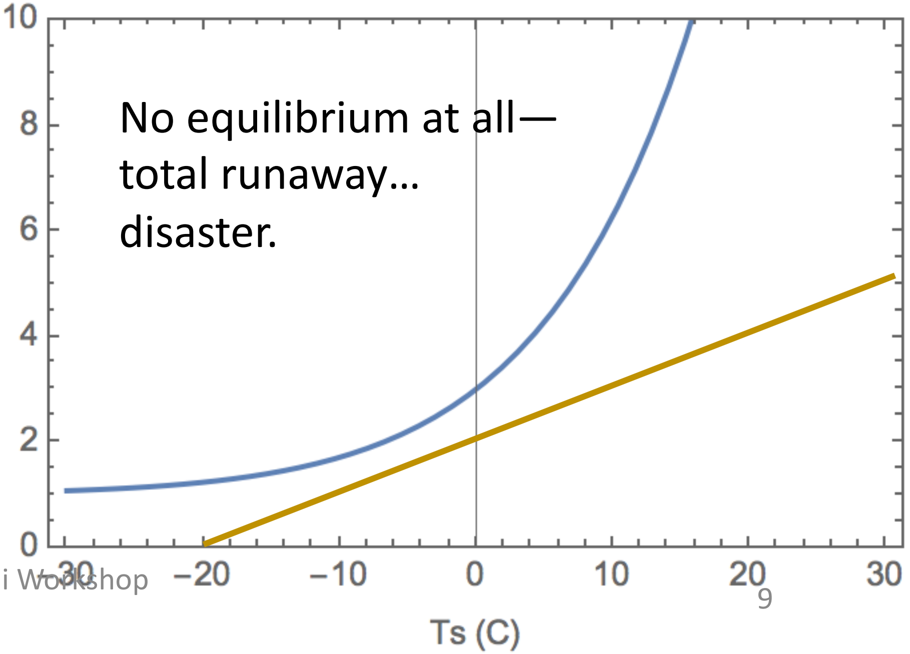


Thermal Runaway



Unstable Equilib

- For a given heat load Q, there is a minimum thermal resistance R needed to maintain a stable temp. This “equilibrium” point is unstable!



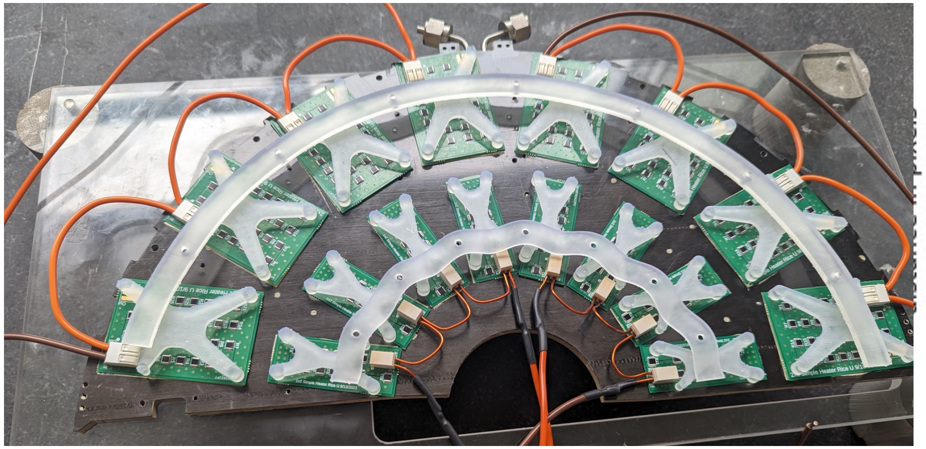
No equilibrium at all—
total runaway…
disaster.

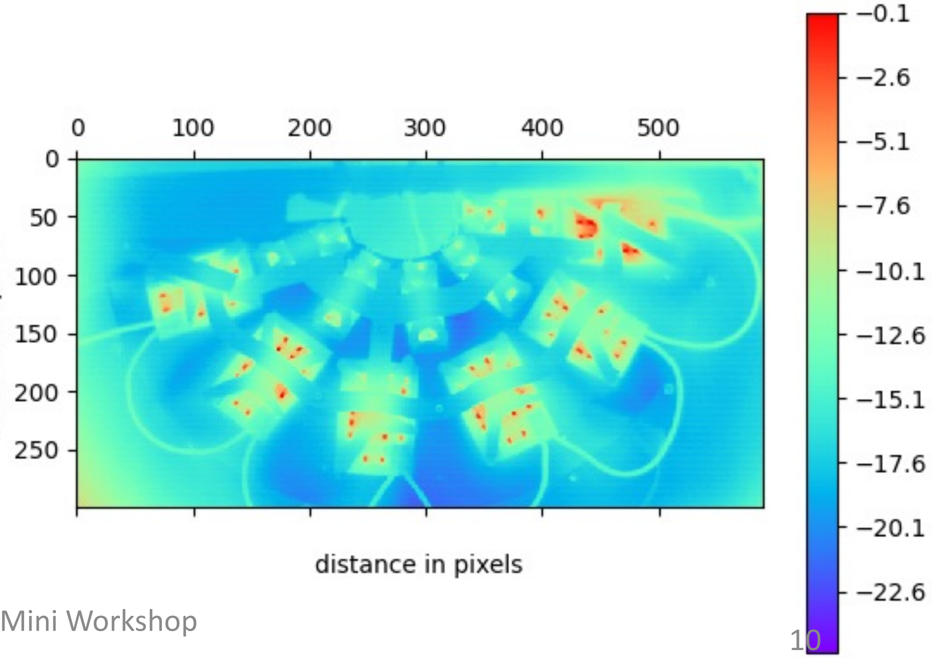
In both cases, R_{th} is too high:
bad design / bad implementation

Note: T_0 is same in both cases: this will be our situation since T_0=-33C is fixed already by cooling experts.

What We Did – Full Dee Testing

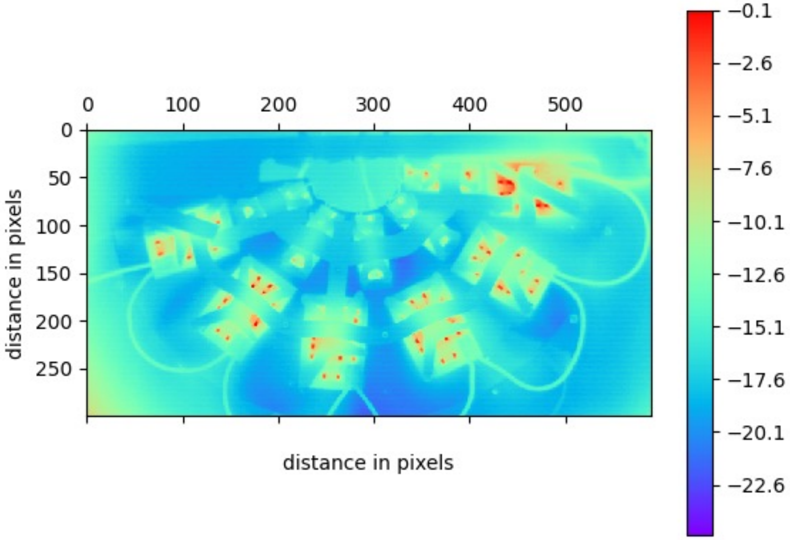
- A full dee thermal test was done on Oct 27th, 2023
- The Dee is populated by the PCB heaters on both side
- We used the CO2 plant to cool down the Dee
- The condition of the environment inside the cold box and the cooling line were closely monitored
- The TIM was deposited by hand with a stencil: ~120 um



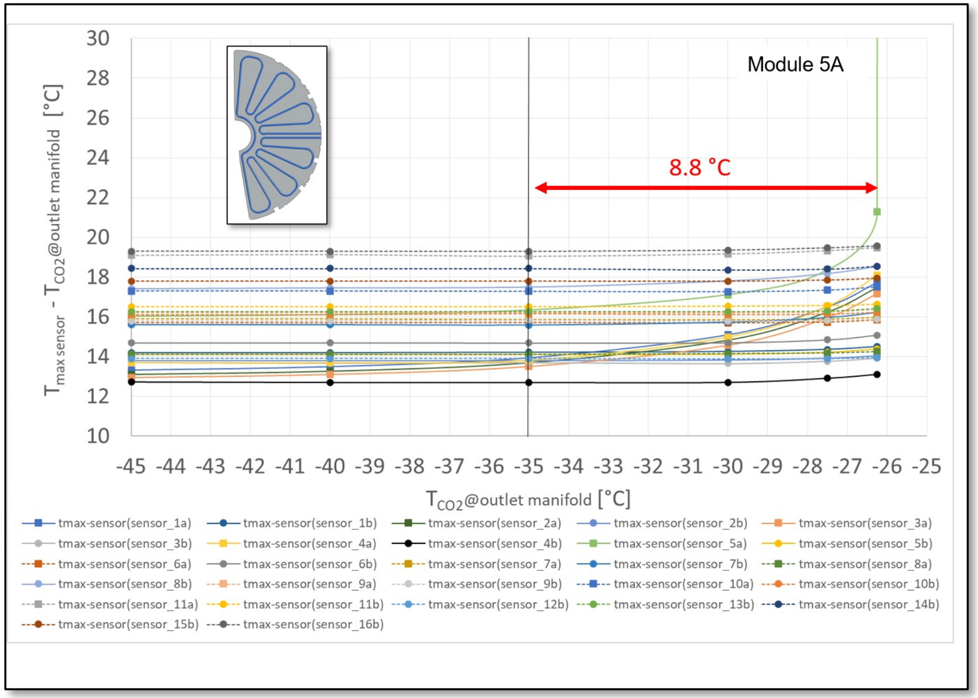


The Current Issue

- Based on the previous simulation, the temperature of the Dee is significantly lower than what we have in our setup



Temperatures w/o dark current in our test



Temperatures with dark current in Ansys simulation

What's Next

We need a real Dee

- It is hard for us to make any conclusion without the actual Dee with the current design. In order to make the Dee, we need the following:
  - **The latest carbon fiber**
  - **The new tube**
  - **Gantry applied epoxy**
- **Due to the limitation of the parts, we will conduct our tests on plaquettes for the time being**

We need to use a more realistic thermal mockup module

- Currently we use the internal NTC data from the pixelalive test as the reference for the temperature of the real module
  - However, we realized that the internal NTC sometimes gives a random temperature (over 100C) It happens ~once per 5 tests
  - We can't put RTDs on a real module to calibrate the emissivity
- Using thermal mockup modules can provide more realistic thermal distributions
- In addition, we can also use them as a practice for figuring out how to install real modules

Summary

- It is very important for us to have a good understanding of the thermal performance of the Dee before we start the production
- We will need all of the newest parts to have conclusive thermal tests and studies
- We will rerun all the tests with plaquette
- We will work closely with the Purdue and Perugia team for the comparison with the simulation