The Additive Manufacturing Moment Measure – A Parallel Computation Technique for Determining Build Variance in the Laser Powder Bed Fusion Process

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MRS 2022 Spring Meeting
5/10/2022

Motivation

Several challenges have motivated many process modeling approaches for laser powder bed fusion (L-PBF) additive manufacturing (AM):

- Quality control of L-PBF AM parts
  - Ensure integrity of build instructions
  - Determine and measure variance from build instructions (digital twin)
  - Develop in-situ process monitoring techniques
- Reduce development cost for build strategies
  - Identify localized defect risk based on processing conditions

Additive Manufacturing (AM): Process Models

Many groups recognize the need for additive manufacturing process models

- High fidelity models
  - Khairallah et al., https://doi.org/10.1016/j.actamat.2016.02.014.
  - Martin et al., https://doi.org/10.1038/s41467-019-10009-2.
  - ….

Physical correctness
Highest computational cost
Part scales are not yet feasible
part scales: $1cm^3$ – $20cm^3$

- Analytical and semi-analytical models
  - Pinkerton et al., https://doi.org/10.1088/0022-3727/37/14/003.
  - Tapia et al. https://doi.org/10.1007/s00170-017-1045-z.
  - Groeber et al., https://doi.org/10.1088/1757-899x/219/1/012002.
  - Tang et al., https://doi.org/10.1016/j.addma.2016.12.001
  - Promoppatum et al., https://doi.org/10.1016/J.ENG.2017.05.023
  - Tang et al., https://doi.org/10.1007/s11665-018-3647-5
  - Stump et al., https://doi.org/10.1016/j.apm.2019.07.008.
  - Schwalbach et al., https://doi.org/10.1016/j.addma.2018.12.004.
  - Gordon et al., https://doi.org/10.1016/j.addma.2020.101552
  - Zagade et al., https://doi.org/10.1016/j.addma.2021.102222
  - Wang et al., https://doi.org/10.3390/cryst11121568
  - …

Lowered computational costs
Layer-wise thermal history
Mesh generation & optimization
Time-step approach
Localized build conditions:
- Not addressed, or
- Memory bounded for part scales

- Graph theory-based models
  - Rao et al., https://doi.org/10.1115/msec2016-8516.
  - Fruggiero et al., https://doi.org/10.1016/j.promfg.2019.09.022.
  - Cole et al., https://doi.org/10.1016/j.ijthermalsci.2020.106383.
  - Yavari et al., https://doi.org/10.1115/1.4043648
  - Yavari et al., https://doi.org/10.1115/1.4047619.
  - …

Lowered computational costs
Point-wise approach
Layer-wise thermal history
Time step approach
Memory bounded for part scales

The Additive Manufacturing Moment Measure (AM3) Approach

<u>Additive Manufacturing</u>

- *"Process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies"*
  - ISO/ASTM 52900:2021, Additive manufacturing - General principles - Terminology

<u>Moment Measure</u>

- Motivated from physics, a moment measure is the generalization of the concept of a moment to a discrete point field of observables

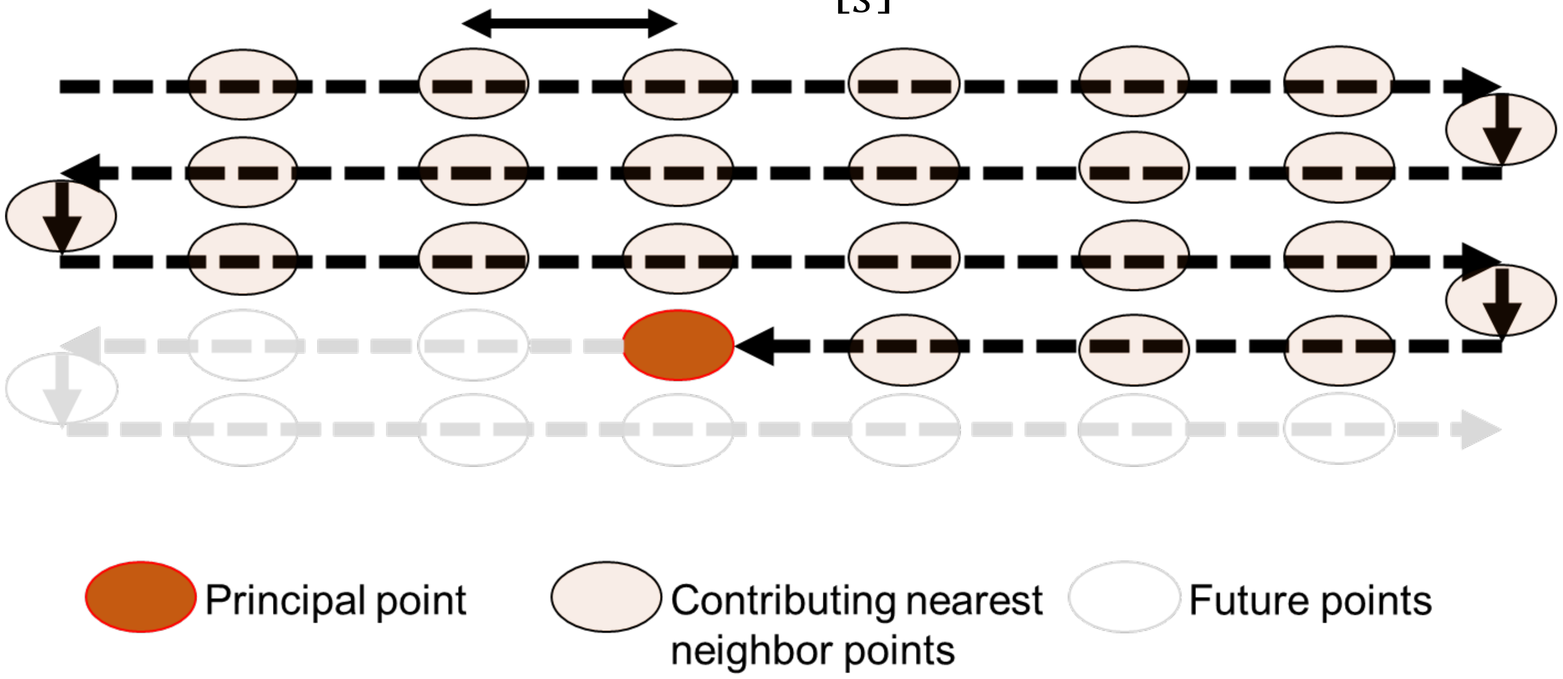
- Combined = Additive Manufacturing Moment Measure (AM3)

  - Rapid part scale modeling of process conditions
  - Compare modeling against in-situ monitoring
  - Evaluate of build instructions
  - Measure variances from build instructions

AM3 Approach: Concept Illustration

- Calculate the moment measure at “principal point” as a sum of conditional intensity functions applied to neighbor points

$$[mm]distance = \frac{\left[\frac{mm}{s}\right] velocity}{\left[\frac{1}{s}\right] sampling\ rate}$$



i j j

AM3 Approach: Point Field

point (*i*, *j*)	x	y	z	power (P)	speed (V)	Time (t)
0	8.89	6.12	3.6	347	509	5504.9752
1	9.08	5.75	3.6	347	1249	5504.9756
2	9.34	5.24	3.6	343	1260	5504.9762
3	9.59	4.77	3.6	345	1330	5504.9766
4	9.85	4.26	3.6	9.4	1263	5504.9772
…	…	…	…	…	…	…
11647	10.66	-0.69	3.6	54	731	5511.2567
11648	10.68	-0.53	3.6	57	234	5511.2572
11649	10.81	-0.5	3.6	57	505	5511.2577
11650	11.06	-0.55	3.6	54	289	5511.2582
11651	10.94	-0.49	3.6	57	720	5511.2587

In-situ process measured point field data for build layer at 3.6 [mm]

AM3 Approach: Build Illustration

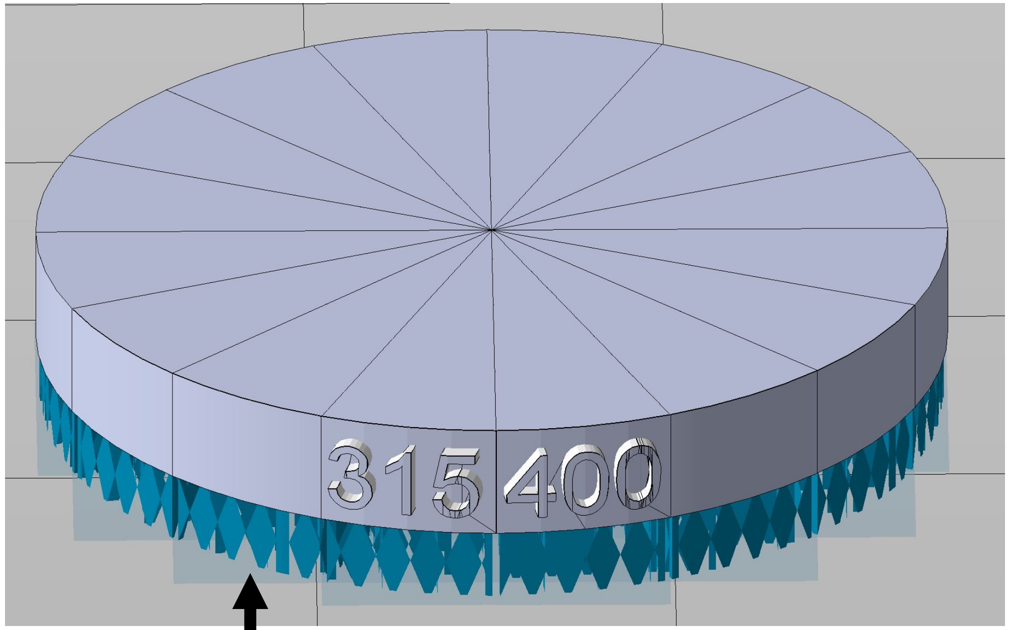
- Ti-6Al-4V L-PBF part with complex process conditions

Build meta-data

  - Speeds: 825, 940, 1060, 1175, 1300, 1400, 1530, 1650 [mm/s]
  - Powers: 350, 275 [W]
  - Contours: 130 [W], 825 [mm/s]
  - Hatch spacing: 0.1 [mm]

- Configurable Architecture Additive Testbed
  - Instrumented for LPBF diagnostic research
  - 1070 [nm] laser, IPG Photonics

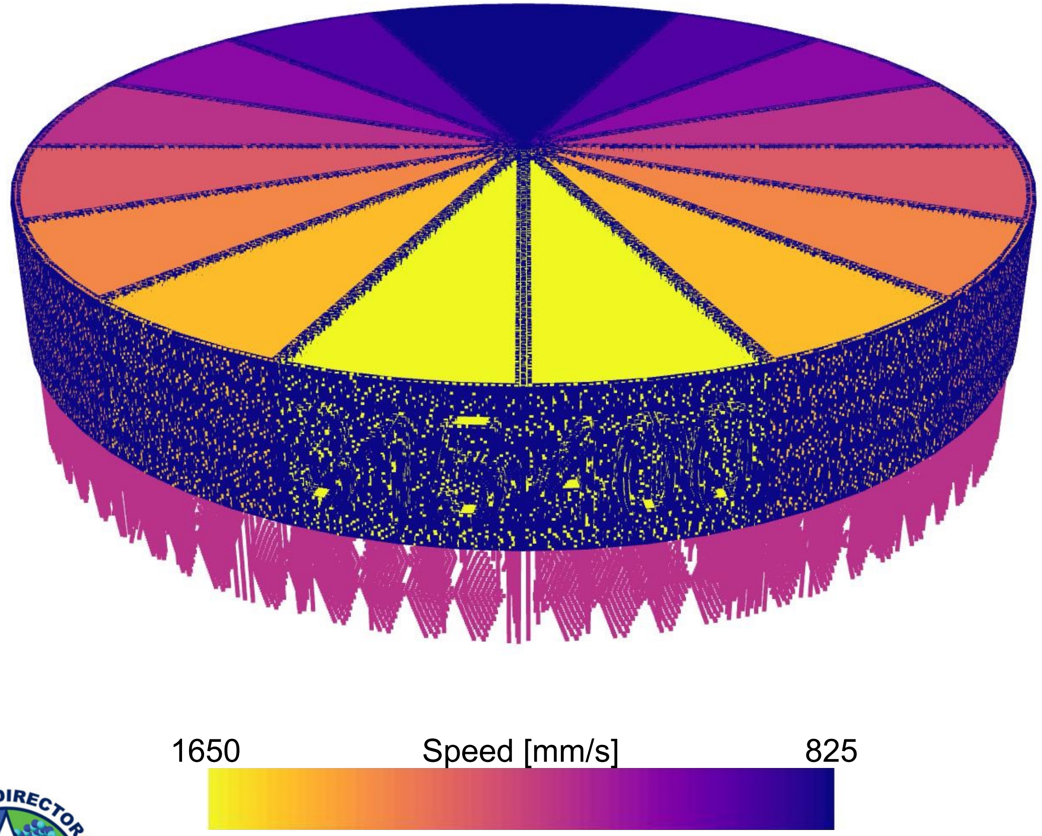
Visualized PBF Part that will be built



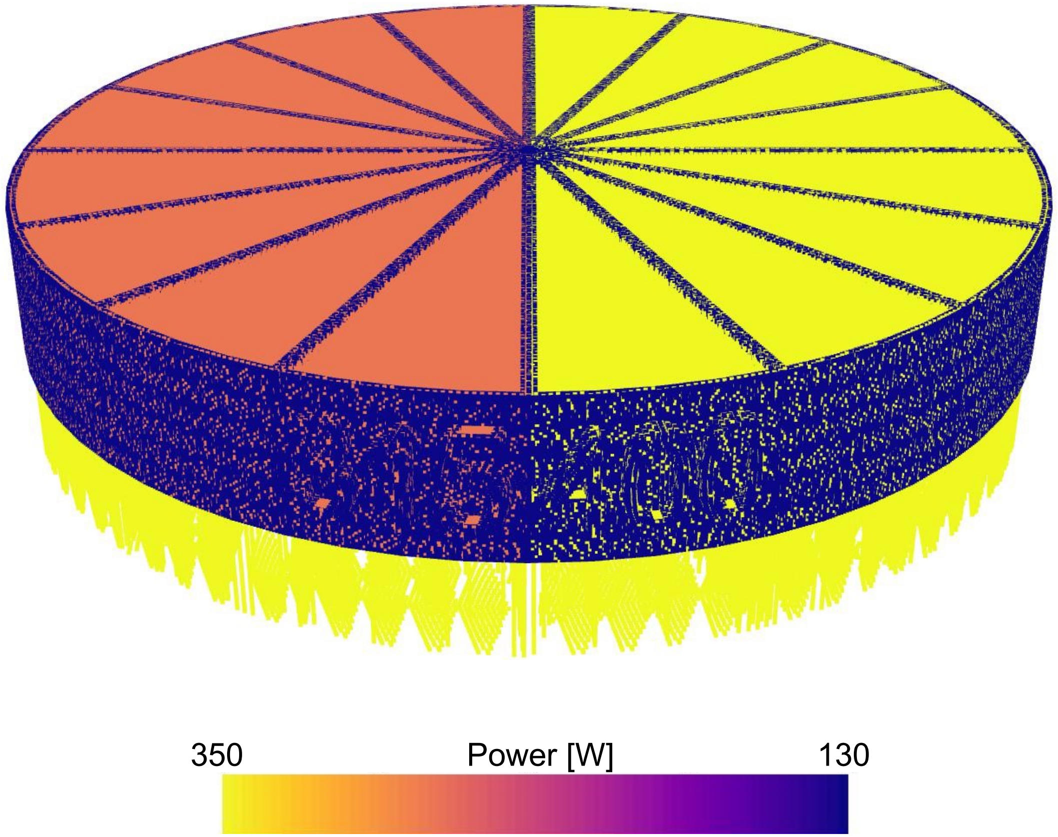
Support material

AM3 Approach: Build Illustration

❖ Speed



❖ Power



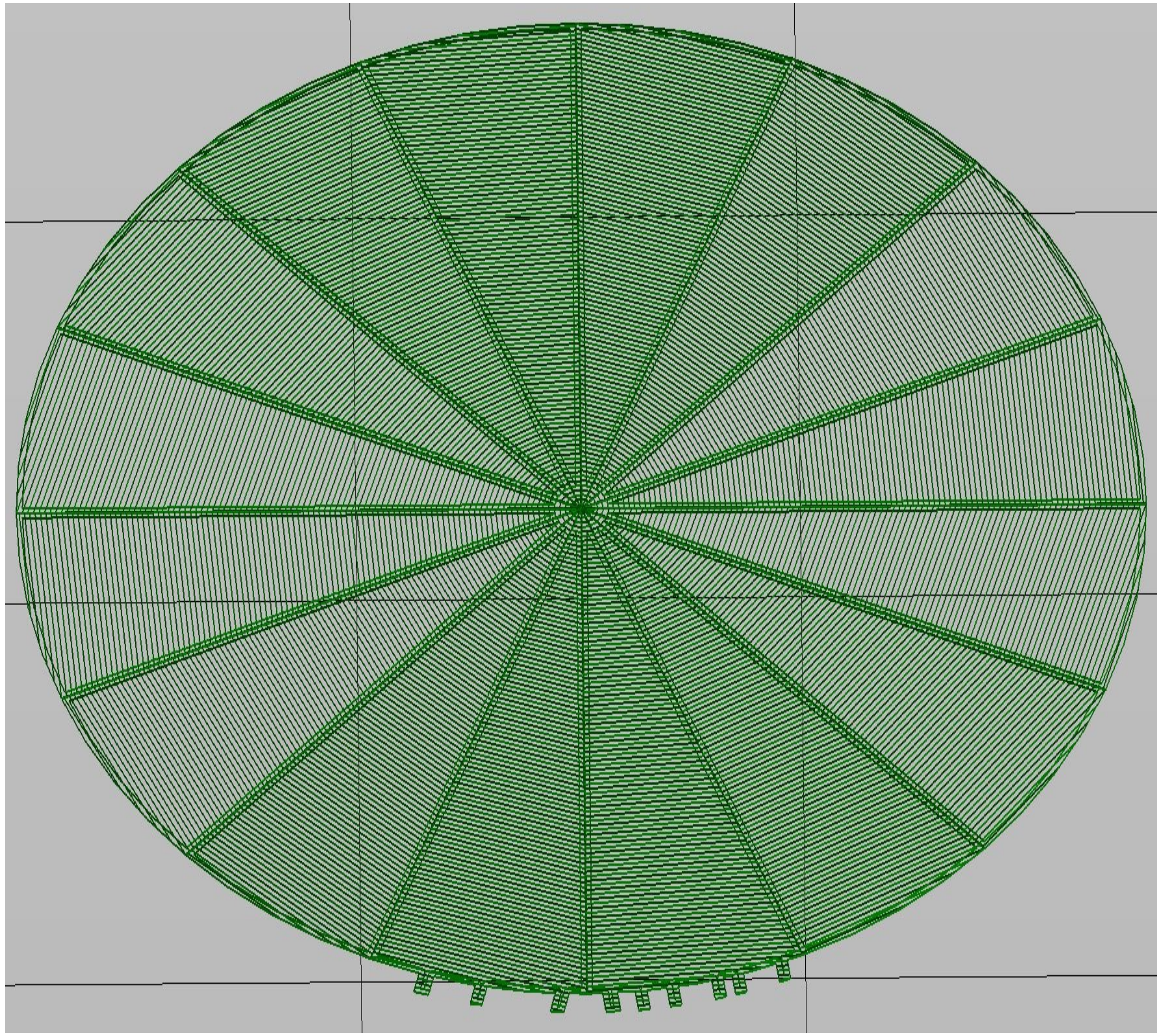
AM3 Approach: Build Instructions

Small subset of total instructions…

$$**LAYER**/3600
$$**POWER**/400.0
$$**SPEED**/1300.0
$$**HATCHES**/1,106,10435,7243,11688,4835,11577,4788,9983,7850,9619,8291,11466,4742,11354,4696,9301,8642,8985,8987,11243,4650,11132,4604,8893,8905,8804,8816,11021,4558,10909,4512,8715,8728,8626,8639,10798,4466,10687,4419,8537,8550,8448,8461,10576,4373,10464,4327,8359,8372,8270,8283,10353,4281,10242,4235,8181,8194,8092,8105,10130,4189,10019,4143,8003,8016,7914,7927,9908,4096,9797,4050,7825,7838,7736,7749,9685,4004,9574,3958,7647,7660,7558,7571,9463,3912,9352,3866,7469,7482,7380,7393,9240,3820,9129,3774,7291,7304,7202,7215,9018,3727,8906,3681,7113,7126,7024,7037,8795,3635,8684,3589,6935,6948,6846,6859,8573,3543,8461,3497,6757,6770,6668,6681,8350,3451,8239,3405,6579,6592,6491,6503,81
$$**POWER**/150.0
$$**SPEED**/700.0
$$**POLYLINE**/1,2,9,11743,4858,11209,5992,10569,7061,9825,8063,8987,8987,8977,8990,-10,3,2,-10,11743,4858
$$**POLYLINE**/1,2,7,10459,6991,9726,7978,8976,8806,512,342,11571,4923,11097,5925,10459,6991
$$**POWER**/400.0
$$**SPEED**/1200.0
$$**HATCHES**/2,106,6867,10686,8951,8937,8866,8852,6216,11076,5712,11342,8781,8767,8695,8682,5284,11544,4862,11742,8610,8597,8525,8512,4808,11631,4759,11515,8440,8426,8355,8341,4711,11398,4663,11282,8269,8256,8184,8171,4615,11166,4567,11050,8099,8086,8014,8001,4519,10933,4471,10817,7929,7915,7843,7830,4422,10701,4374,10585,7758,7745,7673,7660,4326,10468,4278,10352,7588,7575,7503,7490,4230,10236,4182,10120,7417,7405,7332,7319,4134,10003,4085,9887,7247,7234,7162,7149,4037,9771,3989,9655,7076,7064,6991,6979,3941,9538,3893,9422,6906,6894,6821,6809,3845,9306,3797,9190,6736,6723,6650,6638,3748,9073,3700,8957,6565,6553,6480,6468,3652,8841,3604,8725,6395,6383,6310,6298,3556,8608,3508,8492,6224,6212,6139,6127,3460,8376,3411,8260,6054,6042,5969,5957,3363,8143,3315,8027,5884,5872,5798,5787,3267,7911,3219,7795,5713,5702,5628,5616,3171,7678,3122

AM3 Approach: Build Layer

- ❖ Known process steps
- ❖ Complex patterns
- ❖ Localized processing conditions
- ❖ Previous points influence current points



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In-situ process measured point field data for build layer at 3.6 [mm]

AM3 Approach: Equations

(1) $$AM3_i = \sum_{j}^{N} F_{i,j}$$

(2) $$F_{i,j} = \begin{cases} f_{i,j}, & r_{i,j} \leq n_{i,j} \\ 0, & r_{i,j} > n_{i,j} \end{cases}$$

(3) $$r_{i,j} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2}$$

(4) $$n_{i,j} = \begin{cases} R, & 0 \leq \tau_{i,j} \\ -1, & 0 > \tau_{i,j} \end{cases}$$

(5) $$\tau_{i,j} = t_i - t_j$$

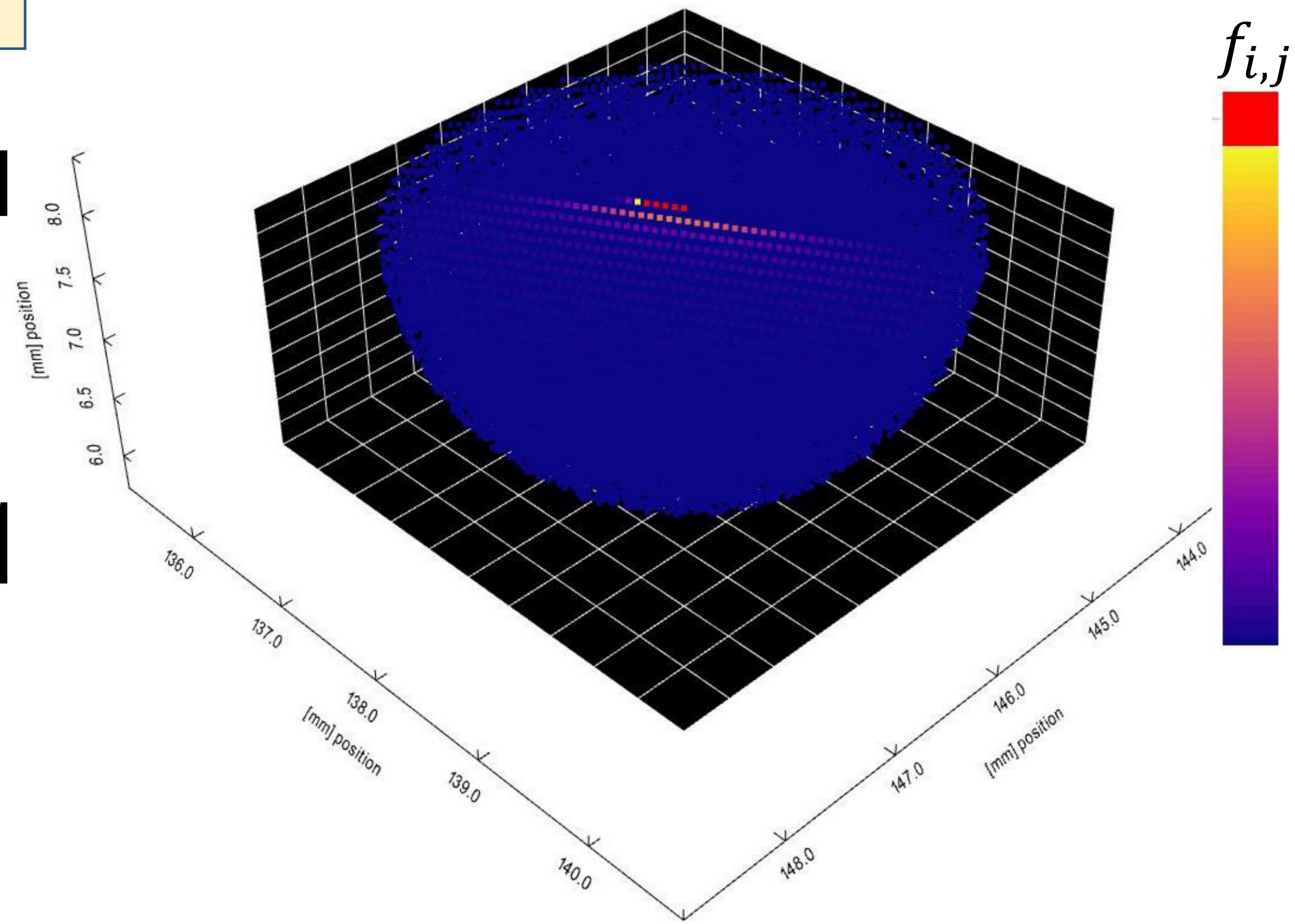
$i, j \in process\ point\ field$

$R = neighborhood\ radius$

AM3 Approach: Concept Illustration

$i, j \in process\ point\ field$

$$AM3_i = \sum_{j}^{N}$$

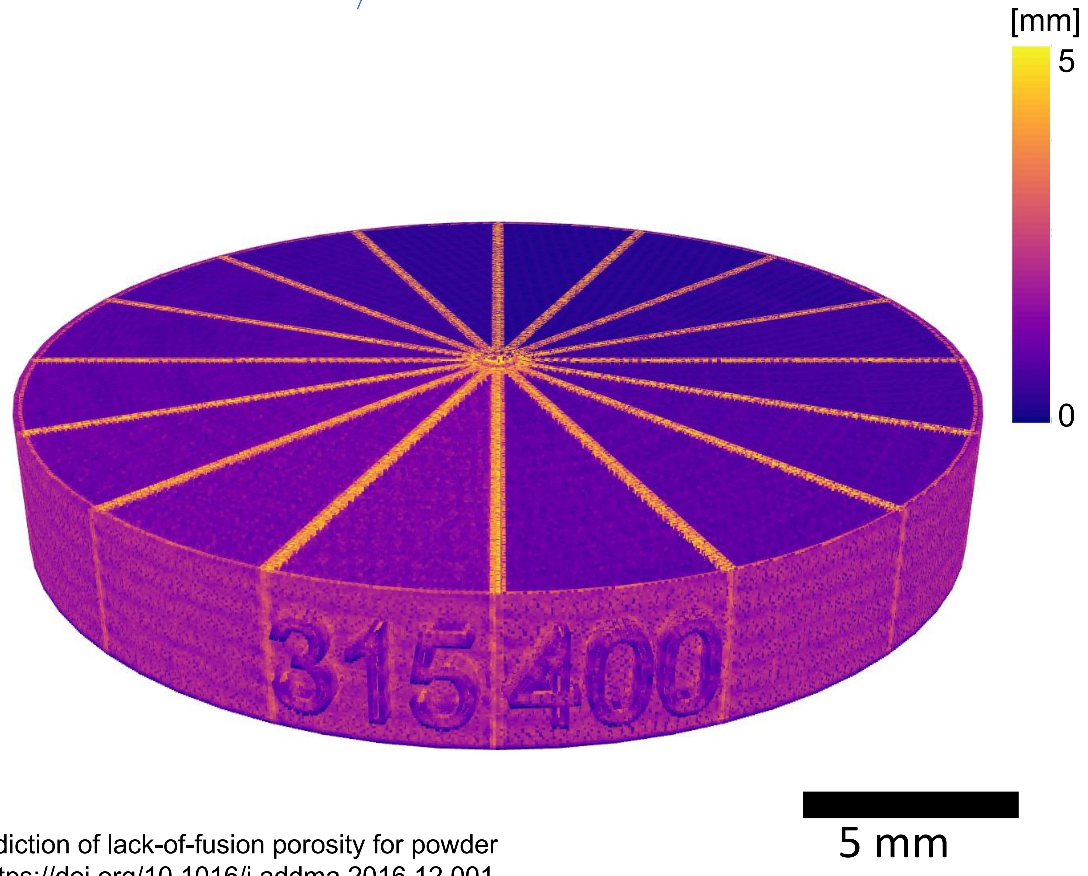


AM3: LoF Moment Measure

$$f_{i,j} = \frac{V_j}{\nu_j}, R \propto 0.5\sqrt{\frac{8}{\pi e}\frac{\lambda P_i}{\rho C_p V_i (T_m - T_0)}}$$

Lack of fusion indicator

- Melt pool width estimation
  - Derived from Rosenthal equation
    - Tang et. al. 2017
- Neighborhood criteria
  - Within specified radius
    - proportional to the melt pool width
  - Lower time-stamp than principal point (past)
  - Additional conditionals can be applied



Tang, M., Pistorius, P.C. and Beuth, J.L., 2017. “Prediction of lack-of-fusion porosity for powder bed fusion.” Additive Manufacturing, 14, pp.39-48. https://doi.org/10.1016/j.addma.2016.12.001

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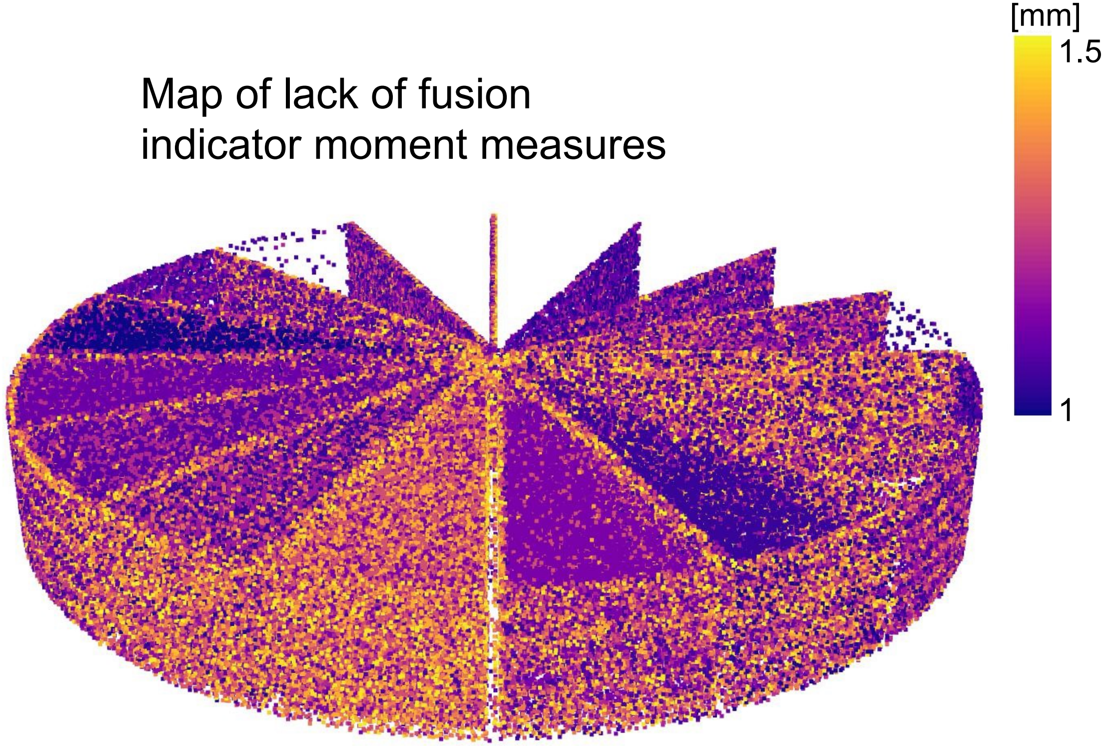
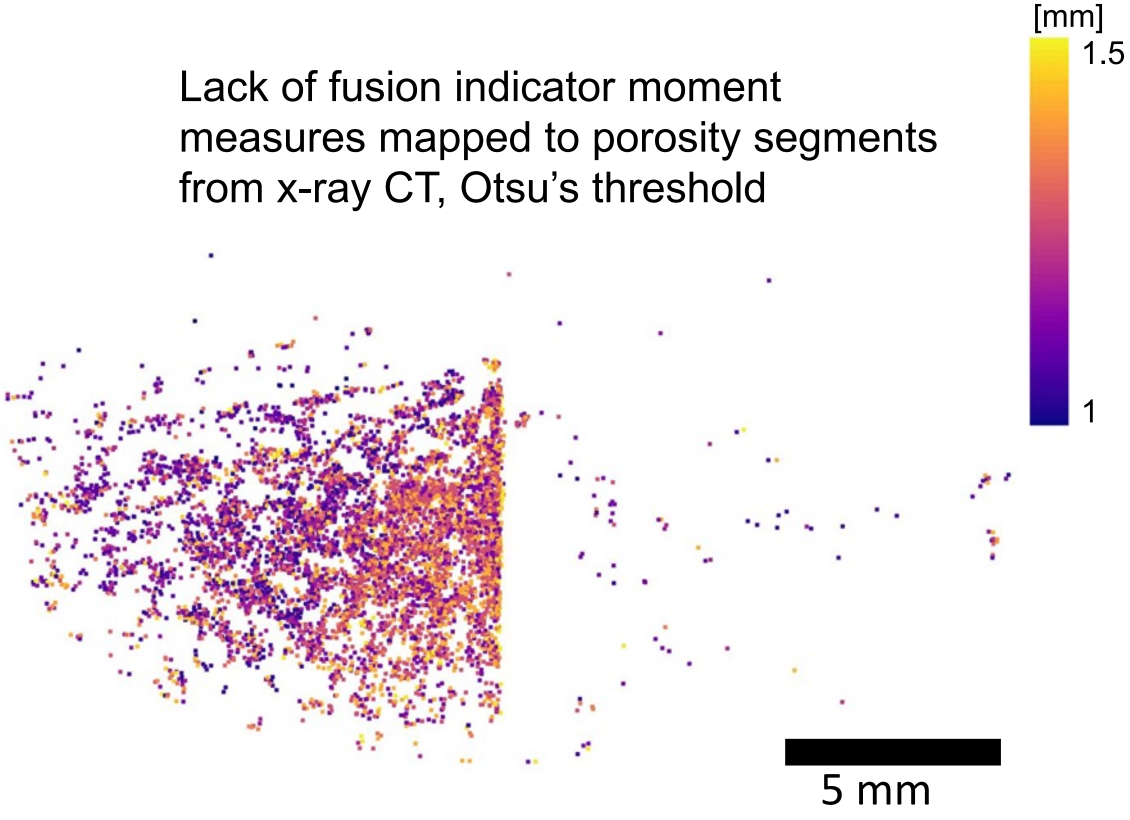
Lack of fusion
indicator

Map of lack of fusion
indicator moment measures



Lack of fusion indicator moment
measures mapped to porosity segments
from x-ray CT, Otsu's threshold

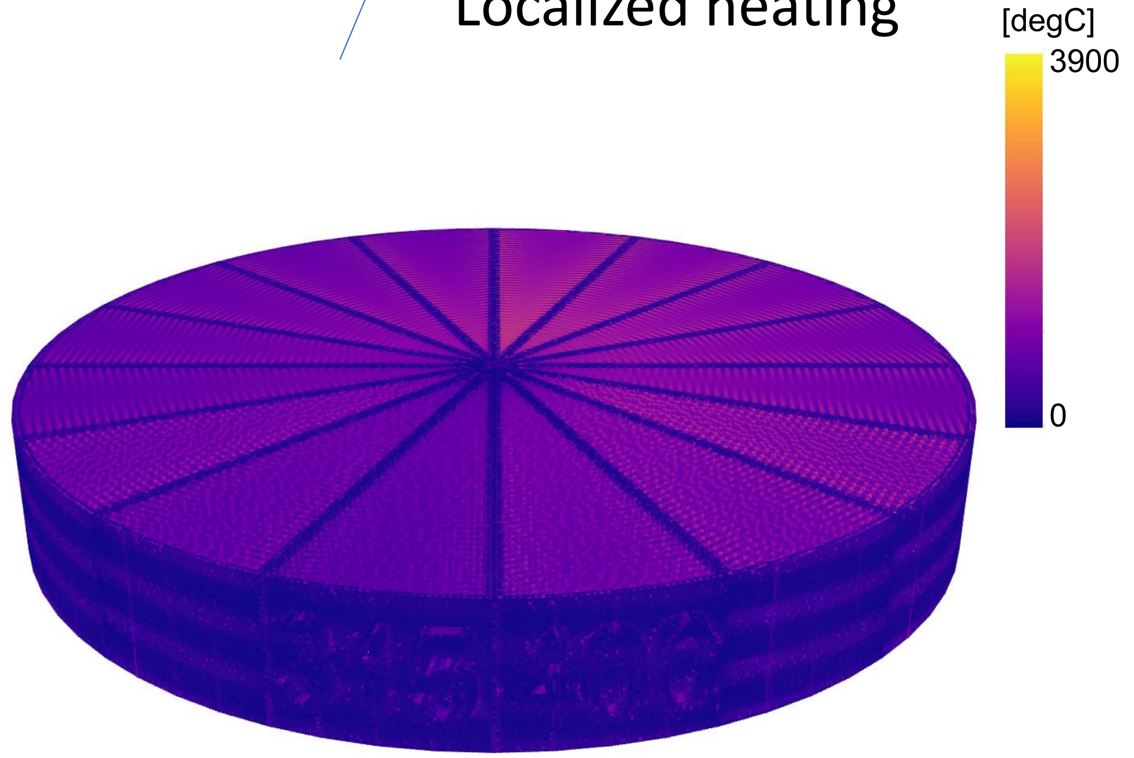


AM3: Thermal Rise Moment Measure

$$f_{i,j} = \frac{\frac{\lambda P_j}{\nu_j}}{\rho C_p \sqrt{2}\pi^{2/3}(\sigma_j^2 + 2\alpha\tau_{i,j})^{2/3}} \, exp^{-\frac{r_{i,j}^2}{2(\sigma_j^2+2\alpha\tau_{i,j})}}$$

Thermal rise:
Localized heating

- Green's function heat equation
  - Adapted from Groeber et al. 2017
- Neighborhood criteria
  - Within specified radius
  - Lower time-stamp than principal point (past)
  - Additional conditionals can be applied



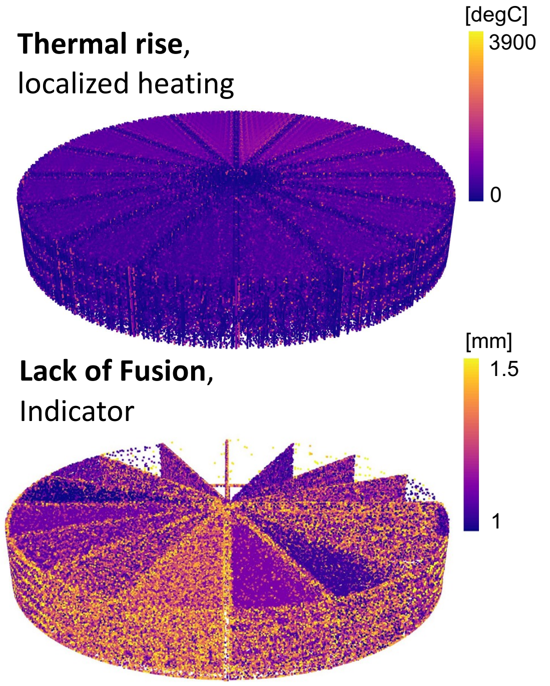
5 mm

Groeber, M A, E Schwalbach, S Donegan, K Chaput, T Butler, and J Miller. 2017. "Application of Characterization, Modelling, and Analytics Towards Understanding Process-Structure Linkages in Metallic 3d Printing." IOP Conference Series: Materials Science and Engineering 219 (July): 012002. https://doi.org/10.1088/1757-899x/219/1/012002. Modified the 6th equation of the article to be compatible with the point field approach.

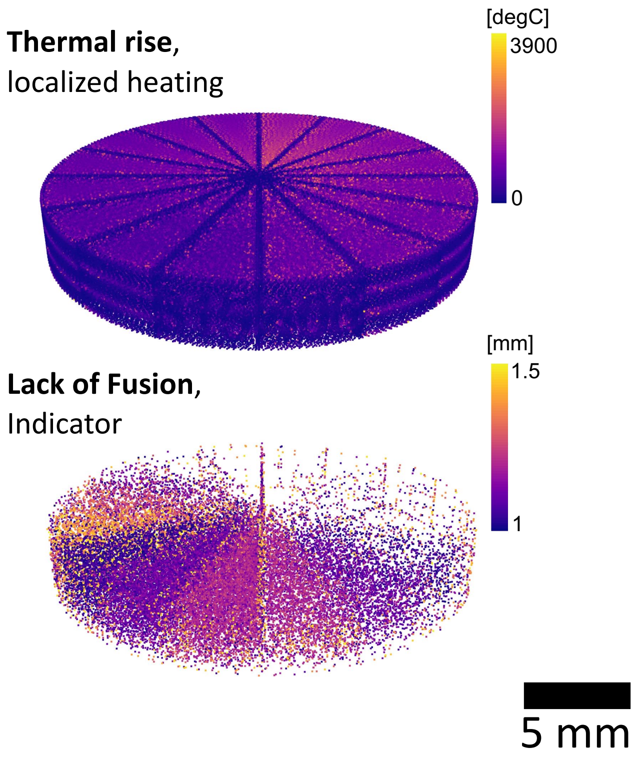
AM3: Point Fields from Build Instructions OR In-situ Measurements

- AM3 approach is good for process to microstructure R&D
- Multiple moment measures calculated with a single pass
- Measures of build variance

Build instructions generated point field



In-situ measurement point field



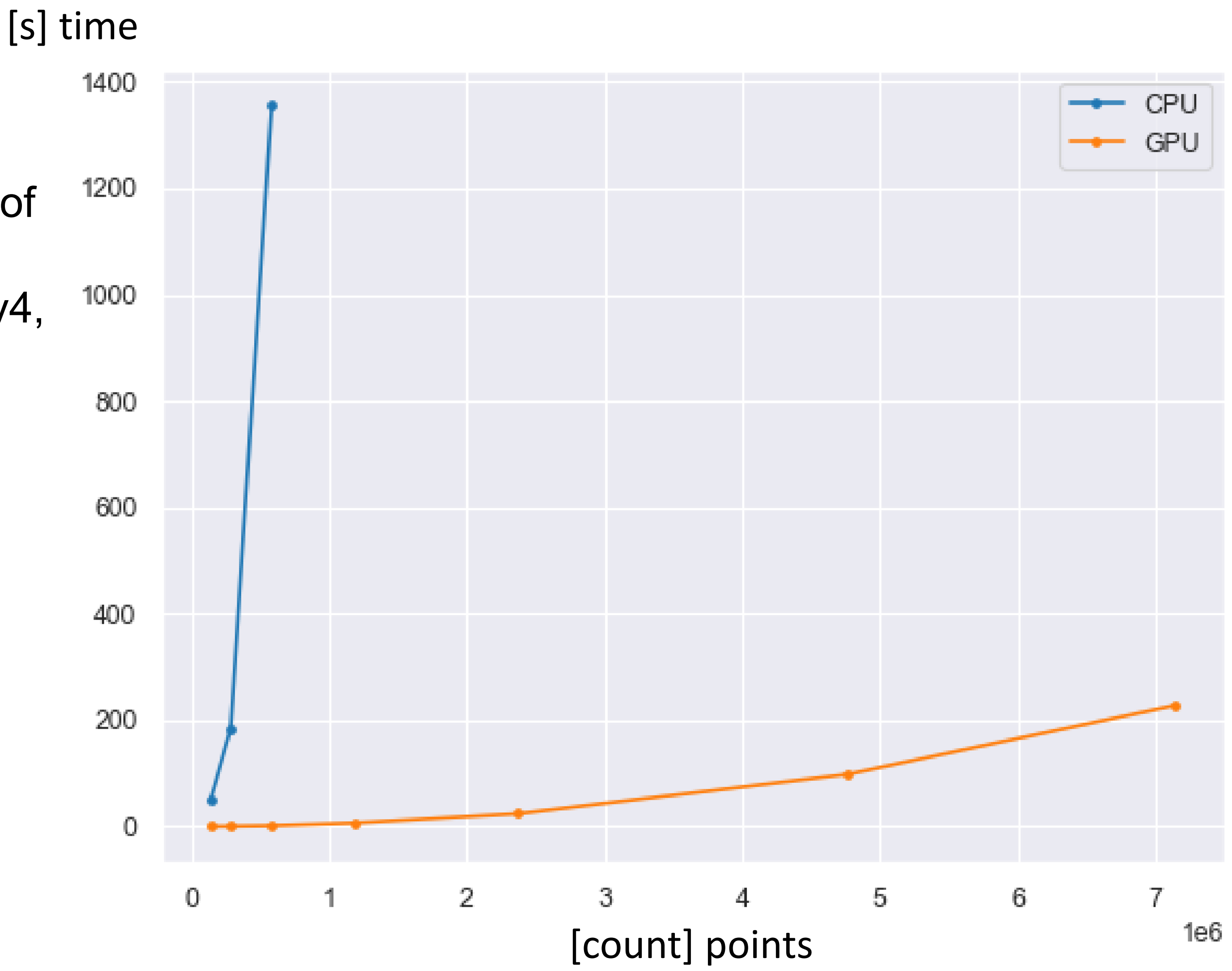
Experimental

Optical microscopy of top surface

CT Scan of Porosity

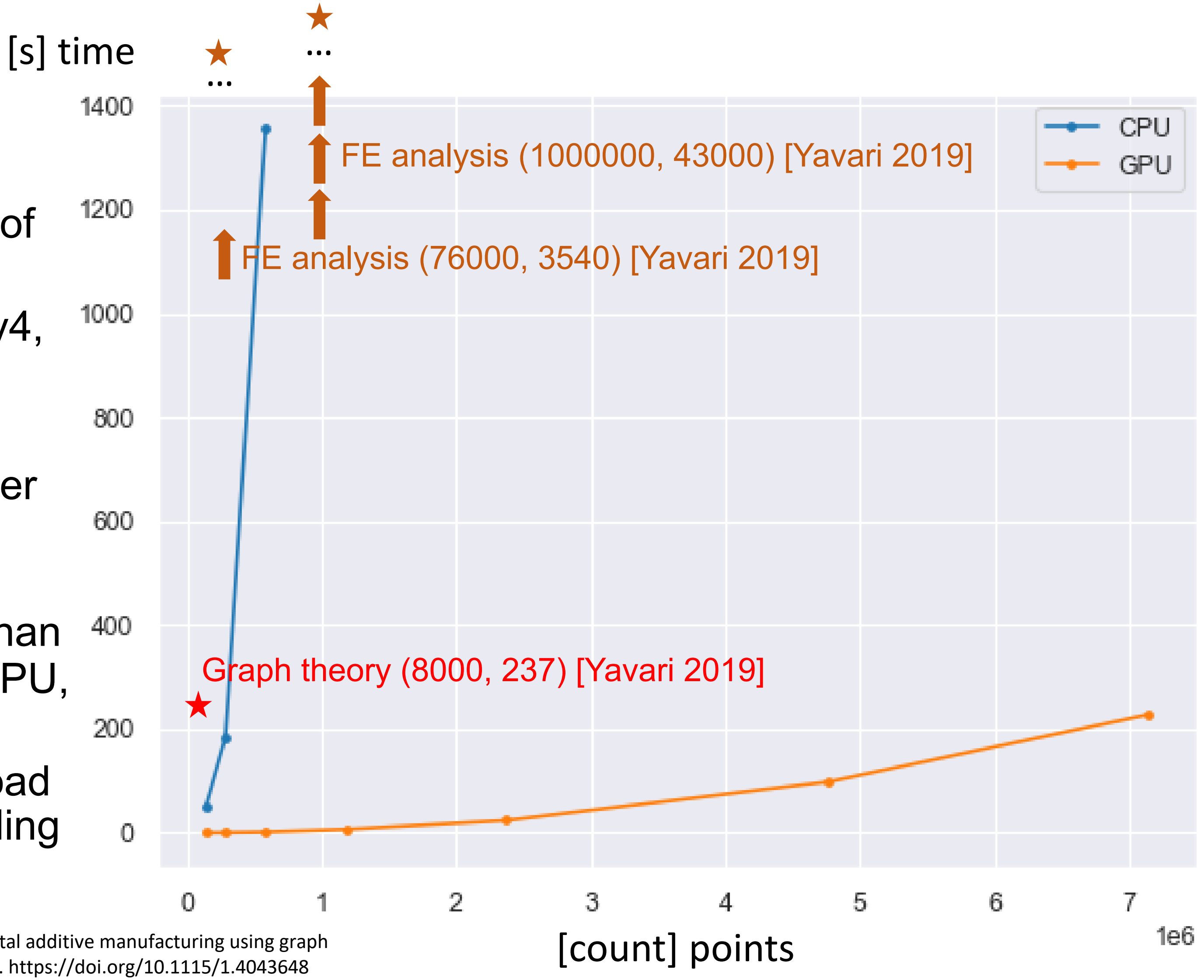
AM3 Approach: Fully Parallel Performance

- AM3 calculation performance:
  - CPU vs GPU per number of points
  - CPU: Intel Xeon E5-2667v4, 128 Gb RAM
  - GPU: Nvidia Titan V



AM3 Approach: Fully Parallel Performance

- AM3 calculation performance:
  - CPU vs GPU per number of points
  - CPU: Intel Xeon E5-2667v4, 128 Gb RAM
  - GPU: Nvidia Titan V
  - AM3-GPU is 10,000x faster than equivalent CPU-FE analysis
  - AM3-CPU is ~10x faster than equivalent graph theory-CPU, 4,000x faster on the GPU
  - Minimization of memory load is key for part scale modeling



Yavari, M.R., Cole, K.D. and Rao, P., 2019. "Thermal modeling in metal additive manufacturing using graph theory." Journal of Manufacturing Science and Engineering, 141 (7). https://doi.org/10.1115/1.4043648

AM3: Conclusions and Future Work

- AM3 is a process point field approach
  - Low-cost process condition models for AM (fast)
  - Quantify localized build conditions
  - Evaluate build quality – instructed vs measured
  - Achieve multiple moment measures with a single pass
- Future Work
  - Determine statistical relationships between AM3 values, in-situ sensor measurements, and the resulting microstructures
  - Improve "physical correctness" by developing multi-pass and boundary informed approaches

Acknowledgements

- NASA, Transformational Tools and Technologies project
- NASA Langley, Advanced Materials and Processing Branch
  - Joel Alexa, Peter Messick, James Thornton, Harold Claytor
    - Analytical Mechanics Associates, Hampton VA
- NASA Langley, Nondestructive Evaluation Sciences Branch
  - William Sommer
    - Analytical Services & Materials, Hampton VA

Back-ups

AM3 Approach: Summary

- Qualitative part-scale process model:
  - Physically informed process indicators
- Minimized Memory Requirements
  - Maximum part scales
  - “Moment” approach avoids “time-stepping”
- Calculation of localized build conditions
  - Thermal rise (localized heating)
    - Keyhole risk & thermal uniformity
  - Neighborhood population
    - Meta-data extraction
    - Lack of fusion indicator
    - Boundary proximity
      - Can be used for boundary conditions
- Point field approach
  - Generated from build file or in-situ measurements
    - “Digital twin”
  - Point wise process analysis
    - Build file integrity
    - Instructed vs measured
    - Build meta-data can be extracted

part scales: $1cm^3$ – $20cm^3$

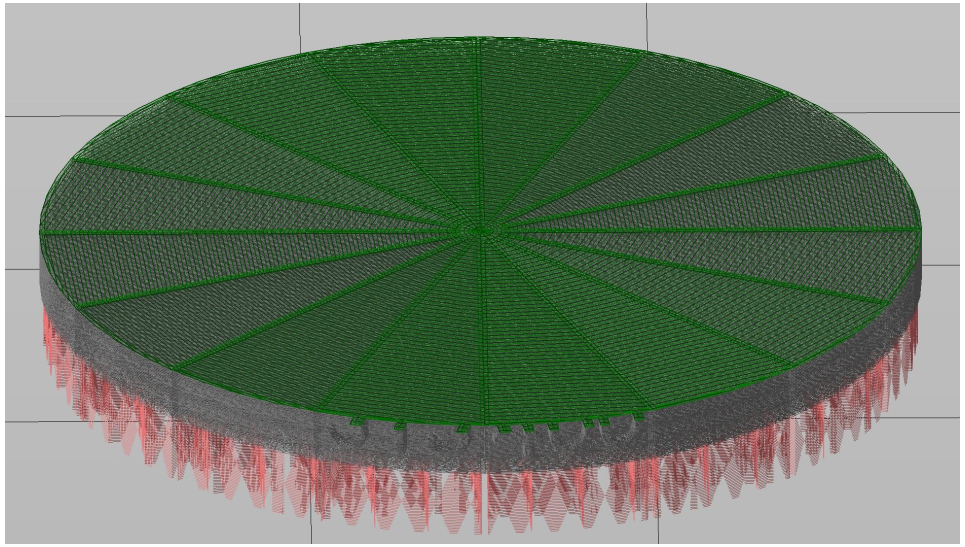
A single time stamp per point in the field results in minimal memory and computation cost

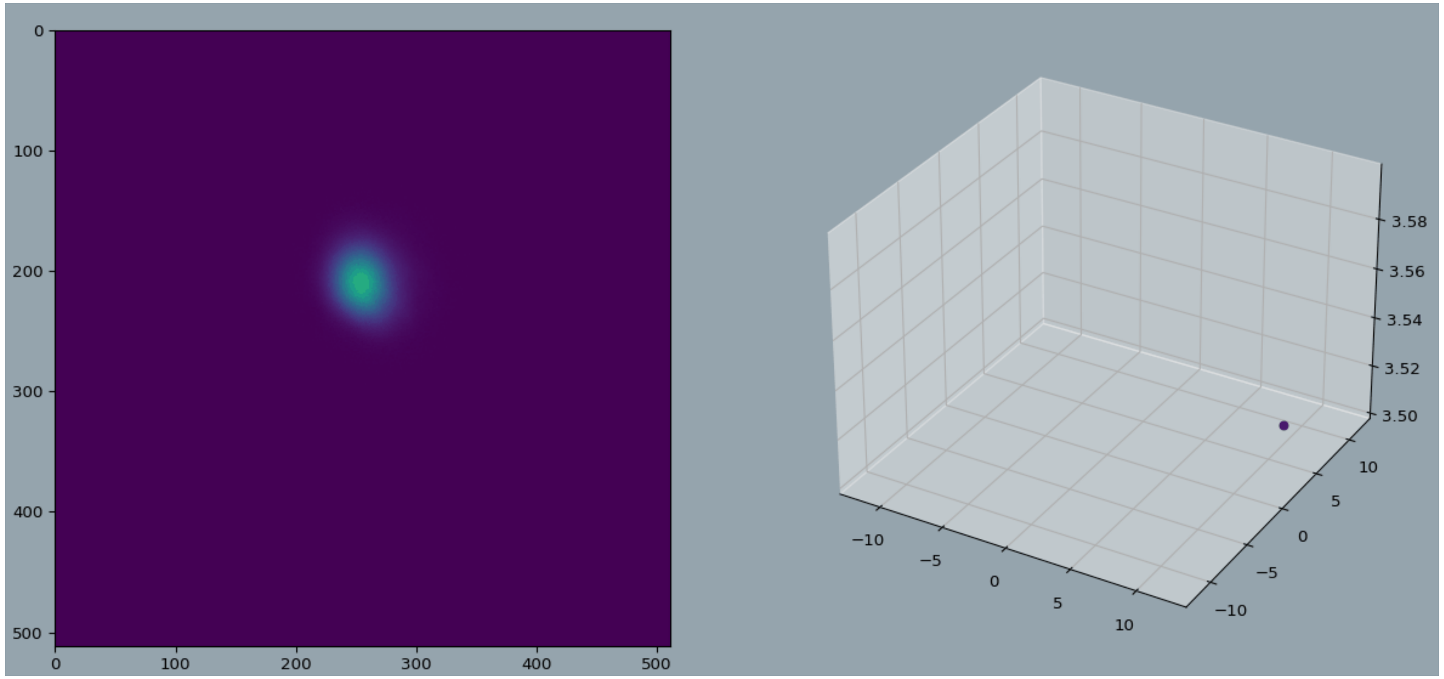
Single pass calculation provides quantifiable & physically informed localized process indicators

No other process modeling approach has been shown to calculate directly from the full-scale build instructions

Additive Manufacturing: Build Measures

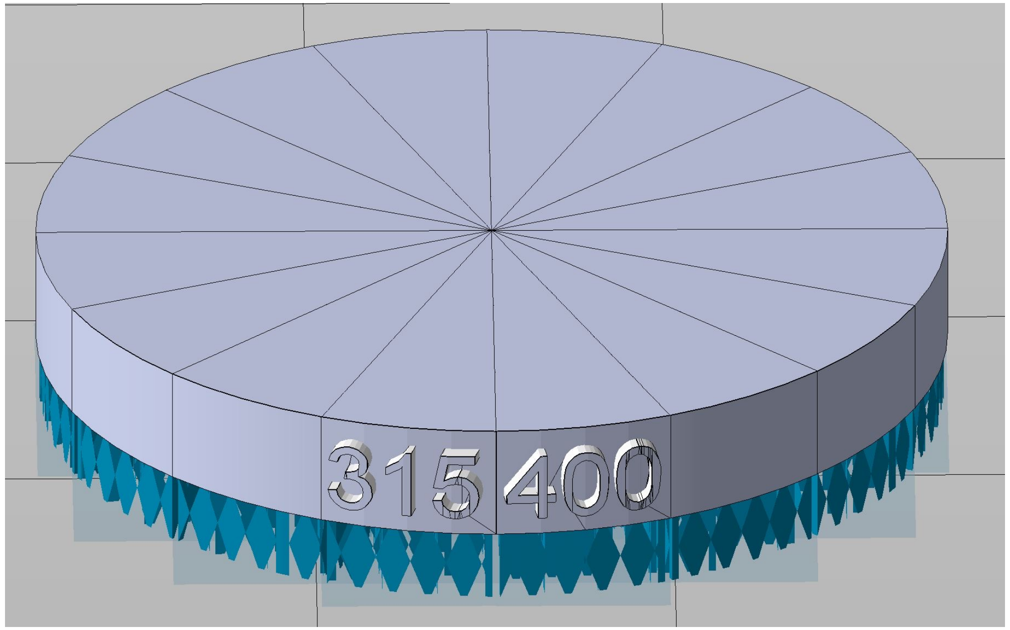
- ❖ Example build measures were taken from near the center of the build height
- ❖ Coaxial imagery of the melt pool during the build
- ❖ Build measure: average coaxial image pixel intensity



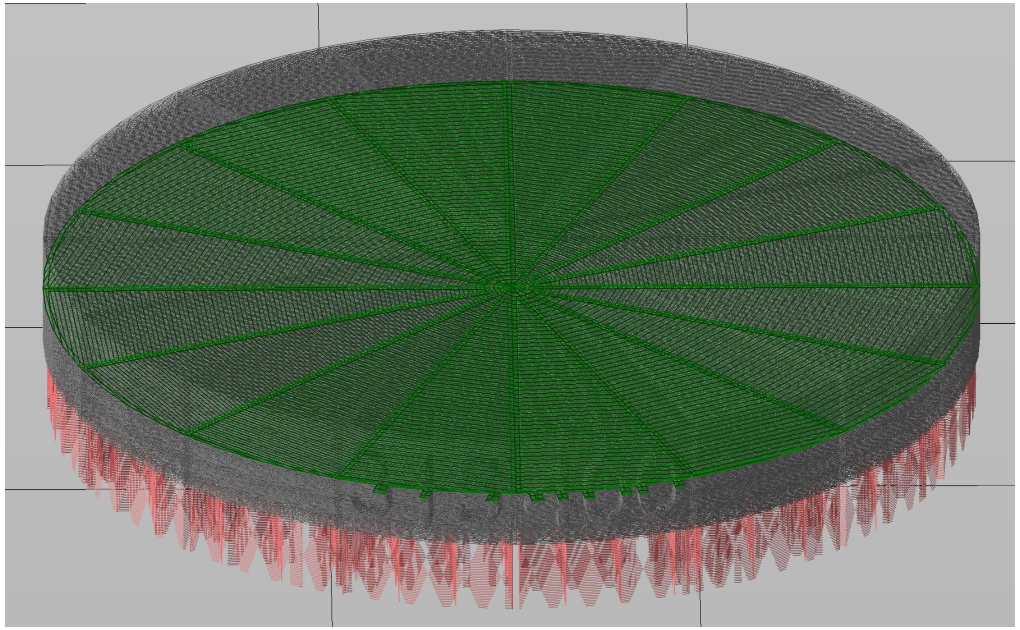


AM3 Approach: Build Illustration

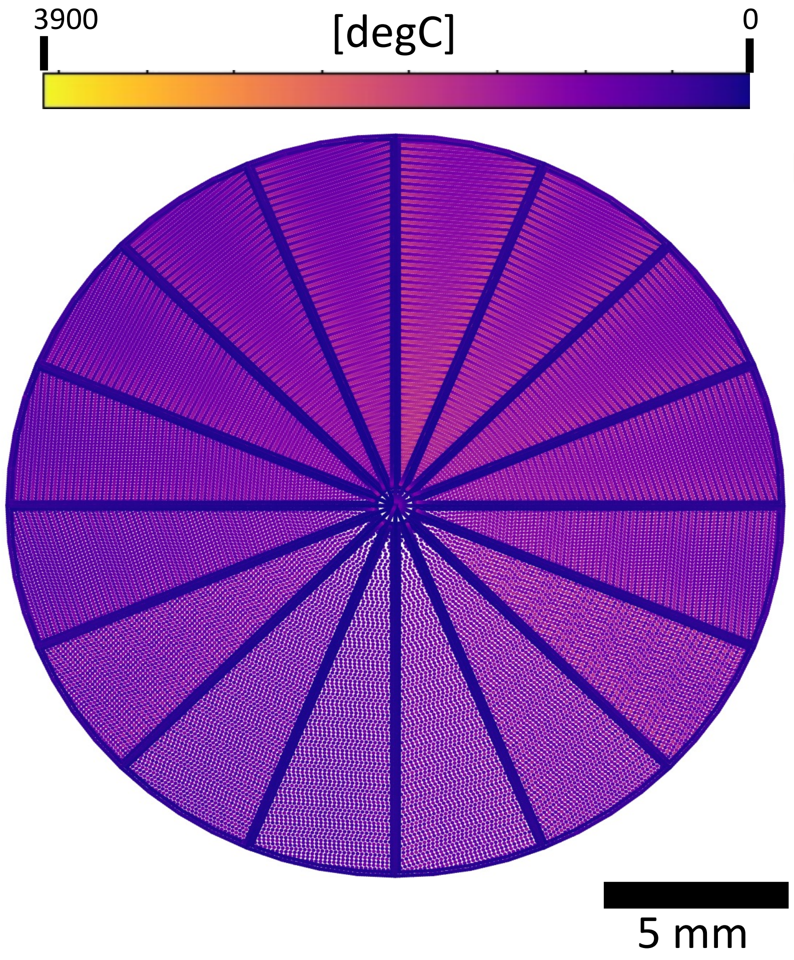
- ❖ Define the geometry of the part and assign a defined processing strategy



- ❖ Slice the part based on the geometry and build strategy: “Build Instructions”

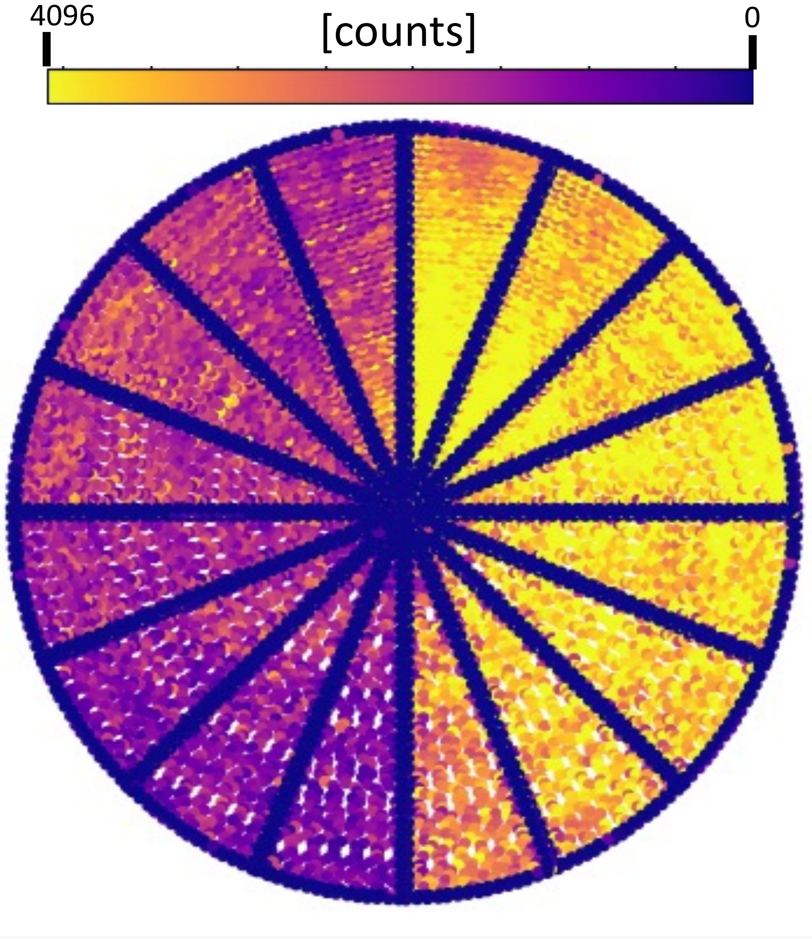


AM3 vs Surface Features vs Sensor Signal



AM3 thermal rise

Microscope Image of the as printed surface



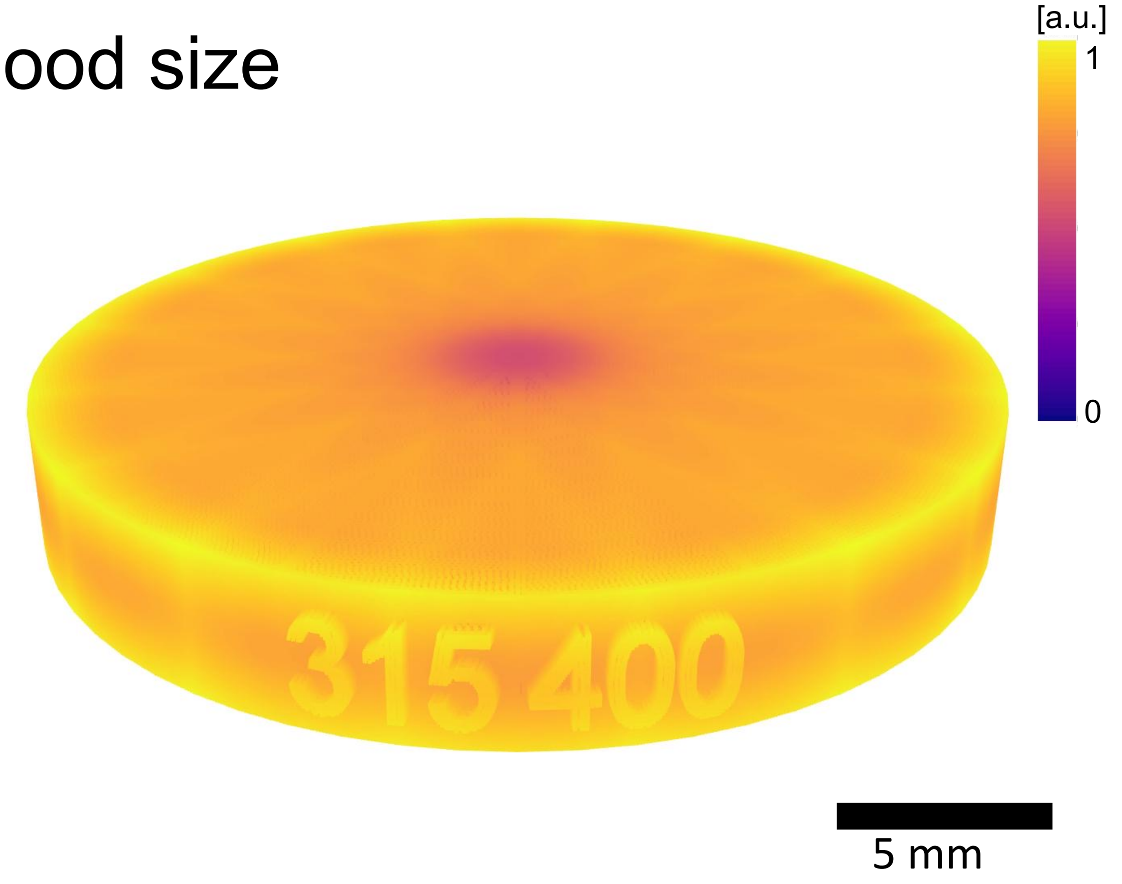
Max intensity from coaxial images

AM3 Process Functions

$$f_{i,j} = \frac{V_j}{v_j}, n_{i,j} = R$$

Boundary proximity, process insensitive

- Moment measure of neighborhood size
- Neighborhood criteria
  - Within specified radius
- Maximum value normalized

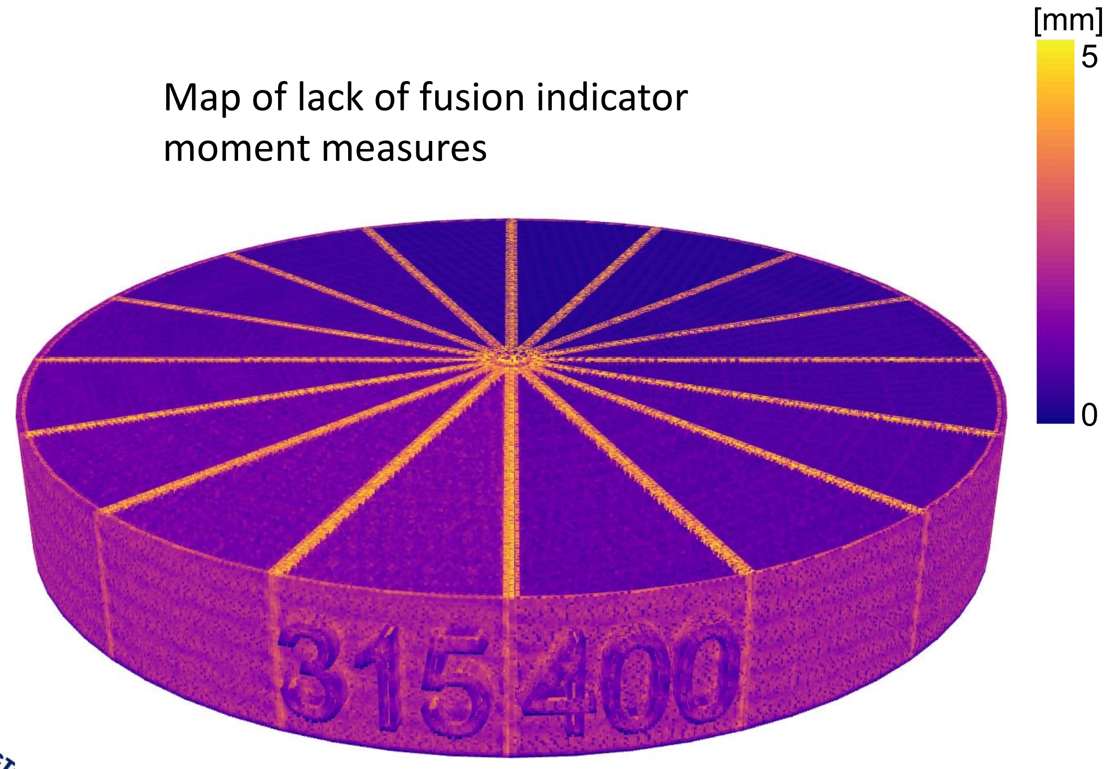


AM3 Process Functions

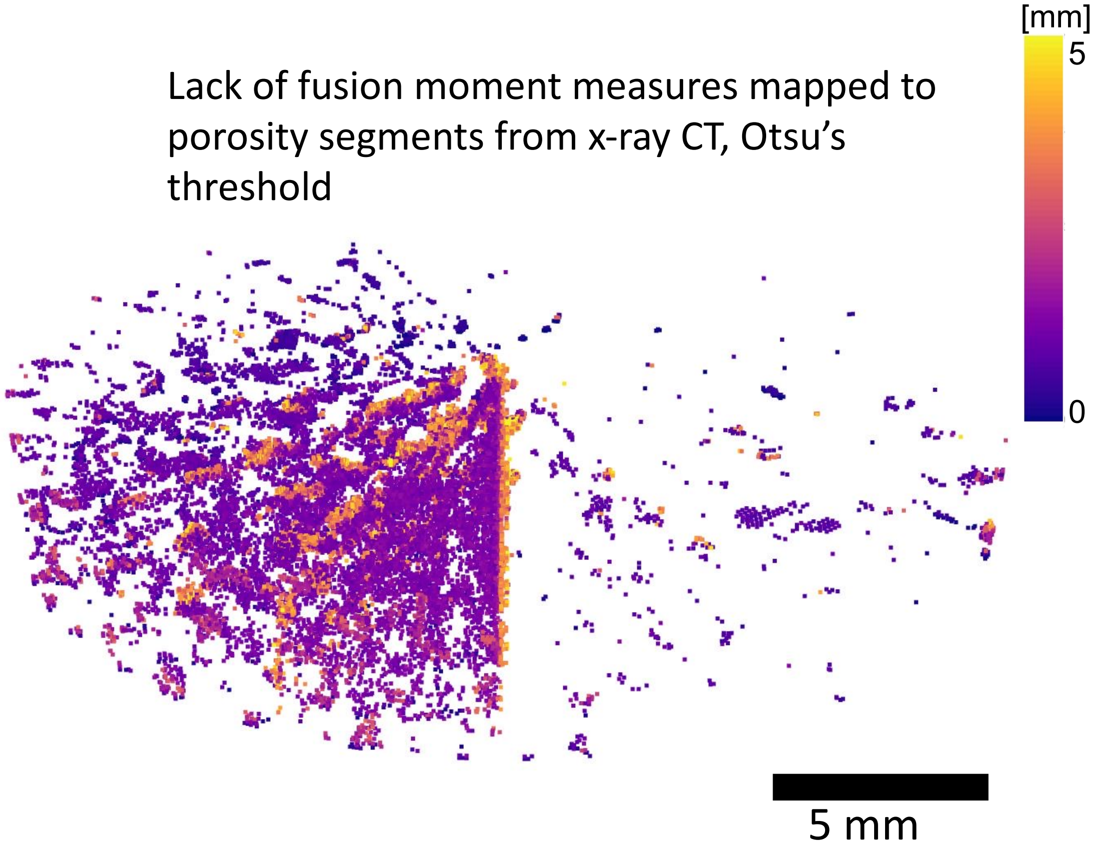
$$f_{i,j} = \frac{V_j}{v_j}, R \propto 0.5\sqrt{\frac{8}{\pi e}\frac{\lambda P_i}{\rho C_p V_i (T_m - T_0)}}$$

Lack of fusion indicator

Map of lack of fusion indicator moment measures



Lack of fusion moment measures mapped to porosity segments from x-ray CT, Otsu's threshold

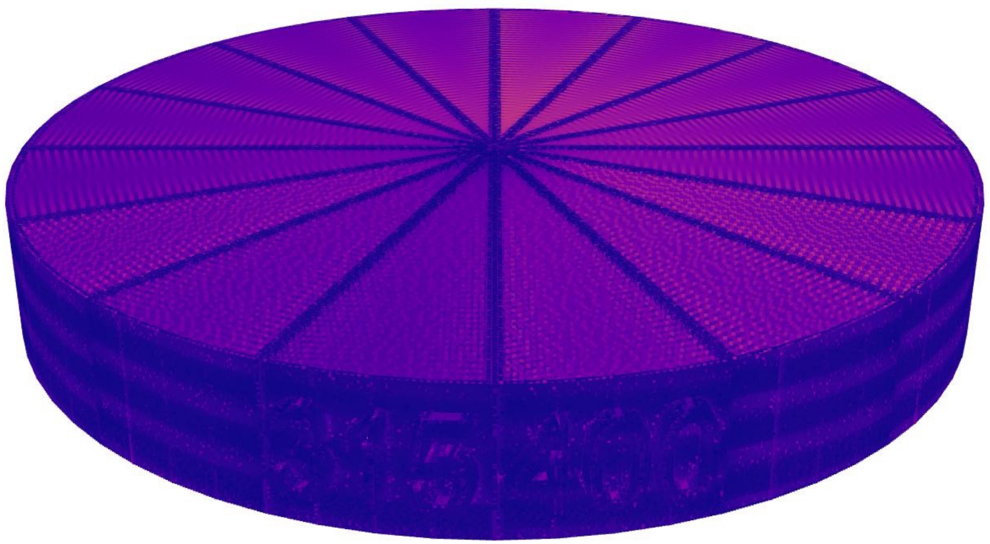


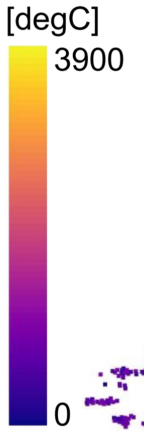
AM3 Process Functions

$$f_{i,j} = \frac{\frac{\lambda P_j}{v_j}}{\rho C_p \sqrt{2}\pi^{2/3}(\sigma_j^2 + 2\alpha\tau_{i,j})^{2/3}} exp^{-\frac{r_{i,j}^2}{2(\sigma_j^2 + 2\alpha\tau_{i,j})}}$$

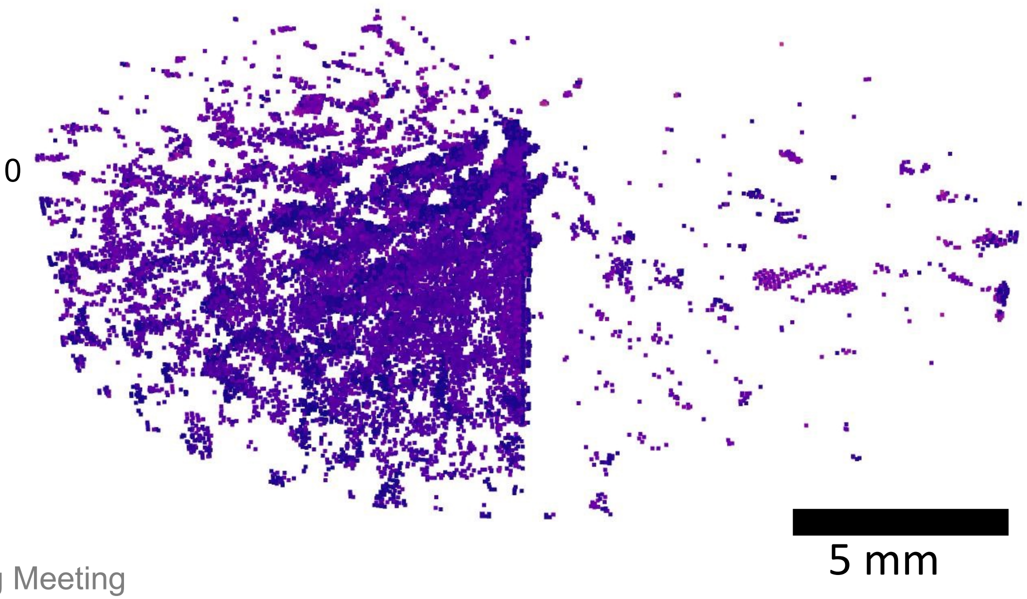
Thermal rise:
Localized heating

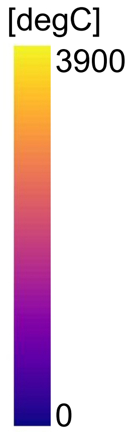
Map of thermal rise moment measures





Thermal rise moment measures mapped to porosity segments from x-ray computed tomography (CT), Otsu's threshold





Additive Manufacturing: Build Parameters

❖ Process enthalpy, Ti-6Al-4V

$$enthalpy = \frac{\lambda C_p P}{\rho\sqrt{\sigma\alpha V}}$$

$$\alpha = \frac{\kappa}{\rho C_p}$$

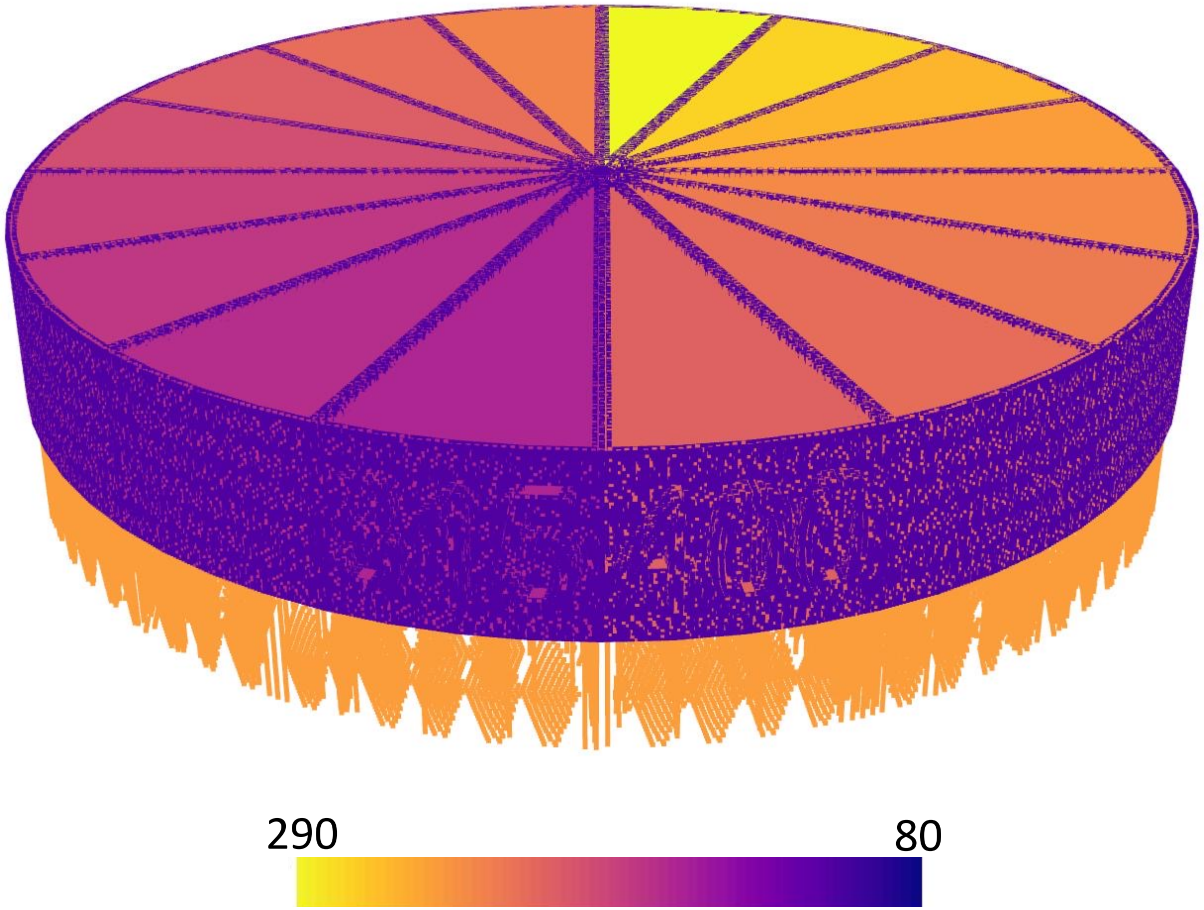
$$\kappa = 7.1 \left[{}^{W}/_{mK}\right]$$

$$\rho = 4252 \left[{}^{kg}/_{m^3}\right]$$

$$C_p = 553 \left[{}^{J}/_{kgK}\right]$$

$$\lambda = 1\ [a.u.]$$

$$\sigma = 0.0004\ [m]$$



Additive Manufacturing & Moment Measure

<u>Additive Manufacturing</u>

- *"Process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies"*
  - ISO/ASTM 52900:2021, Additive manufacturing - General principles - Terminology

<u>Moment Measure</u>

- Motivated from physics, a moment measure is the generalization of the concept of a moment to a discrete point field of observables

- Combined = Additive Manufacturing Moment Measure (AM3)

Moment Measure

- "In probability and statistics, a moment measure is a mathematical quantity, function or, more precisely, measure that is defined in relation to mathematical objects known as point processes, which are types of stochastic processes often used as mathematical models of physical phenomena representable as randomly positioned points in time, space, or both."
  - https://en.wikipedia.org/wiki/Moment_measure
  - D. J. Daley and D. Vere-Jones. *An introduction to the theory of point processes. Vol. {II}*. Probability and its Applications (New York). Springer, New York, second edition, 2008.