

## Experimental Studies of Helicon Wave Excitation, Propagation, Damping and Current Drive on the DIII-D and LAPD Devices\*

R.I. Pinsker<sup>1</sup>, B. Van Compernolle<sup>1</sup>, M.W. Brookman<sup>1</sup>, C.P. Moeller<sup>1</sup>, R.C. O'Neill<sup>1</sup>,  
A.M. Garofalo<sup>1</sup>, C.C. Petty<sup>1</sup>, T.A. Carter<sup>2</sup>, A. Nagy<sup>3</sup>, C.H. Lau<sup>4</sup>, and M. Porkolab<sup>5</sup>

<sup>1</sup>*General Atomics, San Diego, California, USA*

<sup>2</sup>*Dept. of Physics and Astronomy, University of California, Los Angeles, CA, USA*

<sup>3</sup>*Princeton Plasma Physics Laboratory, Princeton, New Jersey, USA*

<sup>4</sup>*Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA*

<sup>5</sup>*Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*

A program to demonstrate high-efficiency off-axis current drive aims to couple 1 MW of power at 476 MHz to DIII-D plasmas in the fast wave polarization, also known as the whistler or helicon wave, to enable a proof-of-principle experiment on helicon current drive [1]. Key attributes of this experiment are the use of a toroidal array of antenna modules of unprecedented width configured as a 30-element comb-line traveling wave antenna (TWA) to launch a well-defined toroidal spectrum of waves at  $n_{\parallel}=3$ , combined with target plasmas with neutral beam and electron cyclotron preheating with excellent confinement and high electron pressure which should result in complete first-pass absorption of the launched power in the mid-minor-radius region ( $\rho \sim 0.5$ ).

Installation of the comb-line TWA into the DIII-D vacuum vessel was completed in February 2020 as shown in the photo in Fig. 1. The modules are mounted at a 15 deg angle from vertical to permit investigation of whether or not parasitic excitation of slow waves due to misalignment of the Faraday screen rods and the total static magnetic field at the antenna face is significant. The alignment is optimized for high-performance plasmas with

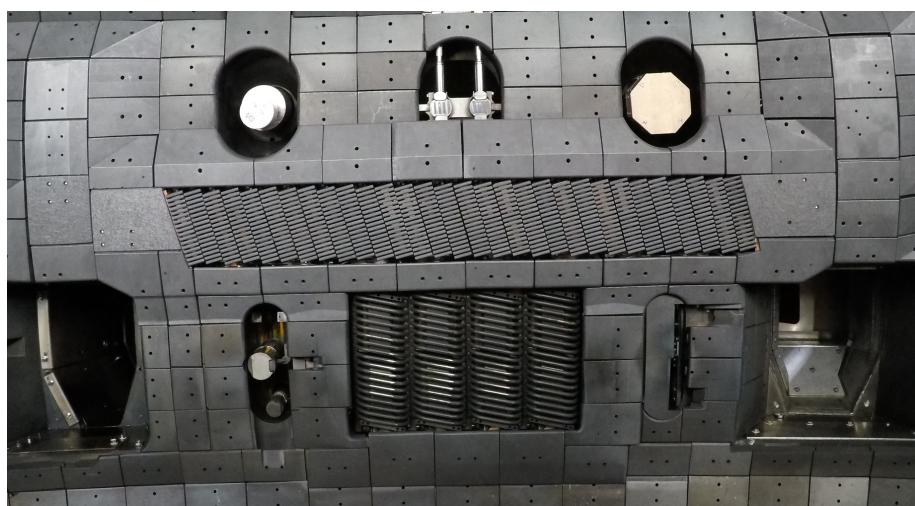


Fig. 1. 30-element comb-line antenna as installed in the DIII-D vacuum vessel in February 2020. The antenna is mounted above the midplane port, where an ICRF FW 4-strap array is located. The antenna and its feed structures, one at each end of the array, which are not visible under their protective graphite tiles, occupies the toroidal angle range of 150 deg to 210 deg.

one choice of the relative signs of the toroidal field and the plasma current, in which the non-inductive current driven by neutral beam injection is maximum. Many important details of the antenna installation are described in [2,3].

The transmission lines conveying the power from the klystron source to the antenna array are primarily 9" (0.23 m) coaxial lines of  $50\ \Omega$  characteristic impedance, operating at close to the upper limit of their bandwidth, with the section of line nearest the tokamak being 6" (0.155 m) coax of  $25\ \Omega$  characteristic impedance. Two 4-port switches in the transmission line system and the Y-junction circulator protecting the klystron are built in fundamental waveguide, so a number of waveguide-to-coax transitions are needed to use these components in conjunction with the coaxial lines. A single large 1.2 MW 476 MHz klystron ("B Factory Klystron") obtained from the Stanford Linear Accelerator Center (SLAC) is used to power the system; operation of the klystron at 1 MW into a test load has been demonstrated at DIII-D. Operation of the klystron into the antenna system began in January 2021 and pulses up to 0.5 MW have been applied to the input of the TWA in conditioning efforts to date (May 2021).

Initial experiments on coupling and antenna conditioning were carried out with a 5 kW TV transmitter as the rf source instead of the klystron. The TWA can be viewed as a two-port device, characterized by a reflection coefficient  $\rho$  from the input end and a transmission coefficient  $T$  from the input end to the output at the other end of the TWA. Adjustments to the array during installation [3] were carried out referring to measurements at instrumentation power levels ( $\sim 1$  mW), and at those levels without a load adjacent to the antenna surface, the magnitude of the voltage transmission coefficient  $|T|=0.7$ , i.e. about half of the input power is left at the output of the 30-element array due to ohmic dissipation in each module and in the stripline feed structures at each end of the array that convey power from the vacuum feedthrough to the fed end of the antenna and vice versa at the downstream end. Application of power in the 50 W – 5 kW range to the antenna in vacuum showed a value of  $|T|$  equal to the linear level of 0.7 up to about 200 W, above which  $|T|$  started to drop, indicating extra dissipation beyond ohmic (skin effect). The decrease saturated at the top of this power range at  $|T|\sim 0.15$ . The hypothesis that this extra dissipation corresponded to a multipactor-related phenomenon was tested by repeating the power scan in atmospheric pressure air, in which multipactor is impossible, and indeed the voltage transmission coefficient remained at the linear level up to the highest power applied in these TV transmitter experiments. It is believed that the electron multipactor discharge is almost entirely reactive, not dissipative, so that substantial dissipation must be due to a transition to a "multipactor plasma" [4], with energy being required to ionize the neutral gas and perhaps dissipated in rf rectified sheaths. One expects that a static magnetic field could mitigate the multipactor discharge formation by disrupting the bounce resonance of the multipactor effect, if the electric fields are perpendicular to the static magnetic field and the

electron gyroradius is smaller than the relevant electrode spacings, which are on the order of a cm. If the electrons that are most efficient in producing secondary electron emission have energies on the order of 100 – 200 eV, the order of magnitude of the critical magnetic field should be  $\sim$ 100 G. The power dependence of the transmission coefficient in vacuum was measured with low levels of toroidal field and indeed a few hundred Gauss field had a strong effect in extending the range of power levels at which linear behavior is observed by a factor of about 3 or 4; these results are exhibited in Fig. 2.

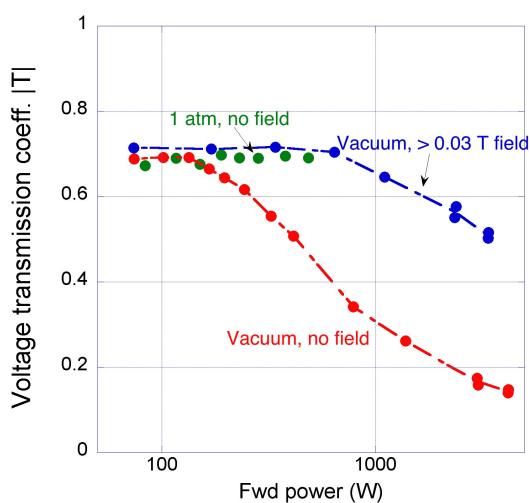


Fig. 2. Comparison of power dependence of transmission coefficient magnitude  $|T|$  without plasma load in three conditions, in the 50-5000 W range of applied power.

even at applied power levels up to 0.5 MW.

Given the linear behavior at power levels below a few hundred W, it was possible to repeat the characterization of the plasma loading of the antenna that was done in 2015-2016 with the low power test antenna [5], extending that work from the 12-element array used therein to the 30-element array, by using the TV transmitter at  $< 200$  W power applied to the TWA. The results have shown a similar dependence of loading on antenna/plasma gap (Fig. 3) as had been reported in the earlier work, and an even greater load-resilience property for the longer array, due to the larger mutual reactance between the modules in the more recent design. Indications to date are that the coupling to the plasma of greater than 75% of the power applied to the upstream end of the array is achievable with a reasonably large antenna/plasma gap in ELMing H-mode plasmas, which was the design target.

When the conditioning level of the TWA and its feeds reaches the needed levels, high-power experiments with tokamak plasmas will characterize the wave power deposition profiles by measuring the non-inductively-driven current with MSE diagnostics; in the best cases, modeling predicts off-axis driven currents in the range of 0.05 - 0.07 MA per coupled MW [1]. Non-linear effects such as PDI in the plasma edge [6] will be assessed.

Substantial effort has gone into conditioning the antenna system, attempting to reduce the effective secondary electron yield below unity to eliminate the multipactor discharge with its significant parasitic energy dissipation. Again the anomalous dissipation is reduced by the toroidal magnetic field in tokamak discharges. The multipactor discharge is observed to require a certain amount of time to develop after the turn-on of the rf power; this time interval is on the order of a few hundred microseconds; on time scales much shorter than this, the linear level of transmission is observed,

To experimentally confirm the linear physics of the wave launching and propagation, a complementary set of experiments are underway on the LArge Plasma Device (LAPD) at UCLA. A 10-element 476 MHz comb-line antenna, using components from the 12-element low-power test antenna formerly in DIII-D [5], was installed in LAPD in January 2020 for this study. The array can be moved radially and rotated with respect to the axial magnetic field in LAPD. Topics to be addressed in the low-power (linear) experiments in LAPD include detailed 3-D characterization of the ray paths and comparison to modeling and correlation of observed loading characteristics of the antenna with wave polarization in the plasma (parasitic slow wave excitation) and with the density profiles adjacent to the antenna surface. The LAPD experiments with the TWA will commence when local conditions relative to the COVID-19 pandemic permit them to be carried out safely, which is expected to be in the summer of 2021.

This work supported in part by the U.S. Department of Energy under DE-FC02-04ER54698, DE-AC05-00OR22725 and DE-AC02-09CH11466. DIII-D data shown in this paper can be obtained in digital format by following the links at [https://fusion.gat.com/global/D3D\\_DMP](https://fusion.gat.com/global/D3D_DMP). The Basic Plasma Science Facility at UCLA is funded jointly by DOE grant DE-FC02-07ER54918 and NSF grant PHY1561912.

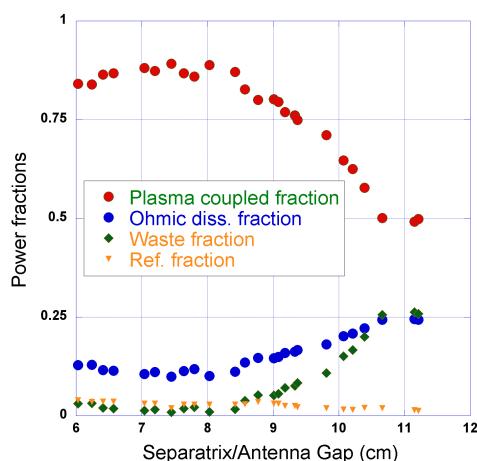


Fig. 3. Dependence of loading parameters on plasma/antenna gap in an L-mode plasma at 125 W forward power (DIII-D shot 183752)

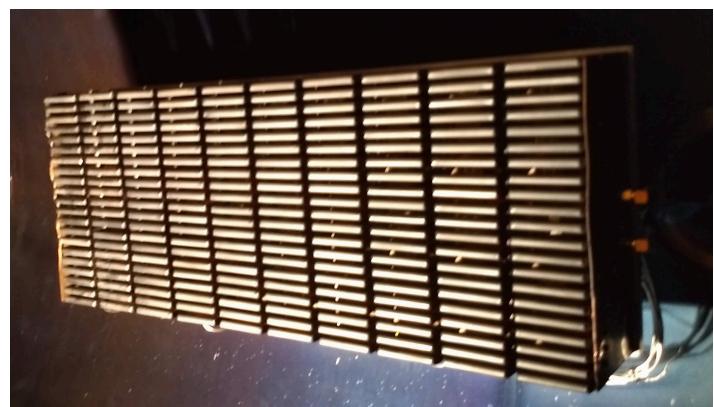


Fig. 4. 10-element comb-line antenna as installed in the LAPD vacuum vessel in January 2020.

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