# IMECE 2020 ASME-CIE Hackathon Problem 2: Melt-Pool Size Prediction for Powder-Bed Fusion Additive Manufacturing (PBF AM)

Yan Lu, Zhuo Yang and Ho Yeung
National Institute of Standards and Technology

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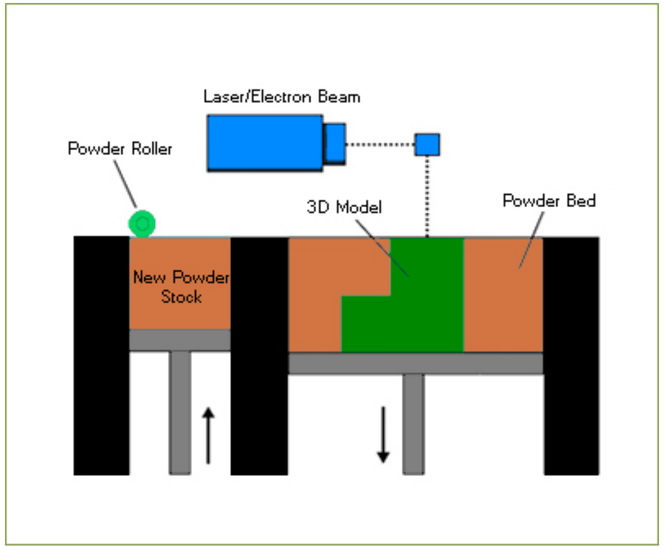
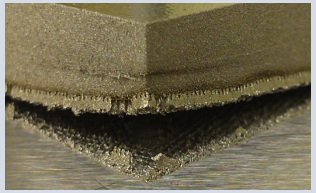
# Powder Bed Fusion Additive Manufacturing

- PBF AM - build parts using a laser beam to melt and fuse material powder layer by layer directly from 3D models, enabling
  - Fabrication of complex heterogeneous parts with fine features
  - On-demand production.
- Slow production adoption due to
  - poor process repeatability
  - lack of effective qualification tools.
- Fundamental issues – lack of the understanding and control of AM processes.
- **Data analytics for AM has the potential to enhance**
  - AM process understanding
  - process setting optimization
  - real-real feedback process variation control
  - quality assurance and certification with reduced time and cost

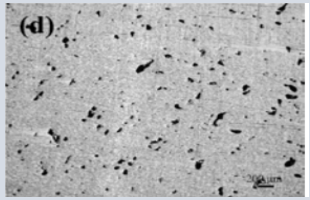



https://www.engineersgarage.com/article_page/3d-printing-processes-powder-bed-fusion-part-5-8/

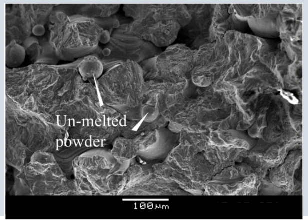
**Build Failure**
- Distortion
- Delamination
- Underbuilding
- Cracking



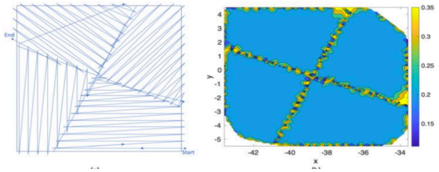
**Structure Defects**
- Lack of Fusion
- Key Holes
- Balling
- Undesired microstructure

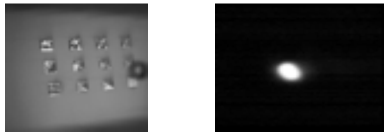


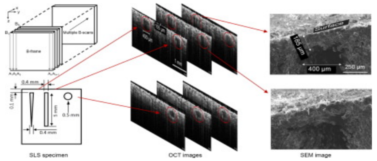

**Part Failure**
- Fatigue
- Fracture
- Corrosion

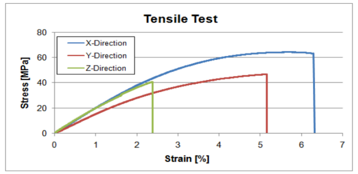


# PBF AM Data Landscape and Data driven Modeling










## Process Parameters

**Controllable**: Laser Power, scan speed, hatch spacing

**Predefined**: Powder size, distribution

## Process Signature

**Observable**: Melt Pool image or intensity; powder surface streaks

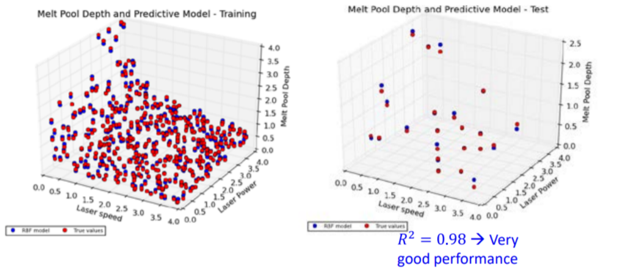
**Derived**: Melt pool size, patterns

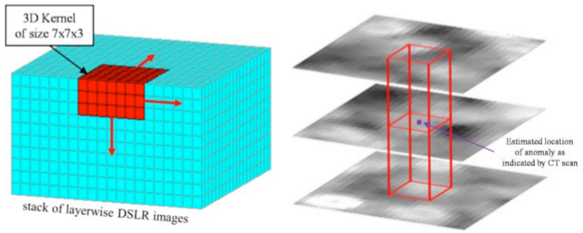
## Structure Properties

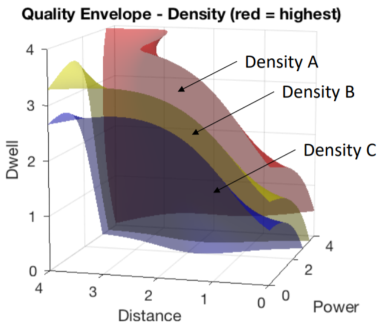
- Porosity
- Residue stress
- Microstructure

## Mechanical Properties/Performance

- Density
- Tensil Strength
- Fatigue



# Melt Pool Monitoring and Predictive Modeling

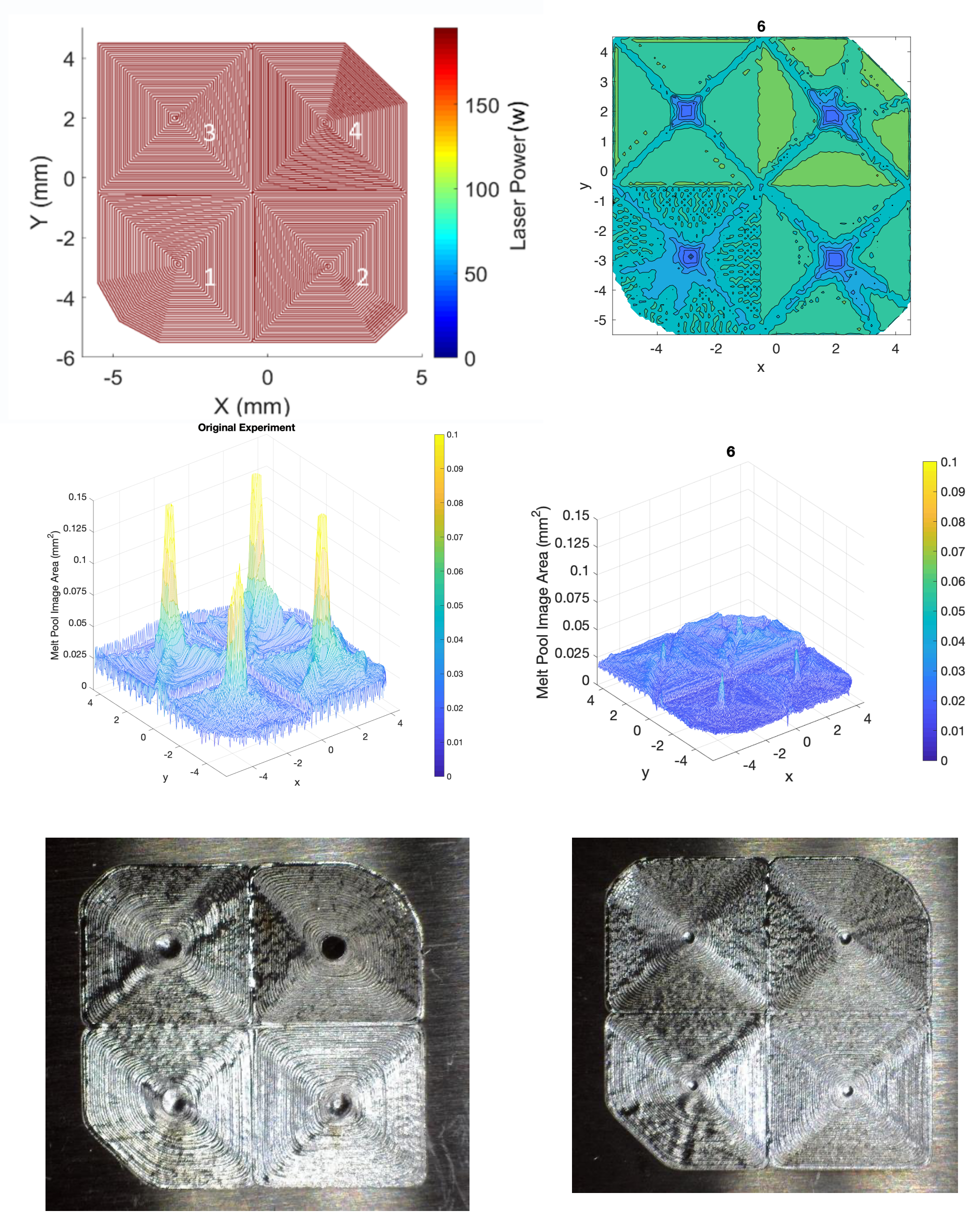
- ❑ Melt pool characteristics are highly correlated to as-built part structure and properties

- ❑ Melt pool measurements provide a valid process signature for both process monitoring and control

- ❑ Two types of melt pool monitoring (MPM) systems:
  - Photodiode/pyrometer
  - High-speed high-resolution camera
  - Coaxial camera-based melt pool monitoring systems generate nominally stationary within the field of view, at a high sampling rate.

- ❑ Melt pool characteristics depend on the process parameters

- ❑ Establish the relationship between the process parameters is a key for melt pool-based process monitoring and control



# Challenges in Melt Pool Size Prediction

- **MPM data registration** – data must be spatially aligned before conducting correlation.
- What kind of **features** to be extracted from the multi-rate, multi scale AM in-process data, e.g., build command (100KHz), co-axial images (20KHz)
- What kind of **relationships** between build commands and in-process measurements?
- How to develop real-time **control,** or layer-wise **control strategy** or process ***optimization*** based on in-process measurements for an AM process?

# Objective

- This hackathon subtopic aims to promote the use of data science in powder-bed fusion AM by predicting the melt-pool size (area) based on build commands, to avoid the time and cost associated with experiments for process planning.

- This will be achieved by developing sets of <u>data analytics tools</u>, <u>predictive models</u>, and <u>process control and optimization algorithms</u> for PBF processes.

- This tool will be an early step in allowing industry to move away from 100% testing and towards <u>**born-qualified**</u> parts.

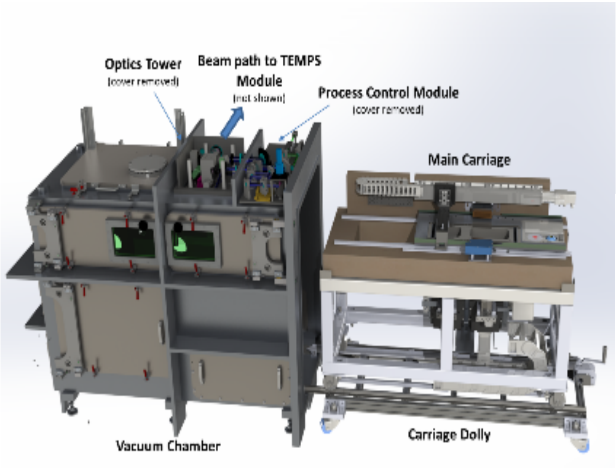
# Experiment and Data

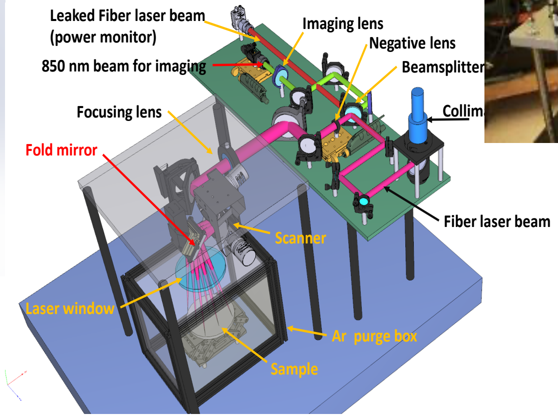
ho.yeung@nist.gov

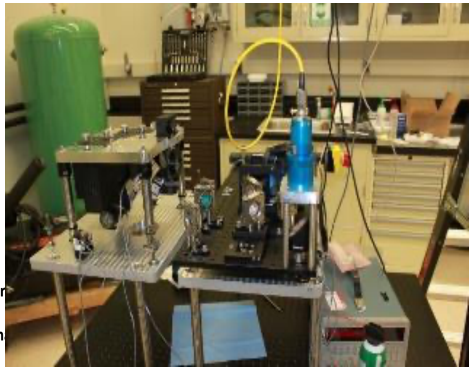
# NIST Additive Manufacturing Metrology Testbed

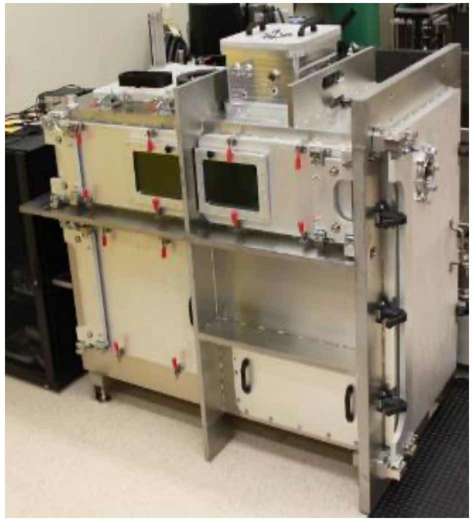
- An <u>open-platform</u> LPBF testbed instrumented for fundamental process study and optimization
- Research the measurement science of various <u>real time monitoring and control</u> methods for measuring and improving AM build quality

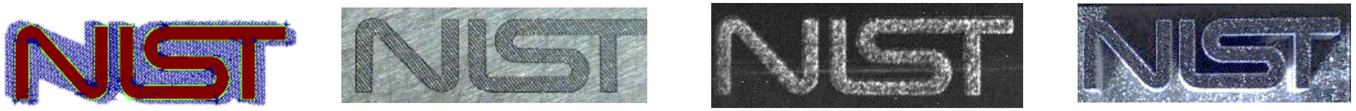
https://www.nist.gov/el/ammt-temps



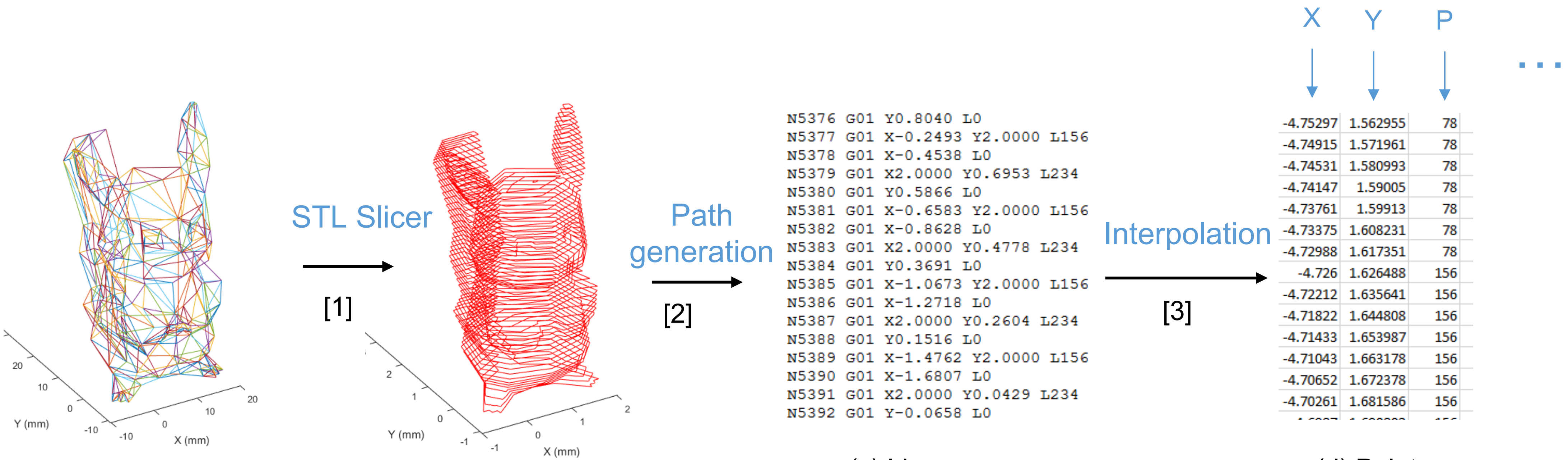







# AM Command File Preparation




(a) 3D STL file (b) layers (c) Lines (d) Points

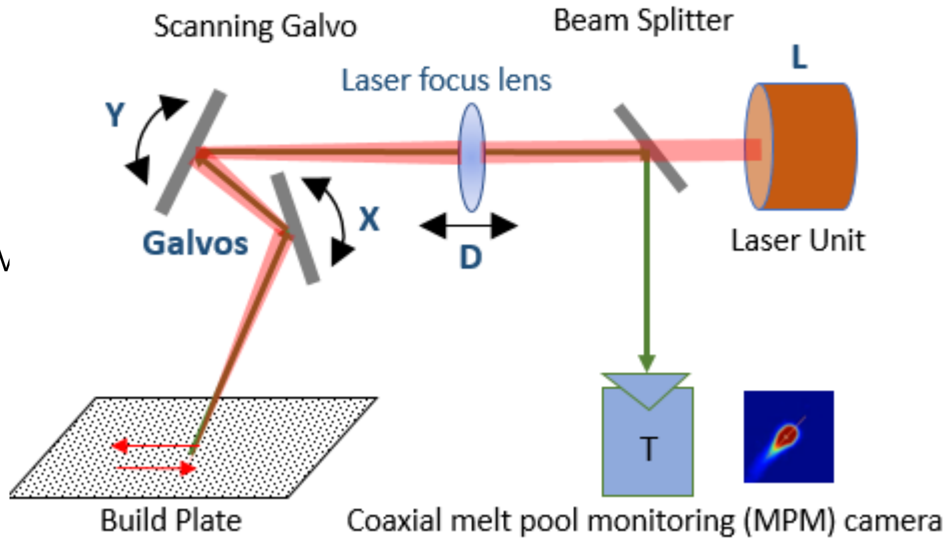
# AM Control and Monitoring

## Digital command array

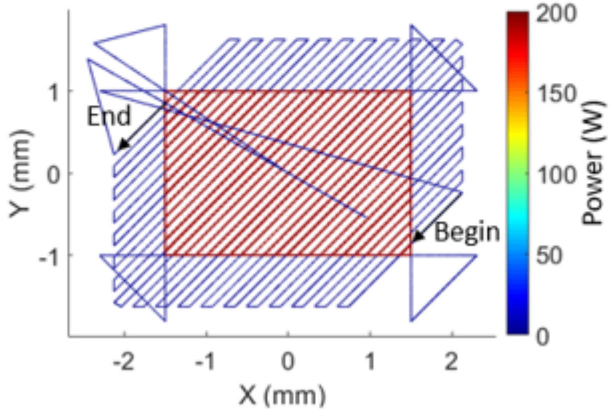
| X | Y | L | D | T |
|---|---|---|---|---|
| 0 | 0.0000 | 0 | 0.1 | 0 |
| 0 | 0.0050 | 100 | 0.1 | 2 |
| 0 | 0.0175 | 150 | 0.1 | 0 |
| 0 | 0.0325 | 150 | 0.1 | 0 |
| 0 | 0.0475 | 150 | 0.1 | 0 |
| 0 | 0.0625 | 150 | 0.1 | 0 |
| 0 | 0.0775 | 150 | 0.1 | 2 |
| 0 | 0.0925 | 150 | 0.1 | 0 |
| 0 | 0.1075 | 150 | 0.1 | 0 |
| 0 | 0.1225 | 150 | 0.1 | 0 |
| 0 | 0.1375 | 150 | 0.1 | 0 |
| 0 | 0.1500 | 100 | 0.1 | 2 |
| 0 | 0.1550 | 0 | 0.1 | 0 |

A line sent to AM controller for execution in every 10 μs

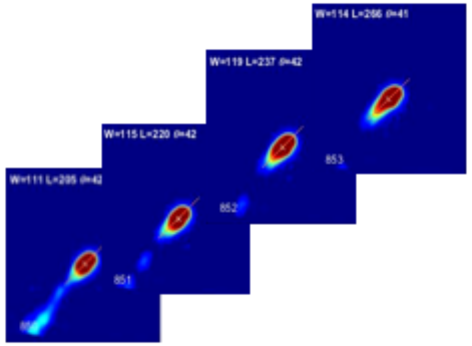
## Scanning and in-situ monitoring hardware



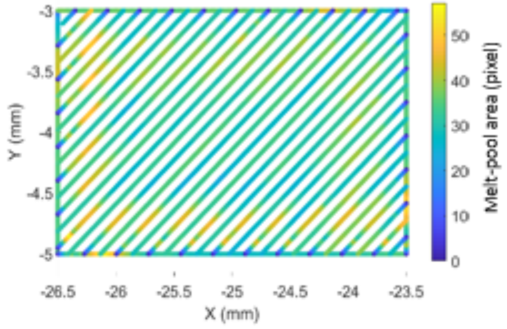

## Scan path and power



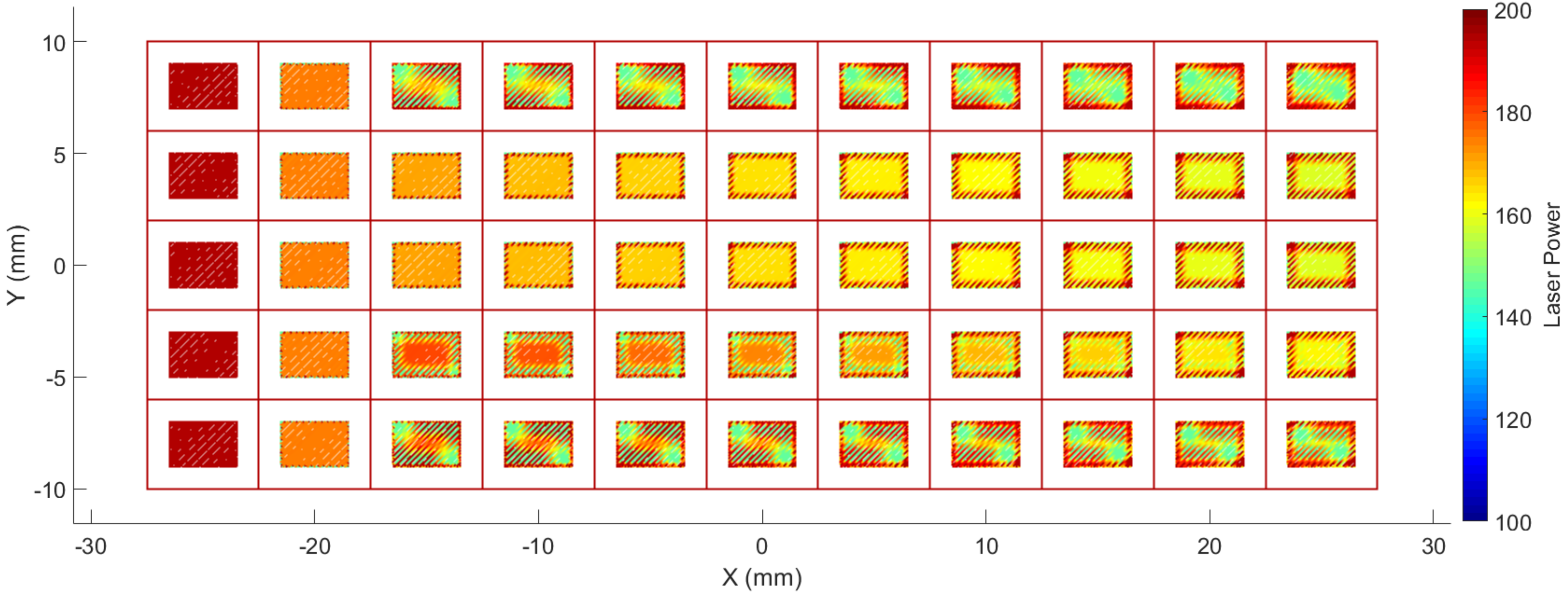

## Meltpool (coaxial) image



## Meltpool area plot at its location



# Experiments

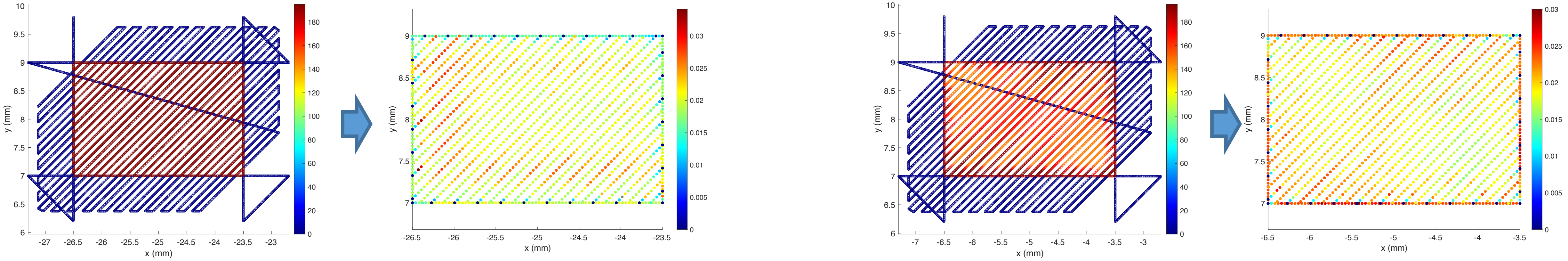



Nominal power = 195 V, laser speed = $10^3$ mm/s, acc = $10^6$ mm/s$^2$

# Melt Pool Size Prediction Problem

# Melt Pool Prediction

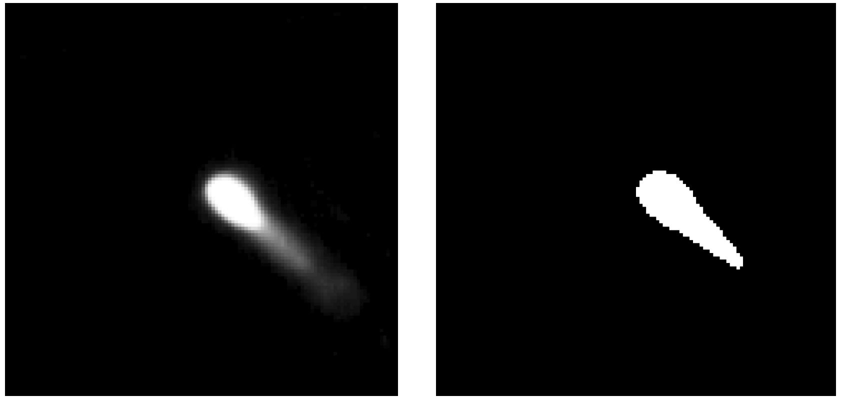
- Melt-pool area predictive model from digital command

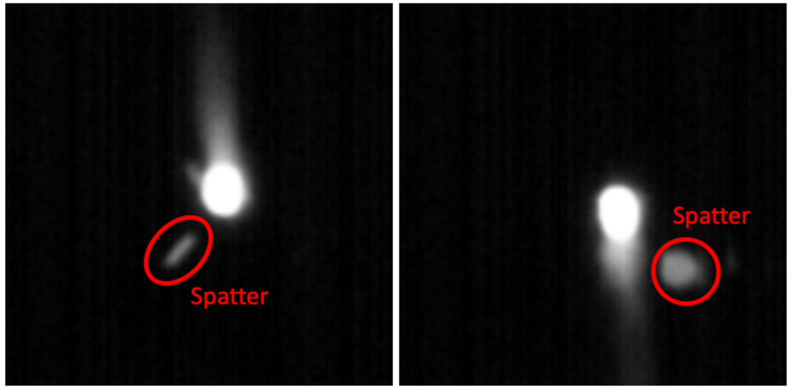



- Data
  - **Input:** Digital commands in .csv files RHF_P01_layer0001.csv
  - **Output**: Melt pool sizes calculated from melt-pool images DAQ_RHF_P01_layer0001_r8d_BMP

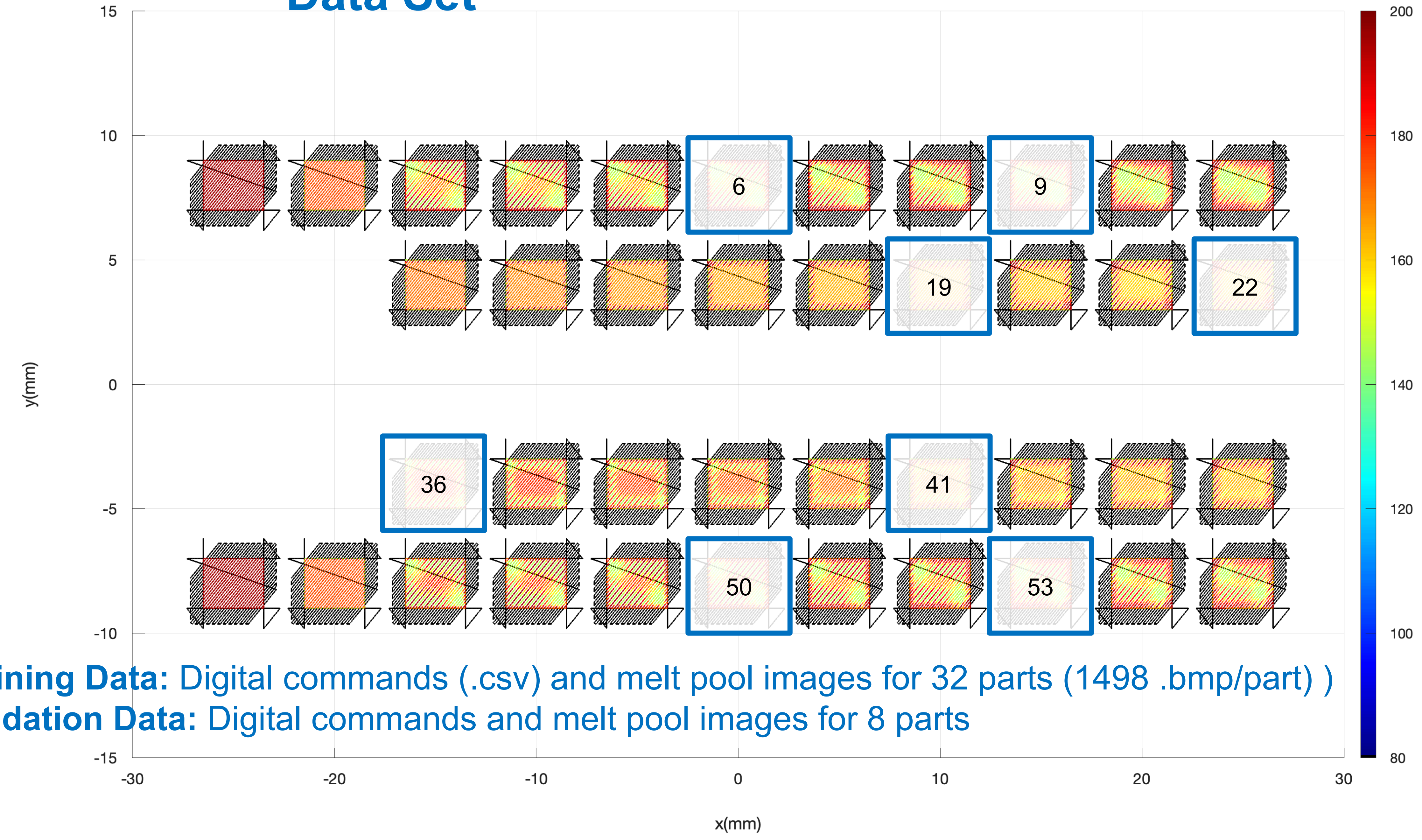
# Melt-Pool Area Calculation

- Melt-pool image 120 x 120 pixels, 8µm/pixel
- Thresholding (grayscale = 80)
- Spatter removed
- Area = pixels * 64 µm$^2$





# Data Set




**Training Data:** Digital commands (.csv) and melt pool images for 32 parts (1498 .bmp/part) )
**Validation Data:** Digital commands and melt pool images for 8 parts

# Judging Criteria

| *Category* | *Criteria* | *Scoring* |
|---|---|---|
| ***Technical Approach (40%)***<br>*Methods and algorithms of the proposed predictive model* | • Requirement analysis and problem formulation<br>• Literature review and exploration of ideas<br>• The development and design of the idea<br>• Scientific soundness of the approach<br>• Creativity of the approach, e.g. exploring melt pool features beyond melt pool size<br>• Soundness of the algorithm (data pre-processing expected)<br>• Readiness of the idea and the approach for implementation, e.g., computational efficiency, code reusability | Excellent (36-40 pts)<br>Very good (29-35 pts)<br>Good (21-28 pts)<br>Limited (13-20 pts)<br>Poor (1-12 pts) |
| ***Results(30%)***<br>*Output performance and V&V* | • Prediction performance measurement based comparison between modeled/measured values evaluated by the Root Mean Squared Error (RMSE) | Excellent (27-30 pts)<br>Very good (22-26 pts)<br>Good (16-21 pts)<br>Limited (10-15 pts)<br>Poor (1-9 pts) |
| ***Data Visualization (15%)***<br>*Clarity, information* | • Overall clarity of data presented<br>• Visualization of data alignment/registration<br>• Data structure<br>• Model development<br>• Trend or correlation analysis | Excellent (13-15 pts)<br>Very good (10-12 pts)<br>Good (7-9 pts)<br>Limited (3-6 pts)<br>Poor (1-2 pts) |
| ***Overall Presentation (15%)****:*<br>*Organization, structure and message conveying* | • Title, headings, labels: Appropriate size, location, spelling, and content<br>• The demonstration of teamwork<br>• Structure and Clarity<br>• Boarder impact of the idea to ME subfields | Excellent (13-15 pts)<br>Very good (10-12 pts)<br>Good (7-9 pts)<br>Limited (3-6 pts)<br>Poor (1-2 pts) |

# Results - Model Performance Metrics

- **Root Mean Square Error (RMSE)**
  - $RMSE = \sqrt{\frac{\sum_{i=1}^{N}(\tilde{y}_i - y_i)^2}{N}}$ (N: # of data, $\tilde{y}_i$: predicted area, $y_i$: observed area
- **Score**
  - Technical Results Points – based on the rank of team's RMSE from low to high

    → Excellent (27-30 pts)

    → Very good (22-26 pts)

    → Good (16-21 pts)

    → Limited (10-15 pts)

    → Poor (1-9 pts)

  - Lowest receive highest points
  - Conclusion also refer to the average performance of all teams

# Submission Requirements

- Deadline – 4:30- 5pm Sunday, Nov. 15
- What to submit?
  - Slides – no change allowed after deadline
    - 8-10 minutes (presentation) + 3-5 minutes (Q&A)
  - Predicted results
    - 1 zip file – Team# (Team01)
    - 8 .csv file – Team#_Part# (Team01_Part06)
      - Predicted melt-pool area ($mm^2$)
      - Single column
      - Rows following the timestamp (1-1498)
- How?
  - GitHub
  - idetccie.seikm@gmail.com