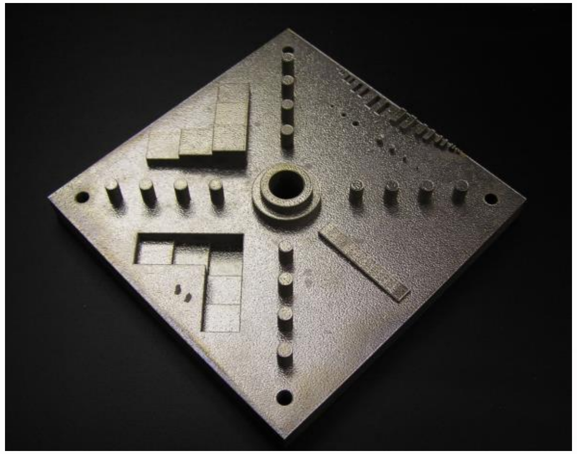
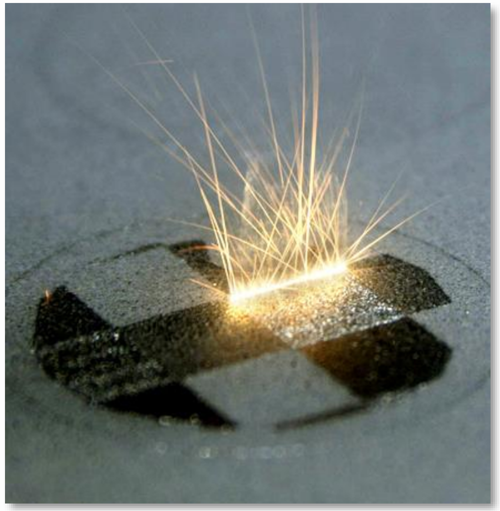
In–situ Process Measurements for Monitoring, Control, and Simulation of AM





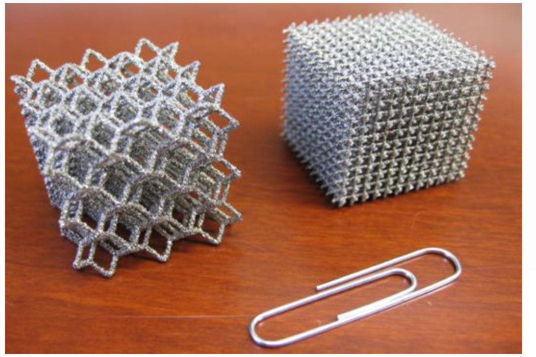
Brandon Lane, Ph.D.

Intelligent Systems Division

Engineering Laboratory

National Institute of Standards and Technology

National Institute of Standards and Technology
U.S. Department of Commerce



Outline

- NIST Measurement Science for AM (MSAM)
- EOS M270 Thermography
- Additive Manufacturing Metrology Testbed
  - Industrially-relevant process monitoring
  - Model-based feed-forward controls
  - Absolute thermometry
  - Other fun measurements!
- Laser Processing Diffraction Testbed (LPDT)
- Dissemination and use of measurements

NIST Measurement Science for Additive Manufacturing (MSAM) Program

- Part of Engineering Laboratory, 7 projects spanning most aspects of metal AM metrology
  - Also AM program in Materials Measurement Laboratory, collaborators throughout NIST, academia, govt., industry.

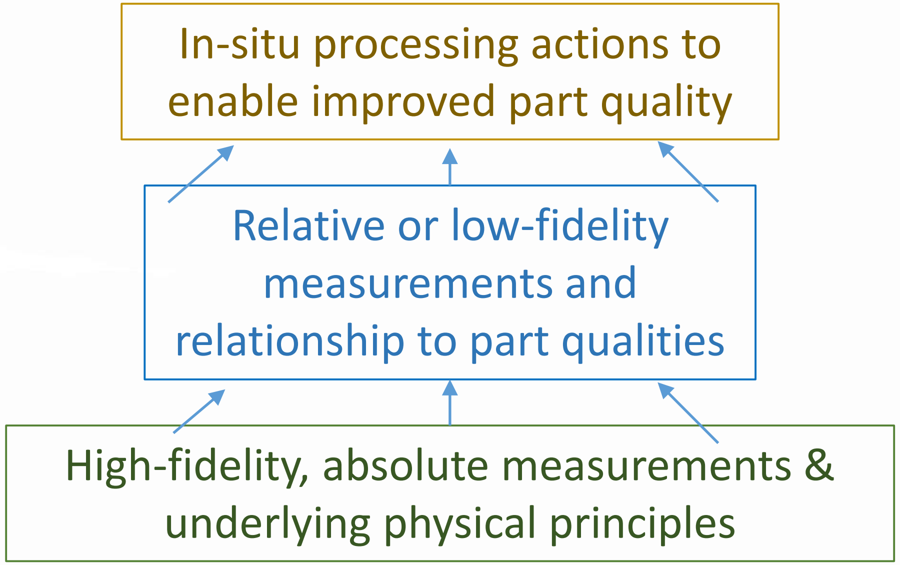
www.nist.gov/additive-manufacturing

- 3 projects discussed today:

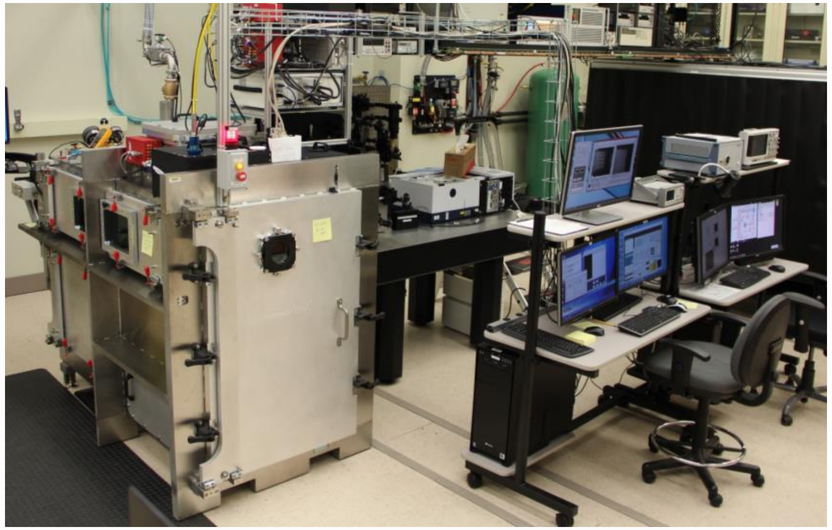
AM Machine and Process Control Methods for AM
PI: Dr. Ho Yeung

Metrology for Real-Time Monitoring of AM
PI: Dr. Brandon Lane

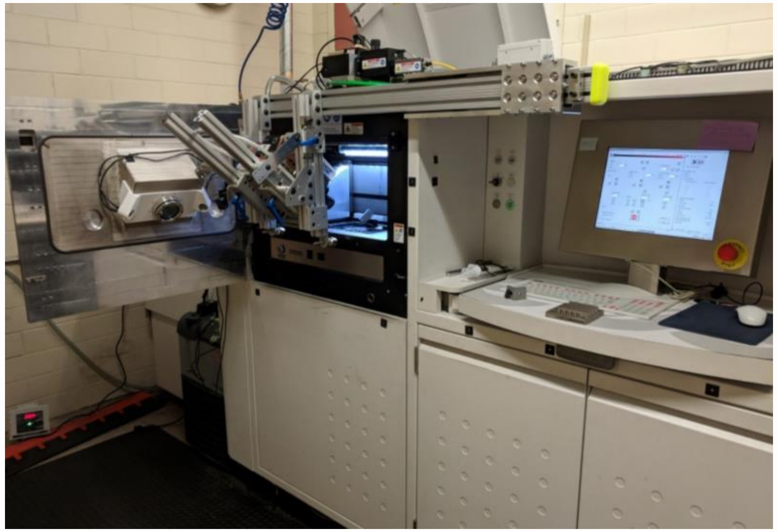
Metrology for Multi-Physics AM Model Validation
PI: Dr. Thien Phan



In-situ AM Metrology Capabilities

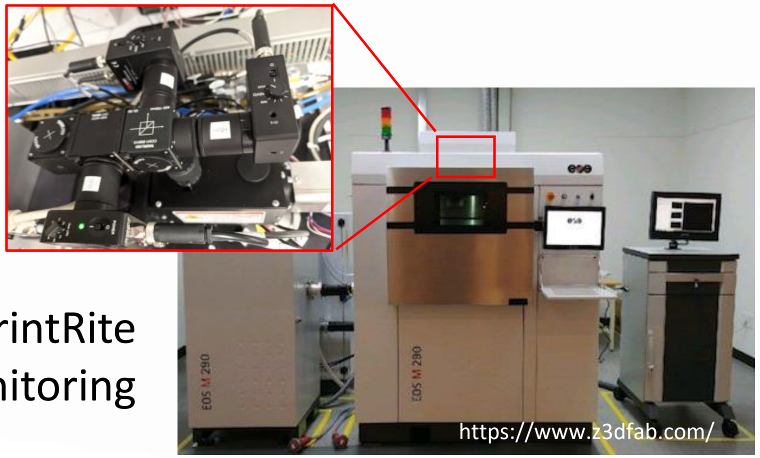


Additive Manufacturing Metrology Testbed (AMMT)
www.nist.gov/el/ammt-temps



EOSM270 LPBF Thermography System
www.nist.gov/el/lpbf-thermography

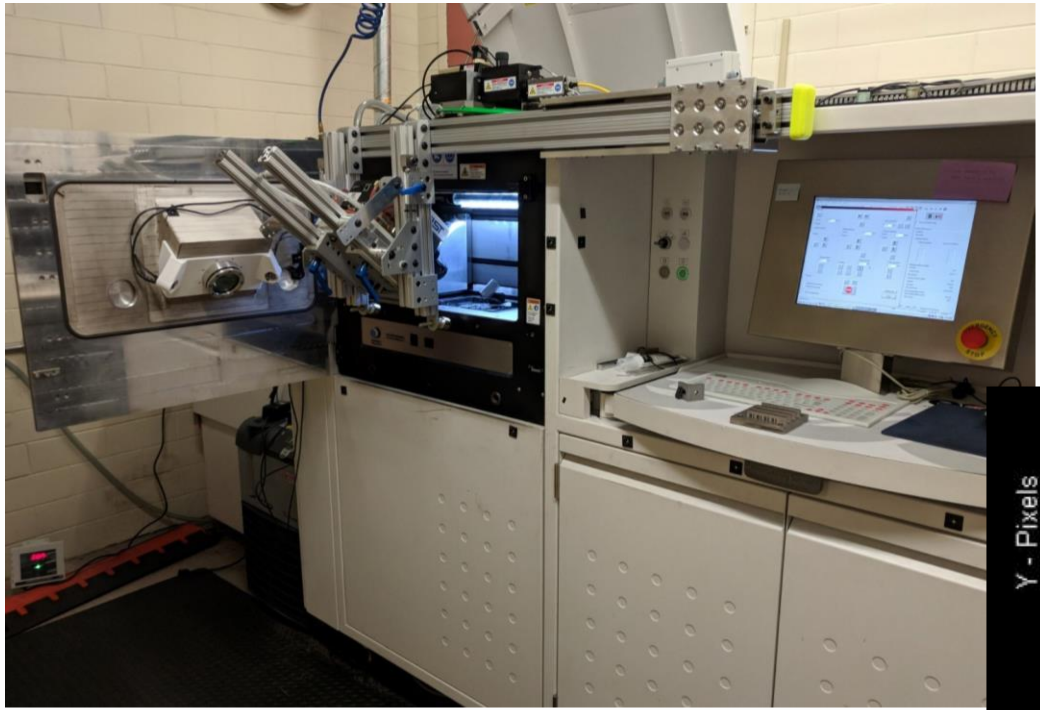
Optomec LENS MR-7 w/ melt pool monitoring (Stratonics)



EOS M290 w/ SigmaLabs PrintRite melt pool monitoring

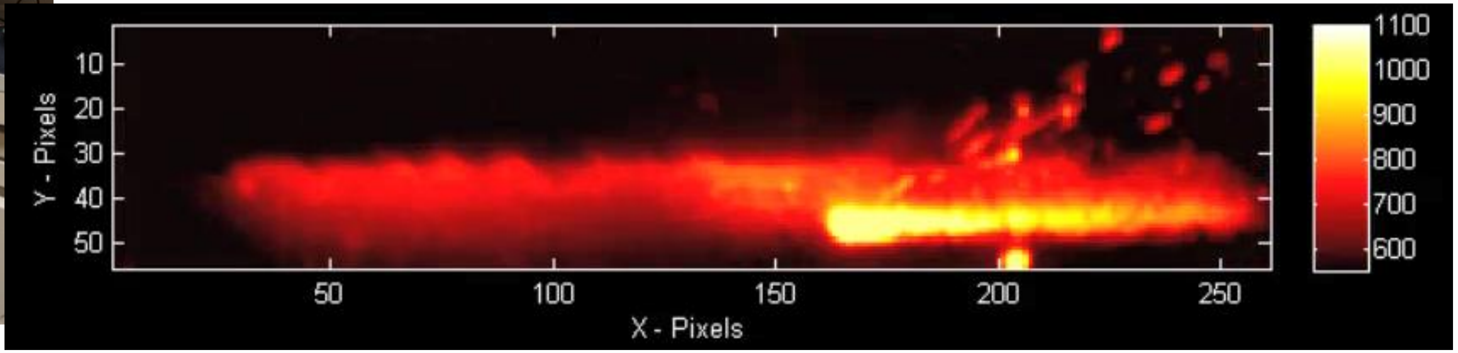
EOS M270 + Thermography System

Part-scale **radiance** temperature and cooling rate measurements during 3D part builds
Rapid testing of different geometries in standard materials



Camera information -> New camera

1800 frames per second	-> 2400+ fps
40 µs integration time (shutter speed)	-> HDR capabilities
360 pixel wide, 128 mm tall field of view	-> 320x256 pixels
44° viewing angle	
Viewable area on baseplate, 12 mm x 6 mm	-> Variable
iFOV – 54 µm x 36 µm	-> min 45x30 µm

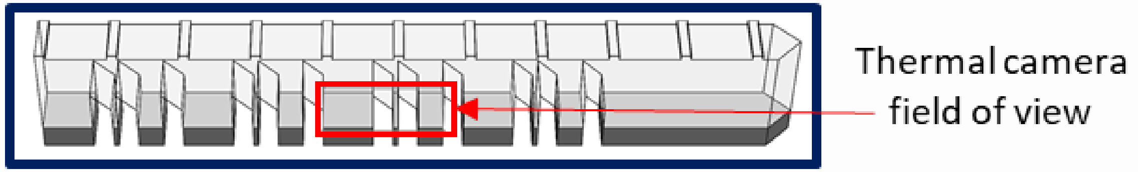


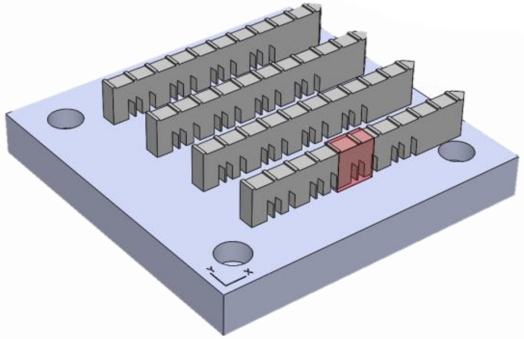
https://www.nist.gov/el/lpbf-thermography

PIs: Jordan Weaver, Brandon Lane

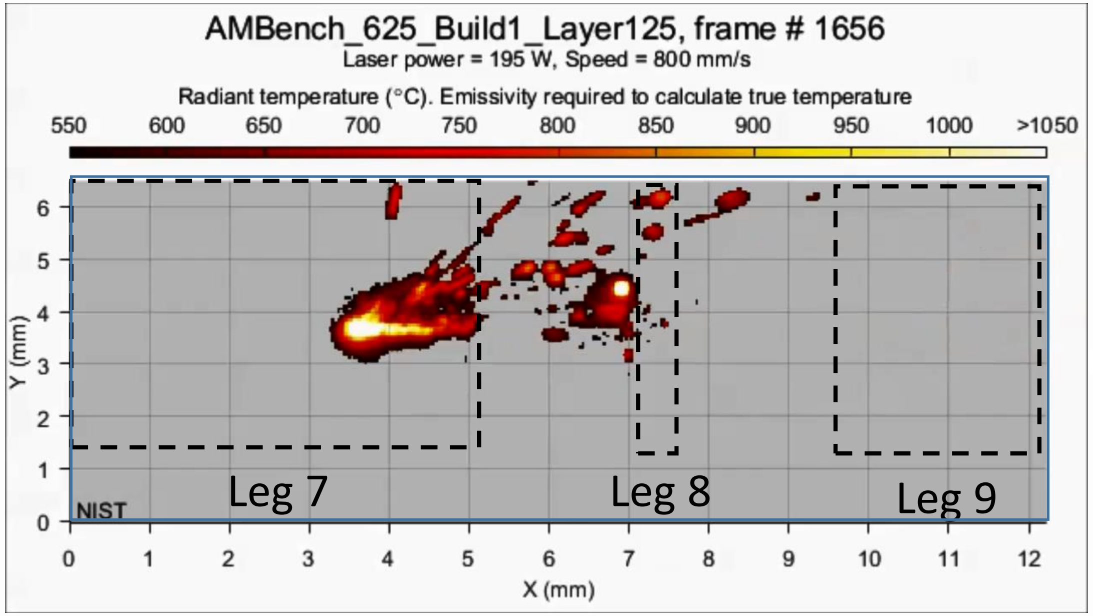
EOS M270 + Thermography System

Mapped MP Length and Cooling rates in 3D build

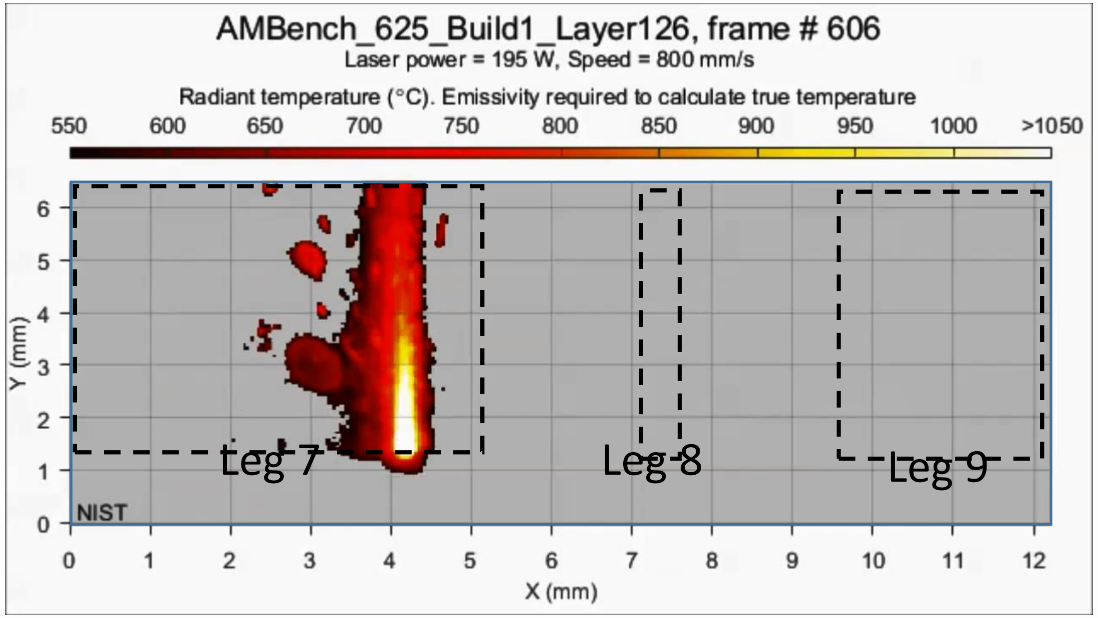




- X-orientation scans
- Odd layer (#125)



- Y-orientation scans
- Even layer (#126)

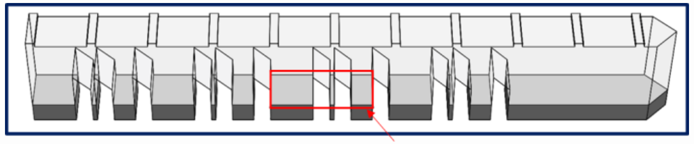


Heigel et al. (2020) *Integrating Materials and Manufacturing Innovation*. https://doi.org/10.1007/s40192-020-00170-8

Data: Heigel et al. (2020) *J. Research NIST*. https://doi.org/10.6028/jres.125.005

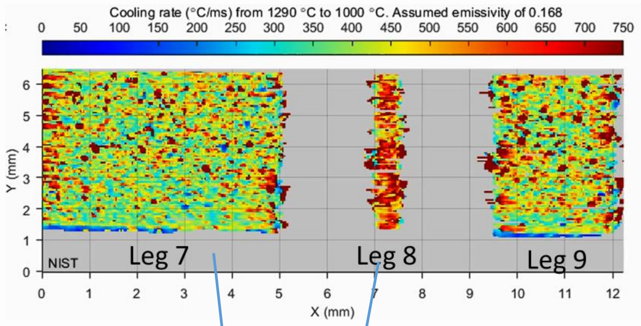
EOS M270 + Thermography System

Mapped MP Length and Cooling rates in 3D build



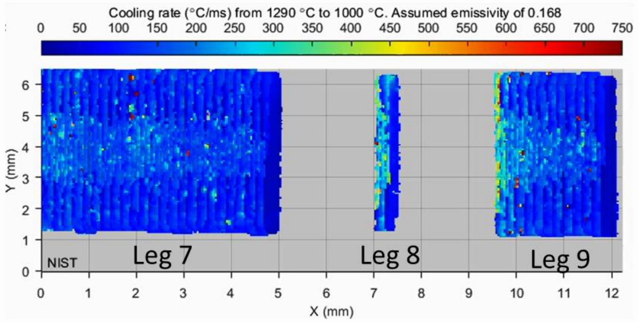
X-orientation scans

Odd layer (#125)

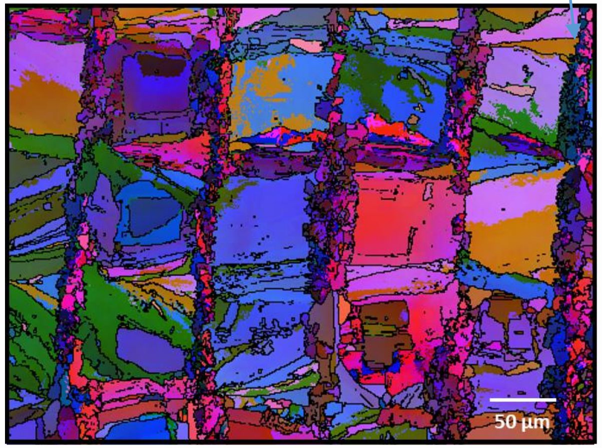


Y-orientation scans

Even layer (#126)

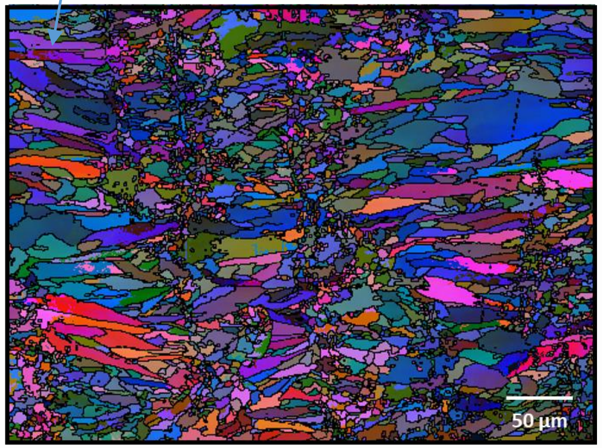


AMB2018-01-625-B2-P1-L4 Thick



Slower Cooling Rate

AMB2018-01-625-B2-P1-L8 Thin

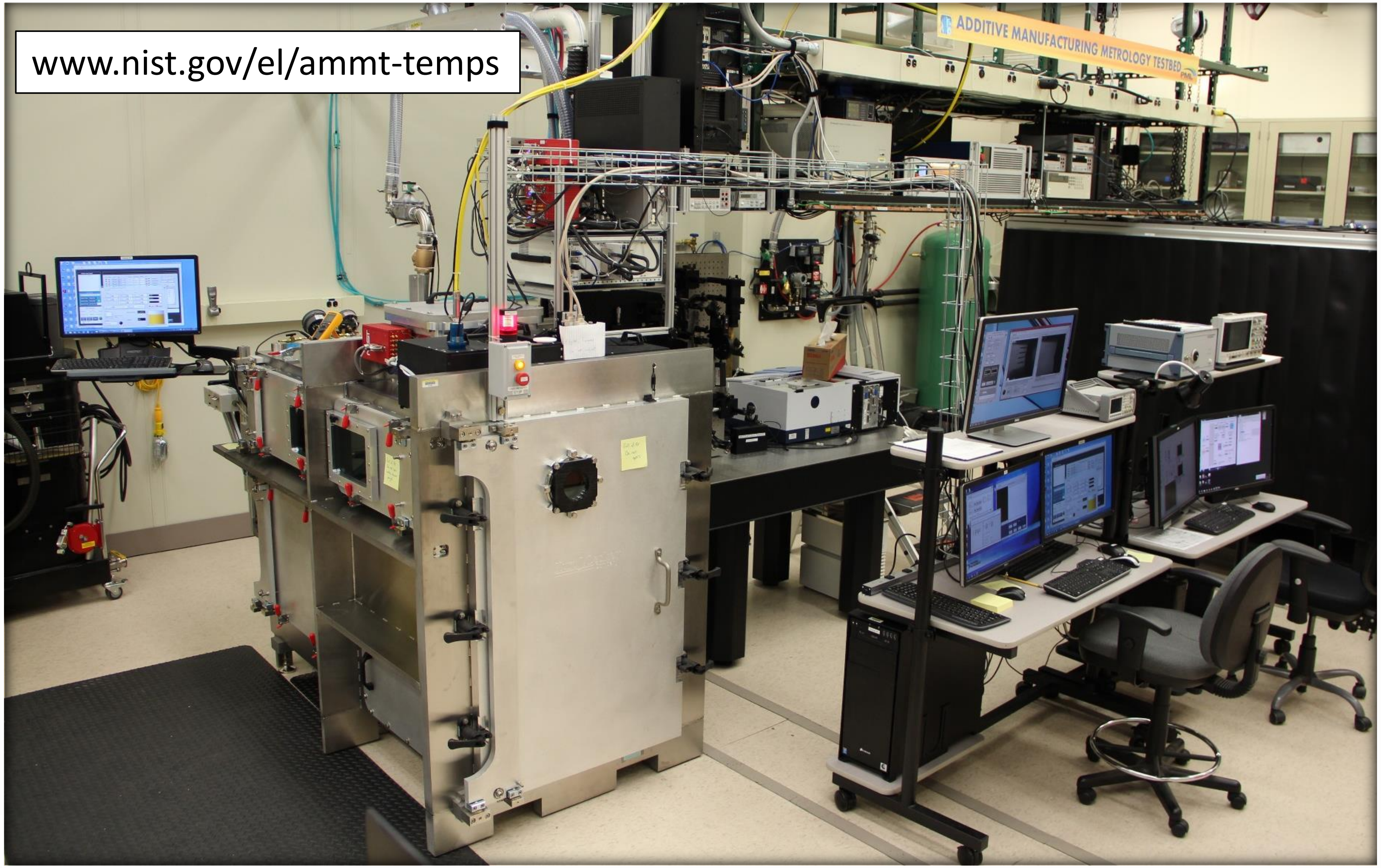


Faster Cooling Rate

EBSD images from
Stoudt et al. (2020) *Integrating Materials and Manufacturing Innovation*. https://doi.org/10.1007/s40192-020-00172-6

All data available at www.nist.gov/ambench/

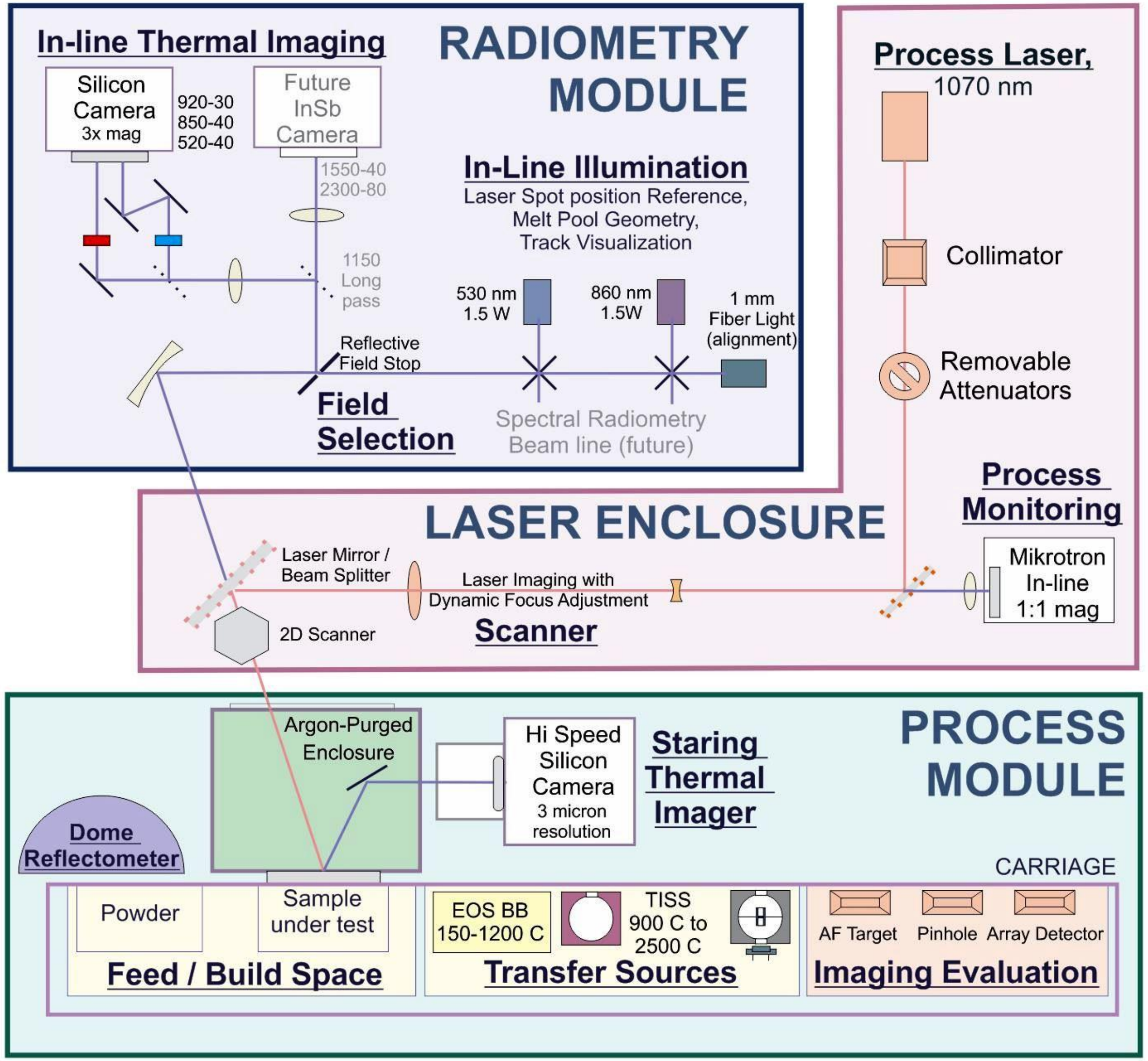
Additive Manufacturing Metrology Testbed (AMMT)



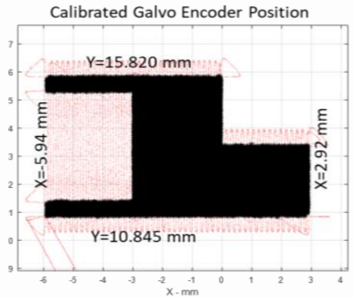
AMMT Guts…

The testbed facility, as shown in the simplified diagram on the right, contains

- Process Chamber – a vacuum enclosure with roll-out carriage, containing Powder Bed Fusion and Optical Metrology equipment, as well as Staring Imager
- Laser Enclosure, including Laser Delivery Optics and In-Line Process Monitoring tools
- Radiometry Module with In-Line Thermal Imaging, Illumination and future Spectral Radiometry instruments
- Control and Support System (not shown), including FPGA-based computer control, and process gas recirculation and conditioning system

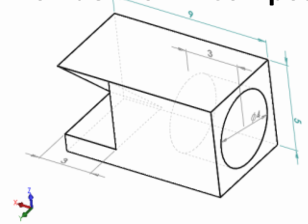


Process Monitoring Data on the AMMT



Part Design + Material data

- CAD Geometry
- Powder PSD + Composition



Digital Command Input

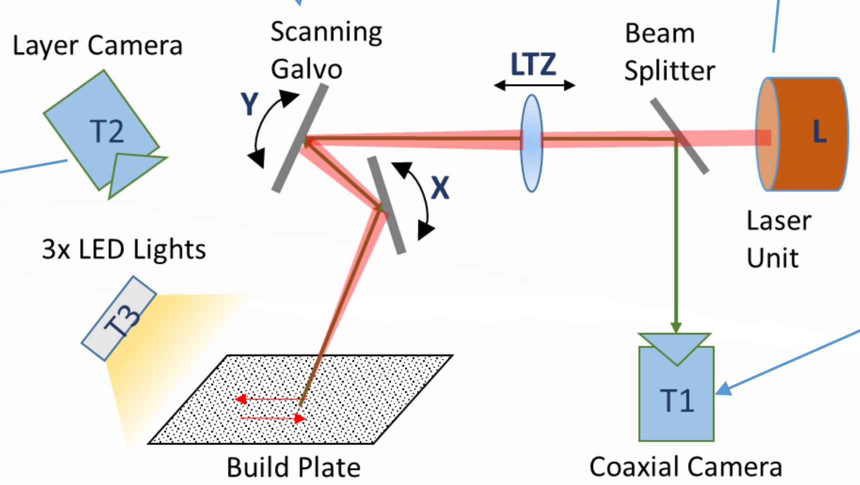
- 100 kHz, synchronous command
- Galvo X,Y position [mm]
- Laser Power [W]
- Trigger (for MPM camera)

Data Acquisition (DAQ)

- 100 kHz Analog encoder/readouts
- Galvo X,Y, LTZ position encoders [mm]
- Laser power monitor [W]

Layer-wise Camera

- GigE, 10.6 MP (windowed)
- ~67 μm/pixel



Co-axial, Melt Pool Monitoring Camera

- ~20000 fps
- 120x120 pixel
- 8 μm/pixel

Ex-situ Characterization

- XCT
- Metallography (planned)

Metadata

- Documented experiment descriptions
- Calibration
- Alignment/registration

www.nist.gov/el/ammt-temps/datasets

Praniewicz (2020) *J. Research NIST (JRES)* https://doi.org/10.6028/jres.125.031

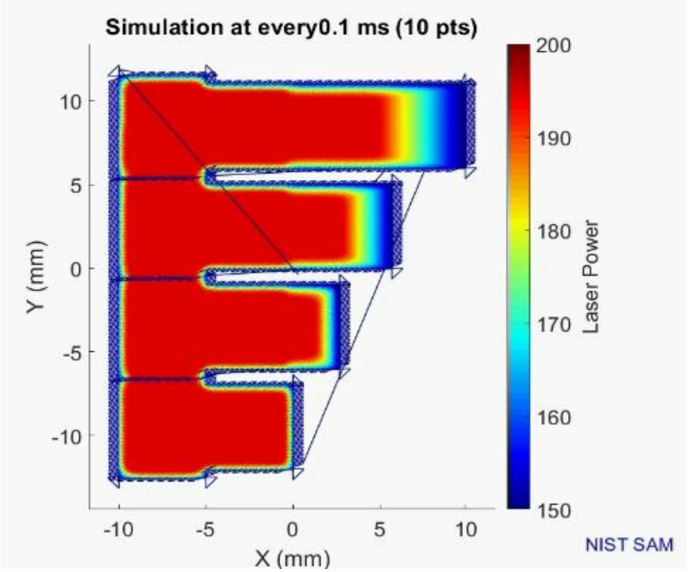
Lane B (2020) *J. Research NIST (JRES)* https://doi.org/10.6028/jres.125.027

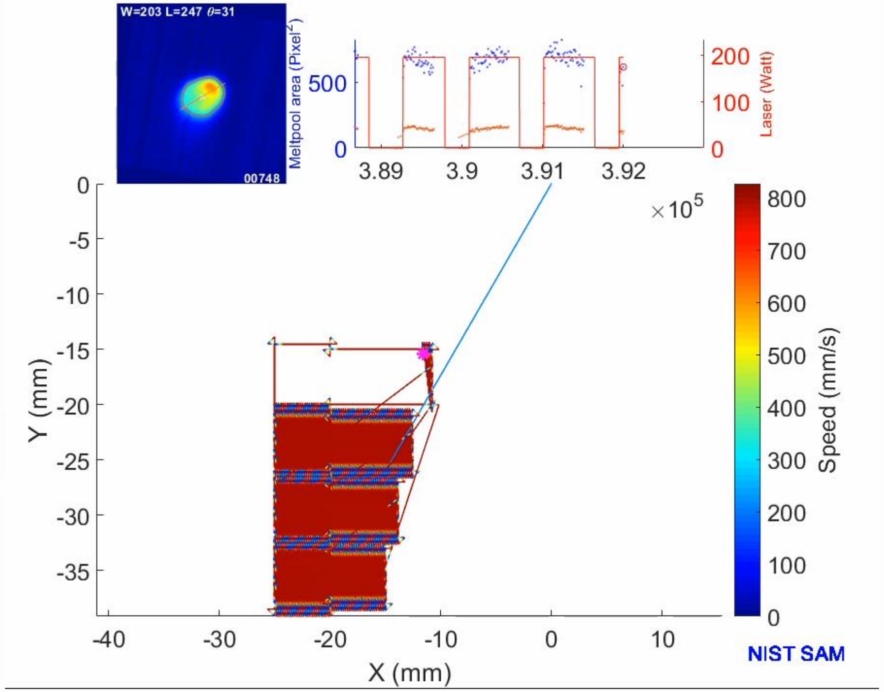
Lane B (2019) *J. Research NIST (JRES)* https://doi.org/10.6028/jres.124.033

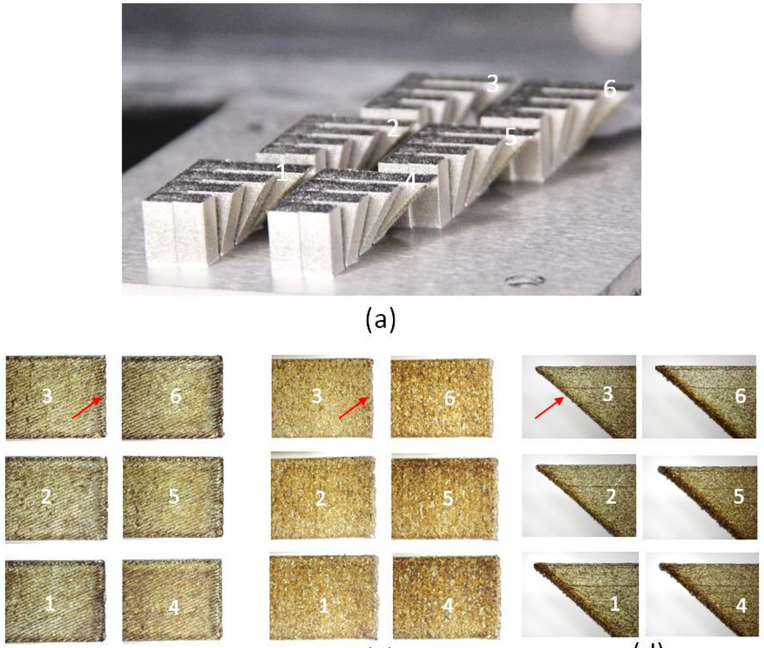
AMMT – Geometry/Thermal Model-based Control

- Geometric Conductivity Factor (GCF) – solid vs. powder in vicinity of melt pool
- Residual Heat Factor (RHF) – time & distance from previous melt pool locations
- Control: Laser power = f[GCF, RHF]

Part 1: No thermal control
Part 3: Highest thermal control







(a) (b) (c) (d)

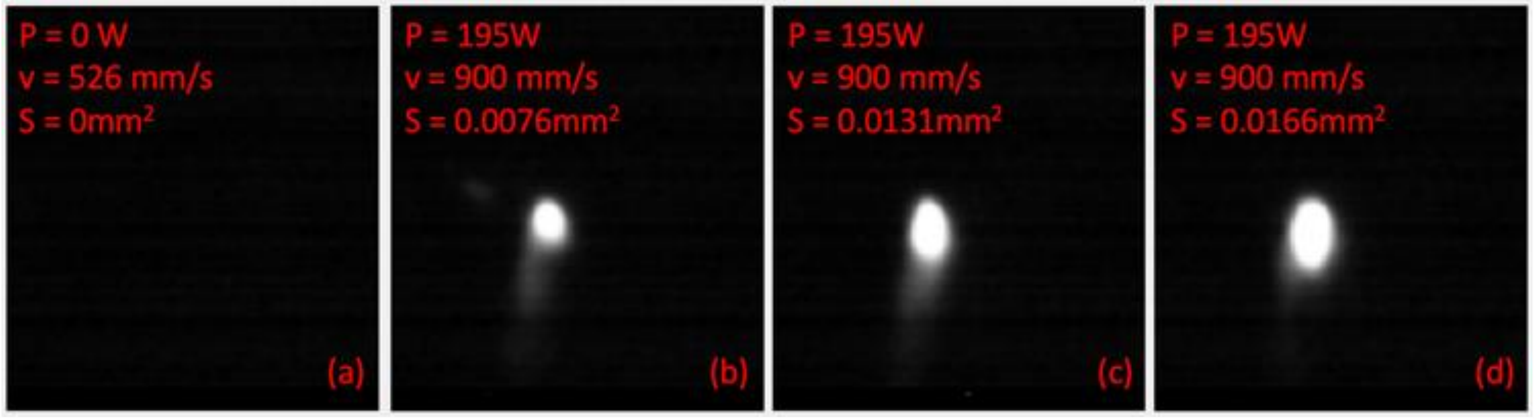
RHF: Yeung H et al. (2020) *Manufacturing Letters* https://doi.org/10.1016/j.mfglet.2020.07.005
GCF: Yeung et al. (2019) *Additive Manufacturing* https://doi.org/10.1016/j.addma.2019.100844

Example Use: Machine Learning-based Control

AMMT scan strategy digital command

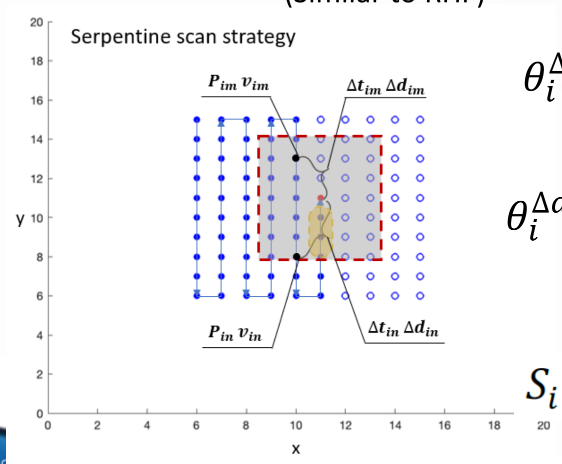
49338	−42.8690	23.5730	195	0
49339	−42.8620	23.5690	195	0
49340	−42.8550	23.5650	195	0
49341	−42.8480	23.5620	195	0
49342	−42.8410	23.5580	195	0
49343	−42.8340	23.5540	195	0
49344	−42.8270	23.5500	195	0
49345	−42.8200	23.5460	195	0
49346	−42.8130	23.5420	195	2
49347	−42.8060	23.5380	195	0
49348	−42.7990	23.5340	195	0
49349	−42.7920	23.5300	195	0
49350	−42.7850	23.5270	195	0
49351	−42.7780	23.5230	195	0
49352	−42.7710	23.5190	195	0
49353	−42.7640	23.5150	195	0
49354	−42.7570	23.5110	195	0
49355	−42.7500	23.5070	195	0
49356	−42.7430	23.5030	195	0
49357	−42.7360	23.4990	195	0
49358	−42.7290	23.4960	195	0
49359	−42.7220	23.4920	195	0
49360	−42.7150	23.4880	195	0
49361	−42.7080	23.4840	195	0

Execute on AMMT, measure MP image features (area)



Neighboring-effect model (NBEM)

(Similar to RHF)

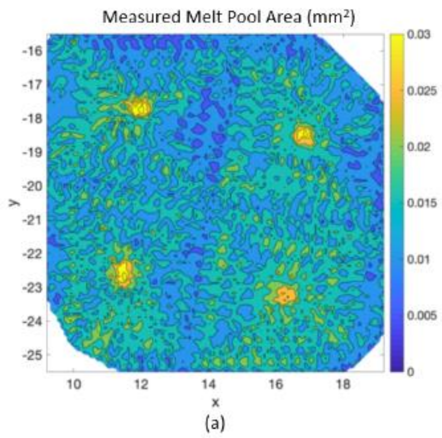


$$\theta_i^{\Delta t} = \sum_{j=1}^{n} f_{\Delta t}(\Delta t_{ij}) \frac{P_{ij}}{v_{ij}}$$

$$\theta_i^{\Delta d} = \sum_{j=1}^{n} f_{\Delta d}(\Delta d_{ij}) \frac{P_{ij}}{v_{ij}}$$

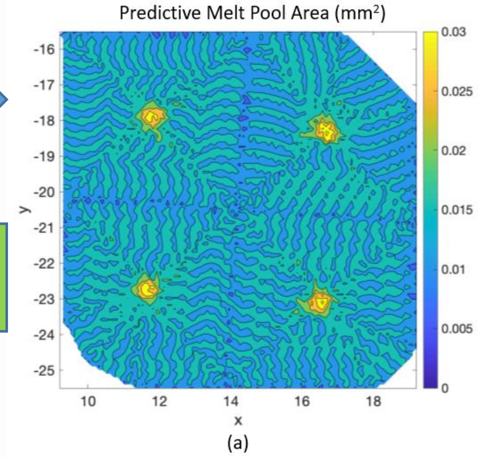
$$S_i = f(P_i, v_i, \theta_i^{\Delta t}, \theta_i^{\Delta d})$$

Build data-driven model, predicting MP image area as function of scan strategy



Now: Predict MP Area based on path

Future: Optimized path based on target MP area



Papers: Yeung et al (2020) *Additive Manufacturing* https://doi.org/10.1016/j.addma.2020.101383[2]
Yang et al. (2020 *J. Comp. Inf. Sci. Eng.* https://doi.org/10.1115/1.4046335
Dataset: Lane B (2019) https://doi.org/10.6028/jres.124.033

AMMT – Radiance Temperature Calibration

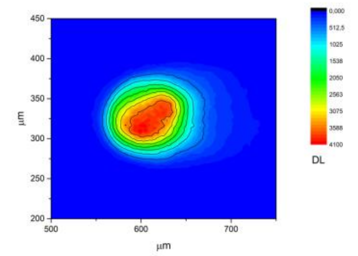
Example: 850 nm, 1000-1880 °C

Primary Standards → **TSP 900** → **Thermogauge HTBB** → **TSP 850 Pyrometer** → **TISS 850 Source (850 nm LED)** → **Imaging system** → **Melt Pool Source**

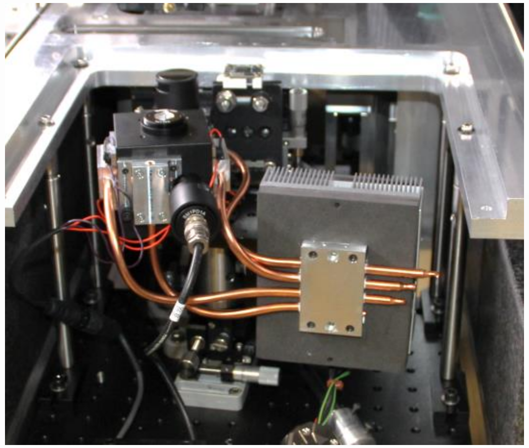
$T_{bb}(V)$

$T_{TSP}(A_{LED})$ & $V(T_{rad})$

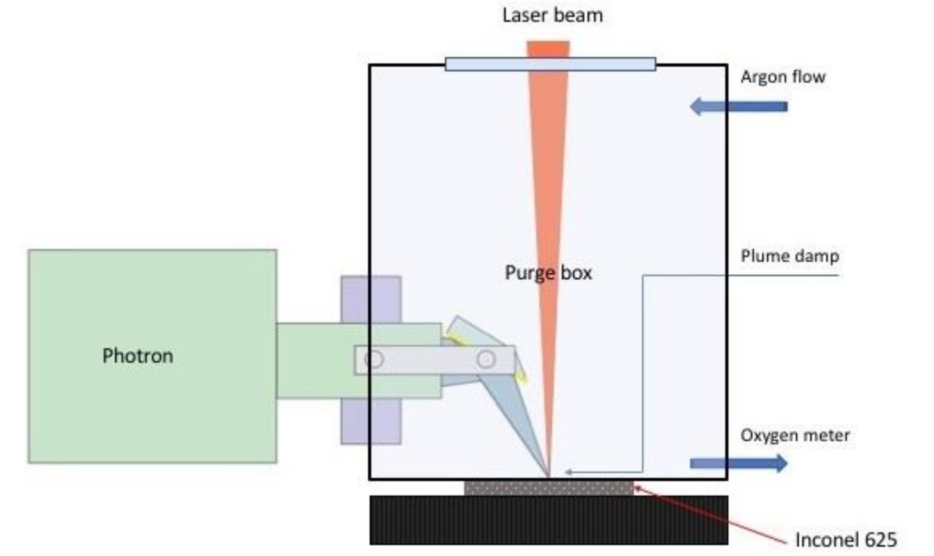
$T_{rad}(DL)$ (1000-1880°C)



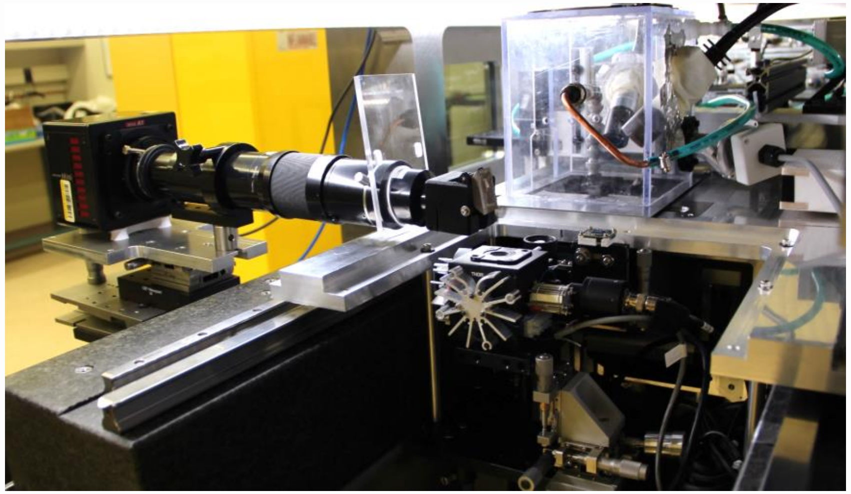
Melt Pool Source



Custom designed TISS 850 LED-driven source for in-situ calibration

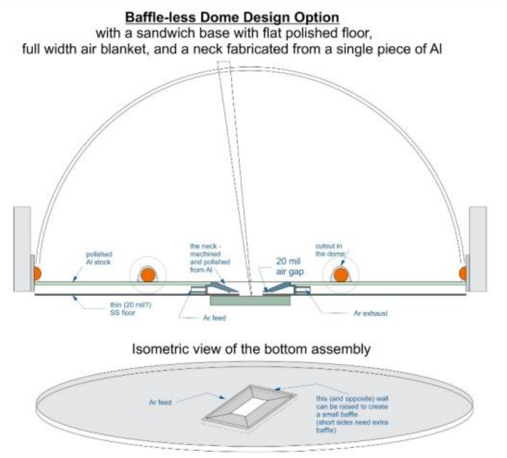


Staring Imager in a measurement configuration, with a high magnification lens and folding mirror

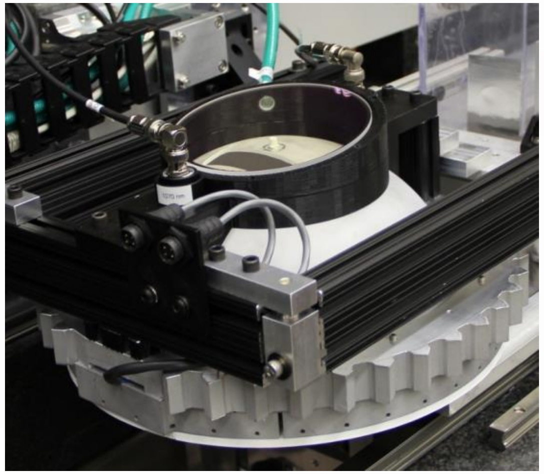


Staring Imager in calibration position (outside of the purge enclosure)

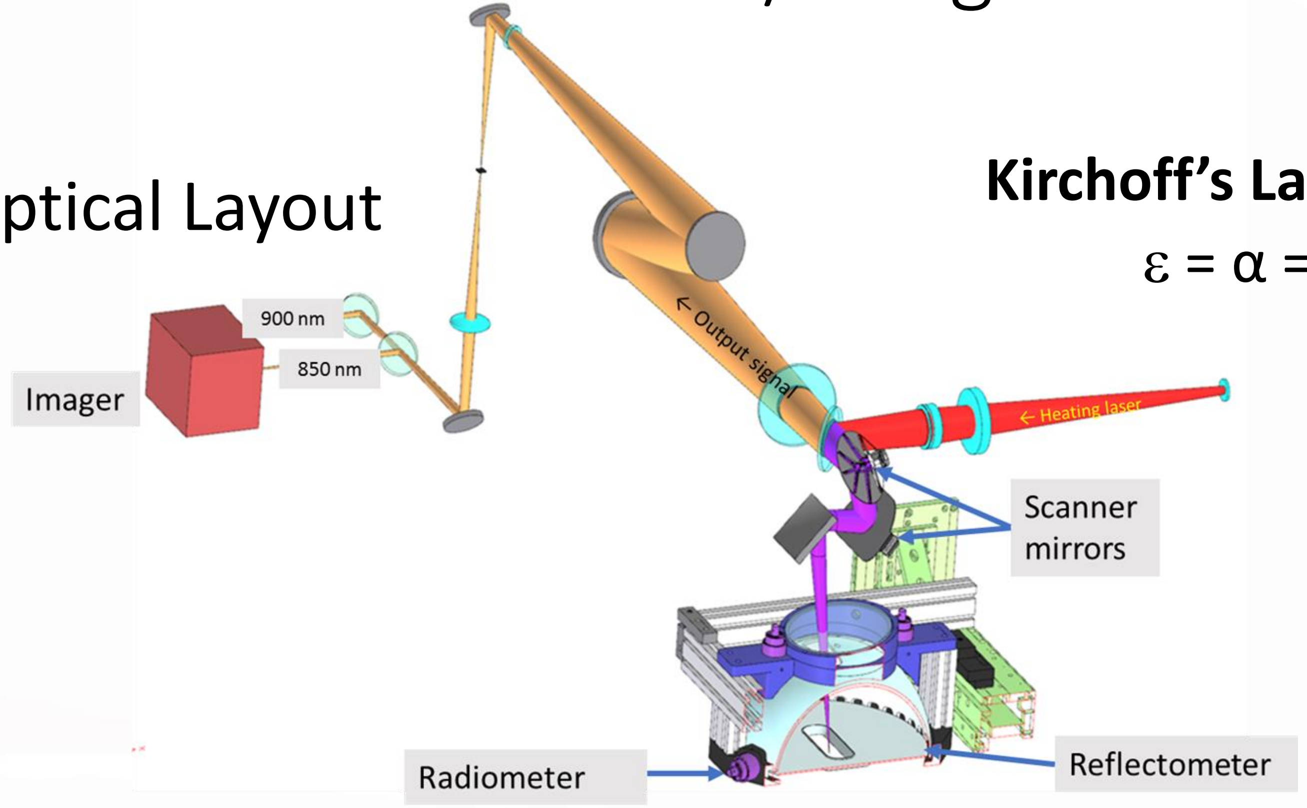
AMMT – Hemispherical Reflectometer/Integrator



Dome Reflectometer Design



Optical Layout



Kirchoff's Law

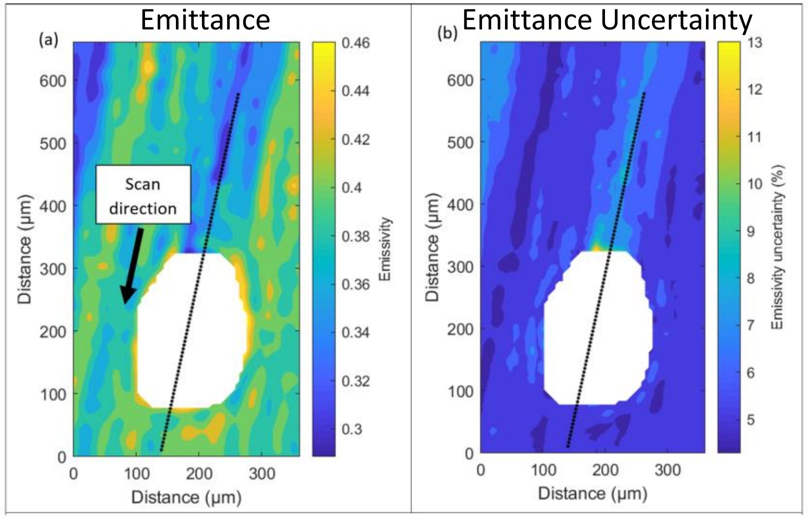
$$\varepsilon = \alpha = 1-\rho$$

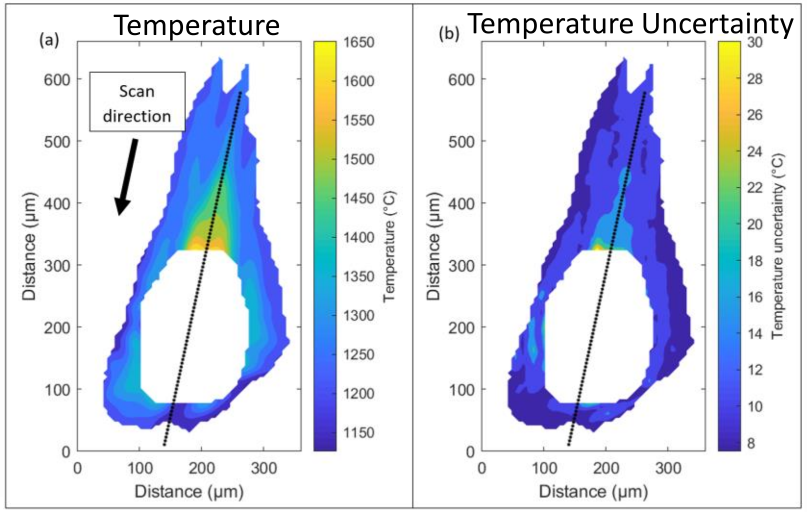
- Designed to provide uniform hemispherical illumination in the sample position
- Hemispherical-Directional Reflectance Factor (HDRF) -> surface emittance

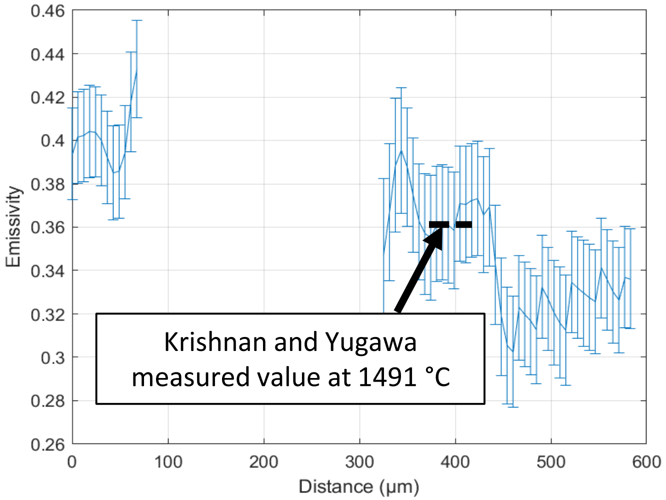
Deisenroth et al. (2020). *Reflection, Scattering, and Diffraction from Surfaces VII* (SPIE) https://doi.org/10.1117/12.2568179
Deisenroth et al. (2021) "Measurement Uncertainty of Thermodynamic Surface Temperature Distributions for Laser Powder Bed Fusion Processes," *J. Research NIST* (in review, expect early 2021 www.nist.gov/people/david-deisenroth)

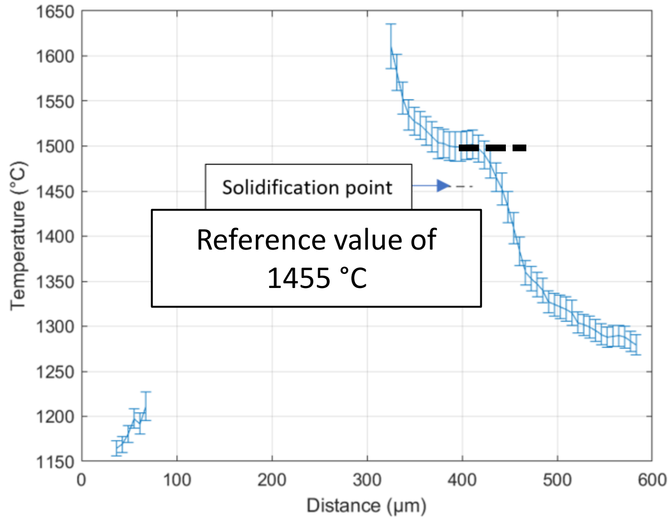
AMMT – Emittance/Reflectance & True T

Example on high-purity 99.998% Ni, measured at 850 nm







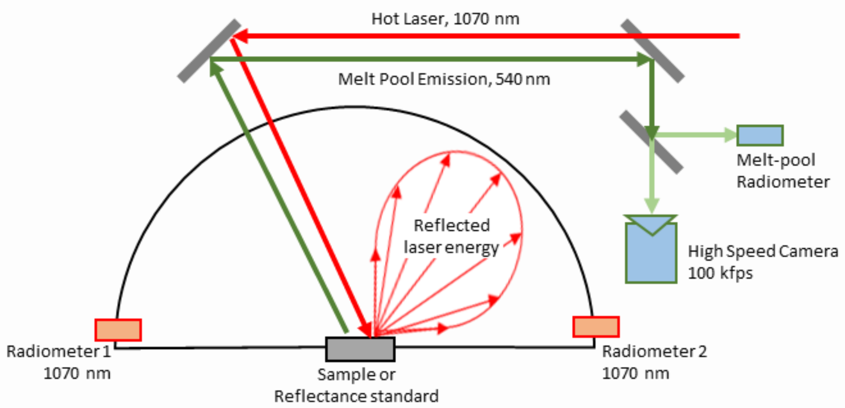


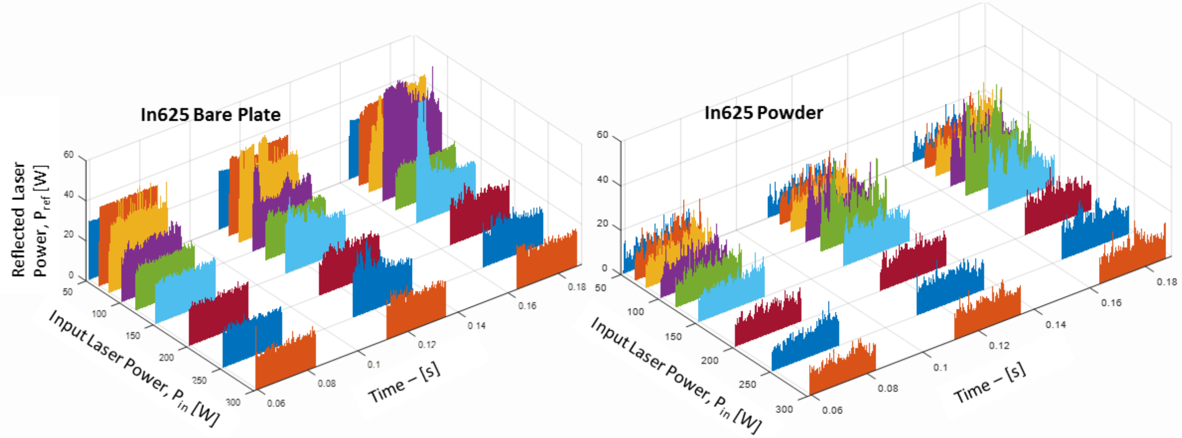
Reference values:
Krishnan, S., Yugawa, K. J. and Nordine, P. C., "Optical properties of liquid nickel and iron," Phys. Rev. B 55(13), 8201–8206 (1997).

NIST Publications:

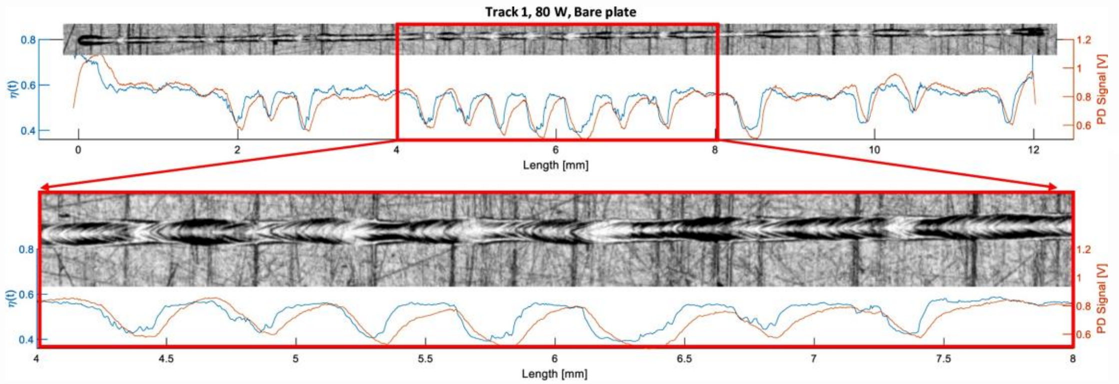
- Deisenroth et al. (2020). *SPIE* https://doi.org/10.1117/12.2568179
- Deisenroth et al. (2021) "Measurement Uncertainty of Thermodynamic Surface Temperature Distributions for Laser Powder Bed Fusion Processes," *J. Research NIST* (in review, expect early 2021 www.nist.gov/people/david-deisenroth)

AMMT – Dynamic laser absorption + energy balance

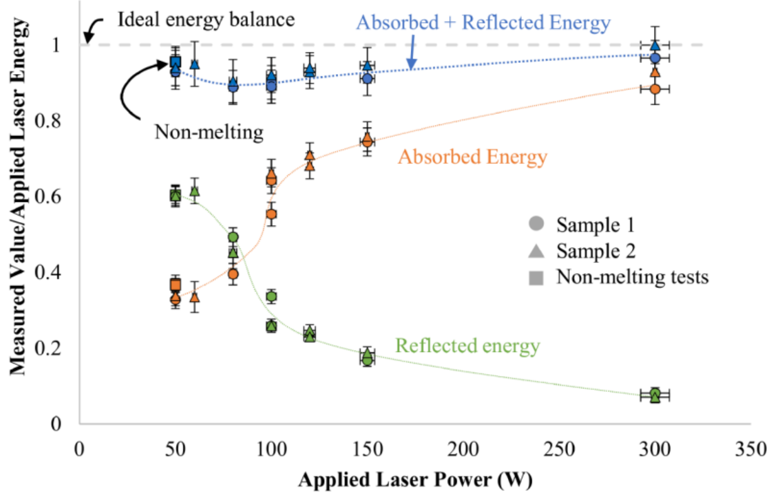




Dynamic laser coupling + melt pool emission + melt pool morphology



Time-integrated reflected + absorbed energy (calorimetry)

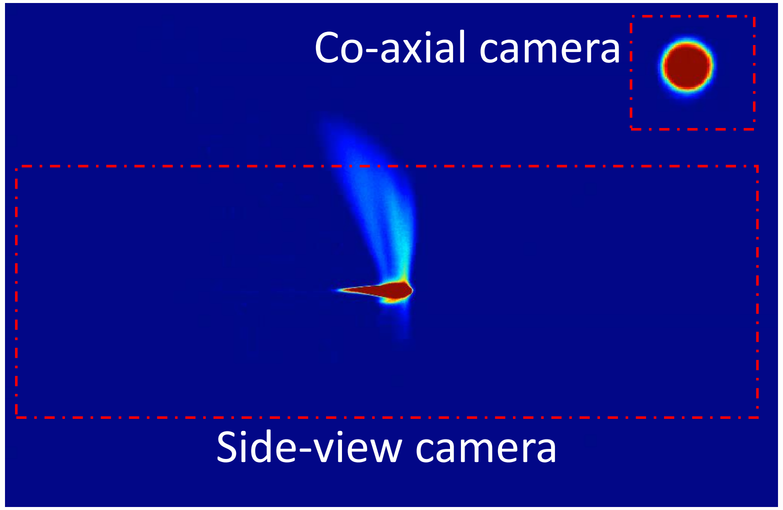


Lane et al. (2020) *Additive Manufacturing* https://doi.org/10.1016/j.addma.2020.101504
Deisenroth et al. (2020) *Proceedings of SPIE* https://doi.org/10.1117/12.2547491
Also see NIST Boulder: PI Brian Simonds, Ph.D.
Allen et al. (2020) *Physical Review Applied* https://doi.org/10.1103/PhysRevApplied.13.064070

AMMT – Plume investigation

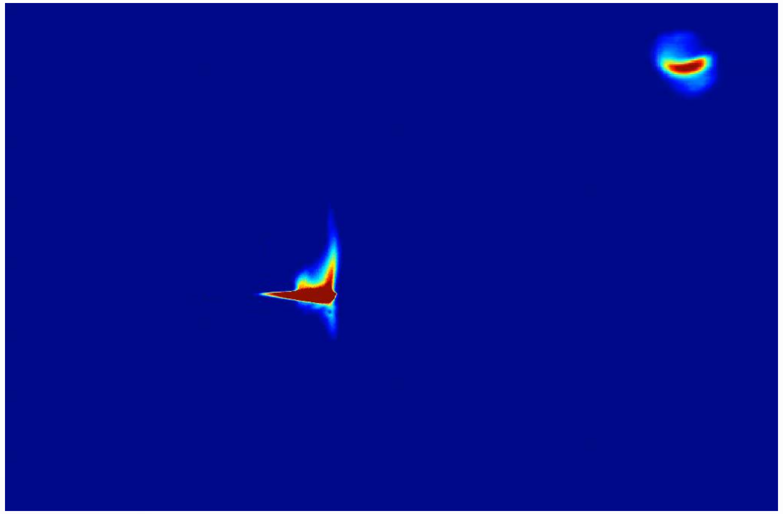
- Synchronous Co-axial + Staring imager for plume investigation
- Coaxial @ 10 K Hz, 95 us / SideView @10 K Hz, 98 us

With Ar blow

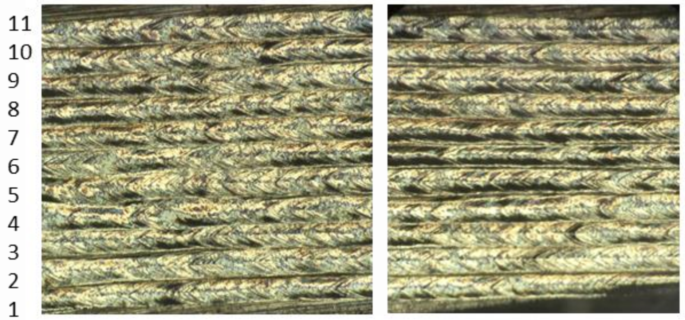


20190515_plume_In625_ArBl_10k_98us_16bits_Gamma1pt3_exp22.mp4

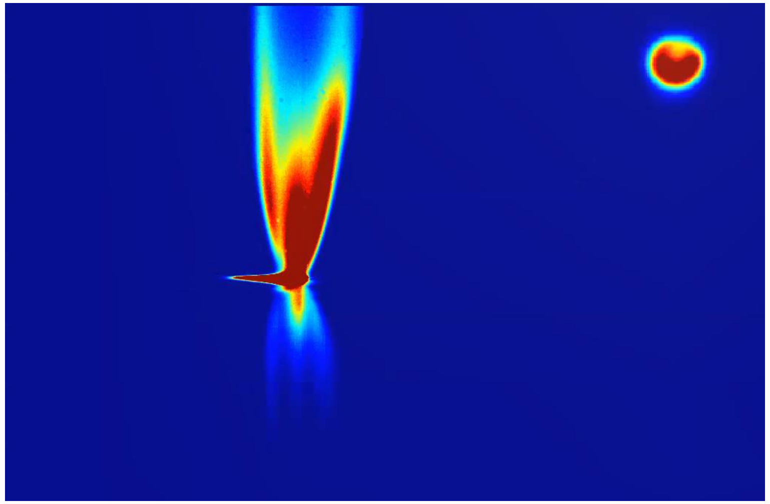
Without Ar blow



20190515_plume_In625_ArFl_10k_98us_16bits_Gamma1pt3_exp23_2.mp4



Without Ar (i.e. in oxygen)



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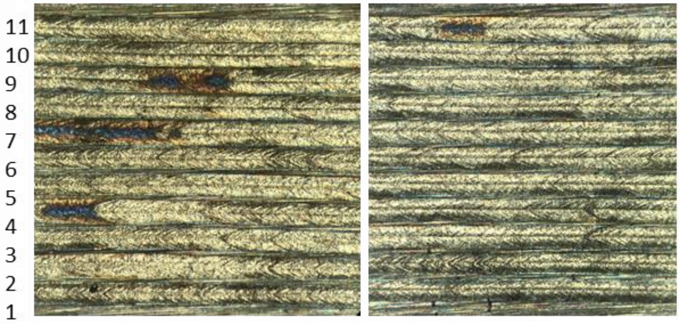
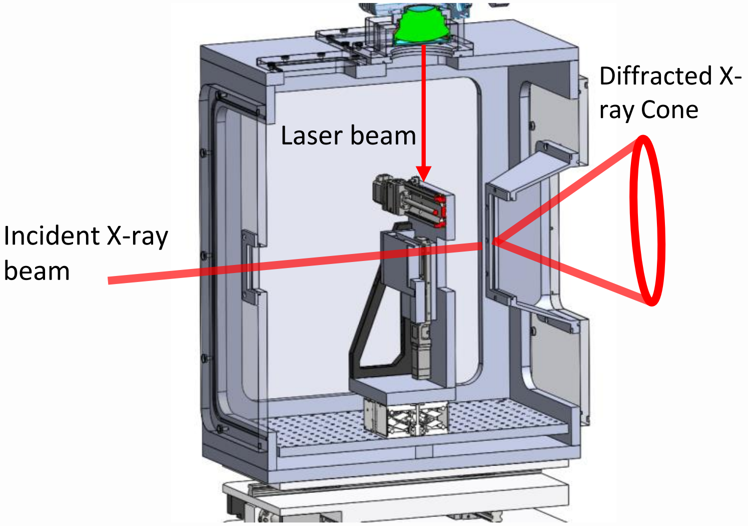
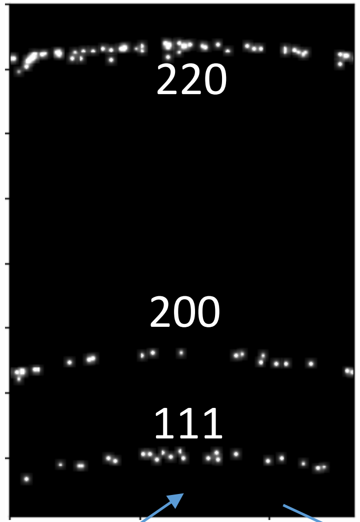
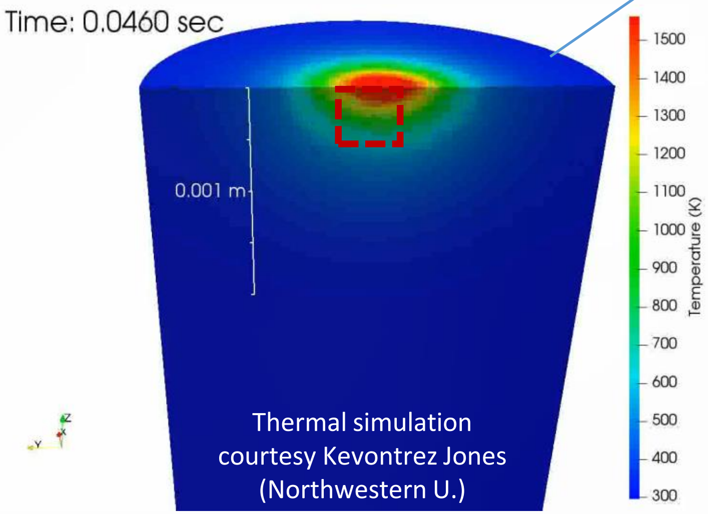


Deisenroth et al. (2020) *Proc. MSEC 2020*
(copy available from authors)

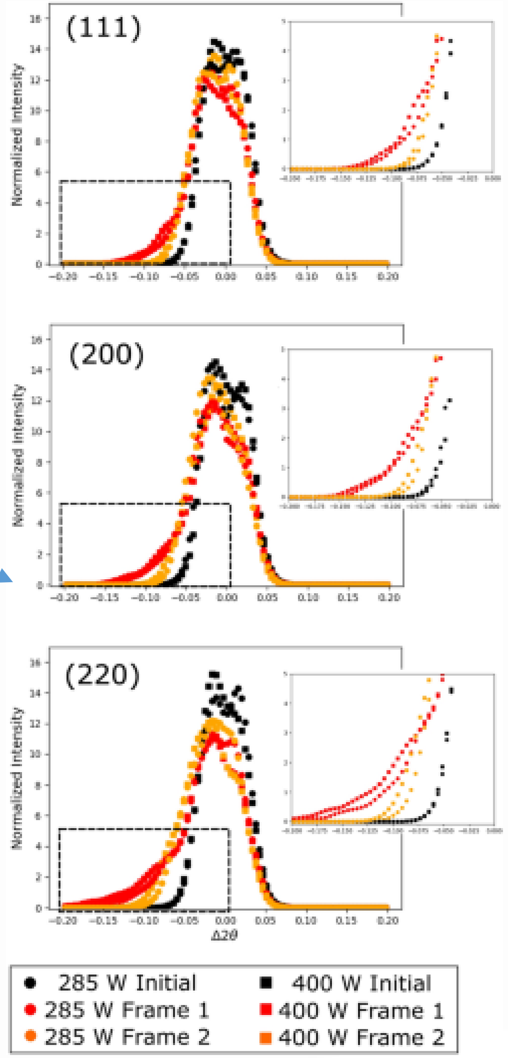
Laser Processing and Diffraction Testbed (LPDT)







Simulated measurement



Cornell University
Cornell High Energy Synchrotron Source

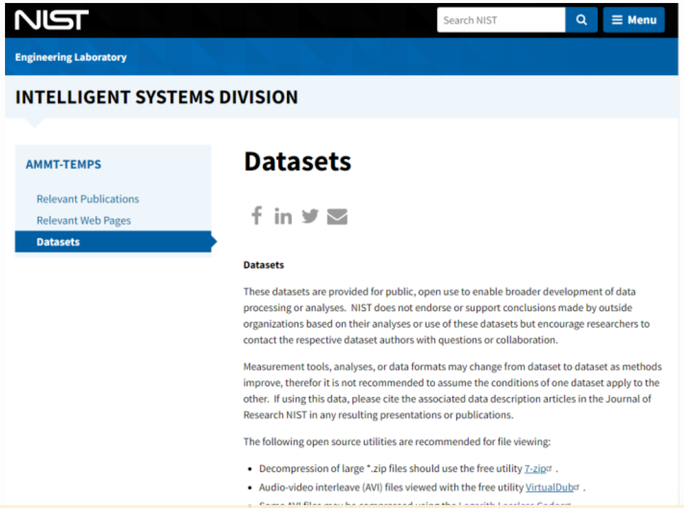
PIs: Thien Phan, Ph.D. (NIST EL)
Darran Pagan, Ph.D. (Cornell-CHESS/Penn. State)

Pagan et al. (2020) A Finite Energy Bandwidth-Based Diffraction Simulation Framework for Thermal Processing Applications. *JOM*. https://doi.org/10.1007/s11837-020-04443-7

NIST AM In-situ Data & Dissemination

AMMT Website

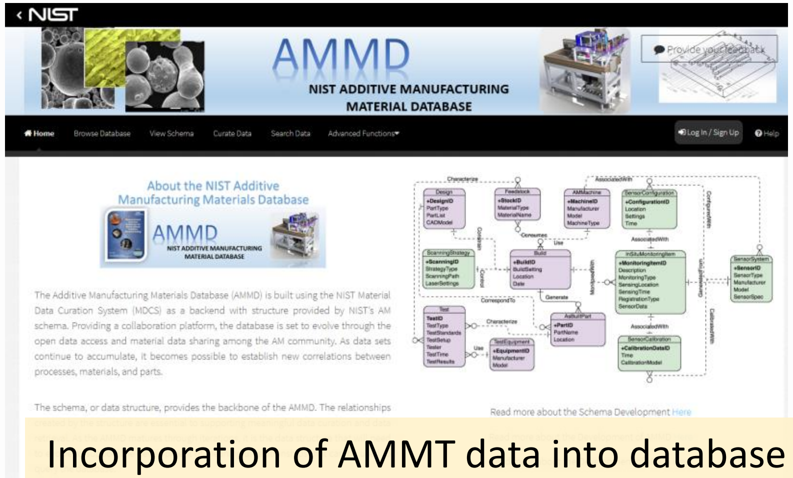
https://www.nist.gov/el/ammt-temps/datasets



Updated in-situ process monitoring datasets from the AMMT

NIST AMMD

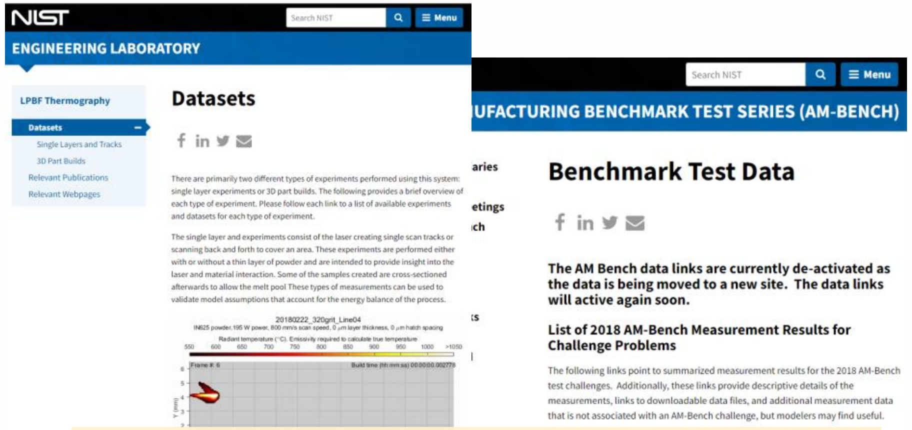
https://ammd.nist.gov/



Incorporation of AMMT data into database
Data visualization tools

NIST LPBF Thermography Website + AM-Bench Website

https://www.nist.gov/el/lpbf-thermography/datasets
https://www.nist.gov/ambench/benchmark-test-data



Staring thermography system on EOS M270
AM-Bench has myriad ex-situ data (res. strain, μ-structure, etc.)

ASME® 2020 HACKATHON
COMPUTER / INFORMATION / ENGINEERING

IDETC-CIE Conference, August 15-16, 2020
https://event.asme.org/IDETC-CIE-2020/Program/Hackathon
IMECE Conference, November 14-15 2020
https://event.asme.org/IMECE/Program/Hackathon

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LPDT Team o

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Questions?