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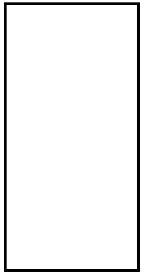

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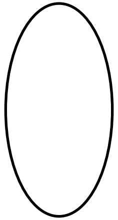


# Novel Radio Frequency Current Drive Systems for Fusion Plasma Sustainment on DIII-D

by

**G.M. Wallace**

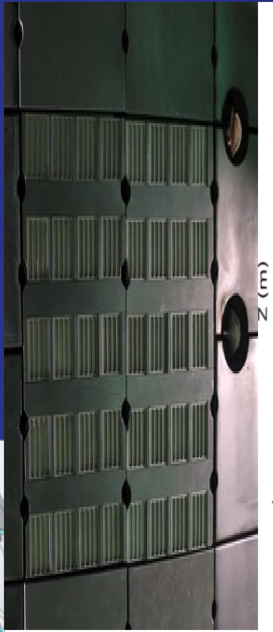
(MIT PSFC)

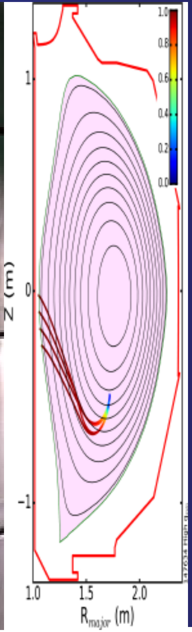
Presented at

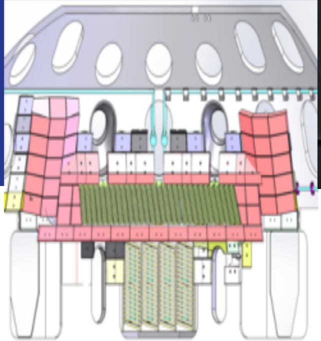
2018 IAEA Fusion Energy Conference

Ahmedabad, Gujarat, India

October 25, 2018







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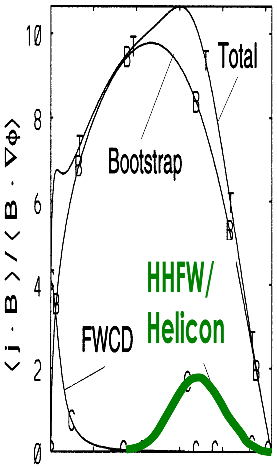
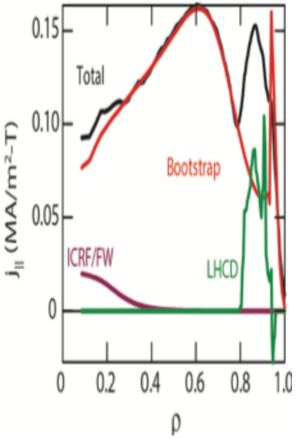
# Efficient, Reliable, Off-axis Current Drive is Required on Future Tokamak Reactors; Better Actuators are Needed

- **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



Adapted from ARIES-RS
Najmabadi et al., FED **38**, 1997.



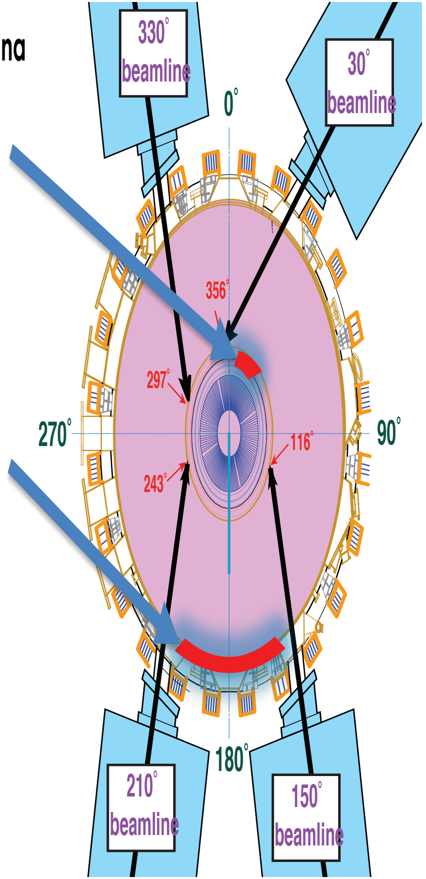
Adapted from ARIES-ACT1
Kessel et al., FST **67**, 2015.

# Two Novel RF Current Drive Actuators Under Development at DIII-D: HFS LHCD and Helicon

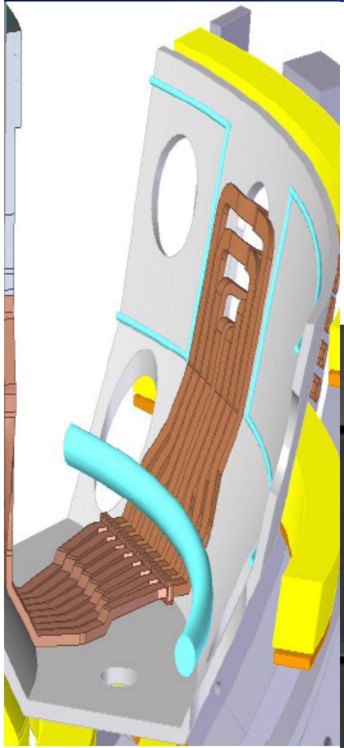
**4.6 GHz HFS LHCD antenna located on inner wall at ~20° toroidal angle**

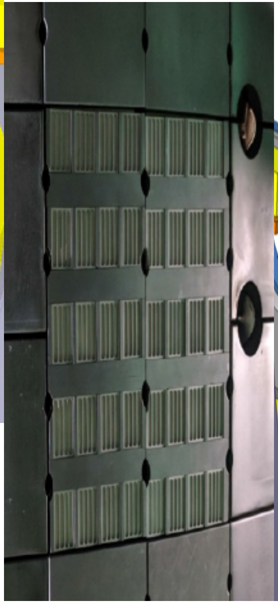
**476 MHz LFS Helicon antenna located at ~180° toroidal angle**

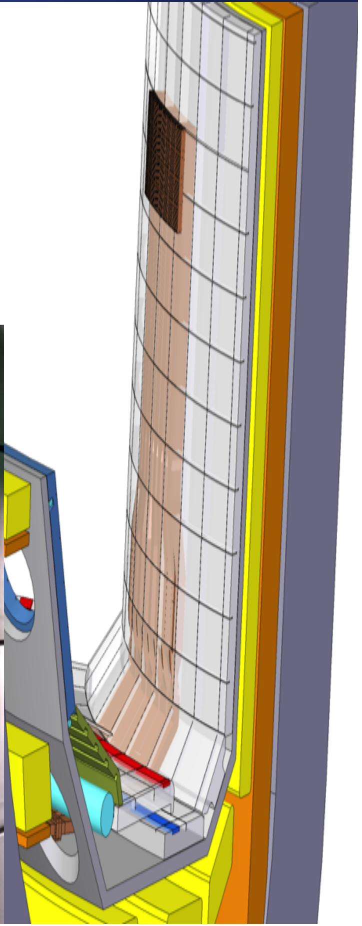
Top-down view of DIII-D



# High Field Side Launch LHCD





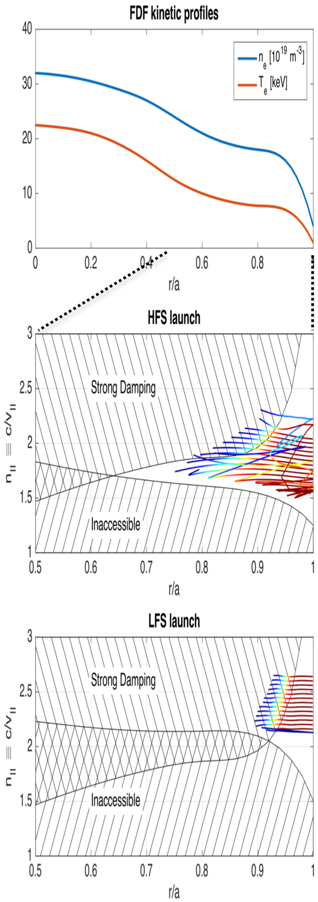


# HFS Launch of LH Waves Improves Current Drive Efficiency, Antenna Longevity, and Tritium Breeding

- **HFS launch *improves* well established LH wave physics[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

Also applies to other HFS RF actuators

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



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[1] Bonoli, et al, Nuc. Fus. (2018)

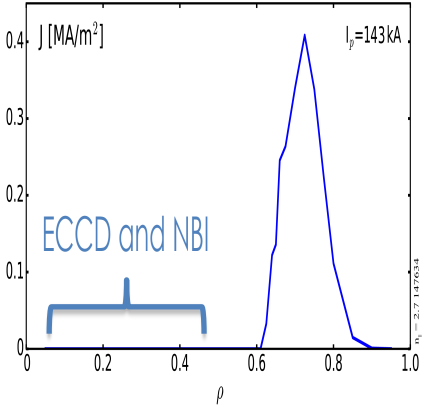
# Excellent Wave Penetration and Efficiency are Predicted for HFS LHCD on DIII-D

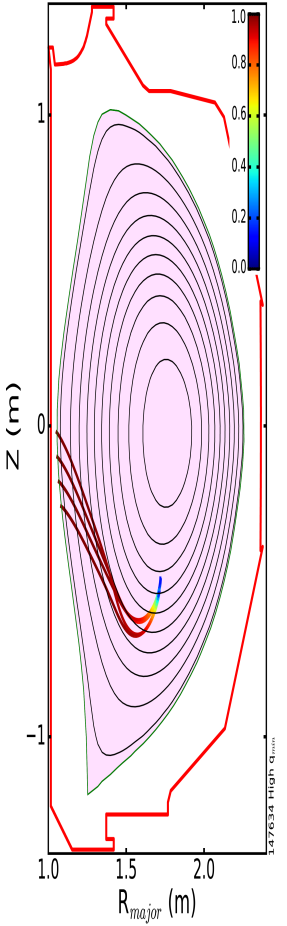
High field side lower hybrid current drive (HFS LHCD) offers potential efficient off axis current drive

HFS LHCD has good wave penetration and single pass absorption

Drives current off axis at 0.6<r<0.8

For high $q_{min}$ discharges, simulations indicate 143 kA/MW coupled, 0.4 MA/m² at r/a ~ 0.7





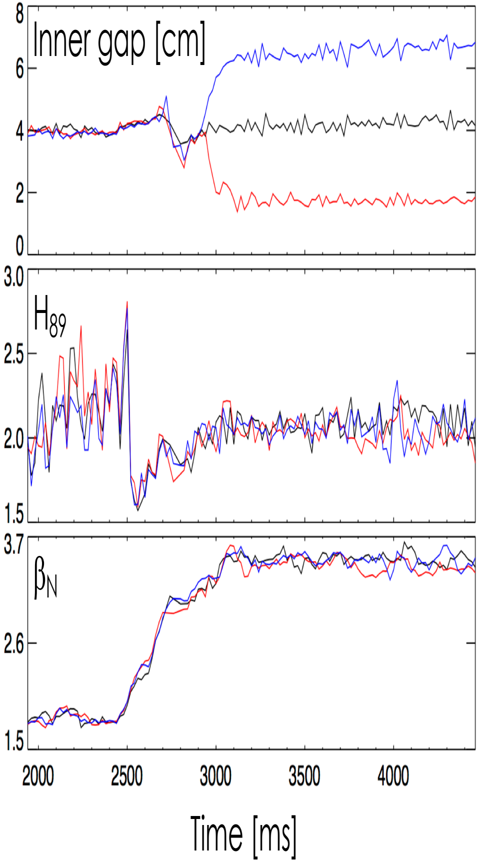
# Experiments Show that Geometry Changes Needed for HFS LHCD have Minor Impact on Plasma Performance

**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**

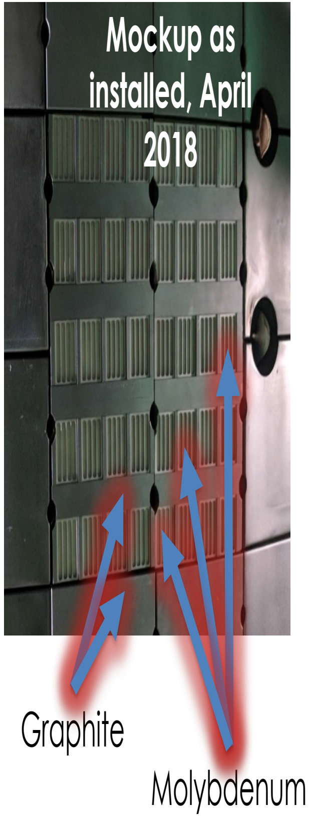
**Observed only subtle impacts of inner gap on confinement & stability**



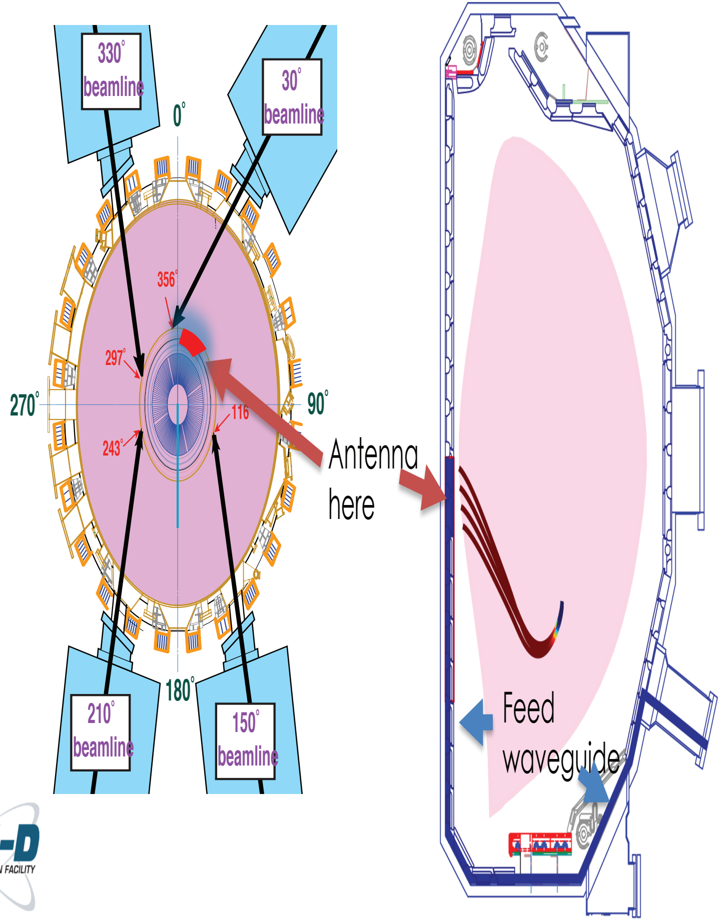
# Mockup Antenna Installed and Operated in DIII-D to Assess Impact of High-Z Materials on the Center Post

- **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


Mockup as installed, April 2018

# Real Estate is Limited on HFS Wall; Antenna Must be Compact in Radial Dimension



Antenna here

Feed waveguide

# Antenna Design Based on Toroidal Multijunction + Poloidal T-junction Waveguide Antenna

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

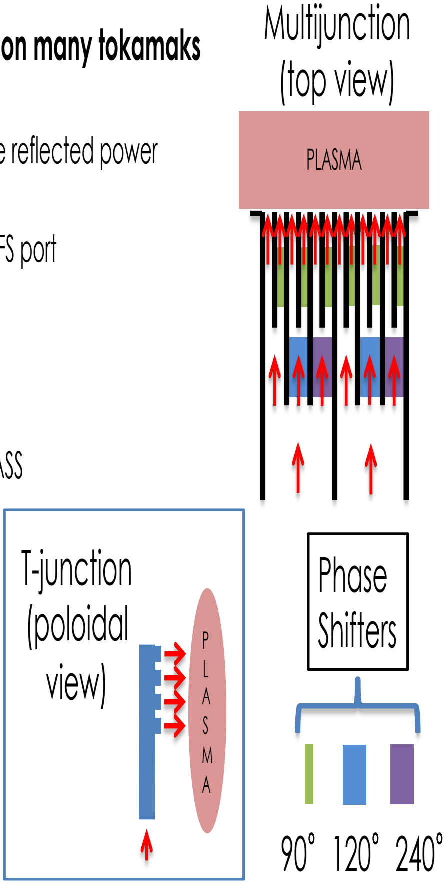
- Self-matching characteristics reduce reflected power towards transmitter
- Conventionally oriented radially in LFS port

**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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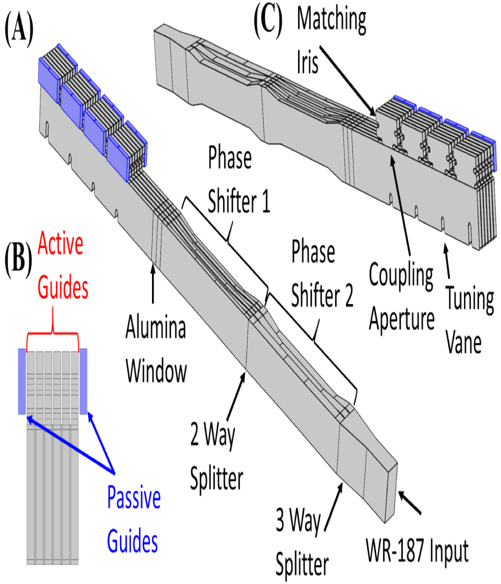
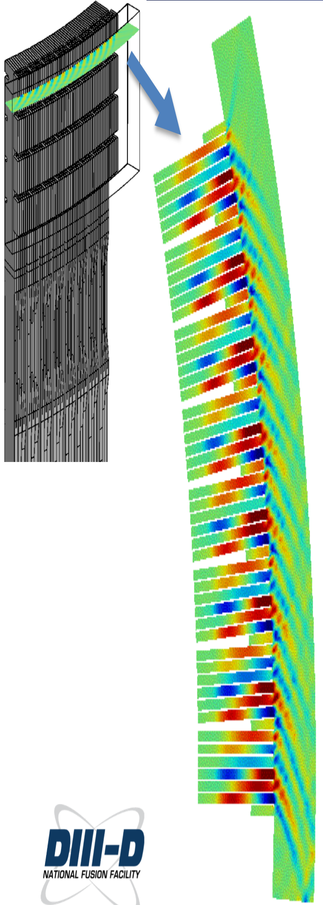


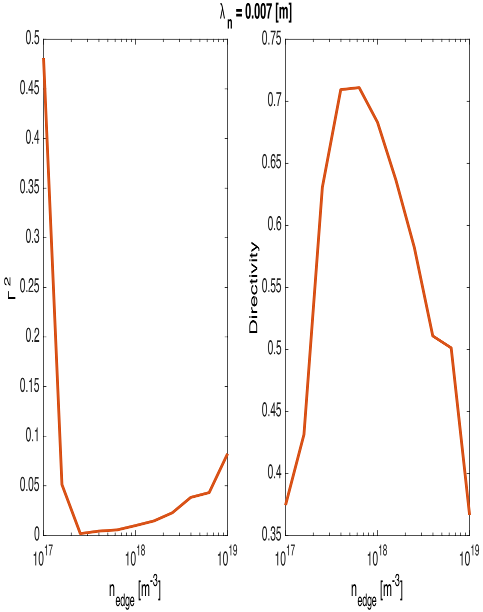
# Antenna RF Simulations Predict Good Directivity and Coupling at Edge Density ~ $0.3\text{-}1\times10^{18}\ \mathrm{m^{-3}}$



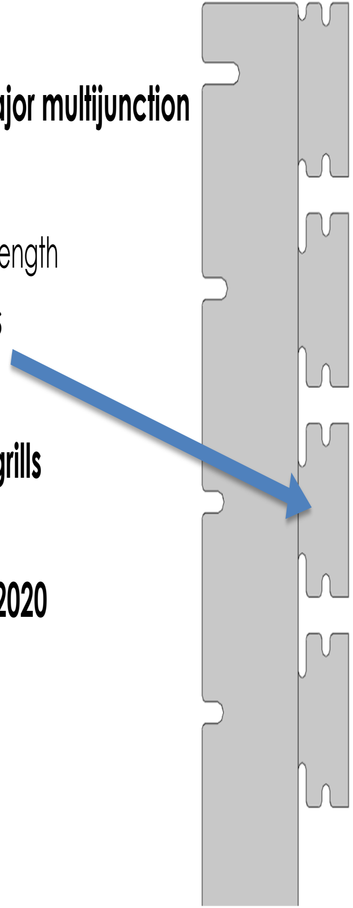
4 rows X 6 columns per MJ/TJ module

Eight MJ/SWA modules launch wave at $n_{||} = 2.7$

Low reflected power ($\Gamma^2 < 1\%$) and high directivity (>60%)



# Antenna will Employ Additive Manufacturing (3D printing)



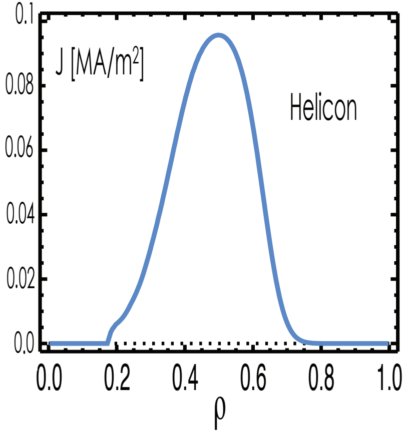
- **3D printing of copper alloy (GRCo-84) for major multijunction and T-junction components**
  - Excellent conductivity, heat tolerance, and strength
  - Able to manufacture complicated geometries at lower cost vs CNC
- **Molybdenum (TZM alloy) for plasma facing grills**
- **Graphite for protection tiles**
- **Installation of full power antenna in DIII-D in 2020**

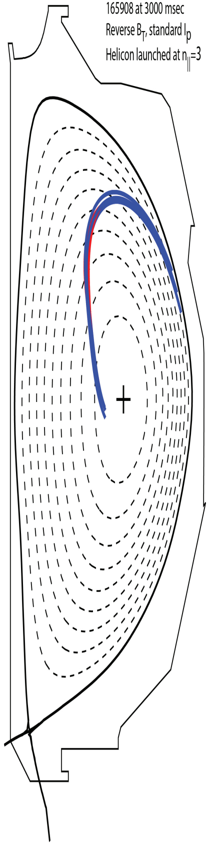
# Physics Basis for Helicon Project

"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



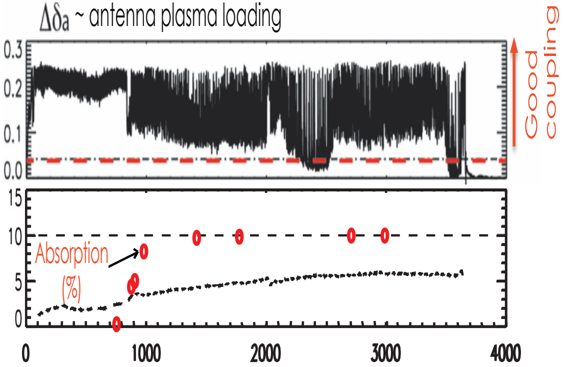


# Low Power Helicon Antenna Tested in DIII-D

# 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

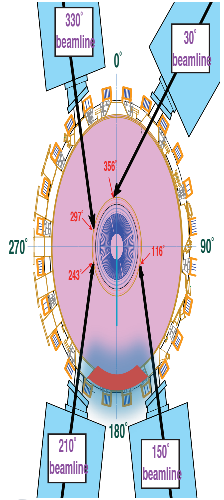


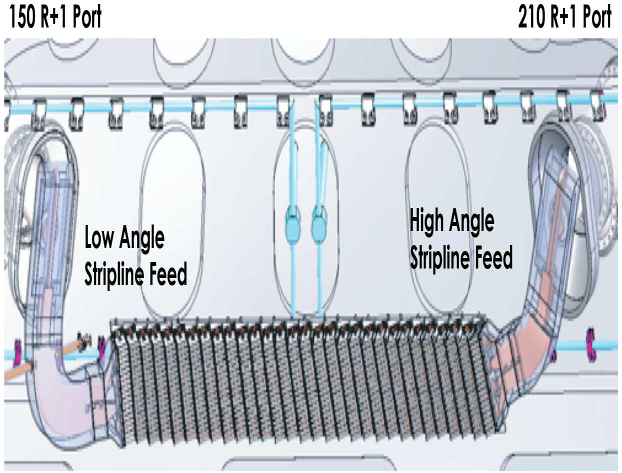
# “Comb-line” Traveling Wave Antenna Launches Fast Wave at 476 MHz

Feedthrus and striplines at each end allow operation in ± $I_p$ configuration

30 mutually coupled antenna modules mounted on water-cooled back plates

1.2 MW klystron from SLAC provides power to antenna



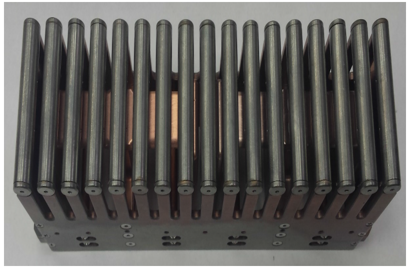


30 Module, 1MW Comb-line Antenna

# 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**

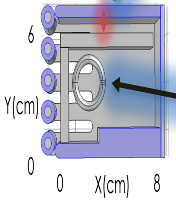
**One Antenna Module**



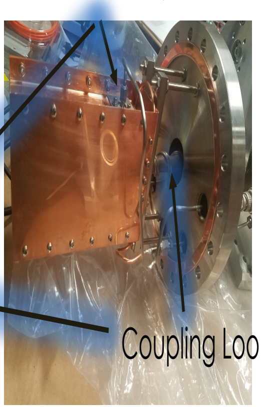
**Tests performed:**

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

Capacitive probe measures $\vec{!}$ in gap



**Quarter Module**



Coupling Loop

**Expt. Module Setup**

# Helicon Antenna Under Construction; Installation in 2019 for Upcoming Run Campaign

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

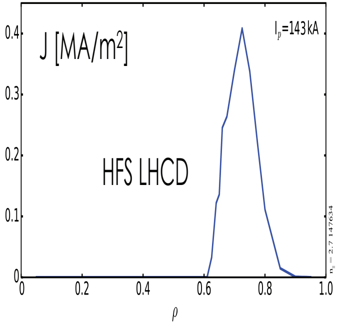
# Conclusions

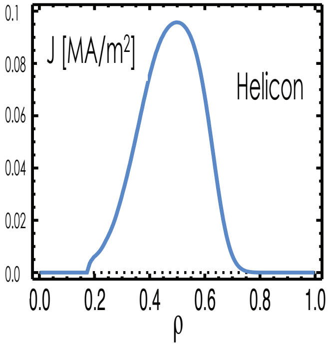
**HFS LHCD and Helicon offer promise of efficient, off-axis RF current drive for DIII-D and future tokamak reactors**

- LHCD: 0.4 MA/m$^2$ at *r/a* ~ 0.7, 143 kA/MW
- Helicon: 0.1 MA/m$^2$ at *r/a* ~ 0.5, 55 kA/MW

**Installation of Helicon antenna in 2019**

**Installation of HFS LHCD antenna in 2020**

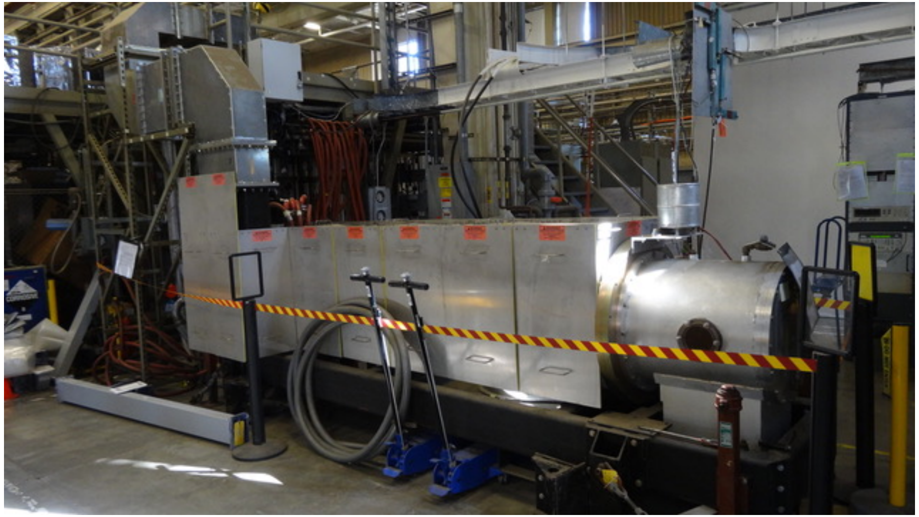




# Additional Slides

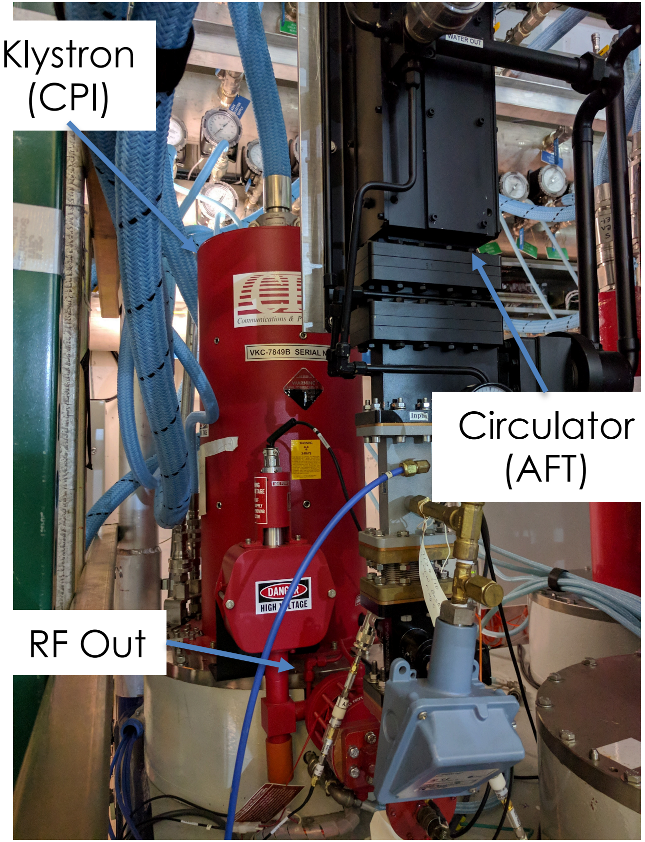
# Single Klystron Provides 1.2 MW at 476 MHz

- 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

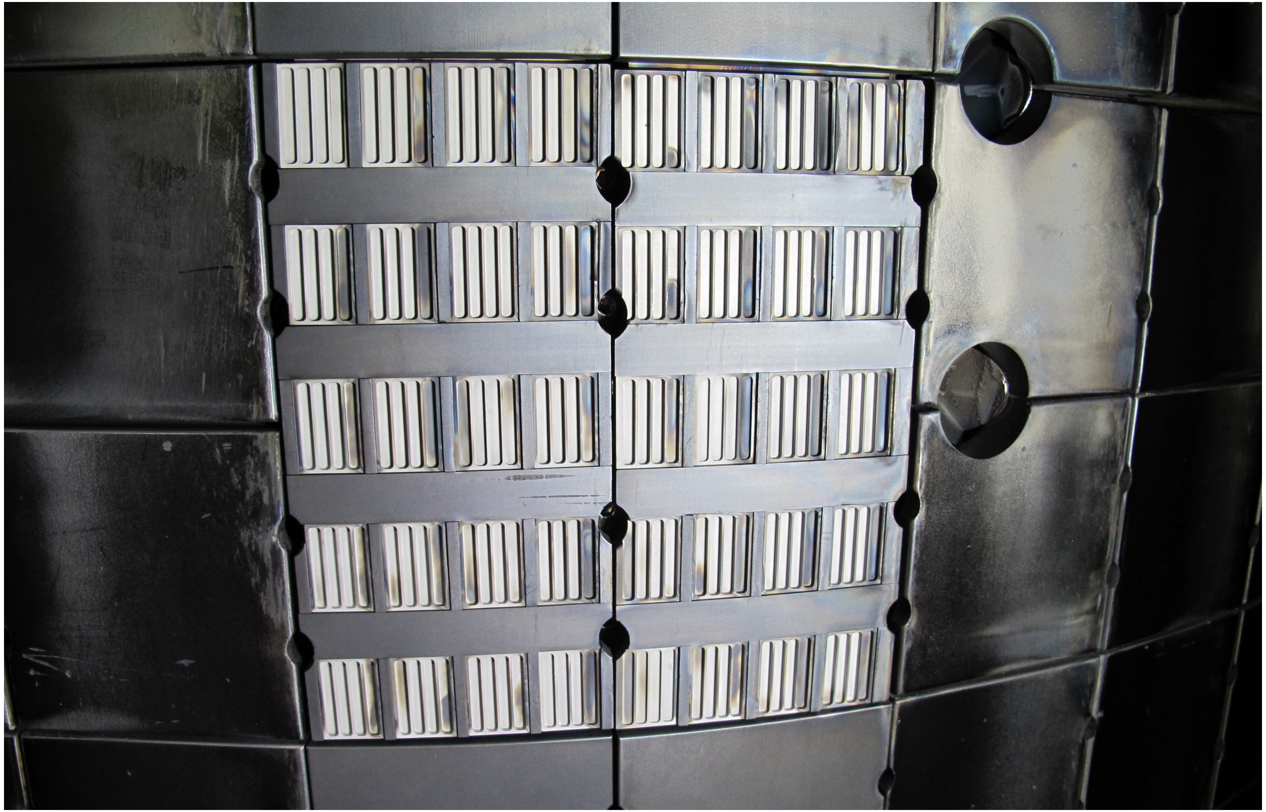


# Multi MW Source Power at 4.6 GHz for DIII-D HFS LHCD

- $f_0$ = 4.6 GHz
- $P_{RF}$ = 0.25 MW/klystron
- Gain = 55 dB
- $V_b$ = 46.5 kV
- $I_b$ = 13 A
- Efficiency = 41%
- 8 klystrons to be located adjacent to DIII-D cell ➔ 2 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

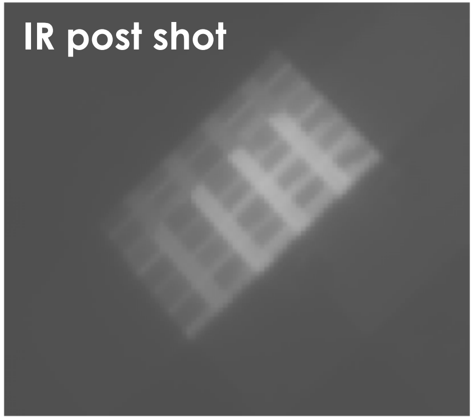


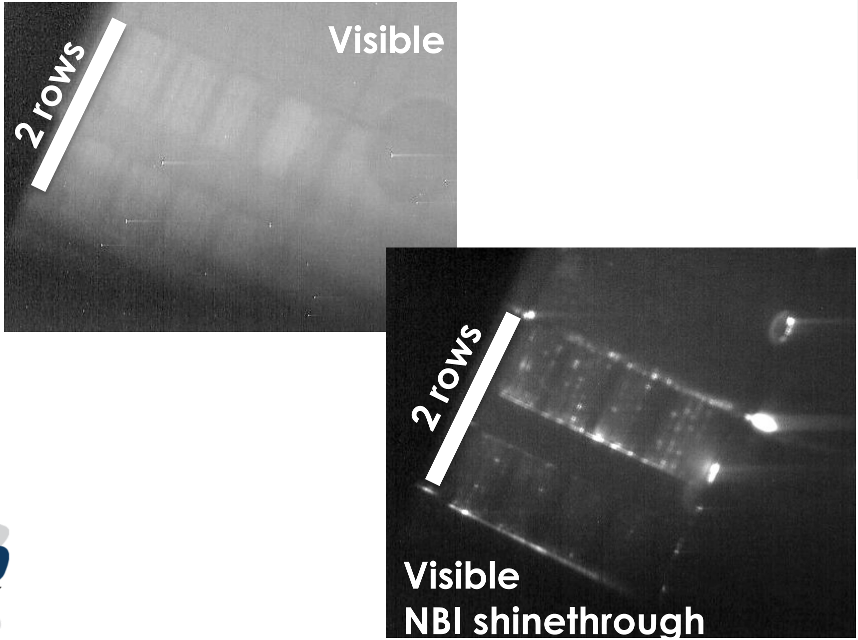
# Post-run Inspection of Mockup: Excellent Condition

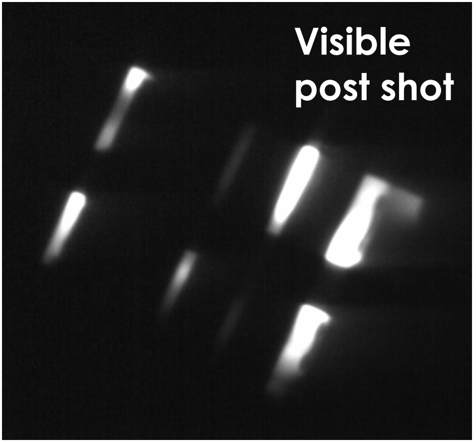


# Inner Wall Limited with Rotating n=1 was Most Severe Test for Antenna Mockup

- **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

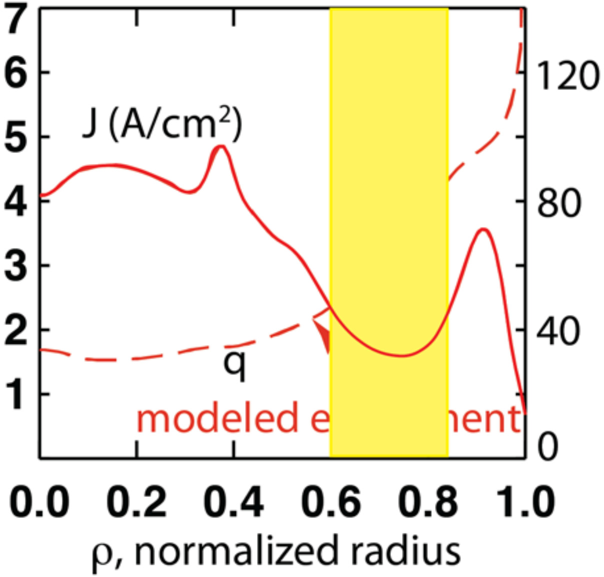






# Two Novel RF Current Drive Actuators Under Development at DIII-D

- **DIII-D uses NBI and ECCD with considerable success at r/a < 0.5**
- **Strong bootstrap current in edge region due to ∇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