The High-Power Helicon Program at DIII-D: Gearing up for First Experiments


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Abstract

Helicon current drive, also called fast wave current drive in the lower hybrid range of frequencies, has long been regarded as a promising current drive tool for reactor grade plasmas. A newly installed MW-level system at DIII-D will be the first test of this technology in reactor-relevant plasmas, where full single-pass absorption is expected. A 30-module traveling wave antenna has been installed and optimized in-vessel in early 2020. The linear electromagnetic characteristics of the unloaded module array have been extensively tested both on the bench and in the vessel at instrumentation power levels. Excellent performance has been achieved, ~2% reflected power and ~1.4% dissipated power per module in air, in a 10 MHz band around 476 MHz. Stripline feeds on both ends of the antenna allow for both co and counter current drive. The installation of a 1.2 MW klystron and associated high-power electronics was completed in Fall 2020. Commissioning of the antenna is ongoing. An important goal of this experiment is to validate the helicon current drive physics basis using an extensive set of new and upgraded diagnostics.

1. INTRODUCTION

Helicon current drive, also called fast wave current drive in the lower hybrid range of frequencies, has long been regarded as a promising current drive tool for reactor grade plasmas [1-4]. Steady-state advanced tokamak reactors require non-inductive current drive in the mid-radius region, near $\rho \sim 0.6$. DIII-D is currently investigating several methods for off-axis current drive [5], i.e., top-launch electron cyclotron current drive (ECCD) in 2019-2020 [6], helicon current drive planned for 2020-2021, and inside-launch lower hybrid current drive (LHCD) [7,8] to be installed in 2021. Wave absorption for helicon and LHCD occurs through electron Landau damping as the subset of electrons with velocity parallel to the static B-field equal to the parallel phase velocity of the wave gain energy from the wave [9]. A key parameter for the wave propagation and absorption is the normalized parallel wave number $n_\parallel = \frac{c_{\parallel}}{\omega}$. Scoping studies for helicon waves by Prater et al [4] showed $n_\parallel = 3$ to be optimal for the wavenumber launched by the antenna, with a predicted 60 kA of driven current at $\rho \sim 0.6$ per MW of coupled power. As the wave penetrates the plasma core, $n_\parallel$ undergoes an upshift to 4-5 at which point the wave is absorbed in plasmas with electron temperature in the ~4 keV range. Helicon current drive is predicted to be effective at high densities and high electron temperatures. The installation of the new MW-level system at DIII-D enables the first tests of this technology in reactor-relevant plasmas, where full single-pass absorption is expected.

2. TRAVELING WAVE ANTENNA

The design of the antenna structure needs to satisfy several requirements, most driven by physics, some driven by practical considerations. The requirement for the helicon high-power antenna is to efficiently launch a high-power unidirectional fast wave in the lower hybrid range of frequencies using a low-loss structure. For typical DIII-D parameters, the operating frequency in this regime is in the hundreds of MHz range. The choice of 476 MHz was determined by the availability of a decommissioned B-factory klystron (BFK) from the SLAC National Accelerator Laboratory (see section 3), with a maximum RF output power of 1.2 MW. The antenna is a traveling wave antenna of the comb-line type[10-12] with a narrow parallel wave number spectrum peaked at $n_\parallel = 3$. It
The input impedance is largely determined by the $\pi$-band of the antenna, acting as a bandpass filter with mid-frequency transmission line components. The expected power helicon antenna at $1 \text{ MW}$ consists of 30 modules, and can be fed from either side to allow for either co- or counter-current drive. Power is transferred toroidally along the antenna through mutual coupling from one module to the next with low losses.

The inner workings of a single antenna module are shown in Fig. 1. Each module has two current straps, supported in the middle by a grounded pedestal. The straps are connected to capacitor plates on either side (vertical in the picture). A number of movable capacitor rods allow for fine-tuning of the capacitance of each module. The inductance of the straps combined with the capacitance of the capacitor plates and rods essentially make each module a resonant RLC circuit. Each module was tuned to the same resonant frequency to within $\pm 0.5 \text{ MHz}$, and with a quality factor ‘Q’ in excess of 1000. The straps and capacitor plates/rods are enclosed in a slotted box with Faraday screen rods to protect the modules from the plasma, and to screen out the electric field component parallel to the rods. The modules are mounted in the DIII-D vessel with the Faraday screen rods aligned with the expected pitch of the magnetic field to minimize parasitic coupling to the slow mode. The straps, capacitor plates and rods, and the slotted enclosure are constructed of CuCrZr. The Faraday screen bars are TZM (molybdenum alloy) which have been coated with a thin layer of boron carbide to prevent introduction of high-Z impurities into the discharge. After each module was tuned, the module was brazed to obtain a low-loss structure. After brazing, the resonant frequency of each individual module was re-confirmed.

The test program evaluated the breakdown thresholds at high RF voltages for a number of prototype helicon components using a 10 kW UHF television transmitter. Tests were performed on multiple module designs and transmission line components [14]. Many tests used resonant circuit designs to produce standing wave voltages of amplitudes equivalent to those produced by $\sim 1 \text{ MW}$ traveling waves. A single strap CuZrCr helicon prototype module fed with a loosely coupled resonator was able to support $22.5 \text{ kV/cm}$ electric fields in a measurement of amplitudes equivalent to those produced by a 1 MW UHF television transmitter. Test programs also found that the single-module resonant frequency downshifts by $2 \text{ MHz}$ as a module is heated from 30 to 300 deg C, an effect caused by the thermal expansion of the capacitive gaps between the module strap and end wall. These results suggested the requirement of optimal antenna performance in a 5 MHz frequency range around 476 MHz.

In the DIII-D vessel the modules are mounted on six Inconel water-cooled backplates, five modules per backplate. A SolidWorks rendering of fifteen modules, mounted on three backplates is shown in Fig. 2. Power is fed from one end of the array and transferred down the array through the mutual inductance between modules. The antenna acts as a bandpass filter with mid-band frequency of 476 MHz. The bandwidth scales with the mutual inductance. The phase shift between modules, $\Delta \phi$, varies with frequency, from monopole ($\Delta \phi = 0$) at the lower band-edge to pi phasing ($\Delta \phi = \pi$) at the upper band-edge. At mid-band, the phase shift between modules is $\Delta \phi = \pi/2$ (90 deg). The phase shift between modules and the center-to-center spacing of the modules on the backplates determines the parallel wave number excited by the antenna. The input impedance is largely determined by the mutual inductance between modules. The plasma loading causes only a small perturbation to the input impedance, resulting in an antenna resilient to changes in plasma loading to the extent that plasma-induced changes to the mutual reactive coupling are small. The depth of the slots in the copper enclosure of the modules determines the mutual inductance between modules. The slot depth was increased for the high-power helicon antenna compared to the prototype low-power helicon antenna [15], resulting in a roughly threefold increase of the mutual coupling. As a result,
the bandwidth of the antenna increased from ~25 MHz to ~60 MHz. Other benefits of the increased mutual coupling are lower peak electric fields, more involvement of the downstream modules, and a reduced sensitivity of the input impedance to variations in the mutual coupling caused by the plasma.

At either end of the array, a specialized end module couples input power from a transmission line into the array, and couples waste power out of the array into a second transmission line. A schematic of the end module is shown in Fig. 3. The end modules contain the same current straps and capacitive plates as the inner modules (cf. Fig. 1), but additionally have four coupling straps, indicated in the figure as the RF feeds connected to ports P1-P4. The RF feed-straps couple power reactively to the main current straps. The distance between the RF feeds and the main current strap can be changed to impedance match the antenna to the transmission line. The four RF feeds are fed with equal power and in $0\pi$ phasing to produce unidirectional poloidal current flow on the main current straps. The end modules can each be connected to four separate coaxial feeds, which was done during testing. In the final installation in-vessel the power is transferred to the end modules through a specialized stripline.

A picture of the partially installed stripline on one end of the antenna is shown in Fig. 4. The front cover and the side cover are removed to make the inner components visible. A second stripline is installed at the other end of the array. A 25 Ohm coaxial transmission line enters the DIII-D vessel through a vacuum feedthrough (not visible) and connects to the back of the stripline. The inner conductor of the input coax connects to the inner conductor of the stripline, which splits into two RF paths. The extra path length along the top of the stripline introduces a $180^\circ$ phase shift between the two paths. Note that a ground plane positioned in between the two RF paths is not shown in Fig. 4 since it had not been installed yet. Each of the two RF paths splits into two equal-power outputs near the end-module. The stripline effectively takes a single high-power input and converts it into four equal power outputs with $0\pi$ phasing, to feed into the end module of the array. The weight of the inner conductors is supported by a stub on either side of the stripline. The stripline is a complex 3D structure, designed to fit closely to the DIII-D vessel wall. Sections of the stripline inner conductor were manufactured by additive manufacturing (AM) techniques in Inconel, and were later plated with copper. During RF testing of the stripline, an as of yet unresolved local impedance mismatch was discovered, which required the use of an ex-vessel tuner. This impedance mismatch had not appeared in full-scale prototypes of the stripline assemblies and at the time of this writing the source of the mismatch in the final stripline assemblies has not been identified. The antenna system is still expected to be resilient to changes in plasma loading since the impedance mismatch is believed to be inside the stripline, and should not be affected by the presence of the plasma, i.e., the ex-vessel tuner will not need to be adjusted during plasma operations.

The linear electromagnetic characteristics of the unloaded module array have been extensively tested on the bench and on a DIII-D mock-up wall at instrumentation power levels, with sub-arrays of 5, 10, 15, 20 and 30 modules on curved backplates, as well as flat on the bench. An issue with large reflected powers observed during initial testing (without the striplines) was successfully overcome, and an optimization procedure was developed and tested on the bench prior to the in-vessel installation. The optimization involves minimizing the reflected power and maximizing the transmitted power in a band near the operating frequency of 476 MHz. The layout of
the modules on the back plates, in a 2-module poloidal stagger pattern (cf. Fig. 5), results in a periodicity in the mutual coupling between modules, which caused significant reflections in the antenna (~20% power reflected). Since the nominal phasing between module is 90 deg at the operating frequency, any even-numbered periodicity in the mutual coupling between modules causes the reflections in the array to add constructively. Separate tests with a set of 20 modules flat on the bench clearly showed that a 2-module periodicity in the mutual coupling along the array results in substantially increased reflections, and associated loss of efficiency of the antenna. The staggered layout of the modules on the back plates was designed to shorten the toroidal connection length at the face of the antenna and thus minimize plasma density penetrating into the antenna modules. Adjustment of the inter-module spacing (in the toroidal direction) compensates for this, resulting in a more uniform mutual coupling between modules along the whole array, and reducing the reflected power to less than a few percent. The optimization procedure consists of re-positioning the modules starting at one end of the array, typically the feed end, until all module positions have been adjusted. The antenna array is then fed from the other end, and the optimization procedure is repeated. After a few iterations, the antenna characteristics are optimal when fed from either end.

The antenna was tested and tuned at instrumentation-power levels at different stages in the installation process in-vessel, i.e., without striplines, with one stripline and with both striplines and ex-vessel tuners installed. The voltage reflection coefficient and voltage transmission coefficient are shown in Fig. 6 for the system comprising the antenna, both striplines and ex-vessel tuner on each side of the antenna. After the optimization procedure, the power reflection coefficient of the 30-module array was reduced to ~1% at 476 MHz, and with less than 4% reflected power in a 10 MHz band. The power transmission coefficient for the 30-module array (without striplines) in air is 63%, indicating a 36% power dissipation in the antenna, or 1.4% per module. Virtually no power is expected to be radiated into vacuum [or air] in the absence of a plasma load near mid-band since the imposed parallel wave number is higher than the free-space wave number at 476 MHz; therefore power ‘missing’ at the downstream end of the array must have been resistively dissipated in the structure, not radiated. In a scenario with 75% of power coupled to the plasma, the total dissipated power in the modules is expected to drop to 17% of the input power, and with 8% of the input power exiting the antenna as waste power. Strong plasma coupling reduces the power traveling along the array and therefore reduces the total resistive dissipation in the array. The first module will still see nearly the same power dissipation as in air/vacuum however, estimated at 14 kW with 1 MW incident on the module. Thermal modeling of the antenna has shown the cooling of the modules to be sufficiently fast to run 6 s 1 MW pulses every 12 minutes, which is the maximum practical DIII-D shot rate.

Data was also acquired in-vessel with a pick-up coil placed near the Faraday screen (see Fig. 7). Both the amplitude and phasing of the magnetic field in front of each module along the array was recorded in the frequency band of interest. Ideally, the amplitude should decay exponentially from the fed end, and the phase difference at 476 MHz between two consecutive modules reduces the total resistive dissipation in the array. The first module will still see nearly the same power dissipation as in air/vacuum however, estimated at 14 kW with 1 MW incident on the module. Thermal modeling of the antenna has shown the cooling of the modules to be sufficiently fast to run 6 s 1 MW pulses every 12 minutes, which is the maximum practical DIII-D shot rate.

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should be constant along the array and equal to 90 degrees. Large variations in the amplitude and phase are indications of a substantial standing mode component in the array. Efficient directional wave launch requires minimizing standing modes. Figure 8 shows the probe data acquired in-vessel. The top panel of Fig. 8 displays the measured phase advance between two consecutive modules at 476 MHz. The phase shifts are uniform along the array, and have the opposite sign when the array is fed from the other end. The middle panel shows the accumulated phase along the array, i.e., the cumulative sum along the array of phase changes between modules, again with opposite slope when the array is fed from the other side. The top two panels clearly show the directionality of the wave propagation in the antenna. The probe amplitude, shown in the bottom panel, decays away from the feed point, and has only small fluctuations indicating no significant standing waves are present. It is important to note here that the antenna behaves very symmetrically when feeding from either end of the array. This is crucial for the planned experiments in order to allow choice of either co- or counter-current drive phasing.

3. RF SOURCE AND TRANSMISSION LINE NETWORK

The RF source consists of a single B-Factory klystron[17] obtained from SLAC, powered by a high-voltage power supply, also obtained from SLAC, which is equipped with a new control system to allow pulsed mode operation. The klystron, driven by a 100 W pre-amplifier, produces a maximum RF output power of 1.2 MW, and operates at a nominal frequency of 476 MHz. A schematic of the RF system is shown in Fig. 9. The high-voltage power supply accelerates electrons from a heated filament along the guide field through 7 RF cavities. Typical beam voltages and currents at nominal output power are 83 kV and 24 A, i.e., a beam power of 2 MW. The waste power in the beam after it has passed through the 7 cavities is deposited onto the collector. The collector can withstand the full 2 MW of beam power (when no RF is produced) for 0.5 s. The RF cavities are driven by a gated RF source at 100 W. Modulation of the output RF power of the klystron is accomplished by adjustment of the RF drive power and/or high voltage adjustment. No modulation anode is required. A circulator is present to protect the klystron from reflected power. The klystron has a 1 dB bandwidth around 476 MHz of ±1.5 MHz. The power at saturation is 1.2 MW, with an effective klystron efficiency of 60%.

A schematic of the transmission line network is shown in Fig. 10. The RF output of the klystron is routed through the circulator to a 9" coaxial feed line, and connects to a 4-port waveguide switching network, located just outside the machine pit wall. Any reflected power returning from the switch towards the klystron will be diverted by the circulator into a 9" coaxial reject line and dumped into a 50 Ohm dummy load (labeled Dummy load 1). The 4-port switches can be configured to send power directly to a second dummy load (labeled Dummy load 2) for klystron conditioning. During normal operation the switches send power to the antenna through a 6" 25 Ohm coaxial line, either to the high-angle-side (HAS) of the antenna, or the low-angle-side (LAS) of the antenna. The 6" line contains both DC outer-breaks and DC inner-breaks (omitted in the diagram), providing up to 15 kV of DC isolation between the DIII-D vessel and the rest of the transmission line. The 6" line then connects via a vacuum feedthrough to the striplines and the antenna. Any power not coupled to the plasma or dissipated in the antenna structure leaving the antenna at the ‘downstream’ end will be directed through the
switches to the 9” waste line and dissipated in dummy load 2. The inset of Fig. 10 indicates where the RF input power is directed for different settings of the waveguide switches. Directional couplers are placed in various places along the transmission line to quantify the line losses, the antenna waste power and reflected power.

**FIG. 10**: Schematic of the transmission line network, not to scale.

### 4. DIAGNOSTICS

The antenna is equipped with a suite of diagnostics shown in Fig. 11. Eighteen RF probes are embedded in a subset of the 30 modules in the array. The RF probes are placed in a recess in the pedestal of the modules, as indicated in Fig 1. The probes are single-turn loops and are connected with high frequency semi-rigid coax through a set of vacuum feedthroughs to instrumentation outside the DIII-D vessel. Each probe is fitted with a stainless-steel cylindrical cap with a narrow slit to limit the magnetic flux onto the coil, and thereby reduce the power levels in the probe to acceptable levels (roughly 70 dB, i.e. a factor of $10^{-7}$ lower than the signal in the antenna strap). The RF probes are placed in groups around the antenna, marked with stars in Fig 11. The end modules each have two probes, one behind the upper straps, one behind the lower straps, to verify that both sides of the modules are fed in phase and with equal power. Any imbalance in the antenna feed would be detected by these probes. The remaining RF probes are distributed along the array in groups to provide measurements of phase and amplitude measurements along the array. The RF probes will initially be used to confirm the antenna has the correct phasing, and to quantify the loading of the antenna array (in addition to loading measurements obtained from ex-vessel directional couplers at both ends of the antenna outputs). At a later stage the probe measurements are planned to be incorporated into an RF-based arc detection system. Six fixed Langmuir probes were installed in tiles around the antenna to measure edge plasma density as well as to provide a secondary capacitive RF measurement; two probes are in tiles near the low-angle stripline, two are in tiles near the middle of the antenna, and two are in tiles near the high-angle stripline. The striplines are equipped with three fiber optic arc detectors to detect light flashes in the stripline due to arcs during operation of the antenna. 39 thermocouples are embedded in the antenna and surrounding tiles, with their locations indicated in Fig. 11. A visible light camera and an IR camera were added to the diagnostics with a nearly full view of the antenna modules. The IR camera is live-streamed to the control room. For each discharge a 30 s video of the IR camera view is stored on a server.

Several new and upgraded diagnostics are planned and under development for the helicon program. An edge density diagnostic will provide density profiles at the antenna. A laser-based technique known as Doppler-
free saturation spectroscopy (DFSS) will be implemented to measure the helicon wave electric field vector over a 2D region of space in the edge plasma near the antenna. For far-field wave measurements, the existing Phase Contrast Imaging (PCI) diagnostic is being upgraded with a heterodyne detection system able to detect fluctuations at 476 MHz.

5. SYSTEM TESTING AT MODERATE POWER

Prior to applying the first RF power onto the antenna various interlocks were tested during the plasma startup phase. A plasma proximity interlock initiates a controlled plasma shutdown if the plasma separatrix-antenna distance drops below a programmed level. Similarly, a controlled plasma shot shutdown is initiated were the IR camera to detect a temperature of over 300 deg C anywhere on the helicon antenna modules. Thermocouple data is used to prevent the start of the next plasma shot sequence if the helicon modules have not cooled down sufficiently after the previous shot.

Tests of the antenna have been carried out in vacuum at moderate powers, up to 5 kW, using a separate UHF television transmitter. A power scan of the waste power exiting the antenna, shown in Fig. 12, exhibits deviation from linear behaviour around 200 W of input power, and subsequent saturation at powers greater than 400 W. The nonlinear behaviour is thought to be caused by multipactoring in the antenna modules, absorbing the RF power incident on the modules. Subsequent power scans in air at atmospheric pressure, when no multipactoring is possible, showed no such nonlinear behaviour. Substantial heating was also observed in the antenna after applying 5 kW to the antenna for several minutes. Images on the IR camera showed the heating localized initially to the first module on the fed side of the antenna, see Fig. 12 inset (a), and then spreading gradually to modules further down the array over the course of many minute-long RF pulses, see Fig 12 inset (b). This is taken as a sign of conditioning of the modules; as the first module conditions, the power is absorbed and/or reflected there, and little power propagates further along the array. After the first module is conditioned, power is transferred to the modules further along the array, which then show increased heating. Conditioning of the antenna at hundreds of kW is ongoing at the time of this writing.

Preliminary tests of the antenna powered at 100 W into plasmas, showed strong coupling to the plasma in excess of 80% of the power coupled, with almost no power exiting the antenna as waste power. The plasma coupling responded to jogs of the radial position of the plasma as expected, with increased coupling when the separatrix is brought closer to the antenna, similar to what was observed with the low-power antenna[15]. The reflected power fraction measured at the RF source increased slightly during plasma operation, but stayed below 5% in all cases, demonstrating the resilience of the antenna input impedance to changes in the plasma loading.

6. PLANNED EXPERIMENTS

Initial experiments with the helicon system focus on determining the coupling efficiency of the antenna at high power under various plasma conditions, as well as establishing antenna performance in preparation of high-power experiments. Comparisons of measurements of the antenna-plasma coupling to theoretical expectations are fundamental in establishing that the expected wave is being excited in the plasma and to quantify the wave power in the discharge. The same methods that were used in the low-power helicon experiments [15] will be utilized in the high-power experiments. In order to evaluate nonlinear effects, the experimental plan also includes searches for power-dependent loading, studies of the effect of the RF power on the plasma edge density profiles, and monitoring of the frequency spectrum of RF waves in the plasma to study parametric decay instabilities.

The power deposition profiles will be experimentally determined to validate ray tracing predictions for helicon waves. The total power absorbed in the plasma is needed to quantify the current drive efficiency (driven current per core-absorbed Watt), and also to gauge if any significant edge losses are present. The principal absorption mechanism is Landau damping on thermal electrons which are thermalized on a short time scale. By amplitude-modulating the klystron power the deposition profiles can be determined from localized measurements of the modulated electron temperature.
The phenomenon of current drive is a more sensitive measure of the interaction in velocity space between electrons and helicon waves than absorption. For example, the current drive efficiency has a strong dependence on the parallel index of refraction and directionality of the waves. Fokker-Planck codes contain a complete model of this wave-particle interaction, but experimental validation of the physics is needed. This is best accomplished by comparing a local measurement of the current density driven by helicon waves to the theoretical computations. The current drive profiles are determined from measurements of the internal magnetic field structure, typically using the Motional Stark Effect (MSE) diagnostic, which yields both the total parallel current density $J_\parallel$ and the parallel electric field $E_\parallel$. The non-inductive current is obtained by subtracting out the inductive component, i.e., $J_{\text{LINI}} = J_\parallel - \sigma_{\text{esc}} E_\parallel$. The contribution from helicon waves is distinguished from other non-inductive current drive sources by comparing two similar discharges with co-plasma current and counter-plasma current injection of the helicon waves. Taking the difference in $J_{\text{LINI}}$ between these two discharges allows the helicon wave current drive profile to be isolated since all other sources of non-inductive current will cancel.

7. CONCLUSIONS

Major elements of the design, construction, installation and commissioning of the helicon current drive system on DIII-D have been successfully completed. These have resulted in a system demonstrating excellent RF performance with low reflected power, low losses and good antenna directivity, and with the ability to launch RF power in co- or counter-plasma current direction. The system enables experiments to determine the non-inductive current profile in high-beta discharges, will shed light on the efficiency to drive current off-axis in steady-state tokamaks beyond ITER, and will provide tools to extend DIII-D’s steady-state research to higher pressure and density.

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