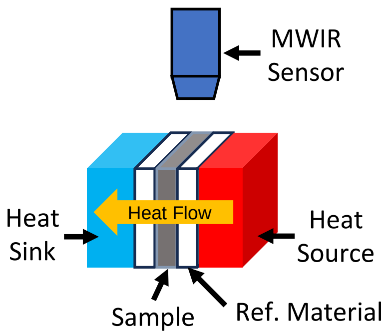
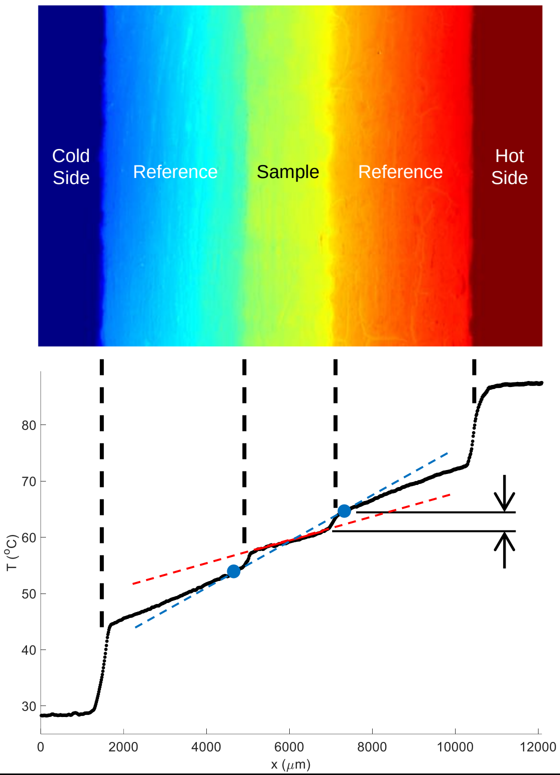
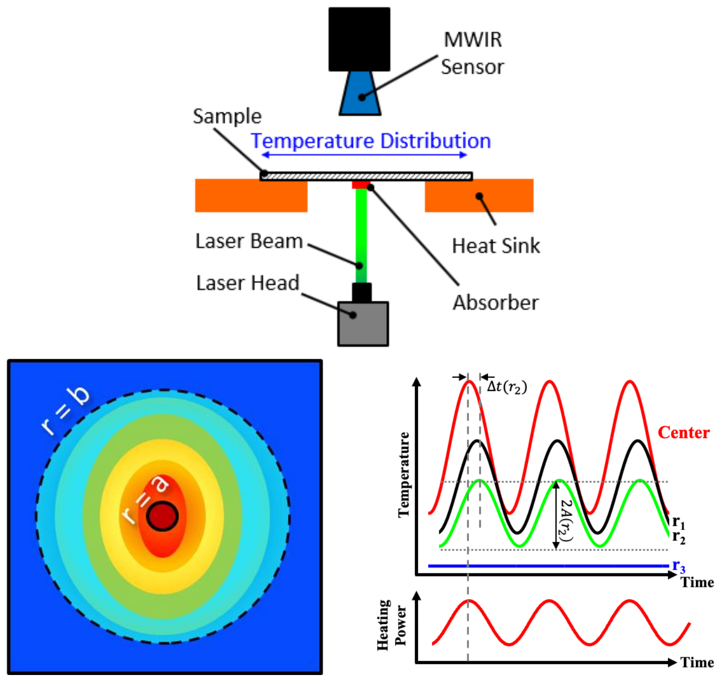
Thermal Metrology for Understanding Tracking Detector Materials

IR Microscopy Enhanced Reference Bar Method





2D Laser Ångström Method



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12th Forum on Tracking Detector Mechanics

MTEC Lab

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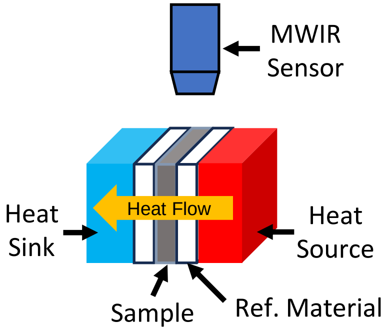
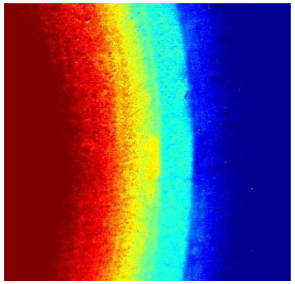
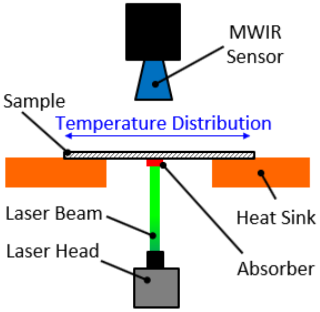
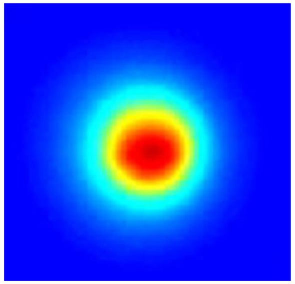
Metrology Development & Property Analysis

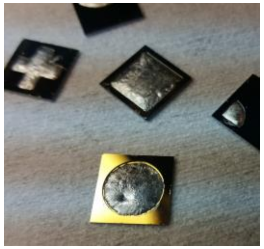




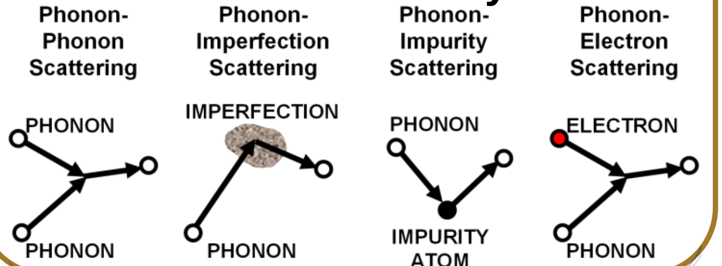




Thermal Management Solution Development



Fundamental Transport Phenomena Analysis



Designing Thermal Measurements

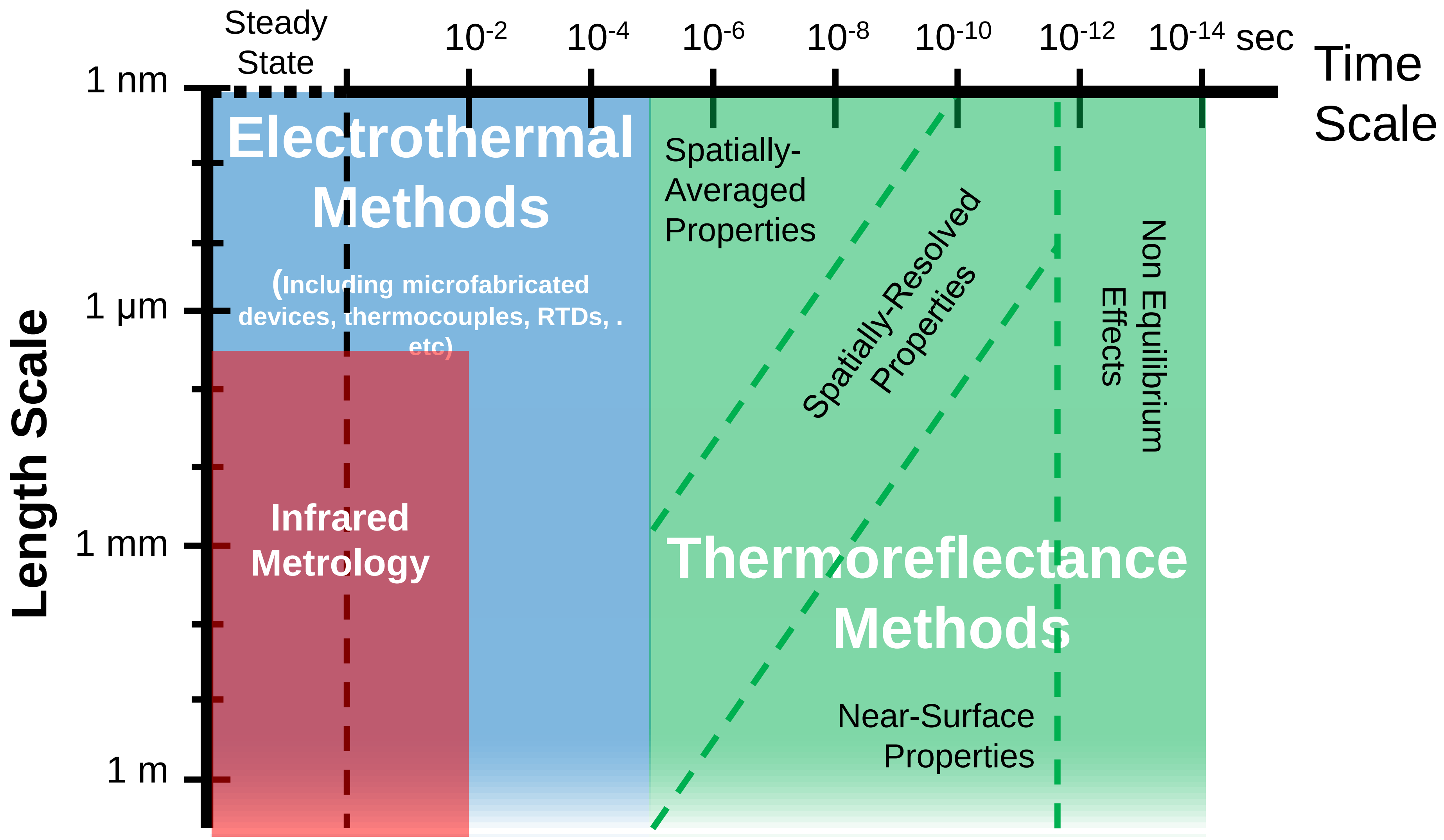
Fourier's Law: $\overrightarrow{q"} = -k\,\nabla T$ Heat Diffusion Eqn: $\frac{1}{\alpha}\frac{\partial T}{\partial t} = \nabla^2 T$

1. How to measure **temperature**?

	Indirect [Heat Diffuses into Sensor]	**Direct** [Heat Diffusion Not Required]
Contact (generally electrical)	Thermocouples, electrical resistance thermometers, scanning probe techniques	Temperature sensitive device behavior (*e.g.* temperature dependent resistance of a nanowire)
Non Contact (generally optical)	Interactions with thin coatings (Fluorescence, Liquid Crystals, Thermoreflectance, etc.)	Temperature sensitive device or material behavior (IR emission, Raman spectroscopy, Thermoreflectance)

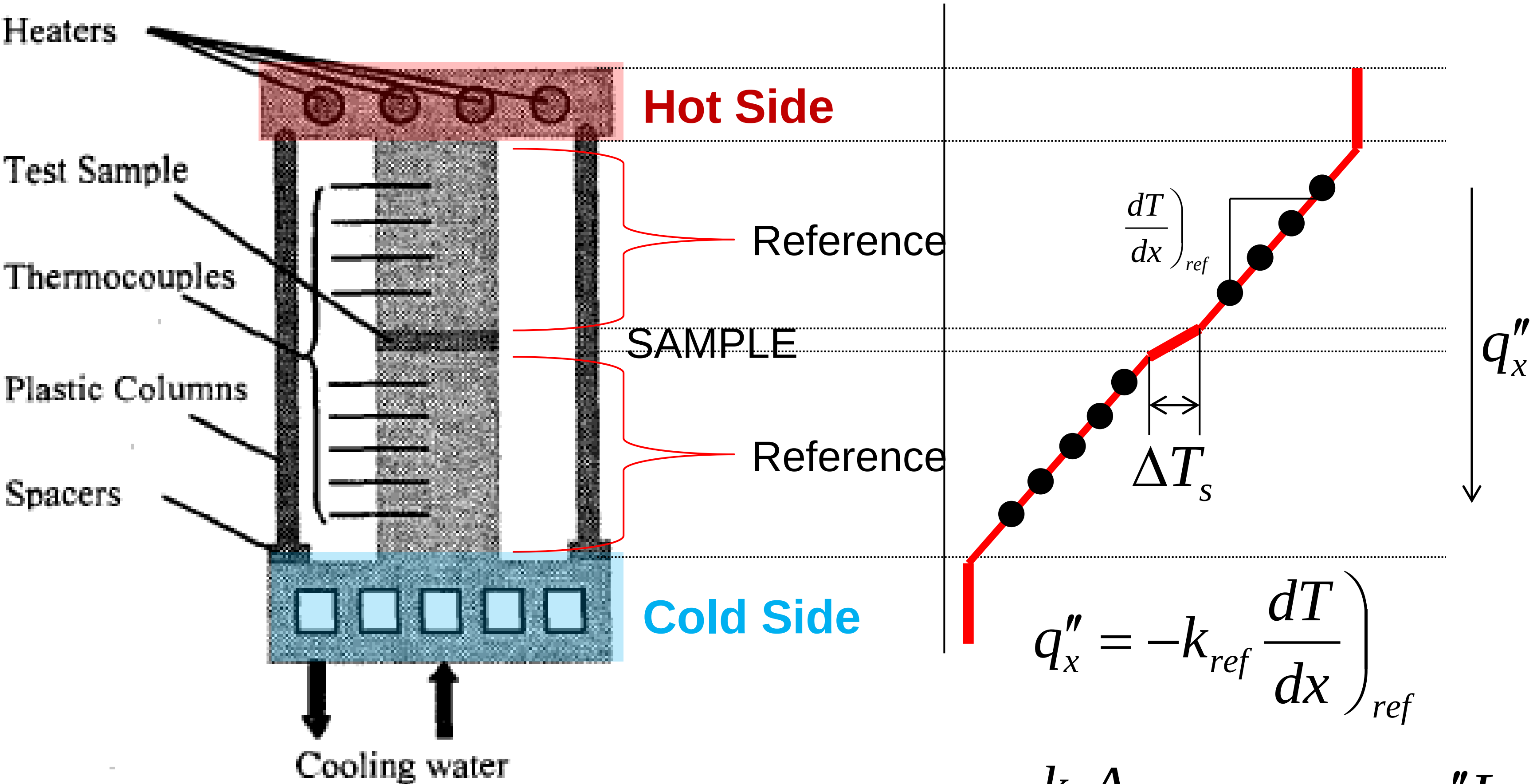
2. How to measure **heat flux**?

Joule heating, use reference materials, quantify optical absorption, …


Steady State
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14} sec
Time Scale
1 nm
1 μm
1 mm
1 m
Length Scale
Electrothermal Methods
(Including microfabricated devices, thermocouples, RTDs, . etc)
Infrared Metrology
Spatially-Averaged Properties
Spatially-Resolved Properties
Non Equilibrium Effects
Thermoreflectance Methods
Near-Surface Properties

Reference Bar Method

ASTM D5470 Reference Bar Method



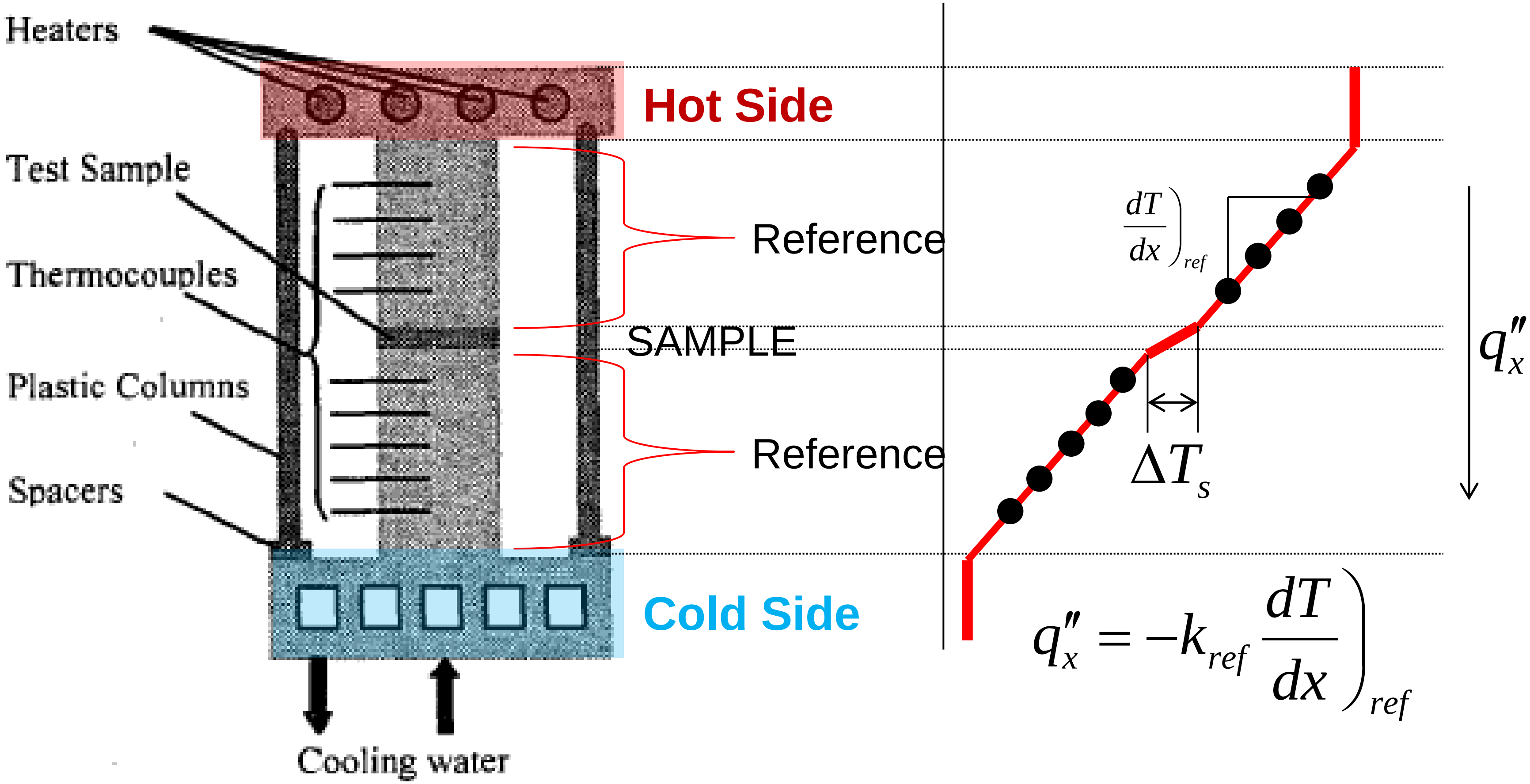
$$q''_x = -k_{ref} \left.\frac{dT}{dx}\right)_{ref}$$

X. Hu, *et al.*, "Thermal conductance enhancement of particle-filled thermal interface materials using carbon nanotube inclusions," in *The Ninth Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITHERM '04)*, 2004, pp. 63-69 Vol.1.

$$q_x = G_{th,s}\Delta T_s = \frac{k_s A}{L_s}\Delta T_s \rightarrow k_s = q''_x L_s \big/ \Delta T_s$$

Reference Bar Method

ASTM D5470 Reference Bar Method



$$q''_x = -k_{ref} \left.\frac{dT}{dx}\right)_{ref}$$

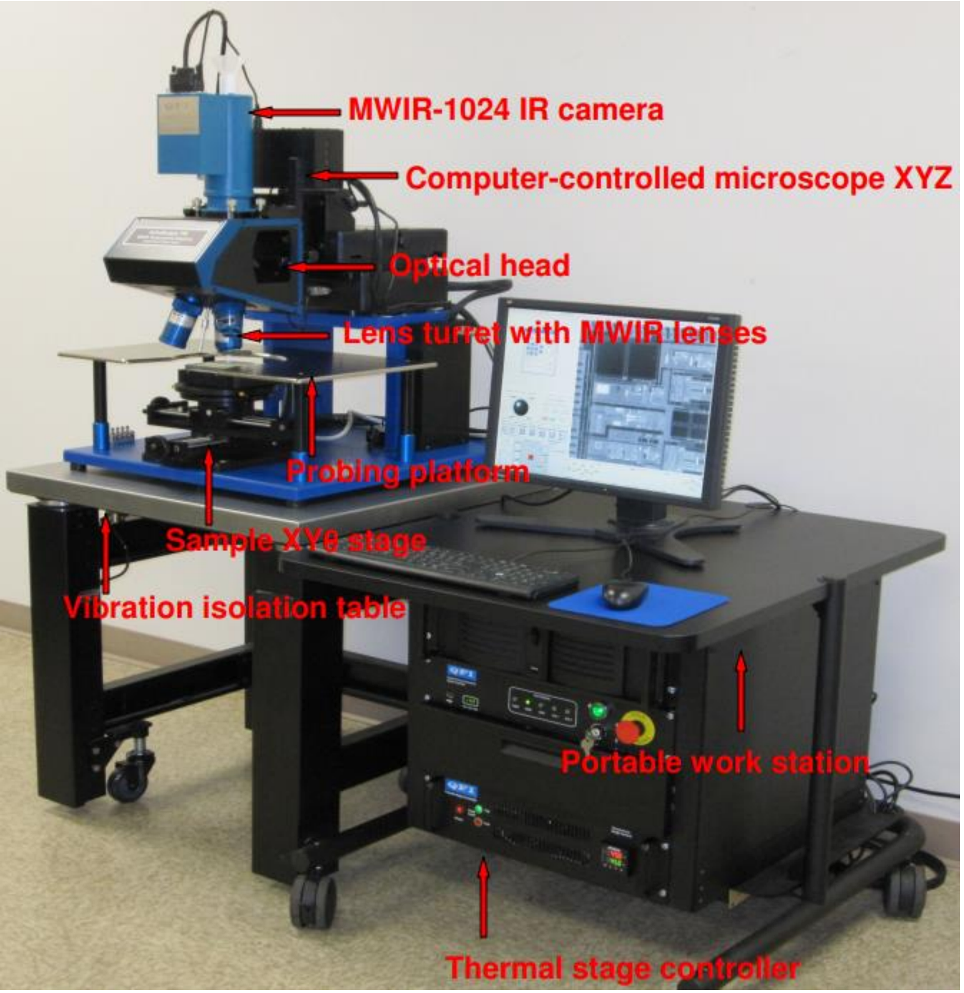
Disadvantages:

- Lack information on contact resistance between sample and the reference bars.
- Place thermocouple directly on sample may damage sample and create unintended heat loss through thermocouple wire.

Temperature mapping using high resolution Infrared microscopy

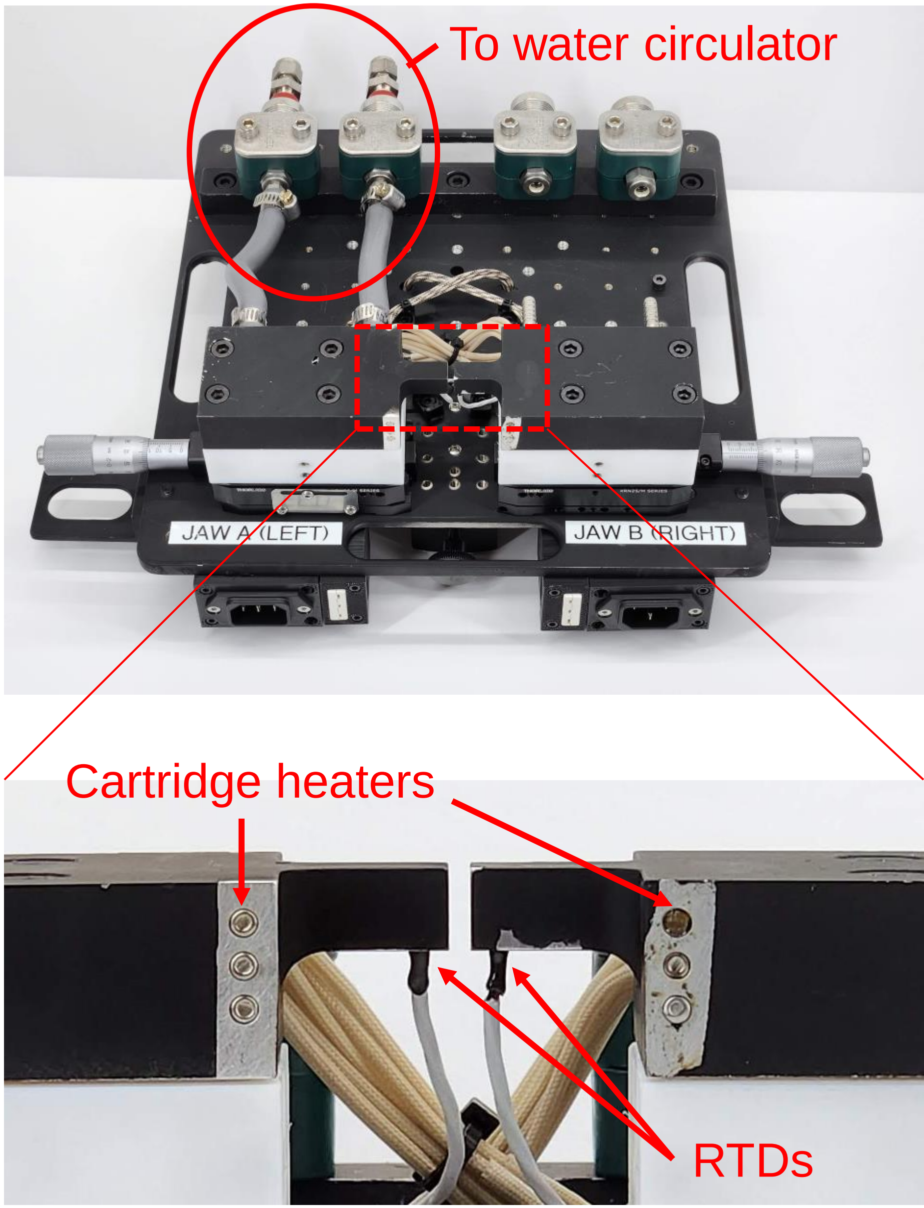
IR Microscope Reference Bar Method

QFI IR Microscope Stage

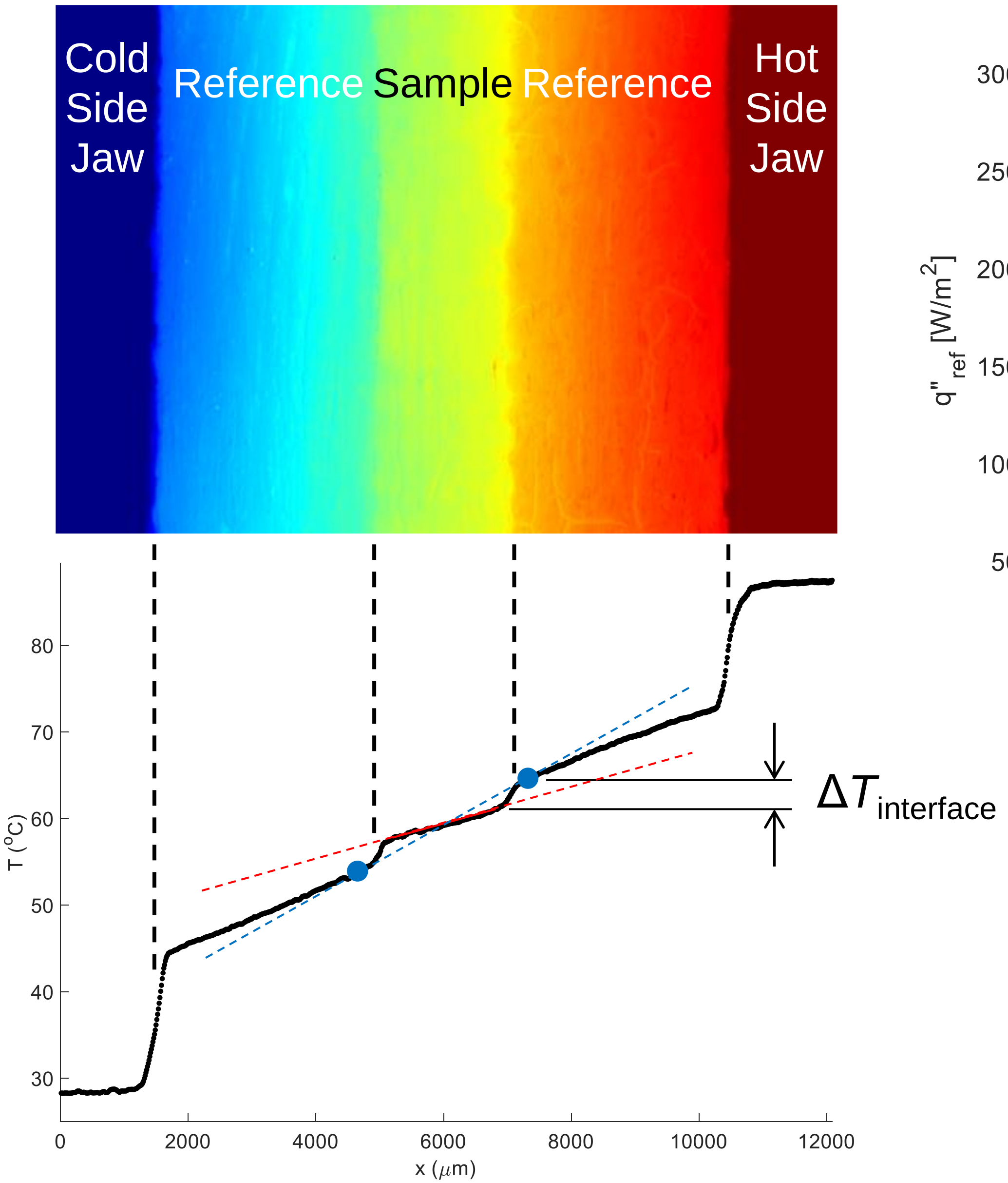


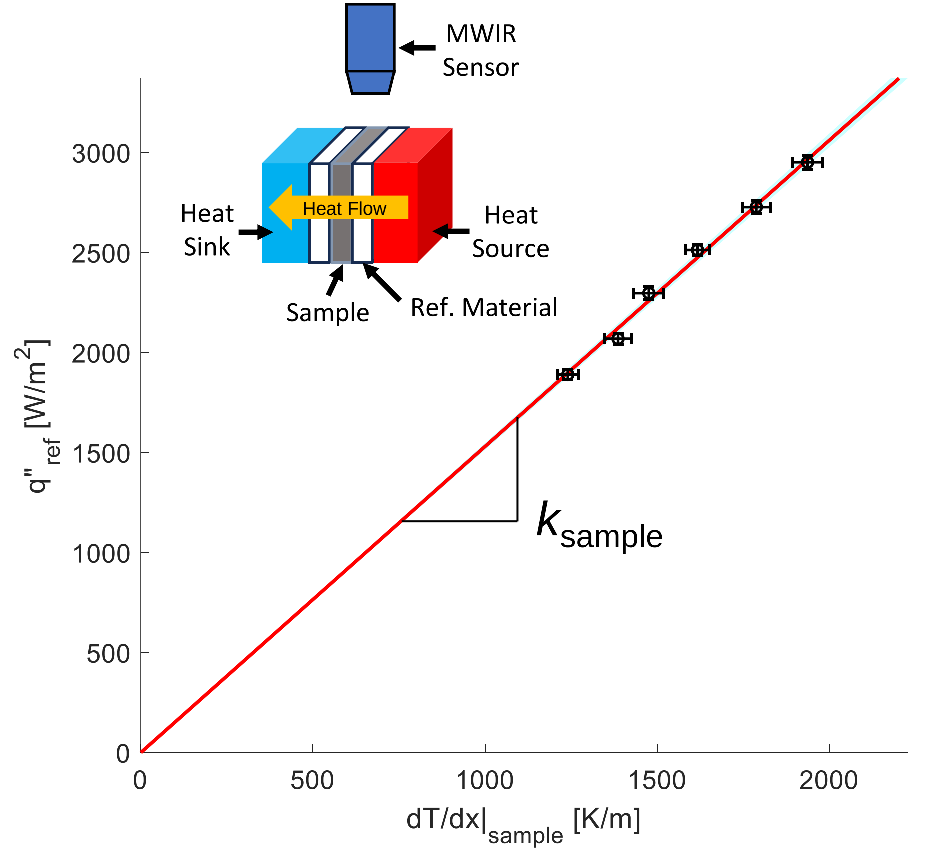
Highest resolution at 0.6 µm per pixel.
Can measure samples with thickness from 10s µm to several millimeters.

Sample Mounting Rig



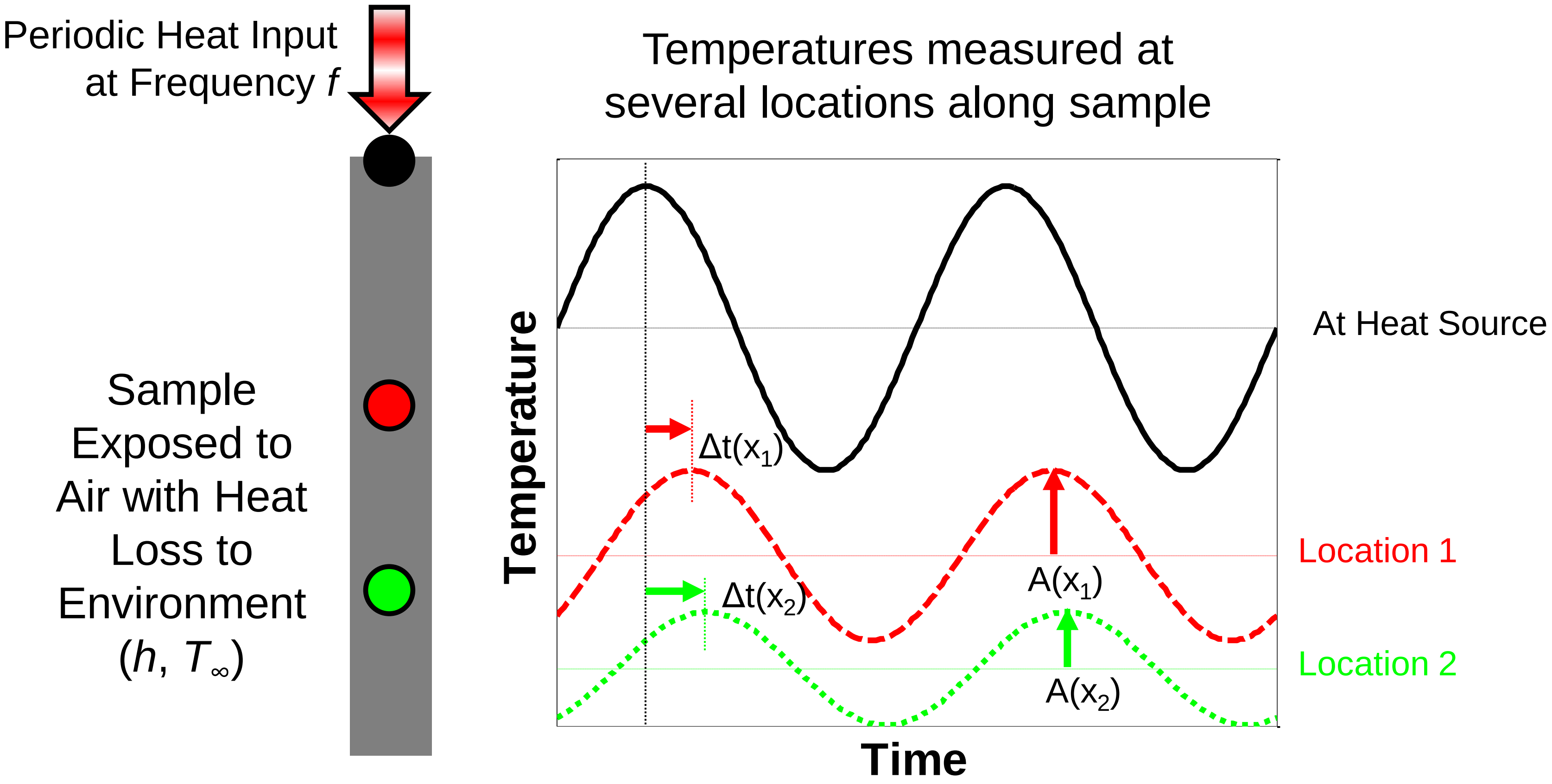
Temperature Mapping and Data Analysis





The interface is clearly visible in the temperature map and can be eliminated from thermal conductivity calculation of the sample.

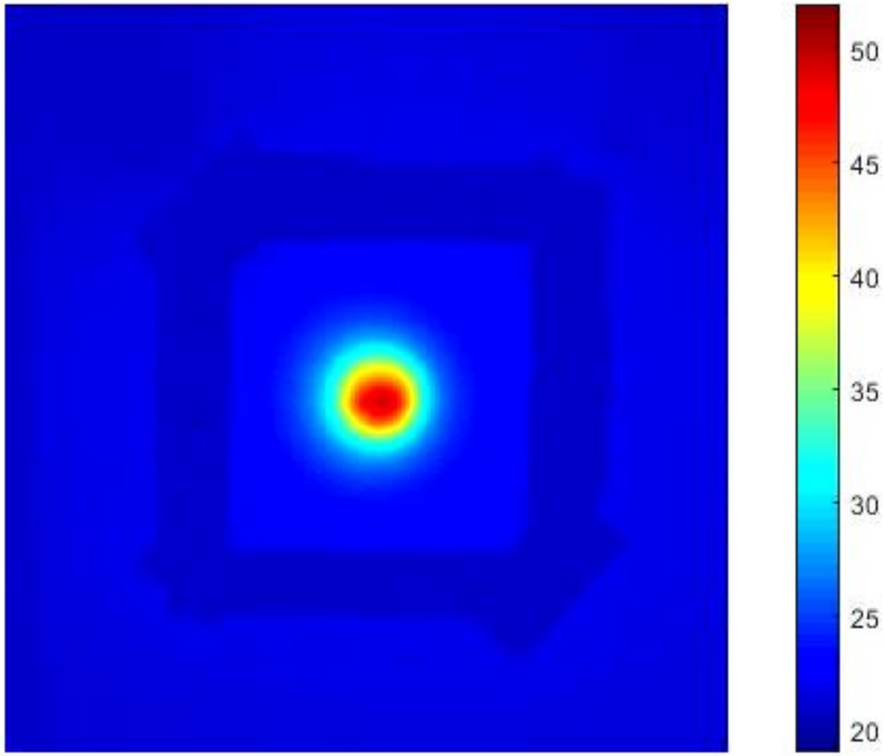
IR- Microscopy Enhanced Ångström Method



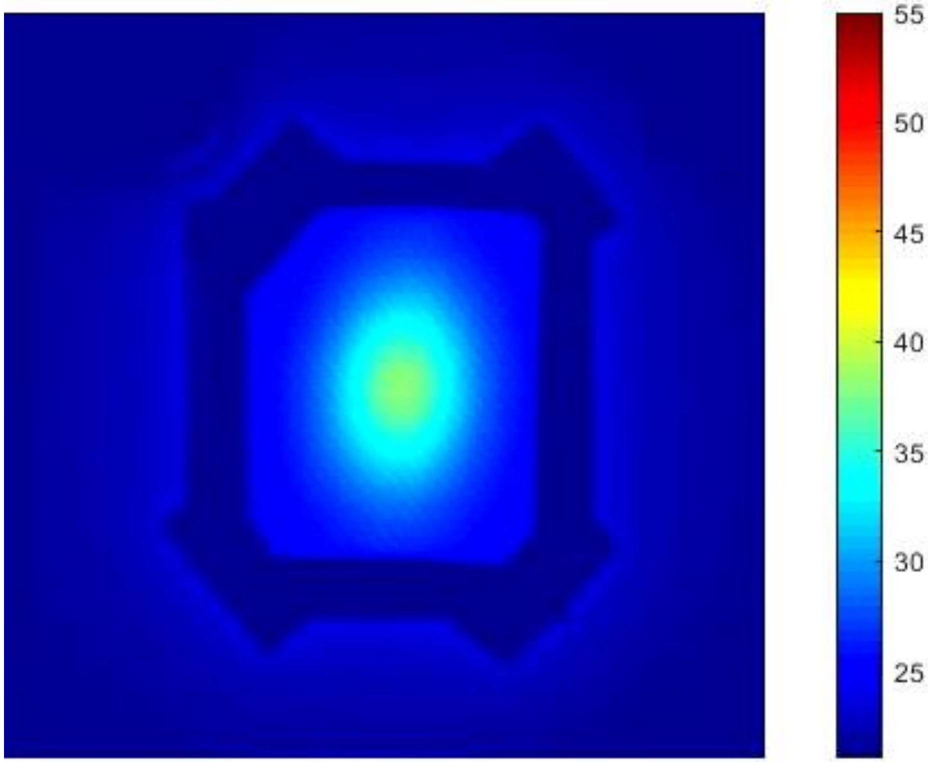
Hahn, Reid, and Marconnet, "Infrared microscopy enhanced Angstrom's method for thermal diffusivity of polymer monofilaments and films", *Journal of Heat Transfer*, 2019.

Anisotropic Property Characterization

Isotropic, low *k*



Anisotropic, high *k*



2D Laser Ångström Method

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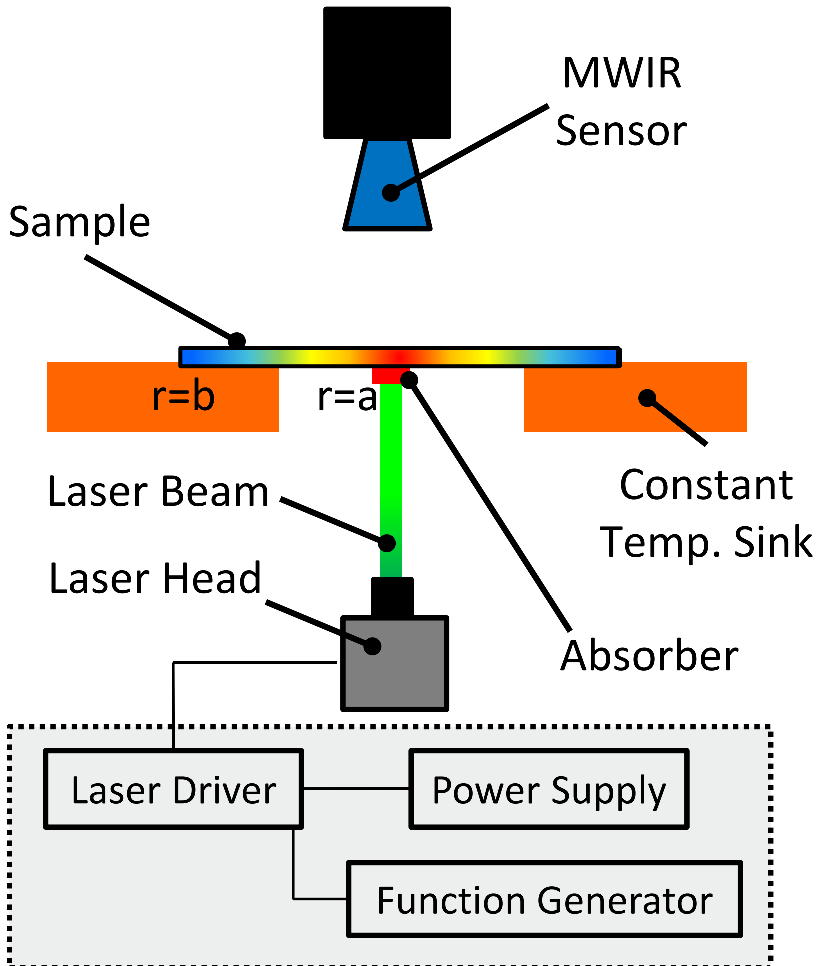
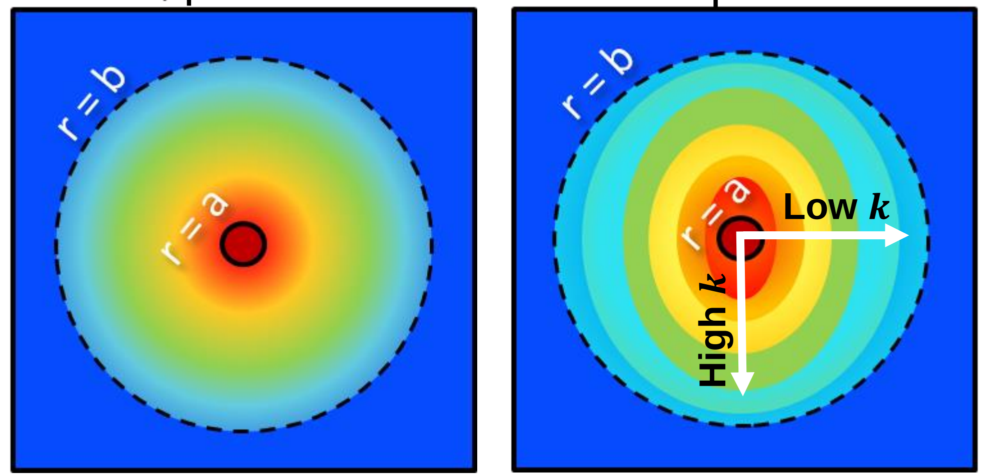
Vertical Section View



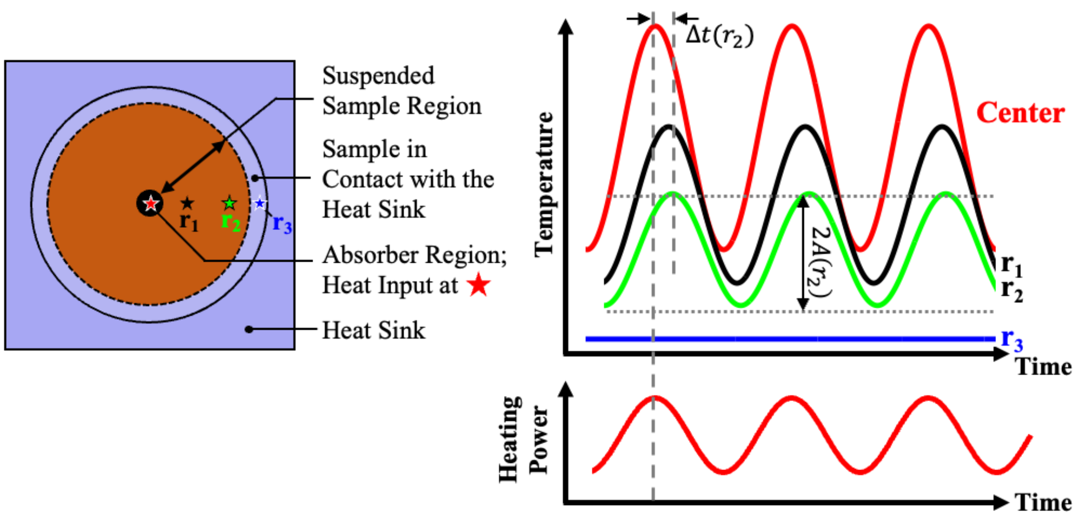
Top view of Surface Temperatures

Isotropic Material

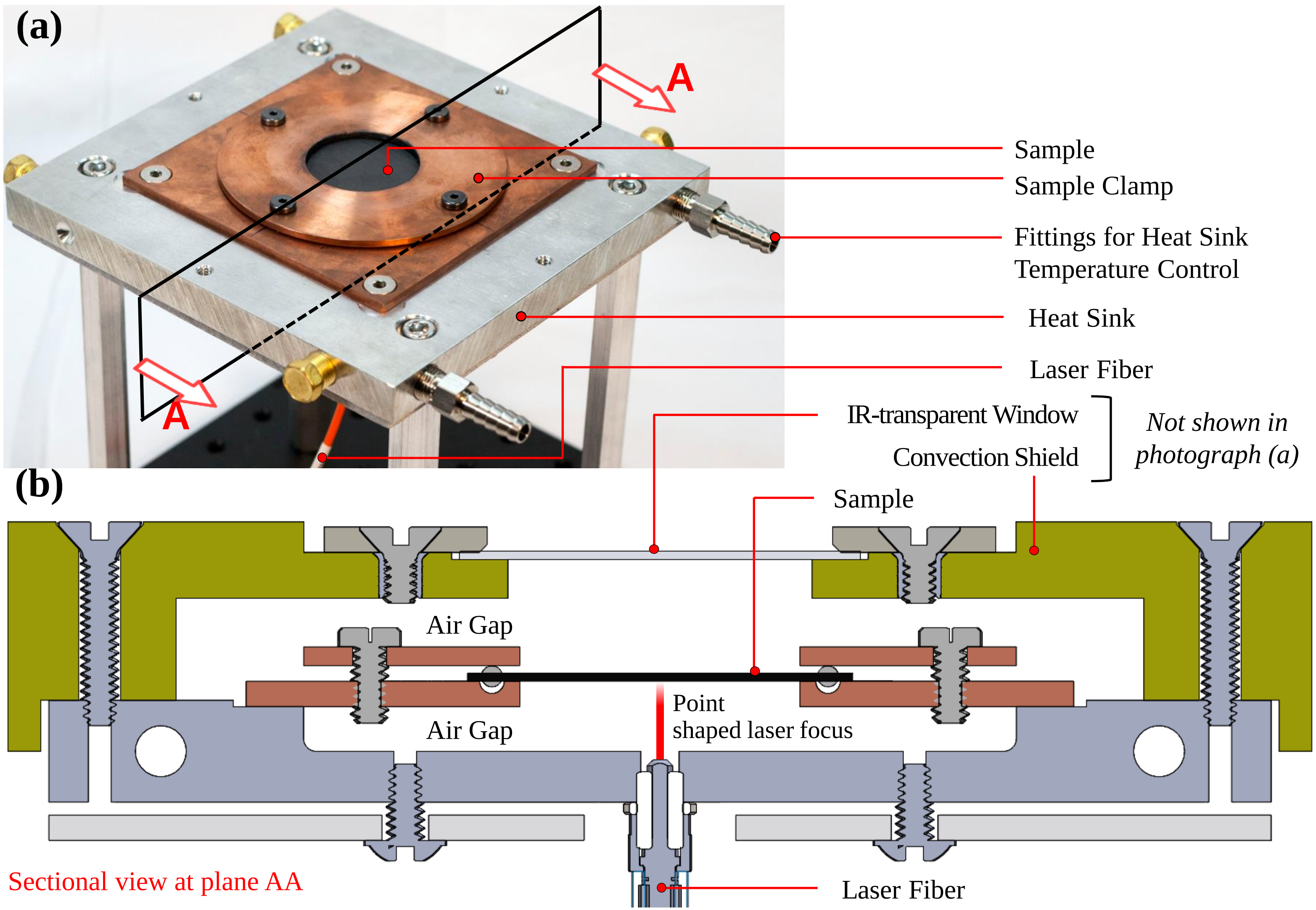
Anisotropic Material



Bottom View and Temperature Response



Experimental Setup



- Measure in-plane isotropic and anisotropic k of self-supporting and free-standing sheets
- Temperature Range: 5-200°C

Model and Data Processing

Governing Equation: $$\frac{\partial}{\partial x}\left(k_x A \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y A \frac{\partial T}{\partial y}\right) - 2hA(T - T_\infty) = \rho C_p V \frac{\partial T}{\partial t}$$

Assume a Time Periodic Solution:

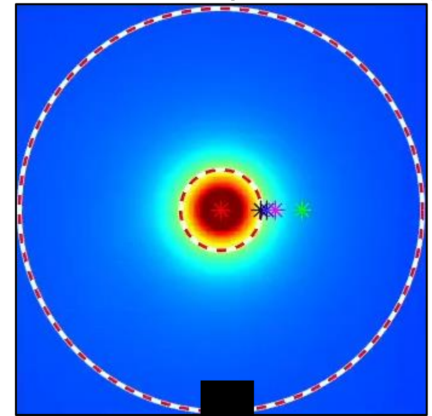
$$T(x, y, t) = [P(x, y) + iQ(x, y)]\, e^{i\omega t}$$

Yields Two Linear Equations for Each Data Point:

$$k_x \frac{\partial^2 P}{\partial x^2} + k_y \frac{\partial^2 P}{\partial y^2} - \frac{2hP}{th} = -\rho C_p \omega Q$$

$$k_y \frac{\partial^2 Q}{\partial x^2} + k_y \frac{\partial^2 Q}{\partial y^2} - \frac{2hQ}{th} = \rho C_p \omega P$$

Transient Temperature Map



Least Squares Fitting for k_x, k_y & h

$$\begin{bmatrix} \frac{\partial^2 P_1}{\partial x^2} & \frac{\partial^2 P_1}{\partial y^2} & -\frac{2P_1}{th} \\ \vdots & & \vdots \\ \frac{\partial^2 Q_1}{\partial x^2} & \frac{\partial^2 Q_1}{\partial y^2} & -\frac{2Q_1}{th} \\ \vdots & & \vdots \end{bmatrix} \begin{bmatrix} k_x \\ k_y \\ h \end{bmatrix} = \begin{bmatrix} -\rho C_p \omega Q_1 \\ \vdots \\ +\rho C_p \omega P_1 \\ \vdots \end{bmatrix}$$

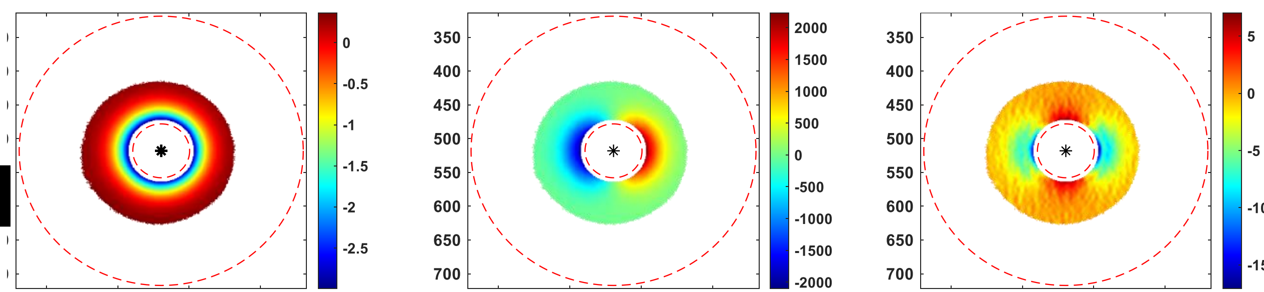
1. Solve a set of linear equations, only unknowns are k_x, k_y & h
2. Minimize objective function

   || [A].[k, h] – [b] ||

→ Fit k_x, k_y & h

1.Calculate the in-phase and out-of-phase components of temperature using Fourier Transform. These correspond to the real (*P*) and imaginary (*Q*) parts of the complex amplitude

2.Numerically evaluate derivatives $\left(\frac{\partial^2 P}{\partial x^2}, \frac{\partial^2 P}{\partial y^2}, \frac{\partial^2 Q}{\partial x^2}, \frac{\partial^2 Q}{\partial y^2}\right)$ at each pixel



***P* (Real Component of Complex Amplitude)** $\qquad \frac{\partial P}{\partial x} \qquad \frac{\partial^2 P}{\partial x^2}$

Demonstration with PEKK Composite

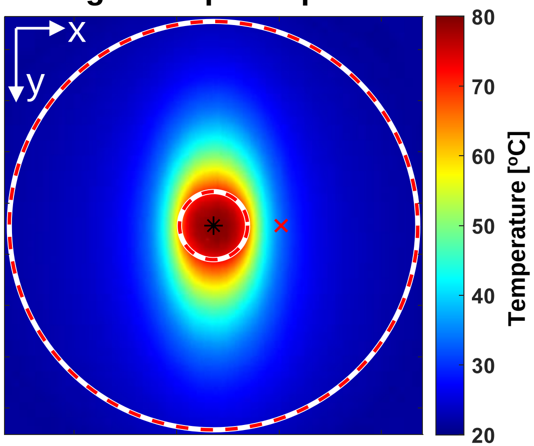
Solvay PEKK Prepreg with Carbon Fiber

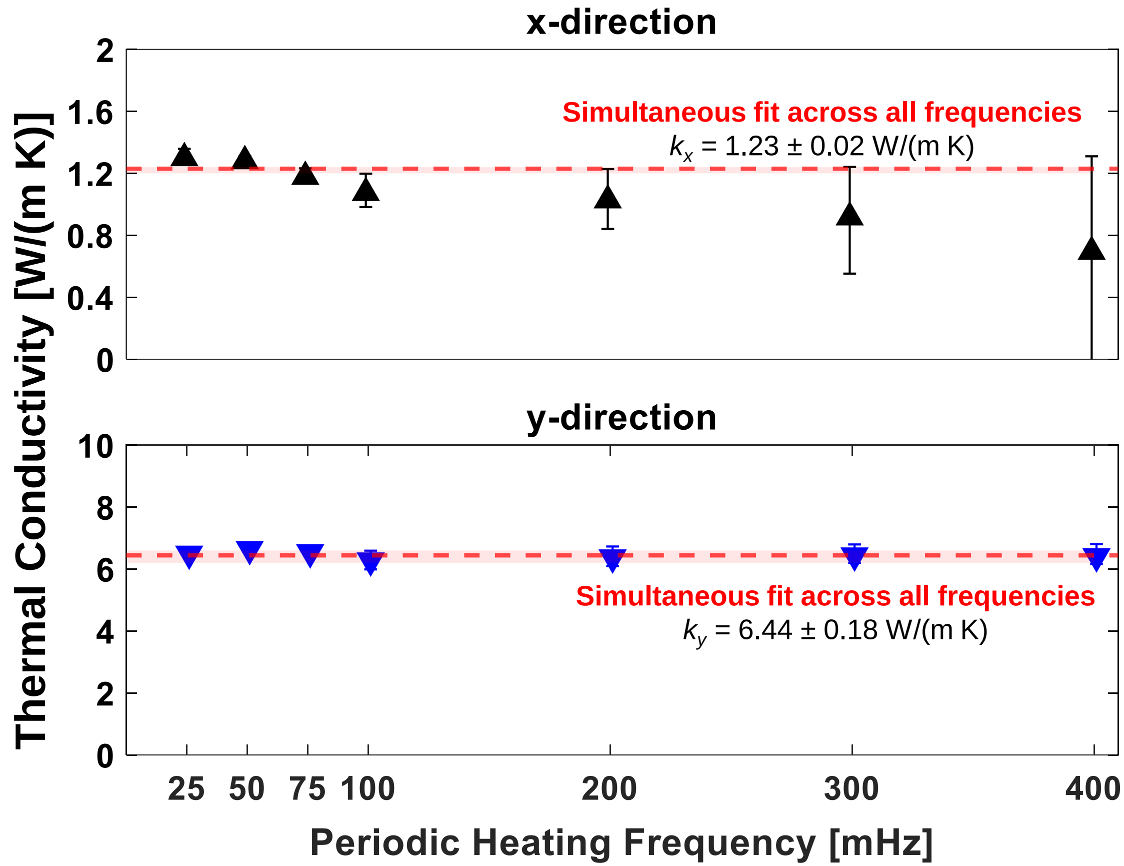
T_g : 160 °C
Thickness: 200 μm
Density: 1300 kg/m³
Tensile Strength: 15 MPa

Expected Properties

k_x = 1 W/(m K)
k_y = 6 W/(m K)

Single Temp. Snapshot



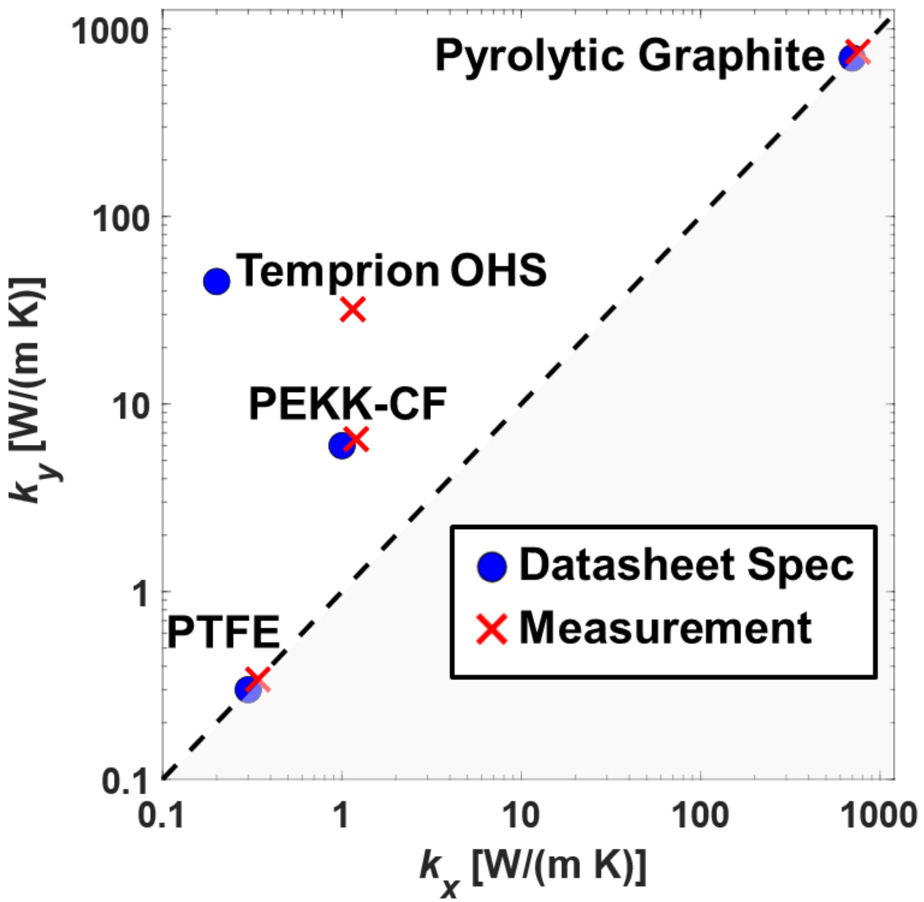


Key advantages of our method:

- Orthotropic thermal conductivity resolved in a single measurement without significant sample preparation
- Measurements can be conducted in air (insensitive to convection)
- No knowledge of boundary conditions or heater power required
- Relatively insensitive to calibration of emissivity

Solvay PEKK-CF sample received from **Dr. Eduardo Barocio** at The Composites Manufacturing and Simulation Center, Purdue University

Wide Range of Applicability



- Can tune frequency or change diameter of suspended region to improve sensitivity across different parameters
- Relatively insensitive to convection losses and to the boundary conditions
- For opaque samples, minimum sample preparation required
- For transparent samples, an infrared opaque coating is required

Check out our newest paper:

Gaitonde et al., “A laser-based Ångström method for in-plane thermal characterization of isotropic and anisotropic materials using infrared imaging”, Review of Scientific Instruments, 2023.

DOI: 10.1063/5.0149659

Summary

- To accurately estimate the heat extraction and thermal risks within the tracking detector, a robust understanding of thermal transport is needed
- New metrology techniques can fully characterize the thermal properties in all directions with high precision
- New thermal challenges in the design of the next generation tracking detector drive the development of new thermally-engineered materials and new metrology techniques to understand performance

Contact Info:

For potential collaboration:

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For details on 2D Ångström method:

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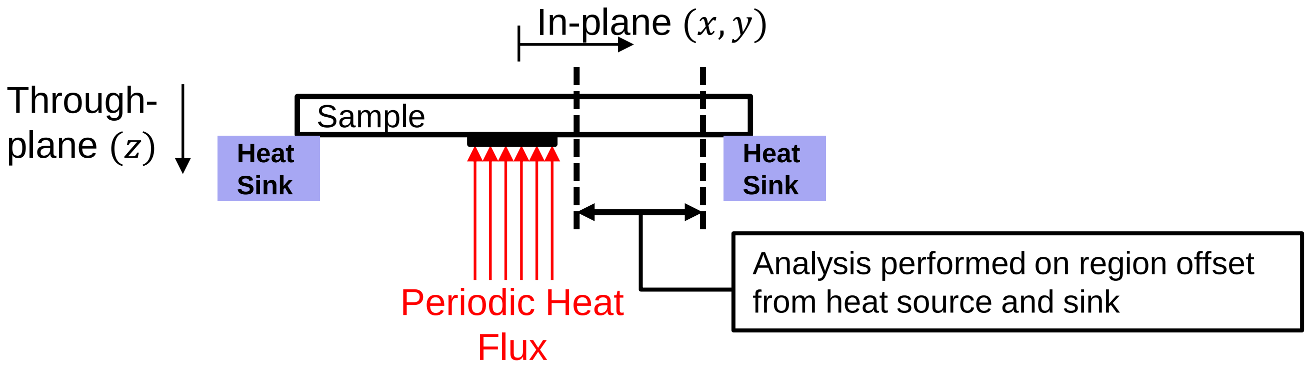
Heating Frequency Limits



- **Heat transfer must be predominantly in the in-plane direction**
  → Assumption valid when the temperature gradients are negligible across the thickness of the sample
  → Heating frequency should be much lower than the thermal penetration depth

$$t \ll \left(\frac{k_z}{\rho C_p \pi f}\right)^{1/2} \quad or \quad \boldsymbol{f} \ll \frac{\boldsymbol{k_z}}{\boldsymbol{\rho C_p \pi t^2}}$$

- **The frequency should be high enough to minimize the effect of the boundaries**
  → This limits the in-plane conductivity relative to experimental setup dimension (R)

$$\boldsymbol{f} \geq \frac{\mathbf{2.98}\, \boldsymbol{k_{x,y}}}{\boldsymbol{\pi \rho C_p R^2}}$$

Hahn, J., Reid, T., & Marconnet, A. (2019). Infrared Microscopy Enhanced Ångström's Method for Thermal Diffusivity of Polymer Monofilaments and Films. *Journal of Heat Transfer*, *141*(8), 1–11. https://doi.org/10.1115/1.4043619