# DARPA NOM4D Phase III Kickoff

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Briefing Prepared for DARPA NOM4D Phase III Kickoff

1/29/2025

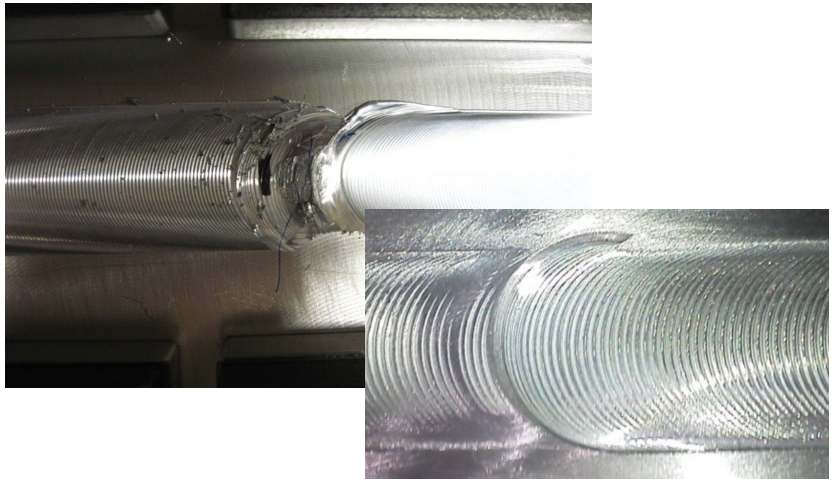
# Agenda

- Overview of NASA’s In-Space Manufacturing Portfolio
- Laser Forming Project Technical Accomplishments

# Why In-Space Manufacturing?

*Reduce Launch Burden Related to Cargo Delivery to Space (image credit NASA)*

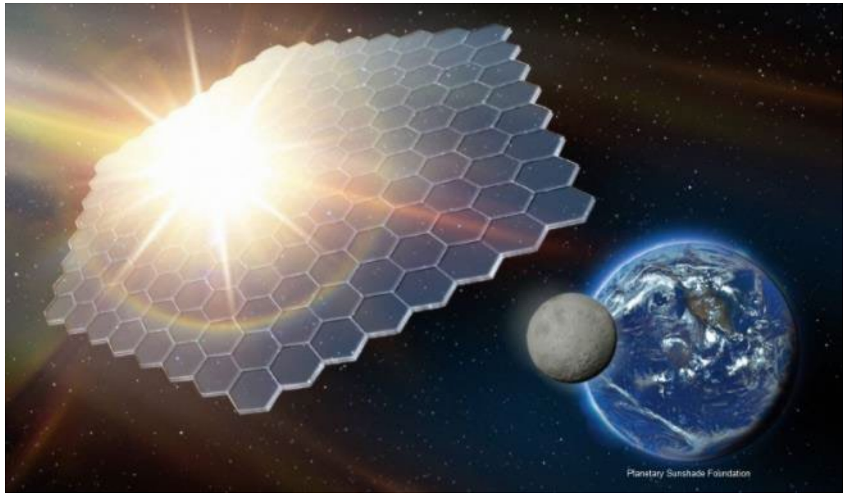
*Reduce launch mass through in-situ resource use (image credit ICON) Moon to Mars Objectives*



*Weld Repair (structural damage, defective weld, damaged weld, etc;)*


*Recycling and Trash Management (image credit NASA)*

*On-demand manufacturing of critical parts and tools (image credit NASA)*




*Build objects too big or fragile to launch*

Bring → Recycle & Reuse → In-Situ Resource Utilization

# In-Space Manufacturing Portfolio

| Ground-based Tests | (Sub)orbital Demos | Lunar Surface Demos |
|---|---|---|
| Electronics | Semiconductors & Microelectronics/Sensors | Sensors & Energy/Power |
| Welding/Additive | Critical Repairs | Storage Tanks/Tall Lunar Tower/Large Infrastructure |

*BPS 2024 Decadal Survey: "What research is needed to improve mechanisms of construction and repair in space?"*

| | | |
|---|---|---|
| Recycling | Inventory of Feedstocks | Polymers/Metals/Textiles |

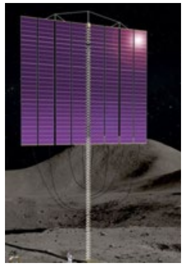
*Pam Melroy (COSMIC 2023): "Recycle, reuse, and sustainability model has to extend throughout the solar system."*

Associated Verification Technology

Human Health Sensor

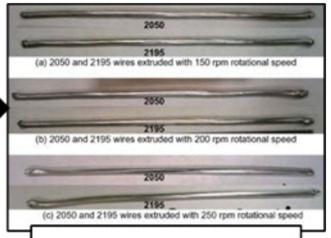
Advanced Toolplate

Laser Welded Demo Joint

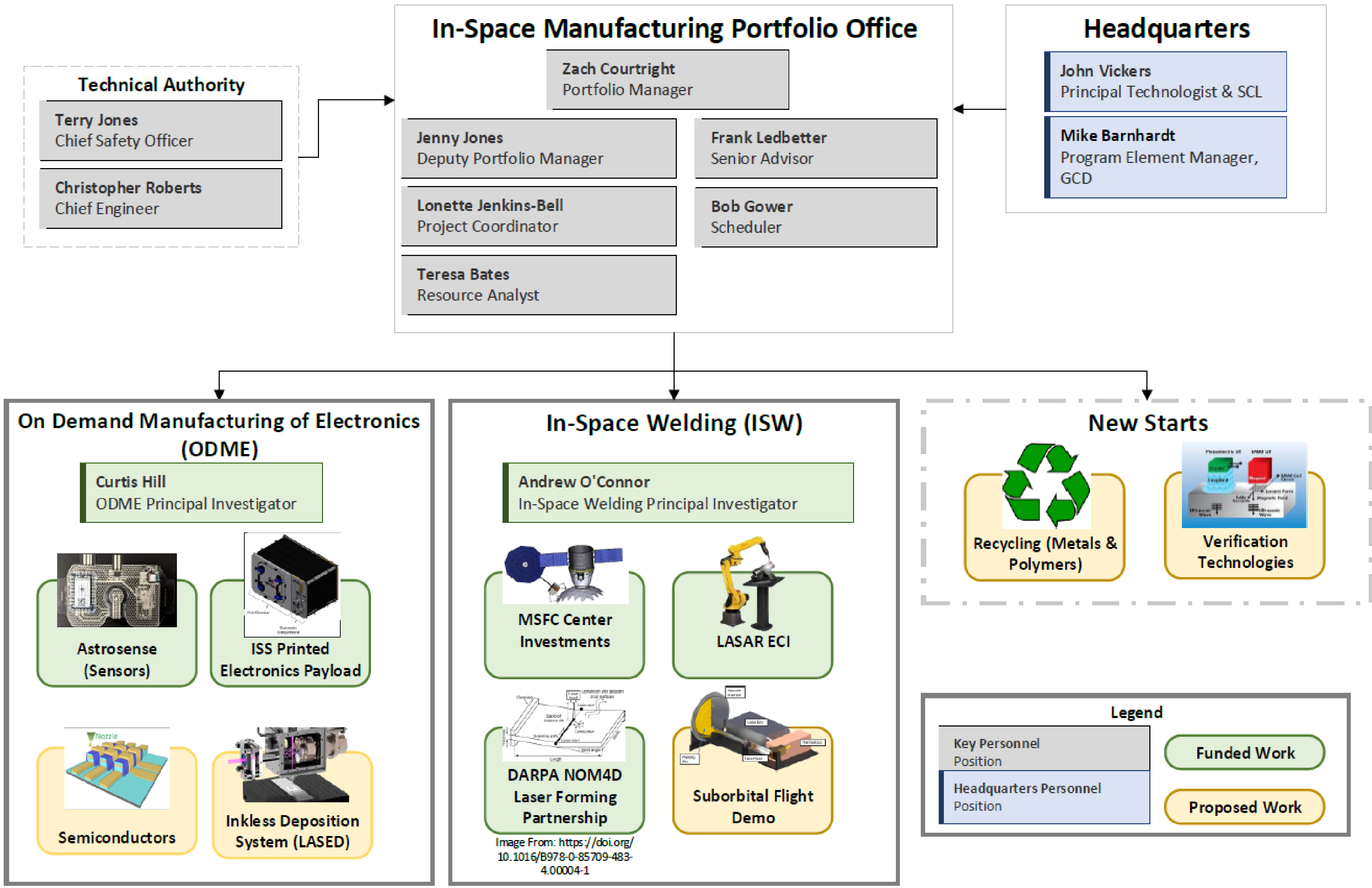


Tall Lunar Tower Model

Aluminum Chips

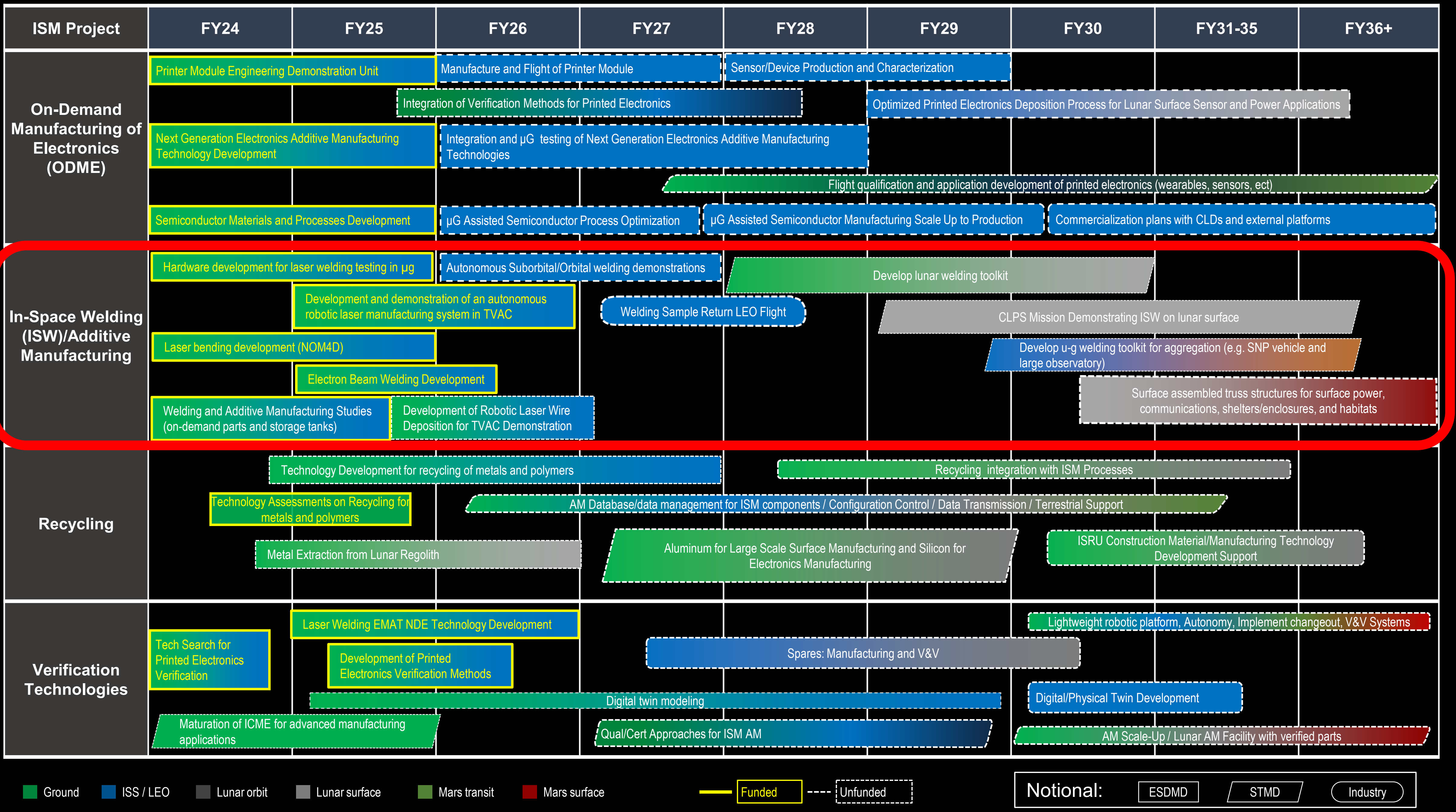



Friction Extruded Wire

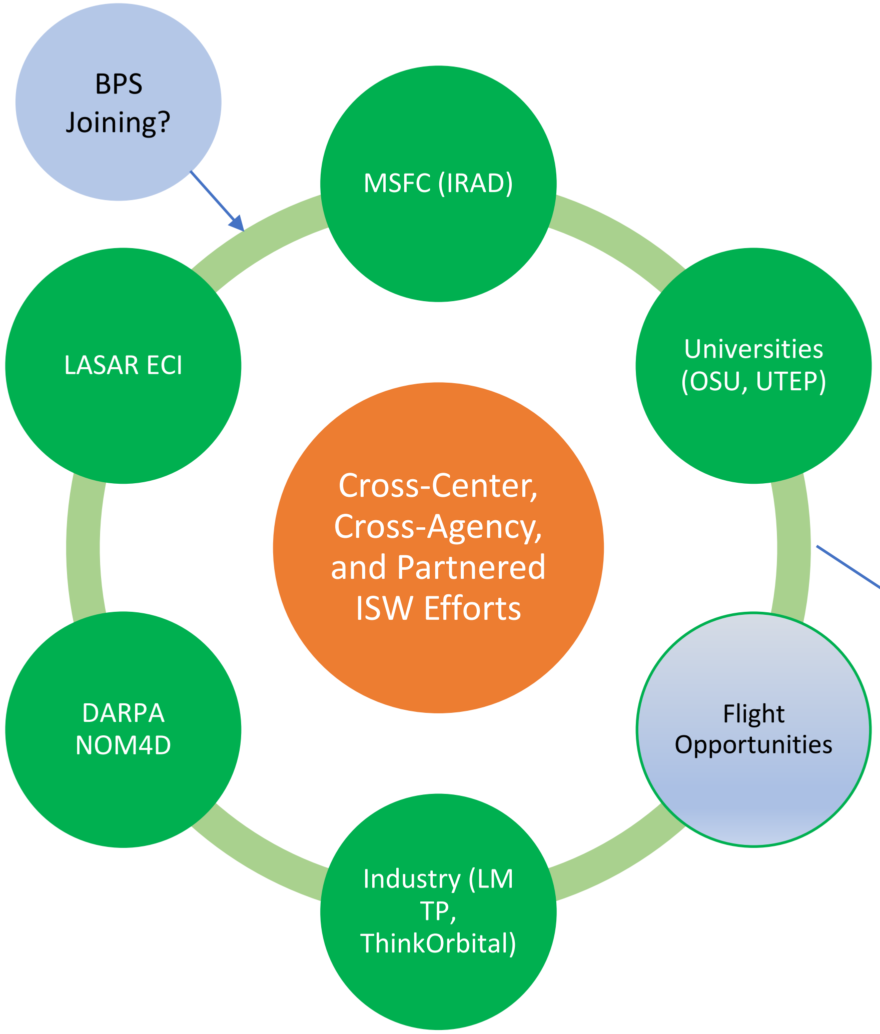


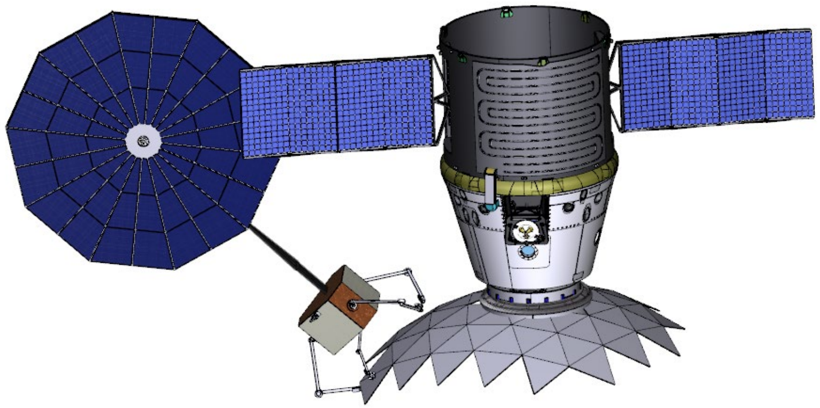

This chart represents a fraction of the team members that make the ISM vision possible.

# In-Space Manufacturing Roadmap



# Ecosystem for In-Space Welding (ISW) at NASA



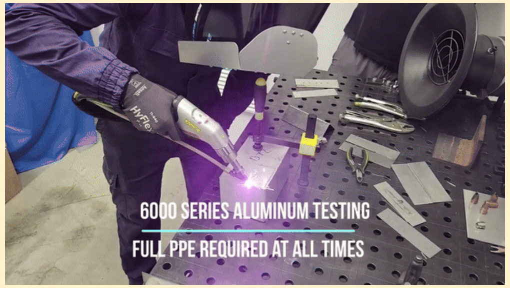



NASA ACO Conceptual drawing

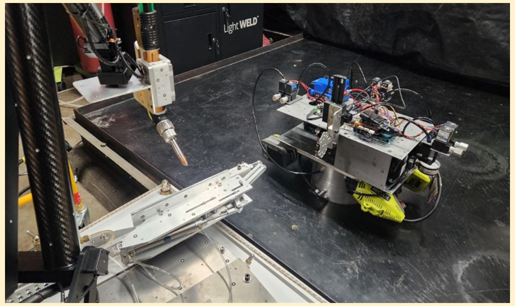
NASA Internal (STMD → ESDMD/SMD)
CLPS Lunar Lander
AFRL/DoD

| Current Efforts |
|---|
| Future Efforts<br>(proposals or groundwork generated) |

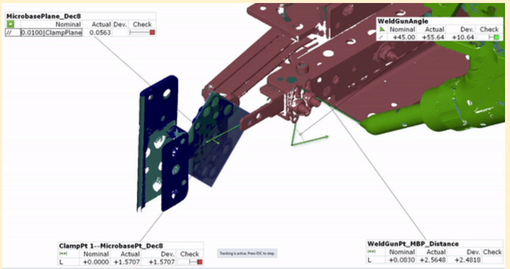
# Maturation through Steppingstone Approach




Handheld laser welder



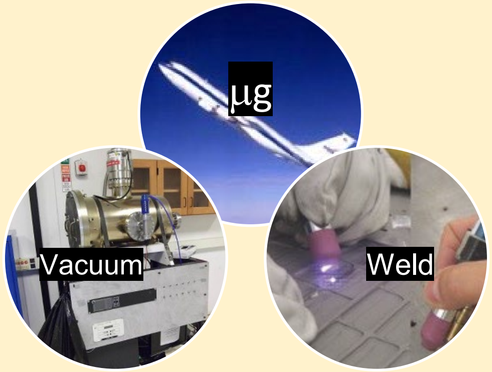
Flat floor assembly & laser welding



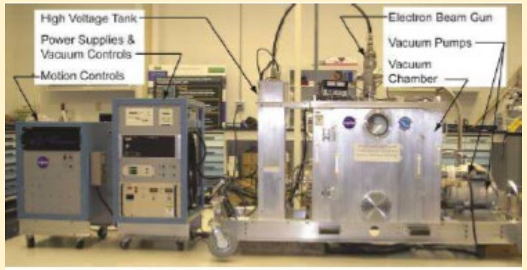
3-DOF ug simulation & Model

Ground Test

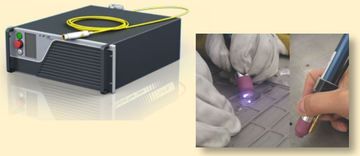
**OSU-NASA Laser Welding partnership**




ZGC flights August 2024 and May 2025

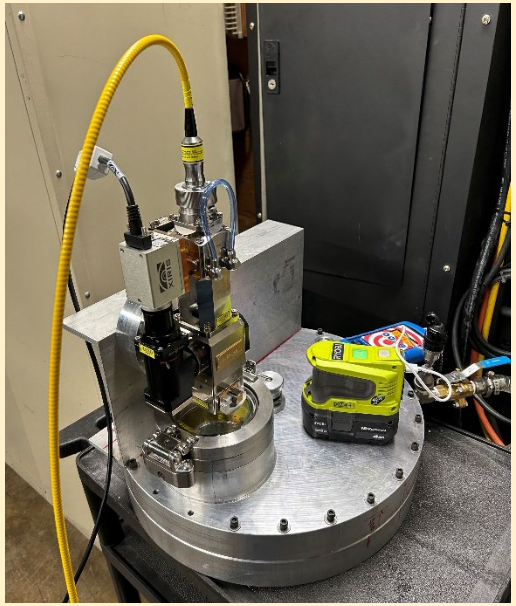



LaRC Proven EBAM Vacuum Chamber

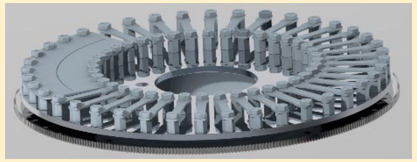


MSFC Laser Beam Welding

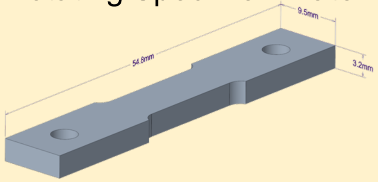
Parabolic Flight



Compact “Discman” System



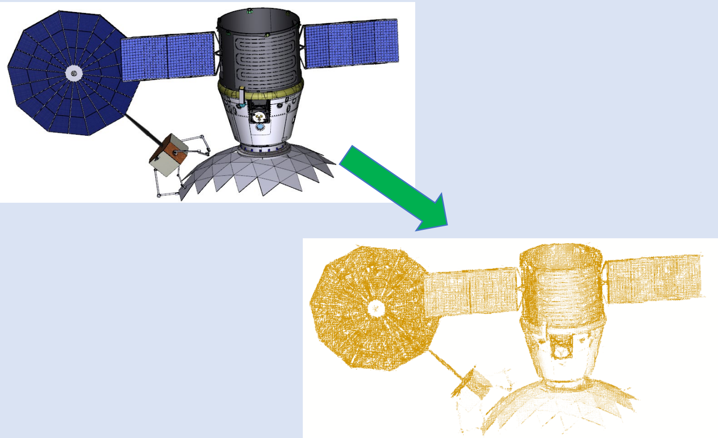
Rotating Specimen Platen

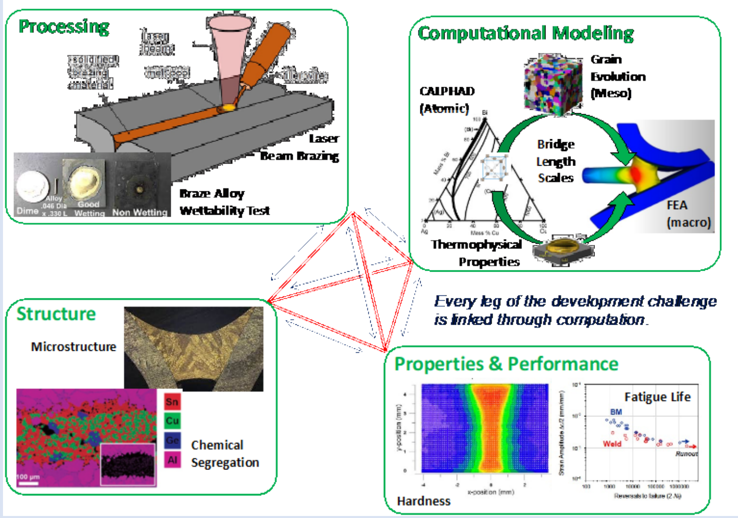



Standard Specimens

Suborbital Flight

Digital Twin of Space Welding



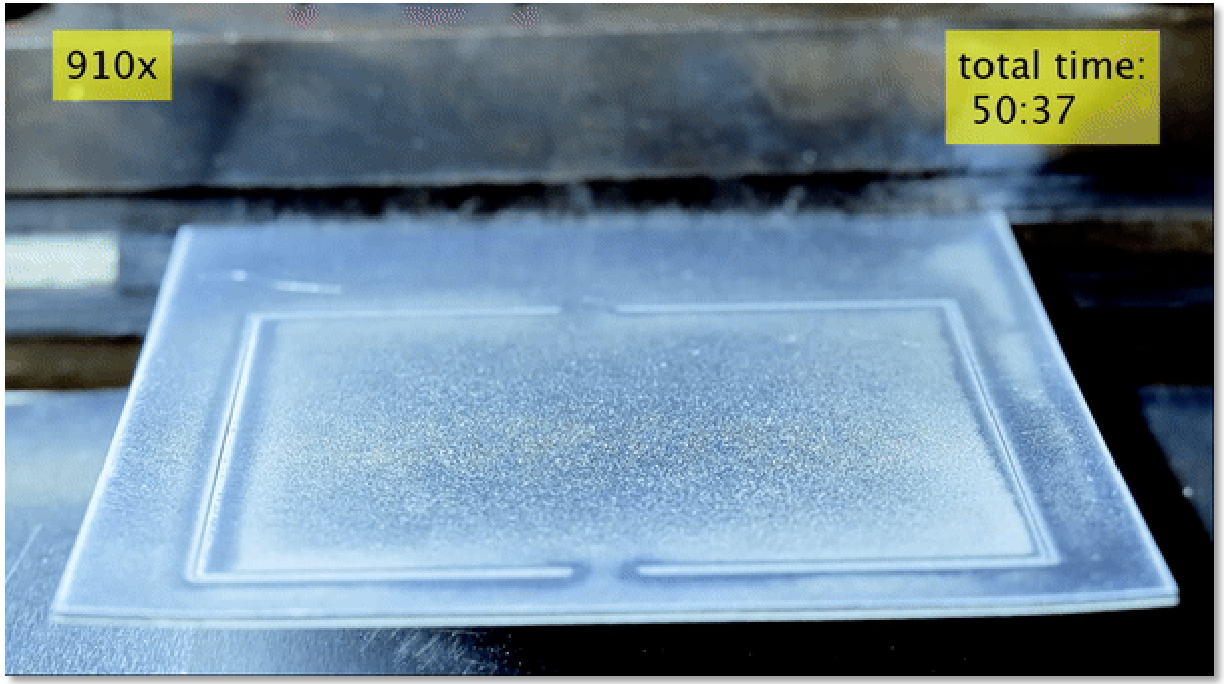



Integrated Computational Materials Engineering workflow of Laser Welding

LBW Image credit: IPG Photonics, ThinkOrbital, www.mechanicalcaveman.com, https://doi.org/10.1016/j.promfg.2019.08.025 (CC BY-NC-ND 4.0)

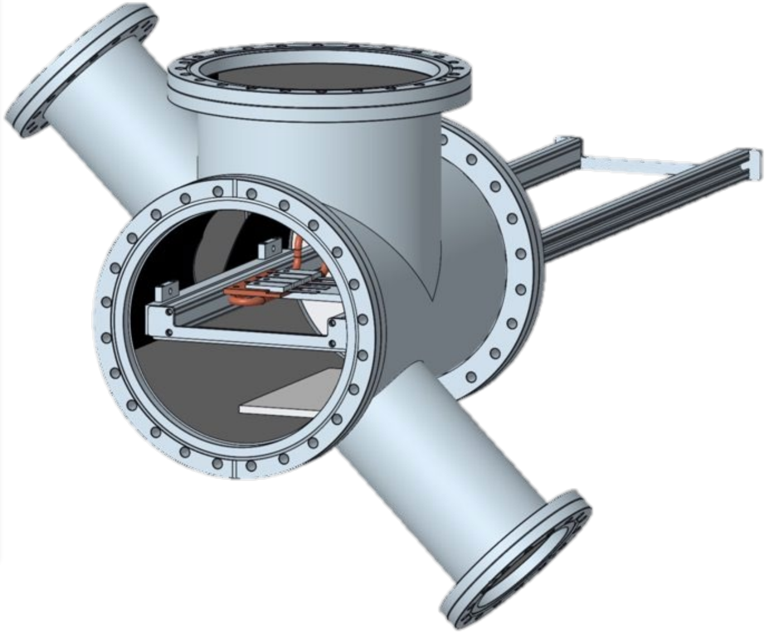
# DARPA NOM4D Partnership: Laser Bending

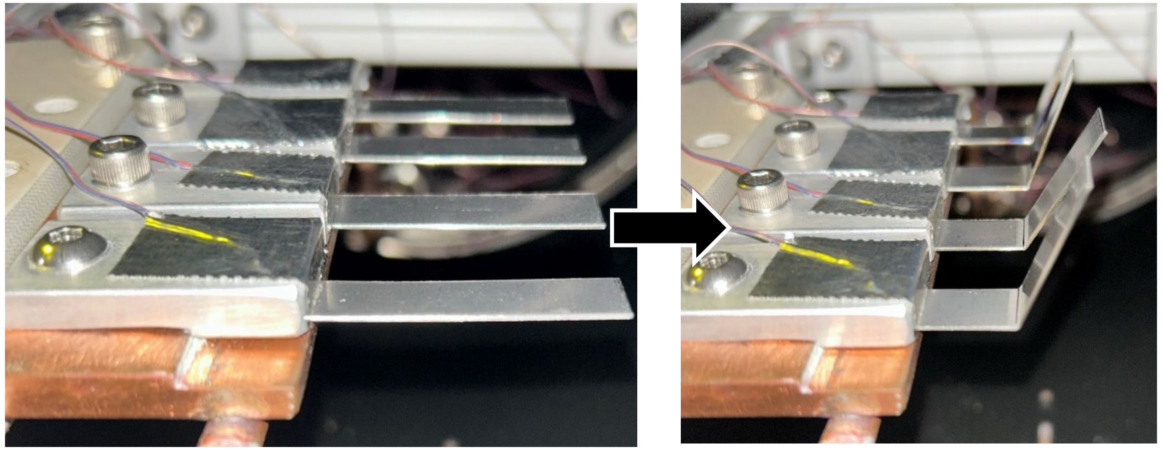
- Develop laser bending in TVAC (non-contact)
- Excellent synergy with In-Space Welding
- Integrated Computational Materials Engineering
- Directly support University of Florida NOM4D performer



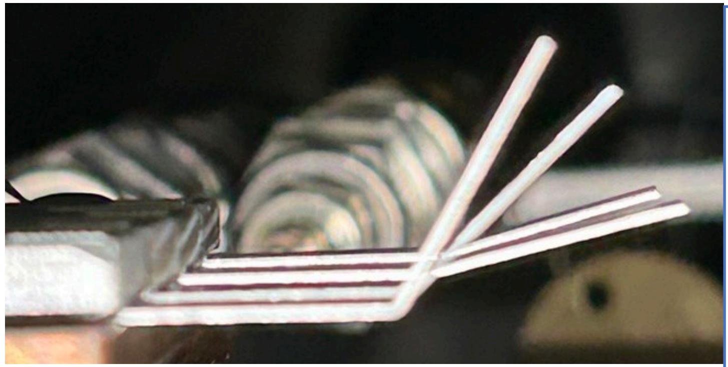

Credit: University of Florida

Laser forming demo advanced SOA two weeks post-project kickoff.

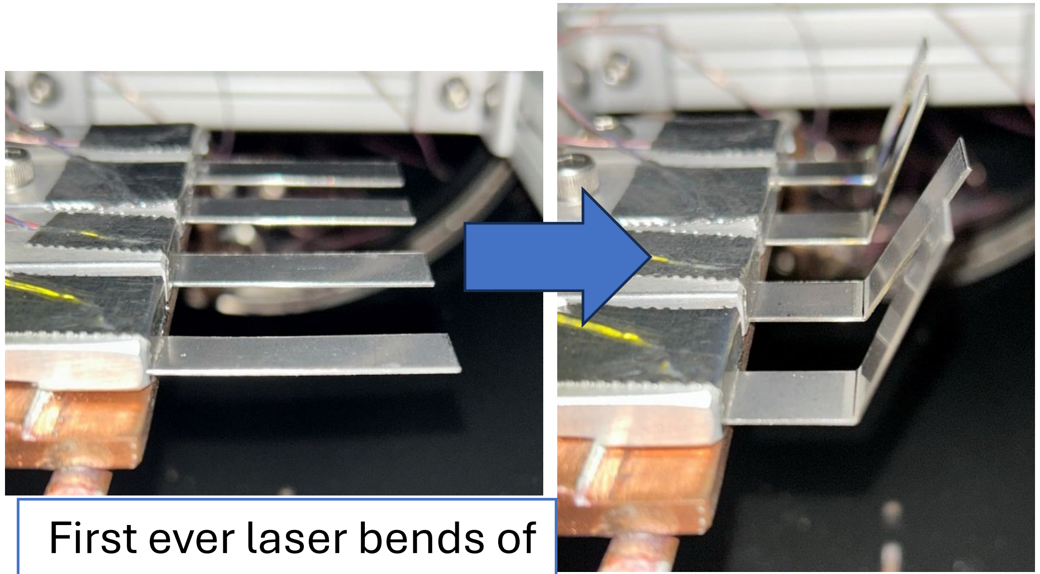




# Big Wins from 2024 Laser Forming TVAC Effort

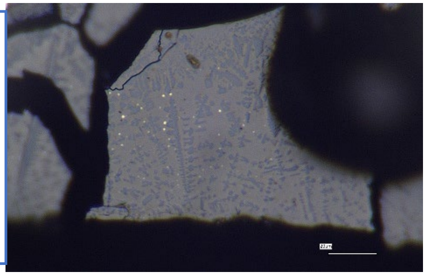


Uncovered severe sensitivities of 3003Al to process, including laser focus risk

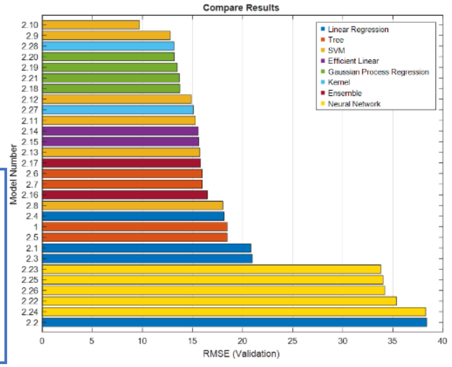


First ever laser bends of 304SS under vacuum at 150 K (-120 °C)

Continuing insights into localized melting and potential oxidation-assisted bending



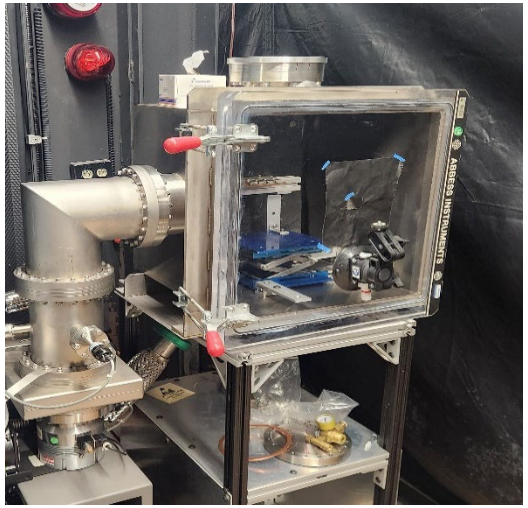
Building Digital Twin via ICME and pioneering ML for laser forming via transfer learning to reduce experimental burden




We have shown that 304SS and 3003Al (and soon Ti64) bend in TVAC
**Now:** understanding the fundamental mechanisms and
maturing the technology for practical application in space

# Versatile T/VAC facilities at MSFC

**V-9 TVAC with custom Tee:**
Vacuum down to ~$10^{-5}$ Pa ($10^{-7}$ Torr);
convective heat transfer suppressed
Temperature held from ~150 to 330 K (-120 to +60 °C);
active thermal control of fixturing/specimens



Developmental vacuum chamber for rapid parameter development

50W laser head with x-y-z scanning optics

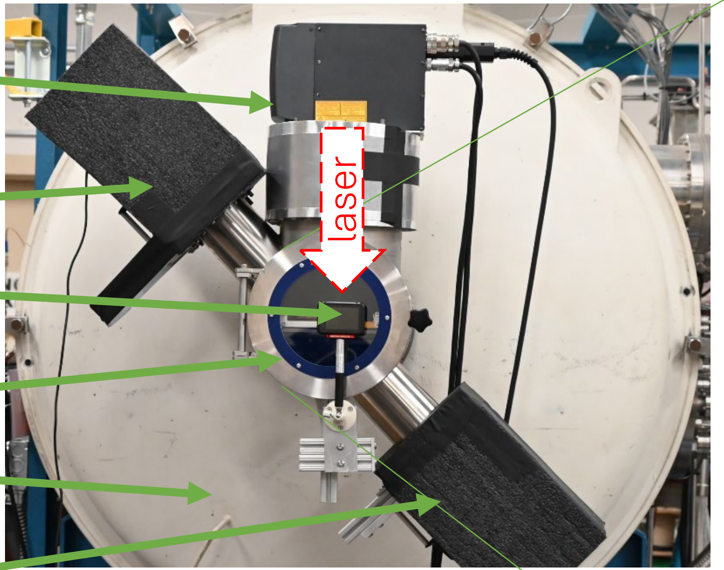
NIR (high-temp.) camera

Optical camera

Custom Tee with fixturing

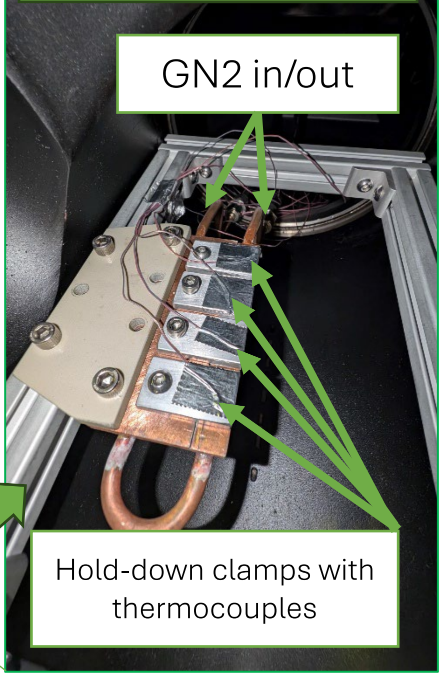
TVAC chamber

LWIR (low-temp.) camera



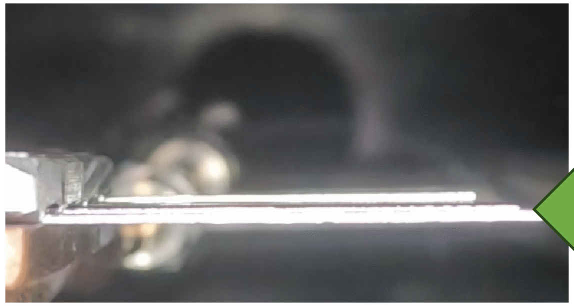

TVAC interior view

GN2 in/out

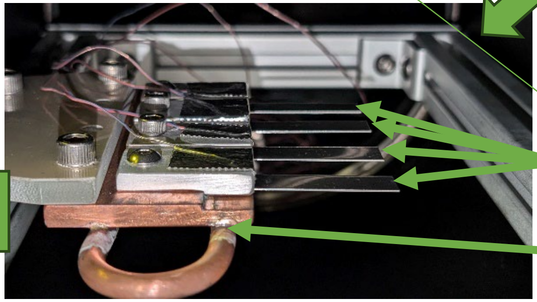


Hold-down clamps with thermocouples

First ever laser forming in TVAC achieved September ‘24



Side-on view during bending

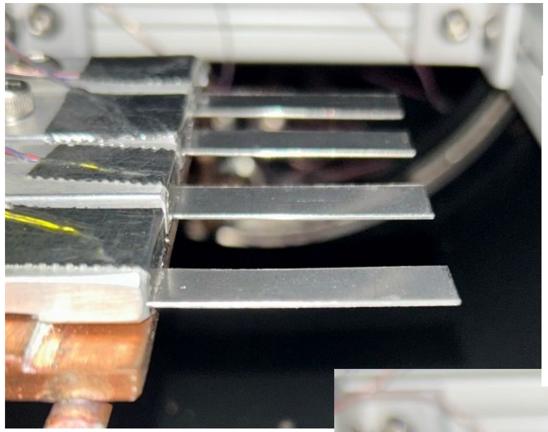


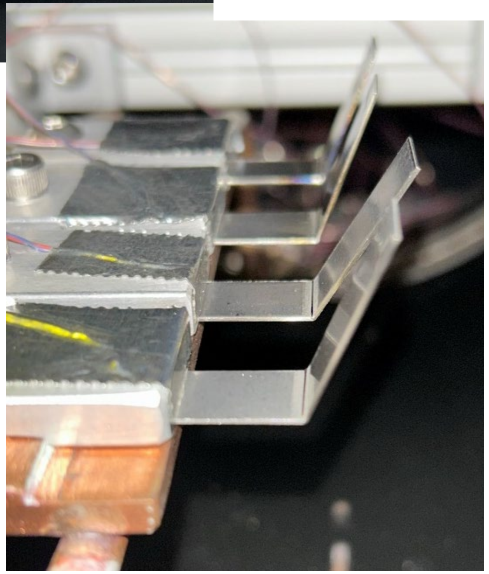
Bending specimens

Thermal backplane with GN2 loop

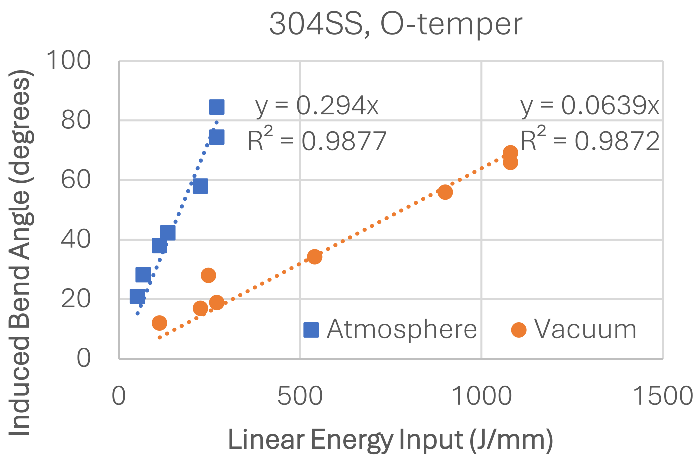
# Remarkably consistent bending in TVAC at same linear energy density for 304SS

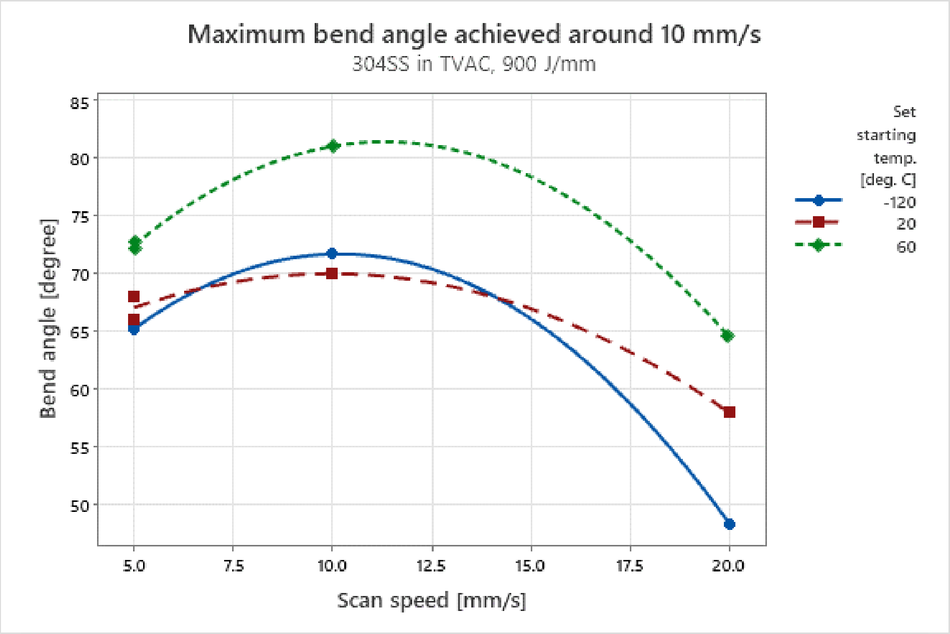
Linear fit model for 304SS gave confidence to proceed to TVAC trials





304SS strips bent at ~150 K (-120 °C) workpiece initial temperature, under vacuum

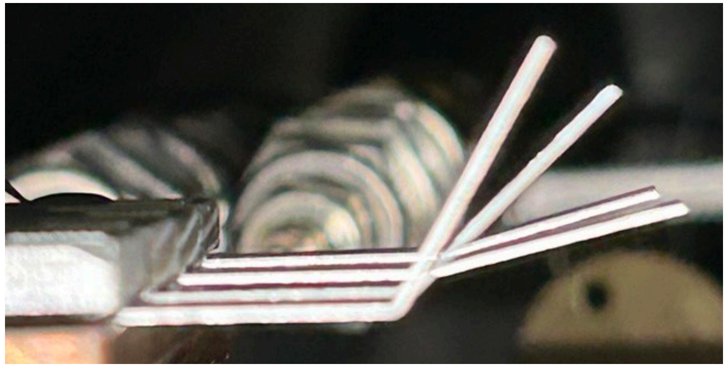


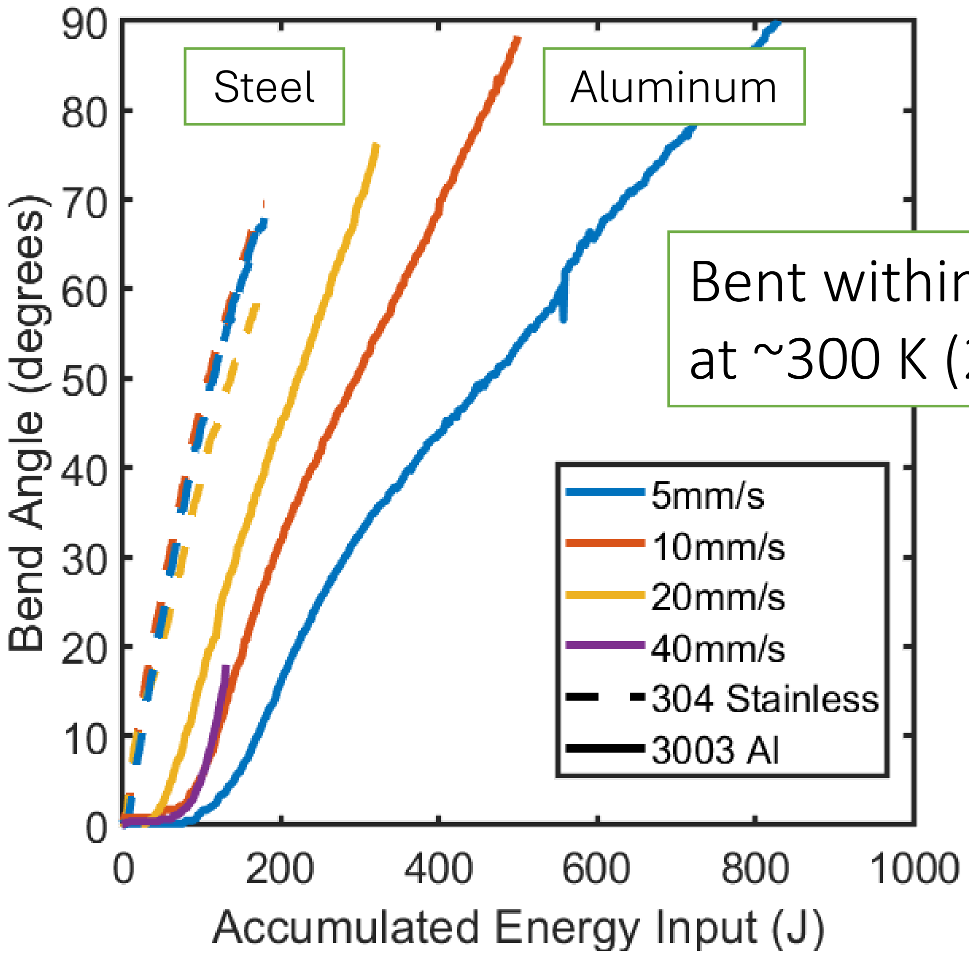

Relative insensitivity to process parameters → domination by thermophysical properties (low thermal diffusivity, large processing window between bending and melting, etc.).

# 3003Al requires more energy to bend than 304SS and is more sensitive to focus, scan speed, temperature, etc.

3003Al more affected by cold temperatures (~150 K; -120 °C); exhibits reduction in bend angle



Slight changes in focus/workpiece displacement radically alter bending in 3003Al (~300 K ; 20 °C)



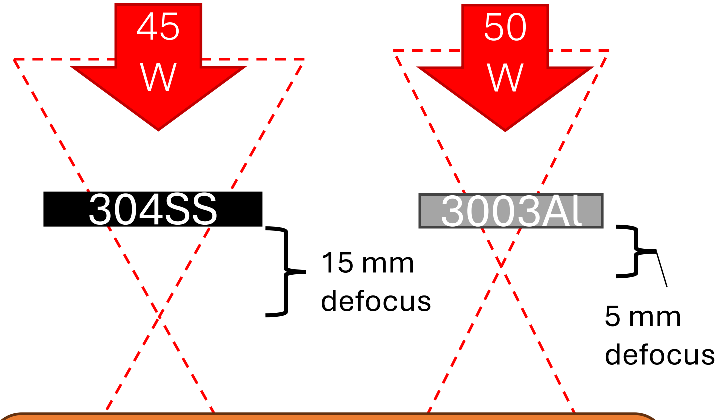

Bent within TVAC at ~300 K (20 °C)

# Narrow process window (focus) risk for 3003Al – mitigating by displacement sensor

3003Al more sensitive than 304SS to changes in spot size from displacement variation

| Material | %Δ in spot diameter | %Δ in spot area/power density |
|---|---|---|
| 304SS | 2 | 3 |
| 3003Al | 4 | 8 |

For a mere 250 μm displacement variation




Mitigating laser focus risk with 30 μm-resolution displacement sensor

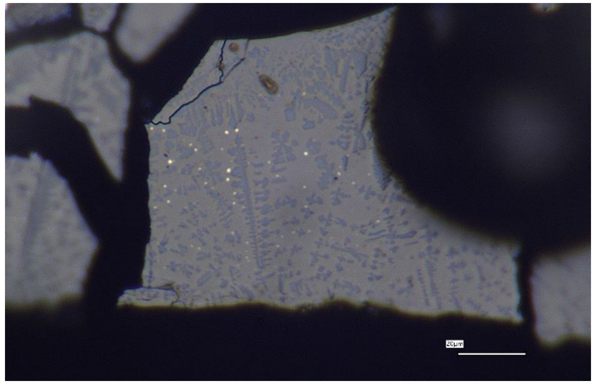
3003Al required higher power and tighter focus than 304SS to induce bending due to slower thermal build-up from order-of-magnitude higher thermal conductivity and laser reflectivity

3003Al also has much lower liquidus than 304SS (~650 °C vs ~1450 °C)

**Thus, processing window for 3003Al is vexingly narrow**
between inadequate power density (no bending) and excessive power density (spatter, melting)

Overlapping sensitivities for 3003Al complicate laser forming
**ALUMINUM NEEDS SUBSTANTIAL FURTHER INVESTIGATION**

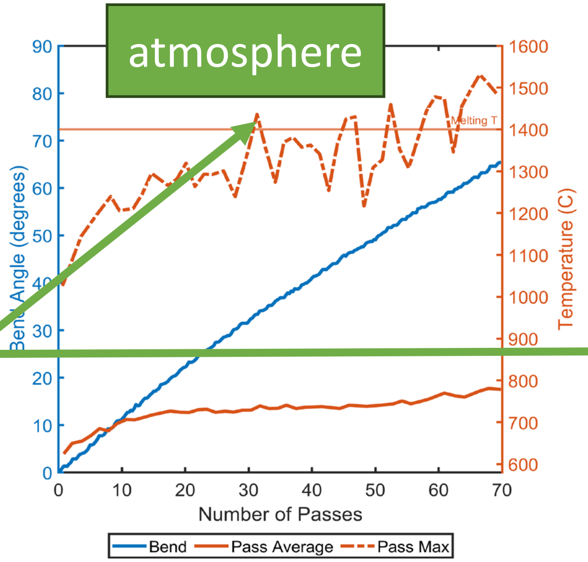
# Exploring how oxidation & oxide layer affects bending

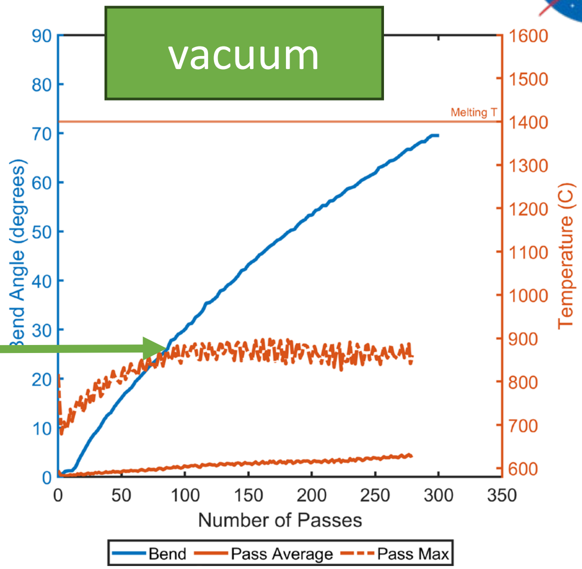


Noted solidification structure indicating localized melting under laser in 304SS

In atmosphere, laser spot hits 304SS liquidus; in vacuum, laser spot remains well below liquidus

Note > 4x reduction in number of passes for bending in air!



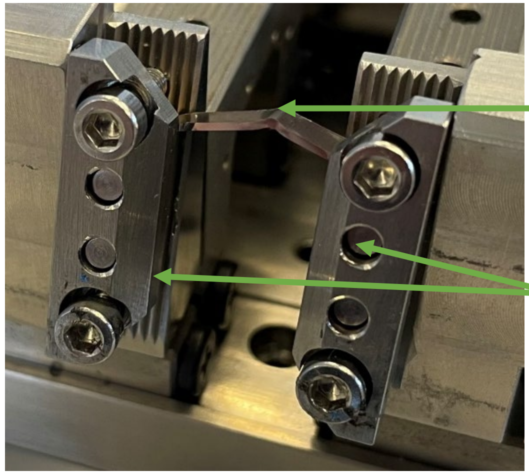

Emerging theory: Localized melting/oxidation enhances thermal build-up and thus bending rate in atmosphere – "mini blast furnace"

Correlating oxide layer thickness, vacuum level, and etching strategy (laser absorption) with thermal data to understand pre-bend delay in aluminum
– a certain thermal build-up is needed to initiate bending

| Condition | Location | Est. oxide thickness [nm] |
|---|---|---|
| Atmosphere | Bulk | 3.71 |
| | Bend region (etched once) | 4.01 (+8%) |
| Vacuum | Bulk | 4.14 |
| | Bend region (many etches) | 3.15 (-24%) |

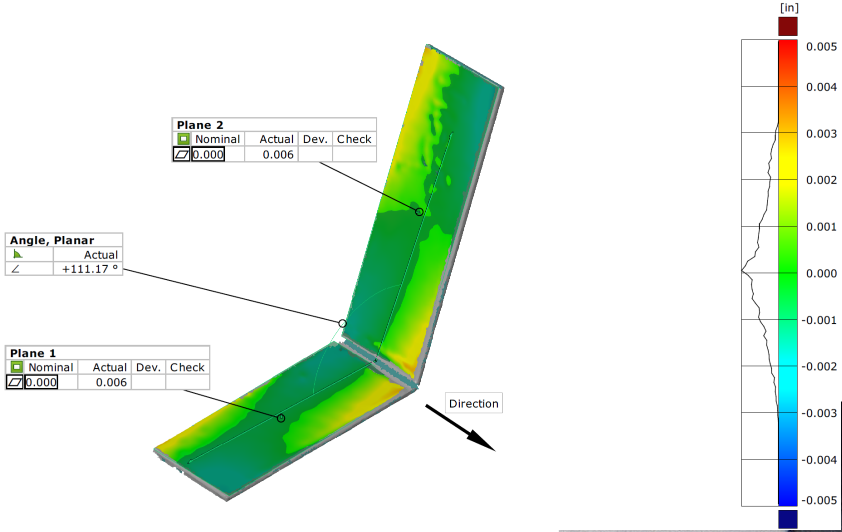
Al 2p and Al 2p oxide from XPS
For trends only; need calibration

# Intensive characterization and properties/performance testing underway



Bent specimen

Tensile grips

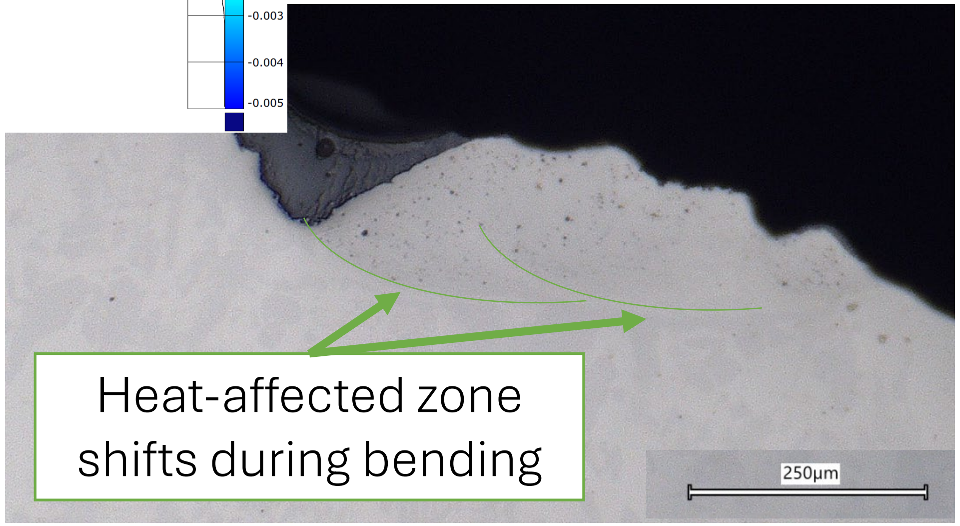



Structured light scans quantify macro-distortion of specimens

First-of-a-kind capability for *in situ* tensile pull during EBSD:

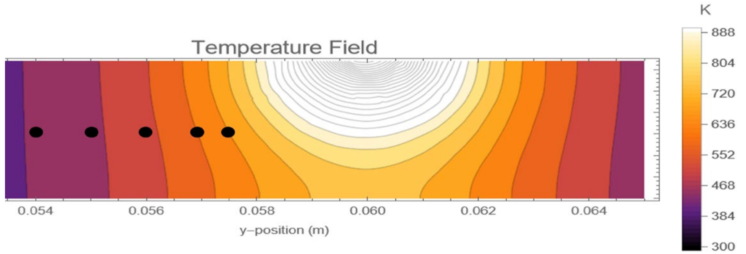
- reveals how microstructure deforms during loading after laser forming
- **informs performance (fatigue, etc.) predictions**

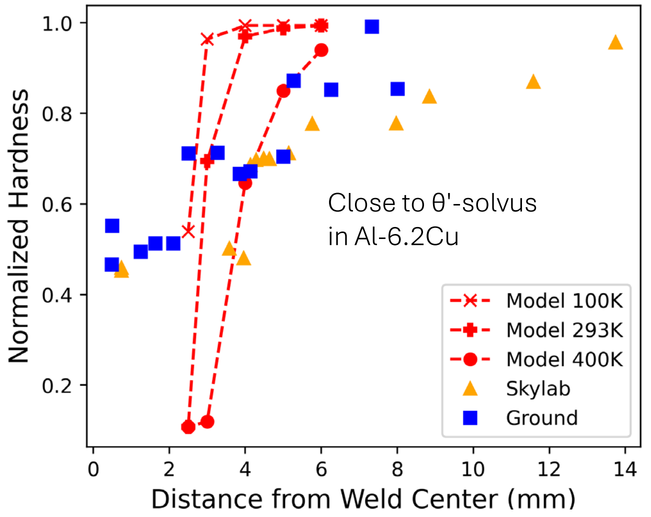
Metallography reveals microstructure of specimens

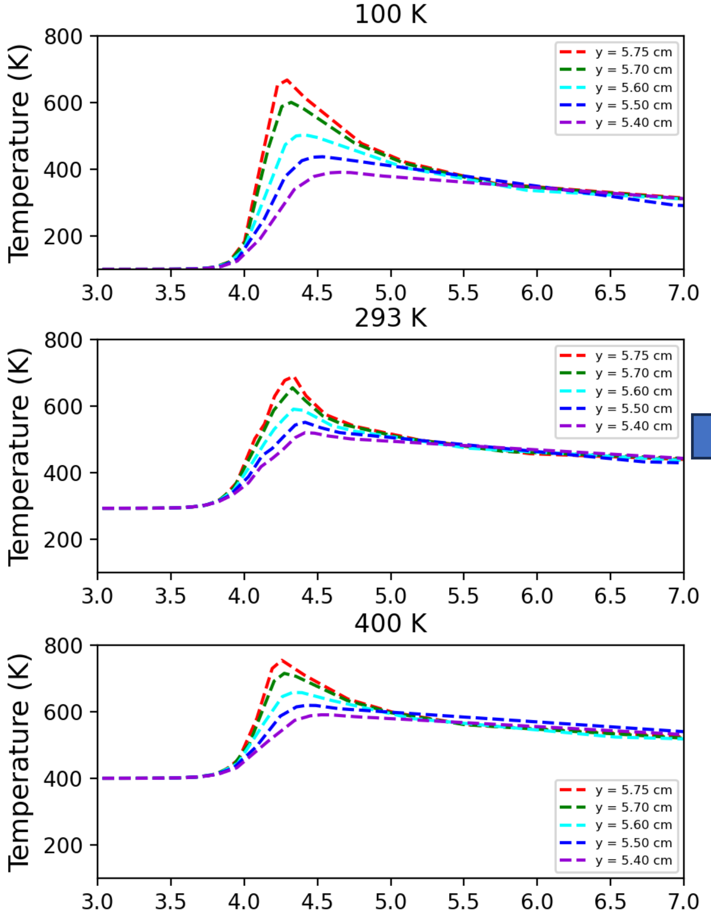


# Building Digital Twin using ICME technqiues

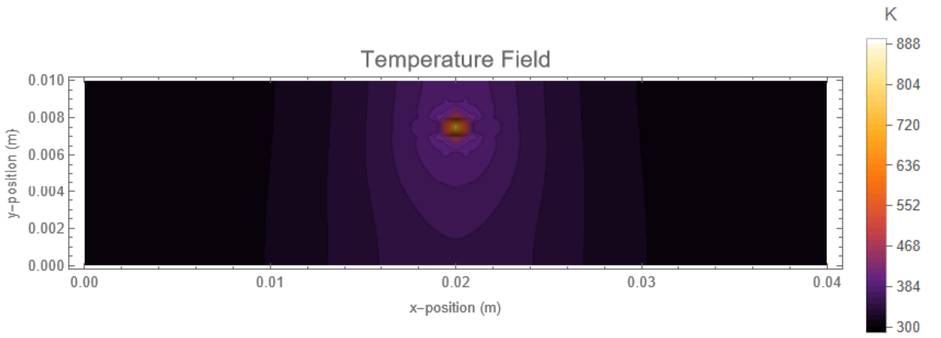
[Computational and Physics-Based Modeling for the Development of in-Space Welding Technology - NASA Technical Reports Server (NTRS)]



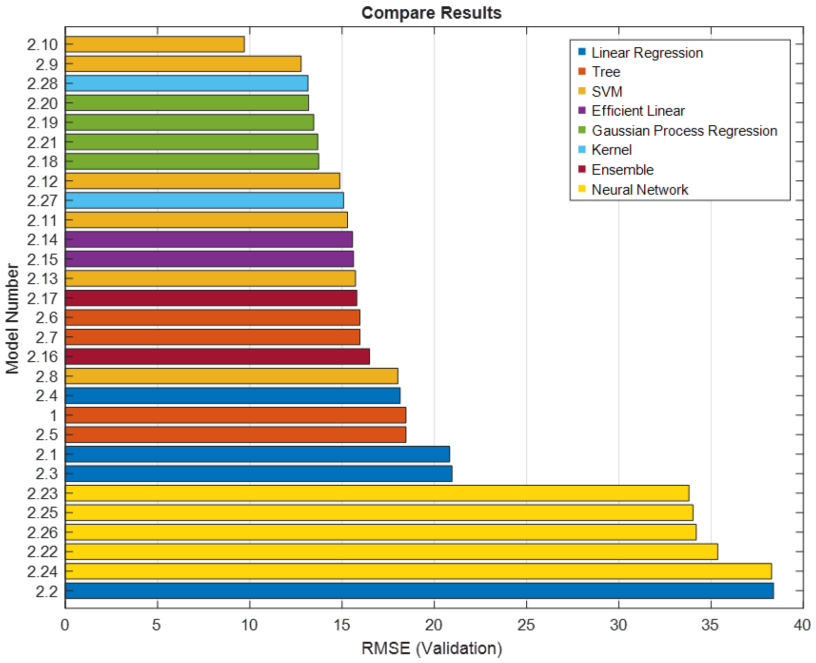

- Previously developed model for welding linked processing-structure-properties via thermal model, precipitation calculator, and hardness estimator



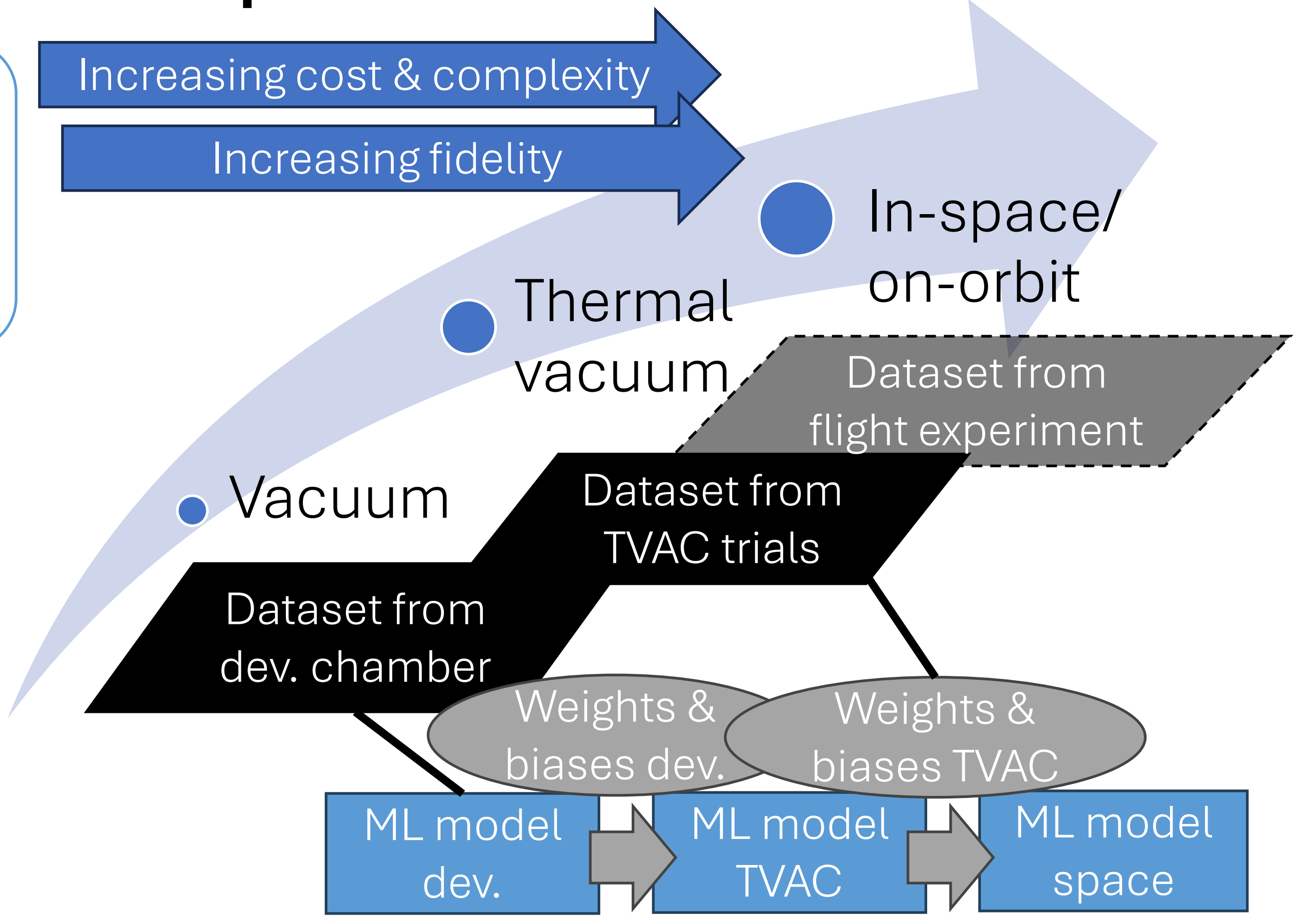

- Approach being extended to laser forming activities, enables physically informed machine learning

# Leveraging AI/ML to reduce experimental burden

ML <u>models to be trained on large developmental dataset</u> linked to limited TVAC/flight datasets while <u>considering delta in gravity, thermals, etc.</u>




Evaluation of various ML model types for laser forming




Transfer learning: train model on more extensive dataset, transfer weights & biases to model for rarefied dataset

# Upcoming and future work

- Demonstration of Ti64 laser forming in TVAC – imminently
- Resolve laser focusing risk – mitigating via displacement sensor
  - Re-run aluminum TVAC trials with displacement sensor and known laser spot size
- Substantial work in materials diagnostics and property testing – what is performance of laser formed specimens w.r.t mechanical utility etc.?
- Continue building Digital Twin via ICME
- Pioneer ML transfer learning for laser forming
- Investigate influence of oxide layer thickness (and etching) on aluminum
- Explore whether localized melting/oxidation enhances bending process

Engineering

Science

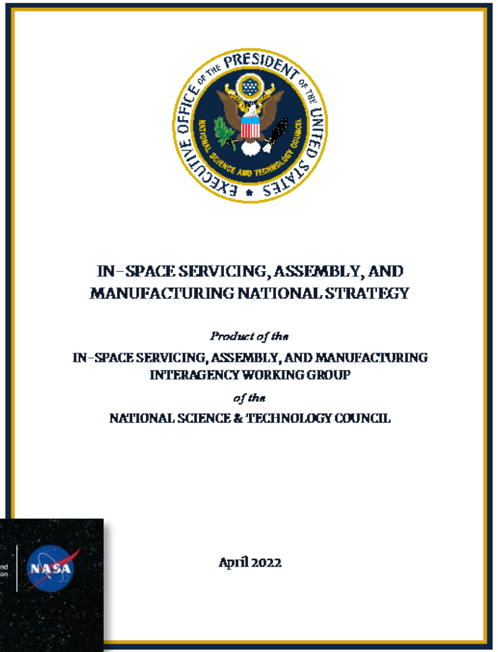
We have shown that 304SS and 3003Al (and soon Ti64) bend in TVAC
**Now:** understanding the fundamental mechanisms and
maturing the technology for practical application in space

# Scale up, transition, next steps

What are your thoughts of the next steps after NOM4D?

- What is the end point of your NOM4D demo?
  - Maturation of laser forming technology in TVAC for relevant engineering alloys so that it is ready for a combined on-orbit demo with laser beam welding (also in development at NASA Marshall)
- What technologies may need further development?
  - Laser beam welding, non-contact NDE, ICME/Digital Twin of in-space laser processes to enable one-shot welds & bends & other manufacturing techniques, supervised autonomy of robotics to automate path planning etc.
- What still needs to be done?
  - Immediate: demonstrate Ti64 in TVAC, mitigate laser focus risk, ramp up materials diagnostics & mechanical testing, continue building Digital Twin via computational materials models, pioneer transfer machine learning for laser forming, investigate oxidation/oxide layer
  - Future: Demonstrate in reduced gravity and on-orbit, demonstrate as part of chain of manufacturing (laser forming as one tool in toolbox), understand performance especially fatigue, improve autonomy of process, link to kinematic models and how to approach & align laser process head with feedstock
- Who should care about your results? Who have you reached out to, or who would you like to reach out to?
  - Companies (Lockheed Martin, ThinkOrbital, etc.) investing in in-space manufacturing, especially laser processes; NASA Marshall already has agreements
  - Defense agencies (AFRL, NRL, ARL, etc.) will needs for manufacturing complex structures from diverse feedstock in extreme environments
  - Presented at Defense Manufacturing Conference 2024, presenting at TMS (materials society) 2025, may present at Lasers in Manufacturing 2025 (international conference)
- How does your approach compare to the state-of-the-art and what application(s) might your technology enable?
  - Mechanical bending in orbit difficult due to reactive forces, size & mass of tooling, and need for physical contact; laser forming eliminates all of these challenges and greatly enhances the diversity of geometries achievable.
- What is the most exciting outcome you can imagine?
  - An automated factory for structures in space capable of forming and joining almost any metallic structure imaginable
- How can DARPA and the government team help?
  - **Continued support, especially advocacy for an on-orbit demo with other laser processes in partnership with OGAs such as NASA, AFRL, etc.**

# Why?


EXECUTIVE OFFICE OF THE PRESIDENT OF THE UNITED STATES

NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

IN-SPACE SERVICING, ASSEMBLY, AND MANUFACTURING NATIONAL STRATEGY

*Product of the*

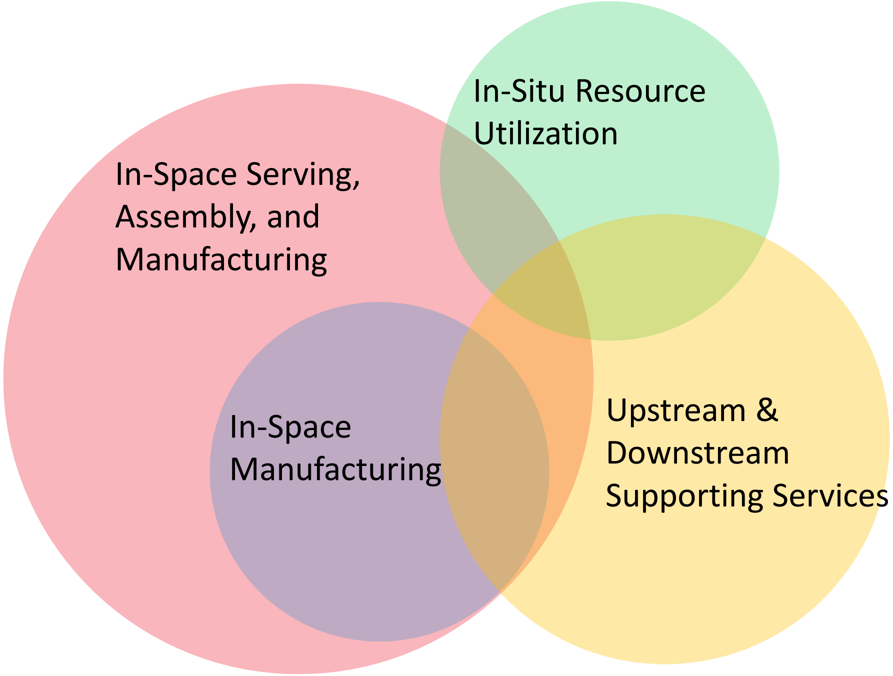
IN-SPACE SERVICING, ASSEMBLY, AND MANUFACTURING INTERAGENCY WORKING GROUP

*of the*

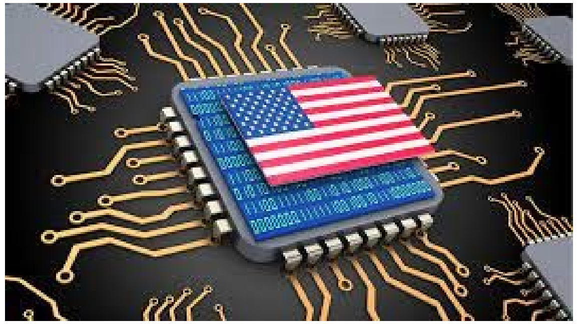
NATIONAL SCIENCE & TECHNOLOGY COUNCIL

April 2022

"ISAM capabilities can create the foundation for sustainable operations and serve as a strategic enabler to spur U.S. scientific and technological innovation, ensure the freedom to operate, and preserve the use of space for future generations."




Adapted from In-Space Manufacturing-2022 Industry Survey
Erik Kulu

M2M Architecture Definition Document: *Manufacture is mentioned 80 times, repair (43), and recycle (6)*

# ISM Addresses STMD Advanced Manufacturing Technology Shortfalls (“Gaps”)


| Gap ID | Gap Title | ISM Portfolio Approach |
| --- | --- | --- |
| 1485 | In-Space Manufacturing of Metals, Electronics, and Polymers (Spares, Repairs, New Parts) | GCD-funded project On-Demand Manufacturing of Electronics (ODME) is currently pursuing in-space manufacturing of sensors for astronaut health and semiconductors for use in space and terrestrially. ISM anticipates resumption of in-space fabrication of metallic and hybrid material components and structures in future fiscal years. |
| 1487 | In Space Welding and Large-Scale Additive Manufacturing | MSFC TIP, proposed ECI, and a DARPA NOM4D collaboration are developing in-space laser-based processing (e.g. welding and bending) to enable critical repairs and construction of large articles such as lunar towers or space-based storage tanks. |
| 1489 | Recycling and Reuse for In-Space Manufacturing | ISM plans to reintroduce a focus on space-based material recycling in FY25, to be followed by recycling of metallics. |
| 1486 | In Situ Qualification, Verification & Validation of Components for Manufacturing, Assembly, and Construction | ISM is utilizing NDE, structured light, and various other inspection techniques to verify and validate form, fit, and function of space-fabricated electronics, components, and structures. |

Ref: Advanced Manufacturing Envision Future Priorities

# Moon to Mars Strategy

## Objective-based Approach – Architect from the Right

LI-4: <u>Lunar Surface Advanced Manufacturing and Construction</u>

LI-8L: Cislunar Orbital/Surface Depots, Construction and Manufacturing

PPS-2: Understanding Physical Systems

AS-6: <u>Understanding Environmental Effects</u>

RT-5: Maintainability and Reuse

RT-6: Responsible Use and Behavior in Space

RT-9: Commerce and Space Development

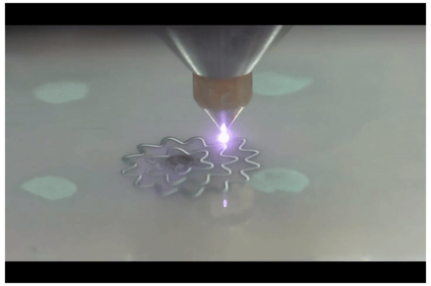
OP-11: <u>In-Space Resources to Reduce Mass</u>

OP-12: <u>Minimize the Disturbance to the Environment, Maximize Reuse/Recycling</u>

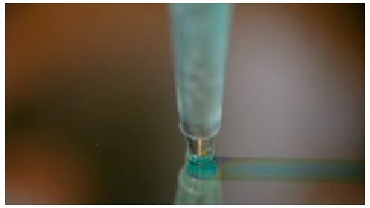
TH-4: In-Space and Surface Habitation

# On-Demand Manufacturing Of Electronics

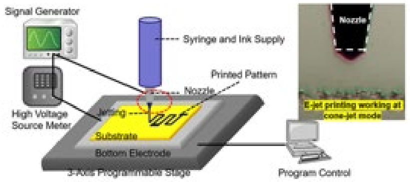
**Goal:** Develop and demonstrate on-demand printing of electronics in microgravity and characterize the impact of microgravity.



Dual Laser Ablation

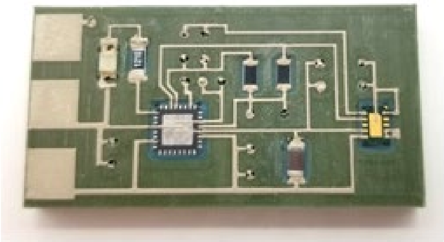


Faraday Electrodeposition of Covetic Copper



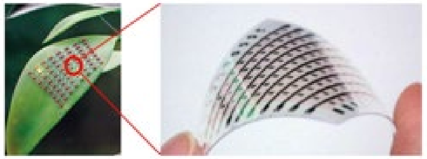

Electrohydrodynamic Ink Jet Printer

Iowa State Parabolic Flight

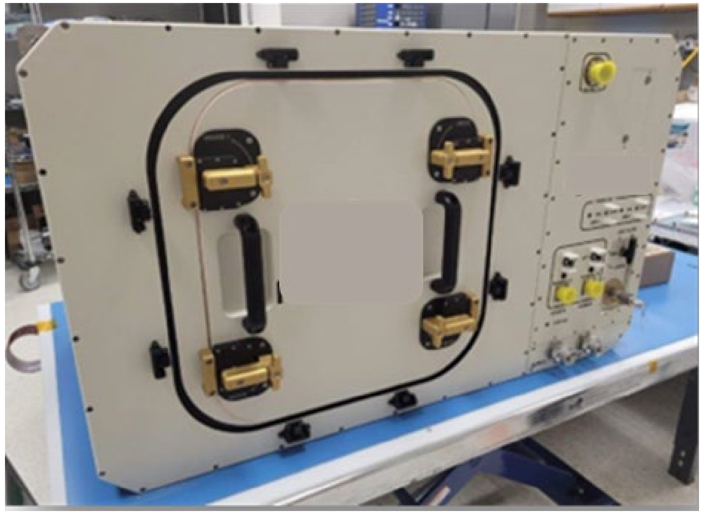


Printed CO2 Sensor (ODME ISS Demo)

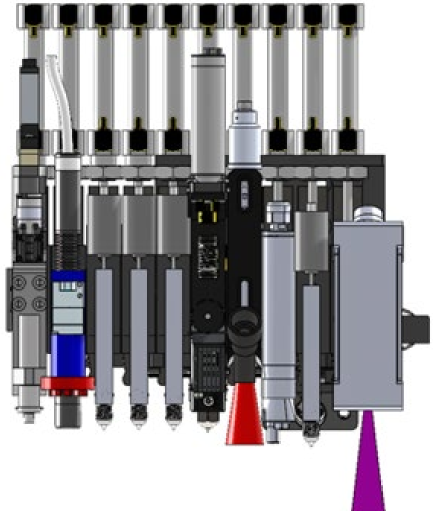
RF Power Harvesting Antennas- UAH



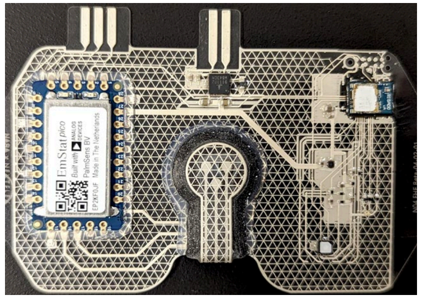
University of Illinois Plant Growth Sensor



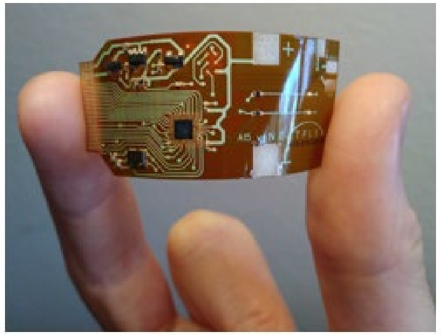
Electronics Printer Module Engineering Development Unit
Image Credit: Redwire



Advanced Toolplate with Newly Developed Deposition Tech

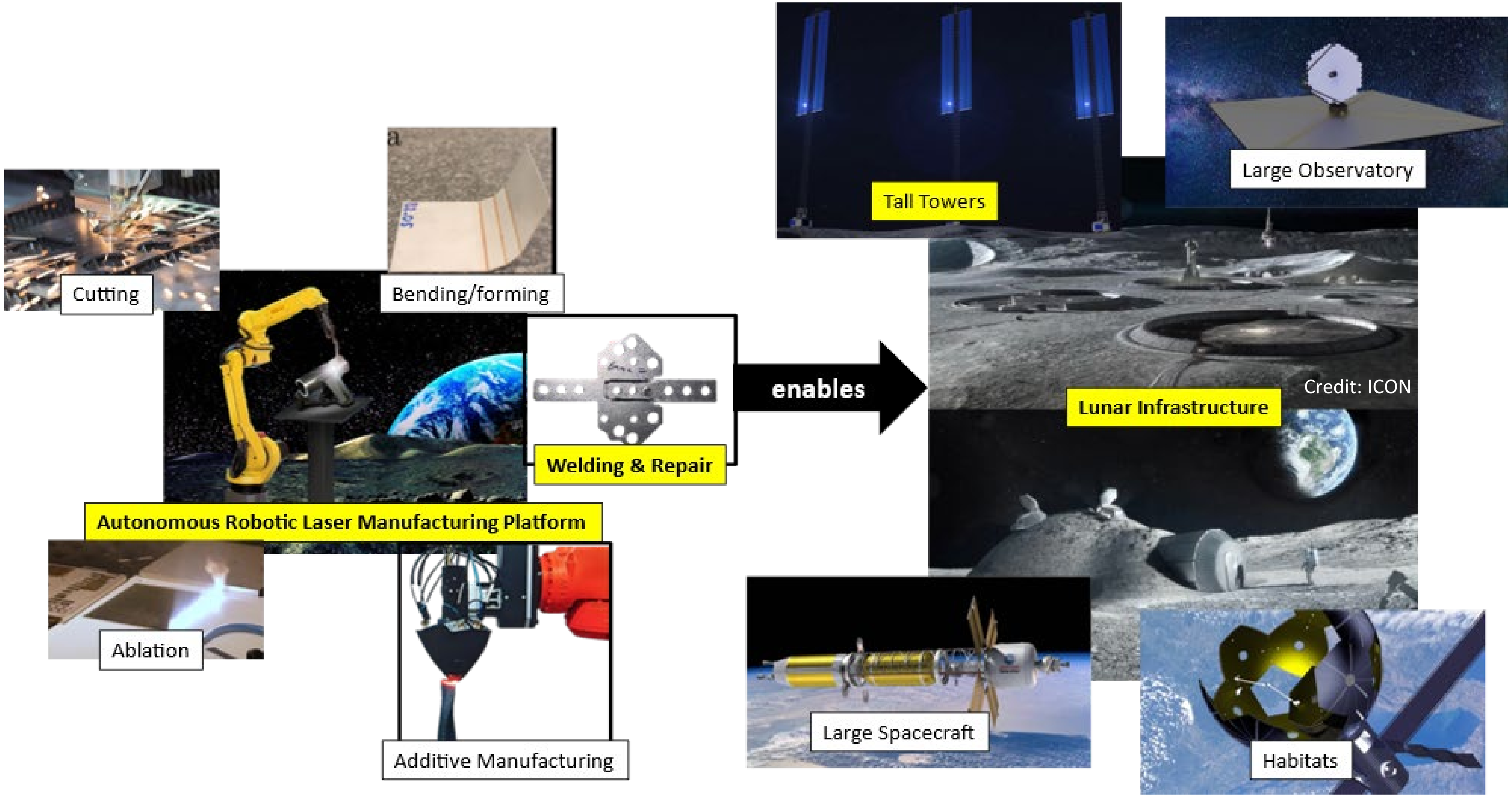


AstroSense FTE Beta Crew Health Biosensor



NextFlex Wireless Flexible Sensor Board

# Lunar Assembly and Service by Autonomous Robotics (LASAR)




Credit: ThinkOrbital/Vojtech Holub

**NASA Core Team Members**

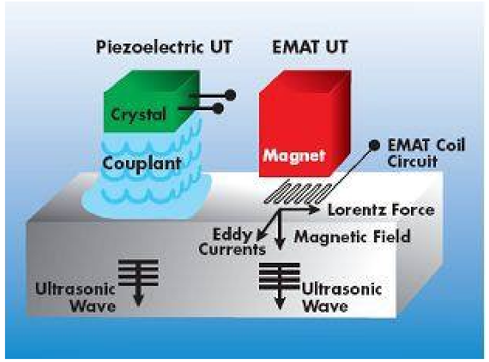
| Name | Center |
|---|---|
| Emma Jaynes | NASA/MSFC |
| Alex Sowell | NASA/JSC |
| Raju Subedi | NASA/MSFC |
| Brace White | NASA/LaRC |
| Supported by: | |
| William Evans | NASA/MSFC |
| Matthew Mahlin | NASA/LaRC |
| Parker Shake | NASA/MSFC |

**External Partners**

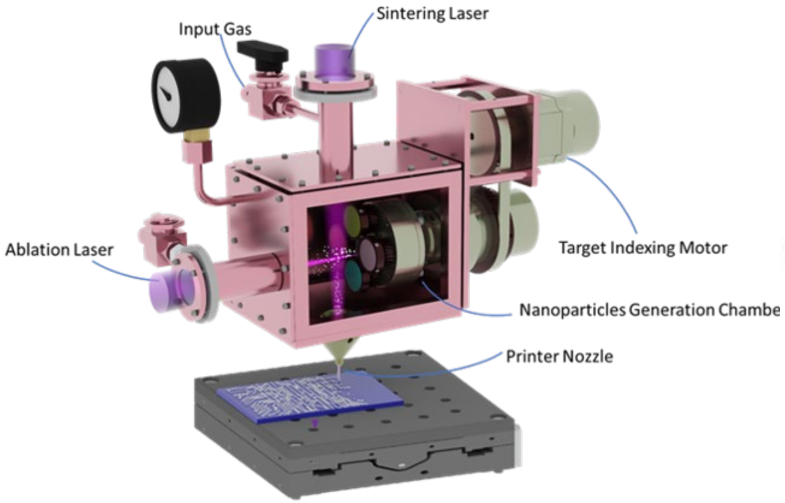
| Name | Role |
|---|---|
| Laserline | Laser Processing Partner |
| Motiv Space Systems | Robotics Hardware Partner |
| PickNik Robotics | Robotics Software & Autonomy Partner |

**Mentors**

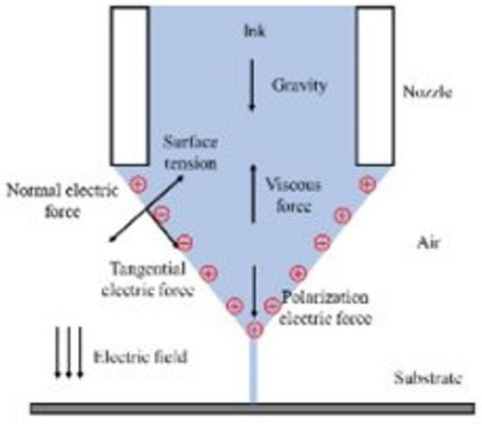
| Name | Role |
|---|---|
| Shaun Azimi | JSC Robotics SME |
| Bill Doggett, PhD | LaRC In-Space Assembly SME |
| John Fikes | MSFC Management SME |
| Jeffrey Sowards, PhD | MSFC Laser Welding SME |



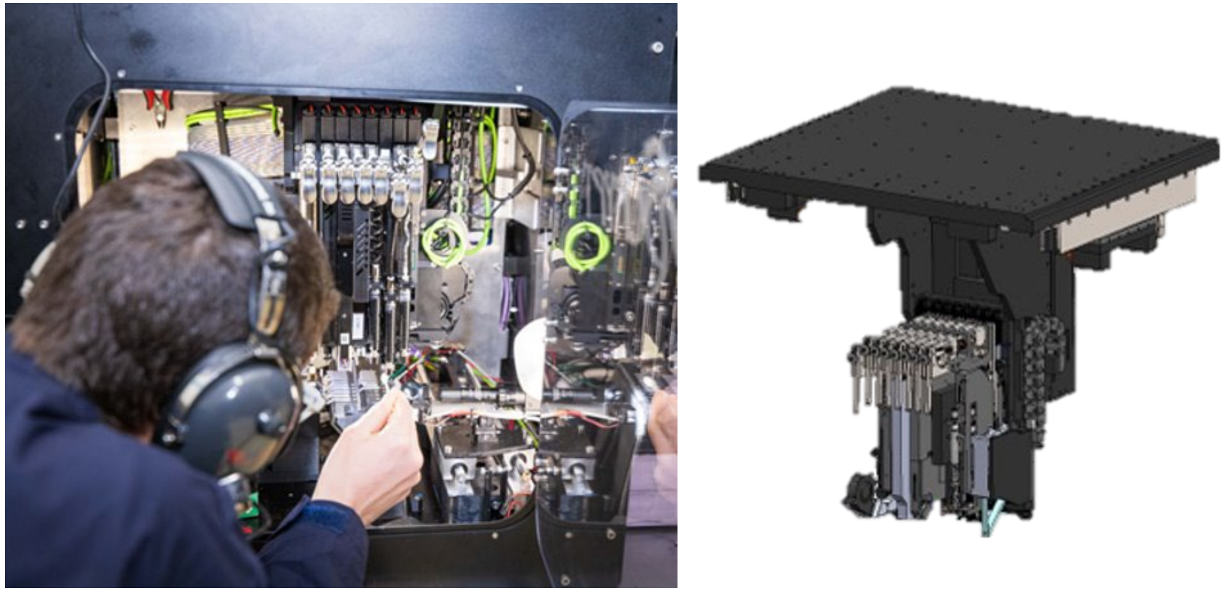
# ODME In-House Capabilities




Dual Laser Ablation



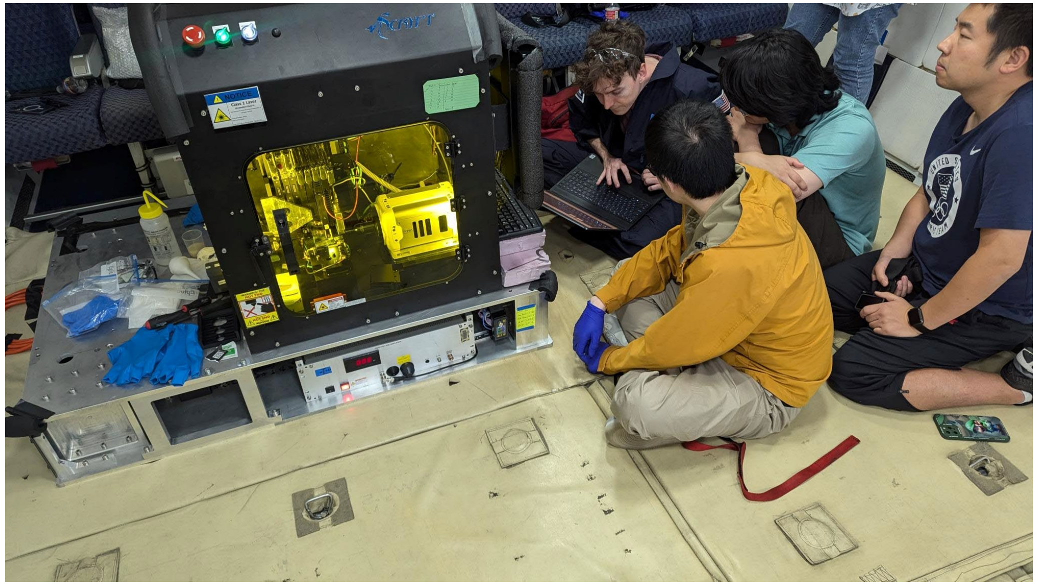

Electrohydrodynamic Inkjet



Parabolic Flight Advanced Toolplate (similar to ODME Printer Module Design)

# ODME Parabolic Flight Campaign Pictures

August 20-22, 2024

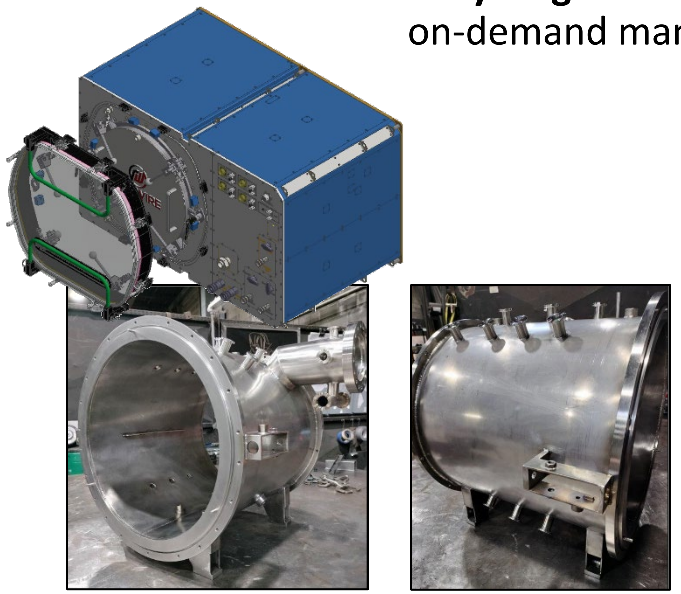


# Recently Closed: On Demand Manufacturing Of Multi-materials Project

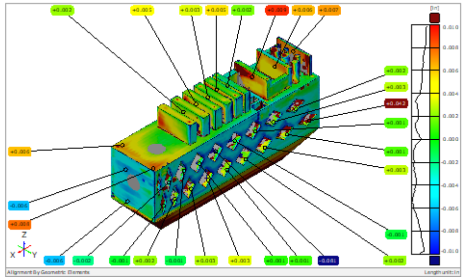
**Goal:** Demonstrate metals additive manufacturing in microgravity and characterize the impact of microgravity.

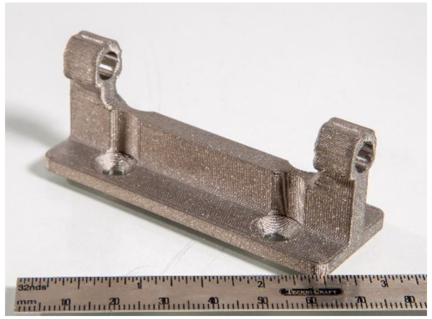
**Sub Projects:**

1. **Outfitting:** Develop the capability to manufacture on-demand utilities, furnishings, tools, etc. for off-earth habitation including the use of In-Situ Resources.
2. **Recycling and Reuse:** Develop the capability to recycle and reuse materials into useable feedstocks for in-space, on-demand manufacturing.



*CAD of Revised furnace module (top). Furnace module hotzone during manufacturing. Image courtesy of Techshot a Redwire company (bottom).*





*Space Suit Wrist Disconnect manufactured by FabLab. Image courtesy of Techshot a Redwire company.*

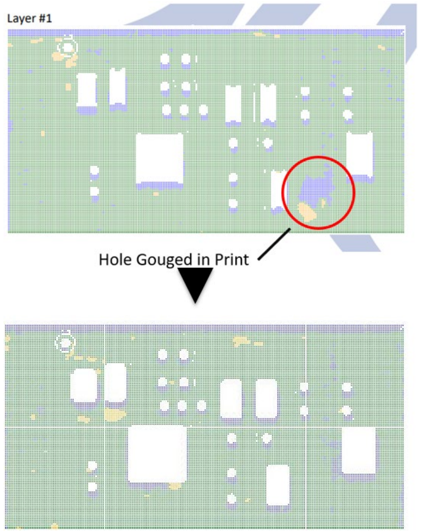



Illustration of inspection and remediation. Image courtesy of Techshot a Redwire company.

# ISM Maturation Utilizing Unique Capabilities

Ground Development


Parabolic Flights - Test

ISS - Demonstrate

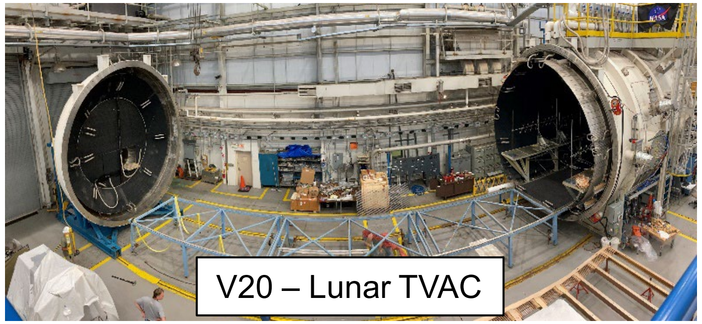

Lunar Habitat – Use

- Iterative maturation toward higher fidelity environments (gravity, atmosphere, temperature, radiation)
- System development and test
- Developing partnerships and project execution approaches


CLDs– Commercialize

Takeaway: We must leverage ground/flight platforms to demonstrate, mature, and commercialize ISM technology.

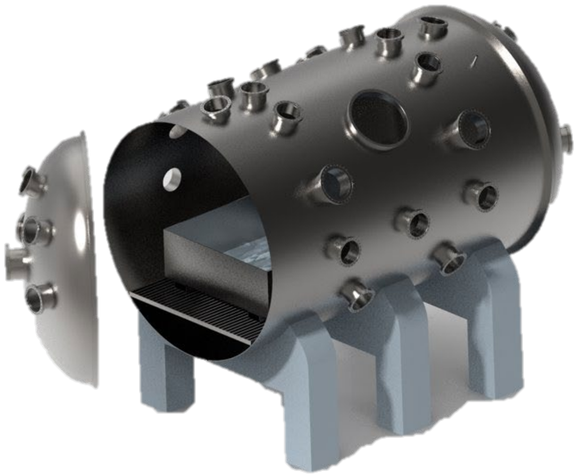
# Leveraging Capabilities ⟶ New Start Development

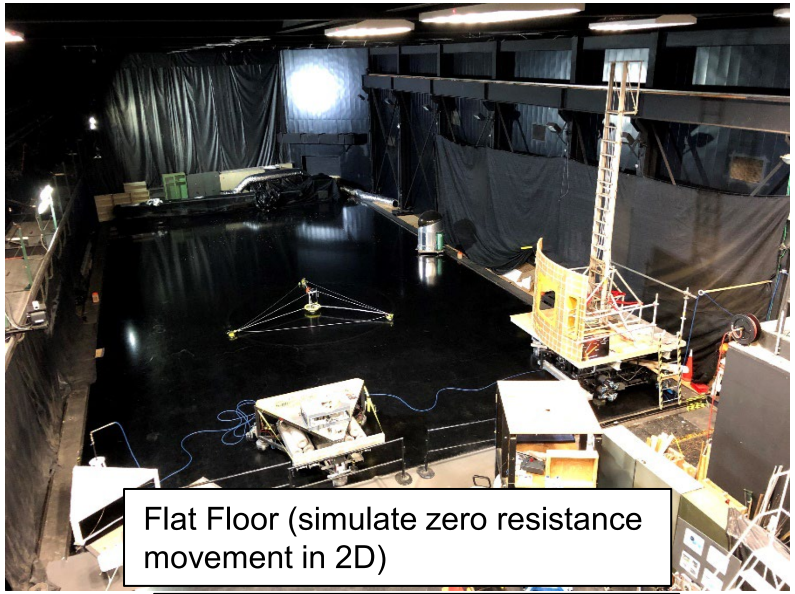

V20 – Lunar TVAC


Solar Wind Chamber

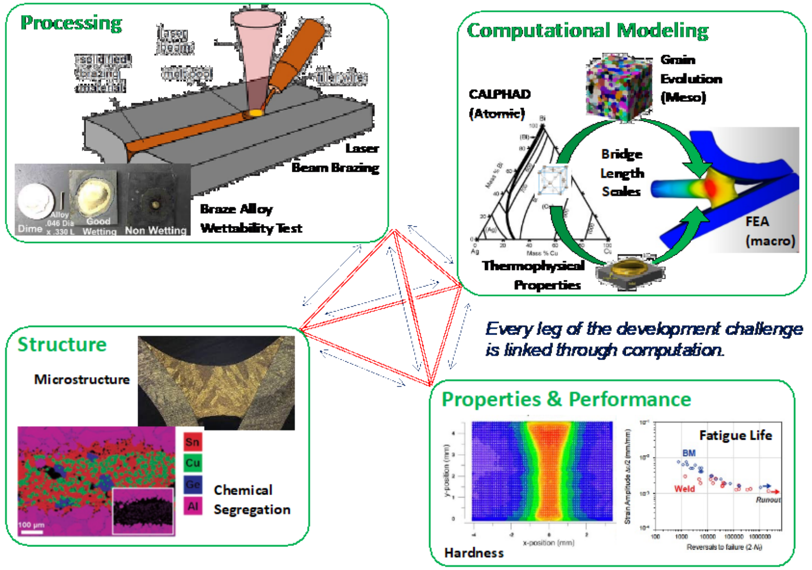

UV Radiation Test Chamber


Charging from Plasma Environments Chamber


Planet Chamber (combines multiple environments => atmosphere, radiation, temperature, regolith)

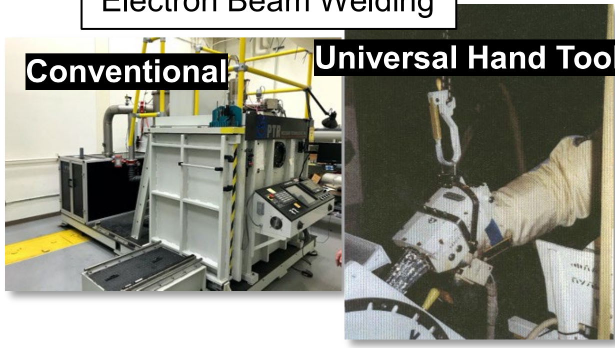

Flat Floor (simulate zero resistance movement in 2D)

Computational Materials Modeling

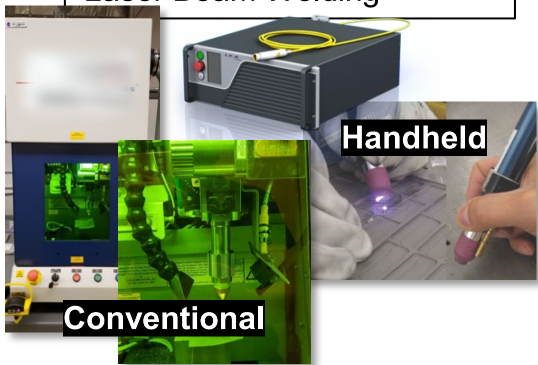



Weld/AM Development & Manufacturing Facilities

Electron Beam Welding



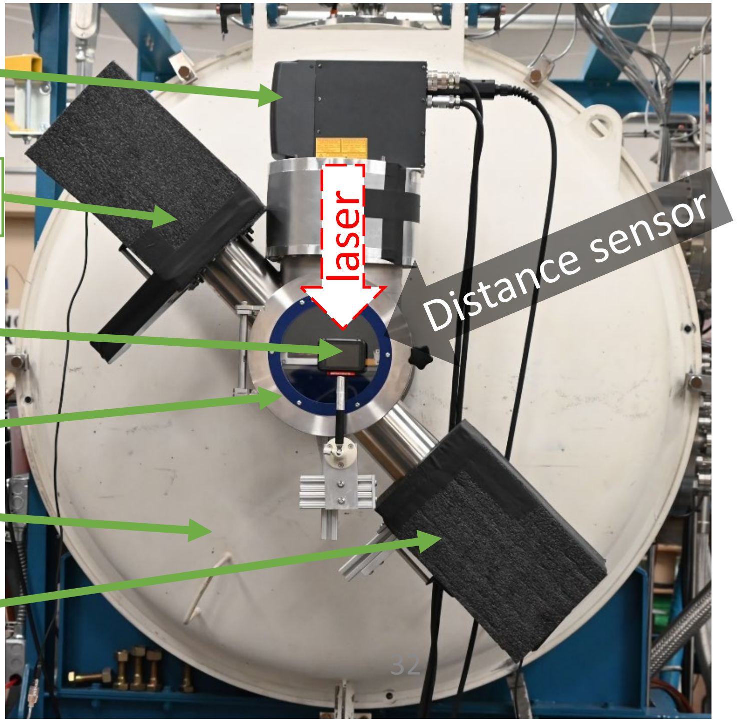

Laser Beam Welding




High Fidelity Experiments Coupled with Computational Modeling, AI/ML, and Digital Twins Enable Sustainable ISM

# Mitigating laser focus risk via distance sensor

- Distance sensor has 30 μm resolution and automatically integrates with laser
- Will adjust spot size based on actual, measured distance from laser lens to workpiece
- Believe that this will improve consistency of aluminum bending trials (re-run?)
- Demonstrates how risk can be addressed in the space environment




Intended update for third round of TVAC trials at MSFC on Ti64 with distance sensor