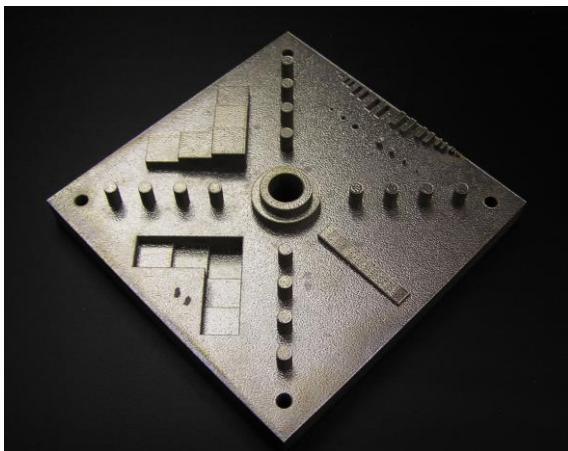


In-situ Process Measurements for Monitoring, Control, and Simulation of AM

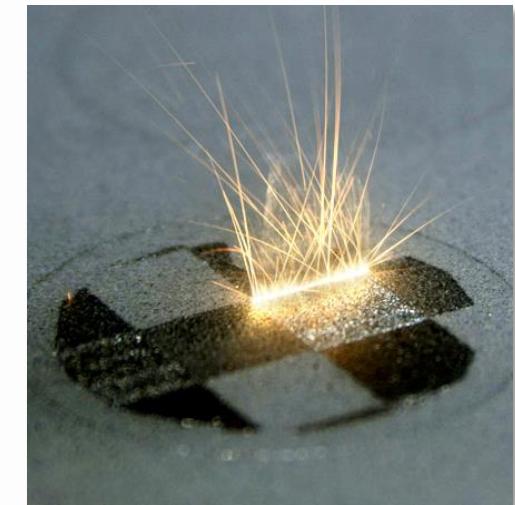


Brandon Lane, Ph.D.

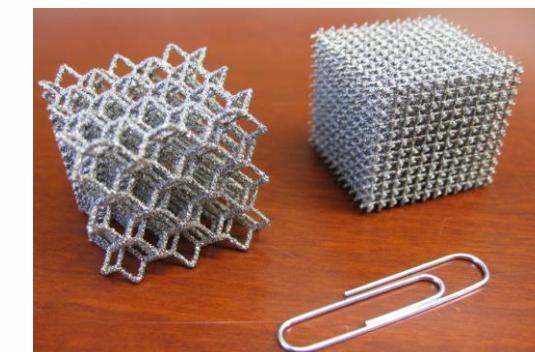
Intelligent Systems Division

Engineering Laboratory

National Institute of Standards and Technology



Disclaimer: Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by NIST, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.



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

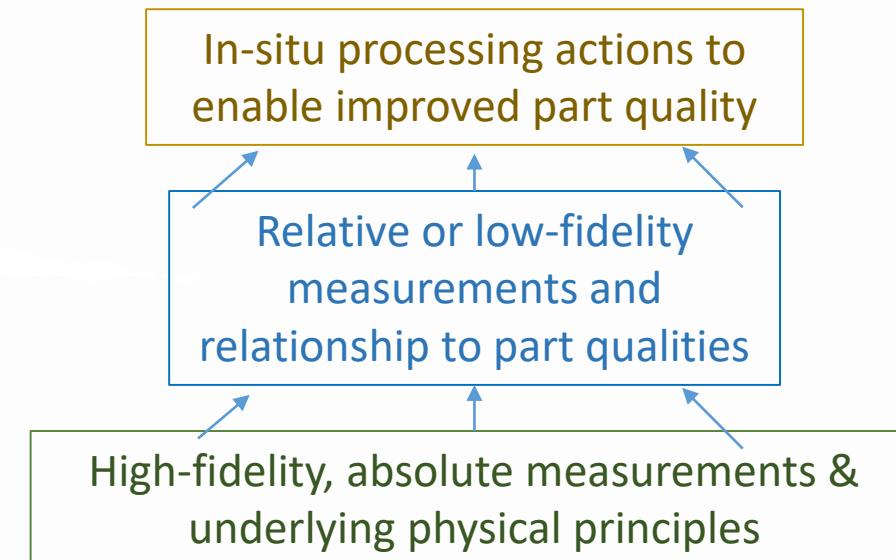
- Part of Engineering Laboratory, 7 projects spanning most aspects of metal AM metrology
 - Also AM program in Materials Measurement Laboratory, collaborators throughout NIST, academia, govt., industry.
- 3 projects discussed today:

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

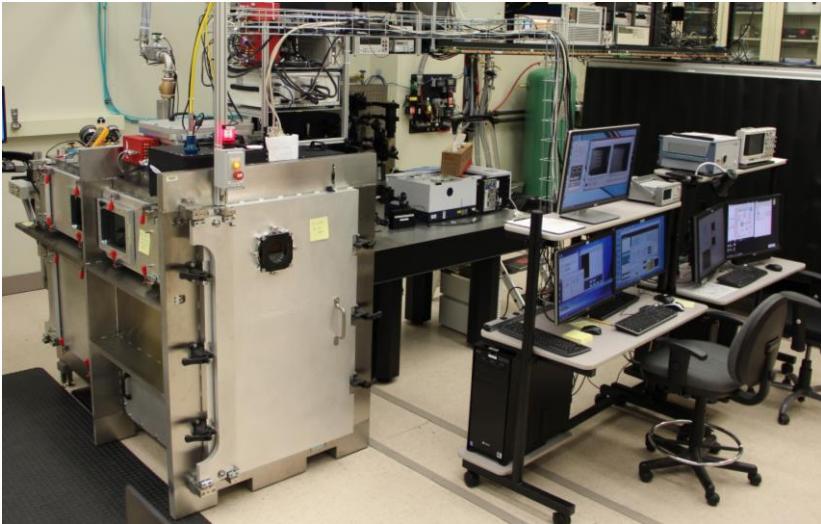
Metrology for Real-Time Monitoring of AM
PI: Dr. Brandon Lane

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

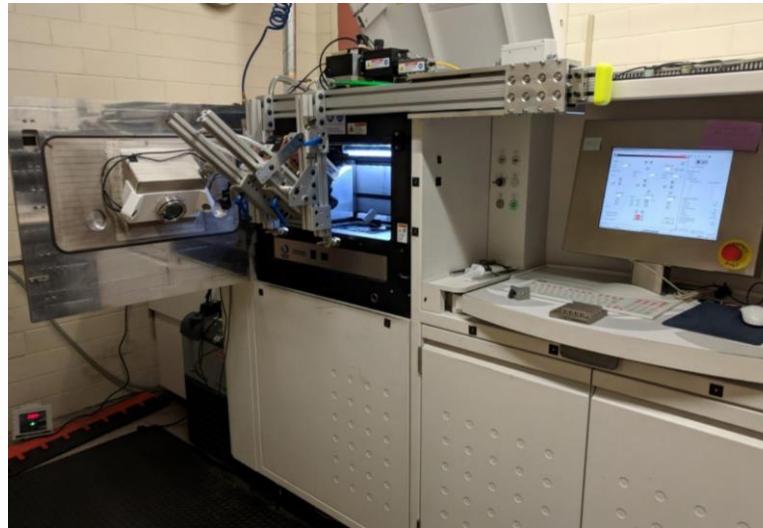
www.nist.gov/additive-manufacturing



In-situ AM Metrology Capabilities



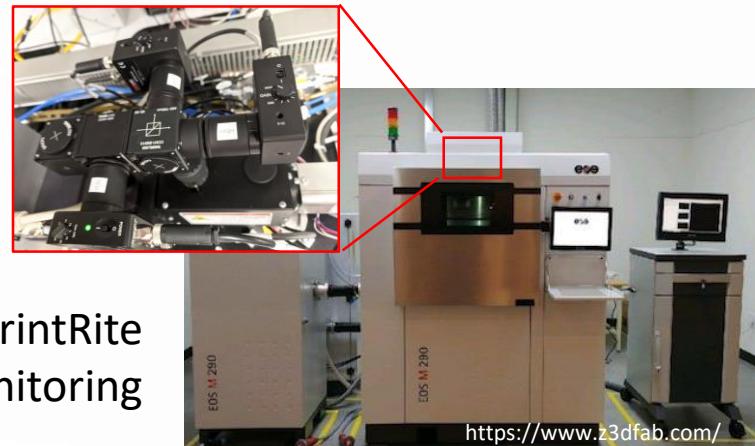
Additive Manufacturing Metrology Testbed (AMMT)
www.nist.gov/el/ammt-temps



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



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

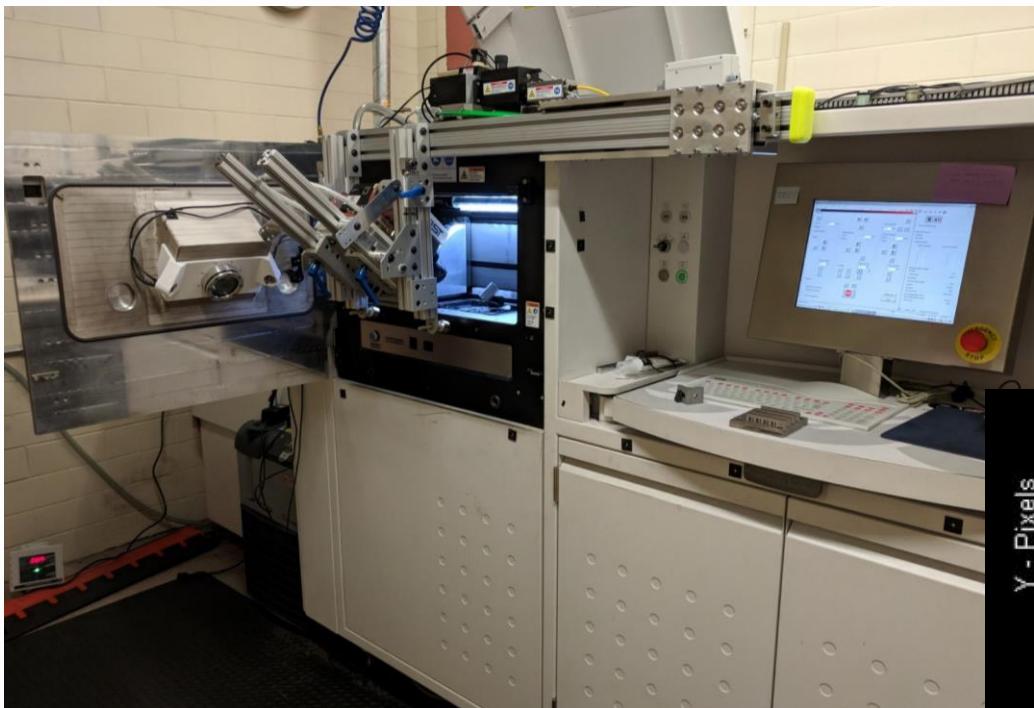


EOS M290 w/ SigmaLabs PrintRite
melt pool monitoring

<https://www.z3dfab.com/>

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 μ s integration time (shutter speed)

-> HDR capabilities

360 pixel wide, 128 mm tall field of view

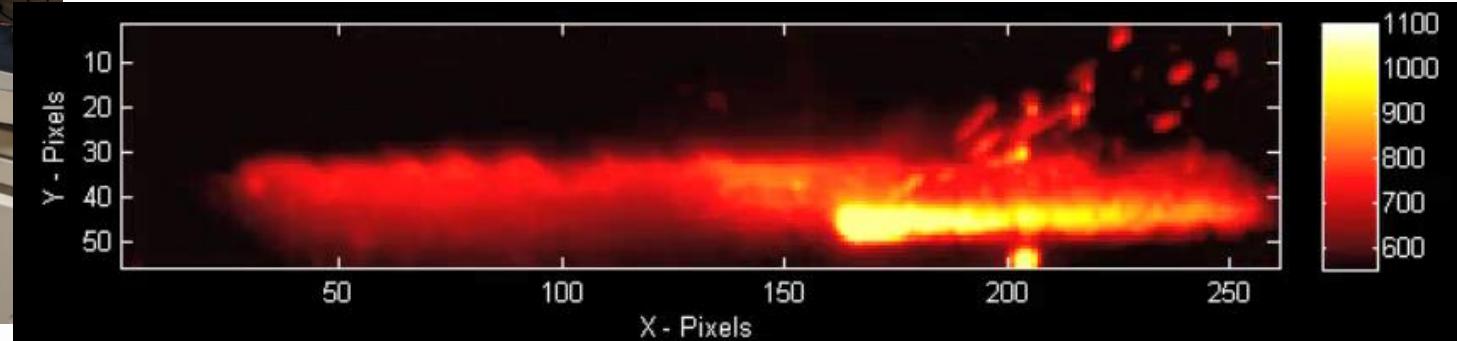
-> 320x256 pixels

44° viewing angle

Viewable area on baseplate, 12 mm x 6 mm -> Variable

iFOV – 54 μm x 36 μm

-> min 45x30 µm

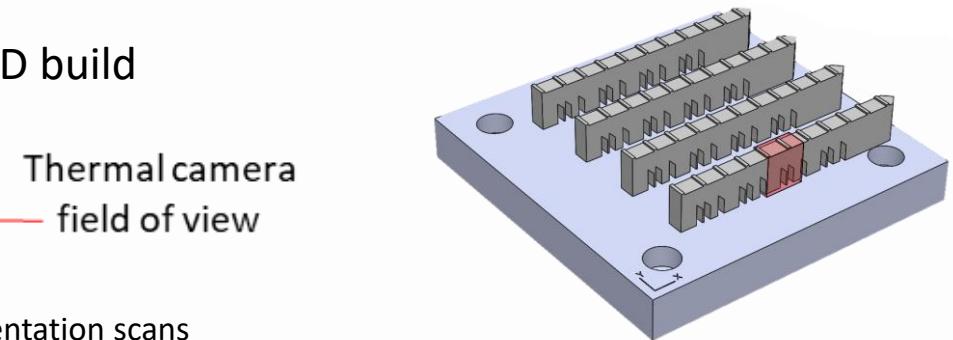
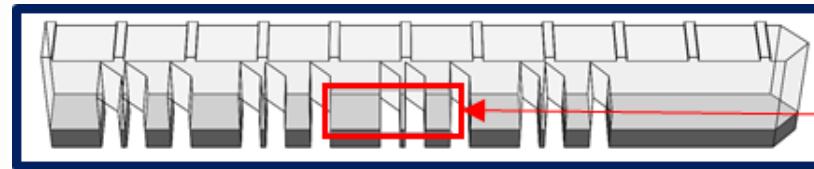


<https://www.nist.gov/el/lpbf-thermography>

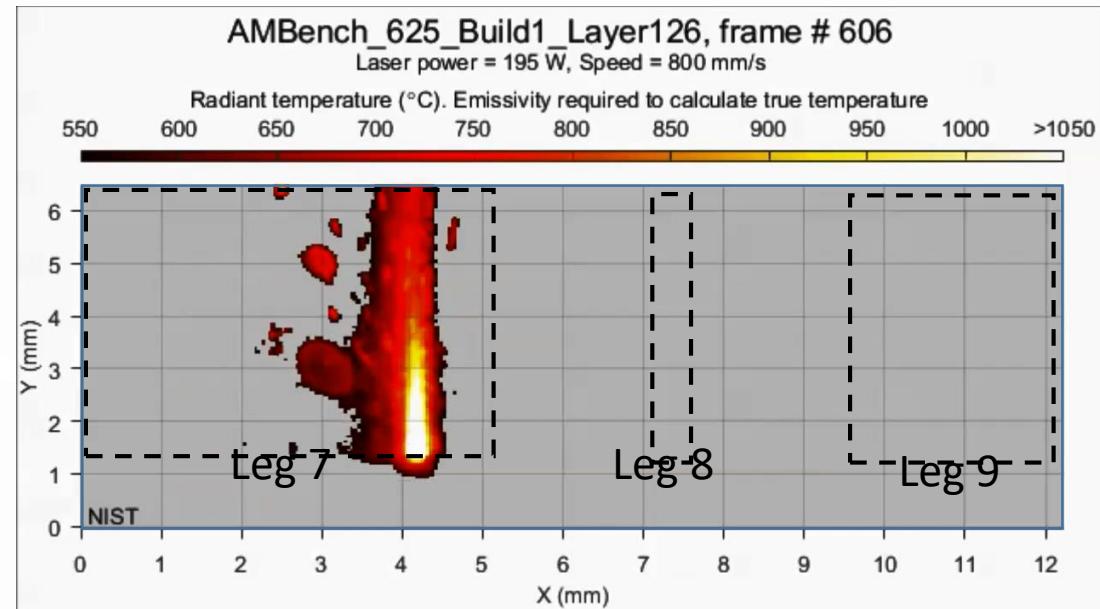
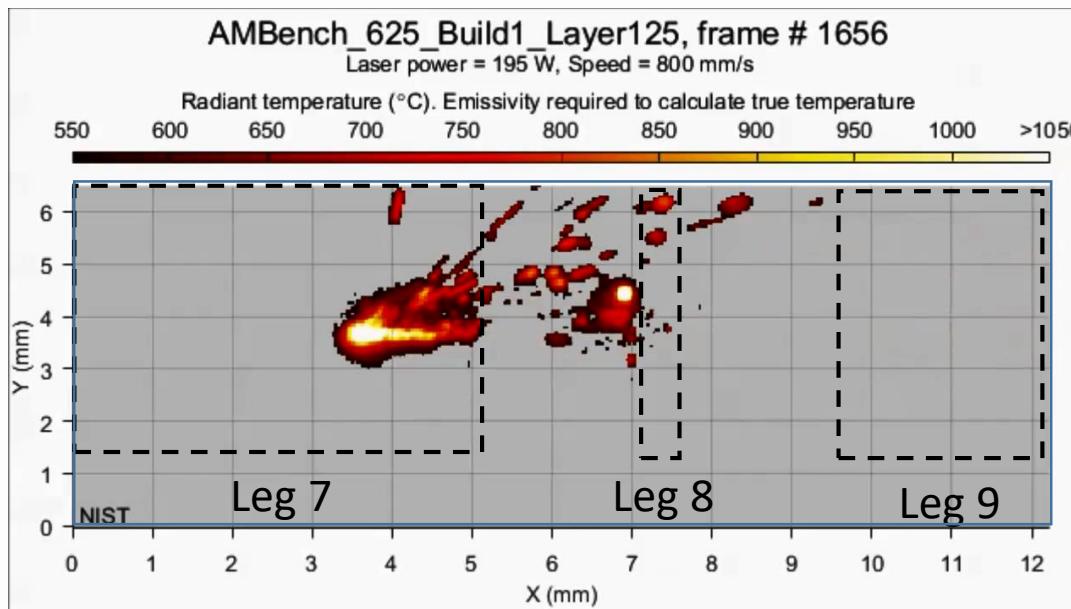
PIs: Jordan Weaver, Brandon Lane

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)

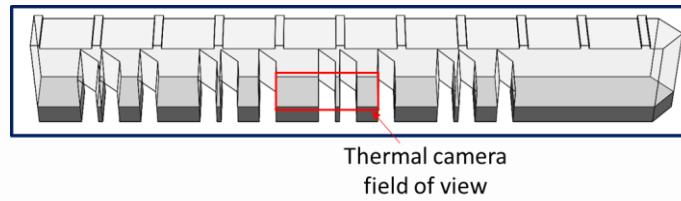


Heigel et al. (2020) *Integrating Materials and Manufacturing Innovation*. <https://doi.org/10.1007/s40192-020-00170-8>

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

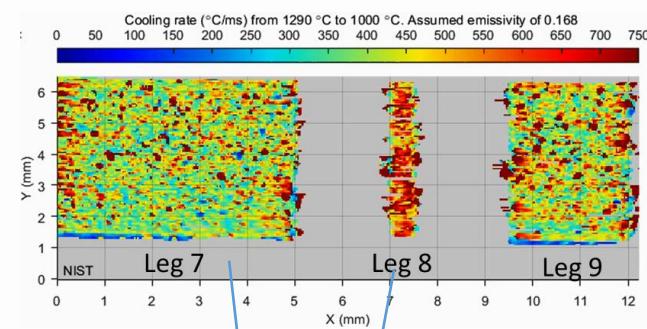
EOS M270 + Thermography System

Mapped MP Length and Cooling rates in 3D build



X-orientation scans

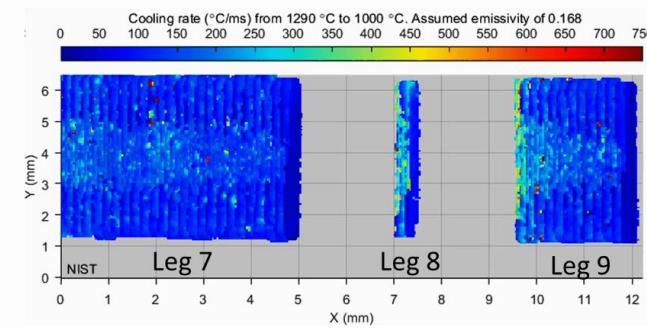
Odd layer (#125)



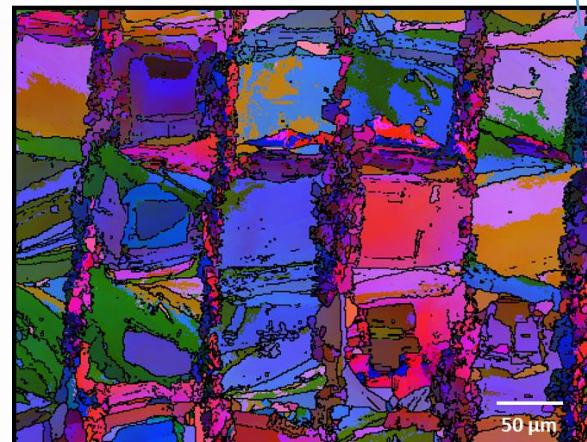
AMB2018-01-625-B2-P1-L4 Thick

Y-orientation scans

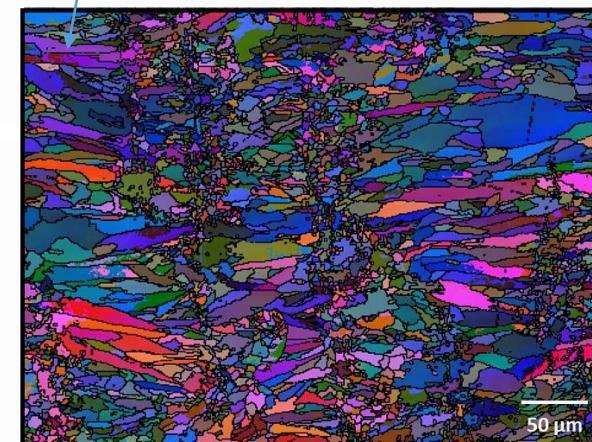
Even layer (#126)



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



Slower Cooling Rate



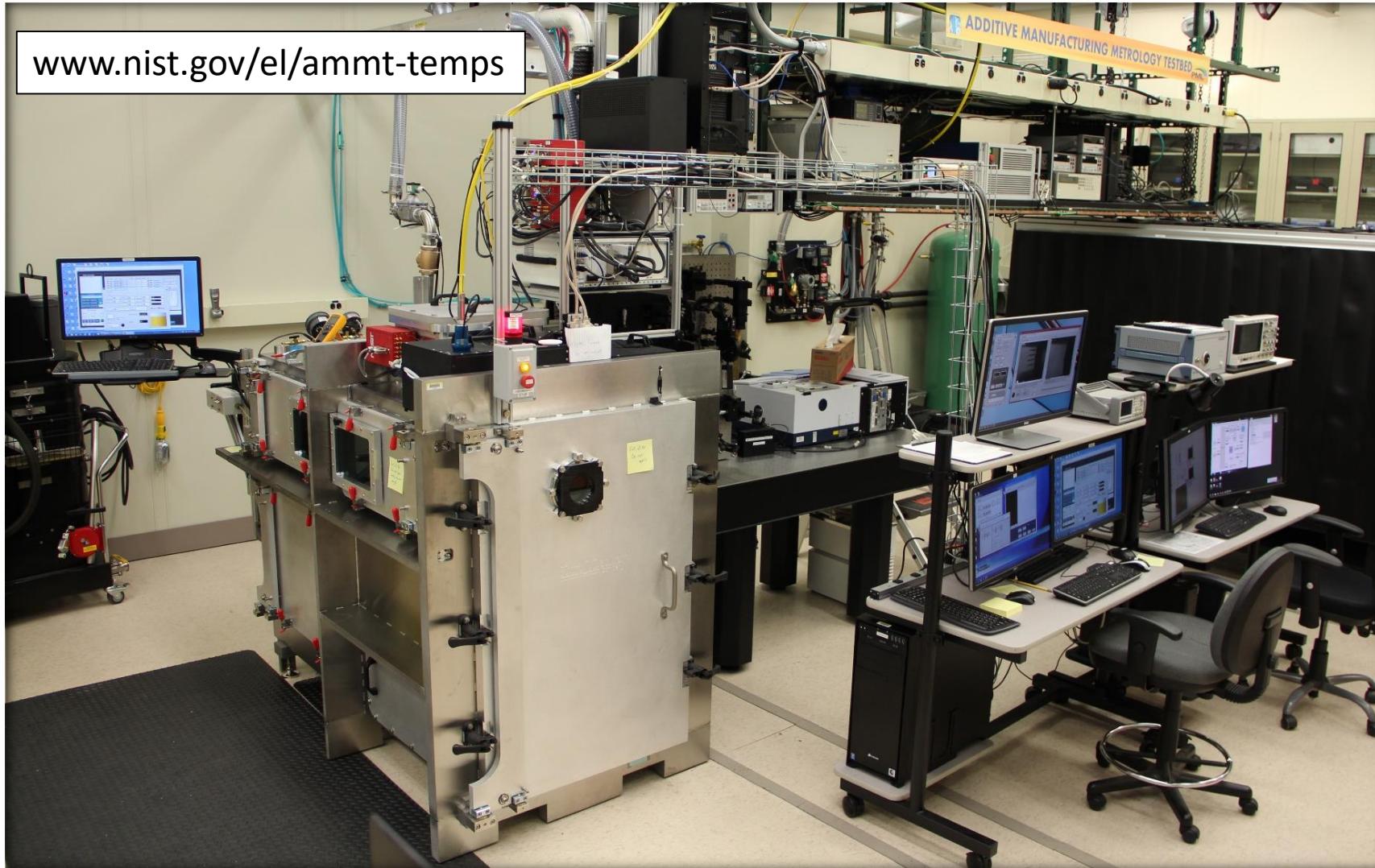
Faster Cooling Rate

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/



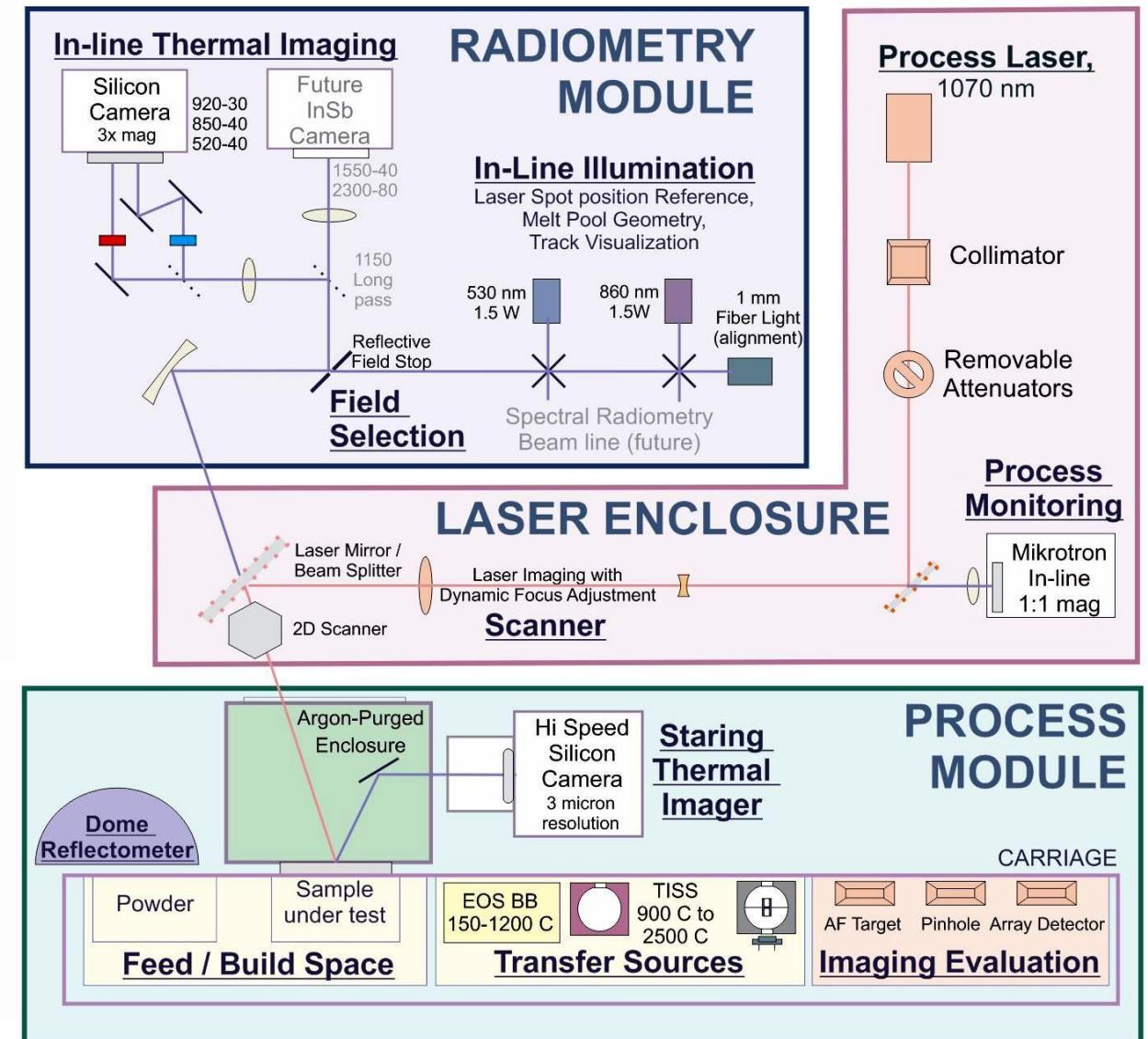
Additive Manufacturing Metrology Testbed (AMMT)



AMMT Guts...

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

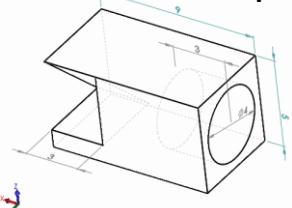
- Process Chamber – a vacuum enclosure with roll-out carriage, containing Powder Bed Fusion and Optical Metrology equipment, as well as Staring Imager
- Laser Enclosure, including Laser Delivery Optics and In-Line Process Monitoring tools
- Radiometry Module with In-Line Thermal Imaging, Illumination 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



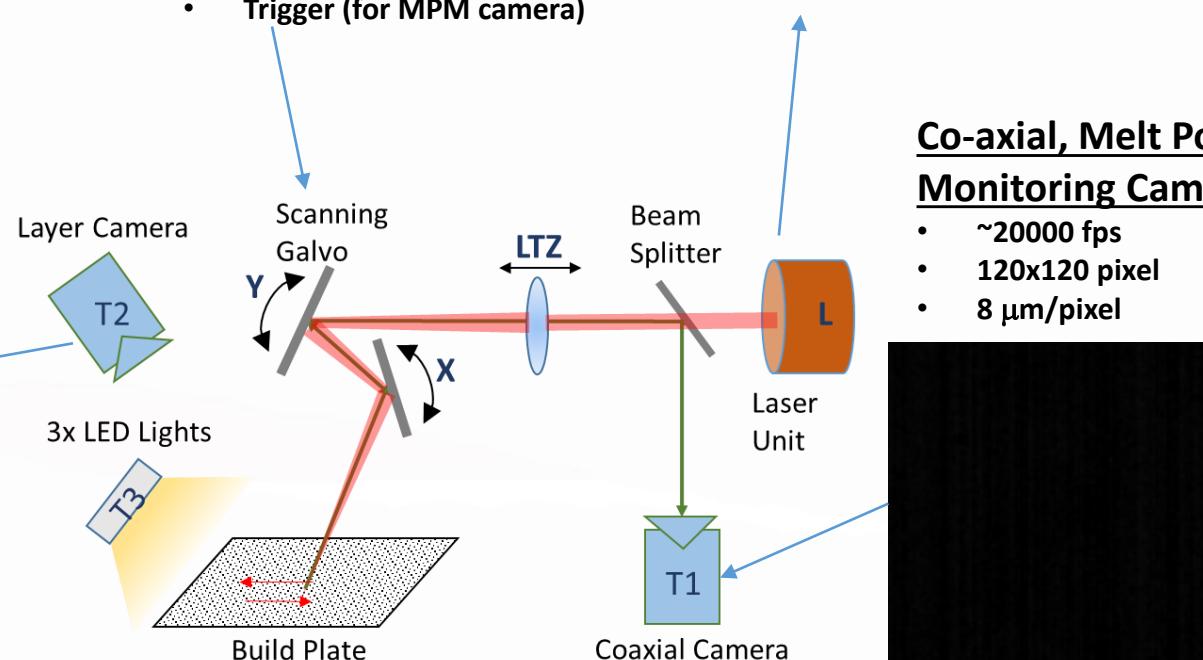
Layer-wise Camera

- GigE, 10.6 MP (windowed)
- $\sim 67 \mu\text{m}/\text{pixel}$



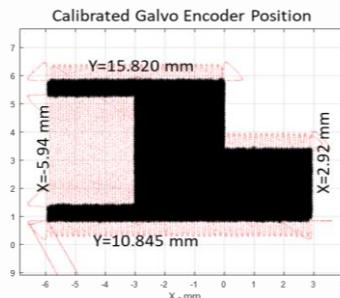
Digital Command Input

- 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]



Co-axial, Melt Pool Monitoring Camera

- $\sim 20000 \text{ fps}$
- 120x120 pixel
- $8 \mu\text{m}/\text{pixel}$



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>

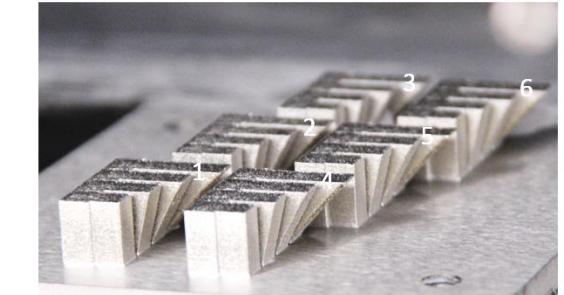
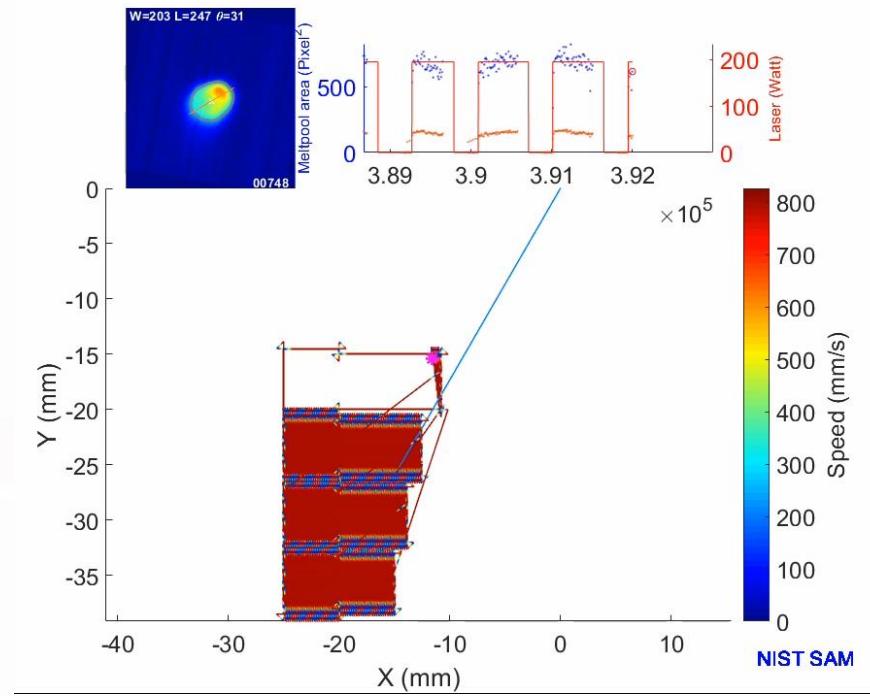
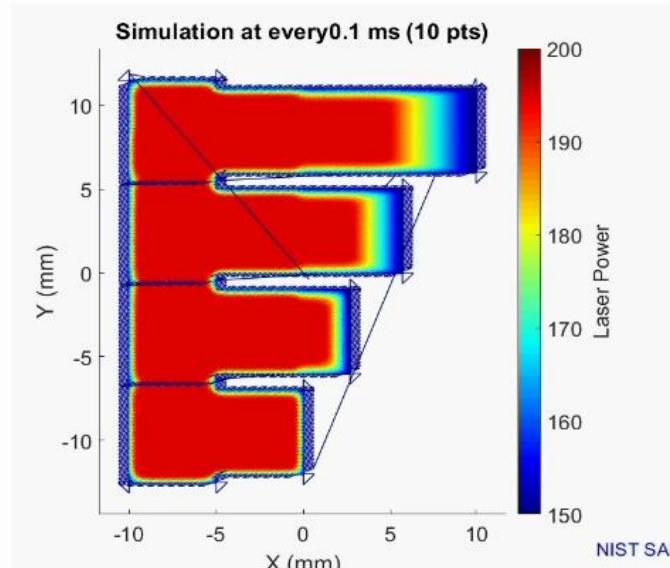
Lane B (2019) *J. Research NIST (JRES)* <https://doi.org/10.6028/jres.124.033>

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



1



(b)

1

(c)

RHF: Yeung H et al. (2020) *Manufacturing Letters* <https://doi.org/10.1016/j.mfglet.2020.07.005>

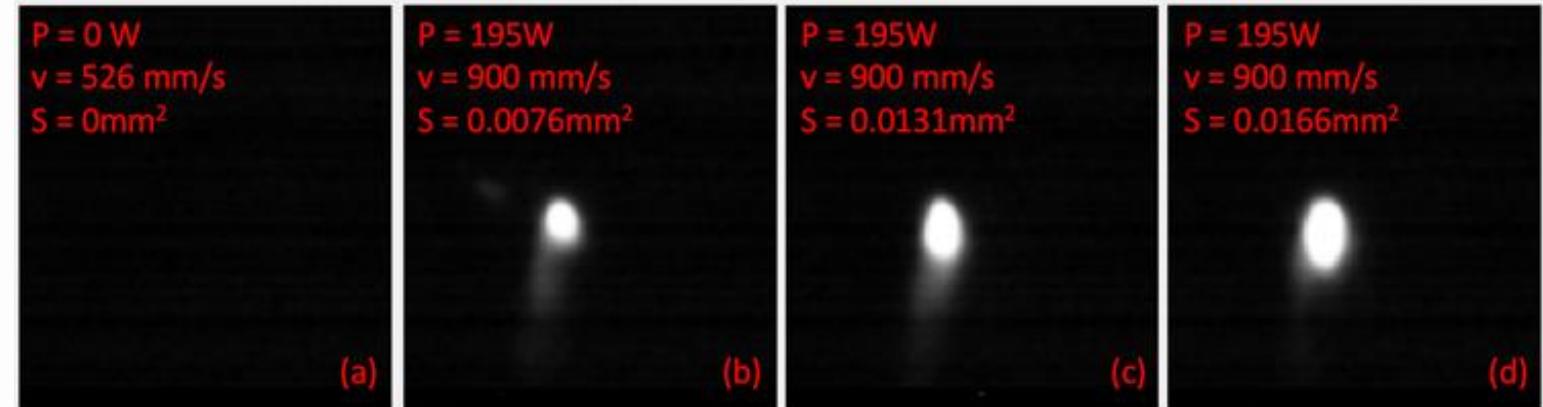
GCF: Yeung et al. (2019) *Additive Manufacturing* <https://doi.org/10.1016/j.addma.2019.100844>

Example Use: Machine Learning-based Control

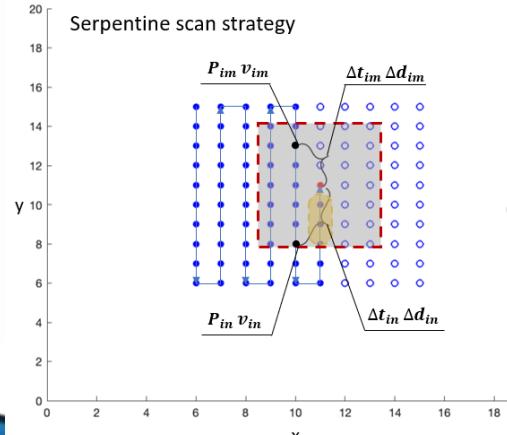
AMMT scan strategy digital command

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)

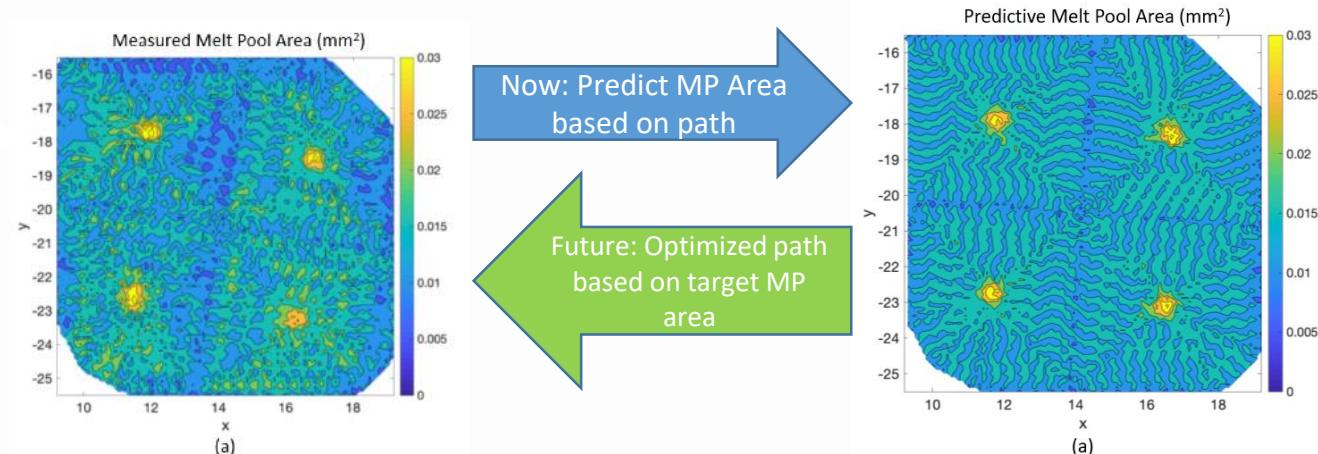


$$\theta_i^{\Delta t} = \sum_{j=1}^n f_{\Delta t}(\Delta t_{ij}) \frac{P_{ij}}{v_{ij}}$$

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

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

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



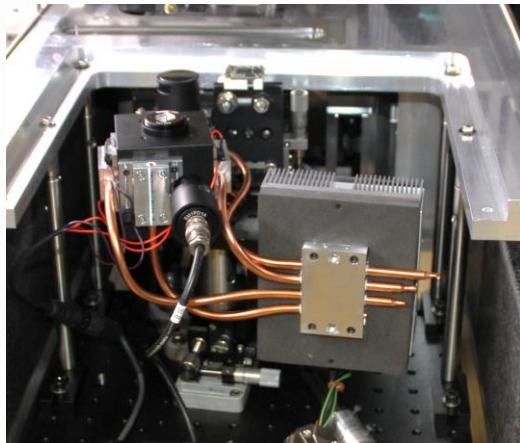
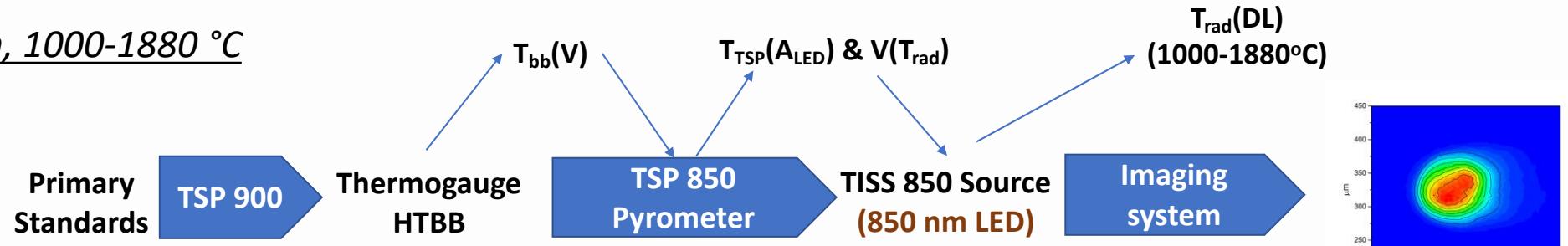
Papers: Yeung et al (2020) Additive Manufacturing <https://doi.org/10.1016/j.addma.2020.101383> [2]

Yang et al. (2020) J. Comp. Inf. Sci. Eng. <https://doi.org/10.1115/1.4046335>

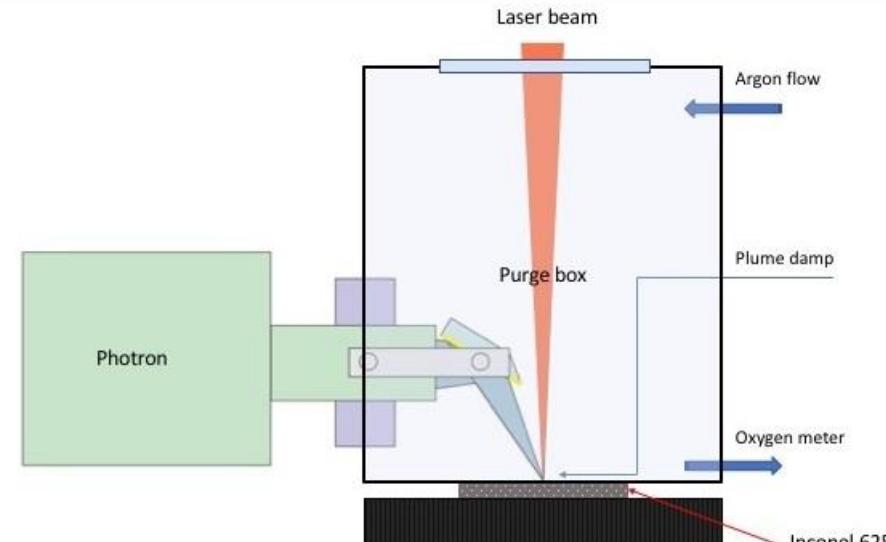
Dataset: Lane B (2019) <https://doi.org/10.6028/jres.124.033>

AMMT – Radiance Temperature Calibration

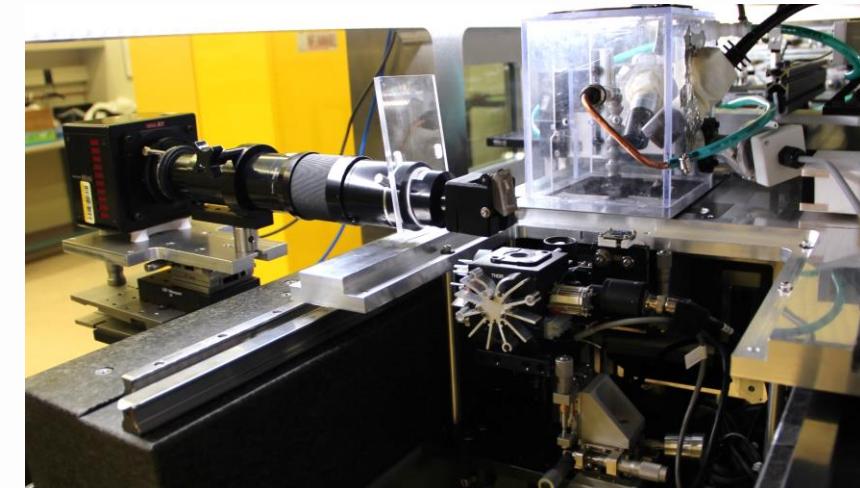
Example: 850 nm, 1000-1880 °C



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

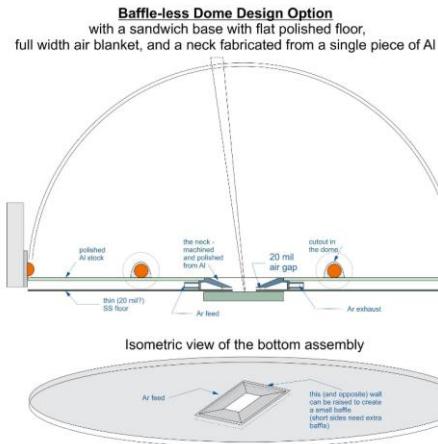


Staring Imager in a measurement configuration, with a high magnification lens and folding mirror

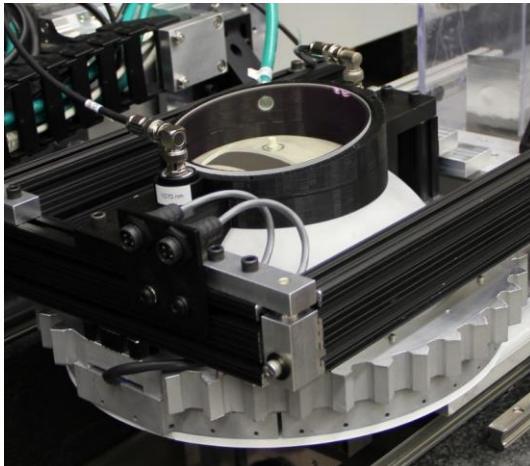


Staring Imager in calibration position (outside of the purge enclosure)

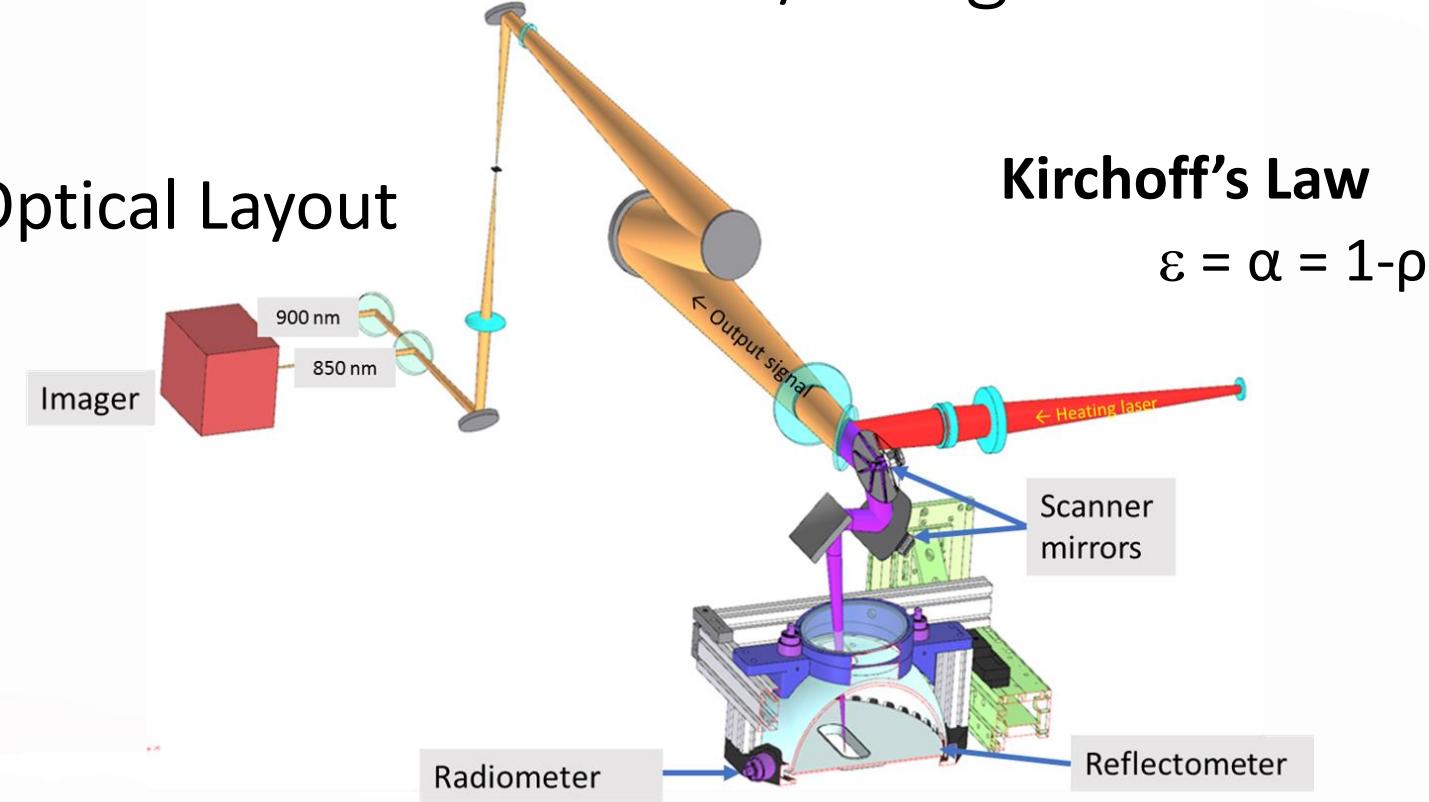
AMMT – Hemispherical Reflectometer/Integrator



Dome Reflectometer Design



Optical Layout



Kirchoff's Law

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

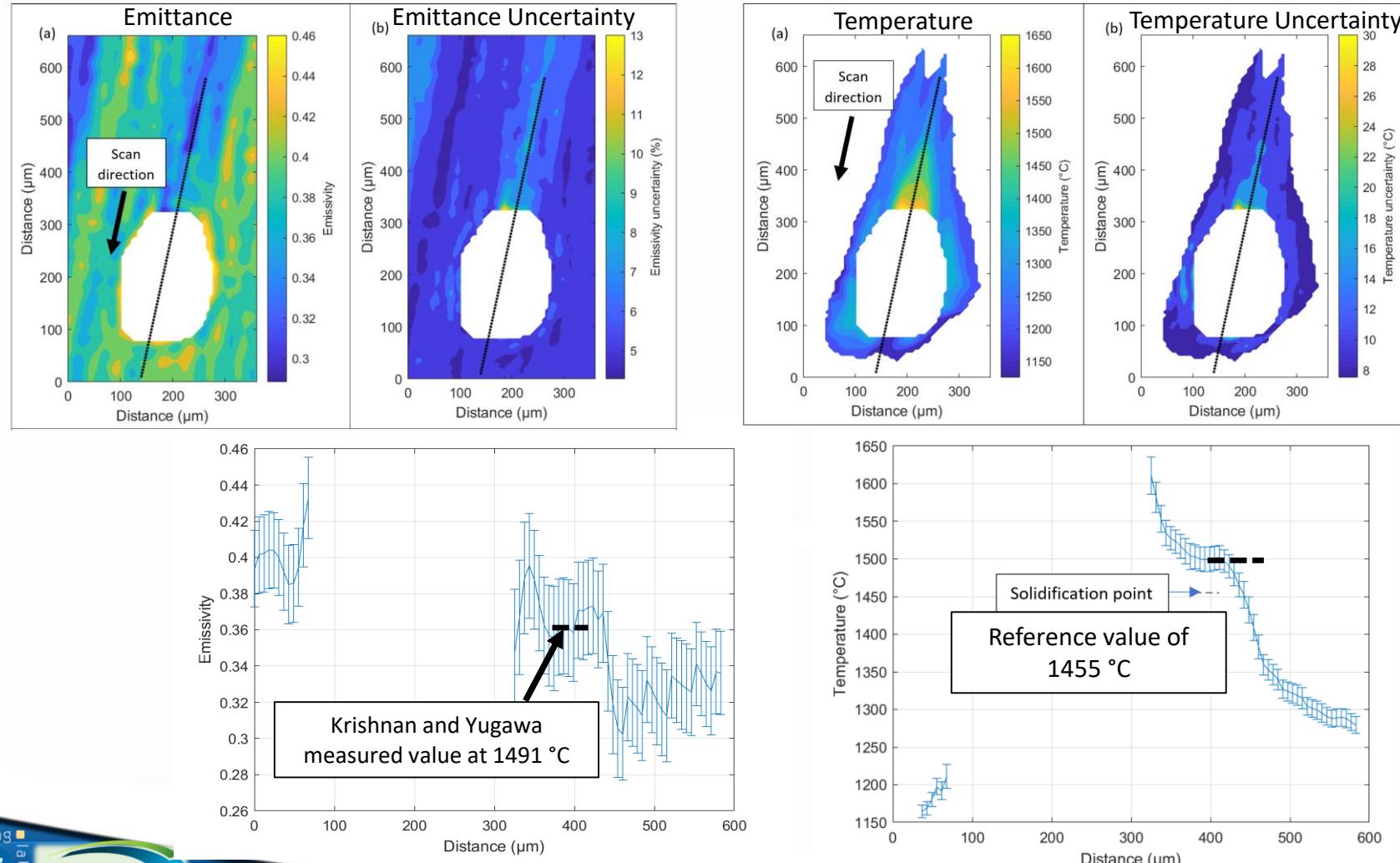
- Designed to provide uniform hemispherical illumination in the sample position
- Hemispherical-Directional Reflectance Factor (HDFR) \rightarrow surface emittance

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



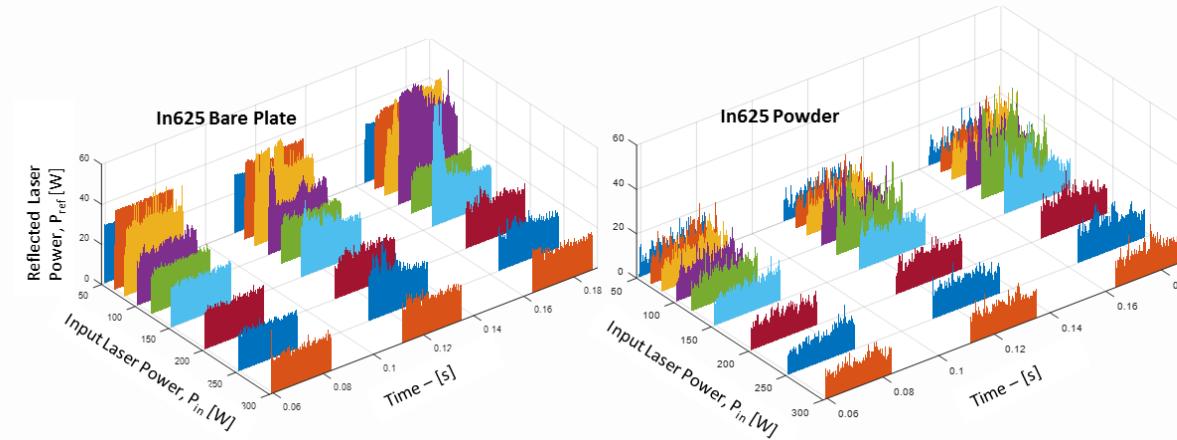
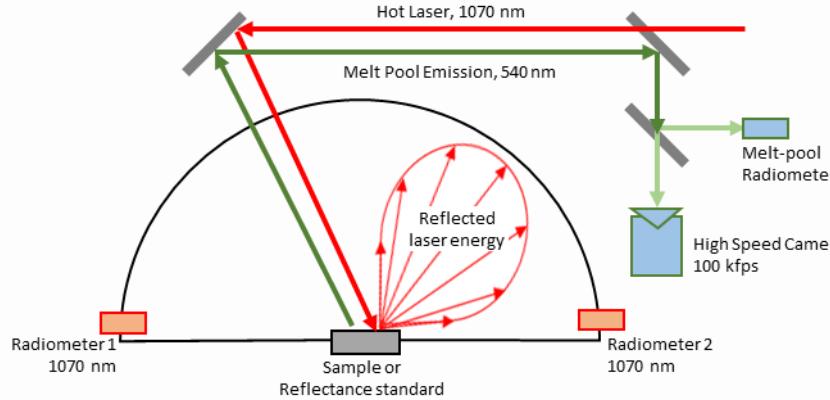
Reference values:

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

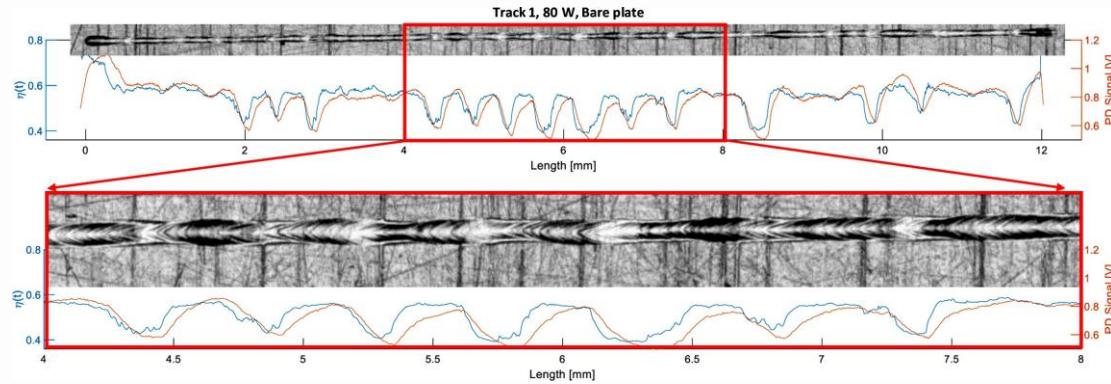
NIST Publications:

- 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)

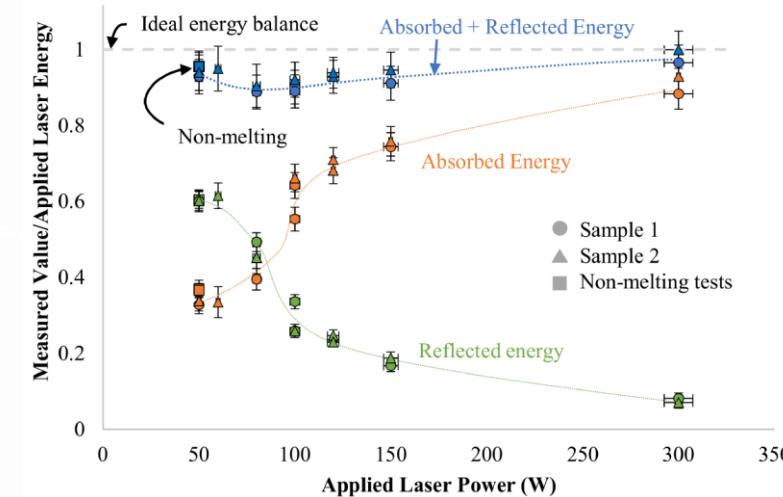
AMMT – Dynamic laser absorption + energy balance



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>

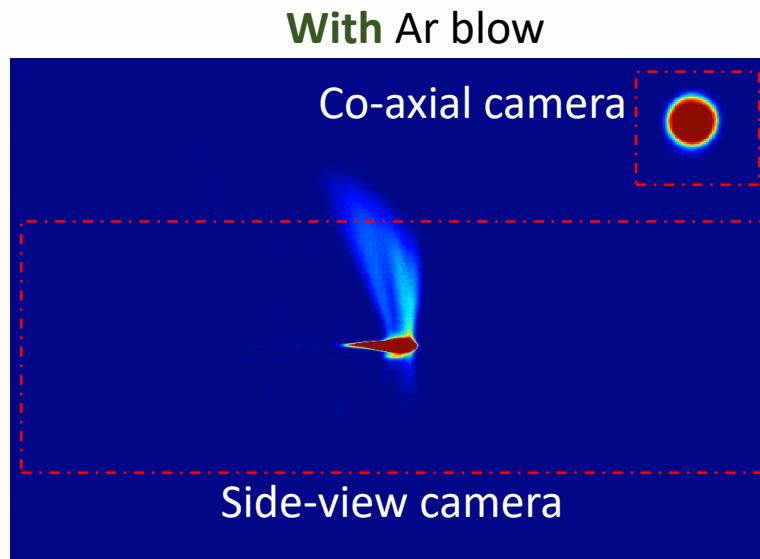
Deisenroth et al. (2020) *Proceedings of SPIE* <https://doi.org/10.1117/12.2547491>

Also see NIST Boulder: PI Brian Simonds, Ph.D.

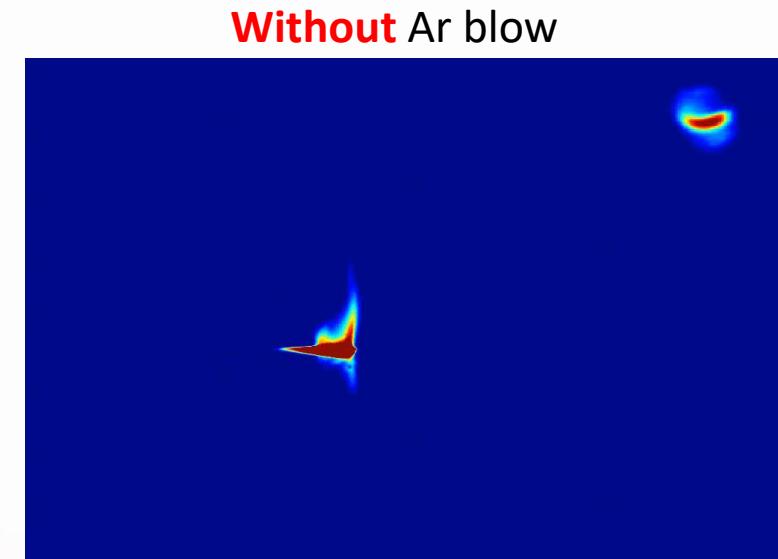
Allen et al. (2020) *Physical Review Applied* <https://doi.org/10.1103/PhysRevApplied.13.064070>

AMMT – Plume investigation

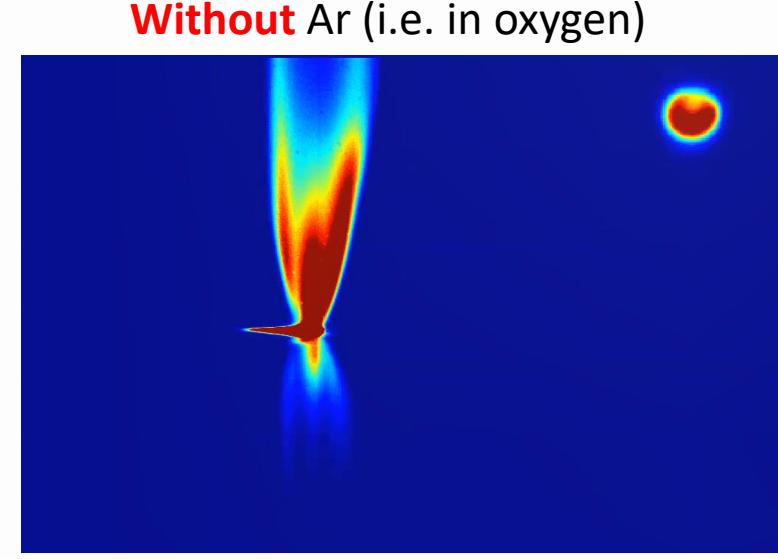
- Synchronous Co-axial + Staring imager for plume investigation
- Coaxial @ 10 K Hz, 95 us / SideView @10 K Hz, 98 us



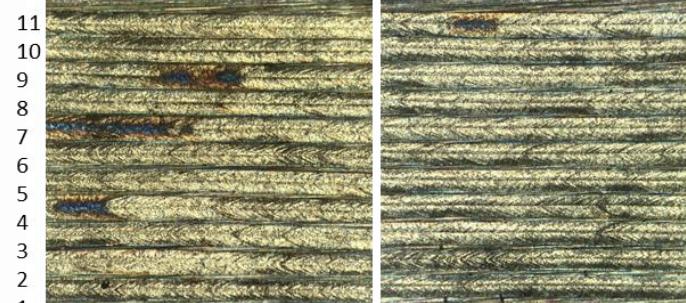
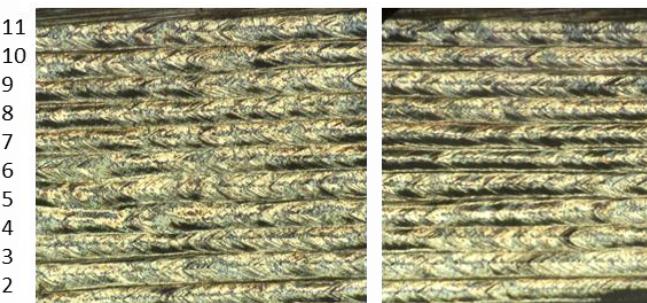
20190515_plume_In625_ArBl_10k_98us_16bits_Gamma1pt3_exp22.mp4



20190515_plume_In625_ArBl_10k_98us_16bits_Gamma1pt3_exp23_2.mp4

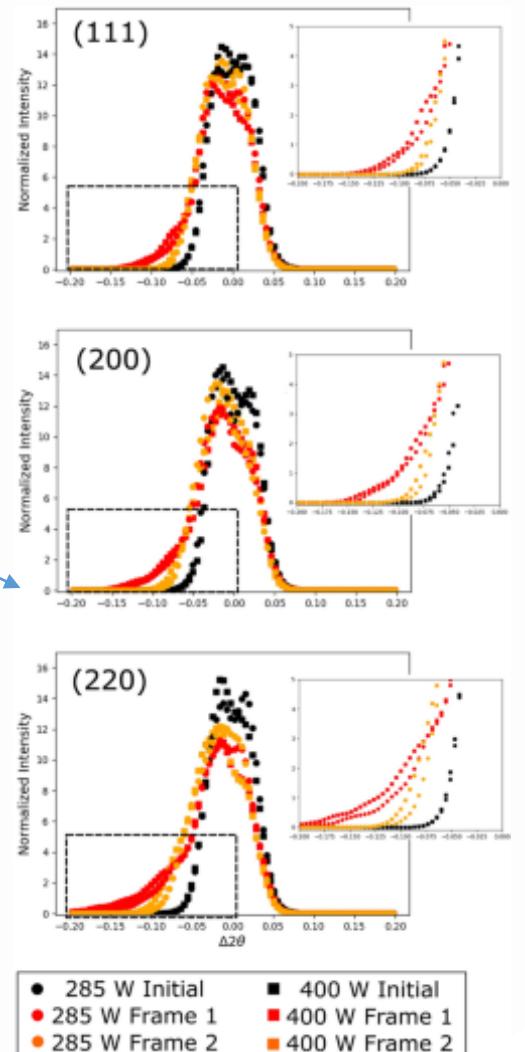
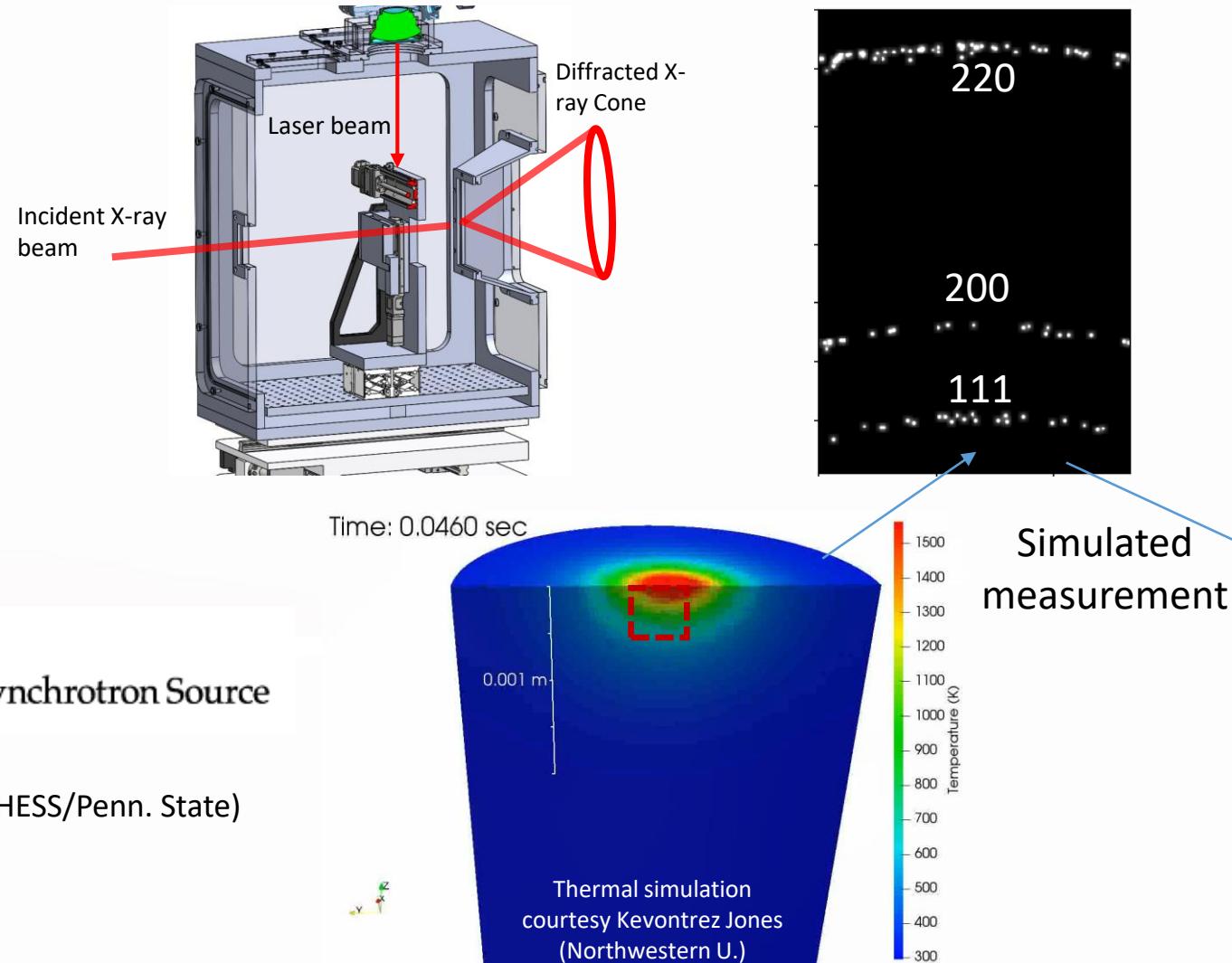


20190515_plume_In625_Oxy_10k_98us_16bits_Gamma1pt3_exp24.mp4



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

Laser Processing and Diffraction Testbed (LPDT)



Cornell University
Cornell High Energy Synchrotron Source

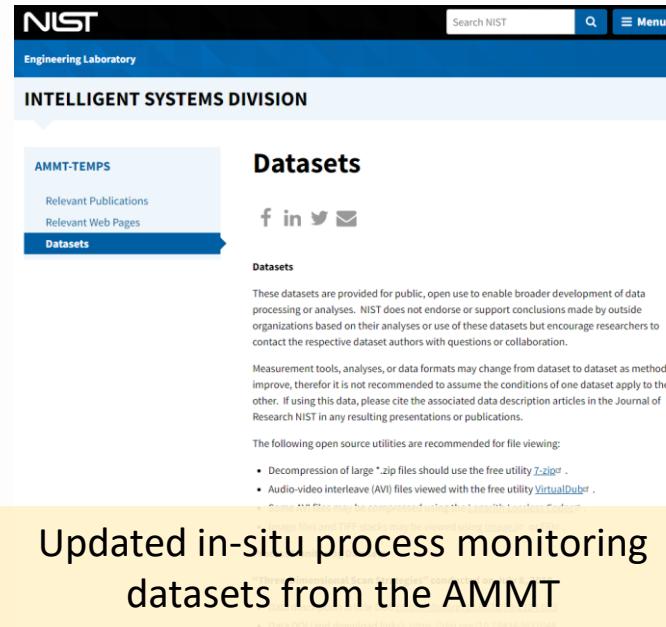
PIs: Thien Phan, Ph.D. (NIST EL)

Darran Pagan, Ph.D. (Cornell-CHESS/Penn. State)

NIST AM In-situ Data & Dissemination

AMMT Website

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



AMMT-TEPS

Relevant Publications
Relevant Web Pages
Datasets

f in 

Datasets

These datasets are provided for public, open use to enable broader development of data processing or analyses. NIST does not endorse or support conclusions made by outside organizations based on their analyses or use of these datasets but encourage researchers to contact the respective dataset authors with questions or collaboration.

Measurement tools, analyses, or data formats may change from dataset to dataset as methods improve, therefore it is not recommended to assume the conditions of one dataset apply to the other. If using this data, please cite the associated data description articles in the Journal of Research NIST in any resulting presentations or publications.

The following open source utilities are recommended for file viewing:

- Decompression of large *.zip files should use the free utility [7-zip](#).
- Audio-video interleave (AVI) files viewed with the free utility [VirtualDub](#).

Source: AM-TEPS for more information about the datasets and their descriptions.

Updated in-situ process monitoring datasets from the AMMT

NIST AMMD

<https://ammd.nist.gov/>



AMMD NIST ADDITIVE MANUFACTURING MATERIAL DATABASE

About the NIST Additive Manufacturing Materials Database

The Additive Manufacturing Materials Database (AMMD) is built using the NIST Material Data Curation System (MDCS) as a backend with structure provided by NIST's AM schema. Providing a collaboration platform, the database is set to evolve through the open data access and material data sharing among the AM community. As data sets continue to accumulate, it becomes possible to establish new correlations between processes, materials, and parts.

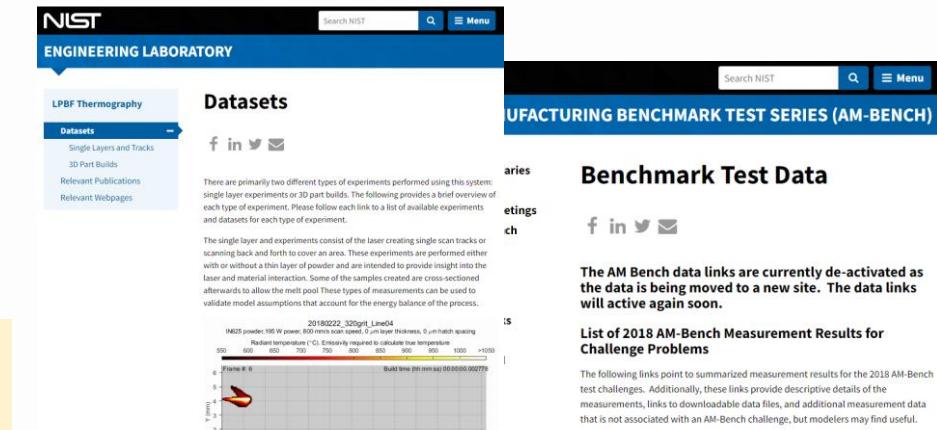
The schema, or data structure, provides the backbone of the AMMD. The relationships between entities define the data model and how data is organized and used in the system.

Read more about the Schema Development [Here](#)

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>



Engineering Laboratory

LPBF Thermography

Datasets

Single Layers and Tracks
3D Part Builds
Relevant Publications
Relevant Webpages

f in 

aries
etings
ch

The AM Bench data links are currently de-activated as the data is being moved to a new site. The data links will active again soon.

List of 2018 AM-Bench Measurement Results for Challenge Problems

The following links point to summarized measurement results for the 2018 AM-Bench test challenges. Additionally, these links provide descriptive details of the measurements, links to downloadable data files, and additional measurement data that is not associated with an AM-Bench challenge, but modelers may find useful.

20180222_320grit_Lin00

IN625 powder, 150 W power, 200 mm scan speed, 0.75 mm layer thickness, 0.75 mm hatch spacing
Radiant temperature (°C) Emery 1000 to calculate true temperature
500 600 650 700 750 800 850 900 950 1000 >1000
Build time (min:sec) 00:00:00.000-00:00:00.000

8 - Frame 8-8
9 -

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

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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Questions?