Additive Manufacturing of Electrical and Thermal Devices: Challenges and Opportunities

PAUL R CARRIERE, PEDRO FRIGOLA, RON AGUSTSSON- RADIABEAM TECHNOLOGIES

TIM HORN, CHRIS LEDFORD – NORTH CAROLINA STATE UNIVERSITY

DIANA GAMZINA, CHRIS NANTISTA - SLAC

NORTH AMERICAN PARTICLE ACCELERATOR CONFERENCE 2019

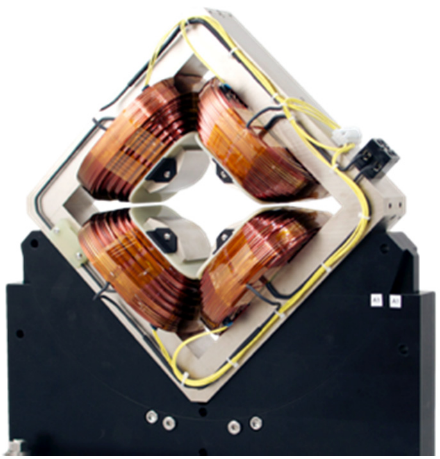
THURS, SEPT 5, 2019

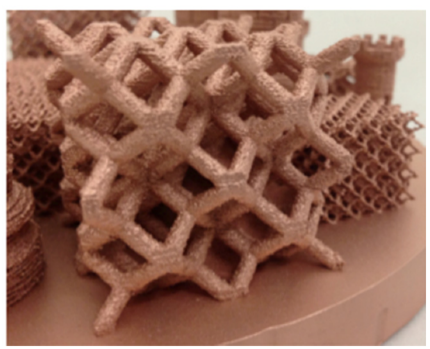
RadiaBeam: Brightness, *Applied*

Founded in 2004 - Santa Monica, California

Accelerator Physics & MeV X-ray systems

- Simulation, design, fabrication and testing
- Cu vacuum devices
- Custom magnet structures





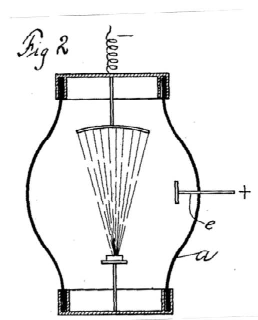
AM Introduction: History

Additive Manufacturing: *Process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive and formative manufacturing methods*

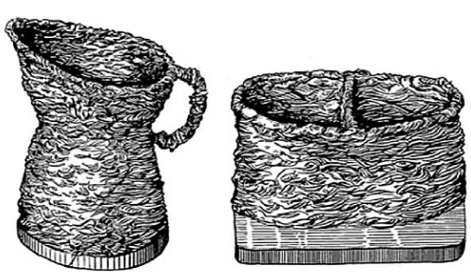
Prehistory: Sheet lamination and weld deposition

Precursor: 1960-1980 CAM + High power beams: LBW, EBW

Modern: 1988 3D Systems sells first stereolithography system



Pirani -1907 - US 848,600
Refractory ebeam powder melting

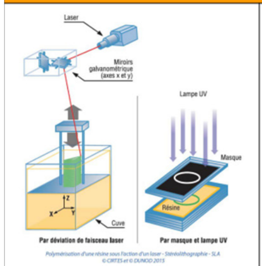
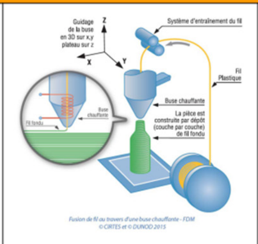
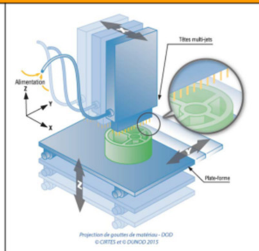
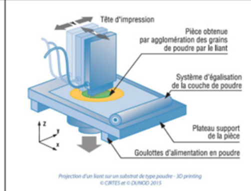
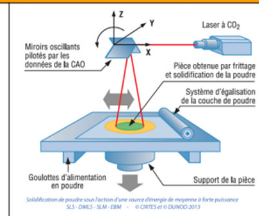
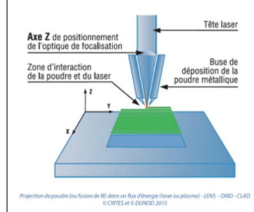
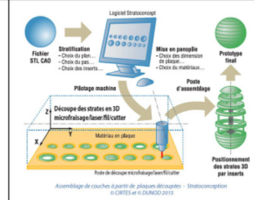


Baker - 1925- US Patent 1,533,300.
3D objects with weld overlay

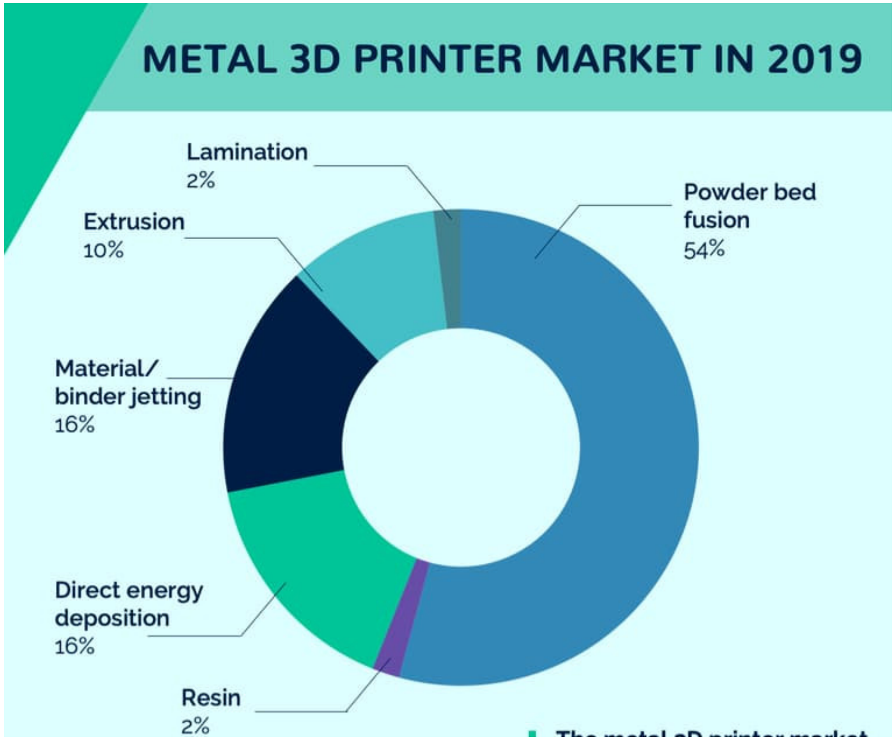
AM Introduction: Metal Printing

Software algorithm + toolpath mechanism + joining

- Solid state: ultrasonic or friction stir welding
- Sintering: Green body + furnace
- Fusion: Laser or ebeam welding

The 7 families of Additive Manufacturing processes (ISO 17296-2)						
						
Vat photopolymeri-zation	Material Extrusion	Material Jetting	Binder Jetting	Powder Bed Fusion	Direct Energy Deposition	Sheet Lamination
SLA **DLP**	**FDM**	**MJ** / MJP / Polyjet NPJ DOD	**BJ** CJP	**SLS** / MJF **SLM** / DSLM EBM	LMD EBAM	**LOM** STRATO-CONCEPTION

AM Introduction: Metal Printing



Key drivers for AM

- Digital manufacturing
- New geometric capabilities
- Bespoke designs
- Accelerate development cycle
- Support legacy systems
- (New materials)
- (Supply chain management)

https://www.aniwaa.com/best-of/3d-printers/best-metal-3d-printer/

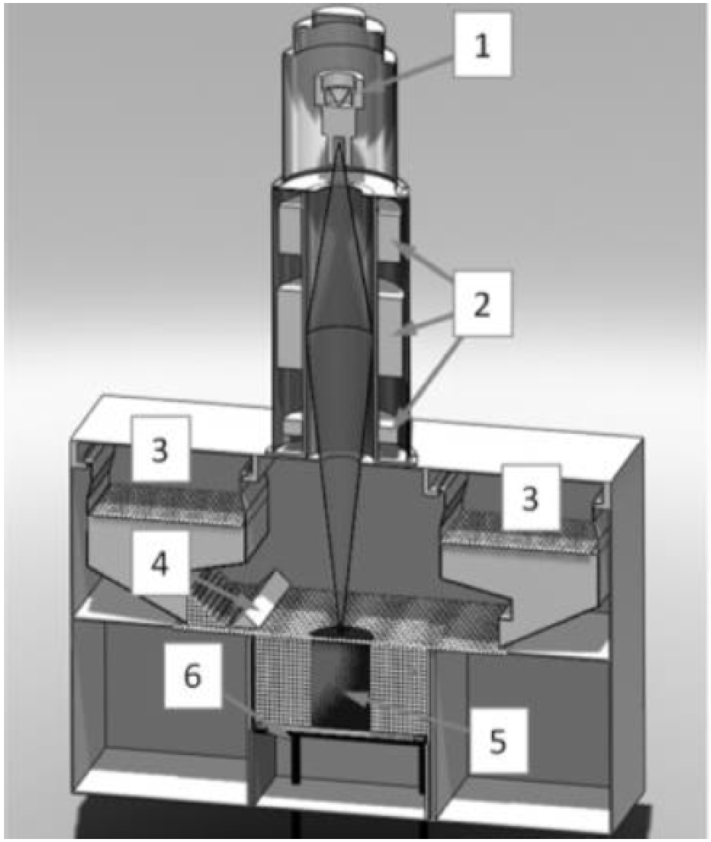
Electron Beam PBF

System Components

1. Thermionic gun (W, LaB_6, 60 kV)
2. Magnetic optics
3. Powder hoppers
4. Mechanical rake
5. Built part
6. Building platform

Process:

A. Lower platform
B. Rake powder onto platform
C. Selectively weld 2D slice of component
D. Repeat



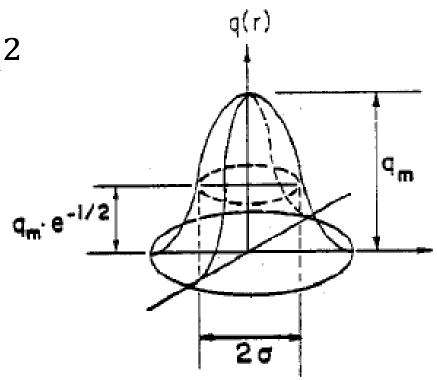
Beam heating

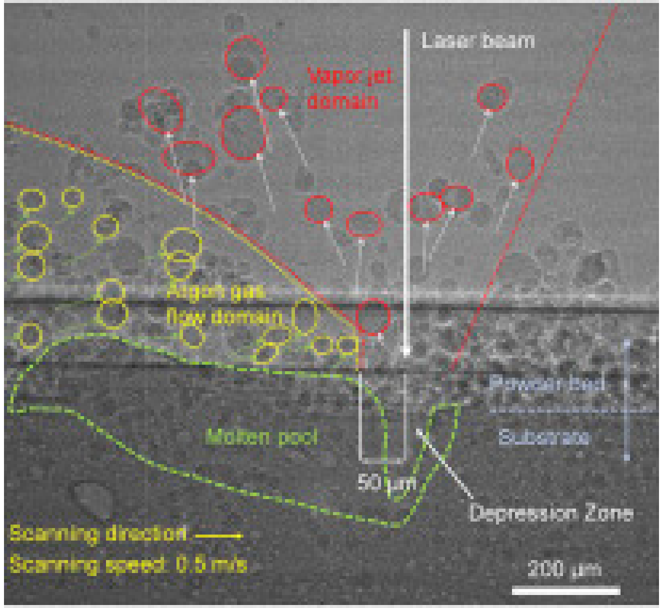
Transverse incident fluence of Gaussian beam travelling at v [mm/s]

$$q(y) = \int p(0, y, t)dt = q_0 \ \exp\left[-{y^2}/{2\sigma^2}\right] {J}/{mm^2}$$

Where centerline fluence

$$q_o = \frac{P}{\sqrt{2\pi}\sigma v} {J}/{mm^2}$$





APS-2018

Transient dynamics of powder spattering in laser powder bed fusion additive manufacturing

Powder layer
Enthalpy of melting

δh_{surf} [J/mm²]: Energy needded to melt powder layer

$$\delta h_{surf} = \Phi t_{pow} * \rho[H(T_{liq}) - H(T_o) + H_{fusion})] {}^{J}/_{mm^2}$$

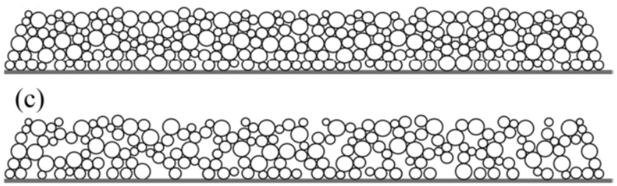
ϕ: [A. U] Powder packing density

t_{pow}:[mm] Powder layer height

ρ:[g mm^{-3}] Bulk density

H_{fusion} :[J g^{-1}] Latent heat of fusion

$H(T_i)$:[J g^{-1}] Volumetric enthalpy at temperature T_i



	Ti64 - e⁻beam	Ti64 - laser
T_o [C]	700	25
ΔH [J g^{-1}]	1049	1466

λ_{melt}: Dimensionless Analysis

Adiabatic dimensionless analysis:

$$\lambda_{melt}\,[\mathrm{A.U}] = \eta \frac{q_0}{\delta h_{surf}} = \eta \frac{P}{\sqrt{2\pi}\sigma v} * \frac{1}{\Phi t_{pow} \rho [H(T_{liq}) - H(T_o) + H_{fusion})]}$$

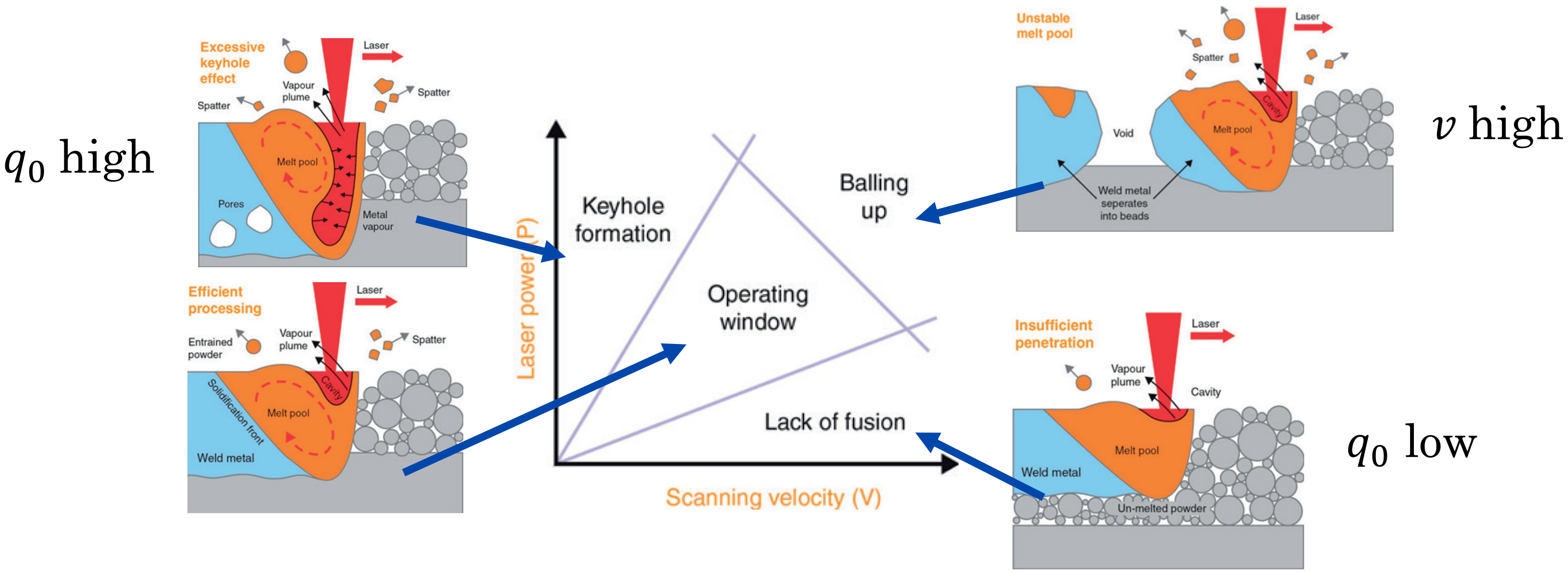
η[A. U.] beam absorption

Roughly: 5 <λ_{melt} <40

- Melt 2-3 layers : bonding and defect repair

Trapp- 2018 - In situ absorptivity measurements of metallic powders during laser powder-bed fusion additive manufacturing

λ_{melt}: Dimensionless Analysis



$$\lambda_{melt}\,[\mathrm{A.U}] = \eta \frac{q_0}{\delta h_{surf}} = \eta \frac{P}{\sqrt{2\pi}\sigma v} * \frac{1}{\Phi t_{pow}\rho[H(T_{liq}) - H(T_o) + H_{fusion})]}$$

AM Powder

Powder is as critical as beam
- Flow like water
- Spreading ≠ gravity-driven flow: No standard yet
- High packing density: spherical shape with narrow PSD

Industrial hygiene
- Costs: Powder recovery and reconditioning

Powder challenges:
- Agglomeration: Difficult to spread <10μm powder
- Developing new powders & process requires investment

Additive Industrialization

Civil Aviation: GE Catalyst engine

2018: first clean-sheet turbo-prop engine in 30 years

1/4 of engine is printed
- Parts consolidation: 855 components into 12
- -5% weight, -20% fuel burn and +10% more power

2-year development cycle
- Tooling-free: Iterate from CAD

GE owns
- Concept Laser, DE: L-PBF
- Arcam AB, SE: EB-PBF
- AP&C, CA: Powder atomizer
- Morris Tech, US: Service bureau

https://generalaviationnews.com/2018/03/07/new-turboprop-engine-ge-designed-catalyst-ga/

https://www.ge.com/reports/treat-avgeeks-inside-look-ges-3d-printed-aircraft-engine/

Civil Aviation: LPT Blades

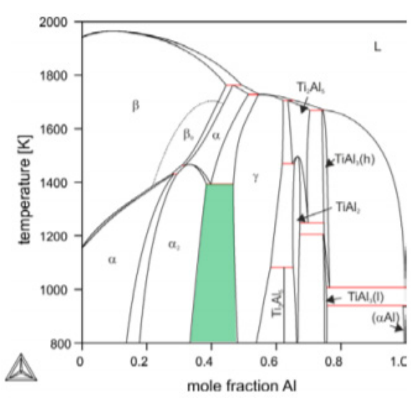
Avio Aero

Ti-48Al-2Cr-2Nb low-pressure turbine blades for GE9X engine

- Strength comparable to superalloys w/ 50% density reduction
- Crack-prone intermetallic: Print at T_o= 1050°C

Avio Aero- Italy:

- x35 printers: 6 blades/print over 3 days (3kW, 200 x 200 x 380mm)
- 60,000 blades by 2023



OPTISYS

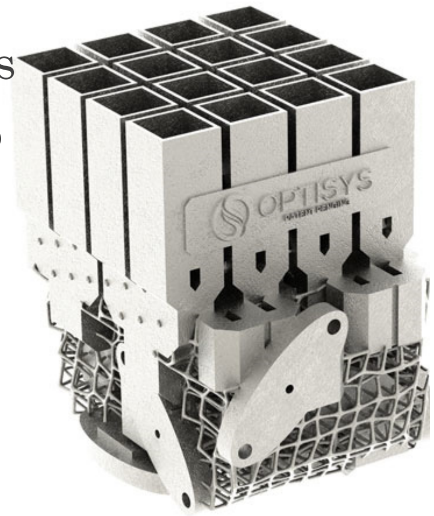
Space: Ka-band antennas

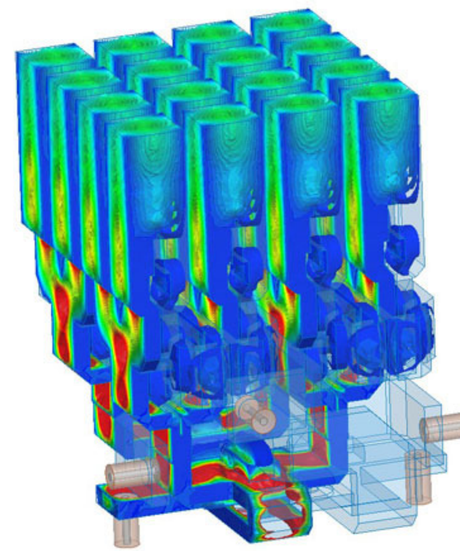
Ka-band 4×4 monopulse array

- Part consolidation: 100's to 1
- Bespoke design: 1 year -> 2 months
- Costs: Production -25%, NRE -75%
- **Weight: -95%**
- System IL reduction despite the higher S_a: no RF joints

Concept Laser w/ AlMgSi alloy

Currently being tested on International Space Station





https://www.mwrf.com/components/additive-manufacturing-yields-optimized-antennas

Medical: Dunlee/Phillips

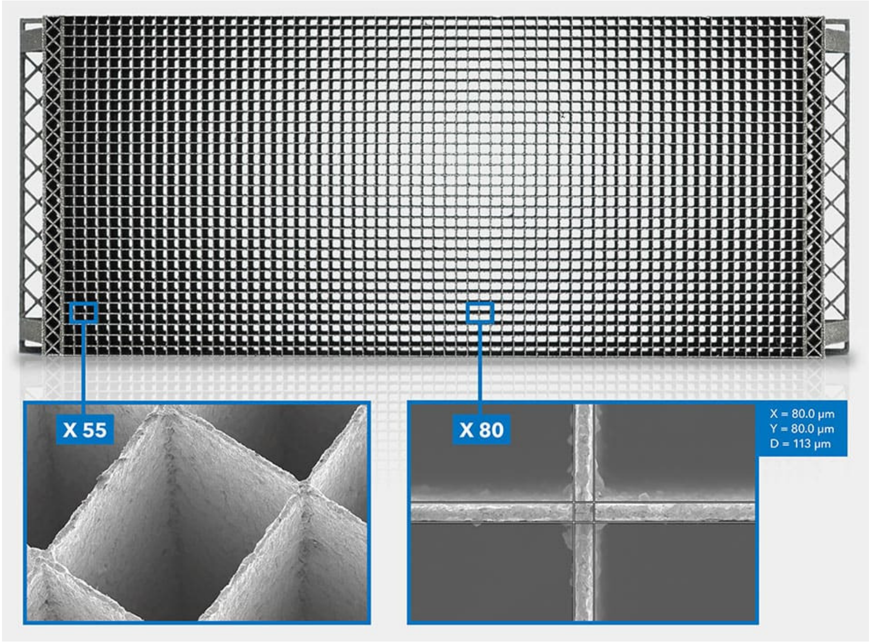
DUNLEE

Radiography: 100% pure tungsten

- Positional accuracy: 25 µm
- Feature size:100 µm
- 300:1 aspect ratios

L-PBF: Modified EOS M280

Patented post-processing



https://www.dunlee.com/a-w/3d-metal-printing/our-offer/anti-scatter-grids-for-ct.html

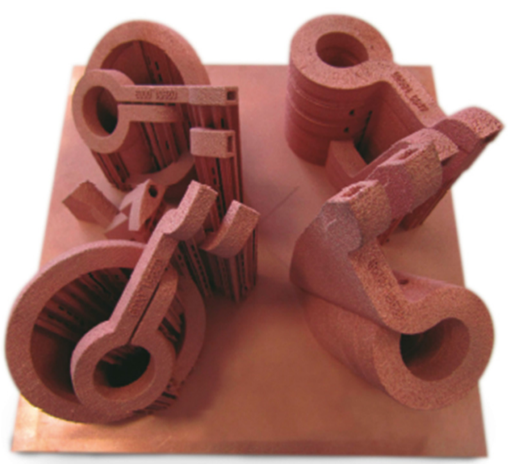
Automotive: GH Inductors

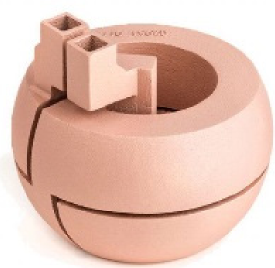
Part-specific induction coils: hardening, brazing, etc.

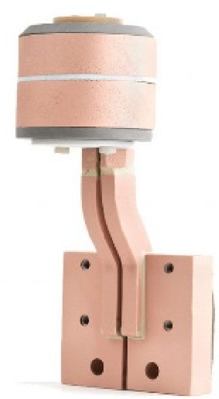
- No brazed joints or human influence
- External surface with internal cooling
- Cu EB-PBF

Extended service life: +100,000/cycles

- Higher initial costs, lower total cost of ownership







https://3dinductors.com/

AM challenges for accelerators

Internal features

- Post-processing & finishing
- Vacuum outgassing and leak rate
- As-built S_a & geometric tolerances

Copper

- Large thermal diffusivity ($\alpha_{Cu} \approx 20\ \alpha_{Ti}$)
- Poor laser absorption at 1.06μm
- Purity: <10ppm O content for hydrogen brazing

Niobium

- Refractory: large latent heat of melting
- Purity: RRR

Industrial focus on structural alloy: Al, Ni, Fe, Ti

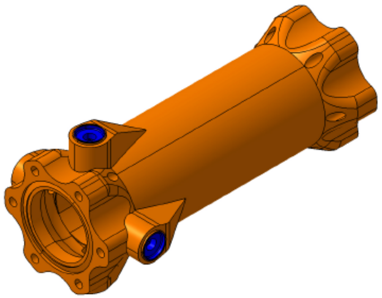
Beam Position Monitor

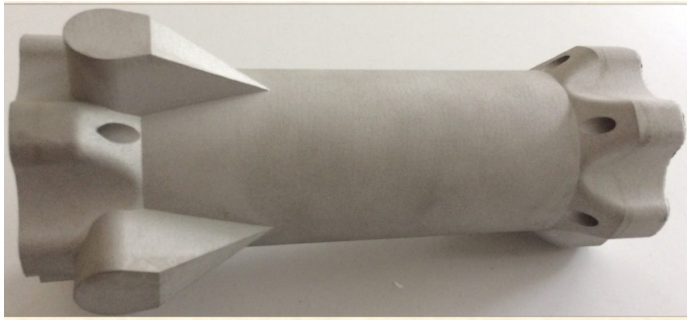
Topologically-optimized, reduced length BPM

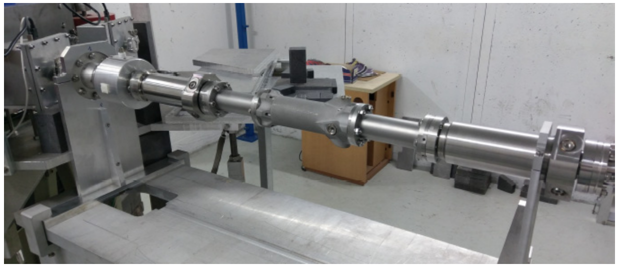
- Cost: -50%, Production time: -60%
- Improved mechanical accuracy/impedance matching
- UHV-qualified w/ as-printed R_a = 6-10µm
- L-PBF of 316 Stainless steel

Post-processing:

- Welding electrical feedthrough
- Machined knife edges







Delure – 2018 - Building accelerator components: A 3D-printed Beam Position Monitor
Jenzer – 2018 - Study of the performances of a 3D printed BPM

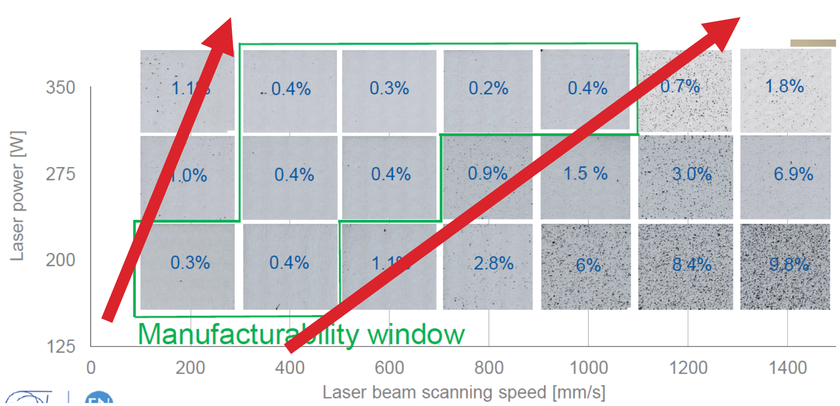
SRF Components

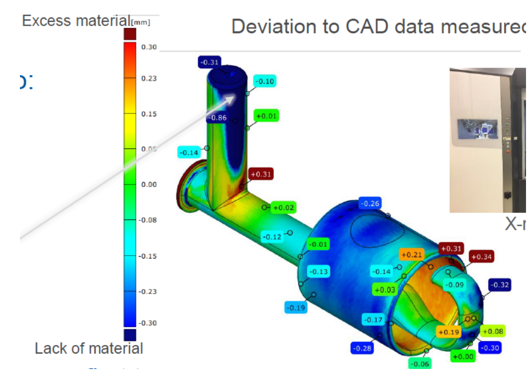
L-PBF of Nb @ CERN: Seam and seamless 6GHz cavity, HOM coupler

- As-built: RRR= 7.2 (Al pickup from atomization, high O,C,H,N)
- As-built: R_a =11µm

Post-Processing

- 1200°C/80Hrs with Ti getter coating: RRR = 112
- MMP Finishing® coupons: R_a =0.07µm w/ etchable embedded abrasives





Gerard-2018 - Additive Manufacturing for RF and Superconducting RF applications

Additive at RadiaBeam

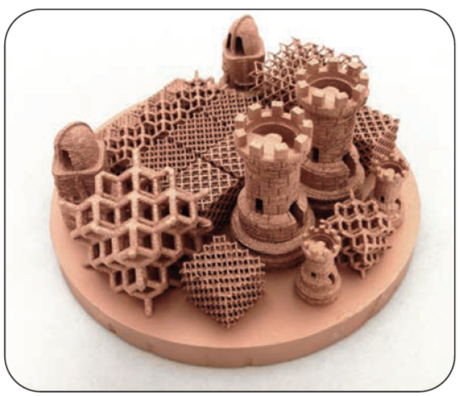
RadiaBeam

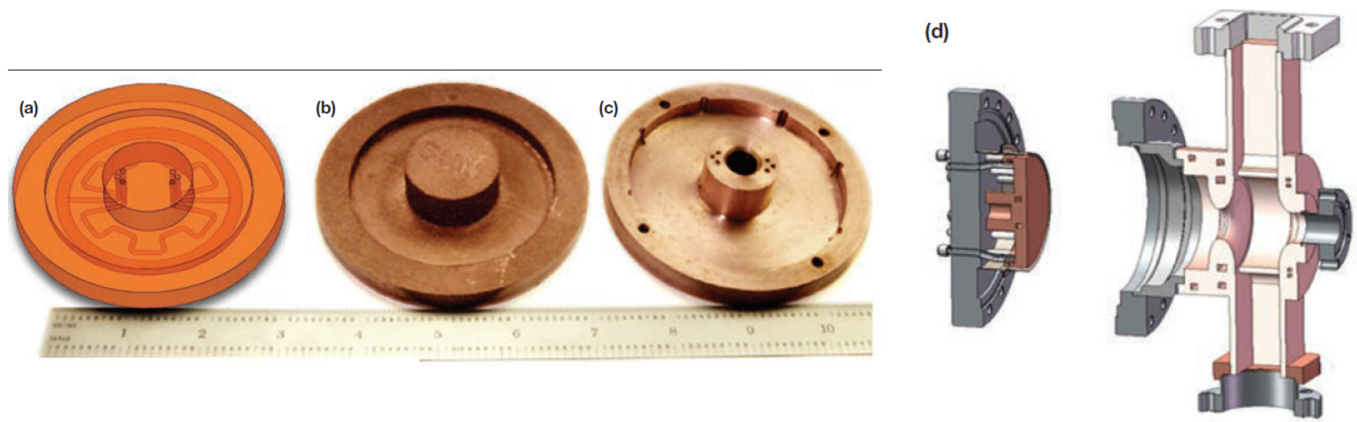
Past efforts: ’09-’13 Copper gun fabrication

Application: Water-cooled RF photocathode, 70MV/m, 3.3MeV

- Powder: 3 different Cu powder vendors
- EB-PBF w/ 99.3% density, 97% IACS
- Post-processing: Oversized & machined

UTEP, NCSU, UCLA: SBIR DE-SC0000867 & DE-SC0000869





Frigola - 2014- Fabricating copper components with Electron beam melting

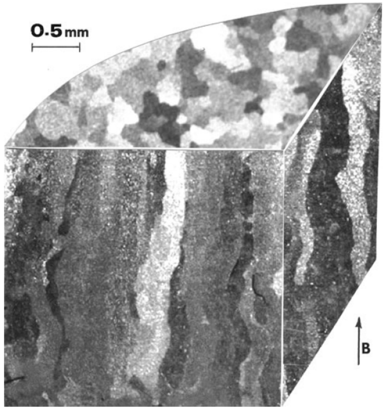
Past efforts: '12-'15 SRF cavity fabrication

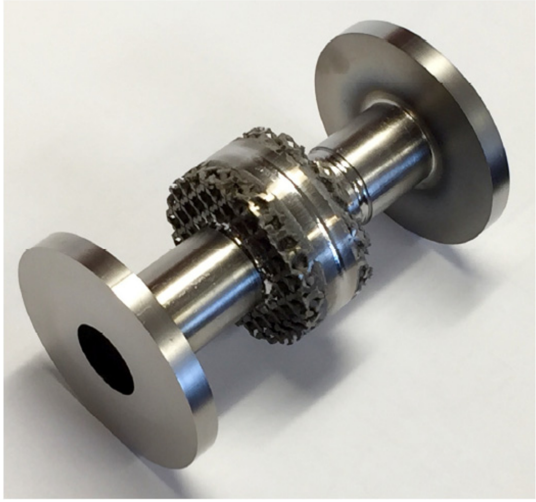
Application: Single cell 3.8 GHz cavities tested

- Powder: Plasma atomized with RRR=40 wire
- EB-PBF: 60kV/20mA , T_o = 600°C
- Post-processing: Oversized, machined, EBW, BCP, HT & BCP
- Q_o =1E9 @ 5 MV/m

JLab, UTEP & NCSU: STTR DE-SC0007666

	EBM Nb (from reactor grade feedstock)	Wrought reactor grade Nb
Density	8.55 g/cm^3	8.57 g/cm^3
RRR	19 -24	~ 40
Thermal conductivity	50 W/m*K	53.7 W/m*K
YS (Rp 0.2)	141 MPa	135 MPa
UTS (Rm)	225 MPa	205 MPa
Elongation	34%	45%





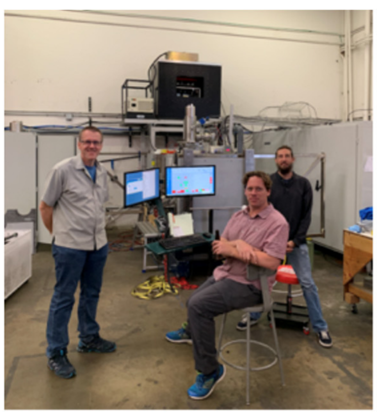
Frigola – 2015 - ADVANCE ADDITIVE MANUFACTURING METHOD FOR SRF CAVITIES OF VARIOUS GEOMETRIES*T

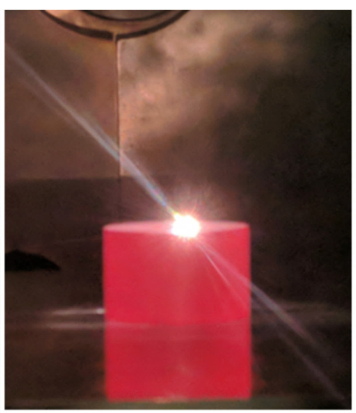
Current effort
Multi-Material EB-PBF

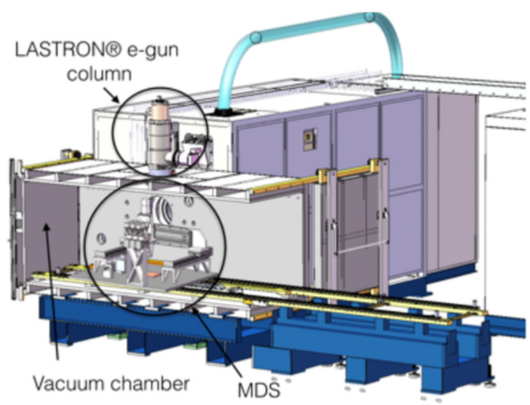
Objective: Combinatorial alloy design using EB-PBF-light

- Single layer powder mixing (i.e. high-entropy alloys)
- 100kV/20kW cryopumped Canmora EBW: 2.5 x 0.8 x 0.9m
- Multi-Material Deposition System (MMDS)

Contract:DE-SC0017688







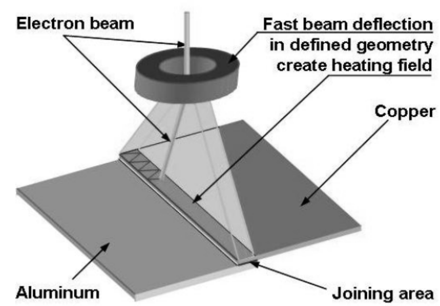


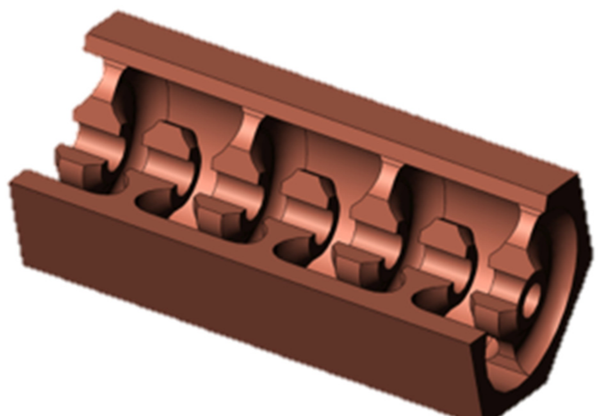
Fig. 3. Processing principle of EB over solidus brazing.

Current effort
AM of vacuum electron device

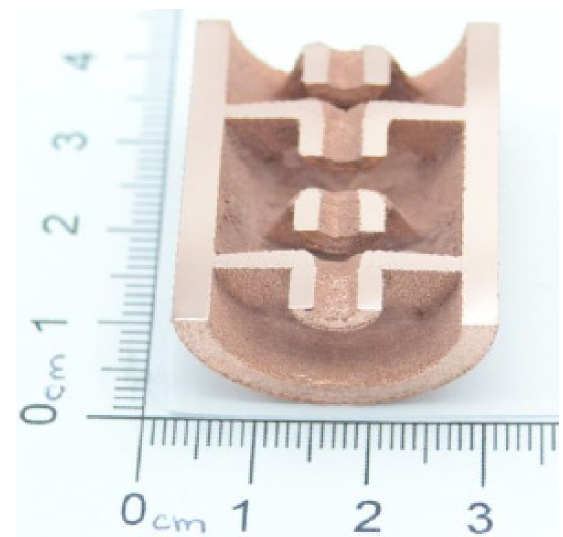
"Establish the critical to quality characteristics of AM OFE copper to enable AM of RF Vacuum Electronic Devices"

Targets: X-band, $S_a = 0.04\mu m$ with <10 ppm O

NCSU, SLAC: STTR N68335-18-C-0103



Coupled Cavity Travelling Wave Tube



EB-PBF @ NCSU Machine Customization

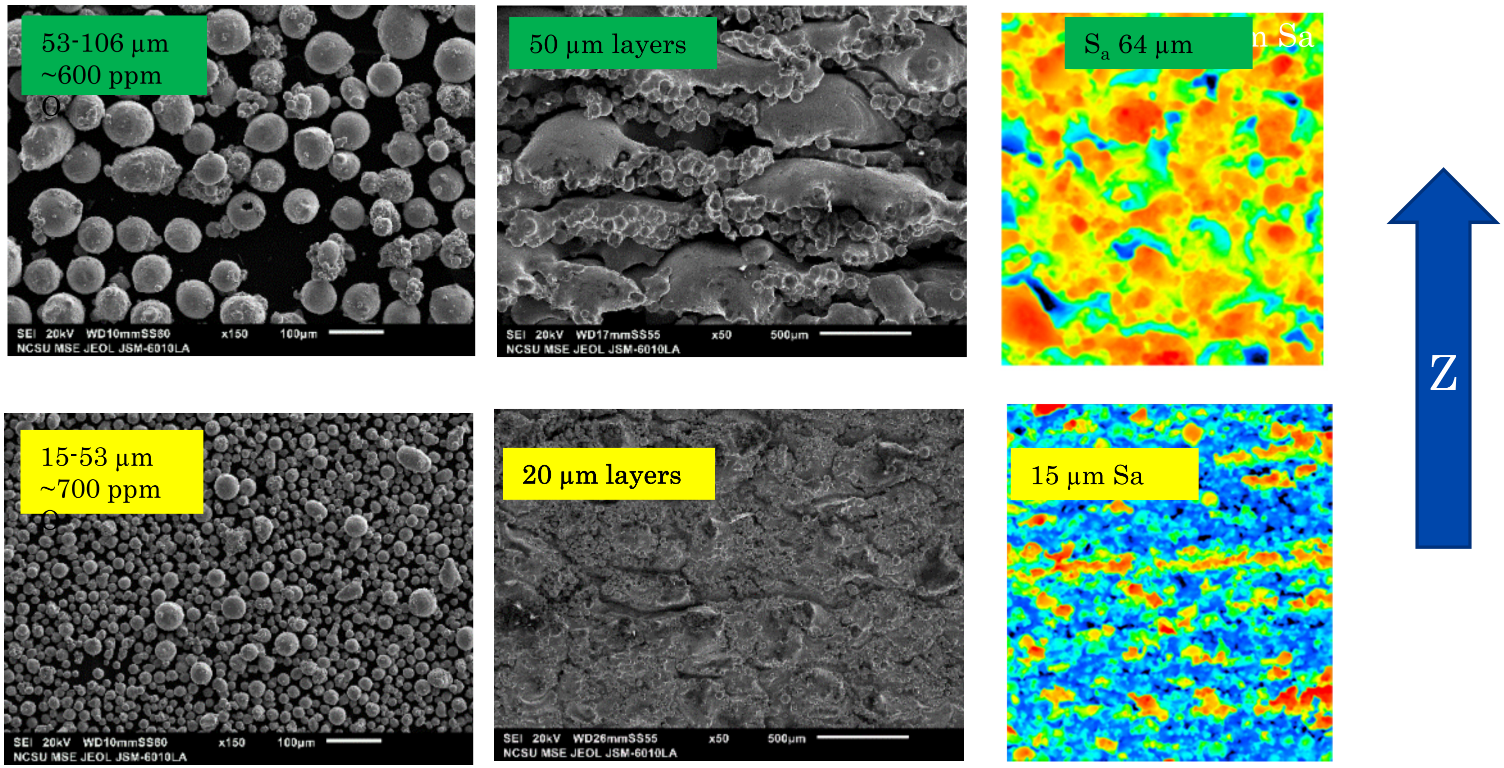
Rebuilt chamber

- Hand polished internals
- In-vacuum powder bakeout
- Inert gas powder loading
- Instrumentation ports
- Smaller build platform

Base pressure: 1E-2 ->1e-7 mbar

Instrumentation: RGA, Near IR & high speed camera

Surface Finish: Powder + Process

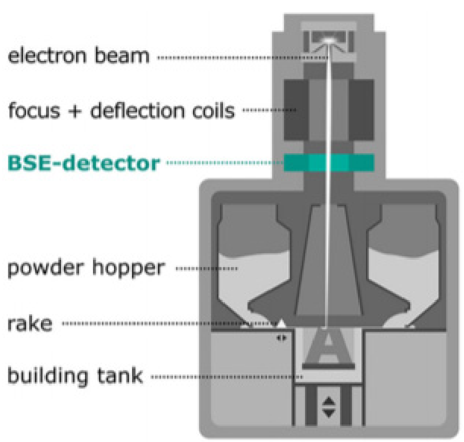


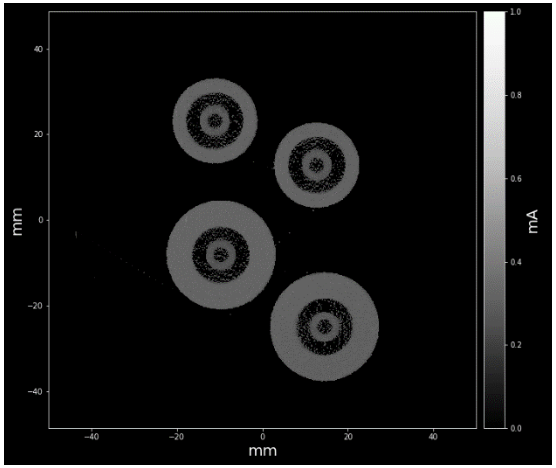
Cu EB-PBF Challenges

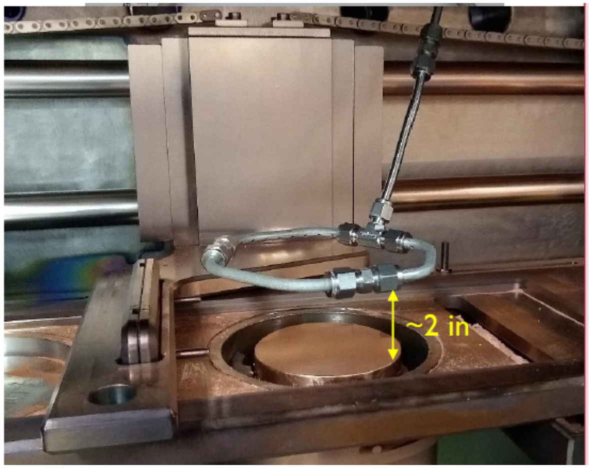
Layer height and powder size reduced: **Spot size dominates surface finish**

- Post-processing: electropolishing/ tumbling
- RF DfAM: Optimize design and printing constraints
- De-powdering

In-progress: BSE camera & in-situ H_2 reduction







Collaborations

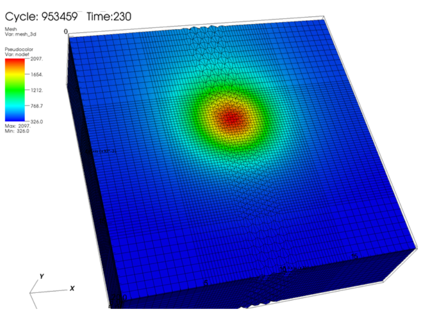
Consortium of Additively Manufactured Copper: GE, Siemens, SLAC and Calabasa Creek (Pending: L3, Northrup Grumman, ORNL, PNNL, SRNL)

radiasoft

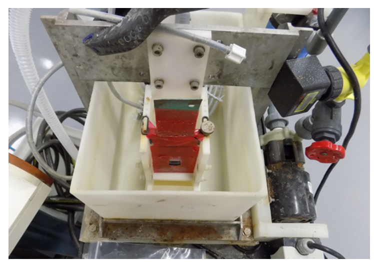
FARADAY TECHNOLOGY®

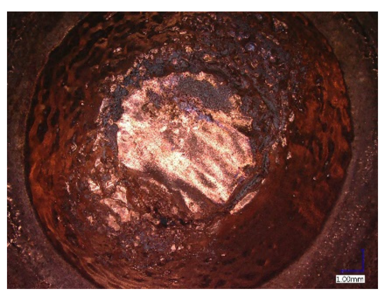
SLAC

AP&C a GE Additive company

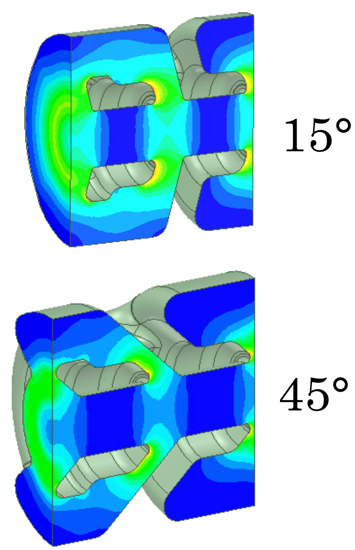


ALE3D simulation

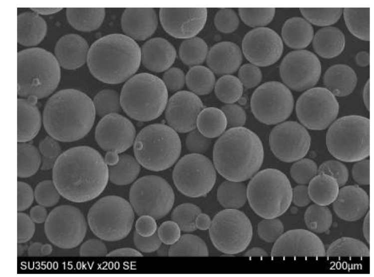


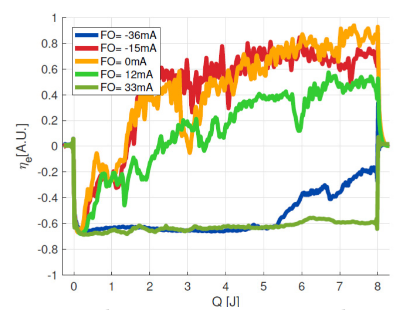


Cu electropolishing



RF DfAM





e$^-$beam/powder diagnostics

Conclusion (1)

Industrial metal AM is *real:* not plastic toys

- 30 years: significant commercial and strategic importance
- Structural alloys: Fe, Al, Ti, Ni
- Will complement conventional manufacturing (ex EDM)

e^-beam PBF improvements are needed:

- Workforce training
- Vacuum systems
- Beam: cathodes, magnets, power supplies, diagnostics
- Powder & powder deposition
- Software algorithms
- In-situ process monitoring

Conclusion (2)

Indirect opportunities for accelerators:

- CT X-ray inspection
- Electron beam optics
- Beamline experiments
- University partnerships

Challenges for accelerators:

- Accelerator equivalent to tensile dog-bones
- DfAM, post-processing and qualification are unique
- Industry coordination for high quality powder (Cold spray)

Thank you!

Summary: Powder Bed Fusion

	L-PBF	EB-PBF
Advantages	o Better R_a: Powder (15-45µm), spot (75µm) o Less complex, many OEMs o Better understood	o High power o Fast deflection o Quasi-vacuum furnace
Disadvantages	o Ar atmosphere o Absorptivity instabilities o Support structures	o Lower R_a: powder (45-106µm) spot (200µm….??) o More complex, single OEM o Limited research

Industrialization: Laser >> Electron beam

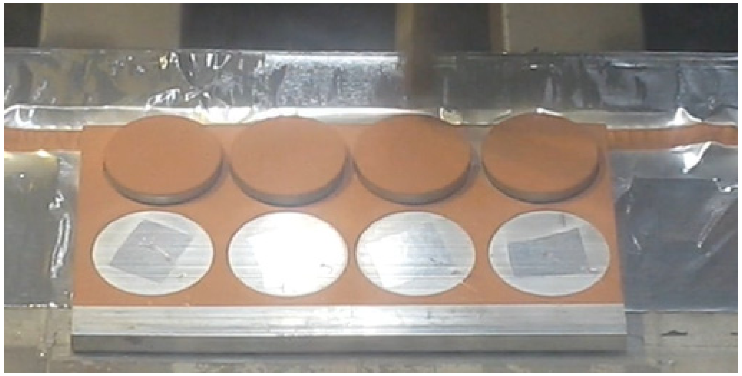
Current effort: Cold spray

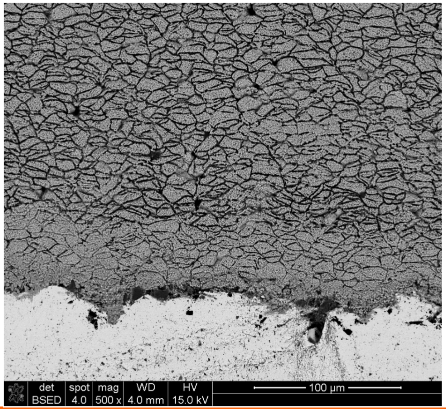
Cold Spray: Selective explosion bonding, solid-state consolidation

- Reduced oxidation, residual stress, HAZ
- Metastable materials via mechanical alloying
- Deposition rate: 1-8 kg/h, machinable, ID coating possible

Objective: Cu coatings of Nb for enhanced conduction cooling with Inovati Technologies, Ca

Contract:DE-SC0019714



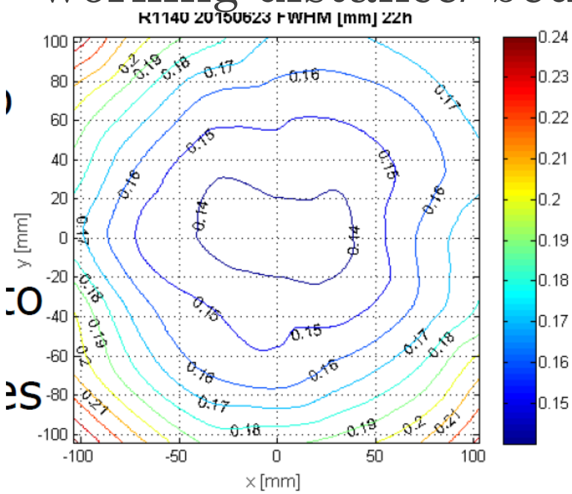


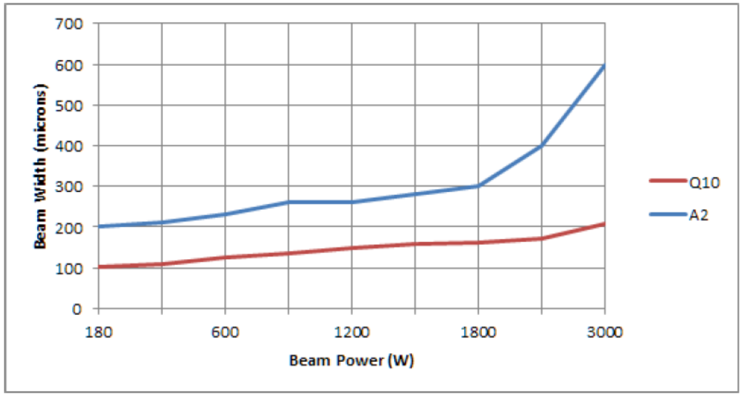
physik:σ Electron beam

The beam diameter is function of

- I_b & V_{acc} (Space-charge effects)
- focus offset
- cathode material/gun
- surface state of cathode
- working distance/ bed position

	Beam diameter (μm)	
z (mm)	Patterns 1, 3	Patterns 2, 4
0	230	300
21.5	400	440
38.9	370	410
41.0	340	390
45.0	320	370
46.1	300	350
47.1	280	340
Ib	4.5mA	9.6mA



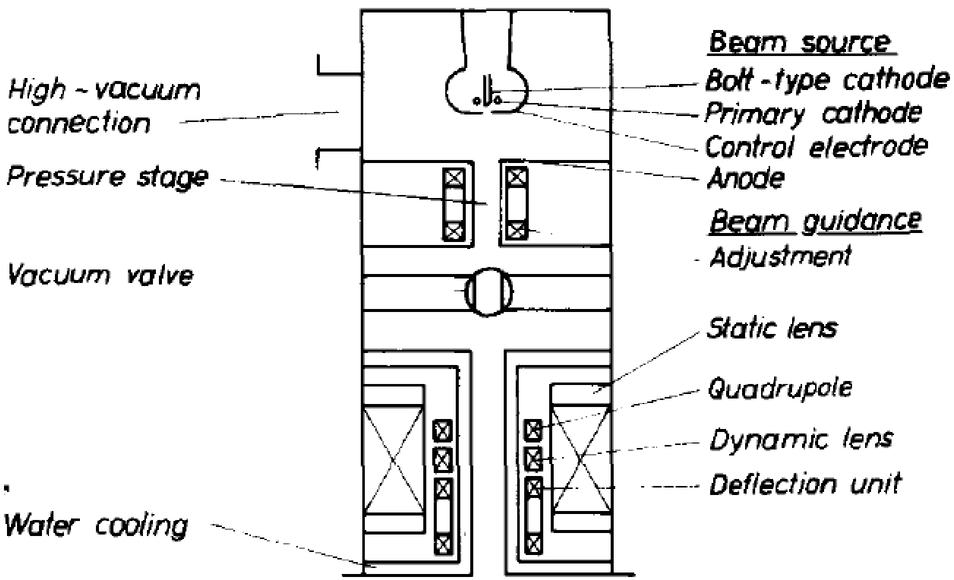


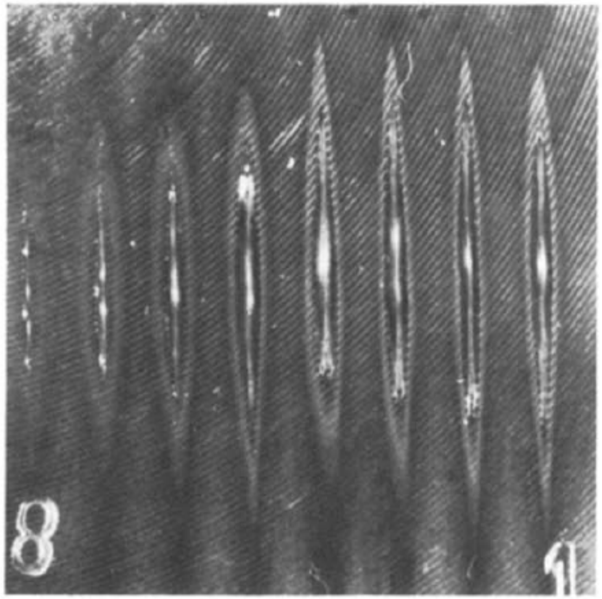
Cordero - 2017 - Nucleation and growth of chimney pores during electron beam additive manufacturing
Sirrus- Arcam - 2014- Additive Manufacturing with EBM - The Route to Production

physik:σ Ellipitical Beam

Von Ardenne 1984: surface ebeam melting with quadrapole EM lens in CTW 5/60 guns

- increased productivity





Schiller - 1984 surface modification by ebeam scanning

Example:Yadroitsev 2010 Variable λ_{melt}

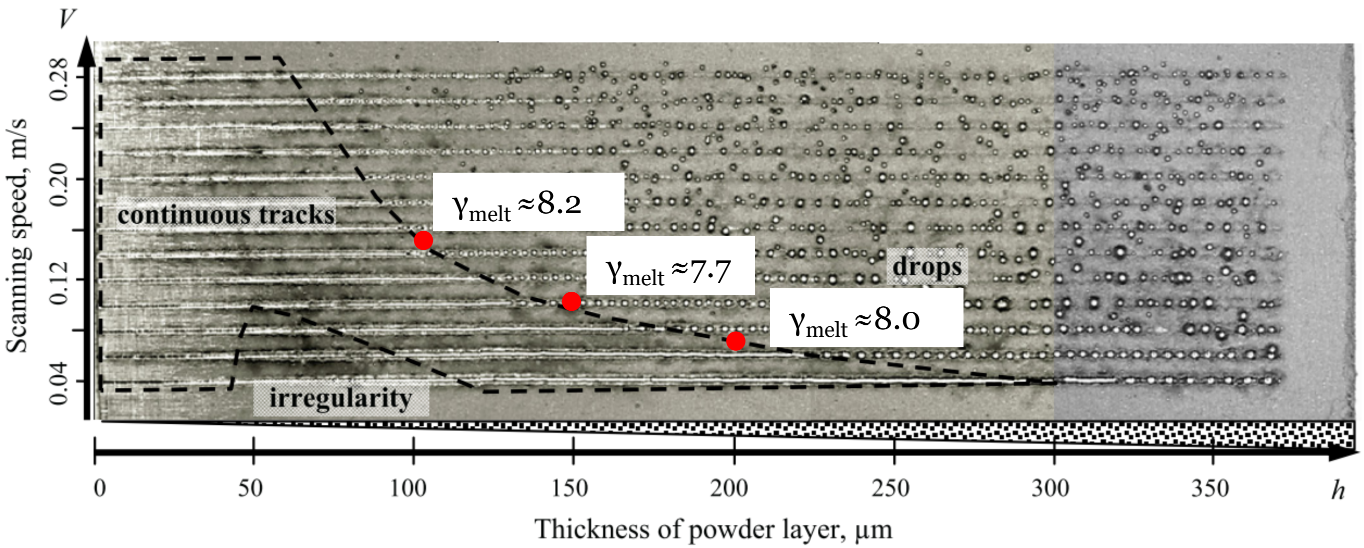
316 SS powder,

physik: 50W laser, v= [40:20:280] mm/s

$\eta_{Fe\text{-}pow}$=0.7 t_{layer} = [0:400]um

$$\gamma_{melt} = \frac{e_{abs-CL}}{\delta h_{surf}}$$

e_{abs-CL}
1.7
2.4
4.01
12.0



δh_{surf}	0	0.21	0.41	0.62	0.83	1.04	1.24	1.45

Yadroitsev- 2010 - Selective laser melting technology, from single laser melted track stability to 3D parts of complex shapes

References

Leach - 2019 - Geometrical metrology for metal additive manufacturing

Bourell - 2009 - A Brief History of Additive Manufacturing and the 2009 Roadmap for Additive manufacturing looking back and looking ahead

Bourell - 2016 - Perspectives on Additive manufacturing

Zhai -2014 - Additive Manufacturing Making Imagination the major limitation

https://www.aniwaa.com/best-of/3d-printers/best-metal-3d-printer/

http://admansol.fr/en/

Eagar - 1983 - Temperature fields produced by travelling distributed heat sources

Lee - 2016 - modeling of heat transfer fluid flow and solidification microstructure of Ni based superalloy fabricated by LPBF

Mindt- 2016- Powder Bed Layer Characteristics: The Overseen First-Order Process Input

Yadroitsev- 2010 - Selective laser melting technology, from single laser melted track stability to 3D parts of complex shapes

Delerue -2018 - Building accelerator components: A 3D-printed Beam Position Monitor

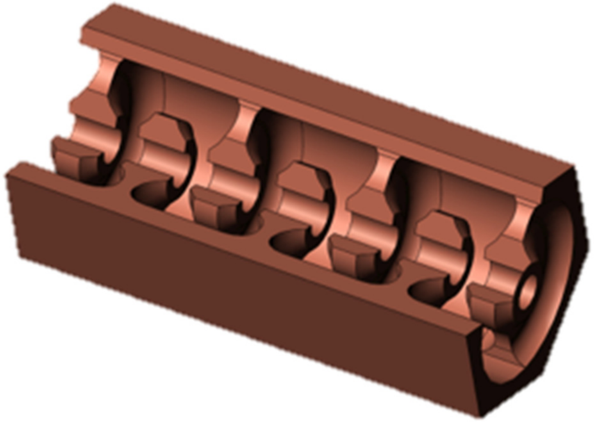
https://www.indian3dprintingnetwork.com/news/gh-induction-introduces-new-website-for-3d-printed-copper-coils/

https://3dinductors.com/3d-inductors/

Challenges of Printing Cu

Material:
- Poor absorption at λ=1.06μm
- Low viscosity: turbulent melt pool
- High thermal conductivity: short melt pool lifetime
- High purity/ low oxygen: ASTM F68 Class 1 Cu <10ppm O
  - $Ø_{particle}$= 50μm -> 0.12nm oxide
  - Sintering kinetics

Design
- Surface finish: S_a = 0.4μm
- Internal features
- Downfacing surfaces
- Overhangs



Dimensionless heat source

Dimensionless heat source size – Eagar 1983

$$\sigma^* = \frac{v\sigma}{2\alpha} \text{ [A.U]}$$

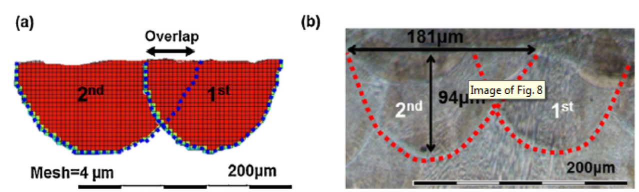
$\sigma^* \approx 0$: Point source/Rosenthal Model ($FWHM = 0$)

σ^* : Distributed source model (Cline/Eagar)

- Fast beam speed: large v
- poor conductors: small α
- large beam spots: large σ/FWHM

PBF processes

- Unidirectional heat flow … te
- Heat is not extracted wi…



Thomas - 2015 - Normalised model-based processing diagrams for additive layer manufacture of engineering alloy

AM Powder

Build table displacement(Δz) does not equal t_{pow}!

- Example: Assume $\Delta z = 0.1$mm and Φ=0.5

	Layer 1	Layer 2	Layer 3
z_{table} [μm]	100	200	300
t_{pow} [μm]	100	150	175
z_{solid} [μm]	0.5*100 = 50	125	212
z_{gap} [μm]	50	75	88

Steady state: t_{pow}= 200um and Δz converges to t_{pow}/Φ = 100um

Contributing factor for challenges of downskin surfaces and overhangs