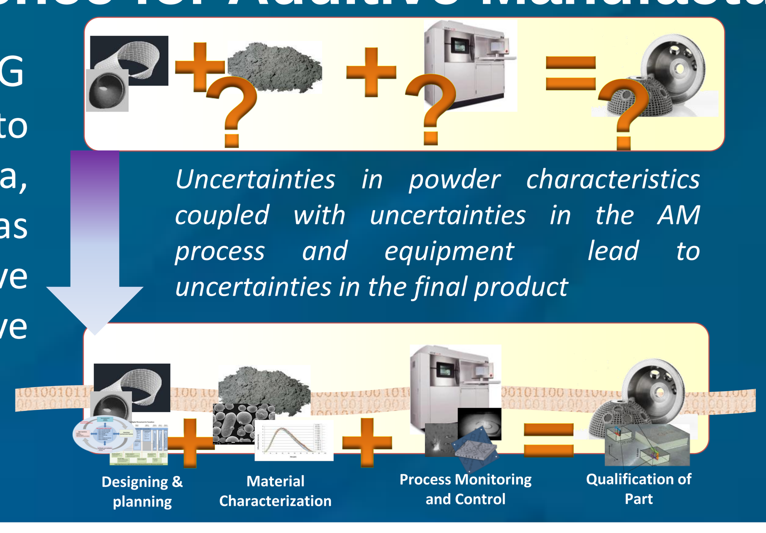
Measurement Science for Additive Manufacturing at NIST

ADDITIVE MANUFACTURING

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 52900:2015)



FOUR THRUST AREAS

- Characterization of AM Materials
- Qualification for AM Materials, Processes, and Parts
- Real-Time Monitoring and Control of AM Processes
- Systems Integration for AM

Rapid Growth of Metals AM in Industry

MAJOR U.S. INDUSTRY INVESTMENT

- Aerospace, Biomedical, Automotive, Rapid Prototyping, ...

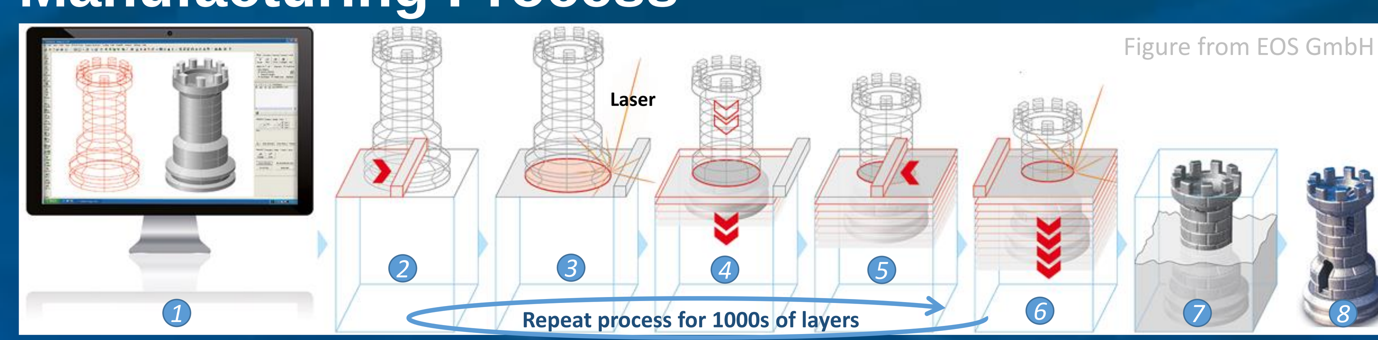
MARKET NUMBERS (Wohlers 2016)

- AM products and services: estimated $2.365B in 2015, +18% from 2014
- Metal AM machine sales: 808 machines sold in 2015, +46.9 % from 2014
- Nearly 5x growth of the AM market since 2010.
- General Electric to invest $1.4B in metal AM OEM acquisitions, announced 2016.

Laser Powder Bed Fusion (LPBF) Additive Manufacturing Process

WHAT IS IT?

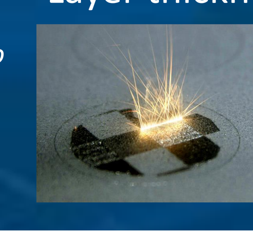
- **Powder bed fusion:** process in which thermal energy selectively fuses regions of a powder bed (ISO/ASTM 52900:2015)
- LPBF is also known as Selective Laser Melting (SLM), or Direct Metal Laser Sintering (DMLS).
- Common materials:
  - Nickel alloy
  - Aluminum alloys
  - Stainless steels
  - Titanium alloys
  - CoCrMo
  - Maraging steels



1. Create 3D geometry model using CAD software 2. Apply layer of metal powder on substrate 3. Solidify powder by melting with controlled laser spot 4. Lower substrate by one layer thickness 5. Spread new powder layer 6. Repeat process for 1000s of layers 7. Remove non-sintered powder 8. Post process to create final part (heat treatment, machining, etc.)

TYPICAL LPBF PROCESSING PARAMETERS

- Laser power: 50 W to 500 W
- Laser spot size: 30 to 200 μm
- Scan speed: 1 to 4 m/s
- Powder size: 5 to 60 μm
- Layer thickness: 20 μm to 50 μm



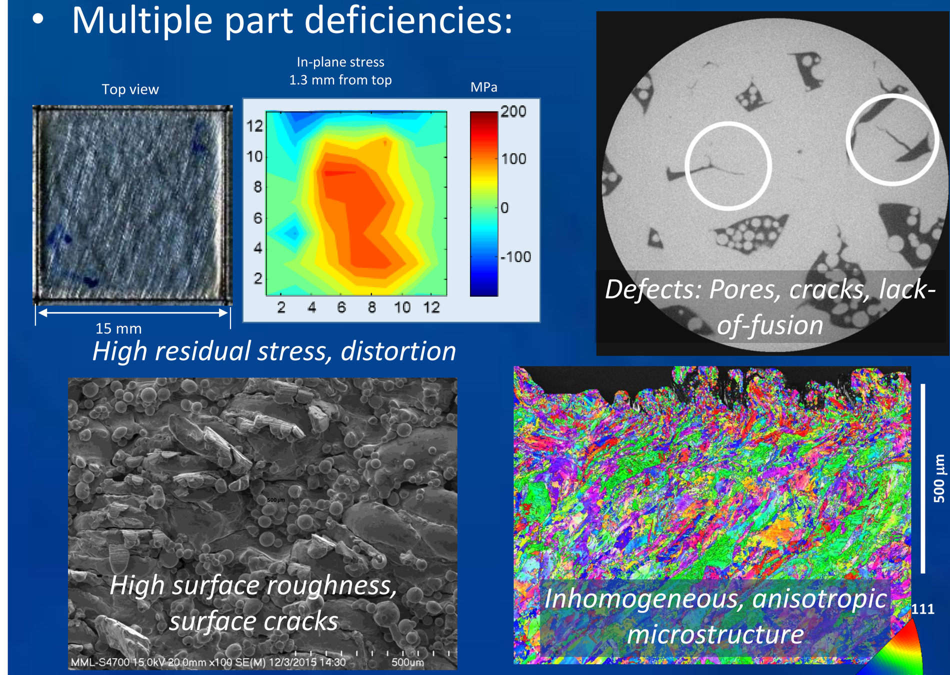
Left: Image of LPBF laser interacting with the metal powder

Above: Example LPBF-built complex geometric structures and parts

Additive Manufacturing Metrology Testbed (AMMT) Research Goals for Advancing LPBF

CHALLENGES

- Inconsistent build quality, part-to-part variability
- Multiple part deficiencies:



SOLUTIONS USING CUSTOM TESTBED

- Enables full control and flexibility to produce well characterized research results
- Integrated through digital thread, results can facilitate rapid part qualification and widespread adoption

LPBF RESEARCH AREAS ENABLED BY THE AMMT

FUNDAMENTAL PROCESS PHYSICS RESEARCH

- Process parameter development
- Laser scan strategy development and optimization
- Defect formation mechanisms (pores, cracks, residual stress)
- Measurement of process physics (melting, wetting, vaporization, radiant emission, plasma emission)

PROCESS MONITORING RESEARCH

- Develop "certify as you build" methodologies
- Calibration/characterization of monitoring instruments
- Probability of detection (PED) analysis of defects
- Develop correlations between input parameters, in-situ process signatures, and final part qualities

CONTROLS RESEARCH

- Open architecture process control (G-code)
- Image/sensor signal processing
- Real-time power/velocity feedforward or feedback control
- Process-intermittent control (once-per-layer)

RESEARCH OUTPUT/GOALS

Rapid material and process development

- Improved fundamental understanding.
- Known required parameters for each new material.

Targeted Sensing:

- Know the physical source of sensor signatures to further guide sensor development, signal processing, and measurement uncertainty

Exemplar reference data:

- Development and validation of models/simulations
- Inter-comparison with outside developers, sensor/controls developers, and OEMs

Monitoring Methods for "Certify as You Build"

- Quality-correlated metrics from sensor signals mapped to x,y,z,t during the build process

Reduced stochastic variability

- High speed feedback control of noisy process

Bottom Line:
Optimized LPBF Process, High Quality Repeatable Parts, Methods for Rapid Certification

SUPPORT for OTHER NIST RESEARCH

- PML and TEMPS Support: provide functional platform for stable, continuous melt pool control for radiometric measurements.
- MML Support: Highly controlled and characterized sample or alloy construction

KEY SYSTEM DEVELOPMENT BENCHMARKS

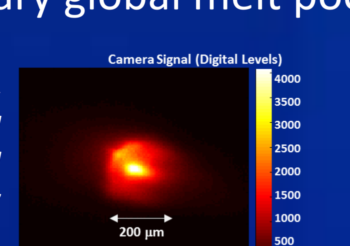
- Co-axially imaged melt pool at high frame rates (>50 kHz)
- 100 kHz laser position, speed, and power control
- Characterization of laser spot intensity distribution, position/speed control errors.
- Multi-layered, continuously monitored AM build
- Power-speed feedback control based on co-axial sensors

AMMT Metrology Systems, Tools, and Capabilities

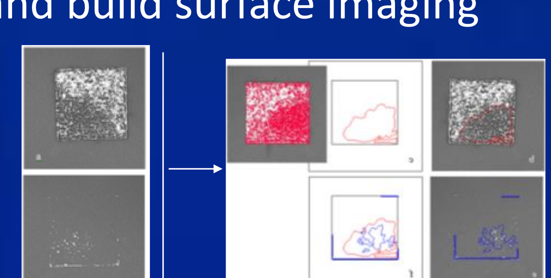
FOCUS ON NON-CONTACT, RADIOMETRIC and IMAGING SENSORS

- Laser co-axial melt pool monitoring and build surface imaging
- Stationary global melt pool monitoring and build surface imaging

Example laser-coaxial melt pool image. Melt pool appears stationary in frame.

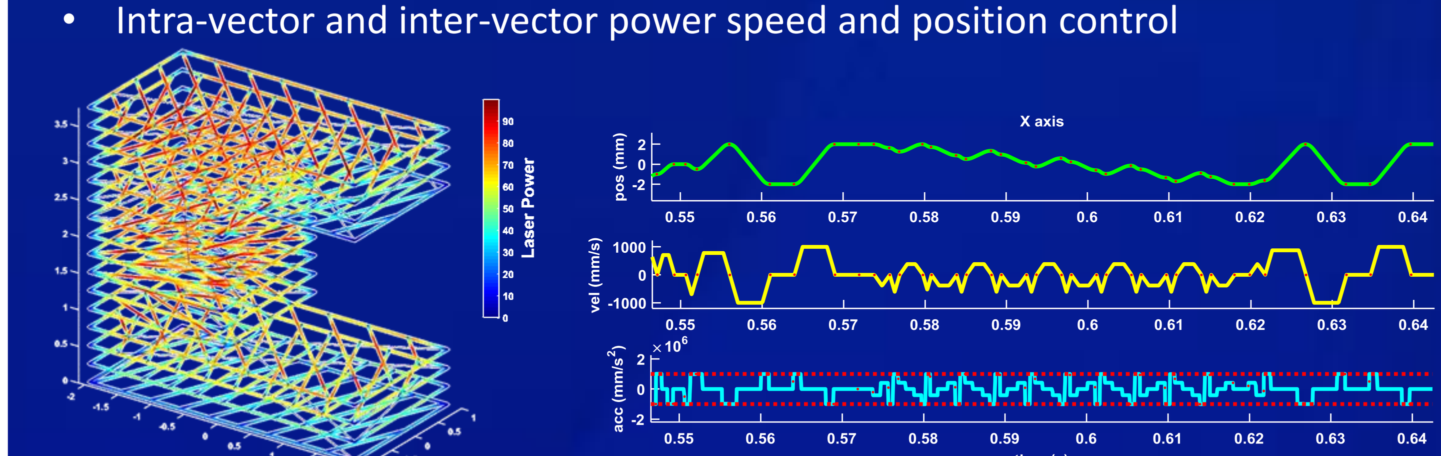


Example layer-wise image of part surface, feature recognition, and corrective action taken by controller

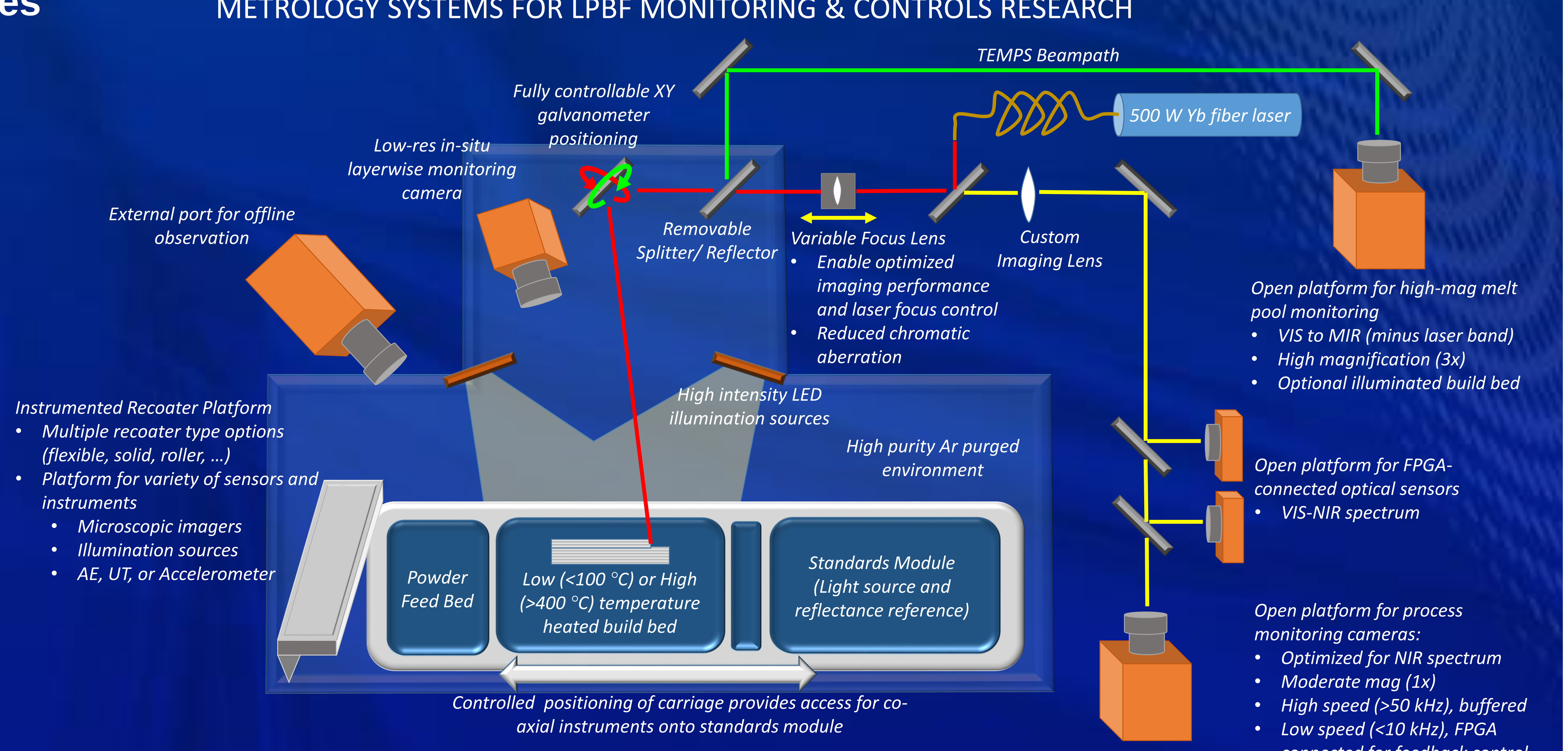


FULL HIGH SPEED CONTROL OF LASER SPOT

- Position, power, speed, spot size control at 100 kHz
- Programmability with "AM G-code"
- Intra-vector and inter-vector power speed and position control



METROLOGY SYSTEMS FOR LPBF MONITORING & CONTROLS RESEARCH

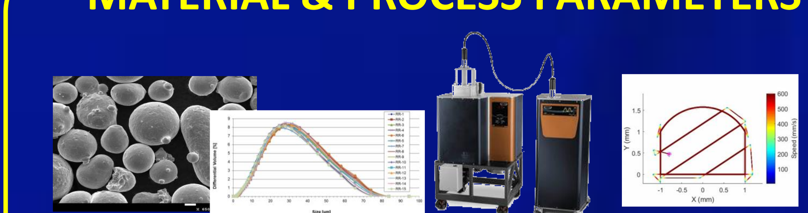


Research Methods

NOVEL SIGNAL ANALYSIS TECHNIQUES

- Determine key signatures from complex signals
- Use to design optimal filtering and signal processing

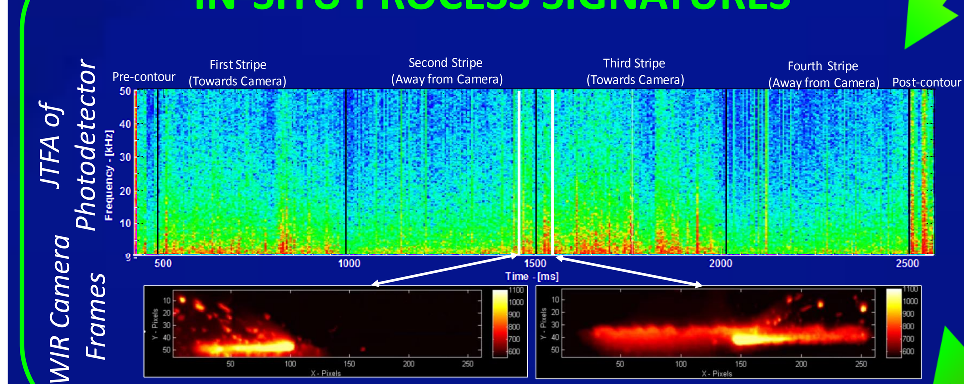
MATERIAL & PROCESS PARAMETERS



Powder materials characterization (physical, chemical, thermal)

Controlled scan strategies

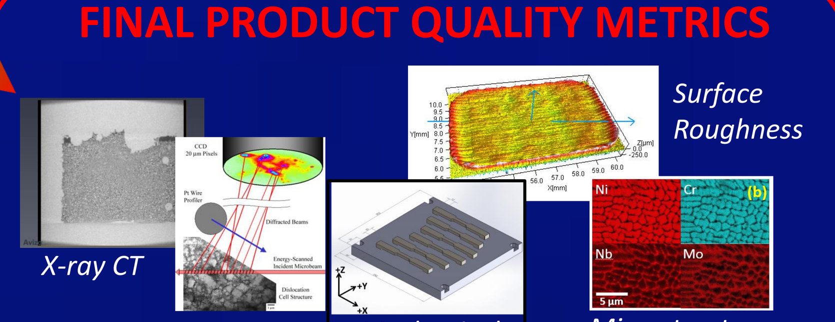
IN-SITU PROCESS SIGNATURES



CORRELATION BETWEEN PROCESS PARAMETERS, PROCESS SIGNATURES, and PRODUCT QUALITIES

- Utilize NIST-wide capabilities and ongoing cross-laboratory collaborations for powder characterization, destructive and non-destructive final part materials testing.

FINAL PRODUCT QUALITY METRICS

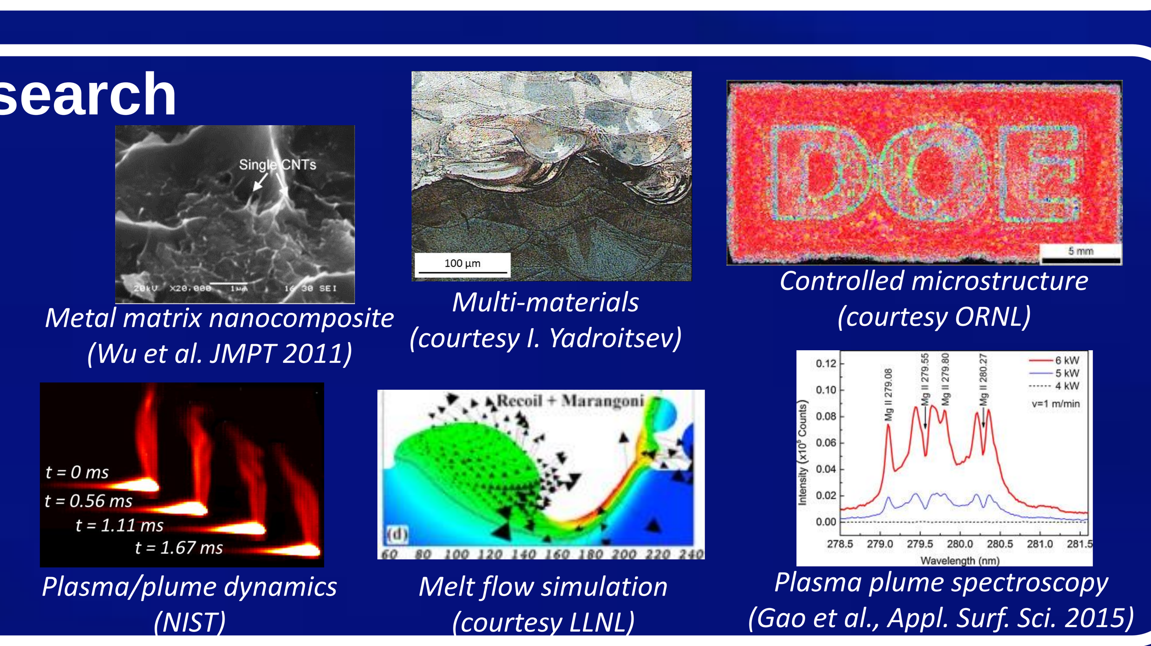


SYNCHRONOUS ACQUISITION of HIGH FIDELITY and LOW FIDELITY SENSOR SIGNALS

- High speed imaging/thermography provides physical context for single-point sensors
- Use to relate observed phenomena (spatter, keyholing, melt pool dynamics, plume dynamics) to detector signal features

Forward-Looking Research Possibilities

- Volumetrically Controlled Microstructure
- High Temperature Melt Flow Dynamics
- Plasma/Plume Dynamics and Spectroscopy
- Ceramics, Composites, and New Alloy Development



Key Beneficiaries

- NIST Laboratories (EL, PML, MML, ITL, CNST, NCNR)
- Industrial stakeholders (R&D, America Makes Members, AMC Members)
- Other federal agencies (DOD, NASA, FAA, FDA)
- Academia and International collaborators