Novel Radio Frequency Current Drive Systems for Fusion Plasma Sustainment on DIII-D

by
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Most steady-state reactor concepts require off-axis non-inductive current drive to supplement bootstrap current. Efficiency is critical for current drive in a reactor to keep recirculating power down.

New CD actuators needed to meet all requirements:
- Off-axis
- High efficiency
- Survivability/lifetime

Two novel RF current drive actuators under development at DIII-D:
- 4.6 GHz high field side (HFS) launch lower hybrid current drive (LHCD)
  - Optimized at higher B and lower $n_e$
- 476 MHz “helicon” or fast lower hybrid wave
  - Optimized at higher $n_e$ and lower B
Two Novel RF Current Drive Actuators Under Development at DIII-D: HFS LHCD and Helicon

4.6 GHz HFS LHCD antenna located on inner wall at ~20° toroidal angle

476 MHz LFS Helicon antenna located at ~180° toroidal angle
HFS launch improves well established LH wave physics\textsuperscript{1}

- Lower $n_{||}$ for higher current drive efficiency
- Better wave penetration
  - Access to inside pedestal in reactor
  - HFS SOL characteristics extend antenna longevity
- Lower heat, neutron, and particle fluxes
- Fewer unconfined fast ion orbits
- Better impurity screening

Engineering challenges to fit HFS antenna in existing tokamak designs;
more available real estate in a clean slate reactor

\textsuperscript{1}Bonoli, et al, Nuc. Fus. [2018]
High field side lower hybrid current drive (HFS LHCD) offers potential efficient off axis current drive.

HFS LHCD has good wave penetration and single pass absorption.

Drives current off axis at 0.6<r<0.8.

For high $q_{\text{min}}$ discharges, simulations indicate 143 kA/MW coupled, 0.4 MA/m$^2$ at $r/a \sim 0.7$.

Excellent Wave Penetration and Efficiency are Predicted for HFS LHCD on DIII-D.
Coupling of LH waves to plasma requires edge density ~ $10^{18}$ m$^{-3}$

Smaller than typical plasma-inner wall gap

2.5 cm thicker inner wall tiles needed for HFS LHRF

Observed only subtle impacts of inner gap on confinement & stability
Mock-up is located same vertical position as planned coupler but at ~300° toroidally vs ~20°

Molybdenum (TZM alloy) dummy waveguides
TZM structure recessed ~1 mm behind carbon protection limiters

Demonstrated that the HFS LHCD coupler will not interfere with general DIII-D operations

Negligible molybdenum source from HFS antenna mockup
No impact on plasma performance
Real Estate is Limited on HFS Wall; Antenna Must be Compact in Radial Dimension

Antenna here

Feed waveguide
Multijunction (MJ) concept proven on many tokamaks (Tore Supra, JET, FTU, EAST)

- Self-matching characteristics reduce reflected power towards transmitter
- Conventionally oriented radially in LFS port

T-junction (TJ) poloidal splitter

- Similar to successful LH2 antenna on C-Mod
- Also tested at low power on COMPASS

Combine two concepts in series

- Low reflection coef.
- Compact radial build
- Toroidal & poloidal split
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Combine two concepts in series
Low reflection coef.
Compact radial build
Toroidal & poloidal split
Antenna RF Simulations Predict Good Directivity and Coupling at Edge Density ~ 0.3-1x10^{18} m^{-3}

4 rows X 6 columns per MJ/TJ module
Eight MJ/SWA modules launch wave at n_|| = 2.7
Low reflected power (Γ^2 < 1%) and high directivity (>60%)
Antenna will Employ Additive Manufacturing (3D printing)

3D printing of copper alloy (GRCo-84) for major multijunction and T-junction components

- Excellent conductivity, heat tolerance, and strength
- Able to manufacture complicated geometries
- At lower cost vs CNC

Molybdenum (TZM alloy) for plasma facing grills
Graphite for protection tiles
Installation of full power antenna in DIII-D in 2020
“Helicon” (in this context) is a fast magnetosonic wave in the LHRF

Relatively weak damping allows for penetration to mid-radius in a reactor

55 kA/MW coupled power, 0.1 MA/m² at r/a ~ 0.5 in DIII-D
Low Power Helicon Antenna Tested in DIII-D
Goal: First Experimental Verification for Helicon Current Drive

Electron pressure not high enough for single pass absorption in previous tests on other tokamaks. High $\beta_e$ discharges on DIII-D will have strong single pass damping at mid-radius → good current drive efficiency.
Feedthrus and striplines at each end allow operation in In configuration
30 mutually coupled antenna modules mounted on water-cooled back plates

1.2 MW klystron from SLAC provides power to antenna
Testing at DIII-D Evaluates High Power Antenna Design

Quarter and half-length helicon antenna modules used for 6 kW power testing, validating full design now being manufactured with ASIPP

Tests performed:
- Module losses (quality factor)
- Voltage standoff with B-field in vacuum
- Multipactor and discharge cleaning

Expt. Module Setup
Coupling Loop
Capacitive probe measures $V$ in gap
Quarter Module

One Antenna Module
Design finalized for full power (1 MW at 476 MHz) antenna
Manufacturing through collaboration between GA and ASIPP
Installation of antenna during “long torus opening” period prior to upcoming run campaign
HFS LHCD and Helicon offer promise of efficient, off-axis RF current drive for DIII-D and future tokamak reactors

LHCD: 0.4 MA/m² at r/a ~ 0.7, 143 kA/MW

Helicon: 0.1 MA/m² at r/a ~ 0.5, 55 kA/MW

Installation of Helicon antenna in 2019

Installation of HFS LHCD antenna in 2020
Single Klystron Provides 1.2 MW at 476 MHz

- Klystron and associated hardware provided by SLAC
- Beam power provided by 2 MW, 80 kV high voltage power supply
- Snubber and circulator protect klystron from faults
Multi MW Source Power at 4.6 GHz for DIII-D HFS LHCD

- $f_0 = 4.6 \text{ GHz}$
- $P_{RF} = 0.25 \text{ MW/klystron}$
- Gain = 55 dB
- $V_b = 46.5 \text{ kV}$
- $I_b = 13 \text{ A}$
- Efficiency = 41%
- 8 klystrons to be located adjacent to DIII-D cell $\Rightarrow 2 \text{ MW source}$
- Thales/Ampegon HVPS to be installed in high voltage yard outside DIII-D building
- Power systems and antenna designed for 5 s full power pulses at 1% duty cycle
Post-run Inspection of Mockup: Excellent Condition
Mock-up carbon tiles have had strong plasma-material interaction

- Visible and IR camera confirm protection tiles were significantly heated during inner wall limited discharges
Two Novel RF Current Drive Actuators Under Development at DIII-D

- DIII-D uses NBI and ECCD with considerable success at $r/a < 0.5$
- Strong bootstrap current in edge region due to $\nabla p$
- Need actuator in off-axis region around $0.6 < r/a < 0.8$

- Two novel RF current drive actuators under development at DIII-D have the potential to fill this hole:
  - High field side (HFS) launch lower hybrid current drive (LHCD)
    - Optimized at higher $B$ and lower $n_e$
    - “Helicon” or fast lower hybrid wave
    - Optimized at higher $n_e$ and lower $B$

Optimum Current Profile is Peaked Off Axis
Adapted from ARIES-AC
T1Kessel et al., FST 67, 2015.
Adapted from C. Holcomb PAC 2017.