Additive Manufacturing of a High Field Side Tokamak Lower Hybrid Current Drive Launcher from GRCop-84

A.H. Seltzman, S. J. Wukitch

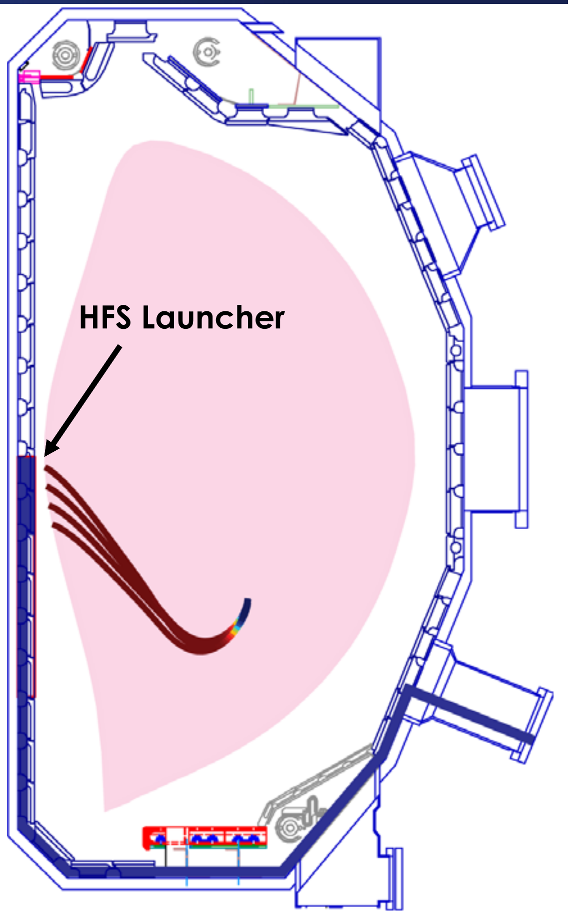
Presented at the
28th IAEA Fusion Energy Conference, 10-15 May 2021

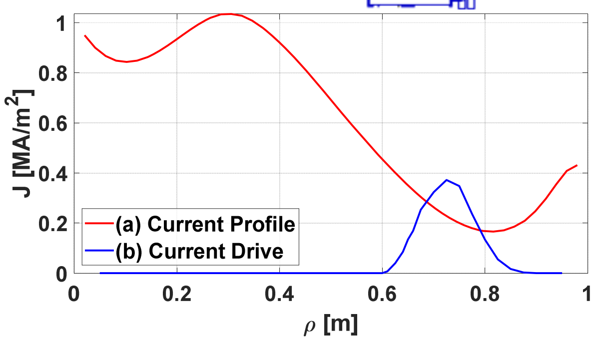
1) High Field Side (HFS) LHCD improves current drive efficiency, coupling, and accessibility
2) Novel multijunction designed with traveling wave power splitter and aperture impedance matching to reduce electric field
3) GRCop-84 withstands high temperature 400C bakeout without annealing and retains sufficient strength to withstand disruption loads
4) Additive manufacturing is a key enabling technology

Plasma Science and Fusion Center

HFS Launched LHCD is a Potential Solution for Efficient Off Axis Current Drive in DIII-D

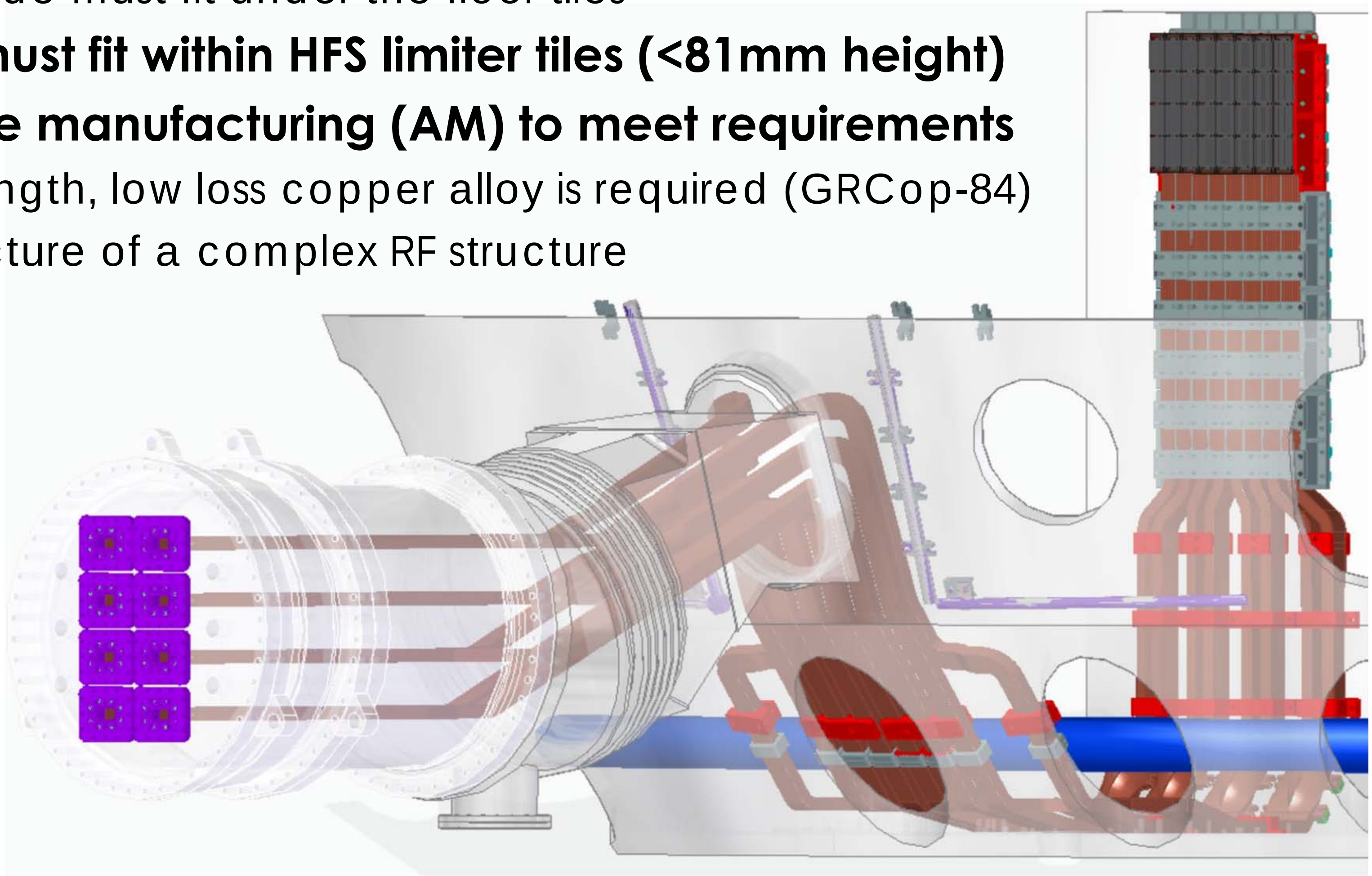
- **HFS launch @ 4.6GHz and $n_{||}$=-2.7 has excellent accessibility and single pass absorption**
- **Improved coupling due to steep density profile and low density fluctuations that minimize scattering and parametric decay losses**
- **ExB drift away from launcher and good magnetic curvature reduce plasma material interactions**
- **1.3MW at grill divided between 8 module ~880kW coupled into correct $n_{||}$**
  - 140kA current drive per MW coupled
  - Peaked off axis ρ~0.6-0.8. (1.7 T)





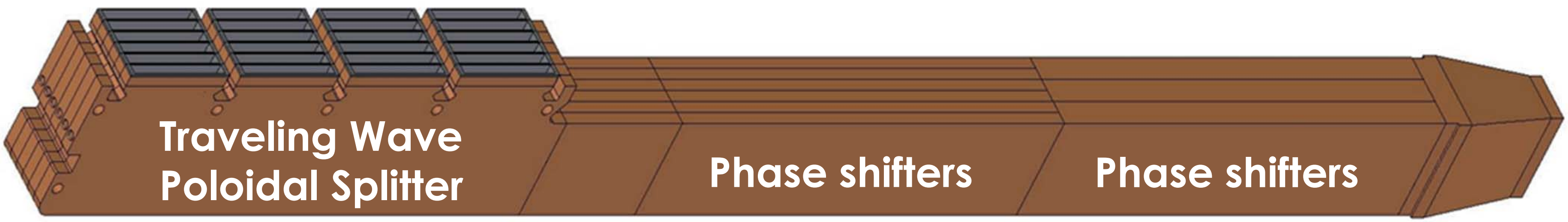
Novel Launcher Design is Required by Limited HFS Access and Constrained Space

- **Challenge routing waveguide under cryopump and divertor**
  - Cryopump is not movable
  - Waveguide must fit under the floor tiles
- **Launcher must fit within HFS limiter tiles (<81mm height)**
- **Use additive manufacturing (AM) to meet requirements**
  - High strength, low loss copper alloy is required (GRCop-84)
  - Manufacture of a complex RF structure

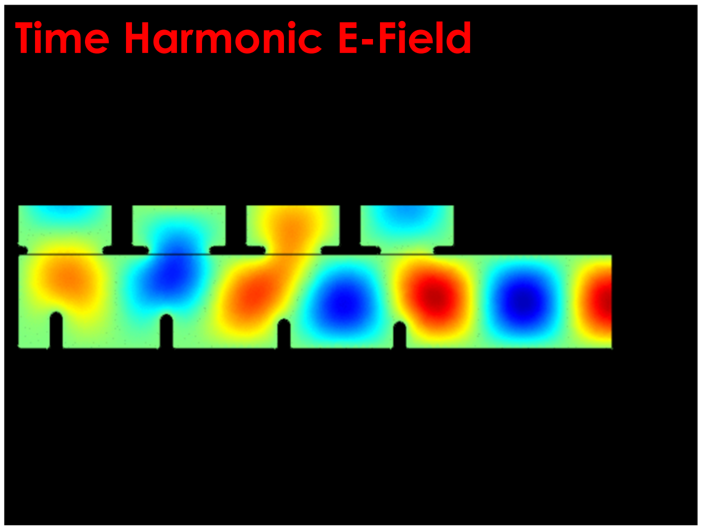


Traveling Wave Poloidal Splitter Reduces Peak Electric Field in Vacuum Section

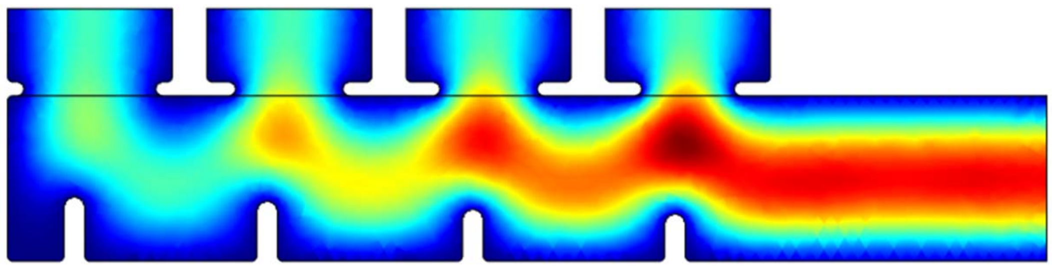
HFS Launcher Module (1 of 8x)



- **Design driven by multipactor breakdown limit of 9.3kV/cm at 4.6 GHz**
- **Traveling wave poloidal splitter reduces |E| by 20% compared to a standing wave divider**



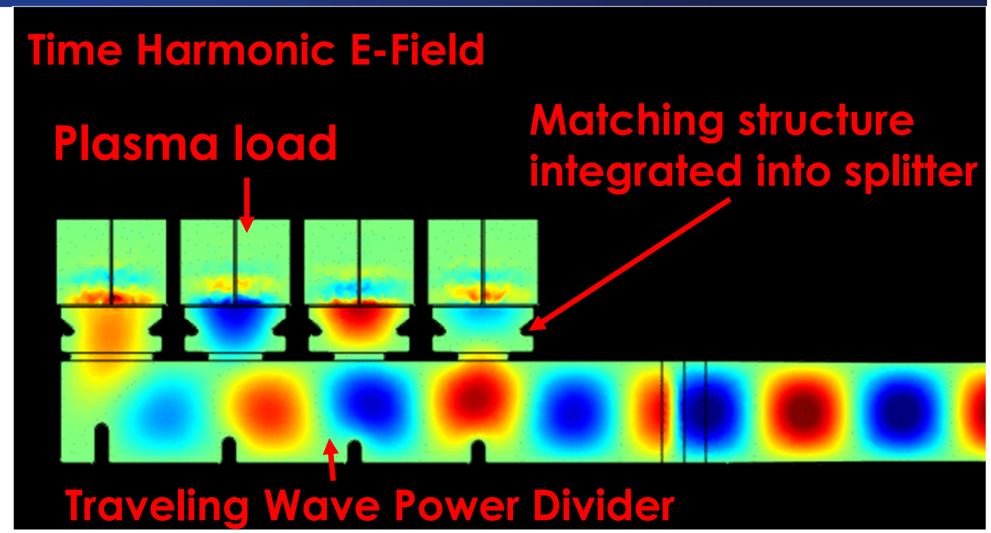
Traveling Wave Poloidal Splitter



Low reflection at plasma facing aperture required for traveling wave operation: Aperture must be impedance matched to plasma

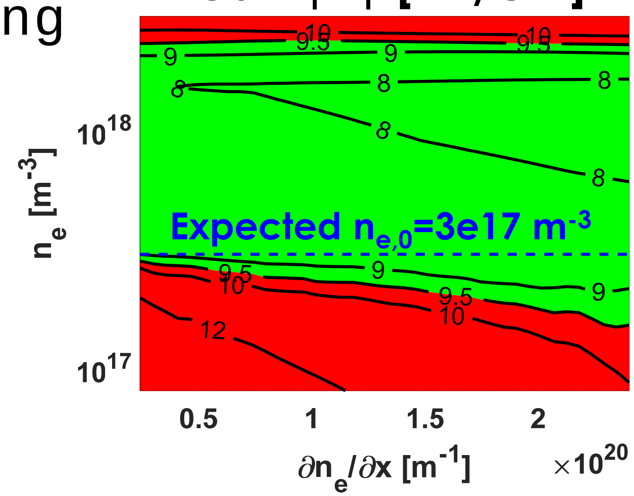
Impedance Matching to Plasma Reduces Circulating Power and Electric Fields Density

- **Aperture matching structure impedance matches waveguide to plasma load**
  - Reduces circulating power and lowers |E|
- **Internal integrated tapered matching structure is very challenging to manufacture**
  - Additive manufacturing offers a path



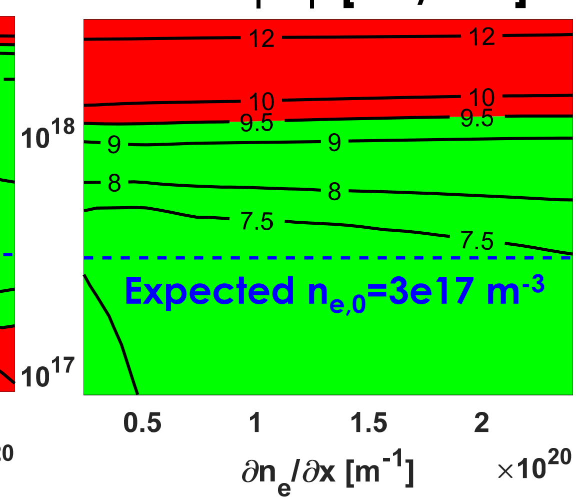
Without Matching

Peak |E| [kV/cm]



With Matching

Peak |E| [kV/cm]

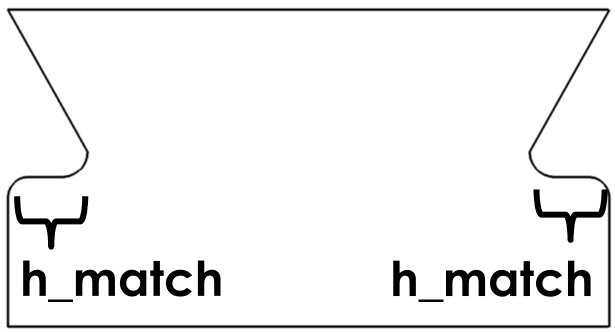


Seltzman, A. H., et al. "A high field side multijunction launcher with aperture impedance matching for lower hybrid current drive in DIII-D advanced tokamak plasmas." *Nuclear Fusion* 59.9 (2019): 096003.

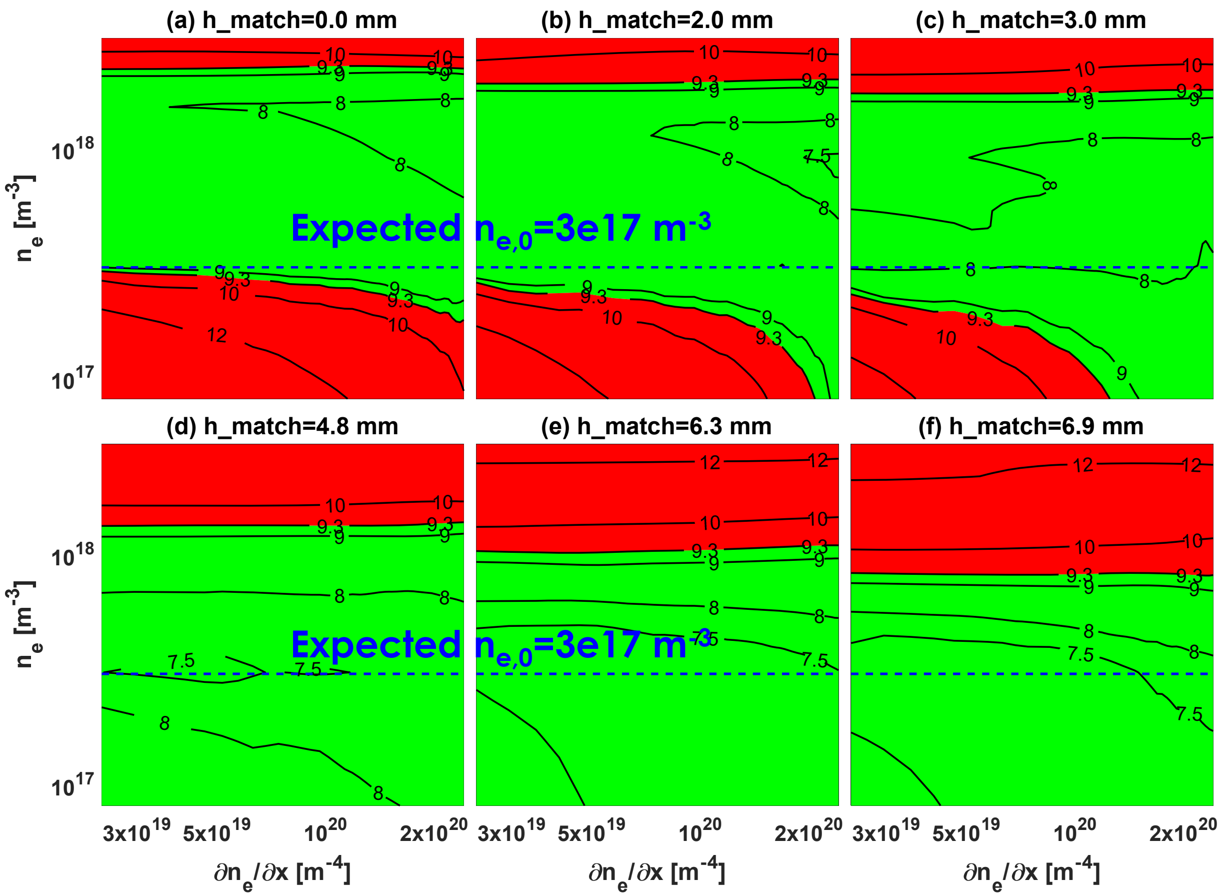
Seltzman, A. H., et al. "Aperture impedance matching for lower hybrid current drive launchers." *AIP Conference Proceedings*. Vol. 2254. No. 1. AIP Publishing LLC, 2020.

Edge Density Range for Optimum Coupling is Selected by Matching Element Height

Low reflectivity coupling region in edge density and density gradient is selected by choosing matching element height



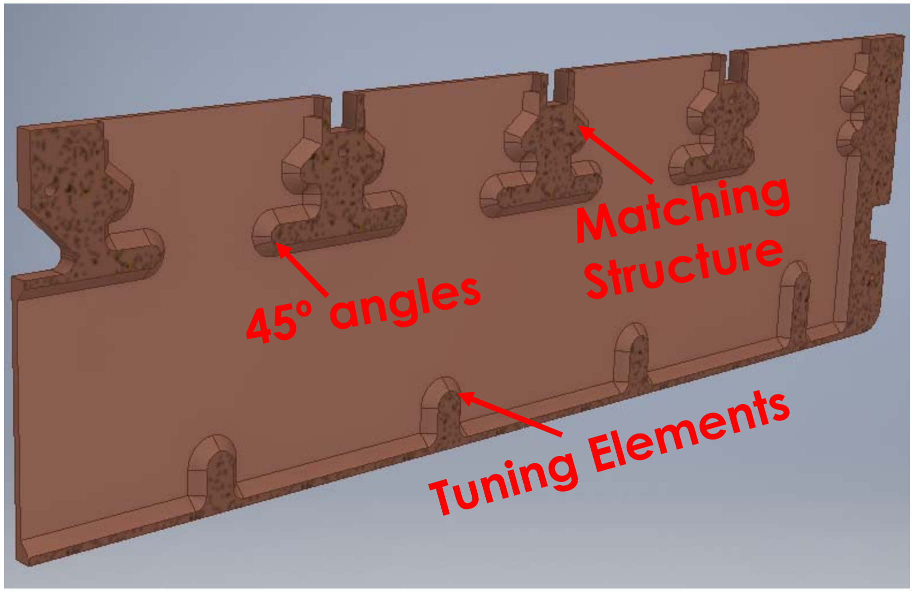
Peak |E| [kV/cm] for 33kW per splitter
Larger |E| indicates more circulating power



Seltzman, A. H., et al. "Aperture impedance matching for lower hybrid current drive launchers." *AIP Conference Proceedings*. Vol. 2254. No. 1. AIP Publishing LLC, 2020.

AM Enables Production of Complex Poloidal Splitter Structures in a Monolithic Print

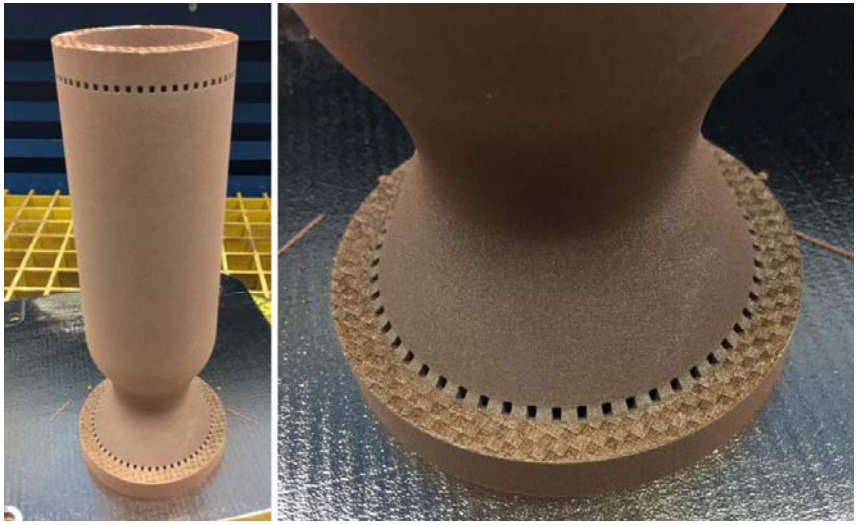
- **Poloidal splitters printed monolithically with 8 splitters per build plate**
- **Complex internal structure, but no internal machining required**
- **45° angles from side walls supports top of waveguide**
- **AM from a high strength copper alloy: GRCop-84**



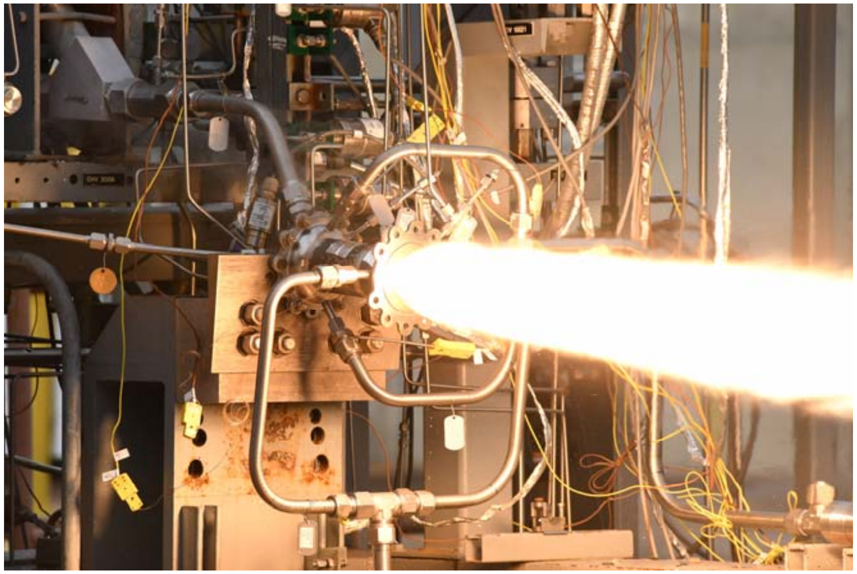
Glenn Research Copper (GRCop-84) is a Relatively New Alloy with Potential for Fusion Applications

- **NASA development for reusable rocket engine combustion chambers**
  - High strength at high temperature
  - High heat flux (100 MW/m^2)
- **Cr_2Nb precipitation hardened copper**
  - 8 atomic % Cr, 4 atomic % Nb
- **GRCop-84 can not be cast**
  - Rapid cooling required to maintain small precipitate size
  - Must be consolidated from gas atomized powder (HIPing, extrusion)
  - Or by **Additive Manufacturing**

Seltzman, A. H., and S. J. Wukitch. "Fracture Characteristics and Heat Treatment of Laser Powder Bed Fusion Additively Manufactured GRCop-84 Copper." ***Mat. Sci. & Eng: A Under Review (2021)***



P.R. Gradl, et al. *AIAA Propulsion and Energy 2019 Forum*

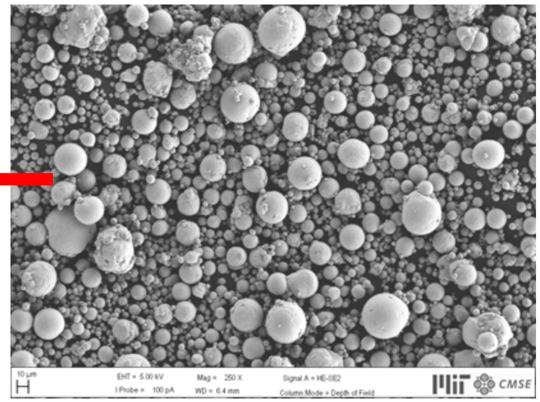


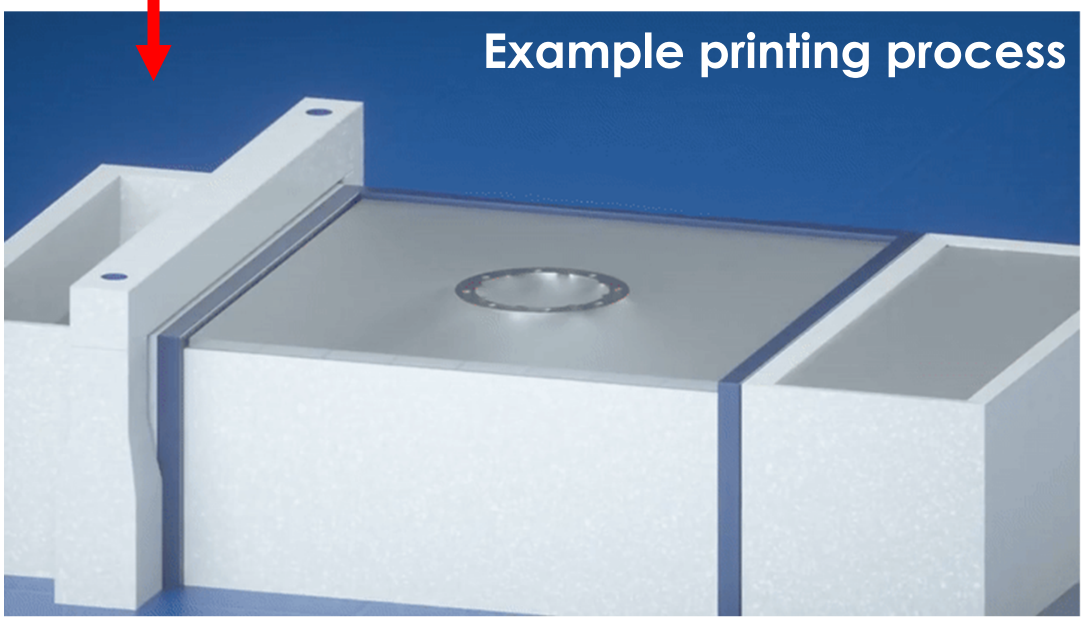
D. Ellis, NASA/TM-2005-213566

AM with LPBF is a Enabling Technology for Complex Launcher and Waveguide Structures

Cusing M2
LPBF Printer

Gas atomized
GRCop-84 powder



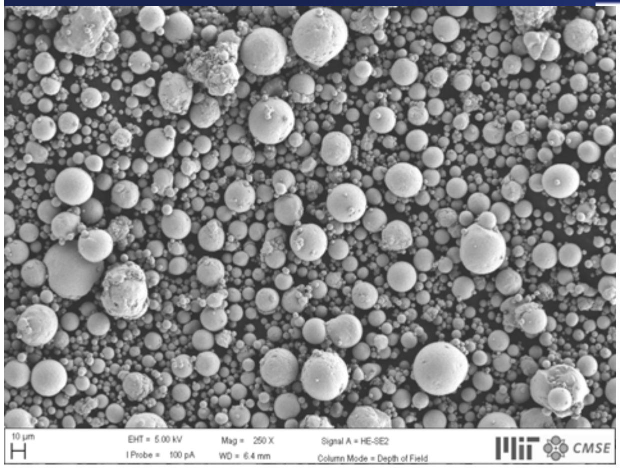


Courtesy of GE additive

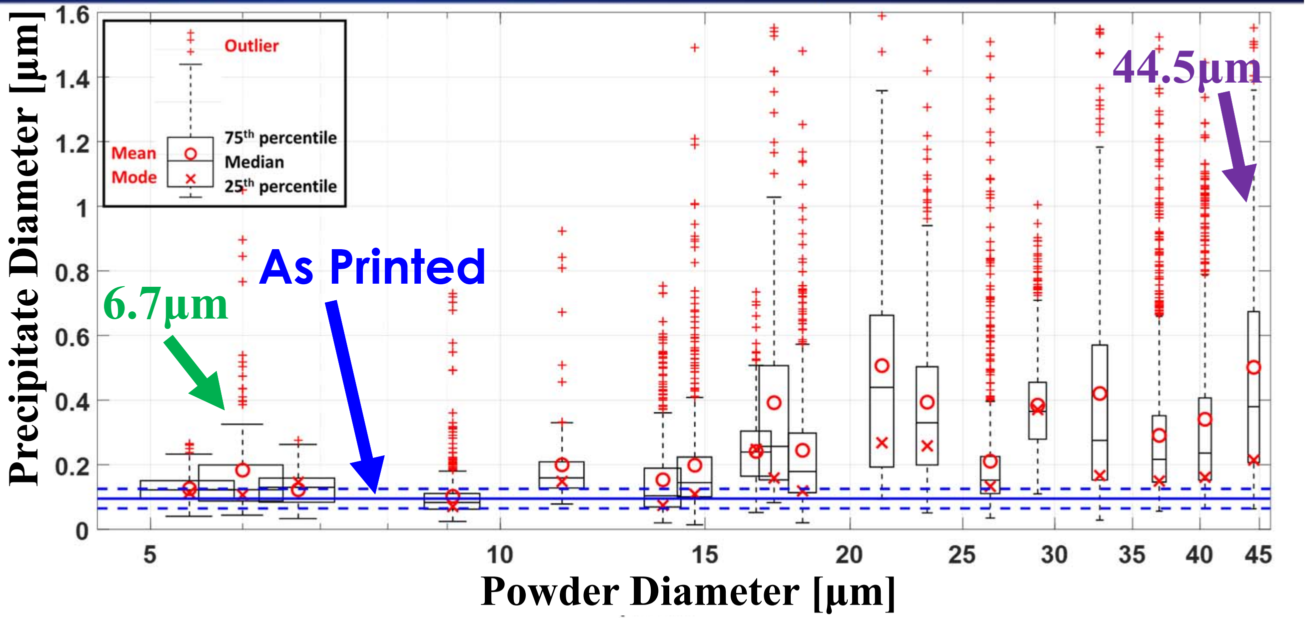
1. Powder layer is dispersed on surface
2. Cross section of part is melted by scanning laser
3. Build plate steps down by layer height
4. Repeat steps

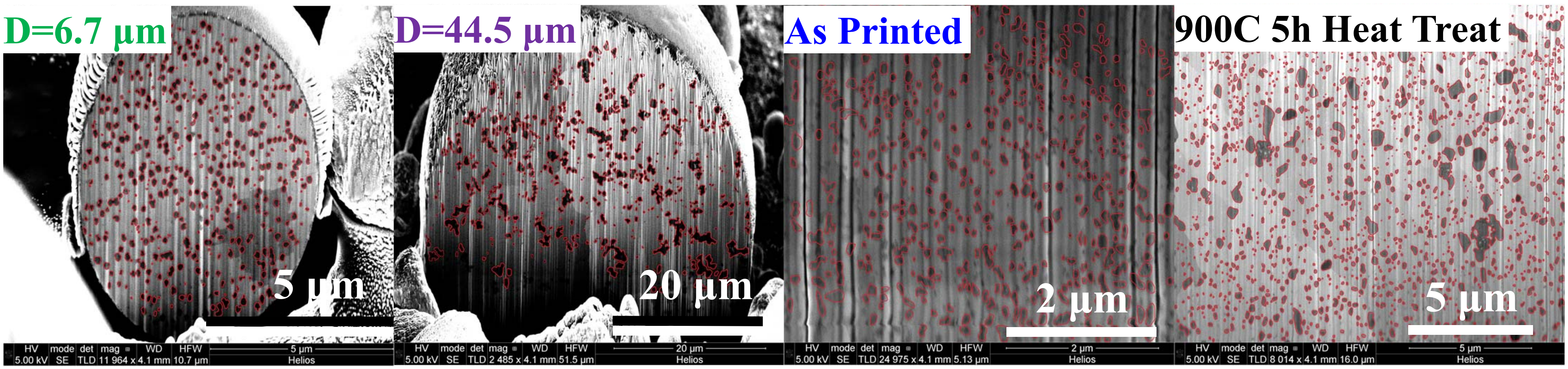
- LPBF GRCop-84 prints fully dense without a HIP process
- Surface smoothing for RF use through chemical polishing
- Maximum build volume of 250mm x 250mm x 350mm
- Laser and E-beam welding for assembling components

GRCop-84 Powder Consolidation with Laser Powder Bed Fusion (LPBF) AM Reduces Precipitate Size



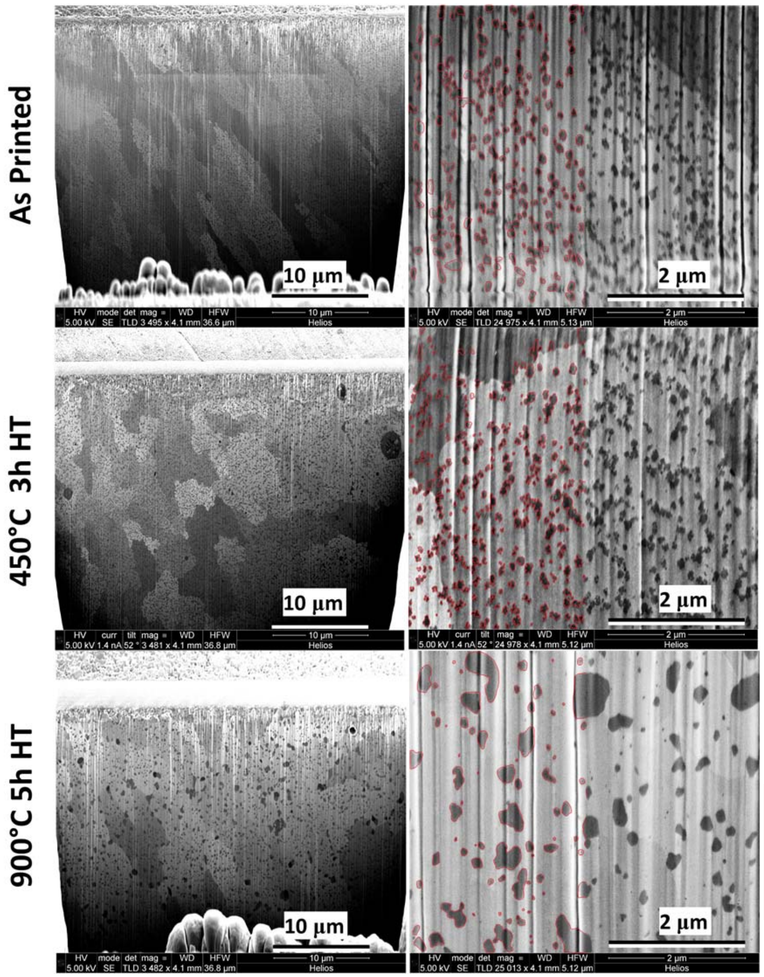
Seltzman, A.H., Wukitch, S.J., "Precipitate Size in GRCop-84 Gas Atomized Powder and Laser Powder Bed Fusion Additively Manufactured Material" Fusion Sci. & Tech. In Press (2021)





- **LPBF results in reduction of precipitate size (μ=95nm, σ=30nm)**
- **Increased Orowan strength compared to HIPing or extrusion from powder**

Heat Treatment of AM GRCop-84 Controls Precipitate Size and Tensile Properties



As Printed

- Yield=500 MPa
- UTS=740 MPa

450C 3h

- Yield=790 MPa
- UTS=970 MPa

900C 5 hour

- Yield=300 MPa
- UTS=520 MPa

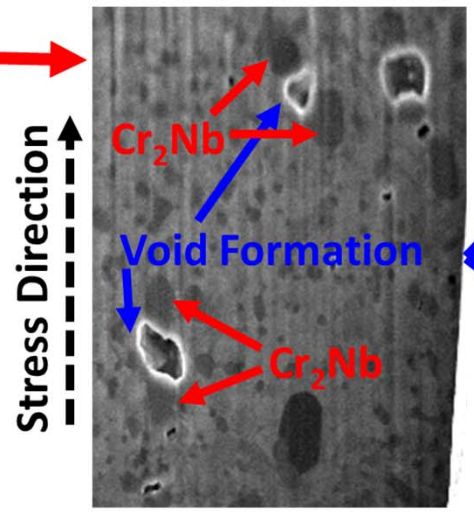
- No coarsening of precipitates at 450C
- Coarsening saturated at 900C
- 200MPa required for disruption loads
- OFC: 50MPa yield after 400C bake in DIII-D
- GRCop-84: 300MPa yield after 900C 5h heat treat

Seltzman, A. H., and S. J. Wukitch. "Fracture Characteristics and Heat Treatment of Laser Powder Bed Fusion Additively Manufactured GRCop-84 Copper." *Mat. Sci. & Eng: A, Under Review (2021)*

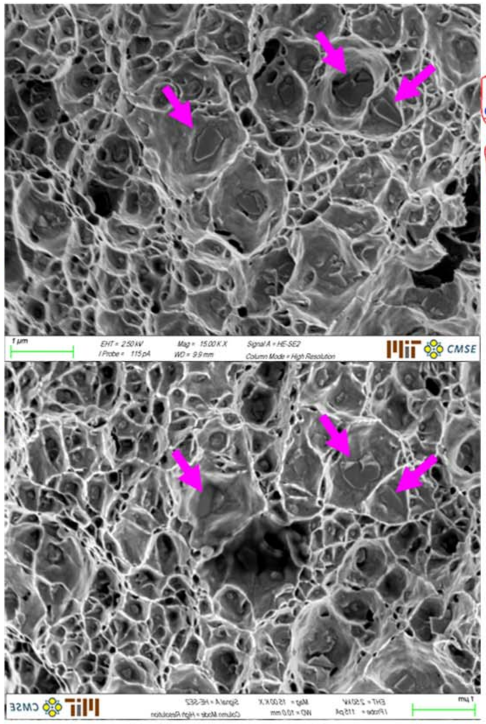
Cr_2Nb Precipitate Fracture Under Tensile Stress Nucleates Voids Leading To Failure Of AM GRCop-84

Fractured GRCop-84 Tensile Test Bar

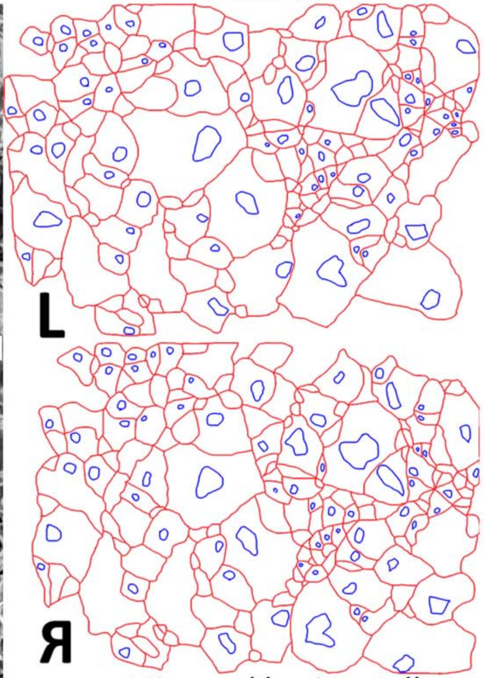
Ion Beam Milled Fracture Cross Section



Opposing Fracture Surfaces



Precipitate and Cusp Locations



Mirrored horizontally

- GRCop-84 fracture typical of ductile rupture
- Additive manufactured material much stronger than extruded or HIPed

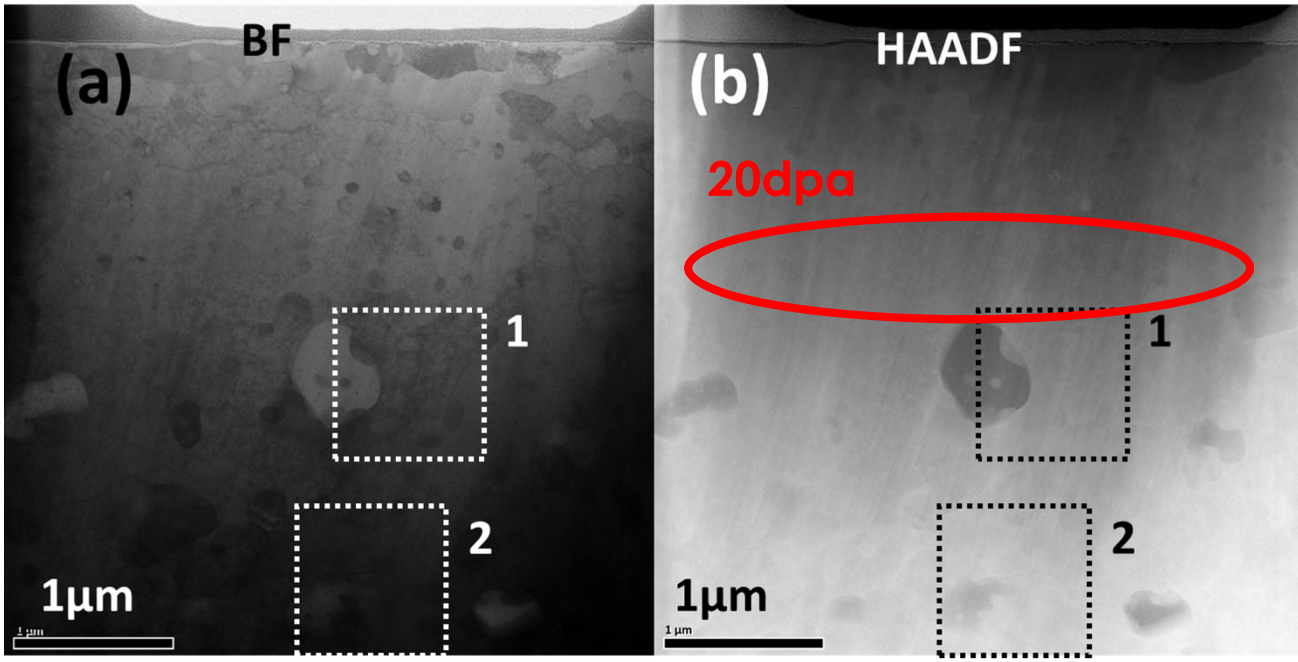
- Cr_2Nb precipitate fracture nucleates voids
- Voids grow from fractured precipitate and coalesce leading to material failure

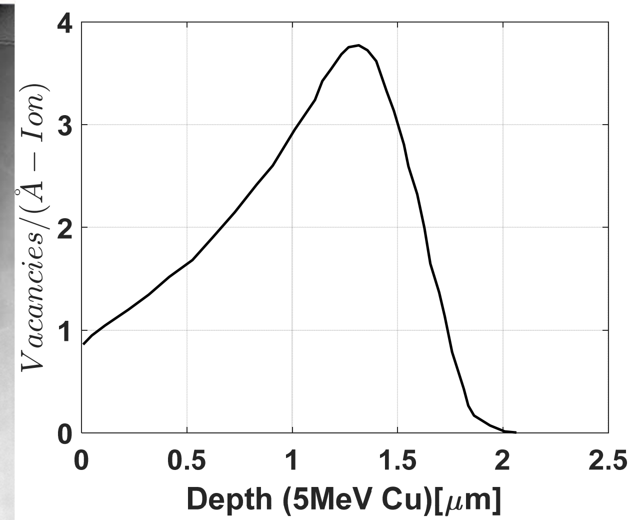
- Cr_2Nb fragments located near cusp center
- Fragment geometry matches on opposing sides

- Cr_2Nb Fragments appear in both opposing cusps
- >80% of cusps populated with a Cr_2Nb Fragment

Seltzman, A. H., and S. J. Wukitch. "Fracture Characteristics and Heat Treatment of Laser Powder Bed Fusion Additively Manufactured GRCop-84 Copper." *Mat. Sci. & Eng: A, Under Review (2021)*

No Voids Observed for Self-Similar 5MeV Cu^{3+} Ion Irradiation to 20dpa or 40dpa at 430C



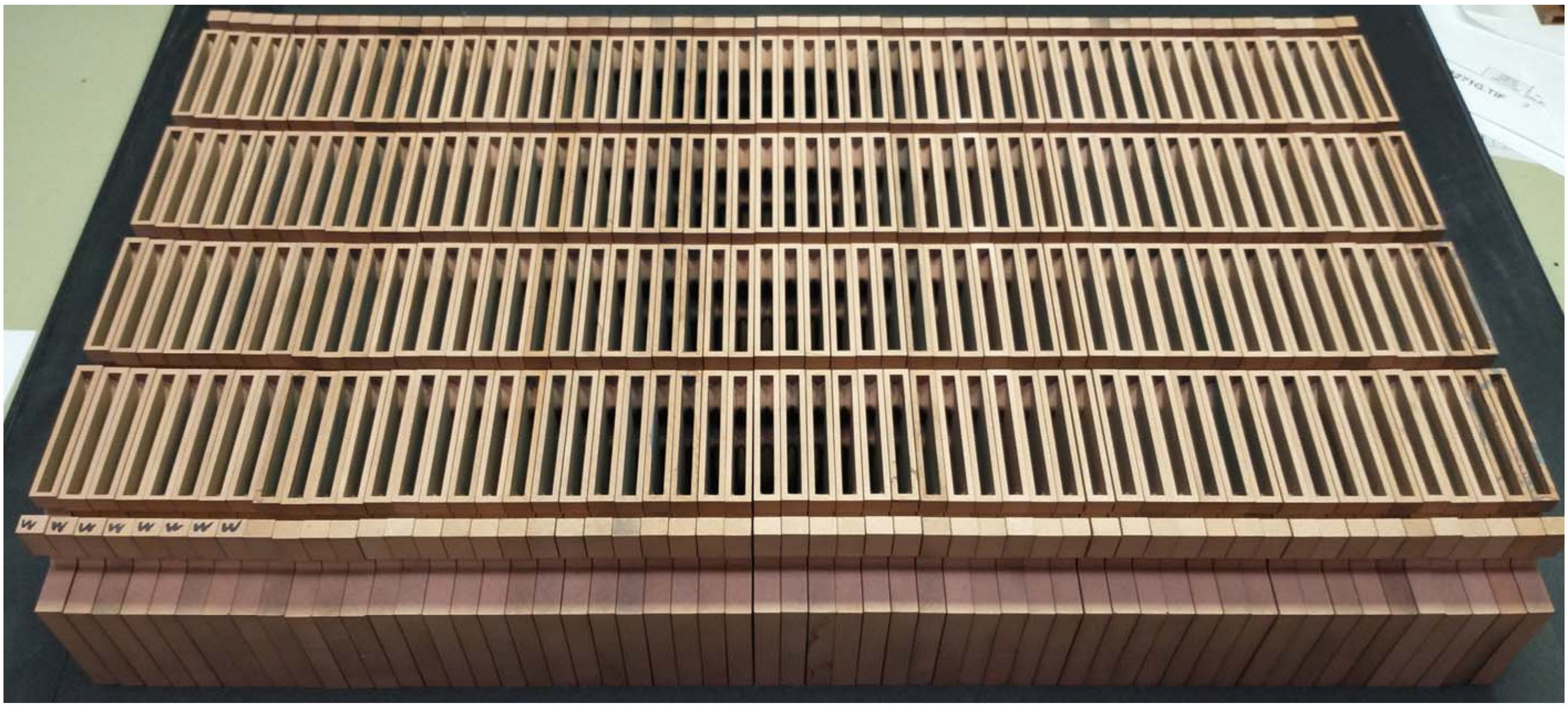


- No voids observed for 20dpa or 40dpa at 430C
- dpa peak depth 1.25um for 5MeV Cu^{3+}
- Tests will be run to 100dpa with and without 10appm/dpa He co-implantation

Seltzman, A. H., and S. J. Wukitch. "Nuclear response of additive manufactured GRCop-84 copper for use in Lower hybrid launchers in a fusion environment." *Fusion Engineering and Design* 159 (2020): 111726.

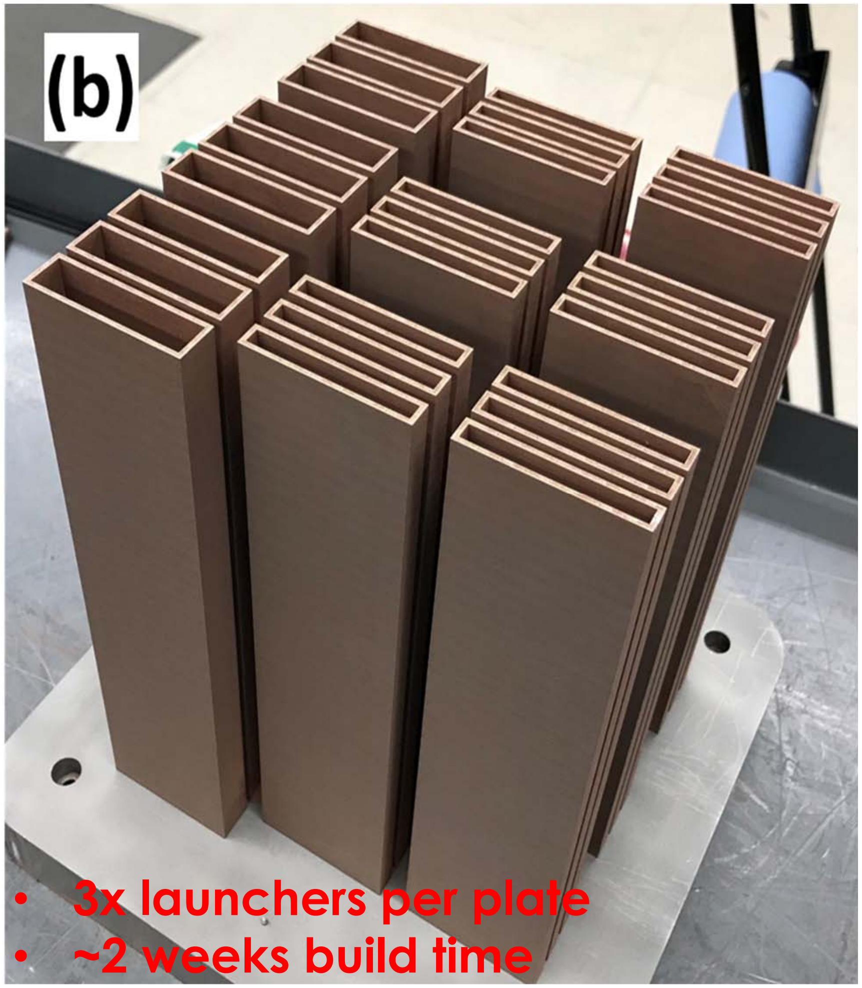
Using LPBF AM Techniques the HFS LHCD Launcher Poloidal Splitters are Printed

- **55x LPBF Printed Poloidal Splitters**

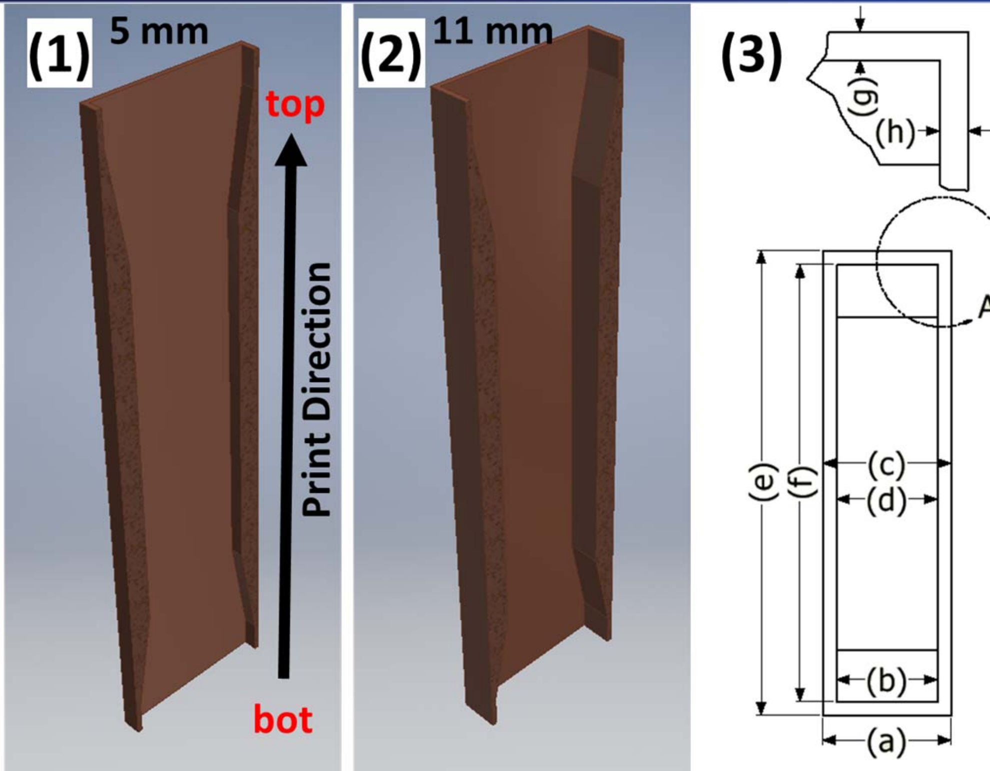


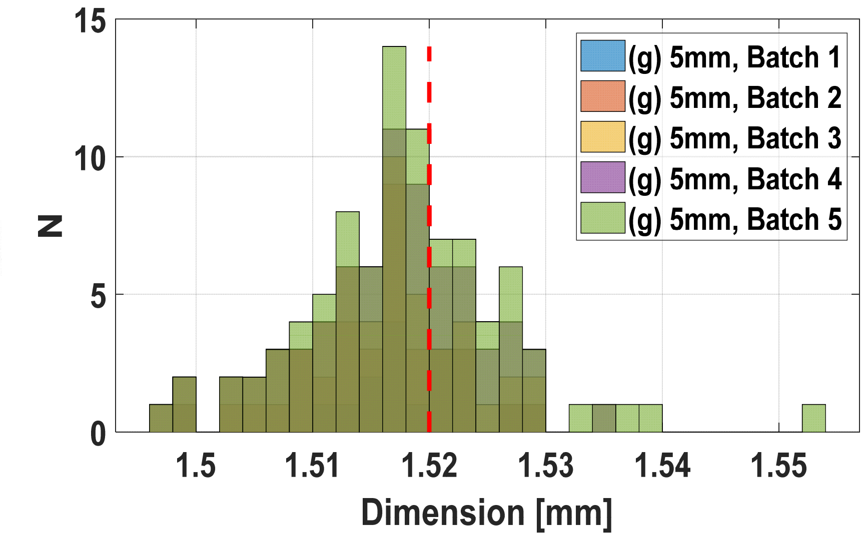
Likewise, AM Enabled Production of the Phase Shifters Without Internal Machining

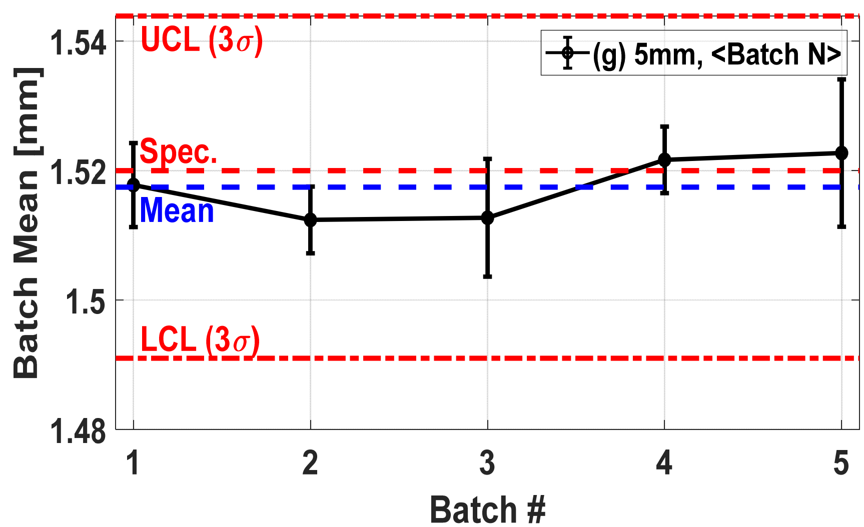
- **Phase shifters printed as monolithic elements**
- **Internal taper produced within rectangular waveguide**



AM Process Has High Accuracy and Reproducibility

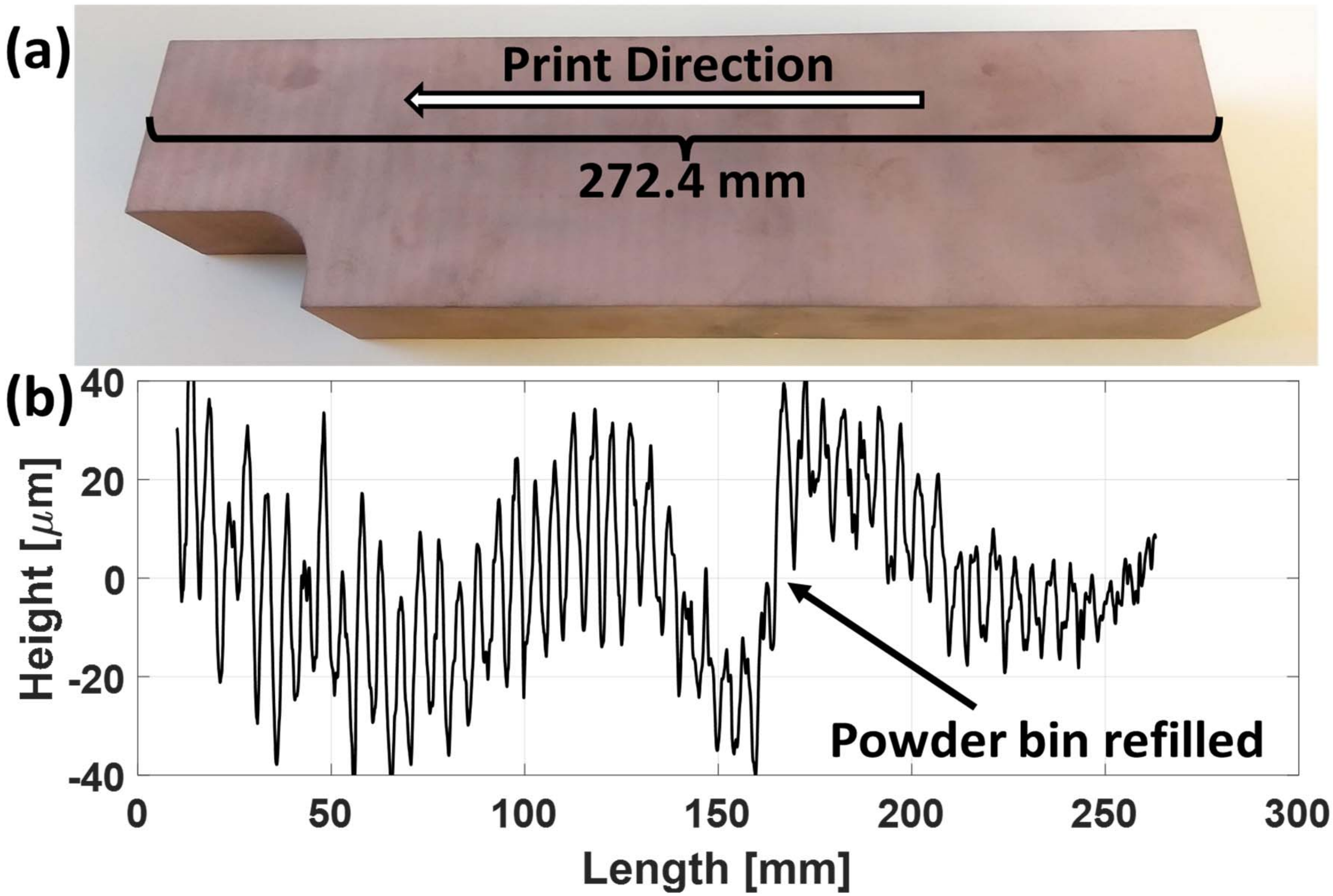






- **Gaussian distribution**
  - Implies well controlled process
- **High batch to batch reproducibility**
- **Dimensions within 10-40μm of specified depending on geometry**

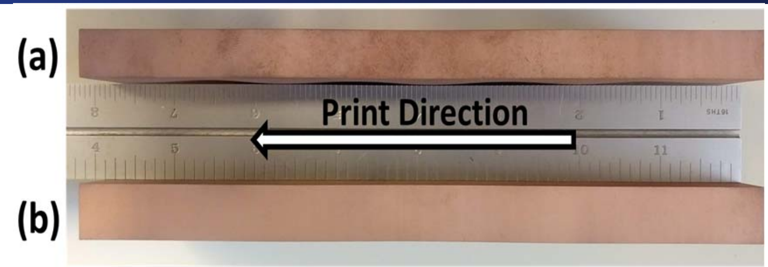
$30\mu m_{pk\text{-}pk}$ Surface Ripple Present in AM GRCop-84 Parts Does Not Prevent RF Use at 4.6 GHz

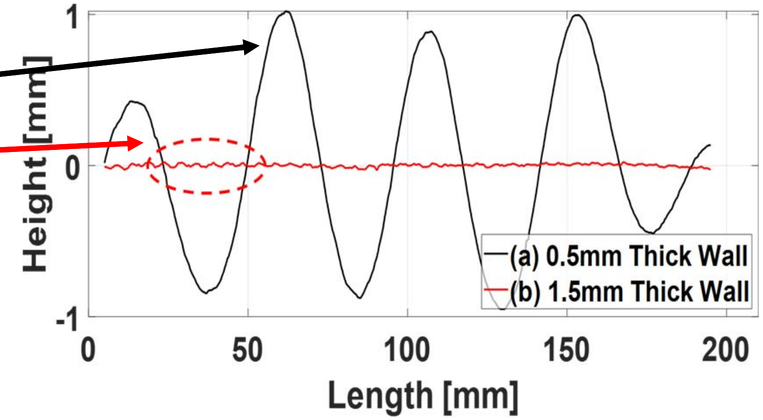


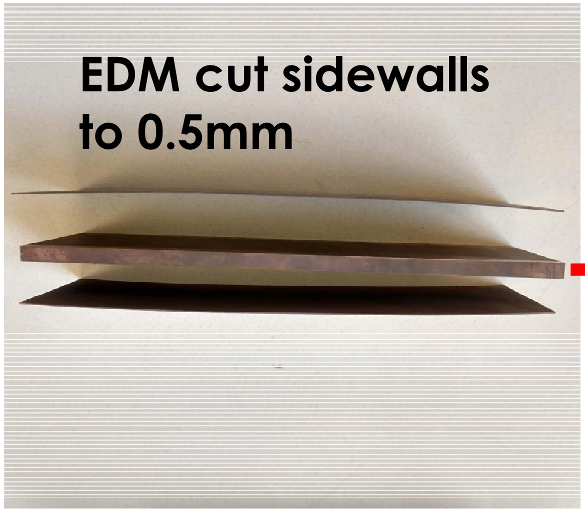
Seltzman, A. H., and S. J. Wukitch. "Resolution and Geometric Limitations in Laser Powder Bed Fusion Additively Manufactured GRCop-84 Structures for a Lower Hybrid Current Drive Launcher." *Fusion Engineering and Design, Under Review (2021)*

AM Process Required Adjustments to Design to Prevent Warping of Thin Walls

- **0.5mm thick walls are required on phase shifters**
- **1mm minimum wall thickness required to avoid warping**
- **Warping on 0.5mm thick walls (a)**
- **No warping on 1.5 mm thick broad walls (b) (30μm$_{pk\text{-}pk}$ Surface ripple)**
- **Print thicker walls, then EDM cut to required 0.5mm thickness**

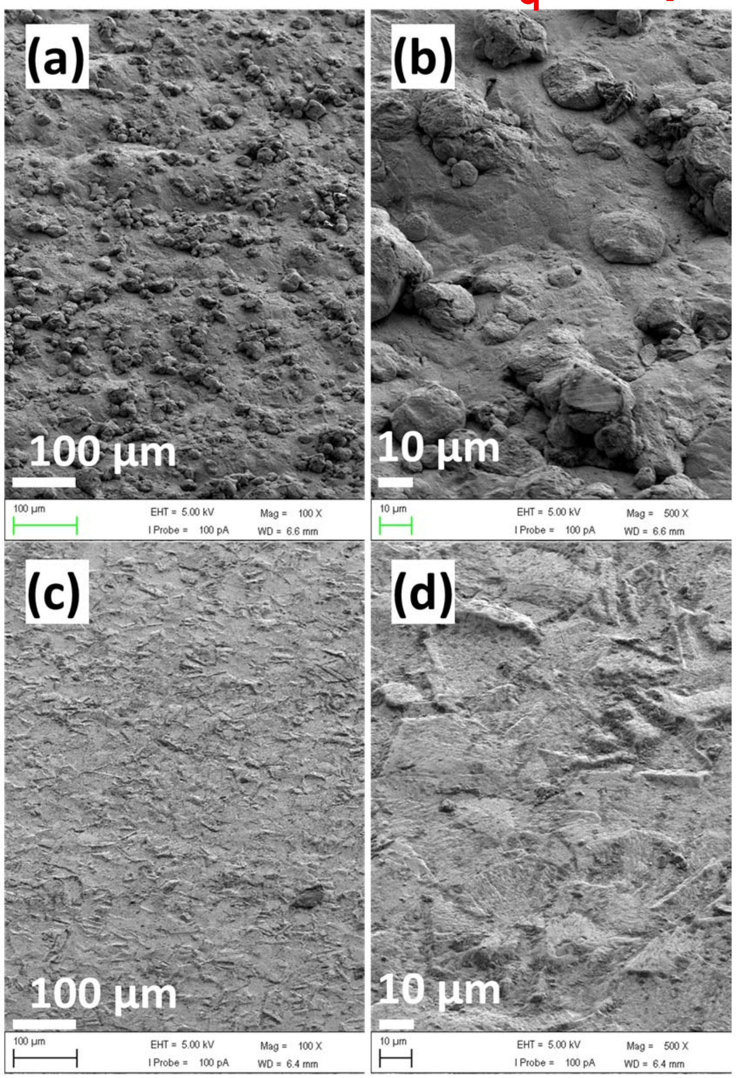




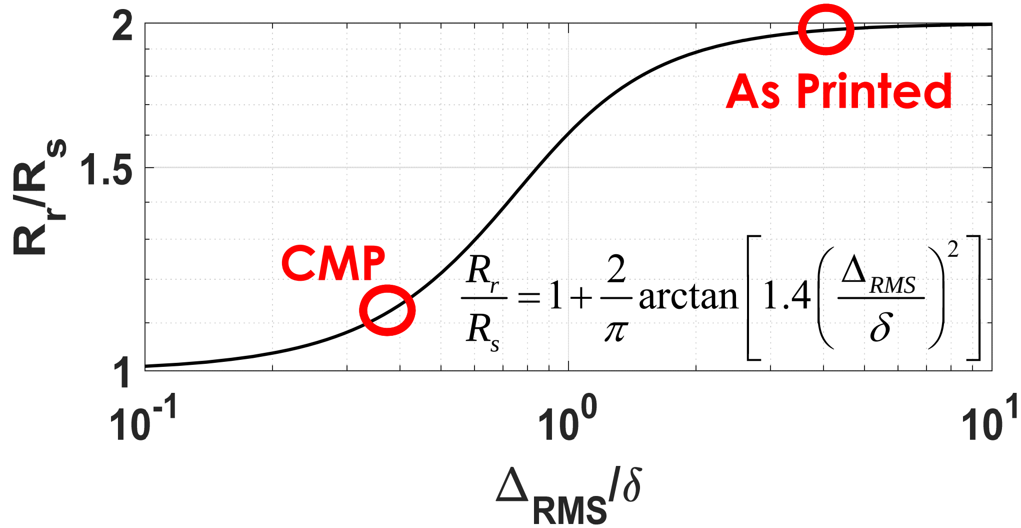


Surface Roughness Induced RF Losses Requires Further Internal Polishing Step on AM Material

As Printed Surface R_q=4.1 µm



OFC Waveguide R_q=0.48µm

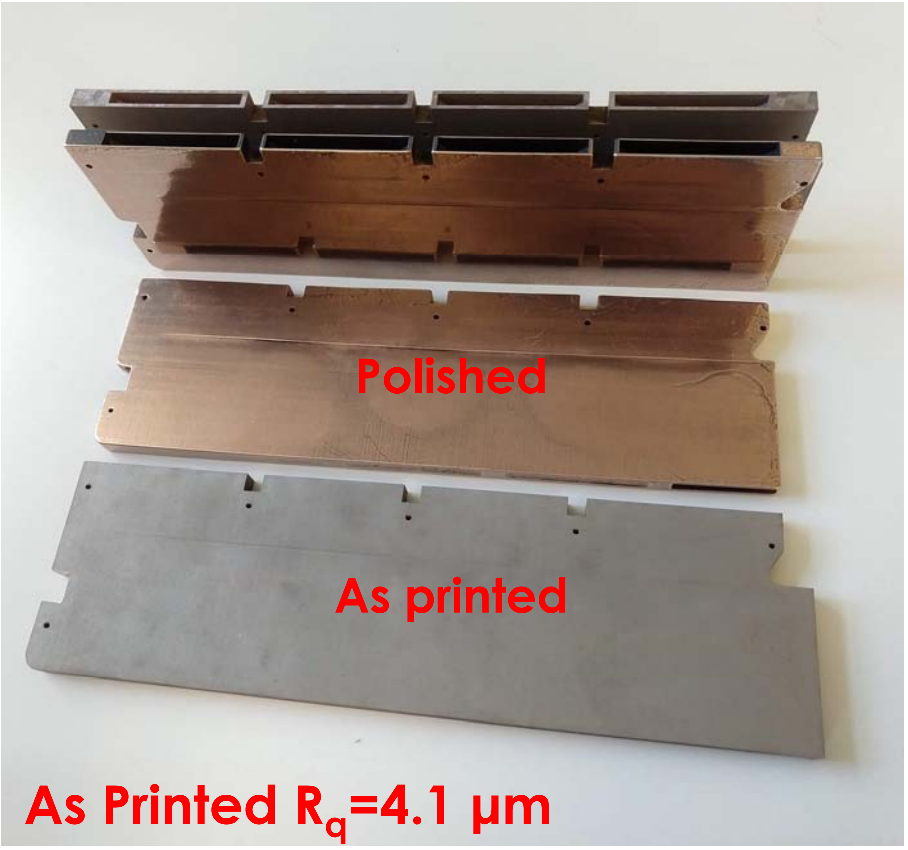


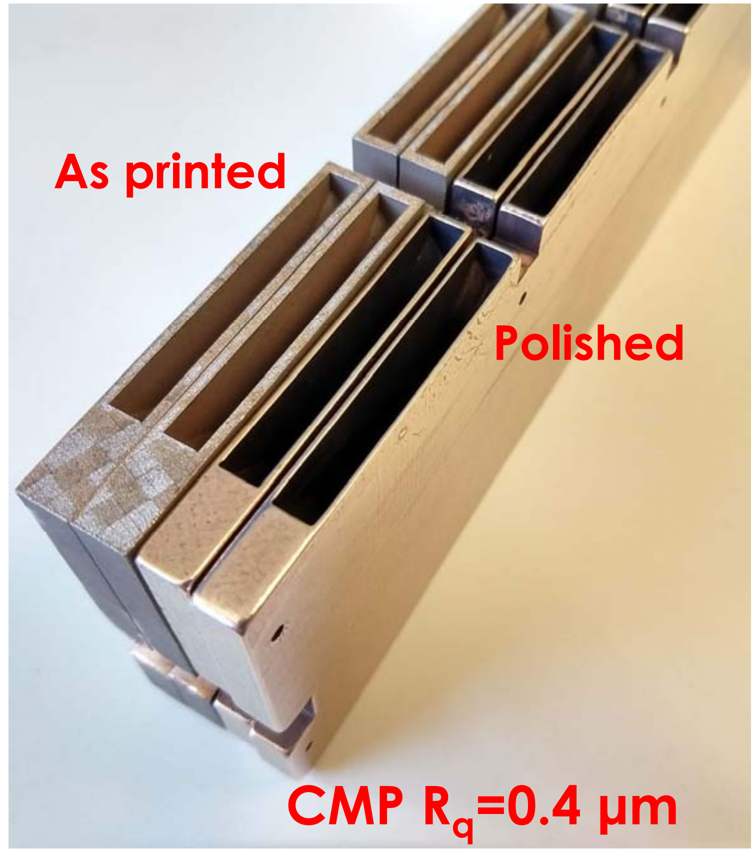
- **Ratio of RF loss increase compared to zero roughness surface related to ratio of RMS surface roughness (Δ_{RMS}=R_q) to skin depth (δ)**
- **At 4.6 GHz, skin depth δ_s=~1 µm in copper**
- **R_q=~0.3-0.4 µm required to minimize loss**

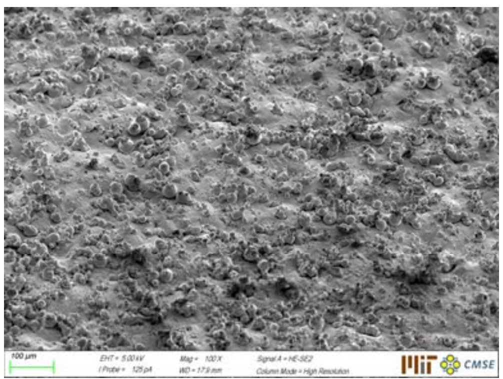
Seltzman, A. H., and S. J. Wukitch. "RF losses in selective laser melted GRCop-84 copper waveguide for an additively manufactured lower hybrid current drive launcher." *Fusion Engineering and Design* 159 (2020): 111762.

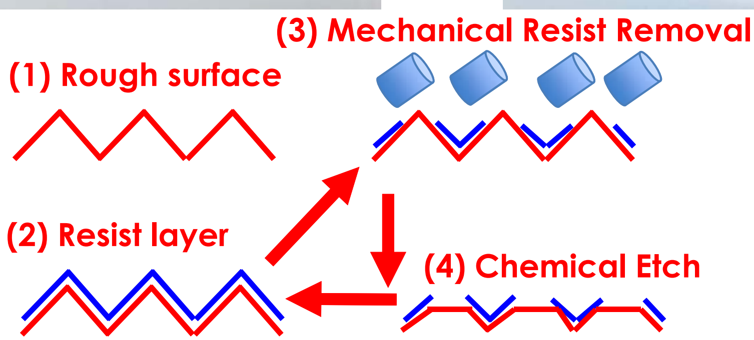
Seltzman, A. H., and S. J. Wukitch. "Surface roughness and finishing techniques in selective laser melted GRCop-84 copper for an additive manufactured lower hybrid current drive launcher." *Fusion Engineering and Design* 160 (2020): 111801.

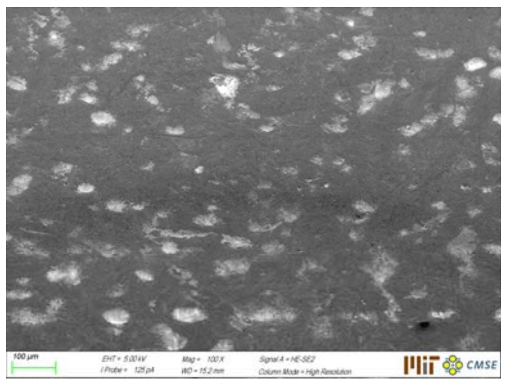
Chemical-Mechanical Polishing Smooths Internal Surfaces to Prevent Arcing and Reduce RF Loss



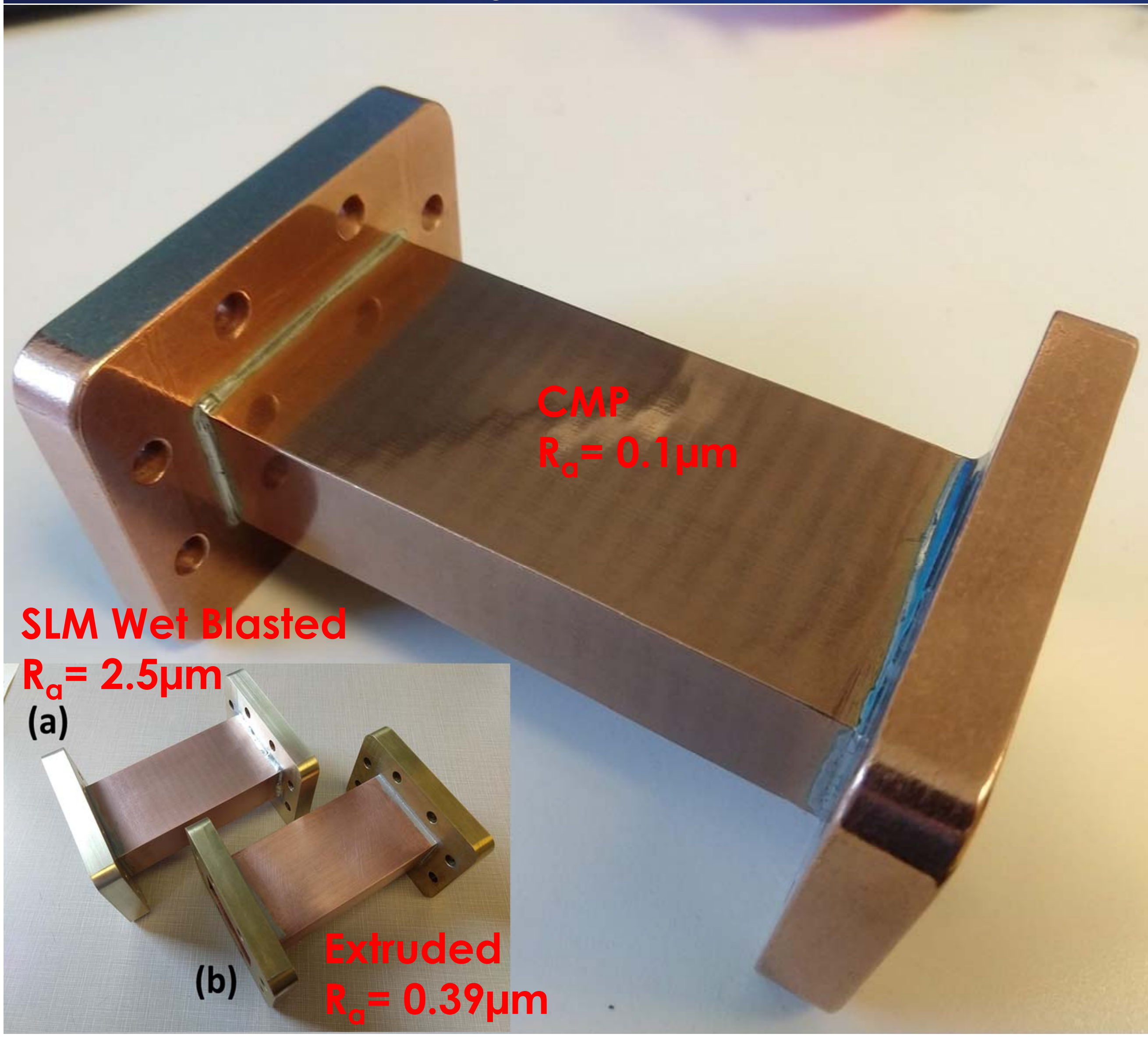


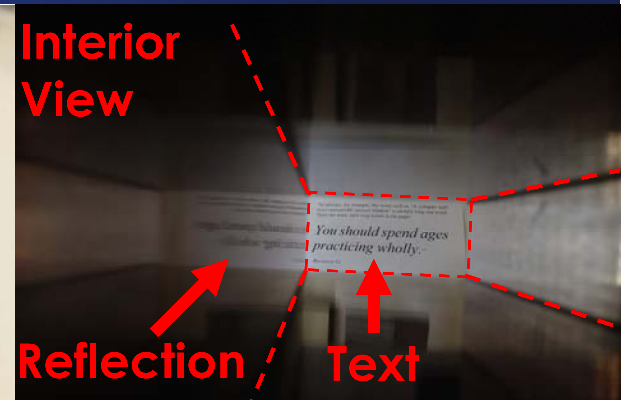


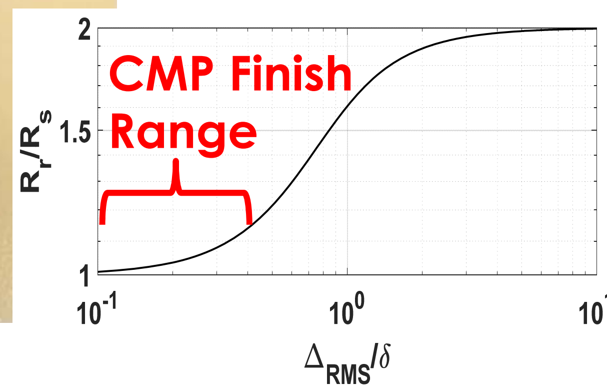




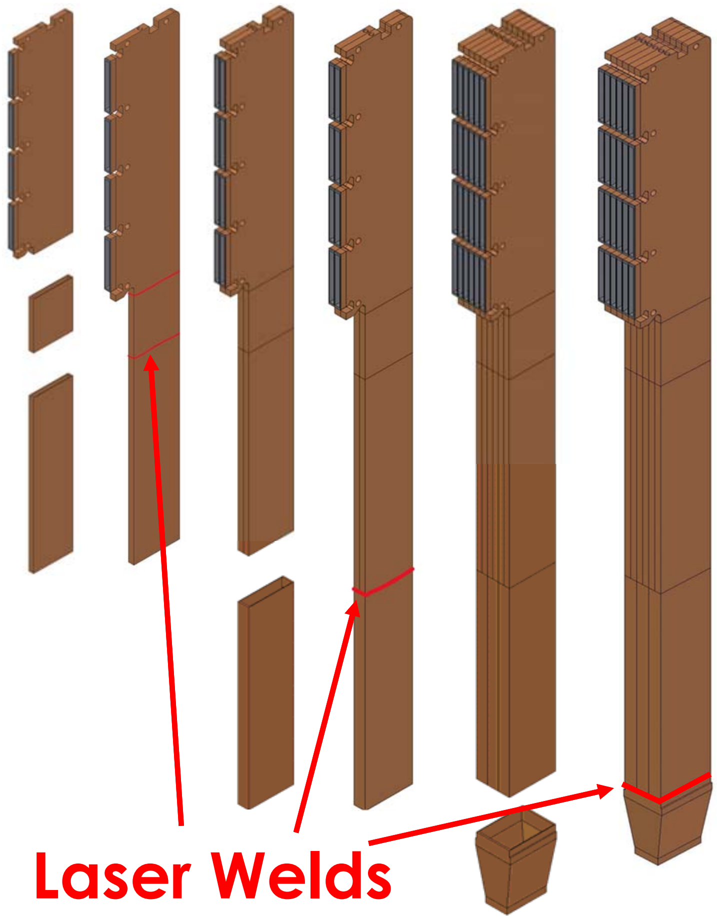
Chemical-Mechanical Polishing Can Achieve R_a=0.1 μm, a Mirror Finish

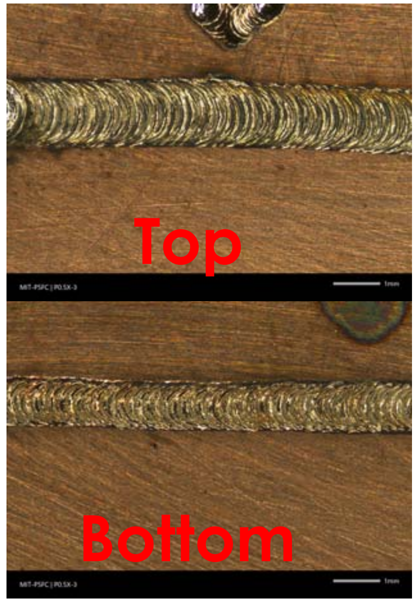


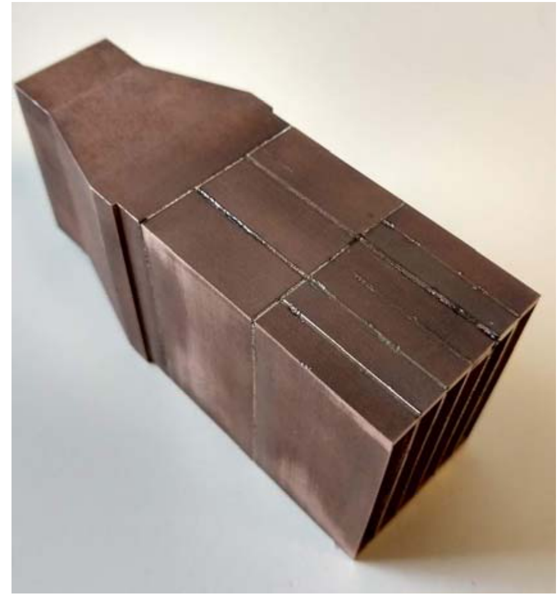




Build Volume Limitations Requires Separate AM of Launcher Sections and Subsequent Laser Welding



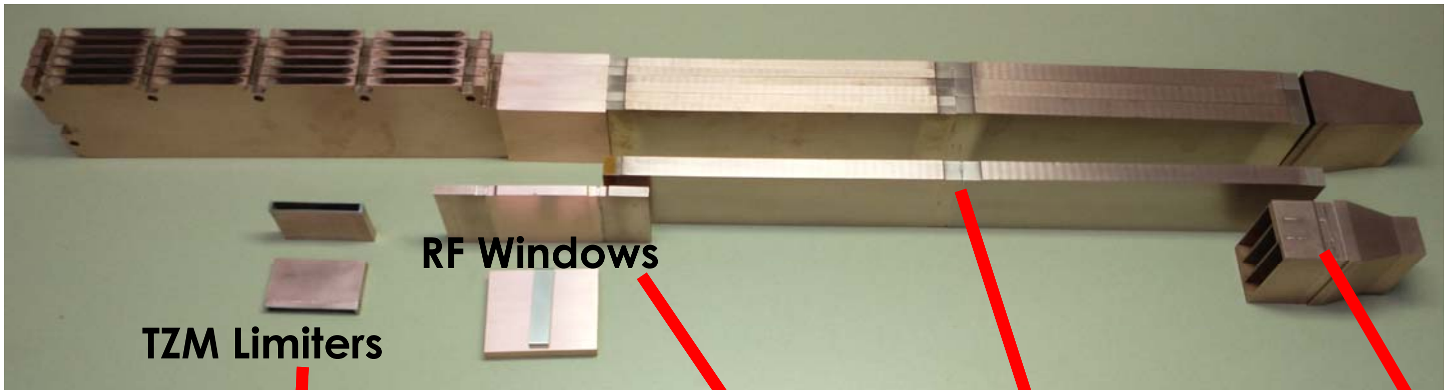




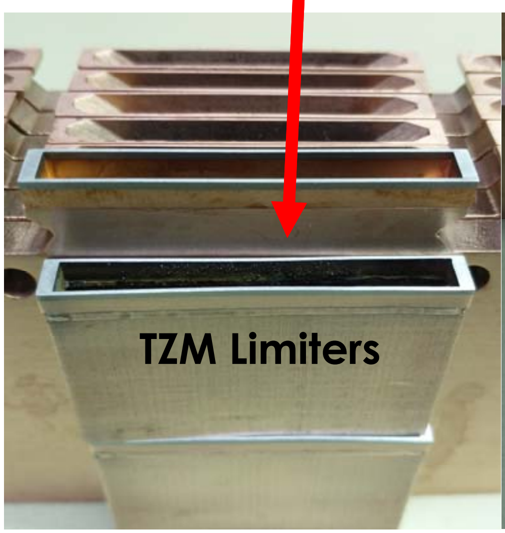
- **Full penetration laser welds**
- **Smooth bottom surface**
- **Tensile Testing: 450 MPa UTS**

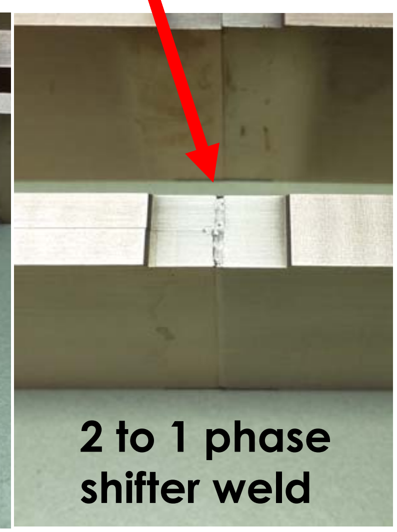
Seltzman, Andrew H., and Stephen J. Wukitch. "Brazing, Laser, and Electron-Beam Welding of Additively Manufactured GRCop-84 Copper for Phased Array Lower Hybrid Launchers." ***IEEE Transactions on Plasma Science*** **(2020).**

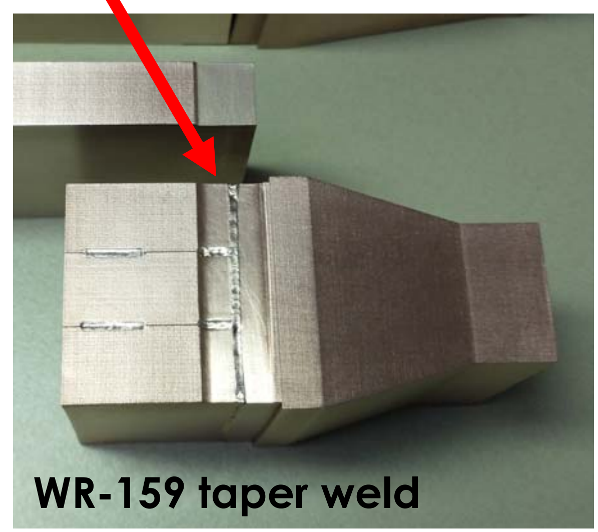
All Weld Types Verified Feasible for Production



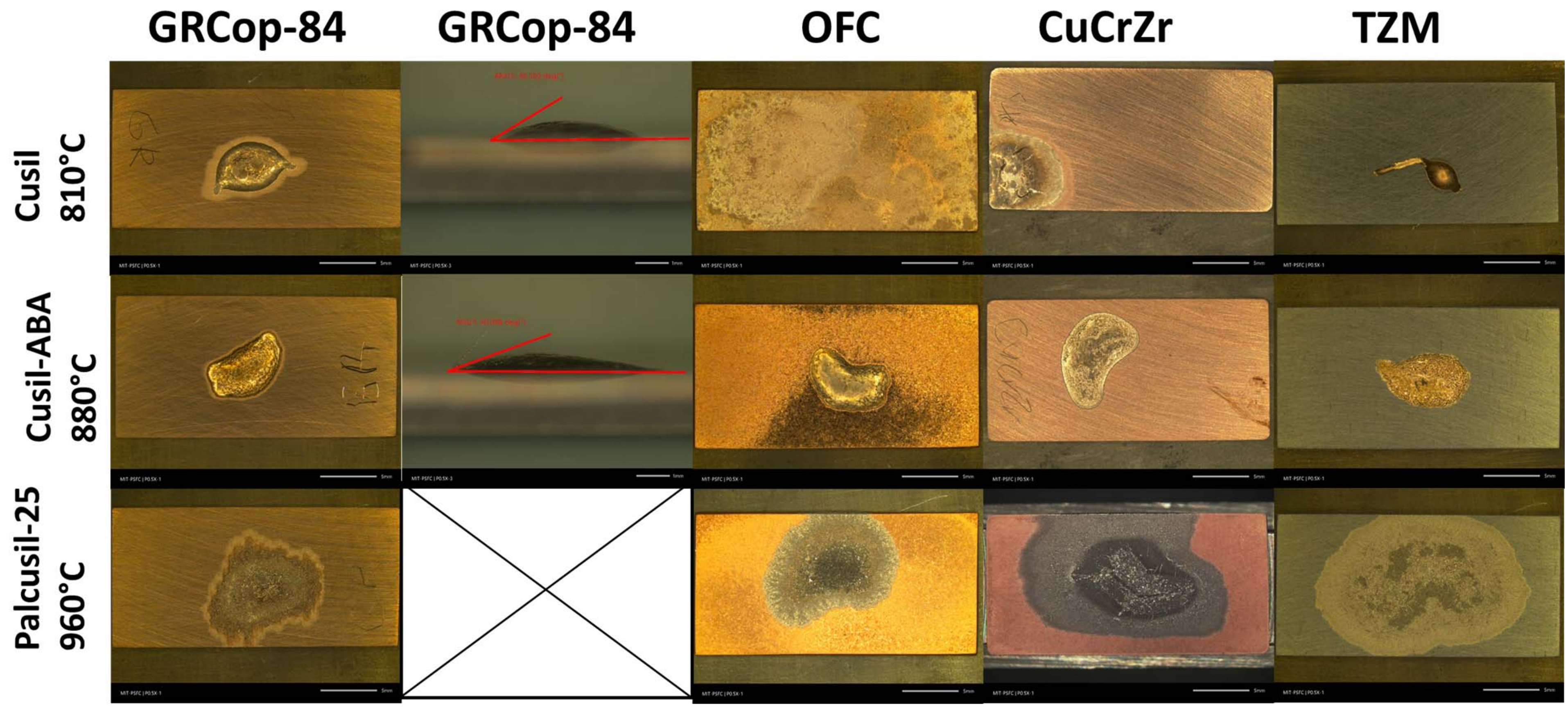
45 Total Welds







Braze of GRCop-84 to TZM Limiters Possible With Active Brazes, Wetting Similar to CuCrZr

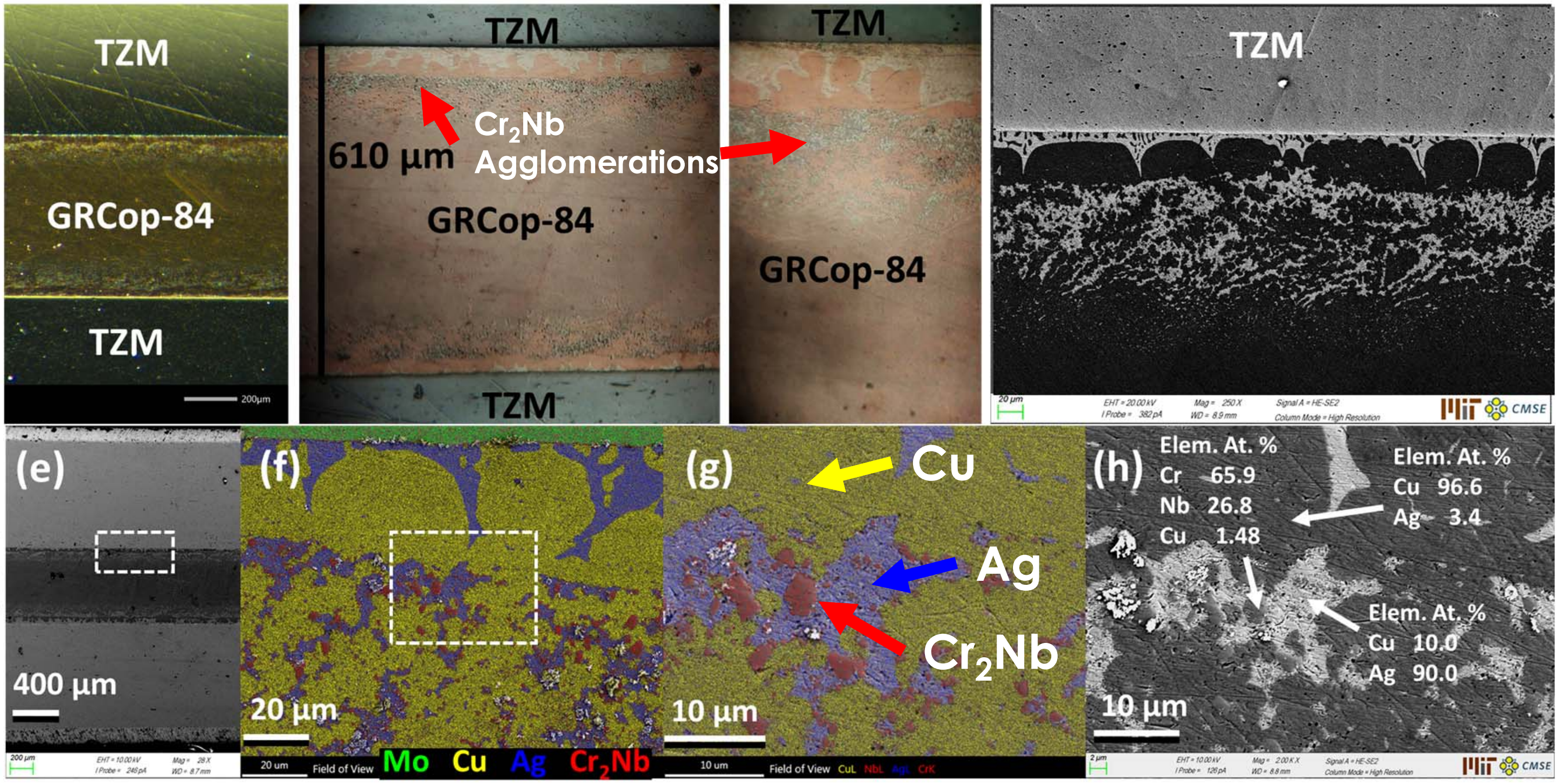


Can braze GRCop-84 to TZM limiter on plasma facing components

Cr_2Nb Depleted from Copper Matrix and Agglomerate Within Silver Infiltrates During Braze

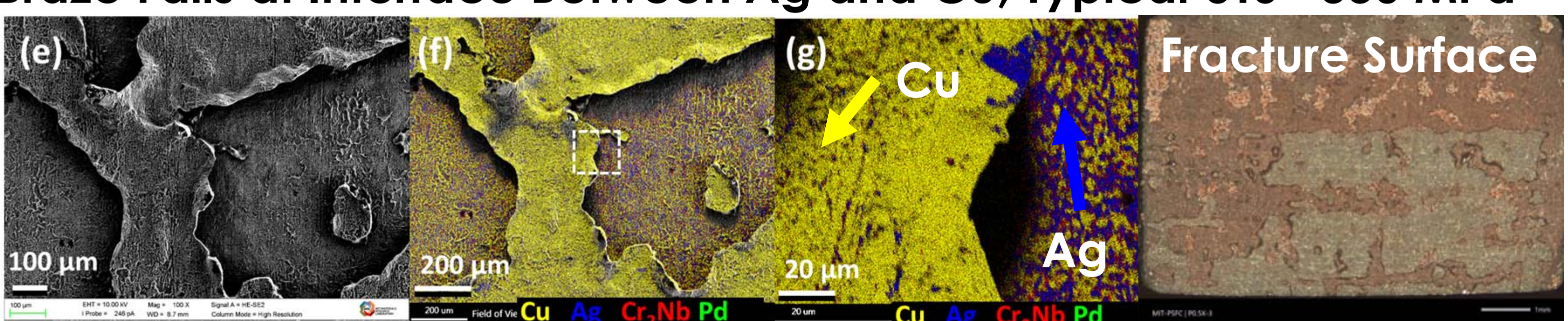
Cusil-ABA 880°C

Cusi-ABA 880°C



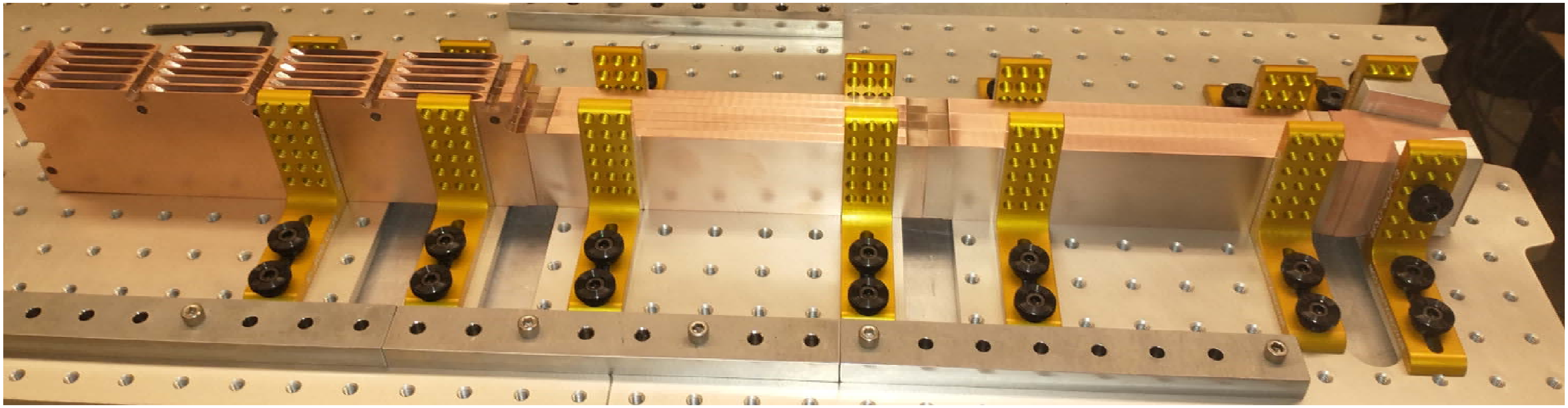
Braze Fails at Interface Between Ag and Cu, Typical UTS ~330 MPa

Cusi-ABA 880°C



Additive Manufacturing of GRCop-84 Enables HFS LHCD Launcher and Future Fusion Engineering

- HFS launch improves CD efficiency and reduces heat flux
- GRCop-84 has excellent AM properties to allow monolithic fabrication of complex RF structures and retains strength after high temp bakeout
- Chemical mechanical polishing of surface for low RF loss
- Launcher assembly to complete in 2021



Work supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences, using User Facility DIII-D, under Award No. DE-FC02-04ER54698 and by US DoE Contract No. DE-SC0018090 under a Scientific Discovery through Advanced Computing Initiative.

MIT | PSFC Plasma Science and Fusion Center

Our Papers on the AM HFS Launcher

- Seltzman, A. H., et al. "A high field side multijunction launcher with aperture impedance matching for lower hybrid current drive in DIII-D advanced tokamak plasmas." *Nuclear Fusion* 59.9 (2019): 096003.
- Seltzman, A. H., et al. "Aperture impedance matching for lower hybrid current drive launchers." *AIP Conference Proceedings*. Vol. 2254. No. 1. AIP Publishing LLC, 2020.
- Seltzman, A. H., and S. Wukitch. "Precision measurement of relative permittivity of aluminum oxide for a high power resonant waveguide window with low return loss." *Fusion Engineering and Design* 147 (2019): 111226.
- Seltzman, Andrew H., and Stephen J. Wukitch. "Brazing, Laser, and Electron-Beam Welding of Additively Manufactured GRCop-84 Copper for Phased Array Lower Hybrid Launchers." *IEEE Trans. on Plasma Science* (2020).
- Seltzman, A. H., and S. J. Wukitch. "Nuclear response of additive manufactured GRCop-84 copper for use in Lower hybrid launchers in a fusion environment." *Fusion Engineering and Design* 159 (2020): 111726.
- Seltzman, A. H., and S. J. Wukitch. "RF losses in selective laser melted GRCop-84 copper waveguide for an additively manufactured lower hybrid current drive launcher." *Fusion Engineering and Design* 159 (2020): 111762.
- Seltzman, A. H., and S. J. Wukitch. "Surface roughness and finishing techniques in selective laser melted GRCop-84 copper for an additive manufactured lower hybrid current drive launcher." *Fusion Engineering and Design* 160 (2020): 111801.
- Seltzman, A.H., Wukitch, S.J., "Precipitate Size in GRCop-84 Gas Atomized Powder and Laser Powder Bed Fusion Additively Manufactured Material" Fusion Sci. & Tech. In Press (2021)
- Seltzman, A. H., and S. J. Wukitch. "Fracture Characteristics and Heat Treatment of Laser Powder Bed Fusion Additively Manufactured GRCop-84 Copper." *Mat. Sci. & Eng: A, Under Review (2021)*
- Seltzman, A. H., and S. J. Wukitch. "Resolution and Geometric Limitations in Laser Powder Bed Fusion Additively Manufactured GRCop-84 Structures for a Lower Hybrid Current Drive Launcher." *Fusion Engineering and Design, Under Review (2021)*