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GENERAL ATOMICS

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Off-Axis Current Drive with Very High Harmonic Fast Waves for DIII-D

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Abstract. Modeling shows that fast waves at very high ion cyclotron harmonics (also called "whistlers" or "helicons") can drive current efficiently in the mid-radius region of a high beta tokamak plasma, as is required to sustain steady-state high performance discharges in a DEMO-like configuration. DIII-D has developed discharges with high electron beta and high electron temperature so that full first-pass damping of the waves is expected to take place off-axis. In a specific existing high-beta DIII-D target discharge, 0.5 GHz fast waves at launched $n_{\parallel}$ ~3–4 would drive a noninductive current of 60 kA/MW at ρ=0.55, where the electron density is ~5×10^{19} m^{-3} and the electron temperature is ~3 keV. With complete first-pass absorption, loss processes associated with weak single-pass damping are minimized. Strong, radially localized absorption on electrons is obtained for local values of electron beta exceeding 1.8%. An appropriate launching structure to excite a well-defined and toroidally directional wave spectrum is introduced: the traveling wave antenna known as the "comb-line". This structure permits the use of a large number of radiating elements in a phased array with feeds only at the ends of the wide, all-metallic antenna. Low power experiments to test such a launcher in DIII-D are planned in 2015, with experiments at the 1 MW level at 0.5 GHz to follow in 2016.

1. Introduction

To sustain high performance discharges in a DEMO-like configuration in a stationary state, modeling [1] shows that non-inductive current drive in the outer half of the plasma is necessary. In typical reactor designs, the established technique of lower hybrid current drive with the slow wave (SW) at frequencies of a few GHz is useful only for current drive in the pedestal region ρ>0.9, due to the very strong damping of the SW, while fast waves (FWs) in the usual low ion cyclotron harmonic range $\omega\sim n\Omega_i$ with n=1-3 are strongly damped on ions. Even if strong ion damping can be avoided, the electron damping is strongly centrally peaked, so electron current drive with these waves is useful only for sustainment in the region around the magnetic axis. Raising the frequency of the FWs from low harmonics to the very high harmonic range, also referred to as the Lower Hybrid Range of Frequencies (LHRF), where FWs are alternately referred to as "helicons" or "whistlers", increases the electron damping and reduces the ion damping, to the point where damping can be complete on the first pass in the mid-radius region.

Experimental efforts to study the FW in the LHRF carried out in 1984-1994 and reviewed in [2] were performed in small devices with very weak first-pass damping, and in this regime the tokamak current drive results were almost indistinguishable from what would be obtained with inefficiently-launched slow waves at the same frequency and parallel wavelength. Reducing the frequency to the moderate ion cyclotron harmonic range of n=4–8 led to the successful demonstration of strong multiple-pass electron damping and central current drive in agreement with theory [3,4]. Slow waves cannot have had any role in the current drive observed in those experiments, because at the frequencies used, they propagate only at $n_e < 8\times10^{17}$ m^{-3}, and not in the confined plasma at all. The electron damping in a single pass was raised to a significant level, up to about 15%-20%, with strong electron preheating provided by electron cyclotron heating (ECH) or neutral beam injection, but with single-pass damping much less than 100%, essentially all the driven current is in the neighborhood of the magnetic axis. To drive current in the mid-radius region, complete first-pass electron damping must be accessed by increasing the frequency into the LHRF [5,6].

In this paper, we perform ray-tracing and full-wave calculations of current drive of a proposed 0.5 GHz FW system in an existing DIII-D discharge, and it is shown that complete first-pass absorption can be achieved at ρ=0.55, provided that it proves possible to efficiently excite the FW at the required parallel wavelength. We then discuss a proposed antenna structure to accomplish this in DIII-D, and outline the experimental program on DIII-D which will test these concepts in the next few years.

2. Ray Tracing Calculations of Deposition and Current Drive

We may gain useful insight into the properties of fast waves as they transition from the regime of low-order cyclotron harmonics to the whistler-like regime in the LHRF by studying ray-tracing in a 1D slab geometry (essentially Snell's law) with the cold-plasma dielectric tensor. We use a measured electron density profile from a DIII-D discharge which we will analyze in more detail later, which is discharge 122976 at 3.0 s. The radial dimension in the tokamak corresponds to the direction in which the density is stratified, labeled as R in the plot (Fig. 1), and the orthogonal direction corresponding to the toroidal direction in the tokamak is the abscissa. The magnetic field is taken to be straight in that direction, and the magnitude of the field is taken to be also plane-stratified in the R direction, scaling as 1/R. In this case, the central field, at R=1.70 m, was 1.5 T. The plasma is taken to be pure deuterium.

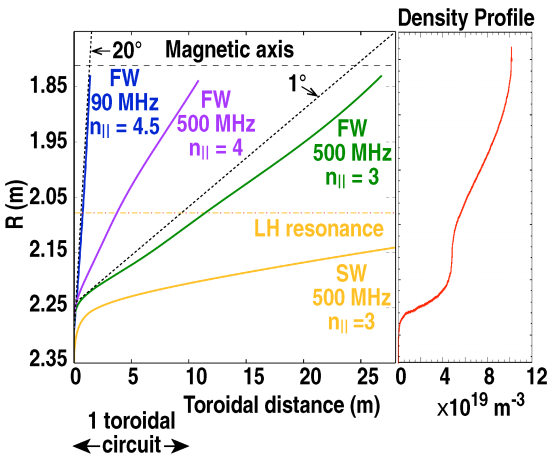

Fig. 1. Ray paths of slow waves at 0.5 GHz and of fast waves at 90 MHz and at 0.5 GHz in a slab geometry, with the density profile and magnetic field taken from DIII-D discharge 122976. R_0=1.7 m, a=0.65 m, $B_T(R_0)$=1.5 T.

In this slab geometry, launching fast waves at 90 MHz from the equivalent of the outboard midplane, in the moderate ion cyclotron harmonic range at f/f_{cD}~8 (where f_{cD} denotes the deuterium ion cyclotron frequency), we find that FWs at a parallel index of refraction $n_{||}$ in the range which would be used for current drive of about 4.5 have the whistler-like property of propagating at an angle to the static magnetic field of less than ~20 deg [7]. In this regime, in the transition between the compressional Alfvén wave and whistler regimes, the angle is at the 20 deg upper limit. Hence the ray reaches the magnetic axis while propagating about a meter in the direction along the magnetic field.

Raising the FW frequency into the LHRF, in which the slow wave can propagate in the lower density part of the plasma at the same $n_{||}$, strongly reduces the angle that the FW ray makes with the magnetic field for $n_{||}$ values of interest. At $n_{||}$=3, the angle is about 0.9 deg and the ray travels 26 m along the field to reach the magnetic axis, corresponding to about 2.4 turns around the torus in the toroidal geometry. Raising $n_{||}$ to 4 increases the angle to about 2 deg and the angle becomes more dependent on density, so that the ray propagates about a single toroidal turn before reaching the magnetic axis. This simple model suggests that when electron damping is included for the FW, raising $n_{\|}$ from 3 to 4 will not result in damping at lower electron temperatures, because of the offsetting increase in the angle that the ray makes with the magnetic field; although the damping per unit distance along the ray is higher at higher $n_{\|}$, the ray takes a shorter path to the plasma center in that case, so that the radial location of the damping is almost unchanged.

To analyze the full axisymmetric toroidal equilibrium, we have performed detailed ray-tracing studies with the GENRAY code [8] in the equilibrium from DIII-D discharge 122976. The rays are launched with a realistic range of poloidal and toroidal wavenumbers centered at $n_{\|}$=3.0, n_{pol}=0 from a point at an elevation of 0.34 m above the outboard midplane of the DIII-D vacuum vessel, where the proposed antenna would be located. The central ray of the bundle is shown in Fig. 2, with the thickness of the ray being proportional to the power deposited per unit length along the path. The light, nearly vertical contours denote the closely spaced deuterium ion cyclotron harmonic layers, in the range of about f/f_{cD} ~ (30–50) in the plasma. Also shown are the radial profiles of driven current and electron heat density for this case. The total noninductive current driven is 60 kA/MW, with the deposition peaking at ρ=0.55, where the electron density is ~5×10^{19} m^{-3} and the electron temperature is 3 keV. Essentially all of the rf power is absorbed in that region on the first pass, minimizing parasitic loss processes (mode conversion, far-field sheath formation, etc.) associated with weak single-pass damping.

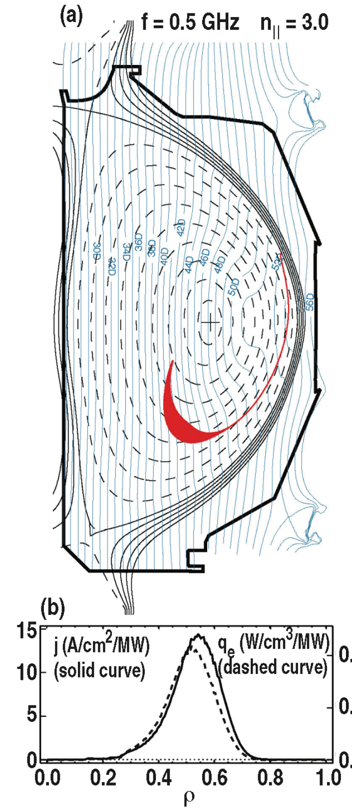

Fig. 2. (a) Ray path of 0.5 GHz whistler in DIII-D equilibrium 122976 with launched $n_{\|}$=3.0. Thickness of ray is proportional to -(1/P)(dP/ds), where P is the power remaining in the ray. (b) Driven current density (solid curve) and electron heating density (dashed) as a function of normalized radius.

Varying the parameters of the equilibrium has shown that the desired strong, radially localized absorption on electrons can be obtained only for local values of β_e [the ratio of the electron pressure $n_e \kappa T_e$ to the magnetic pressure $B^2/(8\pi)$] exceeding about 1.8% [6]. At lower values, the waves propagate to smaller minor radius before being absorbed. As anticipated by the slab model results, varying the launched value of $n_{\|}$ shows that the driven current hardly changes in either magnitude or in radial location in the range of $2.8<n_{\|}<4.2$. We compare the ray tracing with an $n_{\|}$ value at the launch point of 3 with $n_{\|}$(launch)=4 in Fig. 3, which shows that, as in the slab geometry, the steeper angle at which the higher $n_{\|}$ FW ray paths cross the field lines is compensated for by the higher damping rate per unit path length in that case, with the net result that the damping peaks at nearly the same value of normalized radius ρ~0.55.

3. Comparison of Different Absorption Models and of Ray-Tracing and Full-Wave Models

The calculations of electron absorption and current drive with the linear GENRAY ray-tracing code were checked with the completely different model of wave power absorption embodied in the CQL3D Fokker-Planck code [9]. These calculations show only a weak dependence of the radial location of the absorption and of the current drive efficiency on rf power level (Fig. 4), indicating only small deviation from a Maxwellian electron distribution function, in agreement with previous work. By comparison with the nearly electrostatic slow ("lower hybrid") wave, the FW damping is weaker and the quasilinear diffusion coefficients smaller, so that the linear result is a good approximation to the damping up to a much higher power level.

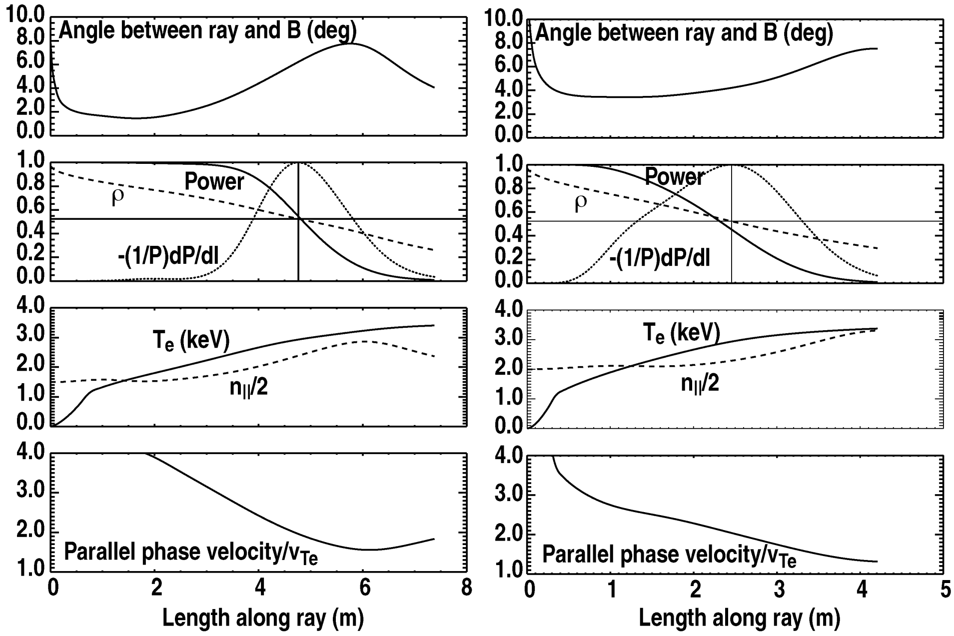

Fig. 3. Ray tracing of 0.5 GHz FWs at launched $n_{||}$=3 (left) and $n_{||}$=4 (right) in equilibrium from 122976. Note the difference in the horizontal scales.

Though we expect ray-tracing (essentially the local approximation) to be accurate for conditions with such short radial wavelengths and strong first-pass absorption, it does neglect diffraction and other higher-order effects. Hence, we have invested significant computational resources towards comparing these ray-tracing results with those from full-wave codes such as STELION [5], and AORSA [10]. Recently, converged AORSA results have been obtained for the same case as the baseline ray-tracing case shown above, except with $n_{||}$(launch)=4. So far it has been practical only to use a single toroidal mode number [N_{ϕ}=94 corresponds to $n_{||}$(launch)=4] and linear damping models; the computation uses 500 (major radial) x 500 (vertical) modes to represent the fields in the plasma and one case consumes 5 hours on 4096 processors to complete. Careful study of the numerical damping parameters used in the computation has been necessary, as this case is quite different in character from the lower frequency regimes studied in Ref. 8 and in other previous work. The result, as displayed in Fig. 5, is that the deposition and driven current profiles are similar to the result of the much less computationally intensive ray-tracing approach, with the computed profiles being slightly broader than those predicted from ray-tracing.

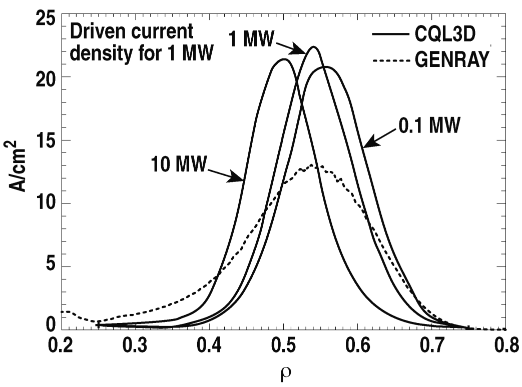

Fig. 4. Illustrating approximate agreement between the linear absorption and current drive model in GENRAY and the quasilinear model embodied in CQL3D. The latter shows that only at 10 MW of power is there a significant change in deposition profile, due to the small size of the departure from Maxwellian distribution function caused by the FWs.

4. Wave Launching

We may conclude from these ray-tracing and full-wave analyses that the desired mid-radius deposition and current drive will be obtained provided that the power can be launched with the desired $n_{\|}$ spectrum. Neither the ray-tracing nor the full-wave codes can address the physics of the wave launching process, for different reasons (the ray-tracing approximation fails in the coupling region, and although in principle it is possible to calculate all of the wave fields excited with a detailed antenna model in the full-wave approach, it is not practical due to the extremely high number of modes that would be required to get adequate resolution). The excitation of the waves involves issues of both linear and nonlinear physics. Linear physics issues include direct excitation of slow waves via the component of electric field parallel to the static magnetic field in a realistic launching structure, unintended excitation of various types of surface waves at the plasma/vacuum boundary, and the effect of wave scattering from density fluctuations in edge plasma, including "stimulated mode conversion" (scattering from fast to slow waves or vice-versa).

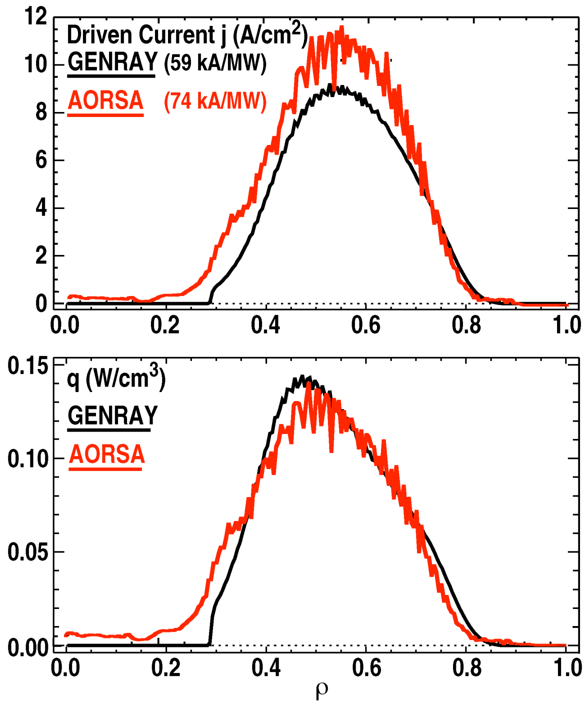

Fig. 5. The full-wave model AORSA (red) predicts similar profiles of driven current (top) and heat deposition (bottom) as the ray-tracing model GENRAY (black), indicating that the local approximation in ray-tracing is reasonably accurate for FWs in this regime.

Many of these undesirable effects are minimized by increasing the $|n_{\|}|$ of the launched waves. However, the linear coupling efficiency is exponentially dependent on $|n_{\|}|$, because the wave amplitudes in the low-density region outside the cutoff radially decay away from the antenna surface as $\exp[-(\omega x/c)(n_{\|}^2-1)^{1/2}]$. Hence the optimal $n_{\|}$ for a given frequency is a trade-off (Fig. 6) between accessibility (higher $n_{\|}$ is better) and difficulty in launching [lower value of $(n_{\|}^2-1)^{1/2}$ is better]. The diagram shows the value of the perpendicular index of refraction for a cold plasma at a fixed magnetic field as a function of density, for $n_{\|}$ values of 2 (neither wave can reach high density) or 4 (FW accessible to arbitrarily high density, SW limited by the lower hybrid resonance). The inverse hyperbolic sine function has been applied to $n_{\perp}^2$ on the vertical axis to provide logarithmic compression for either positive (propagating) or negative (evanescent) values, and linearity around values of $n_{\perp}^2 \approx 0$. FWs at $n_{\|}$=2 begin to propagate at significantly lower density than at $n_{\|}$=4, but even more significantly, the exponential decay is much slower in the evanescent region ($n_{\perp}^2$ is less negative at densities well below the cutoff). However, waves launched with $n_{\|}$=2 reflect back out of the plasma in the opposite

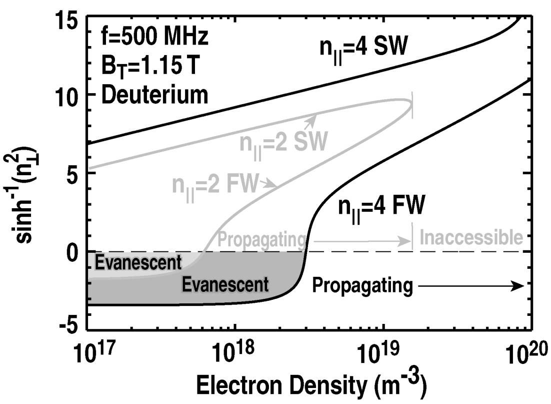

Fig. 6. Accessibility limits the usefulness of lower $n_{\|}$ launch, which otherwise would have much better coupling to an antenna in the vacuum region.

mode from the layer with density of $1.5x10^{19}$ m^{-3}. For either slow or fast wave launch, improved accessibility at higher toroidal fields for a given frequency would permit use of lower values of $(n_{\|}^2\text{-}1)^{1/2}$ and thereby achieve much improved coupling.

5. Design of Experiment, Wave Launching Structures

In order to experimentally evaluate the interplay between the wave-launching and core absorption issues, we are constructing an experiment to be carried out on the DIII-D tokamak. A source of microwave power at 476 MHz is available from a decommissioned accelerator at the Stanford Linear Accelerator Center, in the form of several 1.2 MW CW klystrons. This frequency is suitable for helicon current drive in the lower part of the LHRF for DIII-D toroidal fields between 1–2 T (geometric mean gyrofrequency $\sqrt{f_{cD} f_{ce}}$ = 461 MHz/T for deuterium).

While previous attempts to launch the FW in LHRF used launching structures based on dielectric-filled waveguide arrays, slotted waveguides, and toroidal arrays of individually end-fed poloidal radiating elements, the relatively short vacuum wavelength makes an antenna of the traveling wave type practical. This “comb-line” [11] consists of a array of poloidal rf current carriers (“straps”) in which the straps other than the one at the “upstream” end are fed only via the mutual reactance to the adjacent element. Thus only a single feed is needed which in turn makes a thin radial build and a much larger number of elements possible. Such an antenna at 200 MHz was designed and constructed by GA and demonstrated at medium power levels on the JFT-2M tokamak in Japan in 1996 [12]. A simple scaling of that 200 MHz structure to accommodate 476 MHz is not appropriate, however, because of the reduced radial evanescence length at the higher frequency. At 476 MHz, $n_{\|}$=3, the rf electric and magnetic fields decay away from the antenna surface with an e-folding length of 3.55 cm, and the effective antenna loading decays as the antenna-cutoff distance is increased with an e-folding length of half that value. To make the necessary number of toroidal elements and the width of the antenna practical, it is necessary to reduce the net mutual reactance from element to element from the value that had been used in the 200 MHz design. This results in a higher “Q” for each individual element and larger antenna currents for a given power level. Consequently the fraction of the applied power that is coupled to the plasma in one pass through the structure for a given plasma condition is increased.

The first stage of the experimental program is to construct a low-power (~0.1–1 kW) prototype array with twelve elements, install it into the DIII-D vessel and measure the antenna electrical properties in a variety of DIII-D discharges, in order to ascertain the required width and radial position of the antenna that would allow coupling of ~1 MW of power in a high-power version. This step is necessary due to the lack of reliable data on the radial location of the cutoff layer, where the density is $\sim 1.5x10^{18}$ m^{-3}, particularly in poloidal locations well off the midplane, the proposed array location (as in Fig. 2). To render discharges like DIII-D discharge 122976 free of MHD instabilities it has been found necessary to puff deuterium at a high rate throughout the high-beta portion of the discharge, and preliminary measurements of the scrape-off layer conditions in discharges of this kind show that the scrape-off layer (SOL) parameters resulting from heavy puffing may be favorable for good helicon coupling. Assuming satisfactory results from the prototype antenna, a wider antenna capable of coupling ~1 MW will be installed in late 2015, and one 1.2 MW klystron will be installed at the DIII-D facility. The prototype antenna design is shown as it will be installed into the DIII-D vessel in Fig. 7. Each of the twelve Faraday-shielded modules are rectangular, but will be installed at an angle of about 20 degrees from vertical in order to minimize the component of the rf electric field along the total static magnetic field at that poloidal location for field line pitch angles in the target discharge. This is intended to minimize direct excitation of the slow wave. Each module is a stack of four short poloidal straps, as is visible in the close-up of a single module on the right of the figure, where the back of the module has been made transparent to show the internal structure of the poloidal straps. The assembly is relatively compact, with a poloidal extent (height) of 0.21 m; our expectation is that the high-power version of the antenna will have a toroidal width of approximately 2 m. The need for power feeds only at the ends of the array makes it possible to install the array in a number of locations in the vessel, since the feeds need not be immediately adjacent to the end of the antenna. The installation shown in Fig. 7 will be just below one of the internal coils ('I-coils') used for studies of 3D magnetic fields.

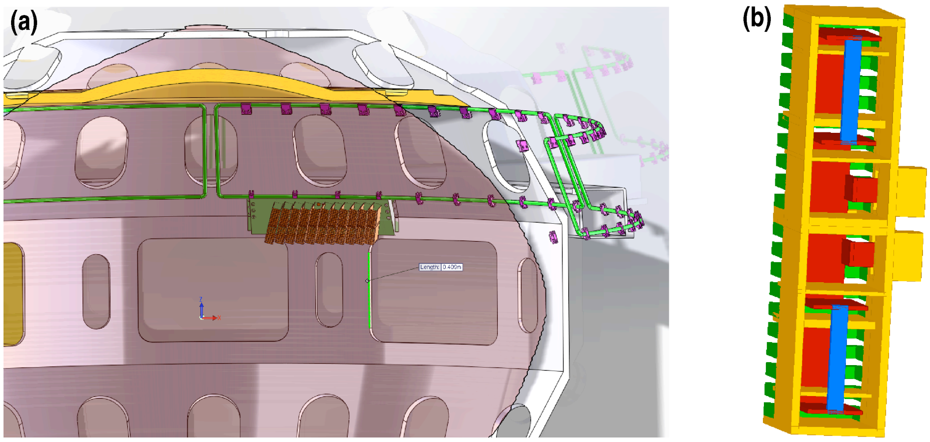

Fig. 7. View of the 12-element prototype comb-line antenna as it will be mounted in DIII-D. The structure shown in green is part of the internal 3D coil system. The drawing on the right shows a rear view of one module, 0.21 m high, with the back made transparent so the four poloidal segments of the current strap can be seen. This module is an end module with twin coaxial feeds; the modules other than the end ones are fed only by mutual reactance from its "upstream" neighbor.

The goals of the 1 MW-level experiment are to demonstrate that the current drive efficiency at mid-radius is in agreement with theory, and to investigate the nonlinear effects that could have an impact on the efficiency with which the helicon can be launched. Regarding the current drive measurement, previous work on DIII-D with central fast wave current drive, off-axis neutral-beam current drive, and electron cyclotron current drive has shown that driven currents of ~1% of the total plasma current can be successfully measured using the motional Stark effect diagnostic. The predicted driven current of ~60 kA/MW would provide significant margin relative to measurability in a ~1 MA discharge.

One class of nonlinear effects that could cause a reduction in the fraction of the applied power that couples to the desired waves is parametric decay instability (PDI). Parametric decay instabilities at high rf powers (MW level) could pose a significant obstacle to the efficient penetration of helicon waves through the plasma edge. While many different kinds of PDI have been studied, it is believed that the most important type of decay is into the kinetic form of the lower hybrid waves (high harmonic ion Bernstein waves) and ion cyclotron quasi-modes, the decay occurring near the lower hybrid resonance layer [13]. This form of instability is believed to be responsible for the density limit in the case of current drive with slow waves in the LHRF in tokamaks [14]. While in the slow wave pump case the dominant instability drive term is $E_{\|}$, in the case of helicon waves $E_{\|}$ is small and the dominant drive is $E_{\perp}$ (through a combination of the $E \times B$ and polarization drifts). In particular, at the ~1 MW power level injected by a comb-line antenna in DIII-D, the perpendicular electric field is predicted to be on the order of 40 kV/m near the the lower hybrid resonance layer. For reasonable plasma parameters in this vicinity, initial PDI growth rates are predicted to exceed 10^7 s^{-1}, and significant convective growth of the decay waves can occur. The possibility of significant nonlinear pump depletion in the proposed DIII-D experiment is a subject of ongoing theoretical study. Ultimately, only experiments can determine the significance of this process under realistic edge plasma conditions.

In summary, we find that the helicon (fast wave in the lower hybrid range of frequencies) shows great promise for efficiently driving non-inductive current in the mid-radius region of high-beta tokamak plasmas, in agreement with previous reactor studies that found only this method appeared to be viable for current drive in this region for reactor-like parameters. Linear ray-tracing and full-wave models predict deposition locations and current drive efficiencies that agree, and bounce-averaged Fokker-Planck quasilinear modeling also produces values and deposition profiles in agreement with the linear computations up to power levels of a few MWs. Remaining issues involve aspects of the excitation of the waves at the edge of the plasma. Both linear and nonlinear aspects require further study; predictive modeling of these aspects requires more detailed knowledge of the plasma parameters in a region of the discharge where precise measurements are difficult. The uncertainties in the linear coupling physics will be addressed in experiments on DIII-D in 2015, with low power coupling measurements to be carried out with a prototype antenna. To address the nonlinear aspects, such as the importance of parametric decay instabilities in the neighborhood of the lower hybrid resonance, and to produce measurable driven non-inductive currents in the mid-radius region, a follow-up DIII-D experiment at the 1 MW level is planned for 2016. Ongoing modeling efforts show the great potential value of this current drive method for devices such as FNSF [6]; recent studies have shown that the technique could even have application in a later phase of ITER.

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