Fiber Scanning Imaging Techniques for Applications in Laser Additive Manufacturing Systems

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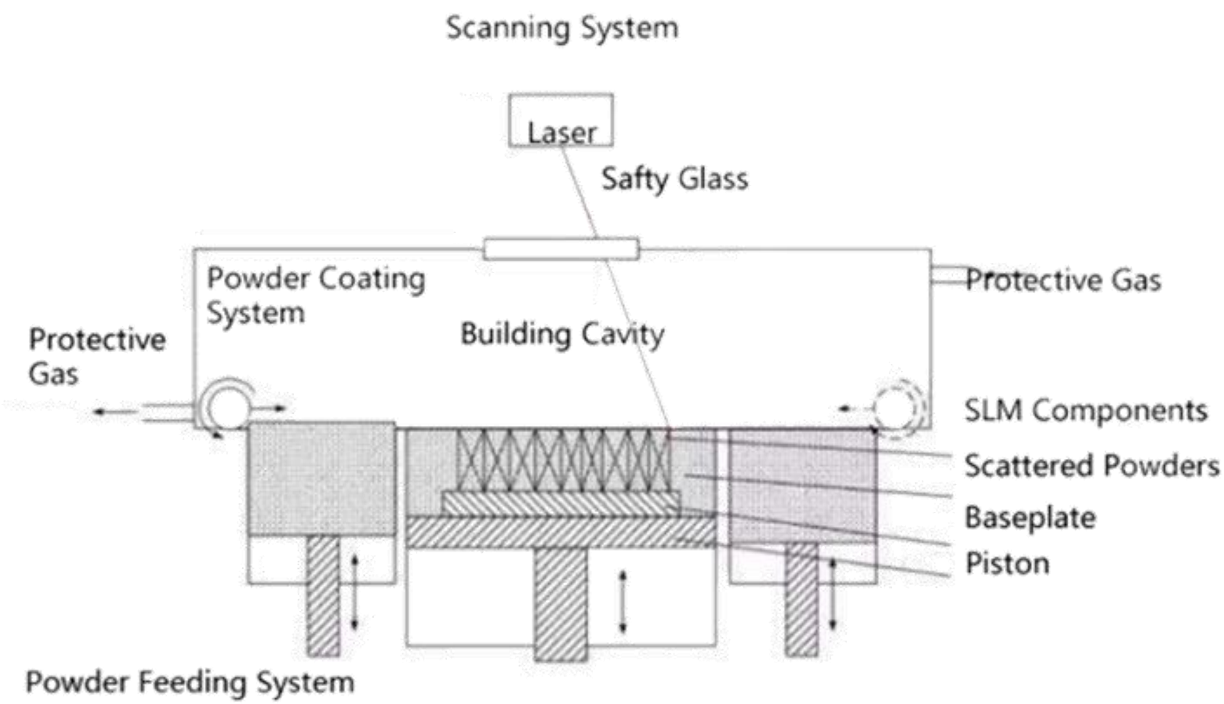
    - Experiment setup and result
  - Thermal Imaging system
    - Introduction
    - Problem statement
    - Experiment setup and result

Introduction to Laser Additive Manufacturing (LAM) of Metals

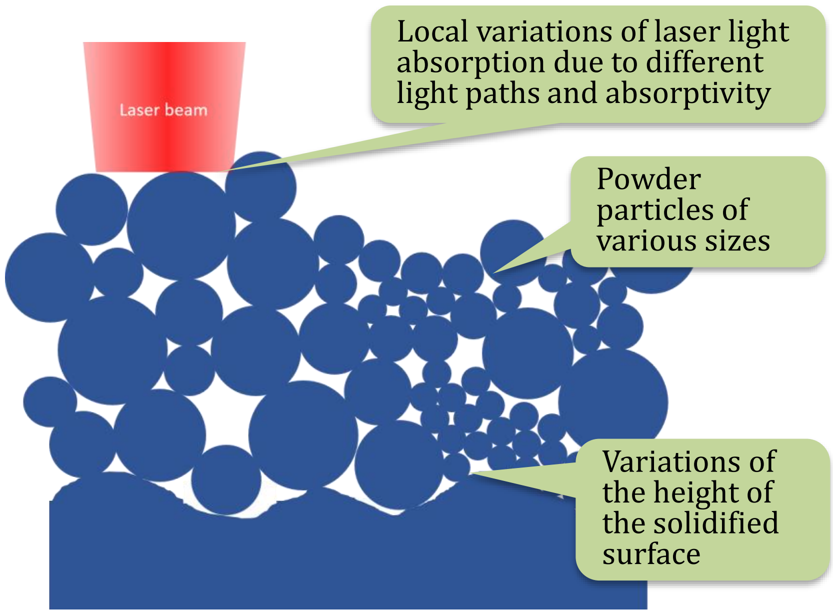


Wiiboox URL:https://www.wiiboox.com/3d-printer-slm250.php

- Metal powder is spread out in thin layers
- A focused high-power laser beam is scanned across the powder surface
- A part is formed layer by layer by selectively melting powder in the desired areas
- Custom parts can be directly formed from a digital model
- Disadvantage: Slow build rate

Problem Statement

- The **quality of parts** manufactured by laser additive manufacturing is **influenced by local variations in powder characteristics**.
- The temperature of the melt pool at the laser hit spot varies with powder characteristics
- Melting and cooling processes vary across the powder bed surface
- Need to control **laser power depending on the location of the laser beam** on the powder bed surface

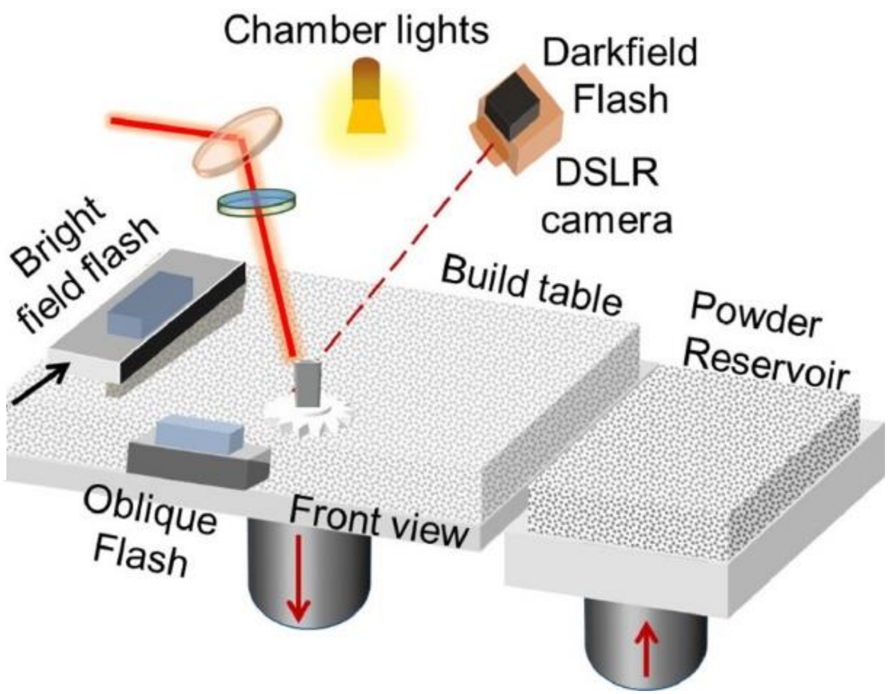


Potential control approaches

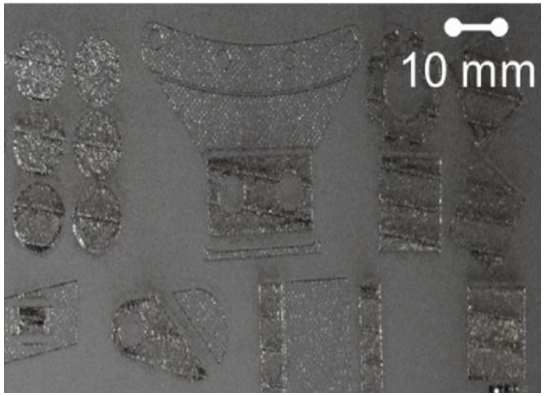
Powder layer characterizations (e.g., powder surface imaging) to enable feedforward control of the laser power incident on the powder surface.

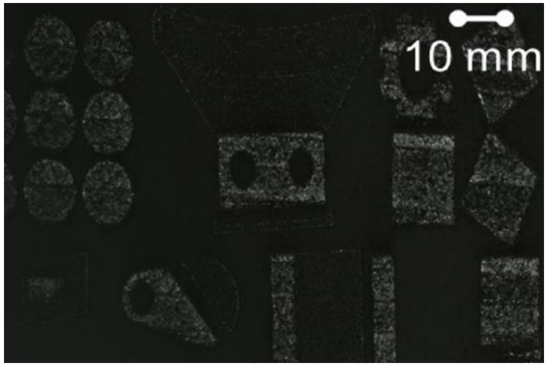
Measure local temperature at melt pool or hit spot of a probe laser to enable feedback or feedforward control of laser power

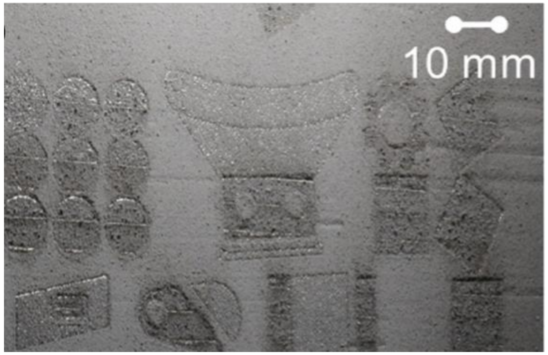
Example for Surface Characterization



F. Imani, Aniruddha et al. *Manufacturing Science and Engineering,* **140**, 101009 (2018).

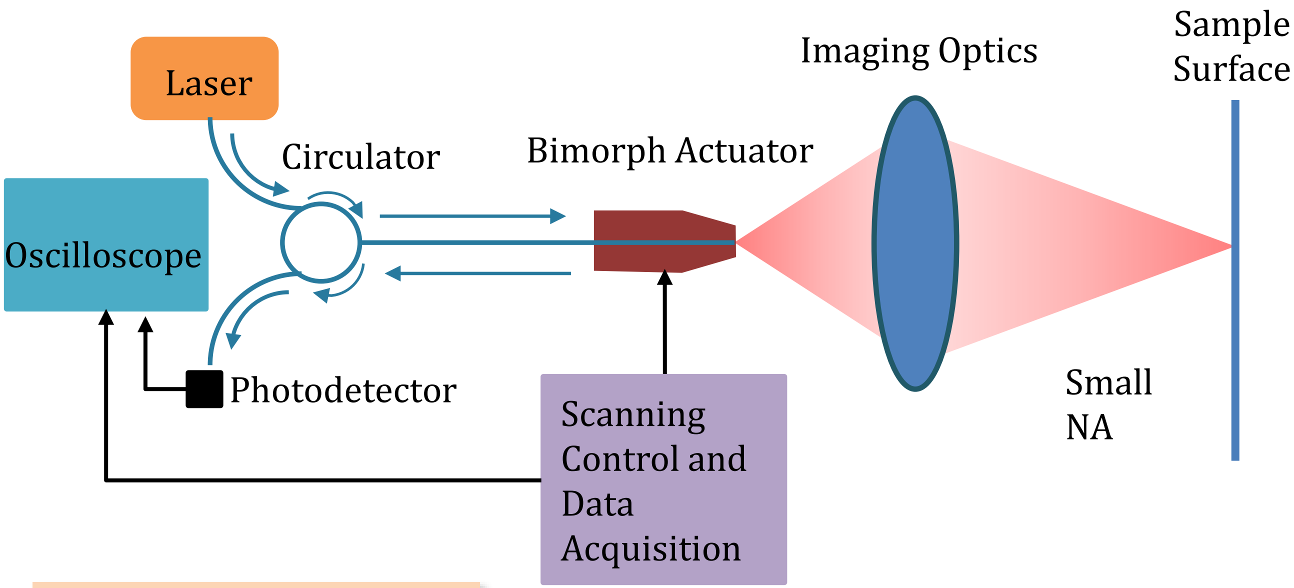




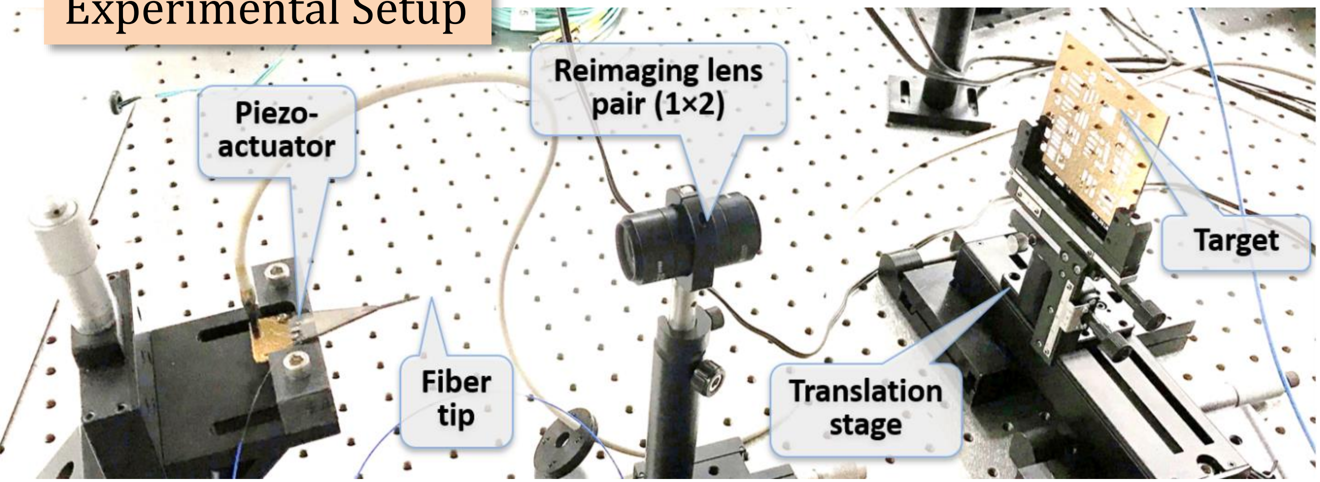


- Images taken of the whole powder bed surface (powder or solidified metal) using a set of different illumination techniques
- Can be used in feedforward control
- Feedback control based on solidified surface only layer by layer

Our Approach: Confocal Imaging with Fiber Scanner

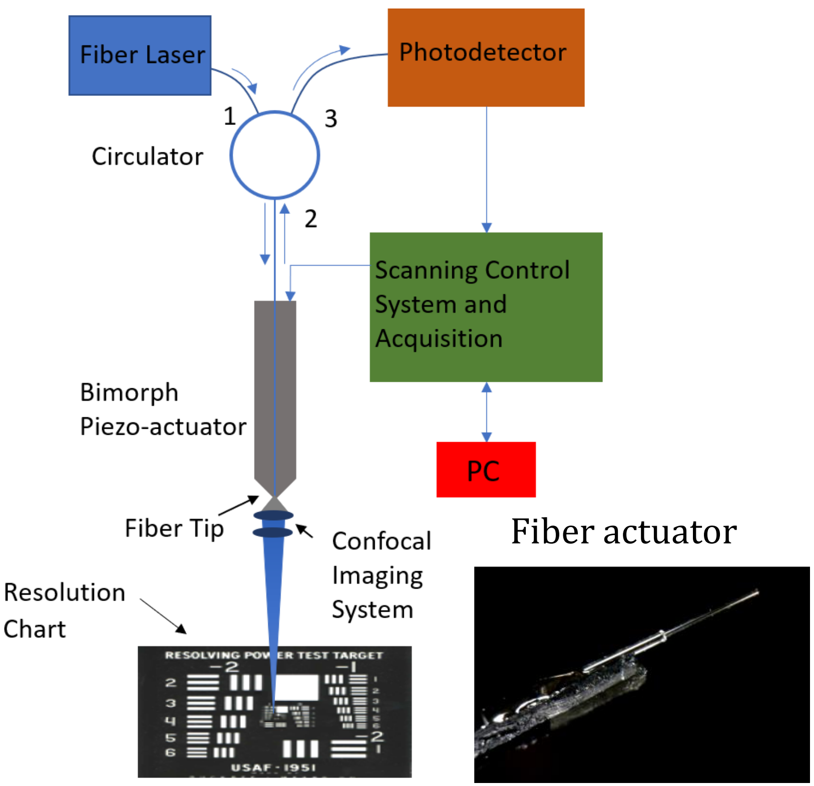


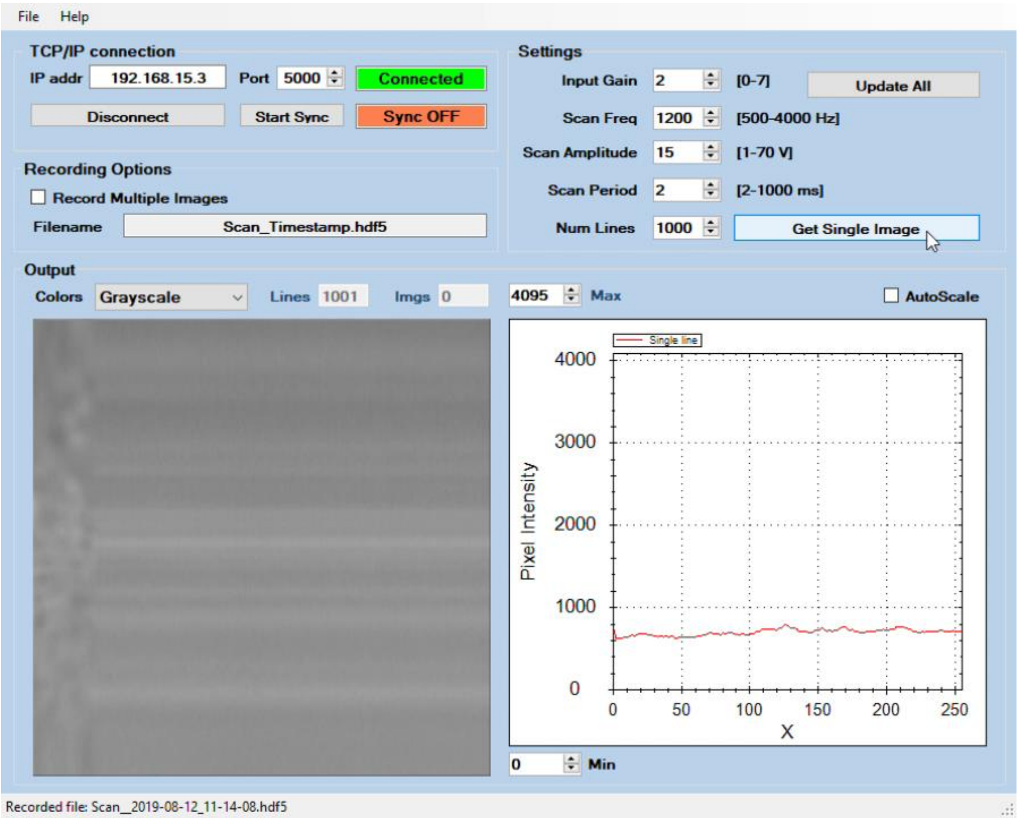
Experimental Setup



- Probe beam emitted through a fiber mounted to a piezoelectric actuator and reimaged onto powder bed surface
- Probe beams scans along a line orthogonal to the processing part surface
- Light reflected from the powder layer or consolidated metal is reimaged onto the fiber tip
- Photocurrent generated by the photodetector is processed to the scanned image of the powder bed surface.

Control and Data Acquisition Electronics and Software



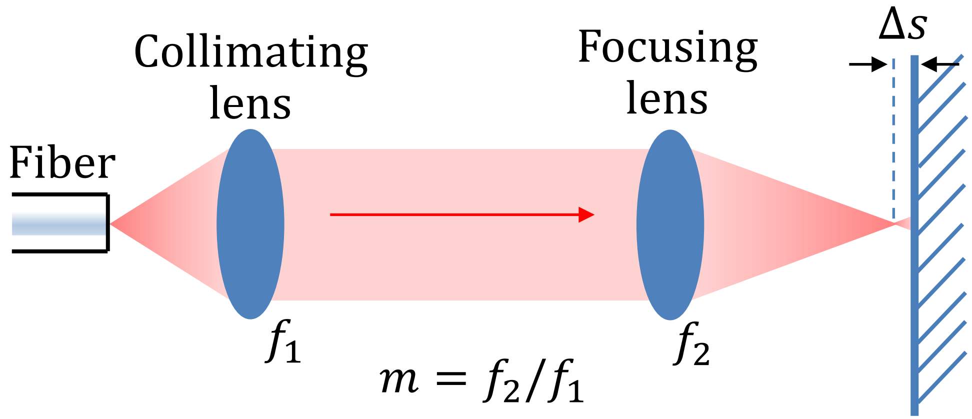


- The piezoelectric bimorph actuator is controlled by custom electronics (provided by II-VI/Optonicus) with supervising control software
- System is also used for data acquisition
- Scanning frequencies between 500 Hz and 4000 Hz, voltage amplitude up to ±70 V
- 256 pixels along line images, 1000 lines maximum in one image

How Do Surface Characteristics Impact Measurements?

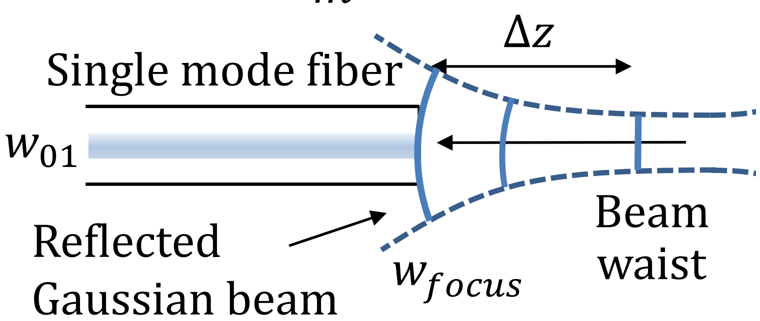
Defocus

Assume target surface is a mirror that is shifted by Δs from the focal plane of the focusing lens.

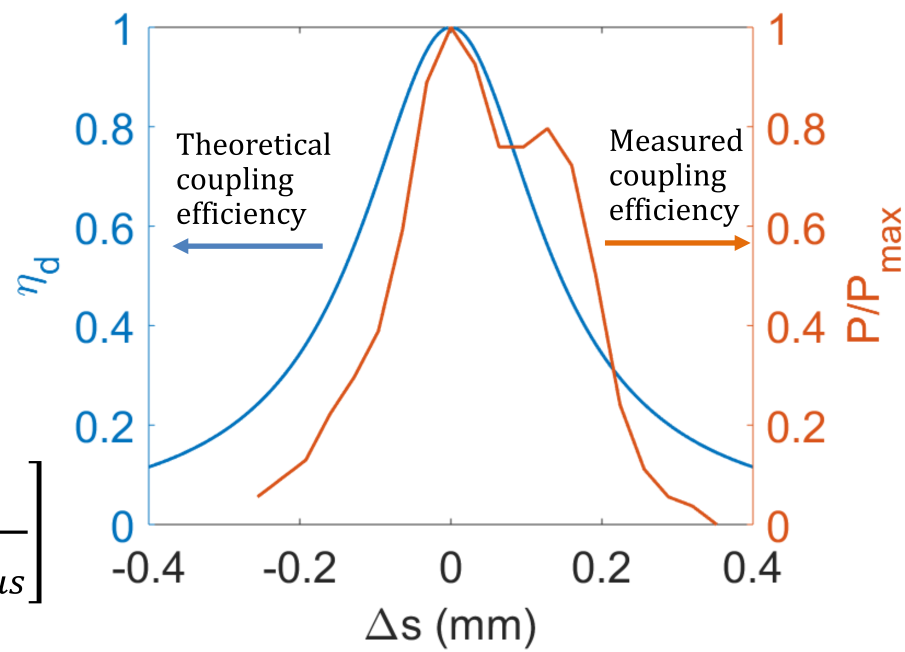


Then the waist of the beam returning to the fiber is shifted by

$$\Delta z = \frac{2}{m^2}\Delta s = 0.5\Delta s$$



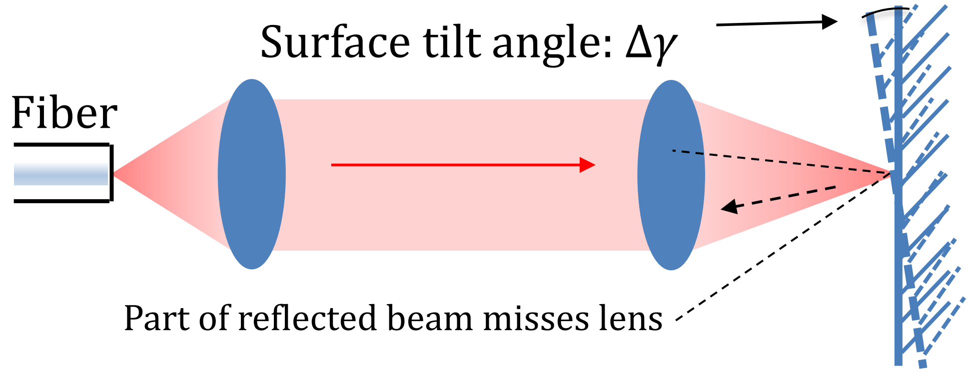
$$\eta_d = \frac{4w_{01}^2 w_{focus}^2}{\left(w_{01}^2 + w_{focus}^2\right)^2}\exp\left[-\frac{2(\Delta z)^2}{w_{01}^2 + w_{focus}^2}\right]$$



- Noticeable impact of spherical aberration in experimental results (double peak)

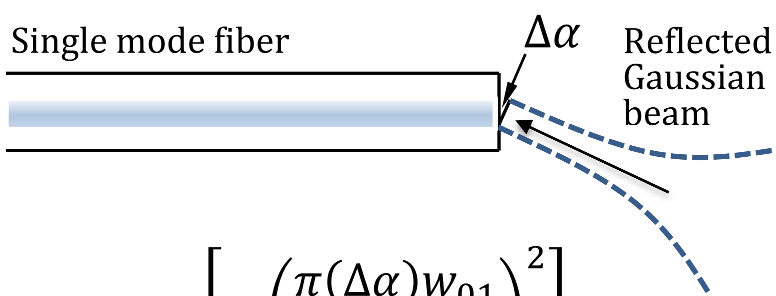
How Do Surface Characteristics Impact Measurements?

Surface Tilt

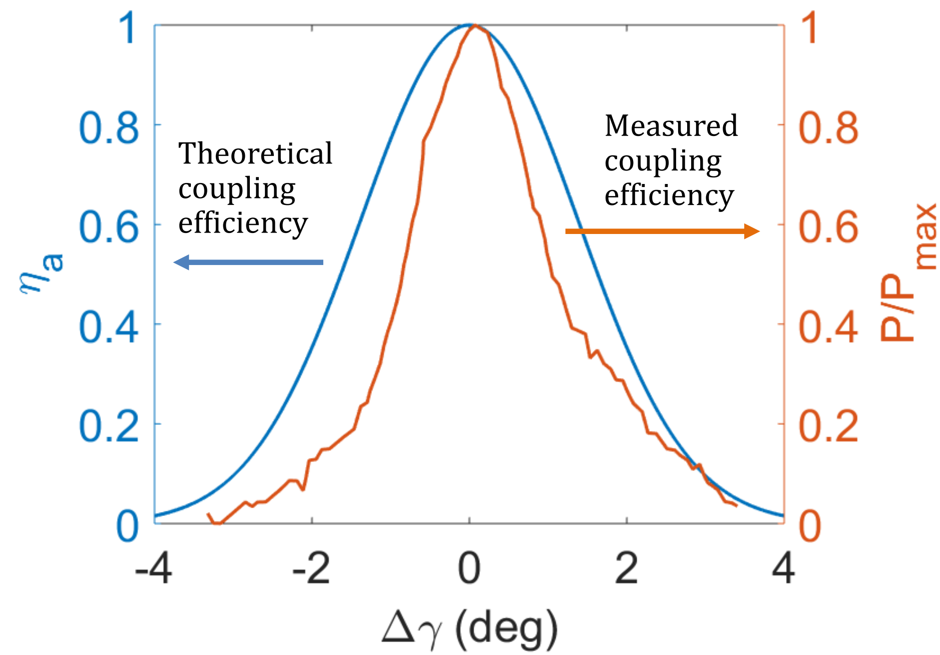


Assume target surface is a mirror that is tilted by angle $\Delta\gamma$ from normal incidence.

The returning beam arrives at fiber under an angle of $\Delta\alpha = m\,\Delta\gamma = 2\,\Delta\gamma$



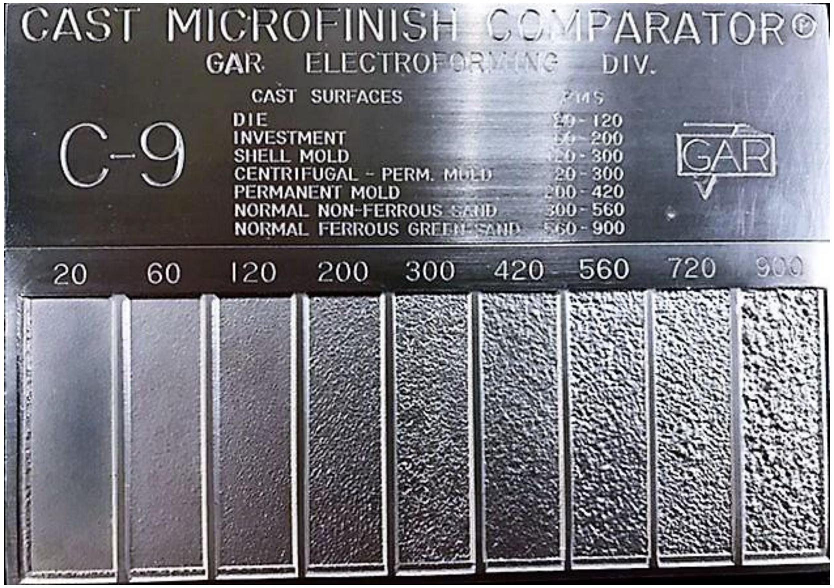
$$\eta_a = \exp\left[-\left(\frac{\pi(\Delta\alpha)w_{01}}{\lambda}\right)^2\right]$$



- Beam deflection causes reflected beam to partially miss the focusing lens.
- Measured curve is narrower than theoretical coupling efficiency

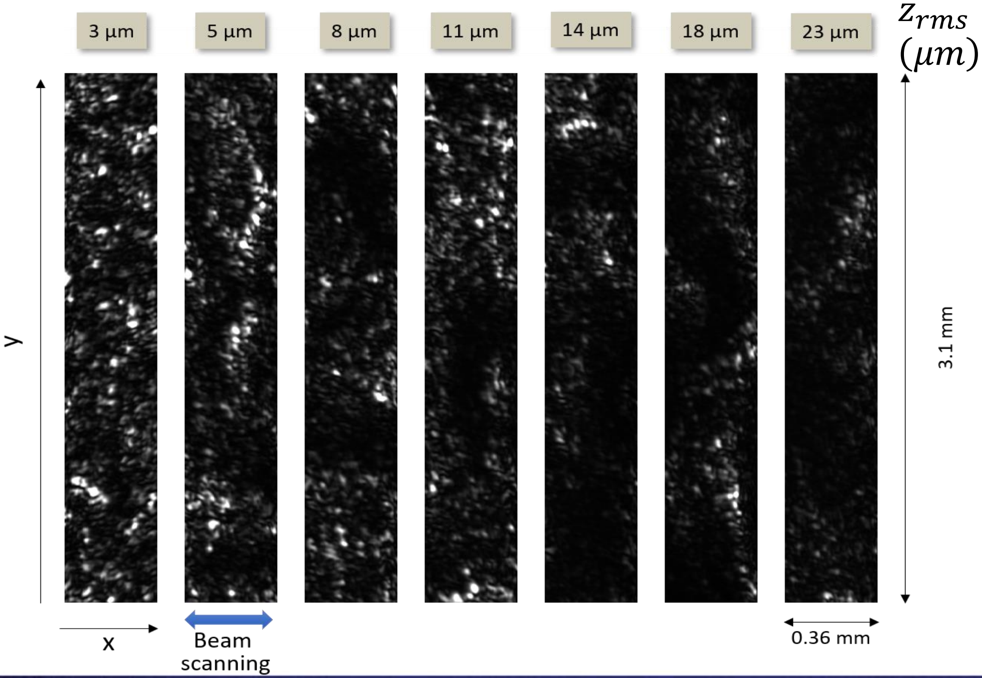
⇒ The confocal imaging system is more sensitive to surface tilts than to defocus

Imaging System Calibration with Microfinish Comparator



- Nine surface areas with different rms surface roughness (provided in microinches on label)
- Calibrated rms surface roughness values in the range of 0.5 μm $\leq Z_{rms} \leq$ 23 μm

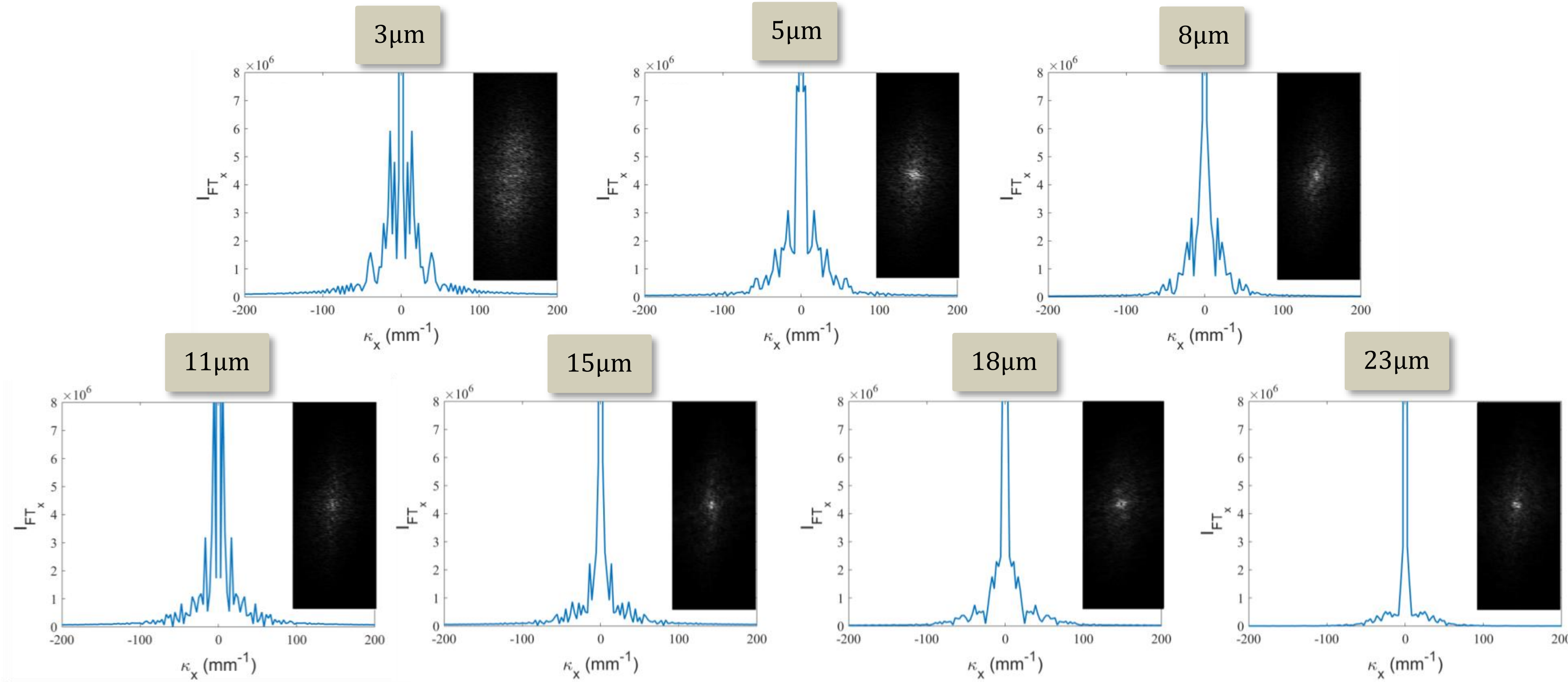
Images recorded with confocal system



- Used $Z_{rms} \geq$ 3 μm (seven areas corresponding to max range of translation stage and mount)
- x: Scanning direction
  y: Target moving direction

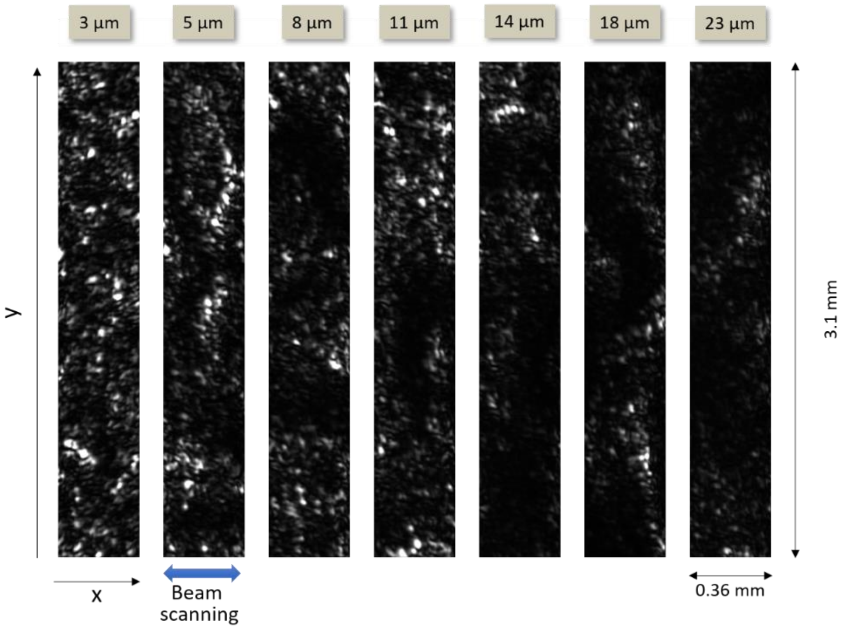
Cross Section of Fourier Spectra of Images Along x Axis

$$I_{FT}(\kappa_x, \kappa_y) = \int\int I(x,y) \cdot e^{-2\pi j(x\kappa_x + y\kappa_y)} dxdy$$

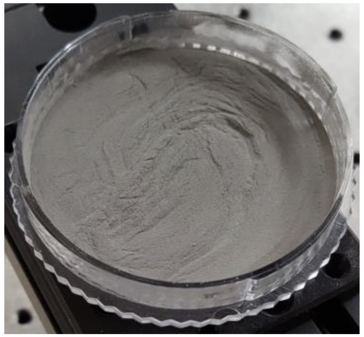


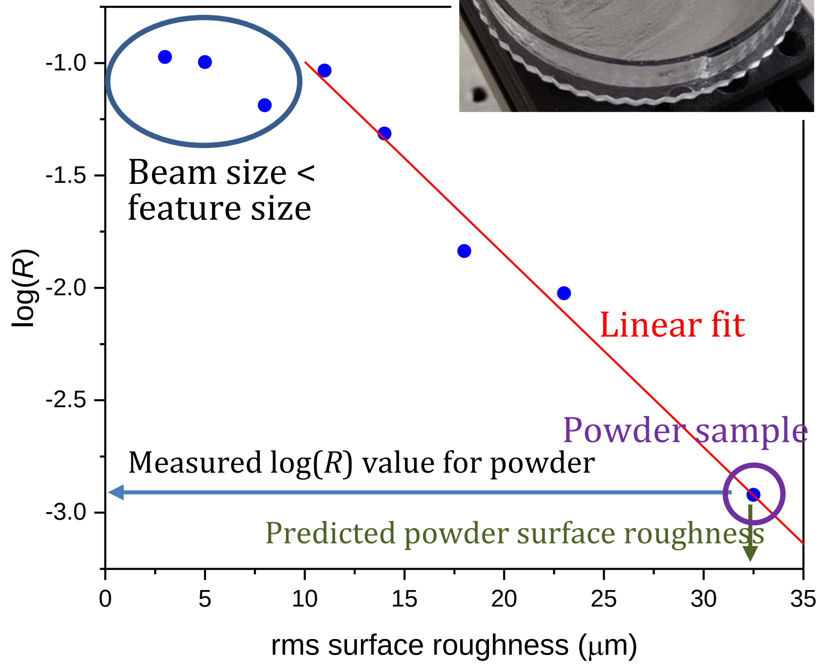
- The rougher surface we have, the narrower peak we get on the cross section of the Fourier spectra
- With rougher surface, the narrower spectrum we get.

Surface Roughness Characterization



Inconel powder sample





Processing of images:

1) Normalized linear image: $I(x,y) = \dfrac{I(x,y) - I_{min}}{I_{max} - I_{min}}$

2) Binary image: $I_B(x,y) = \begin{cases} 1 & \text{if } I(x,y) \geq 0.5 \\ 0 & \text{if } I(x,y) < 0.5 \end{cases}$

3) Fraction, R, of "1s" in binary image: $R = \dfrac{\iint_A I_B(x,y)\,dxdy}{\iint_A dxdy}$

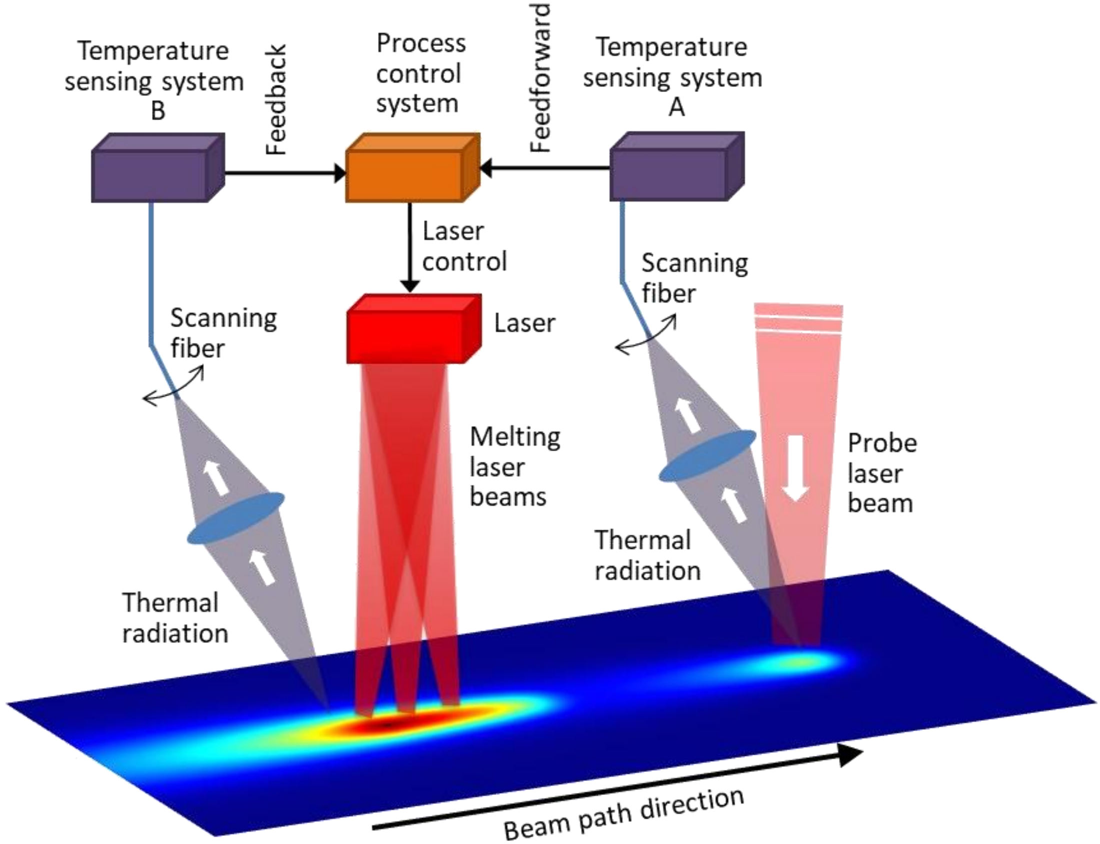
Predicted powder surface roughness matches powder particle sizes between 20 μm and 50 μm

Scanning Fiber Thermal Radiation Measurement System

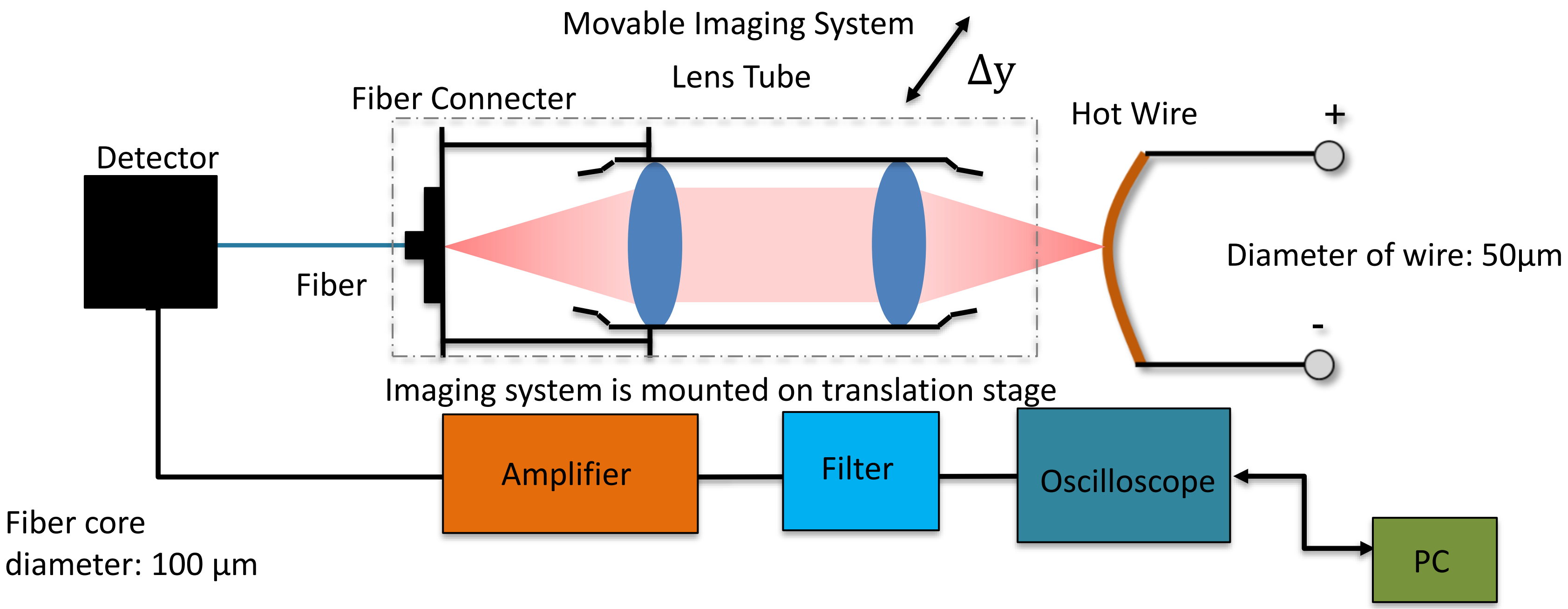
- Determine heating variations at powder bed surface in metal laser additive manufacturing systems using thermal radiation measurements at a pre-heating probe laser beam and/or at the melting laser beam
- Enable feedforward and feedback control of melting laser beam(s) to mitigate impact of local variations of powder characteristics

Concept

- Couple thermal radiation in the wavelength range 2 to 5 μm (emitted by surface spot heated by laser) into infrared fiber
- Measure power coupled into fiber
- Scan fiber across surface to obtain spatially resolved temperature measurements

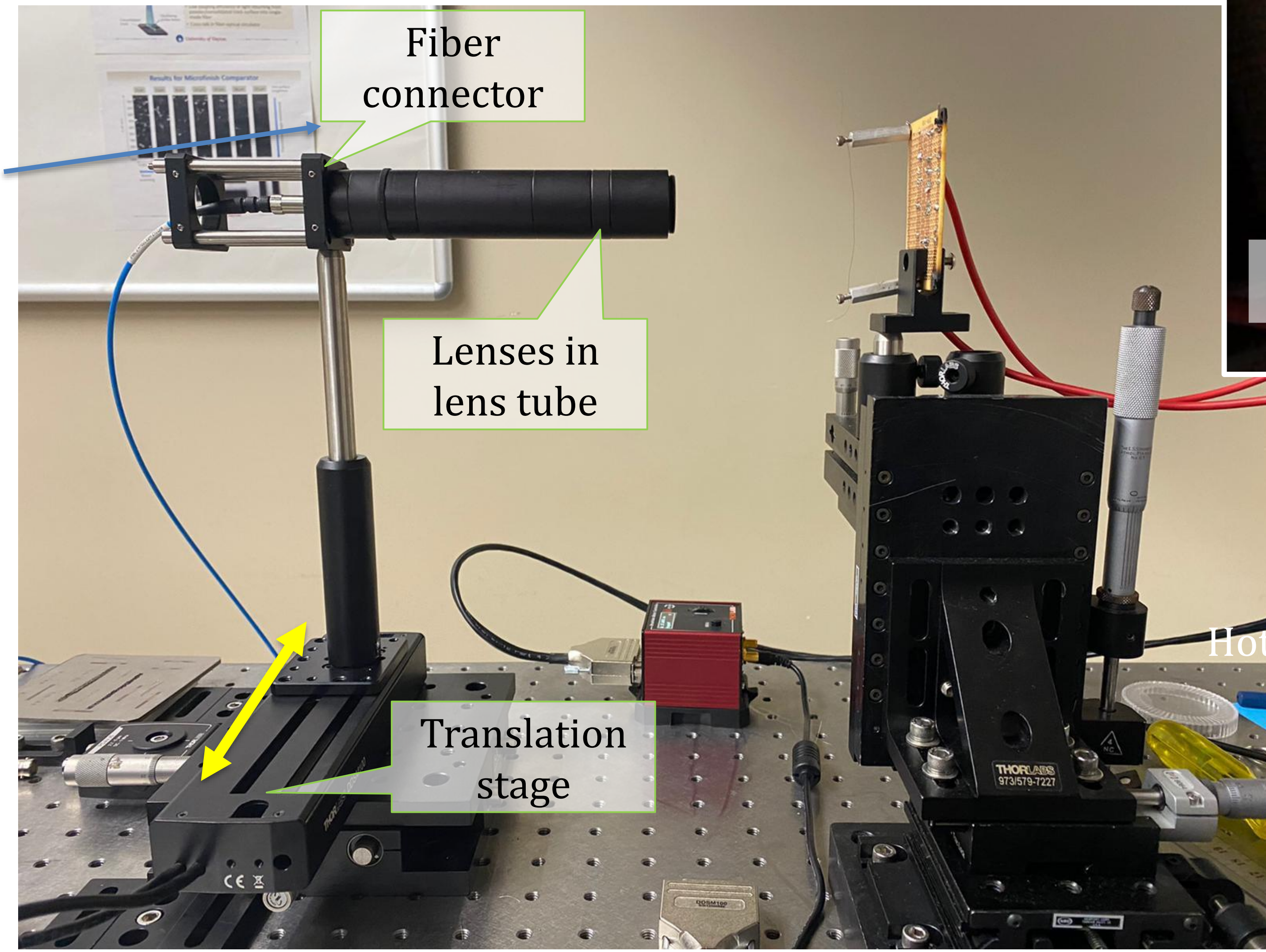


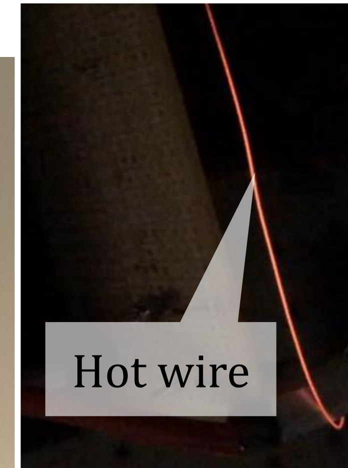
Experimental Setup



- Set up optical imaging system for infrared wavelengths (2 µm to 5 µm)
- Use of a wire with 50 µm diameter as radiation source
- Use infrared fiber to receive thermal radiation and to guide to infrared detector
- No scanning fiber yet; instead lens tube and fiber connector are mounted on fast motorized translation stage
- Scanning in one direction via movement of optical setup relative to radiation source (hot wire)

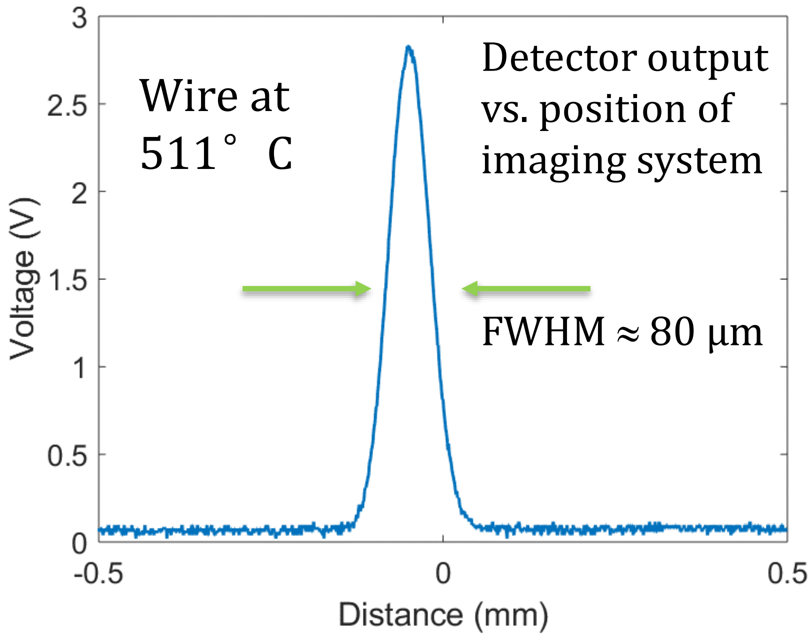
Photo of Experimental Setup





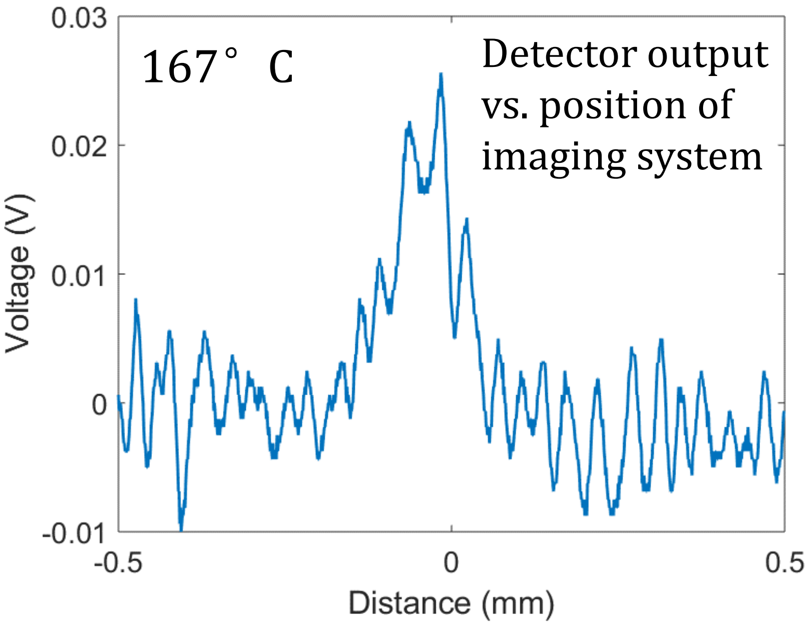
Sample Results

Can we spatially resolve the wire?



- Measured well resolved peak of thermal radiation when scanning across the hot wire
- Full width at half maximum is about 80 µm
- Result is convolution considering 50 µm wire and 100 µm multimode receiver fiber

What is the lowest temperature we can measure with the setup?



- Optimized signal to noise ratio with a combination of low-pass filters before and after signal amplifier
- Signal to noise ratio approached 1 when wire temperature about 167°C
- Well below temperatures of interest for additive manufacturing systems

Conclusion / Future Work

Surface roughness characterization system

- Images obtained with the fiber-scanning confocal imaging system clearly have characteristics that depend on surface roughness
- Further work is needed to characterize surface roughness in-situ (near real-time)

Thermal radiation measurement system

- Demonstrated capability to fiber-couple and measure thermal radiation originating from a small source
- Optimized signal conditioning and assessed low-temperature limit for measurements
- Future work includes:
  - Demonstration of temperature stabilization
  - Built fiber scanner with infrared fiber

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Thank you