11 Feb 2026

MDF Capabilities for Klystrons

Dr.’s Paul Prichard, Amy Elliott

Manufacturing Demonstration Facility

ORNL IS MANAGED BY UT-BATTELLE LLC
FOR THE US DEPARTMENT OF ENERGY

Dr. Paul Prichard

ORNL Distinguished R&D Staff

Former Corporate Fellow at Kennametal

Dr. Amy Elliott

Mechanical Engineer

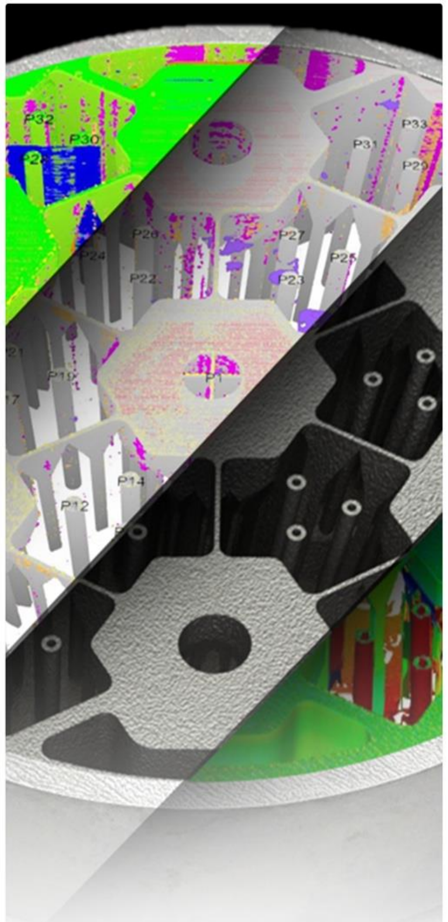
15+ years in Additive Manufacturing (inkjet focused)

18+ Patents

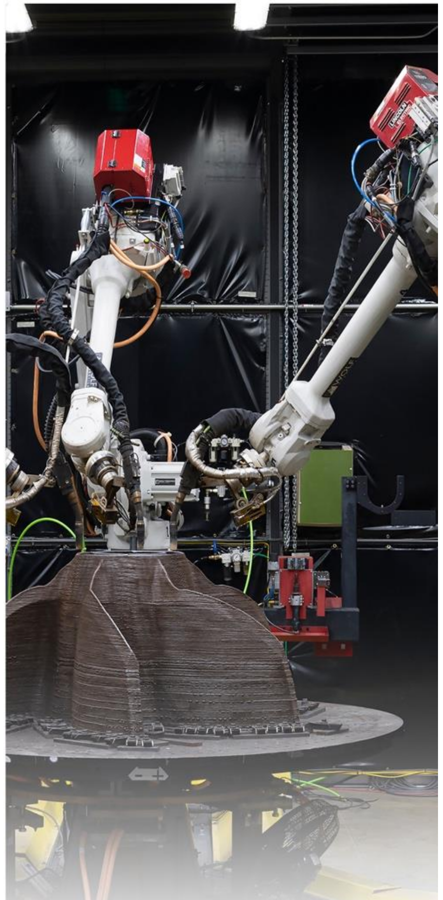
MDF Core Research

Novel materials

Convergent manufacturing



Smart manufacturing



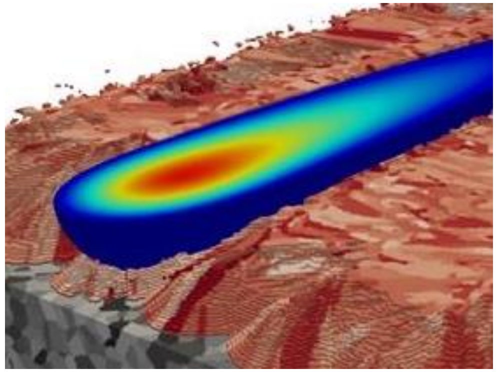
Robotics, automation & controls

Additive Manufacturing Technologies @ MDF:

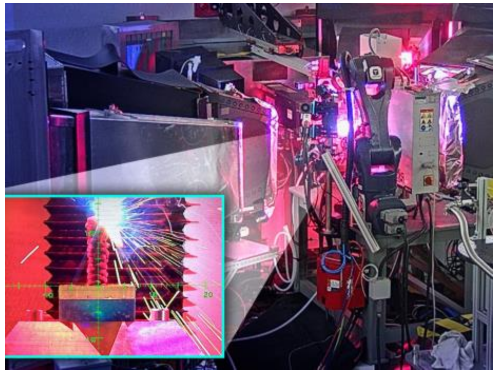
- Laser Melting
- Electron Beam Melting
- Binder Jet (Metals & Ceramics)
- Ceramic AM
- Large-scale Metal
- Directed Energy Deposition
- Hybrid (DED+Machining)

ORNL's capabilities help industry solve the most challenging energy science and manufacturing challenges

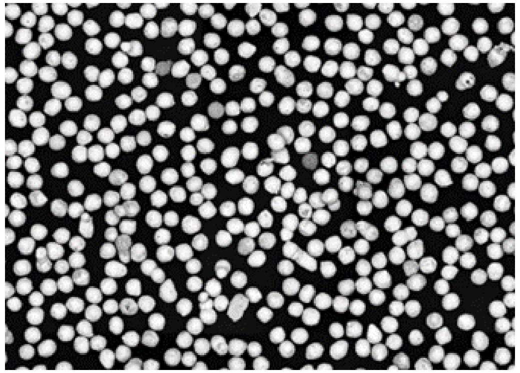
Computing



Neutrons



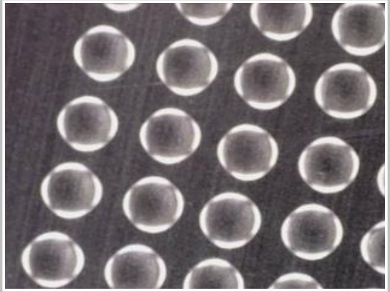
Materials and chemical processes



Resilient materials

Fusion and fission

Energy science

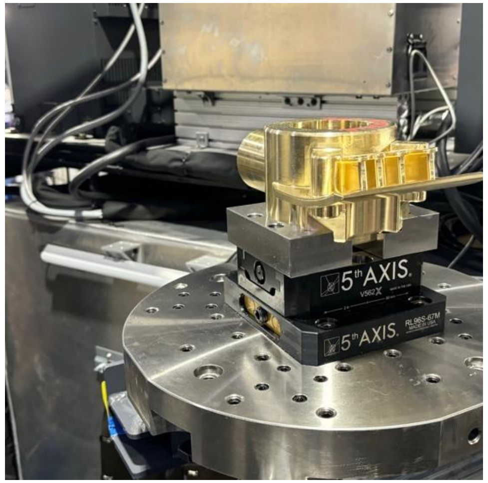


Isotopes

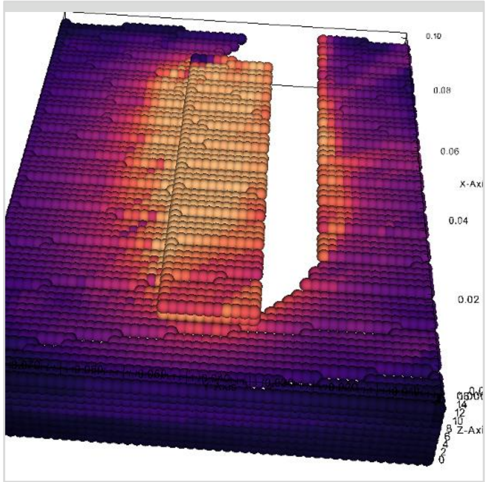
National security

Oak Ridge National Laboratory

MDF research capabilities

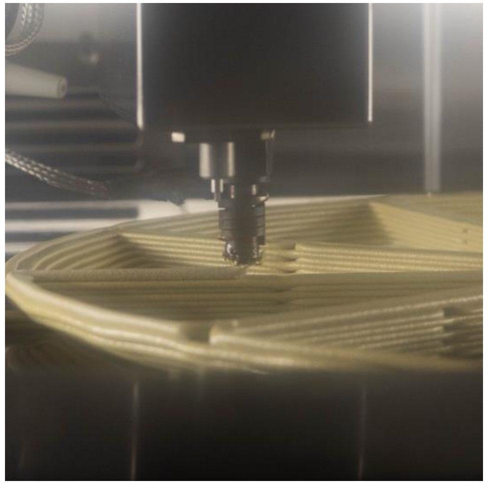


Convergent



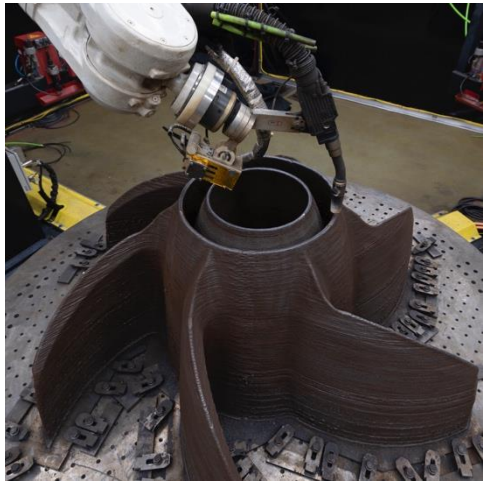
Digital

Composites



Feedstocks

Novel Alloys



Robotics, Automation & Controls

Machining & Machine Tools

Additive Manufacturing

AM Value: Part Consolidation, Reduced Mfg. Steps, Enhanced Performance

Part Consolidation

https://all3dp.com/1/3d-printing-for-part-consolidation-the-ultimate-guide/

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Process Consolidation

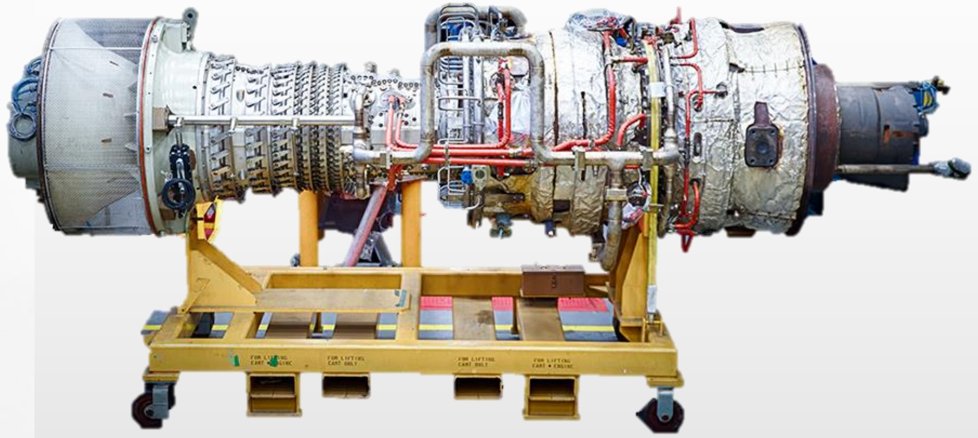
GE LEAP Fuel Nozzle:
- 20 Parts → 1 Part
- 95% Inventory Reduction
- 30% Cost reduction
- Significant Process Consolidation

Performance Improvement

https://all3dp.com/1/3d-printing-for-part-consolidation-the-ultimate-guide/

AI processes validate and qualify new designs of 3D-printed blades for use inside turbine hot section

- 72 prototype blades 3D printed from nickel-based superalloy Inconel 738
- In situ scanning and scan-path optimization to validate and qualify new designs
- **3–4%** increase in efficiency, or ~**$1.5M** per engine, per year, can be achieved through optimizing engine designs using AM compared to conventional processes
- Using electron beam melting instead of investment casting for prototyping showed **savings of $100,000–$500,000**



Blade array successfully tested inside 7MW Mercury 50 gas turbine engine

MDF

Solar® Turbines
A Caterpillar Company

Oak Ridge National Laboratory

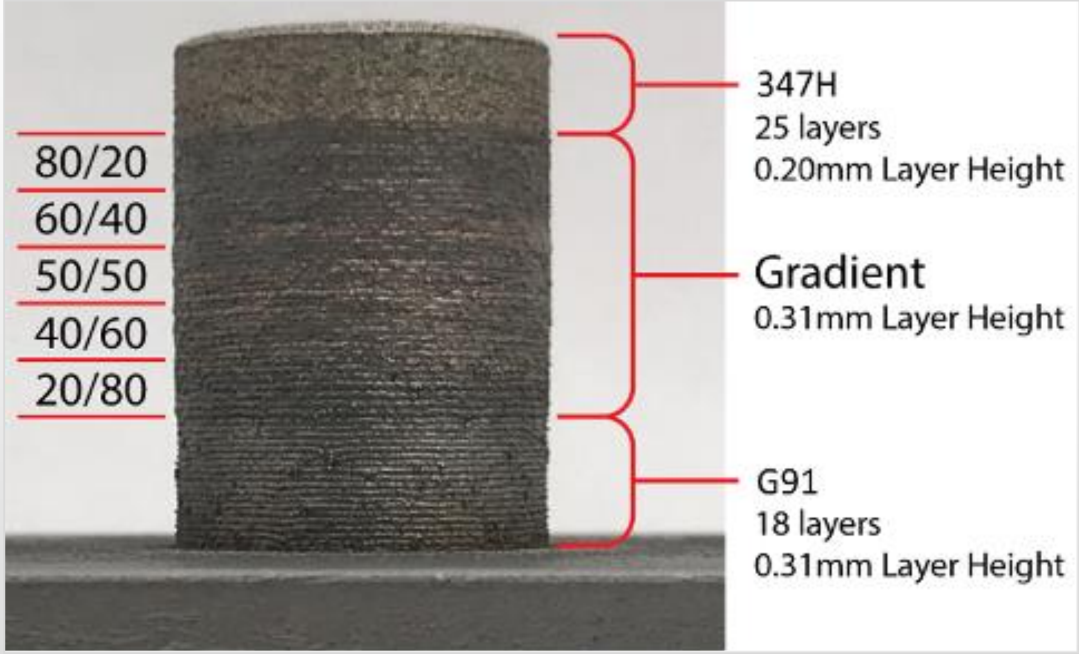
Developed graded transition joints to prevent thermal fatigue in fossil-fuel power plants

Using advanced materials science and additive manufacturing to enhance plant reliability, extend infrastructure lifespan, and support grid stability

Austenitic steel

Transition joint

Ferritic steel

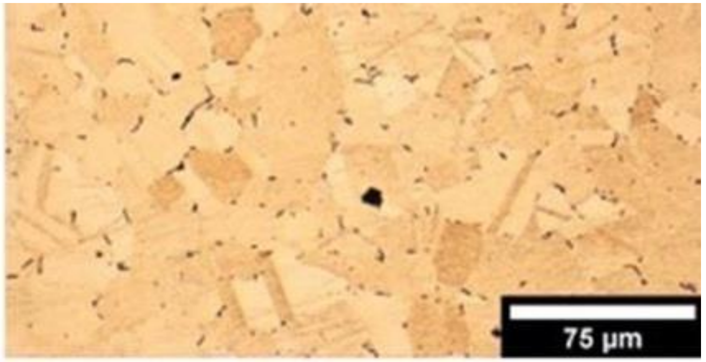


Excited? Hold On! Important Caveats to AM (Risks)...

Grain Structure

Weld-Based:

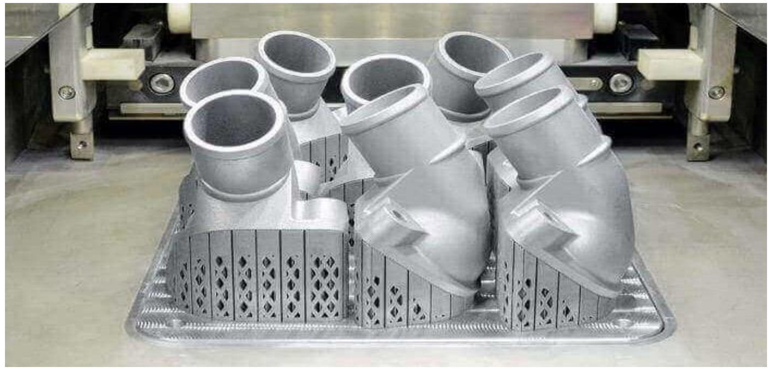
Sinter-Based:



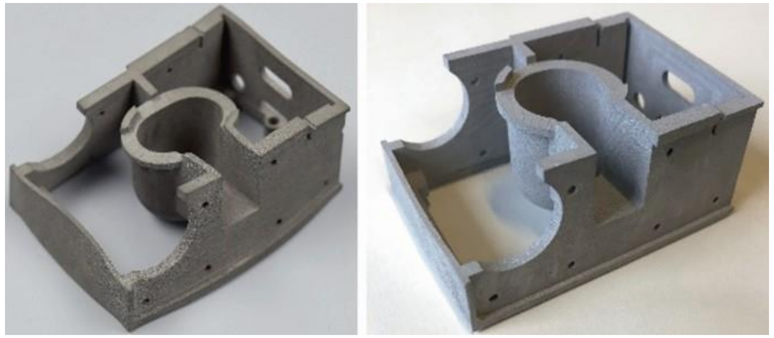
https://doi.org/10.1007/s12289-023-01755-2

Geometry Control

Weld-Based:



Sinter-Based:



https://doi.org/10.1007/978-3-662-69327-8_10

Material Purity

Weld-Based:

- Elemental evaporation
- Oxygen pickup
- Spatter/soot inclusion

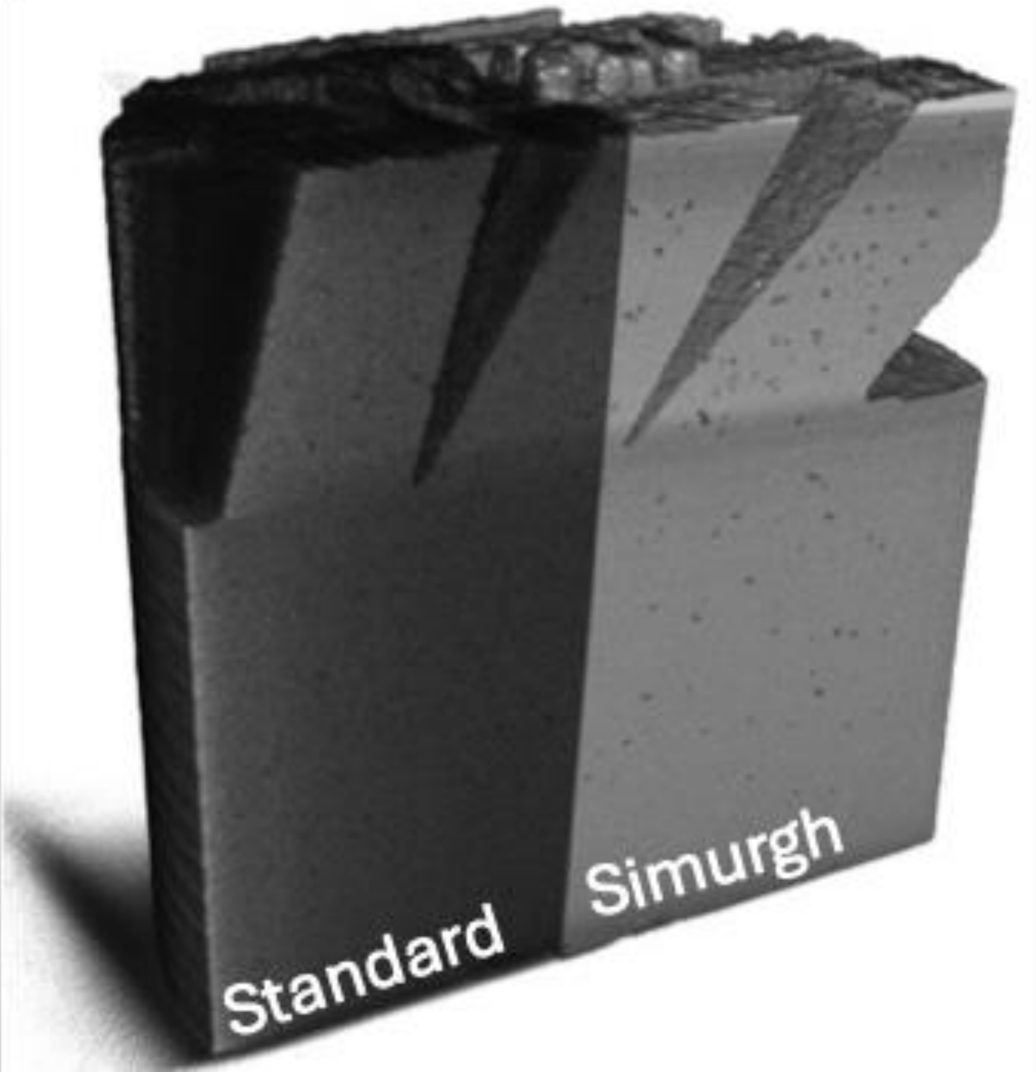
Sinter-Based:

- Carbon can be left by polymer (but the right burnout technique can eliminate this problem)
- Oxygen contamination during sintering if not careful

AI-Powered X-ray CT reconstruction software enables rapid materials development and process optimization for qualification

SIMURGH

- **>12X** faster scan times leading to **2–10X** lower cost
- **>4X increase** in defect detectability
- **4** licenses, with growing interest
- **>$19M** commercial impact to date
- **80% reduction** in process optimization time for additive manufacturing
- **2–3X increase** in productivity through process optimization



Licensees

NIST
INL
ZEISS

OAK RIDGE National Laboratory

MDF

AI-based software for producing born-qualified parts from directed energy deposition systems

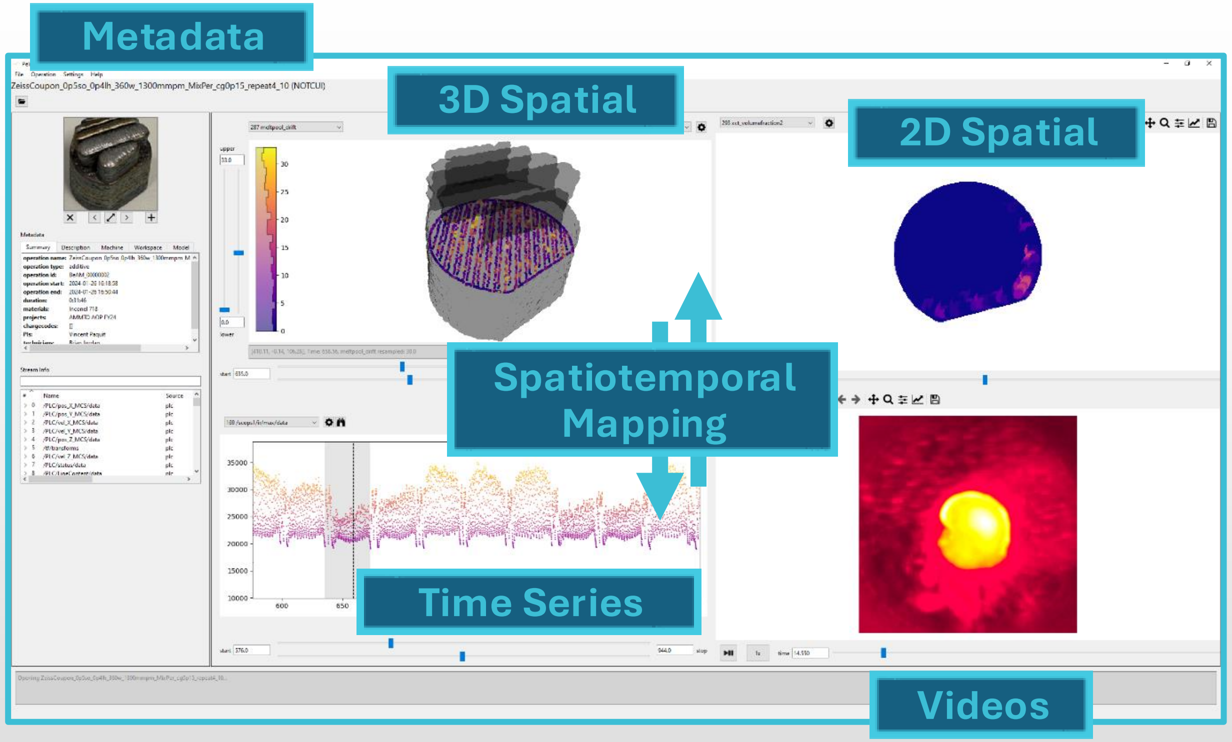
PELICAN

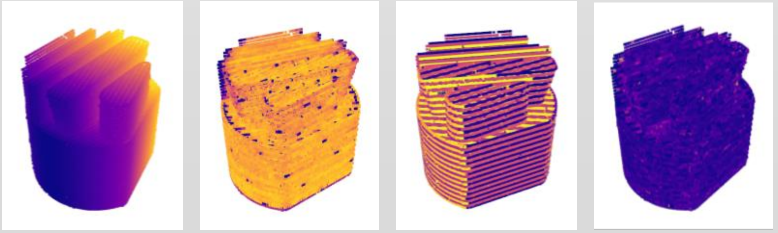
Innovation

- A context-first, data-driven analysis tool
- Cross-platform, sensor agnostic, multi-modal data visualizations with API/GUI functionality and AI/ML pipelines

Progress to Date

- **5** machines, **380+** builds, **4** materials
- **4** manufacturing processes (laser blown powder, wire arc, large scale polymer, machining)
- **1** dataset released (laser-blown powder DED)





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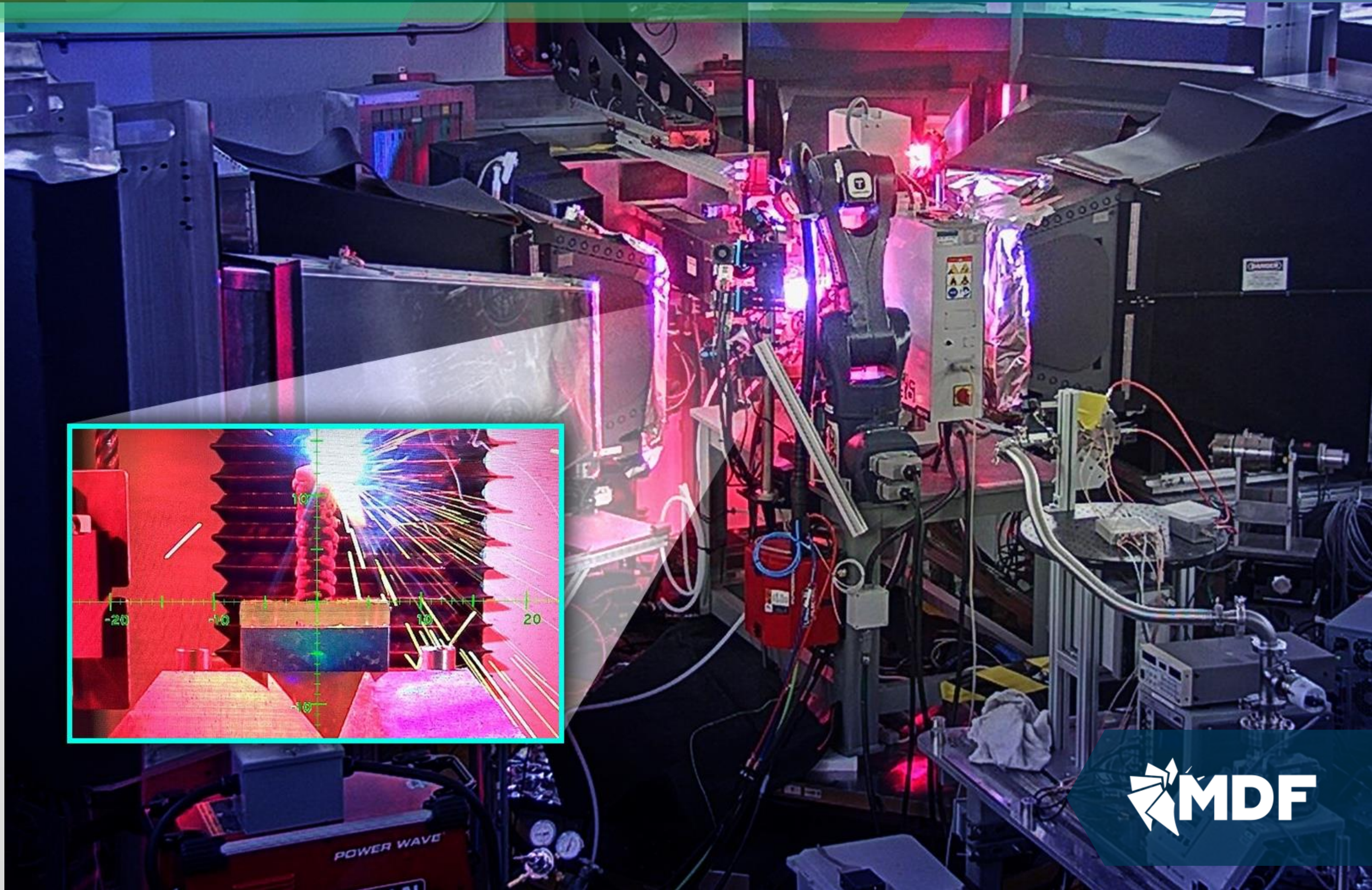
ORNL-developed platform performs operando neutron diffraction studies of metals during additive manufacturing

- Provides insight into the evolution of phase transformations and stressors during production
- Helps accelerate development of new materials and process strategies



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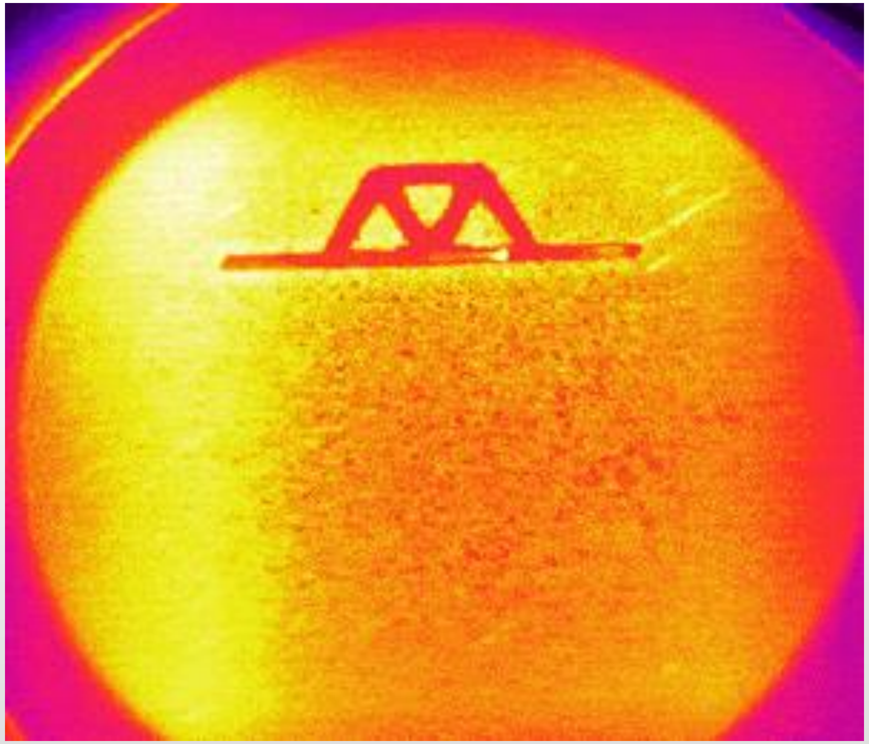
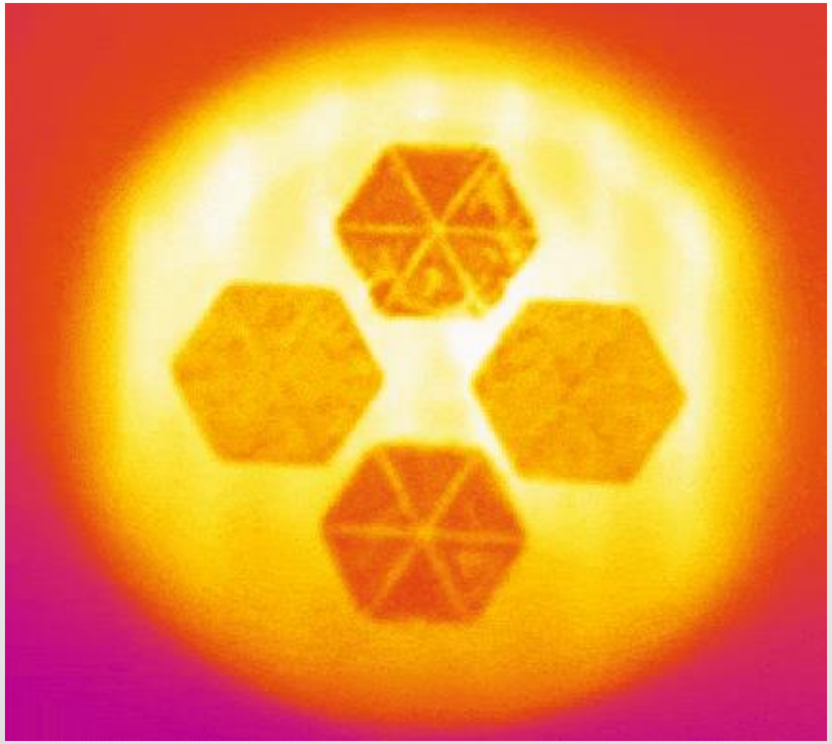
MDF

First 3D-printed, defect-free refractory alloy components

- Design of refractory alloys for additive manufacturing
- Developing the processing science of fully dense and defect-free refractory alloys in complex geometries
- Enabling next-generation plasma-facing components for turbines, aerospace, fission, and fusion energy



Molybdenum



Tungsten

MillMax for CNC machines increases productivity for US machine shops

- Dynamic measurement of cutting systems
- Optimal process parameter selection reduces time, cost, and scrap rates
- **>$24,000** saving per successful measurement
- Reduced machine time by **>140,000 hours**
- **83:1 ROI**
- **>$42M** in profit improvement for American metalworkers

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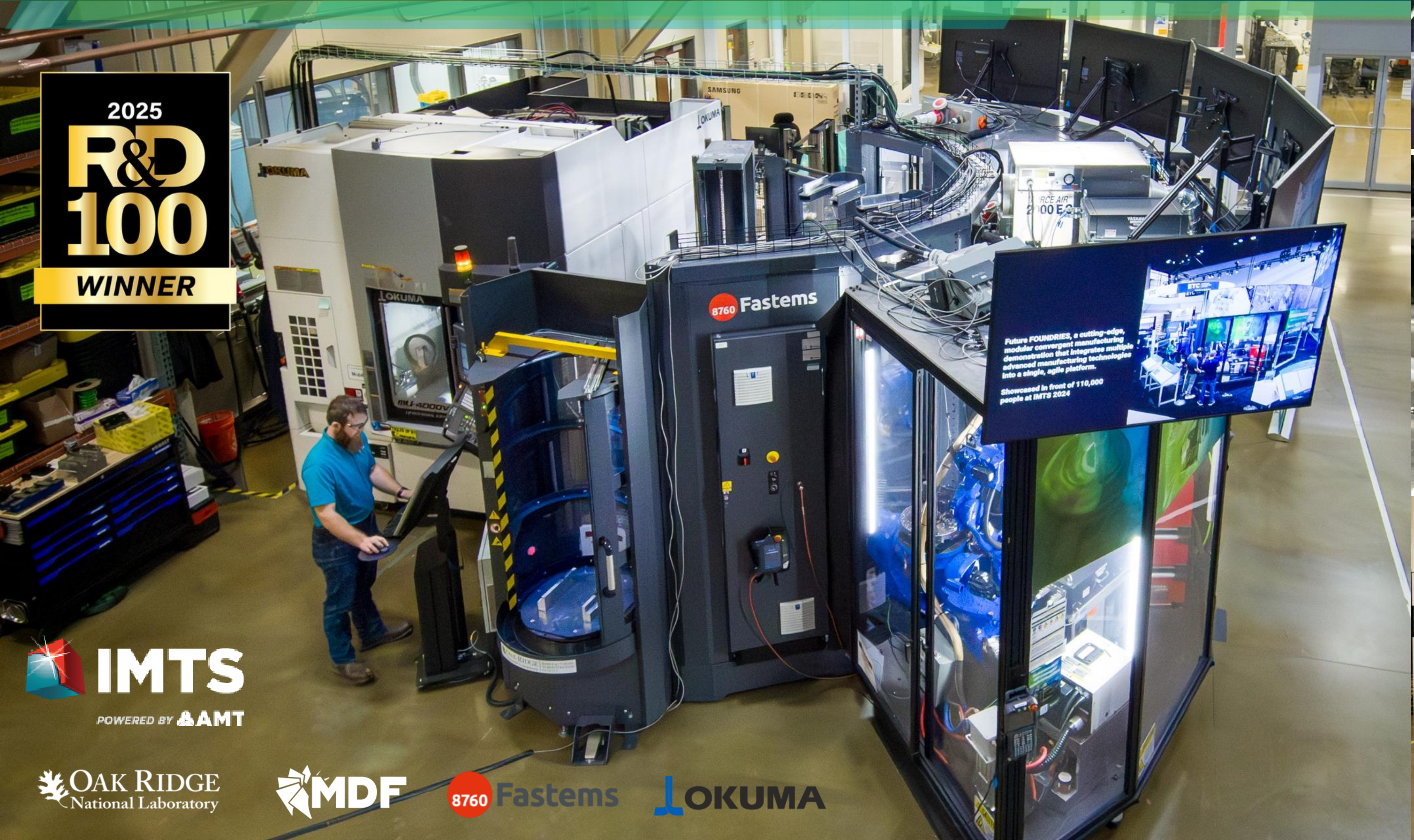
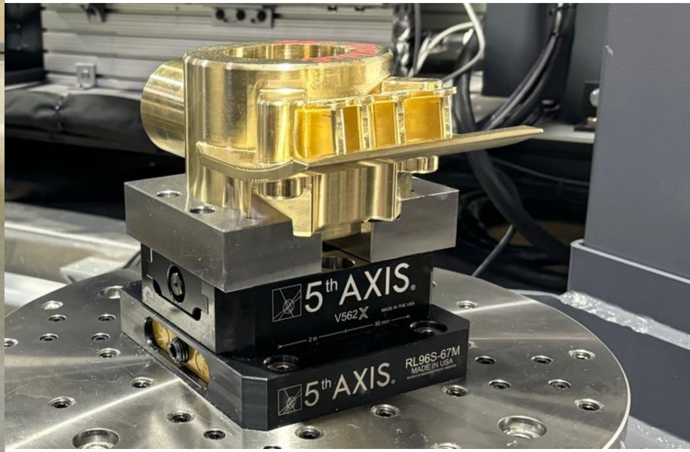
Multi-system convergent platform for high-mix, low-volume fabrication and repair





Current work

METAL ADDITIVE MANUFACTURING ... PHYS. REV. ACCEL. BEAMS 27, 054801 (2024)

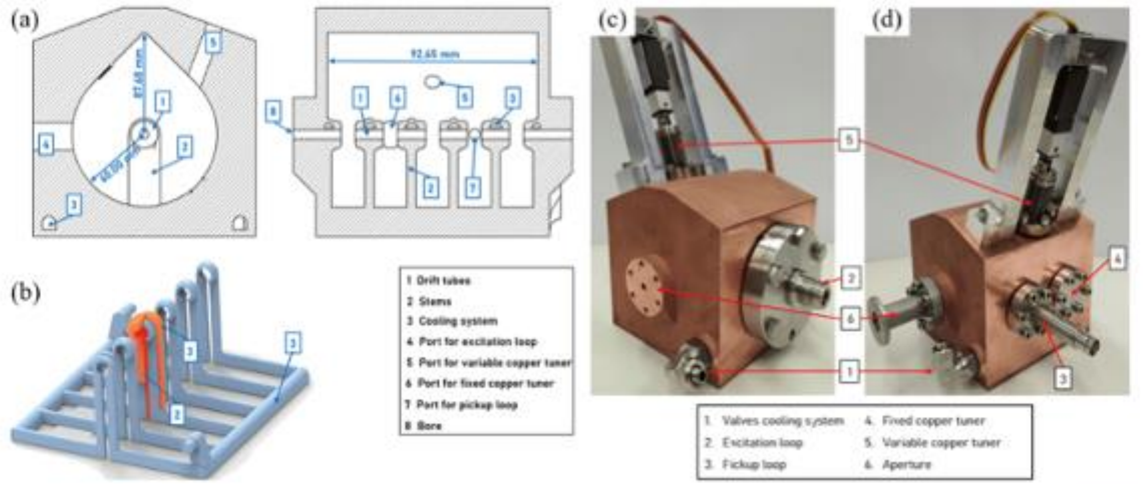


FIG. 17. Design of (a) DTL cavity and (b) cooling system and (c) front and (d) rear view of the fully equipped prototype [154].

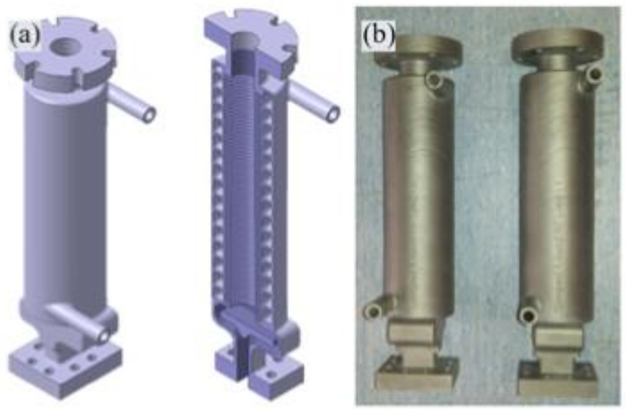


FIG. 22. (a) CAD model and (b) photograph of additively manufactured Ti6Al4V WR90 waveguides [209].

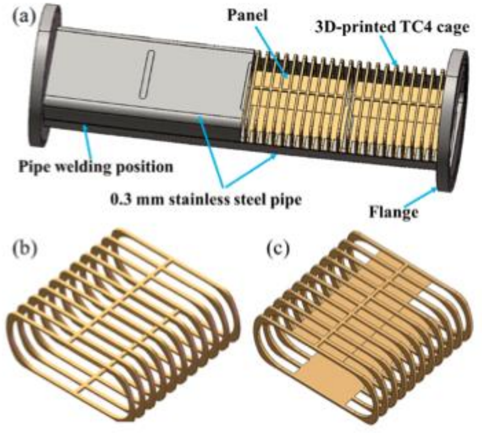


FIG. 34. CAD models of (a) thin-walled dipole-magnet vacuum chamber with internal stiffening cage, (b) initial cage design, and (c) cage design with additional cover panels for coupling impedance reduction [230].

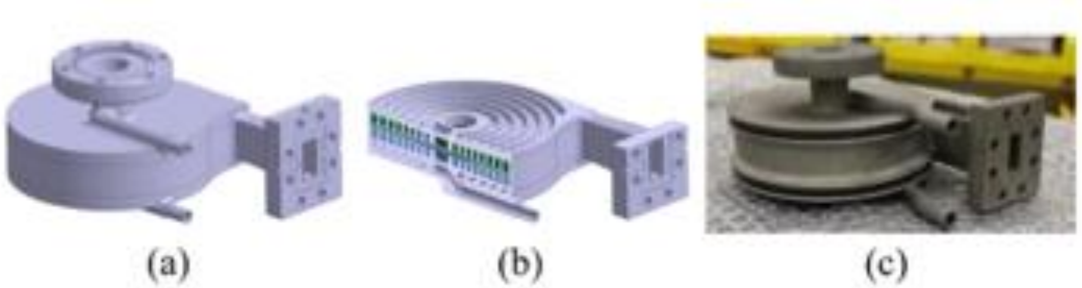


FIG. 24. (a) CAD model, (b) cross section showing the spiralized waveguide and vacuum pumping holes, and (c) photograph of additively manufactured spiral rf load [209].

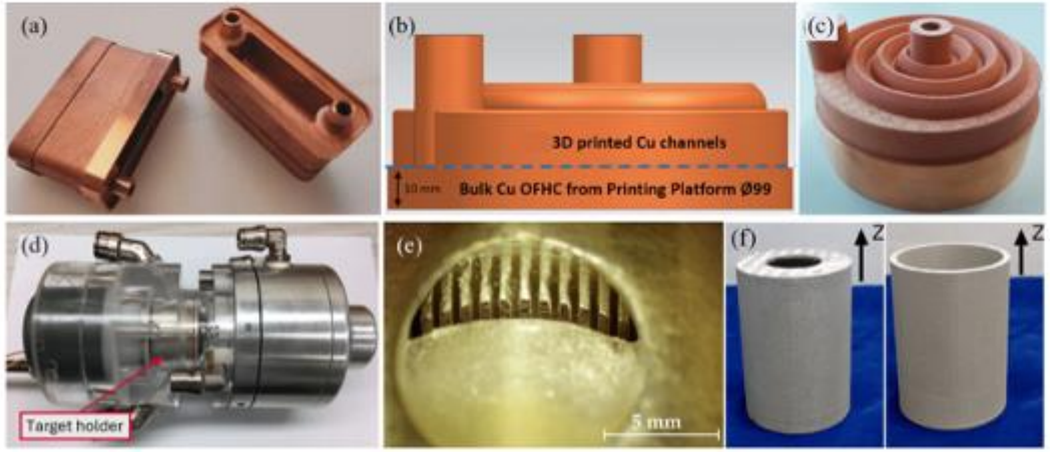


FIG. 30. (a) Additively manufactured crotch absorbers, (b) CAD design and (c) photograph of copper beam dump made by PBF-LB/M [224], (d) photograph of target assembly of the IBA Cyclone® 18/18 cyclotron with (e) detail of the internal cooling system of the additively manufactured target holder [227], and (f) cylindrical magnetic shielding structures made by PBF-LB/M [149].

Potential Areas of Interest

Anode Support
*SST 304/316 and OFE Cu**
UHV envelope**

Focus Electrode
SST 304/316
UHV compatible**
High polish and cleanliness

Cathode
Sintered tungsten matrix, barium impregnate, embedded W-3Re heater encapsulated by alumina
Operates at 1,000° C
UHV compatible

Cathode Support
SST 304/316 and OFE Cu
UHV compatible
Large thermal gradient

HV Seal/RF Windows
Alumina ceramic and SST 304/316 or CuNi weld joints
UHV envelope
Holds off 50 – 500 kV

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*Note that OFE Cu is required because hydrogen brazing is a common assembly method used in klystrons. Oxygen in the Cu causes blisters. Additive manufacturing can potentially avoid this through many means.

**UHV envelope: is a boundary surface for 10^{-9} torr
**UHV compatible: not a boundary, but must operate in 10^{-9} torr

Evaluation Method: AM Value, Risks, Mitigations for Klystrons

Klystron Component	AM Value	AM Risk	Mitigation / Controls
Cathode & Electron Gun Components	Reduced Lead time; advanced microchannel design in future	Low: Contamination/Tungsten purity with Binder Jet AM	Highly controlled feedstock, process, and furnace cycles
Structural / Support Hardware (non-vac)	Part consolidation; reduced lead time; lightweighting; design flexibility,	Low: dimensional accuracy, LPBF AM cost and lead time	Standard AM qualification; post-machining of interfaces; dimensional inspection
Vacuum Shells / Enclosures (Non-RF)	Near-net shape for large parts; reduced welds; cost reduction at low volume	Low: Residual porosity; distortion during HIP or heat treatment	HIP to close porosity; conservative wall thickness; full machining of sealing surfaces; helium leak testing
Rotatable Flanges & Mechanical Interfaces	Integration of features; reduced part count; customization	Low: Seal integrity; dimensional accuracy	Finish machining of sealing surfaces; established vacuum flange standards; leak and torque testing
Waveguides (Straight / Simple Geometry)	Fewer joints; geometric flexibility; faster iteration	Medium: RF surface roughness; dimensional sensitivity	Hybrid AM + machining; internal surface polishing; frequency-dependent acceptance criteria
Cooling Jackets & Manifolds	Conformal cooling; proven AM architectures; improved thermal performance; fewer brazes; part consolidation/lead time	Medium: Internal porosity (extremely sensitive); leak risk; reduced thermal conductivity	Conservative channel designs; HIP; pressure and helium leak testing; thermal property characterization
Collector Bodies (Non-RF Regions)	Integrated cooling; part consolidation; design optimization	Medium: Heat-flux limits; microstructural variability; vacuum compatibility	Copper process selection; porosity and grain structure characterization; thermal cycling tests
RF Cavities & Drift Tubes	Limited (geometry exploration only)	Field emission; RF loss; tight tolerances; inaccessible surfaces	Restrict AM to tooling or rough preforms; full finish machining; extensive RF and surface qualification
Ceramic Components & Ceramic-Metal Interfaces	Lead time	Very low defect tolerance, sinter distortion	Sinter modelling and fixturing; technology development in defect avoidance.

Cathode Technology and Performance Requirements

Anode Support
*SST 304/316 and OFE Cu**
UHV envelope**

Focus Electrode
SST 304/316
UHV compatible**
High polish and cleanliness

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UHV compatible
Large thermal gradient

HV Seal/RF Windows
Alumina ceramic and SST 304/316 or CuNi weld joints
UHV envelope
Holds off 50 – 500 kV

Step 1: Porous Tungsten matrix
- 74% - 84% density
- Machined to dimension w/o smearing pores by filling with plastic then baking out plastic

Step 2: Work function-reducing impregnant
- BaO-CaO-Al_2O_3 impregnant in varying ratios
- 4:1:1, 5:3:2, 6:1:2, 3:1:1
- W pellet is covered in the powder and fired to impregnate

Step 3: Work function-reducing coating
- OsRu thin film coating
- Sputter coated to ~500 nm

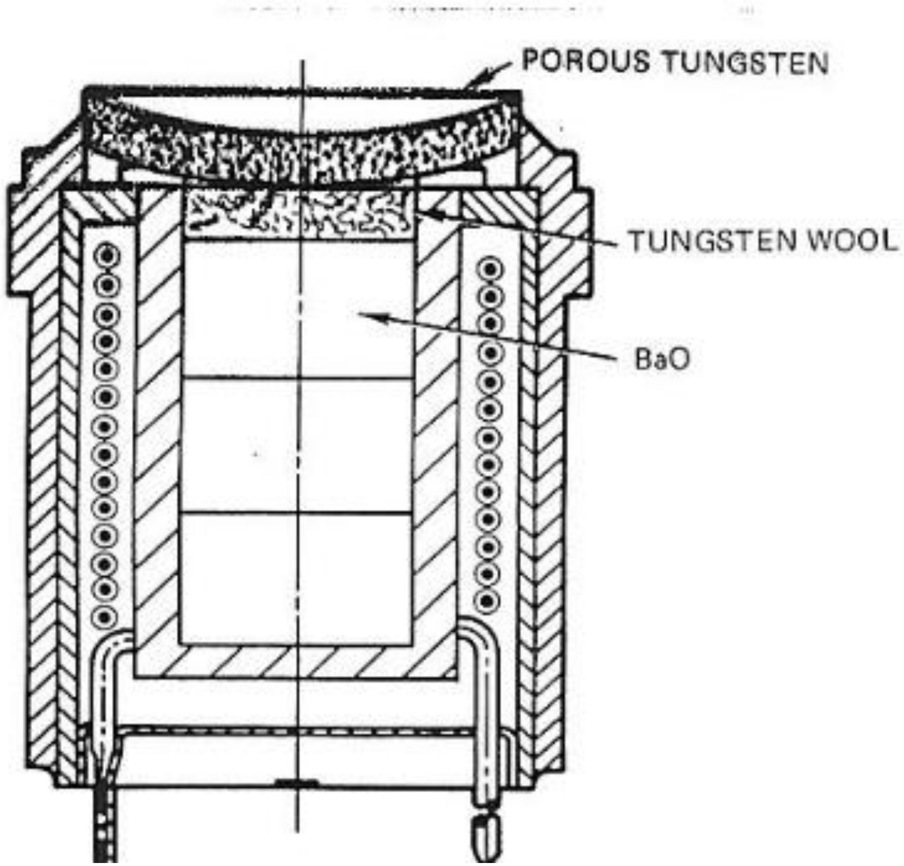
Step 4: Integration into a full assembly
- High-temperature braze to a support structure with thermal isolation
- Addition of a W-Rh or Mo heater and the requisite electrical isolation, either potted or captured Al_2O_3

Step 5: Operation
- Current densities between 1 – 100 A/cm^2 depending on operation; UHV compatible, typically ~10^{-8} torr
- High temperature operation at 1050 C
- Long life >100,000 hours

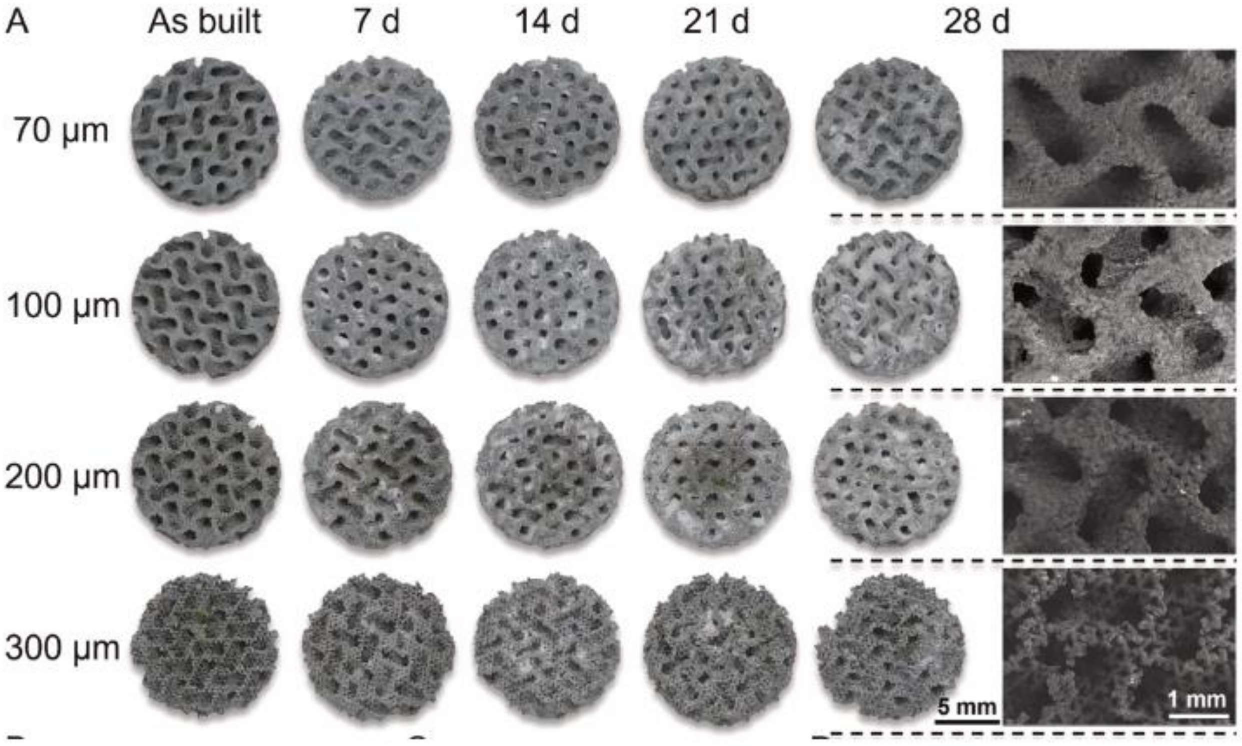
*Note that OFE Cu is required because hydrogen brazing is a common assembly method used in klystrons. Oxygen in the Cu causes blisters. Additive manufacturing can potentially avoid this through many means.

**UHV envelope: is a boundary surface for 10^{-9} torr
**UHV compatible: not a boundary, but must operate in 10^{-9} torr

Construction of W Cathode – Additive benefits



Dispenser Cathode Technology Review
3M Brochure 2013



- Graded porosity control
- Dimensional control
- Demonstrated Tungsten printing

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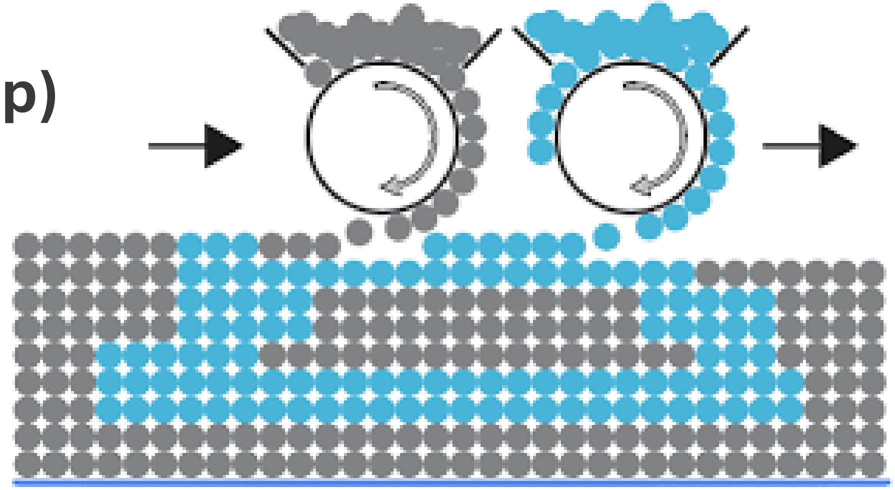
Future Concept: Multi-material AM

Multi-powder deposition for AM via Aerosint
(Not a current MDF Capability, but on our roadmap)

Powder drums, similar to toner cartridges, pattern multiple powders at high resolution.
Fitted onto a binder jet machine, multi-material devices can be created through printing and co-sintering.

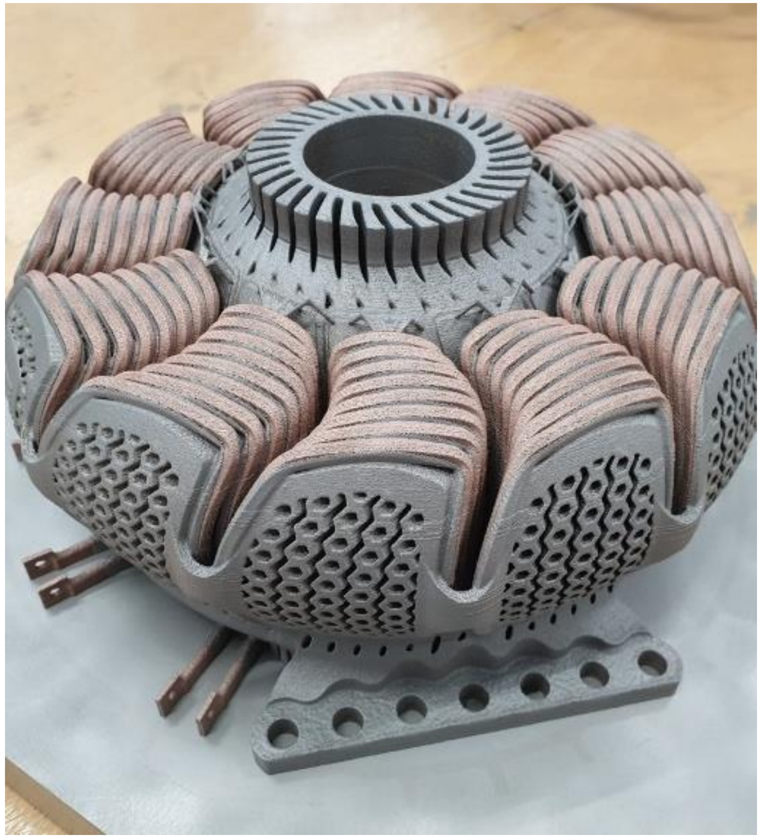


https://www.additivemanufacturing.media/articles/video-how-multimaterial-laser-powder-bed-fusion-works

Aerosint.com

Future: Multi-Physics Design AI + Multi-material AM

(not a current MDF/ORNL Capability, but on our roadmap)



*NOT ORNL WORK → LEAP 71
PicoGK – Open source, physics-based design tool

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Questions?