Using Rigorous Measurements to Guide and Validate Our Understanding of AM Processes

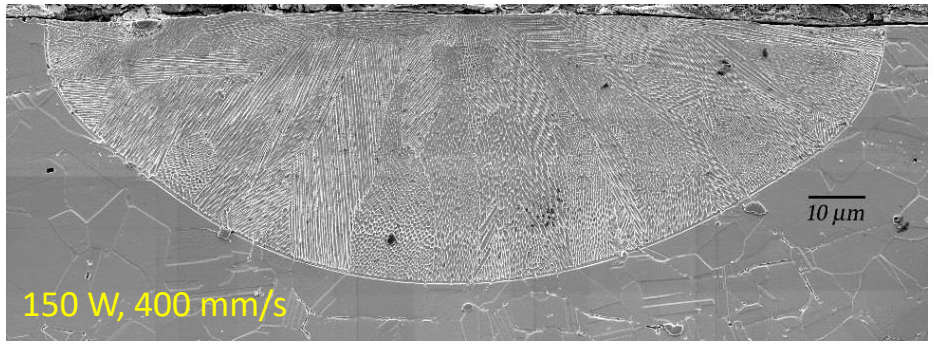
Lyle Levine, NIST

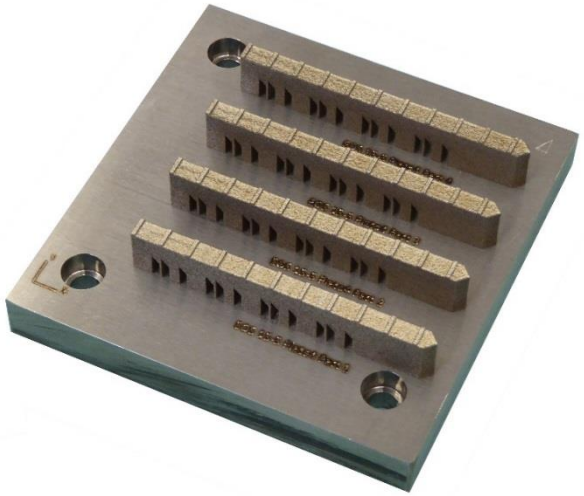
CHiMaD

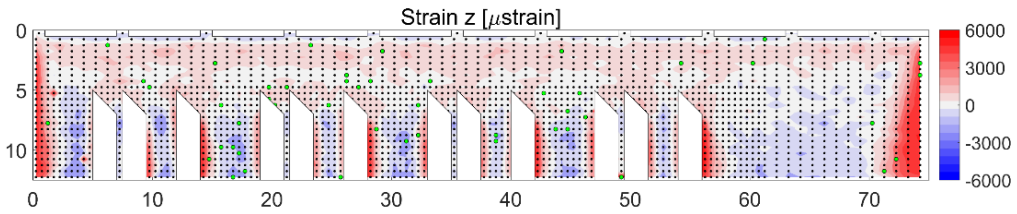
Industrial Additive Manufacturing Workshop on Metals and Ceramics
Brookhaven National Laboratory
April 25, 2019

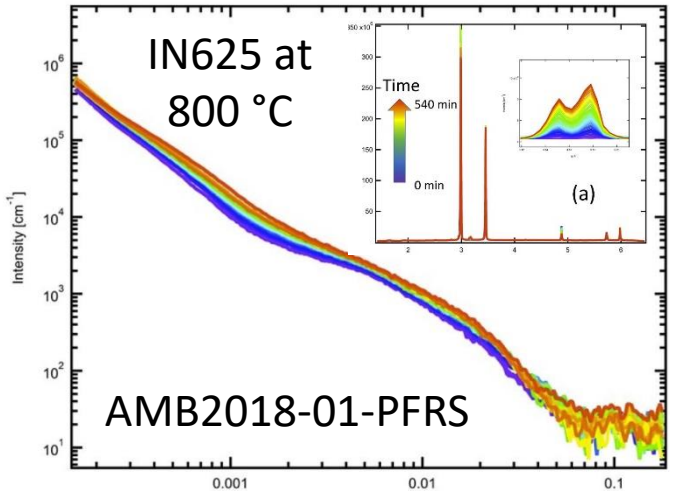
AM BENCH2018 | ADDITIVE MANUFACTURING BENCHMARKS

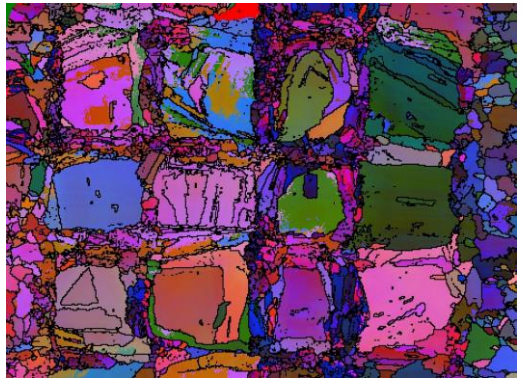
ECP EXASCALE COMPUTING PROJECT











Metals Additive Manufacturing at NIST: Not a Single Effort

Engineering Laboratory

Material Measurement Laboratory

Physical Measurement Laboratory

NIST Center for Neutron Research

Information Technology Laboratory

Acknowledgements

Lyle Levine (MML/MSED Project Leader)

Synchrotron X-ray & NCNR
Andrew Allen
Thomas Gnaupel-Herold (NCNR)
Lyle Levine
Fan Zhang

TEM/SEM
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Maureen Williams

Quant. Metallography, Corrosion & Mech. Prop.
Carlos Beauchamp
Sandy Claggett
Eric Lass
Kil-Won Moon
Rick Ricker
Mark Stoudt
Kwangtae Son (USC)

High Rate Deformation
Steve Mates

Finite Element Modeling
Kevontrez Jones (NU)

CALPHAD-Approach Modeling
Carelyn Campbell
Zhi Liang

Phase-Field Modeling
Jon Guyer
Trevor Keller

Close EL Collaborators:
Brandon Lane
Jarred Heigel

Synchrotron X-ray and Neutron Experts
Ho Yeung
Thien Phan

Close PML Collaborators:
Steven Grantham
Sergey Mekhontsev

Primary External AM-Bench Collaborators

Argonne National Laboratory
Jan Ilavsky
Saul Lapidus

Los Alamos National Laboratory
Don Brown
Maria Strantza (now LLNL)
Bjørn Clausen

Cornell (CHESS)
Darren Pagan

UC Davis/Hill Engineering
Christopher D'Elia
Michael Hill
Adrian DeWald

Naval Research Laboratory
Richard Fonda
David Rowenhorst

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Primary Additive Manufacturing Synchrotron X-ray and Neutron Activities

Advanced Photon Source

- *Macroscale Residual Stress (6BM)*
  Thien Fan, Lyle Levine
- *USAXS/SAXS/WAXS (9ID-C)*
  Fan Zhang, Andrew Allen, Lyle Levine
- *Microbeam Diffraction (34ID-E)*
  Lyle Levine, Thien Phan
- *Powder Diffraction (11BM)*
  Fan Zhang
- *In Situ Imaging (32ID-B)*
  Starting with Tao Sun (APS)

CHESS

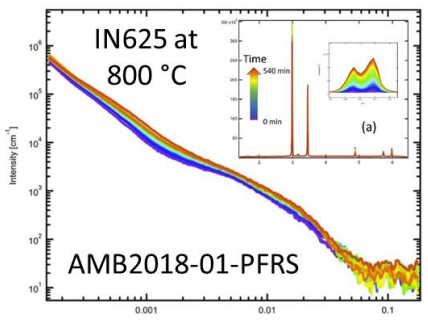
- *Macroscale Residual Stress*
  Thien Fan, Lyle Levine
- *In Situ Diffraction/Imaging*
  Thien Phan – NIST instrument

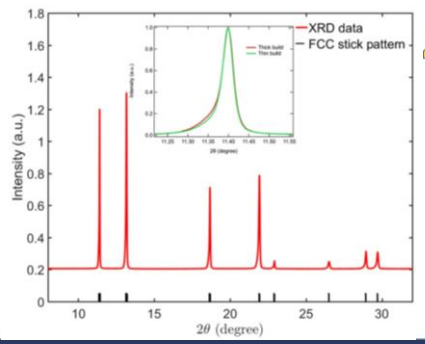
NCNR

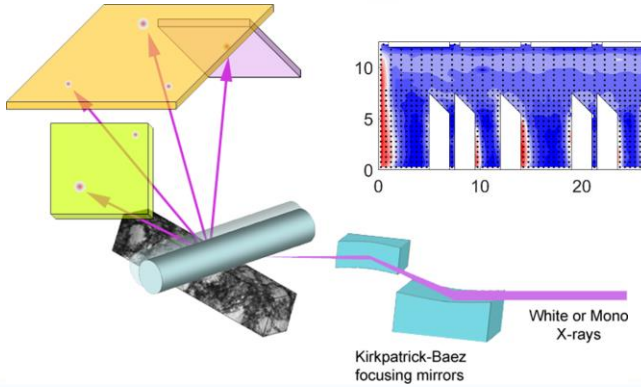
- *Macroscale Residual Stress*
  Thien Fan, Thomas Gnaupel-Herold

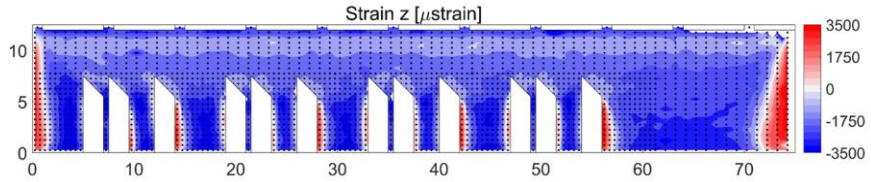
Primary External Collaborators

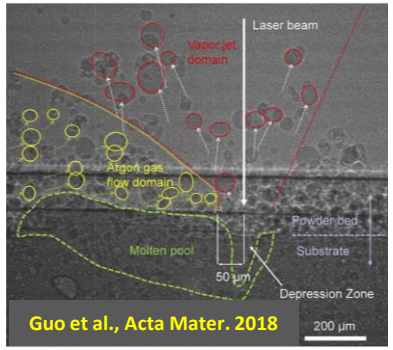
- *APS*
  Jan Ilavsky, Wenjun Liu, Jon Tischler, Tao Sun
- *CHESS*
  Darren Pagan
- *LANL*
  Don Brown, Bjørn Clausen
- *LLNL*
  Maria Strantza



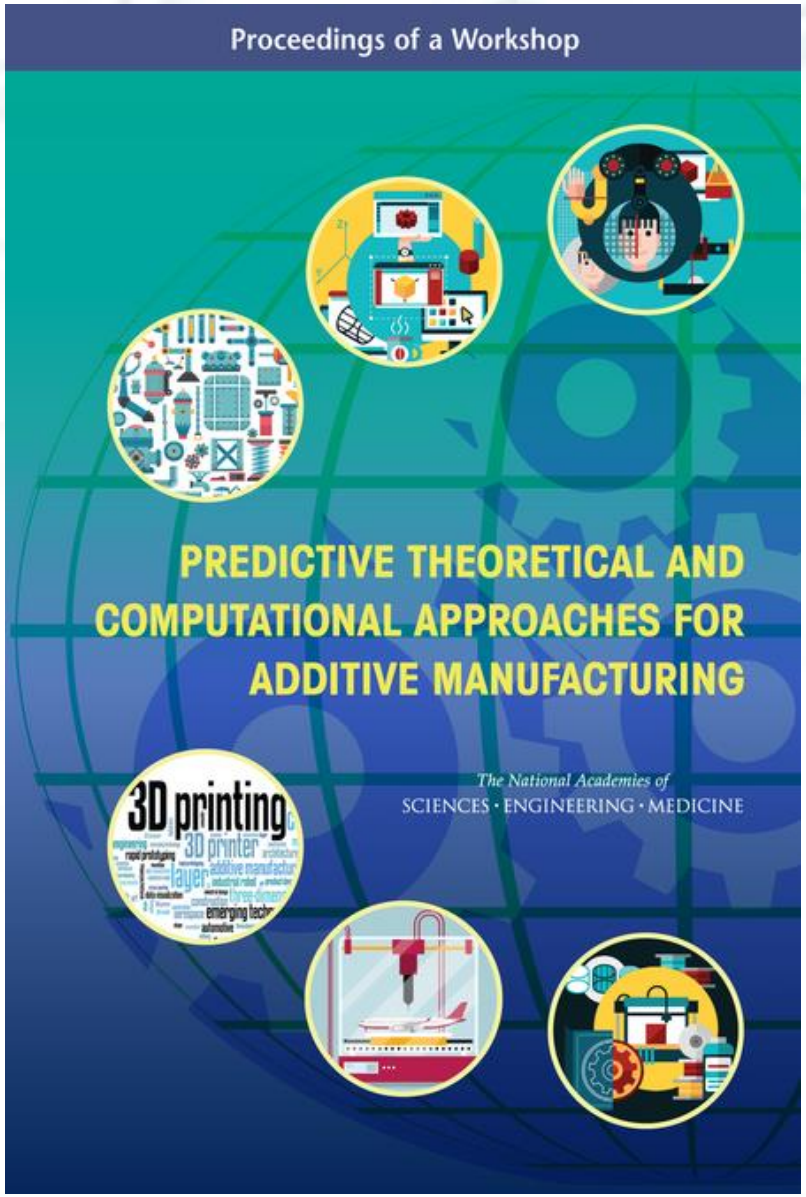








AM-Bench was born on October 7, 2015



What is AM-Bench?

A continuing series of highly controlled benchmark measurements for additive manufacturing, with modeling challenge problems and a corresponding conference series

Primary Goal

To allow modelers to test their simulations against rigorous, highly controlled additive manufacturing benchmark test data

Who benefits?

- Simulation software companies
- Companies that use AM
- AM machine manufacturers
- End users of AM products
- Academia, national labs
- Everyone!

AM-Bench Organization
www.nist.gov/ambench

Steering Committee

Lyle Levine (USA, Chair)
Weidong Huang (China)
Carolin Körner (Germany)
Lars-Erik Lindgren (Sweden)
Wing Kam Liu (USA)
Ade Makinde (USA)
John Turner (USA)

2018 AM-Bench Organizing Committee

Lyle Levine and Brandon Lane (NIST co-Chairs)
Richard Fonda (NRL)
Jarred Heigel (NIST)
Brandon McWilliams (ARL)
Kalman Migler (NIST)
Shawn Moylan (NIST)
Mark Stoudt (NIST)

2018 Benchmark Measurements – an extensive collaboration

- National Institute of Standards and Technology
- U.S. Naval Research Laboratory
- U.S. Army Research Laboratory
- Argonne National Laboratory (Advanced Photon Source)
- Los Alamos National Laboratory
- Cornell High Energy Synchrotron Source
- UC Davis / Hill Engineering

AM-Bench Organization

Scientific Committee (60 organizations, 83 members)

3DSIM:	Chris Robinson
AFRL:	Mark Benedict
	Edwin Schwalbach
ANL:	Tao Sun
ARL:	Larry Holmes
	Ricardo Rodriguez
ASTM:	Mohsen Seifi
Autodesk:	Bill Yackabonis
Carnegie Mellon:	Jack Beuth
	Anthony Rollett
Clemson:	Fadi Abufarha
Dassault Systemes:	Subham Sett
ESI Group:	Mustafa Megahed
EWI:	Yu-Ping Yang
GE:	Ade Makinde
Georgetown Univ.:	Claire McIlroy
	Peter Olmsted
Honeywell:	Alonso Peralta-Duran
IHI Corporation:	Akihiro Sato
IUPUI:	Jing Zhang
Imperial College:	Minh-Son Pham
Johns Hopkins:	Vicky Nguyen
	Somnath Ghosh
KTH:	Greta Lindwall
KU Leuven:	Philip Eyckens
LANL:	Marianne Francois
Lockheed-Martin:	Craig A. Brice
LLNL:	Chris Spadaccini
Luleå Univ.:	Lars-Erik Lindgren
MadeInSpace:	Derek Thomas
MS State:	Steven Daniewicz
NAFEMS:	Philip Eyckens
National Academies:	Wing Kam Liu
NASA Ames:	Dogan Timucin
	Kevin R. Wheeler
NASA Glenn:	Chantal K. Sudbrack
NASA Goddard:	Theodore Swanson
NASA JPL:	R. Peter Dillon
NASA Langley:	Edward H Glaessgen
NASA Marshall:	Stacey Bagg
	Tracie J. Prater
	Arthur Brown
NIU:	Federico Sciammarella
NIST:	Carelyn Campbell
	Jonathan Guyer
	Nik Hrabe
	Brandon Lane
	Lyle Levine
	Felipe Lopez
	Li Ma
	Kalman Migler
	Shawn Moylan
	Richard Ricker
NRL:	John Michopoulos
	Scott Olig
	Alberto Pique
	David Rowenhorst
Northwestern:	Jian Cao
NSWCCD:	Charles R Fisher
Oxford PM:	Tony Decarmine
ORNL:	John Turner
	Sun Xin
Pratt & Whitney:	William Brindley
Purdue:	Yung Shin
Quad City Manuf.:	Eric J. Faierson
QuesTek:	David Snyder
Rolls-Royce:	Benjamin C Saunders
Sandia:	Lauren Beghini
	Hy D Tran
Siemens:	Daniel Reznik
TUM:	Stefan Kollmannsberger
Texas A&M:	Alaa Elwany
Univ. Alabama:	Kevin Chou
Univ. Conn.:	Rainer Hebert
Univ. Texas El Paso:	Jorge Mireles
Univ. Wisc.:	Natalie Rudolph
UTRC:	Tahany El-Wardany
	Vijay Jagdale
VTT:	Anssi Laukkanen
Unaffiliated:	Slade Gardner

Benchmark Measurements

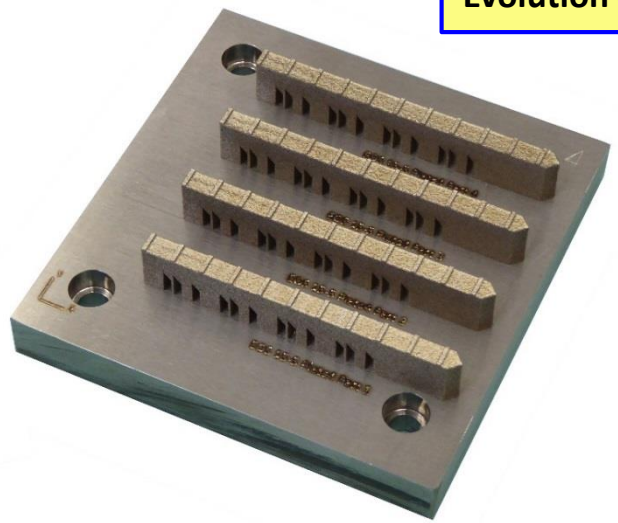
AMB2018-01: Laser powder bed fusion 3D builds of nickel-based superalloy IN625 and 15-5 stainless steel test objects

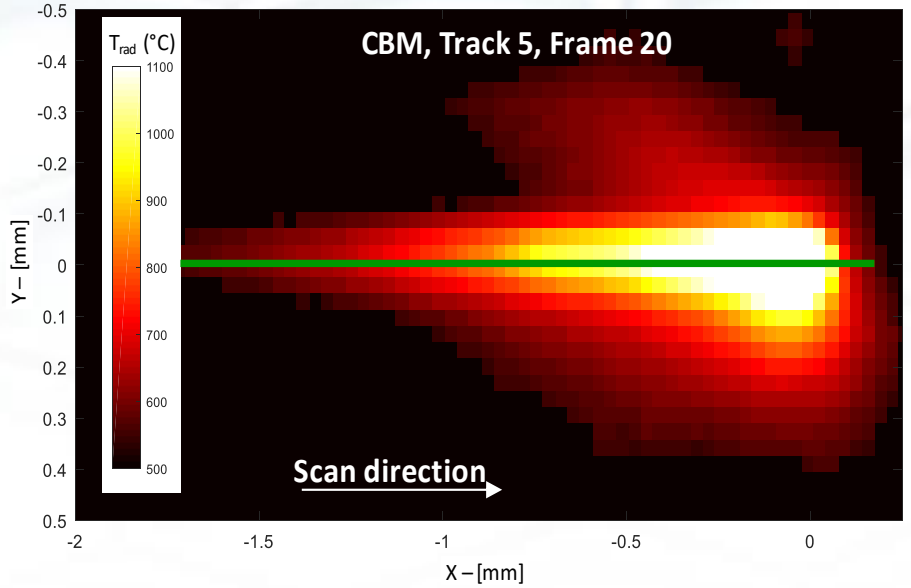
• **Part deflection**	CHAL-AMB2018-01-PD
• **Residual elastic strains**	CHAL-AMB2018-01-RS
• **Microstructure**	CHAL-AMB2018-01-MS
• **Phase fractions**	CHAL-AMB2018-01-PF
• **Phase evolution**	CHAL-AMB2018-01-PFRS

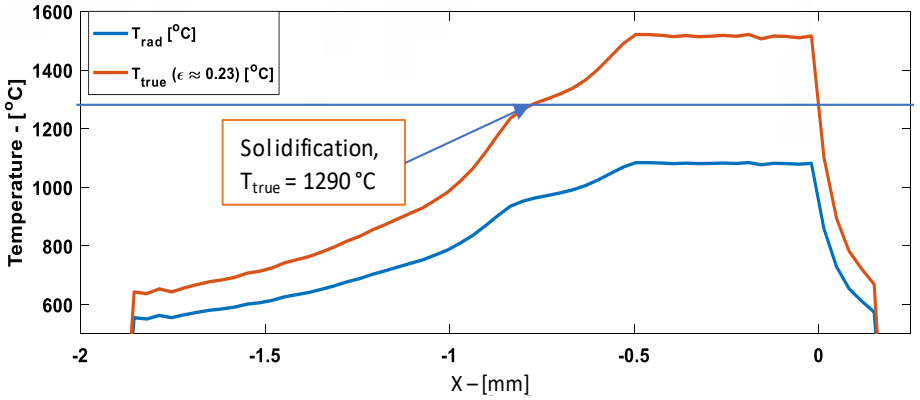
Feedstock Characterization
+
Detailed Build Information
+
In Situ Measurements
+
Residual stresses
+
Distortion
+
Microstructure
+
Evolution during Annealing

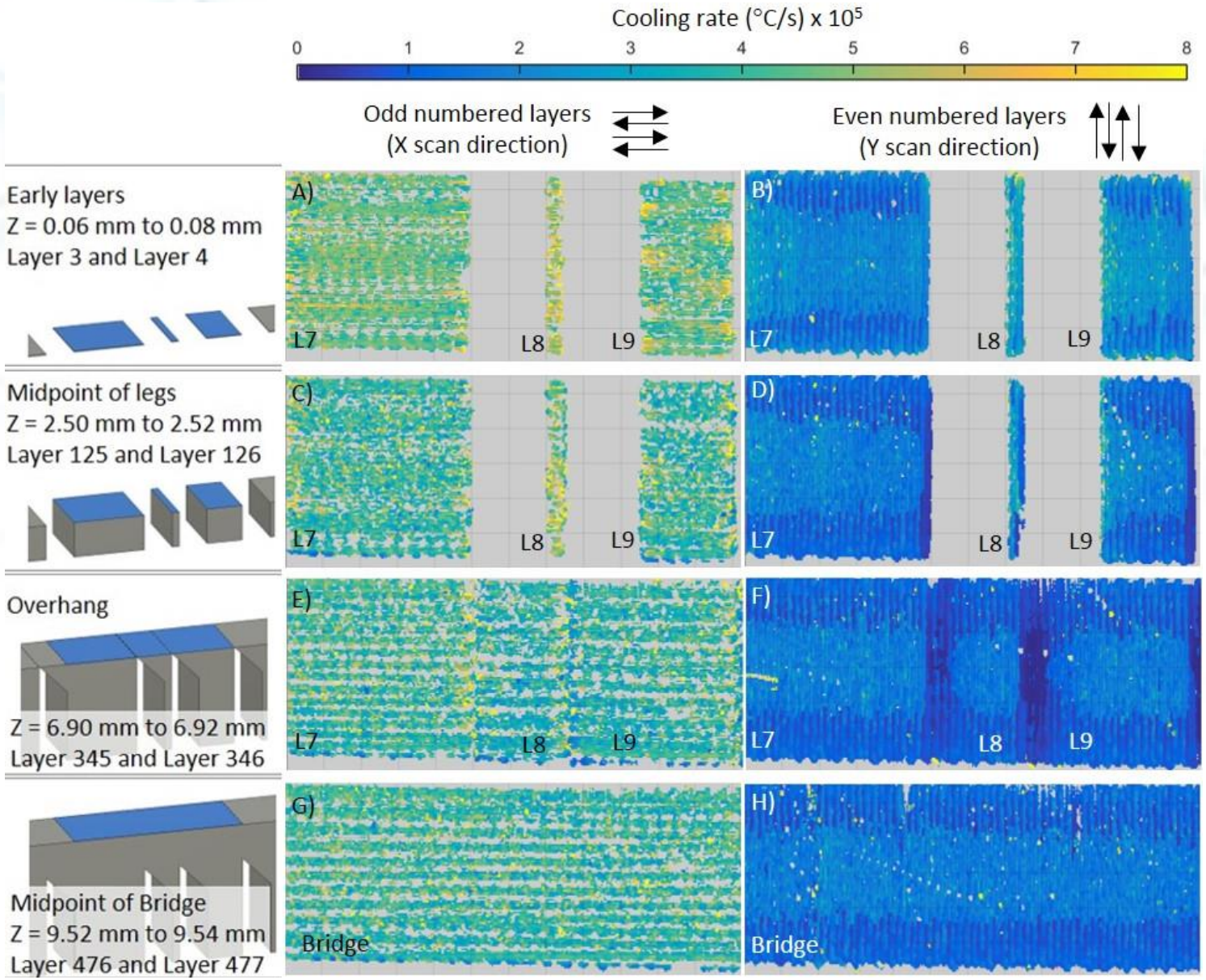
NIST: Andrew Allen, Carolyn Campbell, Sandra Claggett, Thomas Gnaupel-Herold, Jarred Heigel, Brandon Lane, Lyle Levine, Thien Phan, Mark Stoudt, Jared Tarr, Maureen Williams, Fan Zhang
LANL: Donald Brown, Bjørn Clausen, Maria Strantza
ANL (APS): Jan Ilavsky, Saul Lapidus
UC Davis/Hill Engineering: Christopher D'Elia, Michael Hill, Adrian DeWald
Cornell (CHESS): Darren Pagan

21 Scientists, 6 organizations



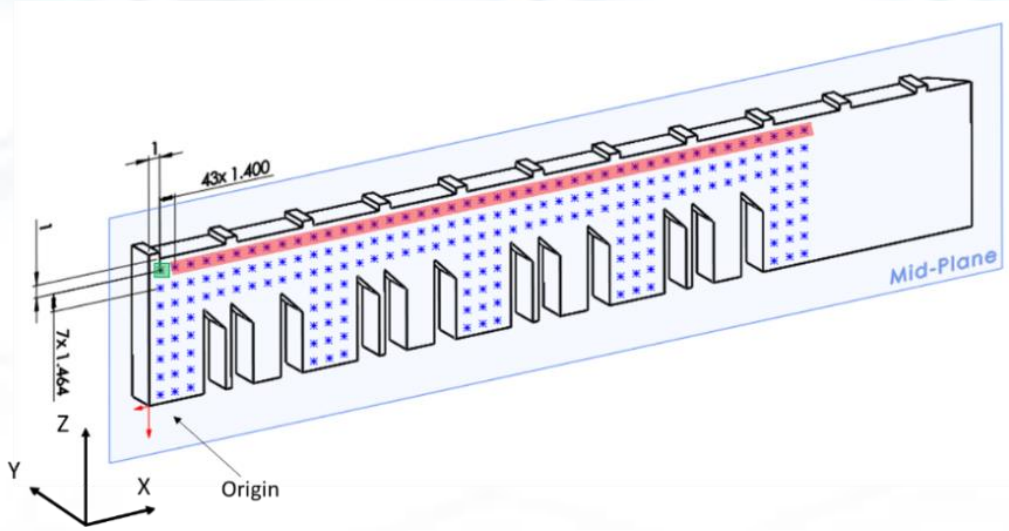

CBM, Track 5, Frame 20
T_{rad} (°C)
1100
1000
900
800
700
600
500
Scan direction
Y – [mm]
X – [mm]

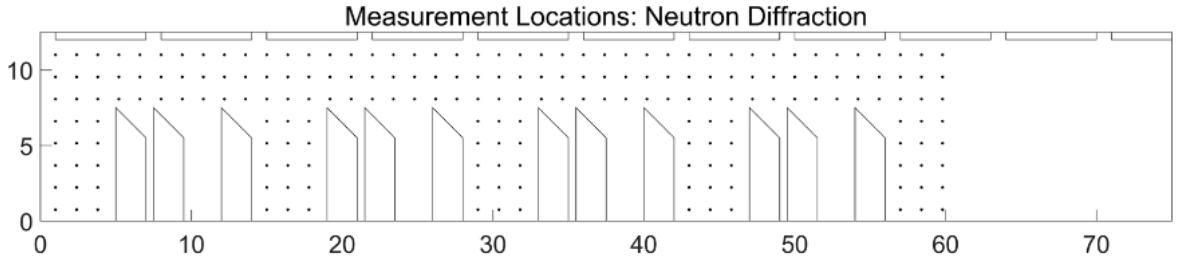

T_{rad} [°C]
T_{true} ($\epsilon \approx 0.23$) [°C]
Solidification,
T_{true} = 1290 °C
Temperature - [°C]
X – [mm]


Cooling rate (°C/s) x 10^5
Odd numbered layers
(X scan direction)
Even numbered layers
(Y scan direction)
Early layers
Z = 0.06 mm to 0.08 mm
Layer 3 and Layer 4
Midpoint of legs
Z = 2.50 mm to 2.52 mm
Layer 125 and Layer 126
Overhang
Z = 6.90 mm to 6.92 mm
Layer 345 and Layer 346
Midpoint of Bridge
Z = 9.52 mm to 9.54 mm
Layer 476 and Layer 477
A)
B)
C)
D)
E)
F)
G)
H)
L7
L8
L9
Bridge

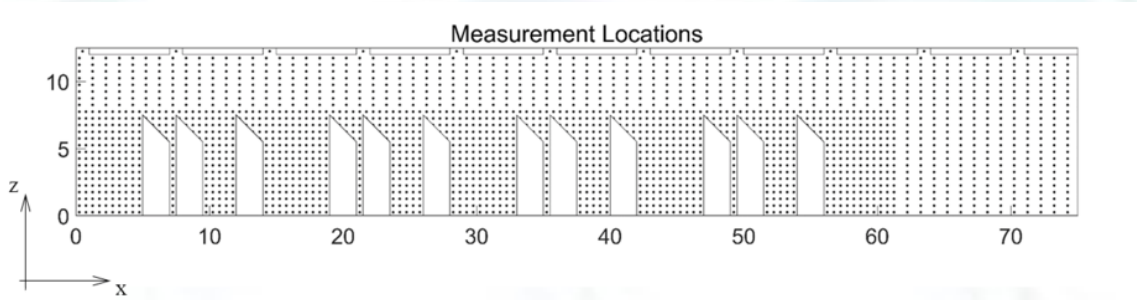
PI: J. Heigel

Neutron diffraction

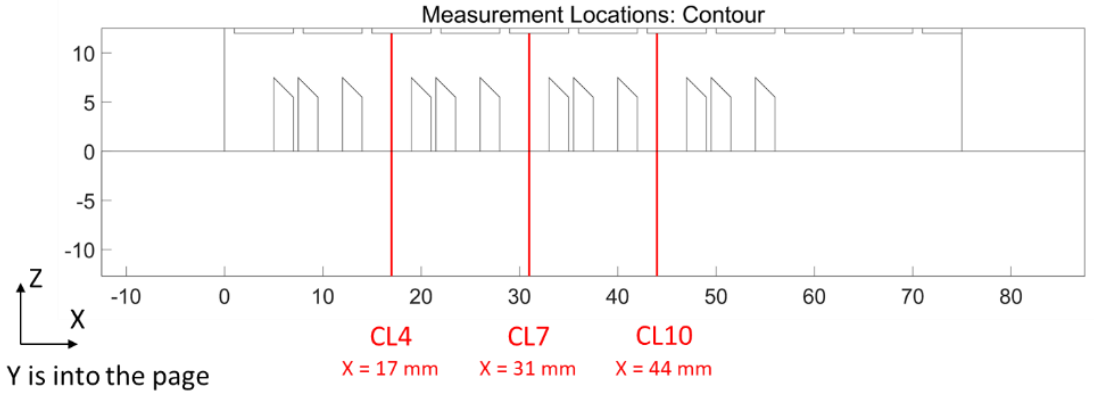




Synchrotron X-ray diffraction

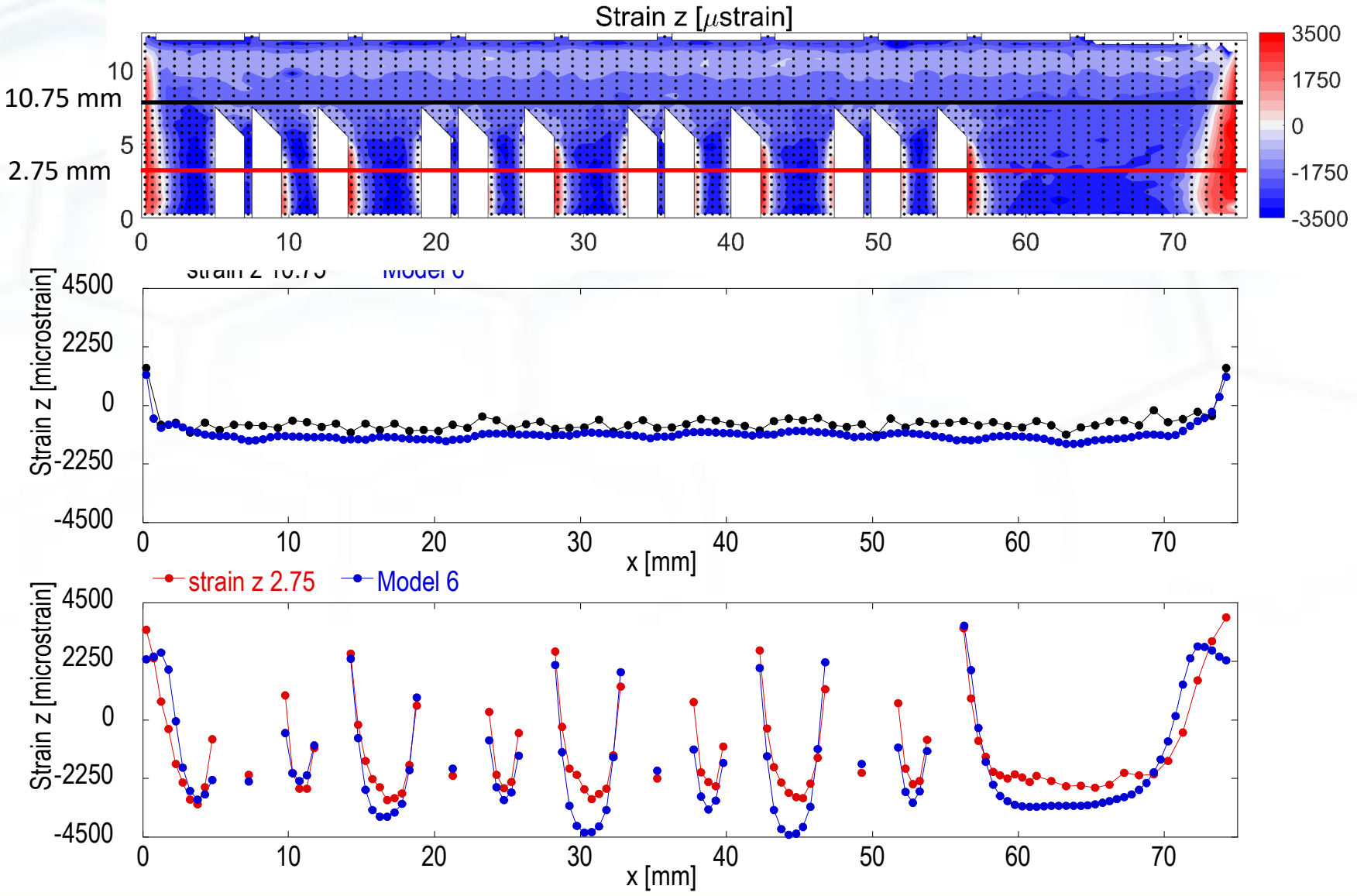


Contour method



PIs: T. Phan, M. Strantza, M. Hill

XRD comparison with model 6

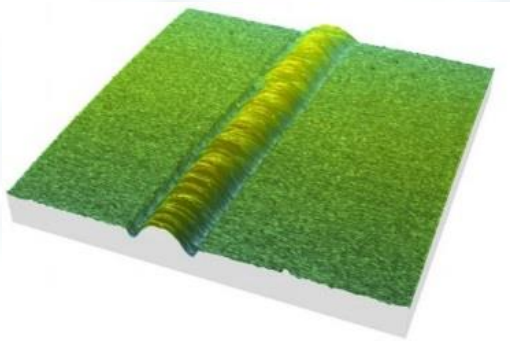


IN625

Benchmark Measurements

AMB2018-02: Individual laser traces on bare metal plates of IN625, using the three cases: A) 150 W, 400 mm/s, B) 195 W, 800 mm/s, C) 195 W, 1200 mm/s.

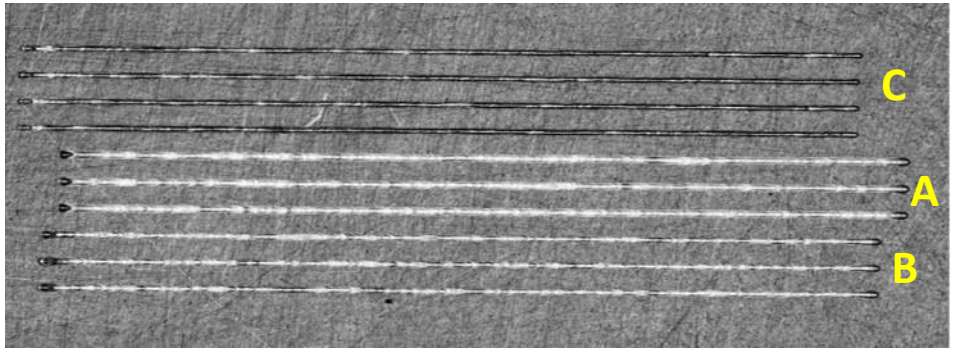
• **Melt pool geometry**	CHAL-AMB2018-02-MP
• **Cooling rate**	CHAL-AMB2018-02-CR
• **Topography**	CHAL-AMB2018-02-TP
• **Grain structure**	CHAL-AMB2018-02-GS
• **Dendritic microstructure**	CHAL-AMB2018-02-DM
• **Three-dimensional structure**	CHAL-AMB2018-02-3D



NIST: Carolyn Campbell, Sandra Claggett, Jarred Heigel, Vladimir Khromschenko, Brandon Lane, Lyle Levine, Sergey Mekhontsev, Thien Phan, Richard Ricker, Mark Stoudt, Maureen Williams, Ivan Zhirnov

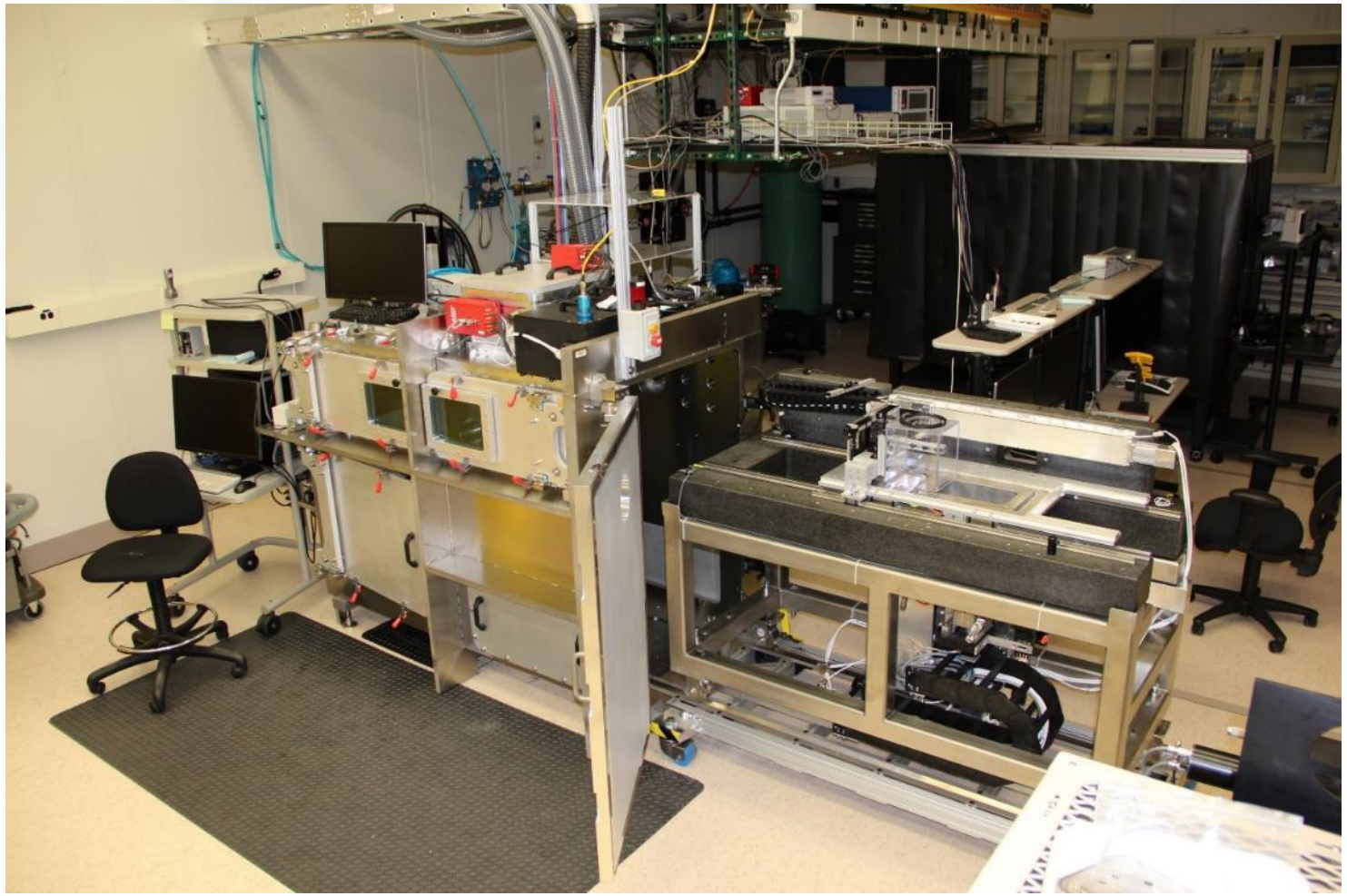
NRL: Richard Fonda, David Rowenhorst

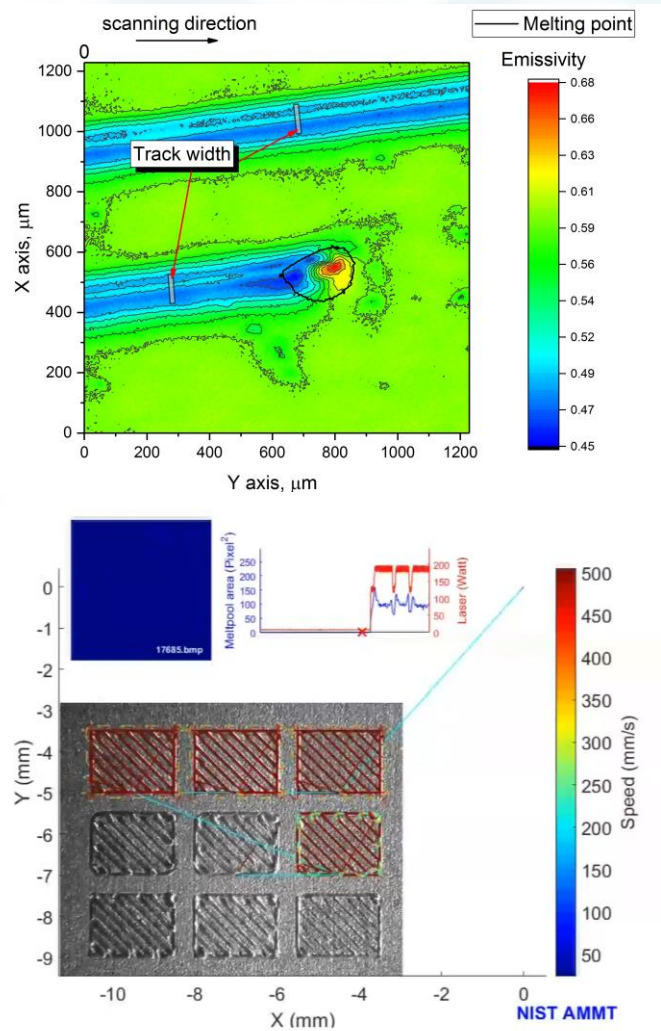
14 Scientists, 2 organizations



NIST Additive Manufacturing Metrology Testbed (AMMT)

B. Lane (EL), H. Yeung (EL), S. Mekhontsev (PML), S. Grantham (PML)

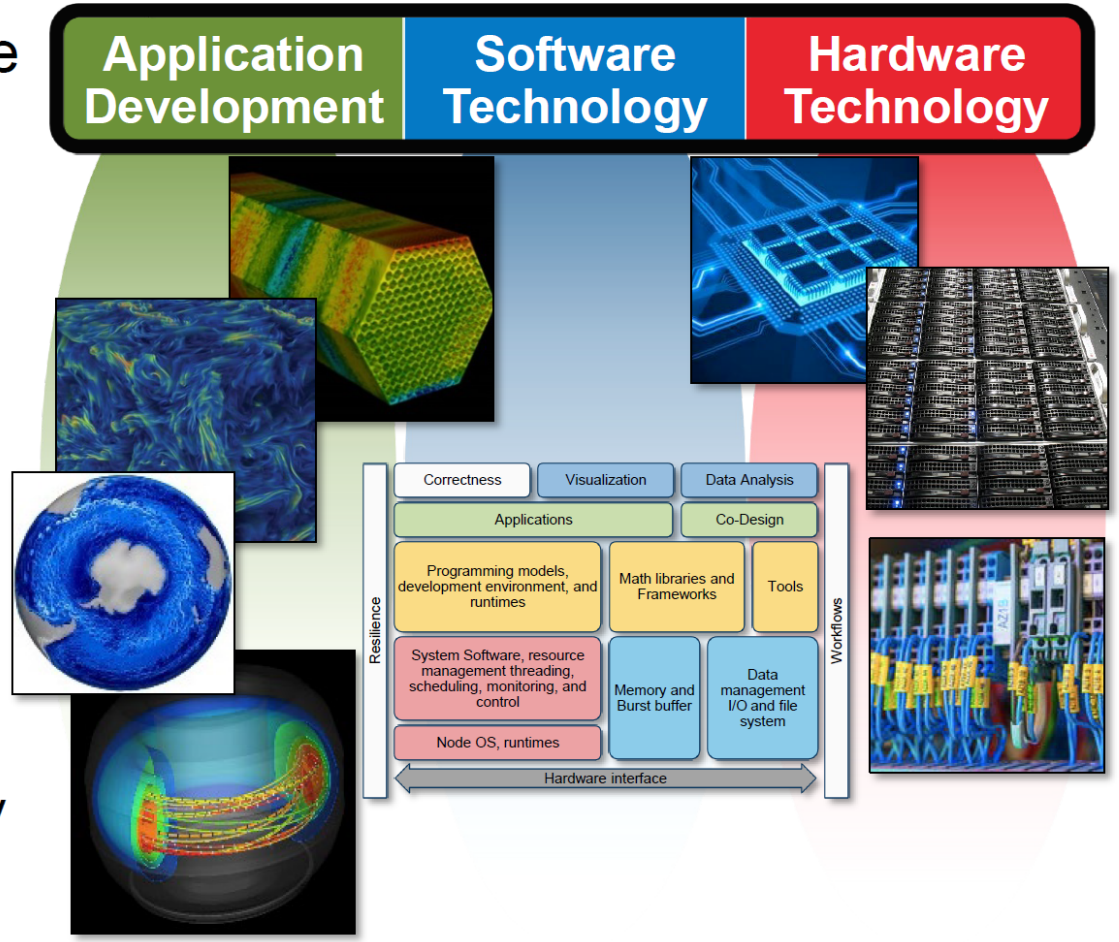




The Exascale Computing Project (ECP) is a collaboration between two DOE offices – The Office of Science (SC) and The National Nuclear Security Administration (NNSA)

A 7-year project (FY17-FY23) to accelerate development of a capable exascale ecosystem

- 50x the performance of 20 PF/s systems in operation in 2017
- Power envelope of 20–30 MW
- Resilient (average fault rate: ≤1/week)
- A software stack that meets the needs of a broad spectrum of applications and workloads
- Led by DOE laboratories, executed in collaboration with academia and industry



TRANSFORMING ADDITIVE MANUFACTURING THROUGH EXASCALE SIMULATION (EXAAM)

Advanced Manufacturing

Gaps and Opportunities

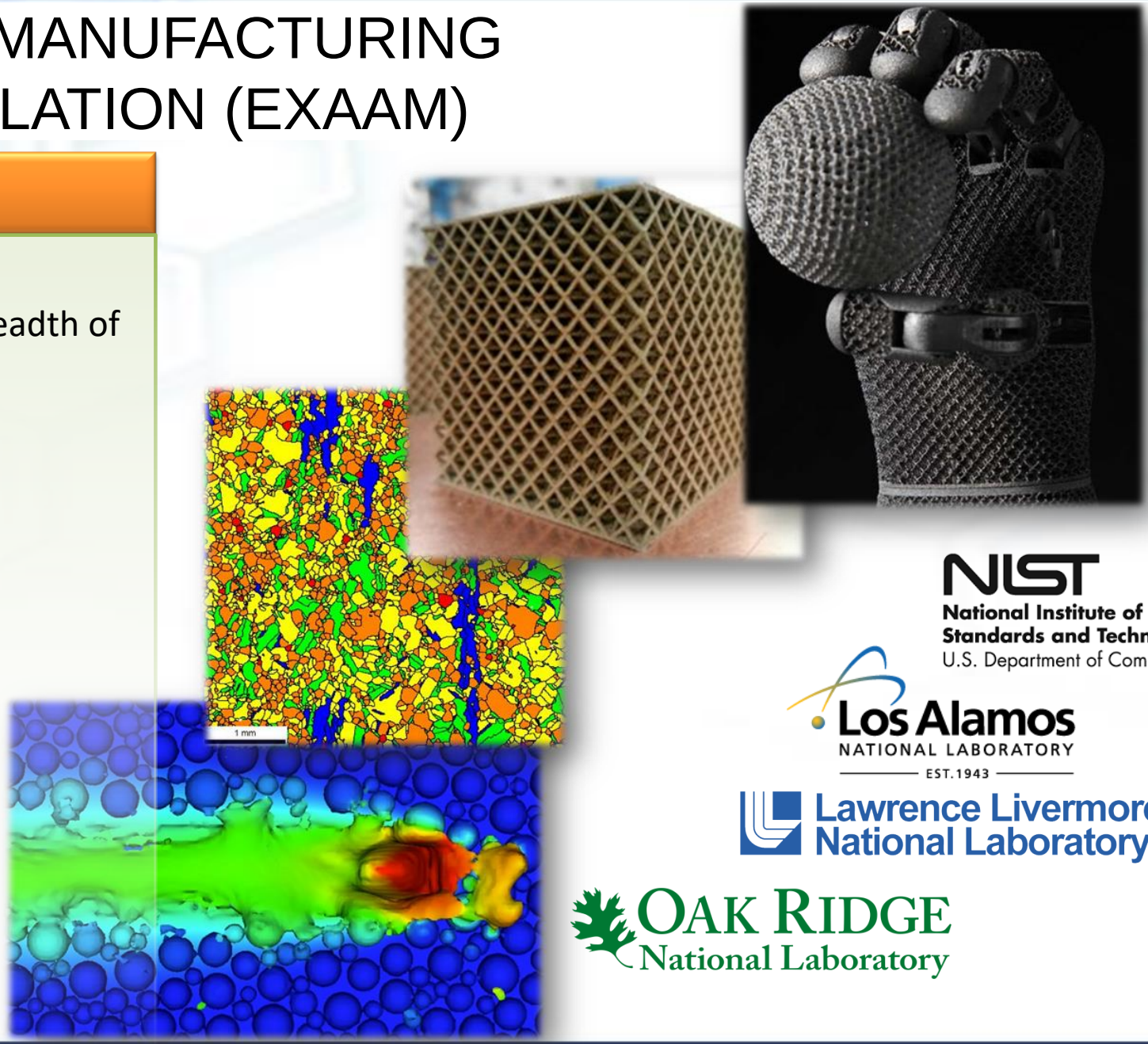
- Improve quality, reliability, and application breadth of additive manufacturing (AM)

Simulation Challenge Problems

- Continuum level predictions of non-uniform microstructure and its relationship to process parameters
- Predictive mesoscale models for dendritic solidification scale-bridged to continuum

Prospective Outcomes and Impact

- Routine qualification of AM parts via process-aware design specs and reproducibility through process control
- Fabrication of metal parts with unique properties such as light weight strength and failure-proof joints and welds



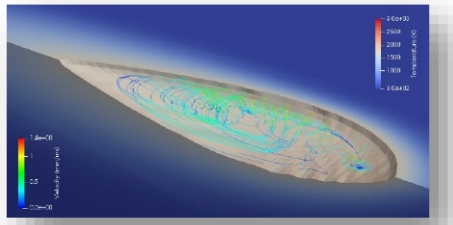
NIST National Institute of Standards and Technology U.S. Department of Commerce

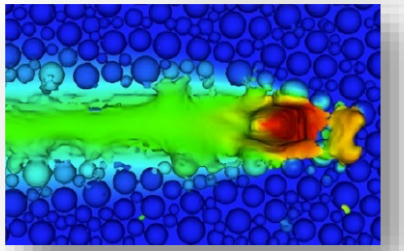
Los Alamos NATIONAL LABORATORY EST. 1943

Lawrence Livermore National Laboratory

OAK RIDGE National Laboratory

Additive Manufacturing Physics / Process Workflow and Selected ExaAM application codes (components)





Source temp. field, thermal properties, melt pool characteristics, net energy deposition

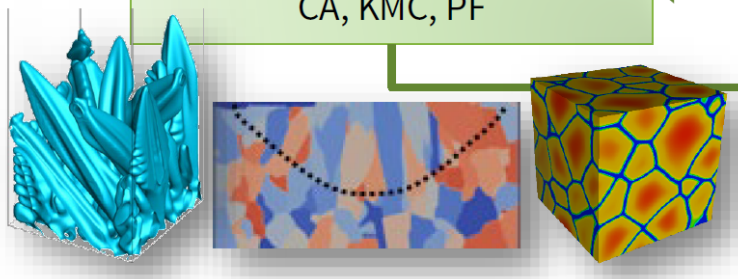
Melt pool scale
Eulerian FVM, ALE FEM, mesh-free / particle methods

Powder layer properties and beam parameters

Melt pool geometry, Composition, Solidification

Powder
DEM

Microstructure modeling
CA, KMC, PF



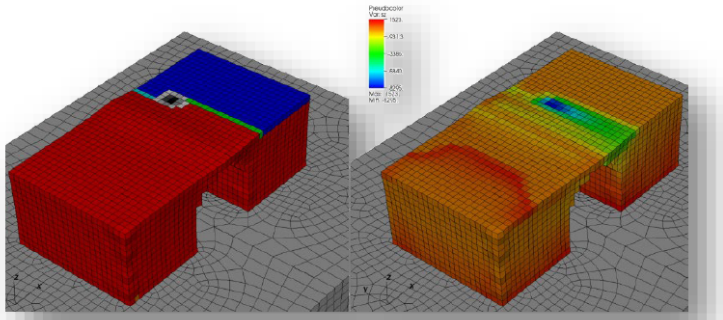
Residual stress, location-specific properties

Part scale
Lagrangian FEM

Residual stress, thermal profile

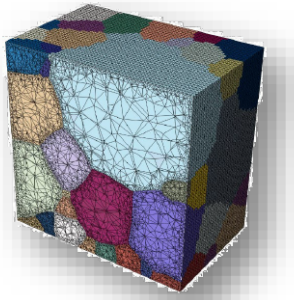
Performance
Lagrangian FEM

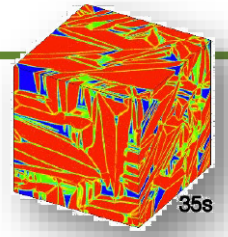
Topology / shape optimization



Microstructure informed material properties

Property modeling
Lagrangian FEM

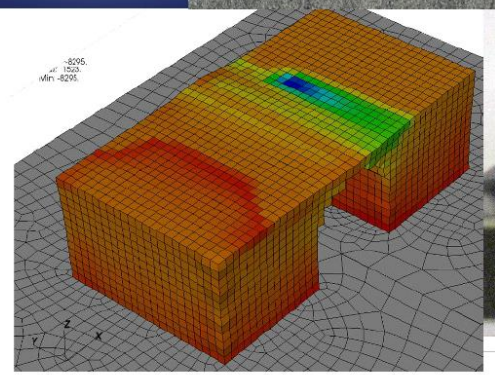


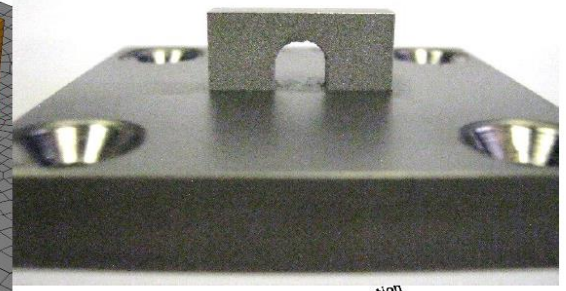


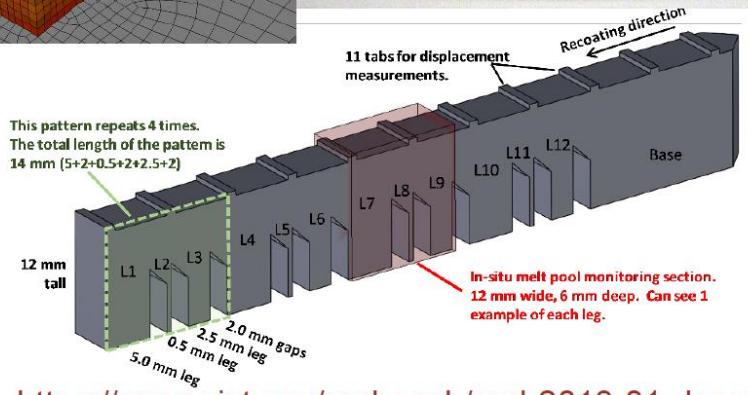
Evolving microstructure and defect statistics

Capability development driven by test problems

- Continuum scale
  - Single melt pool, multiple melt pools
  - Single track, multiple tracks
  - Single layer, multiple layers
  - Full part
- Mesoscale
  - Solidification
  - Solid-state phase transformation
- Coupled
  - Microstructure (composition, orientation, etc.)
  - Properties
  - Residual stress







https://www.nist.gov/ambench/amb2018-01-description

Community problem specifications, experimental data, and simulation results (e.g. AM-Bench, https://www.nist.gov/ambench)