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

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

- HFS launch @ 4.6GHz and $n_{\parallel}=-2.7$ 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 $n_{\parallel}$
  - 140kA current drive per MW coupled
  - Peaked off axis $\rho \sim 0.6-0.8$. (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 9.3 kV/cm at 4.6 GHz
- Traveling wave poloidal splitter reduces $|E|$ by 20% compared to a standing wave divider

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

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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.

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/m²)

- Cr₂Nb 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

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

- Cusing M2 LPBF Printer
- Gas atomized GRCop-84 powder

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

Example printing process:

- 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

Courtesy of GE additive
**GRCop-84 Powder Consolidation with Laser Powder Bed Fusion (LPBF) AM Reduces Precipitate Size**


- LPBF results in reduction of precipitate size ($\mu=95\text{nm}$, $\sigma=30\text{nm}$)
- Increased Orowan strength compared to HIPping or extrusion from powder
Heat Treatment of AM GRCop-84 Controls Precipitate Size and Tensile Properties

As Printed
- Yield=500 MPa
- UTS=740 MPa
- No coarsening of precipitates at 450C
- Coarsening saturated at 900C

450C 3h
- Yield=790 MPa
- UTS=970 MPa
- 200MPa required for disruption loads

900C 5 hour
- Yield=300 MPa
- UTS=520 MPa
- OFC: 50MPa yield after 400C bake in DIII-D
- GRCop-84: 300MPa yield after 900C 5h heat treat

Cr$_2$Nb Precipitate Fracture Under Tensile Stress Nucleates Voids Leading To Failure Of AM GRCop-84

- GRCop-84 fracture typical of ductile rupture
- Additive manufactured material much stronger than extruded or HIPed
- Cr$_2$Nb precipitate fracture nucleates voids
- Voids grow from fractured precipitate and coalesce leading to material failure
- Cr$_2$Nb fragments located near cusp center
- Fragment geometry matches on opposing sides
- Cr$_2$Nb Fragments appear in both opposing cusps
- >80% of cusps populated with a Cr$_2$Nb Fragment

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

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

- 3x launchers per plate
- ~2 weeks build time
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
30μm pk-pk Surface Ripple Present in AM GRCop-84 Parts Does Not Prevent RF Use at 4.6 GHz

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-pk Surface ripple)
- Print thicker walls, then EDM cut to required 0.5mm thickness

EDM cut sidewalls to 0.5mm
Batch of EDM cut phase shifters
Surface Roughness Induced RF Losses Requires Further Internal Polishing Step on AM Material

As Printed Surface $R_q=4.1 \mu m$

OFC Waveguide $R_q=0.48 \mu m$

- Ratio of RF loss increase compared to zero roughness surface related to ratio of RMS surface roughness ($\Delta_{RMS}=R_q$) to skin depth ($\delta$)
- At 4.6 GHz, skin depth $\delta_s=1 \mu m$ in copper
- $R_q=0.3-0.4 \mu m$ required to minimize loss


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

As printed
Polished
As printed
Polished

As Printed $R_q=4.1 \text{ \mu m}$
CMP $R_q=0.4 \text{ \mu m}$

(1) Rough surface
(2) Resist layer
(3) Mechanical Resist Removal
(4) Chemical Etch

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Chemical-Mechanical Polishing Can Achieve $R_a = 0.1 \mu m$, a Mirror Finish

- CMP: $R_a = 0.1 \mu m$
- SLM Wet Blasted: $R_a = 2.5 \mu m$
- Extruded: $R_a = 0.39 \mu m$

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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

All Weld Types Verified Feasible for Production

Poloidal Splitter
6x Phase Shifter
3x Phase Shifter
RF Windows

45 Total Welds

TZM Limiters
RF Windows

WR-159 taper weld
2 to 1 phase shifter weld

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

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<th>GRCop-84</th>
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Can braze GRCop-84 to TZM limiter on plasma facing components
Cr$_2$Nb Depleted from Copper Matrix and Agglomerate Within Silver Infiltrates During Braze
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

Our Papers on the AM HFS Launcher


