

[REGULAR POSTER TWIN] Additive Manufacturing of a High Field Side Tokamak Lower Hybrid Current Drive Launcher from GRCop-84

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We present a High Field Side (HFS) Lower Hybrid Current Drive (LHCD) launcher for DIII-D (1) to validate HFS launch scenarios, Figure 1 (a), incorporating a novel traveling-wave power divider and aperture impedance matching structure for good coupling over a wide range of edge density conditions, produced with additive manufacturing from Glen Research Copper 84 (GRCop-84) a high strength, high conductivity copper alloy with resistance to swelling at high DPA. HFS LHCD is a key enabling technology for a steady state tokamak reactor, where inward particle drifts reduce plasma-material interaction (PMI) for launcher longevity, while the favorable magnetic profile allows lower $n_{||}$ resulting in higher efficiency current drive with single-pass damping at increased penetration depth. No emission of molybdenum lines from the plasma core were detected under any operating condition or direct NBI strikes with a molybdenum HFS grill mockup, (b), and no post-run damage to the molybdenum grill mockup was observed.

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Electric field is reduced below the multipactor arcing threshold of 9.3 kV/cm by a traveling wave power divider, and an aperture impedance matching structure (2) within each launcher aperture. A thin inductive tuning element near the plasma surface tunes aperture impedance to match plasma surface impedance, resulting in low circulating power within the launcher, Figure 1 (c). The matching element allows tuning the region of lowest circulating power, simulated as $|E|$, (d), to match plasma conditions, estimated to be $n_0=3 \times 10^{17} \text{ m}^{-3}$ in a DIII-D advanced tokamak discharge. Simulations of an HFS multijunction launcher with aperture impedance matching in COMSOL, Petra-M, and ALOHA shows acceptable edge densities between $n_e=8 \times 10^{16}$ to 1×10^{18} and return loss as low as -34 dB. GENRAY simulations show single pass damping of a 4.6 GHz LH wave at a $n_{||}=-2.7$ launch at $r/a=0.6-0.8$ (e) with a current drive efficiency of 140 kA/MW.

Selective laser melting (SLM) 3D printing allows rapid construction of RF launcher structures at full density without a subsequent hot isostatic pressing step to achieve vacuum compatibility, Figure 2 (a), in configurations not possible with conventional machining out of materials with superior mechanical properties. SLM printed GRCop-84 has a UTS of 720 MPa, increasing to 780 MPa after a 600°C stress relief and 2 hour heat treat at 450°C, exceeding CuCrZr (560 MPa) and Glidcop AL-15 (460 MPa), allowing better tolerance of disruption loads while tolerance of high temperature excursions to 800°C for extended durations without loss of strength allows exposure to transient heat loads that cause permanent degradation to CuCrZr. Stability of the Cr₂Nb precipitates results in modest reduction in tensile strength to 520 MPa after a 5 hour exposure to 900°C (d).

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Brazing, laser, and electron beam welding of GRCop-84 produce favorable joining results (3). Brazing of GRCop-84 is similar to CuCrZr (e), and direct brazing to TZM limiters with active brazing alloys is possible. Launcher components are assembled (b) with laser or e-beam welding processes; precipitate structure is maintained during pulsed laser and electron beam welding (f). GRCop-84 laser welds exceptionally well due to higher absorption of 1060 nm wavelength in comparison to OFC.

Surface roughness that dominates RF loss in SLM printed GRCop-84 waveguide is addressed with mass finishing and polishing (c). As printed roughness of $R_a=3.4 \mu\text{m}$ is reduced to $R_a=0.025 \mu\text{m}$ when polished with 6 μm diamond. Chemo-mechanical polishing reduces surface roughness to $R_a=0.17 \mu\text{m}$ and can reach interior surfaces that are not physically accessible to mechanical polishing allowing launchers to be printed as a monolithic unit.

Grain and precipitate size in SLM printed GRCop-84 is similar to existing alloys with low swelling and reduction in conductivity (CuCrZr, Glidcop, MZC) at high DPA predicts good tolerance to neutron exposure. Irradiation with 5 MeV Cu ions to 20 DPA at 430°C results in no observable void formation at the deposition location (g). Transient Gradient (TG) spectroscopy provides measurement of thermal conductivity of as-printed and irradiated material.

Development of SLM 3D printing of GRCop-84 for fusion power applications is an emerging technology with the capability to improve LHCD launcher designs and may be extended to first wall, divertor, and RF source components.

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