Design Considerations and Research and Development of a Comb-line Traveling Wave Antenna for Helicon Current Drive in DIII-D[*]

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In the search for efficient methods of non-inductive current drive for tokamak reactors, attention has turned to current drive using fast waves in the lower hybrid range of frequencies, referred to as whistler waves or, more recently, helicons [1]. Early experiments on this were carried out soon after the successful demonstration of current drive with the other propagating cold-plasma wave in this frequency range, the quasi-electrostatic slow lower hybrid wave. The biggest challenges in these experiments, reviewed in [2], were (1) to obtain sufficiently strong single-pass damping, essentially by producing a plasma with sufficiently reactor-like electron beta, and (2) to efficiently excite a wave with high enough parallel index of refraction $n_\parallel$ with a wave launcher at the edge of the plasma. Both of these obstacles have been in principle overcome in the DIII-D tokamak recently. At least one operating regime has been identified [3] with simultaneously high density and electron temperature at mid-radius ($\rho{\sim}0.5$) to yield predicted full first-pass absorption of 0.5 GHz helicons launched at $n_\parallel{\sim}3$. The launcher concept, developed by General Atomics in the early 1990s [4,5] and demonstrated at 0.2 GHz on JFT-2M [6], is the 'comb-line' traveling wave antenna. As viewed from the plasma, this launcher looks like a wide phased array of many conventional Faraday-screened poloidally-oriented current-carrying straps, while the feature that makes a large number of radiating elements practical is that rf power is fed only to one end of the array (the 'upstream' end); power not radiated into the plasma from the fed element couples to the adjacent element via mutual reactance. If any power remains at the 'downstream' end of the structure, it is coupled out of the vacuum vessel via a feed structure identical to the one at the other end. Ideally, the lack of any internal reflections, or reflections from the downstream end means that a high degree of directivity is achieved, and the large width of the array, comparable to or exceeding the wavelength in vacuum, produces a narrow, well-defined $n_\parallel$ spectrum.

The basic electrical properties of such a structure can be derived from a simple lumped-element model [6] illustrated in Fig. 1. Here we assume that each Faraday-screened module interacts with its nearest neighbors predominantly via mutual inductance (rather than mutual capacitance.) As discussed in the monograph by Brillouin [7], the structure acts

as a bandpass filter with the center of the passband, where the phase difference between the current in one loop and the adjacent one is 90 deg at the self-resonant frequency of each loop, i.e. at $\omega = \omega_0 \equiv 1/\sqrt{LC}$. If we make the customary definitions $m = M/L$, $Z_c = \omega_0 L$, and $r = R/Z_c$ (or $Q = Z_c/R = 1/r$), we find that the frequencies of the upper and lower band edges are given by $\omega_{edges} = \omega_0/(1 \pm 2m)$, and that at the lower (upper) band edge the phase shift from one module to the next is 0 deg (180 deg). These expressions are for the limit of negligible dissipation R; taking into account small but nonzero dissipation (R representing the sum of the ohmic losses and the excitation of waves in the plasma), meaning $R \ll 2\omega_0 M$, we find that at mid-band the complex multiplier relating current and voltage in one module to the next is approximately $\pm i\left[1 \mp (r/2m)\right]$. This yields the relationship

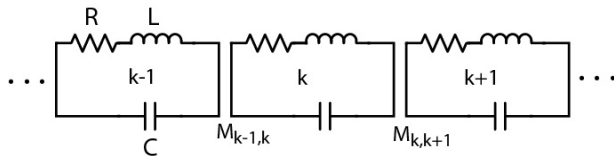

Fig. 1. *Simplest lumped-element model of a comb-line, where the self-inductance of each module is L, the capacitance is C, the mutual inductance between adjacent modules is M, and the sum of the resistive losses and the wave loading if plasma is present is R.*

between the lumped parameters of the modules and the observable power transmission coefficient $|T|^2$ from one module to the next:

$$|T|^2 \cong \left(1 - \frac{R}{2\omega_0 M}\right)^2 \approx \left(1 - \frac{R}{\omega_0 M}\right) \quad \text{for}$$

$R \ll 2\omega_0 M$.

The comb-line is a dispersive structure, in that the phase velocity and group velocity (the speed with which energy propagates) along the structure are not equal. This can be shown by introducing the simplest aspect of the one-dimensional geometry to the model, by defining D as the center-to-center distance from one module to the next. The wavenumber is then $k = \frac{2\pi}{\lambda} = \frac{\Delta\phi_R}{D}$, where the phase difference between one element and the next in radians is $\Delta\phi_R$. Then the phase velocity $v_{ph} = \frac{\omega}{k} = \frac{\omega D}{\Delta\phi_R}$ (at mid-band, $v_{ph}(\omega = \omega_0) = 4Df_0$) and the group velocity at mid-band, neglecting R, is $\left|v_{gr}(\omega = \omega_0)\right| = 2\pi m D f_0$. Increasing the fraction of the mutual inductance to the self-inductance (m) increases the group velocity without affecting the phase velocity, and at mid-band, $\left|v_{gr}/v_{ph}\right| = \left(\frac{\pi}{2}\right)m$.

A key practical question is: what is the efficiency with which power fed into the comb-line can be coupled into the plasma? How many elements must be in the comb-line to couple a specified fraction of the applied power to the plasma? As for any kind of wave launcher, this depends on the plasma loading per element and on the vacuum losses per element, i.e. on R with and without plasma. For a given antenna, the vacuum losses per element can be determined by a measurement of Q for a single module, though care must be taken to not permit the single module to radiate into vacuum. The plasma loading will depend strongly on details of the electron density profile in the near field region of the

antenna, chiefly on the distance between the antenna surface and the right-hand cutoff for the fast wave and on the density gradient in the region of the cutoff. Since these parameters are not well known in the poloidal region of DIII-D in which the antenna is to be installed, a low-power measurement was made in 2015-16 on DIII-D with a 12-element prototype antenna at the same poloidal (and toroidal) location where a subsequent high-power antenna will be installed [8]. The primary goal of this experiment was to determine whether the plasma loading in the operational regime with predicted full single-pass absorption was sufficient to yield an efficiency of 75% or greater with a 30-element high-power antenna. To extrapolate from the results of that low-power experiment to another antenna with more elements, examination of the scaling of the efficiency with antenna parameters is necessary. We find that the fraction of the power applied to the upstream end of the antenna that is coupled to the plasma in one pass through the structure is given by $\frac{P_{pl}(N)}{P(1)} \cong \left(1 - \frac{P(N)}{P(1)}\right)\left(1 - \frac{r_v}{r}\right)$, where $P(1)$ is the power applied to the structure, r_v is the inverse of the unloaded Q_0 of a module, r is the inverse of the Q of a module with plasma loading, and $P(N)$ is the power remaining after the last (Nth) module, which is assumed to be dissipated in a termination. This assumes perfect impedance matching to the feed line at the upstream end and a matched termination at the downstream end (no reflections), and that the effective mutual inductance between modules is not changed significantly in the presence of the plasma from the value without plasma load. To extrapolate from the low-power prototype with 12 modules to the 30-module high-power version of the antenna requires knowledge of the unloaded Q of a single module of each design and of the mutual inductance coupling factor $m=M/L$ for each design. In [8], it was assumed that the high-power antenna modules would be geometrically identical to those of the low-power prototype so that m, and hence the group velocity through the structure, would be identical in the two antennas. Hence the extrapolation involves only the achievable unloaded Q of the module for the high-power design and the number of modules in the structure. With the demonstration of a large increase in the unloaded Q of a module for the high-power design, the plasma loading measured in the desired plasma regime led to the projection of > 75% efficiency for the high-power antenna design with 30 modules. Bench tests of more than a single module are necessary to test the assumption of unchanged normalized mutual m for the high-power design, which have not been completed at this writing.

Other practical aspects of the high-power comb-line design are being studied in a test stand, consisting of a vacuum chamber in the bore of a 0.1 T solenoid and a 13 kW rf power supply in the 400-800 MHz range. So far, testing of one-fourth of a single module of the high-power design, shown in Fig. 2, has been carried out to determine the effect of multipactor discharge and to study the high-voltage breakdown limit of the module design. This has been performed at relatively low power by placing the quarter module in a high-Q

resonant circuit. So far, studies of multipactor discharges have shown that the tendency of such discharges to detune the resonator can be eliminated by conditioning. A quarter module with bare copper surfaces has been compared with one with TiN-coated surfaces; the behavior of the module with bare copper appears to be better in some ways. A half-wavelength-long section of the stripline which will convey ~1 MW of power from the vacuum feedthrough to the fed end of the antenna has been constructed and resonated; these tests are also underway and will be reported in a future publication.

Fabrication of the high-power comb-line has begun; installation of the structure in the DIII-D vessel and subsequent operation of the system at 1 MW are planned in 2020.
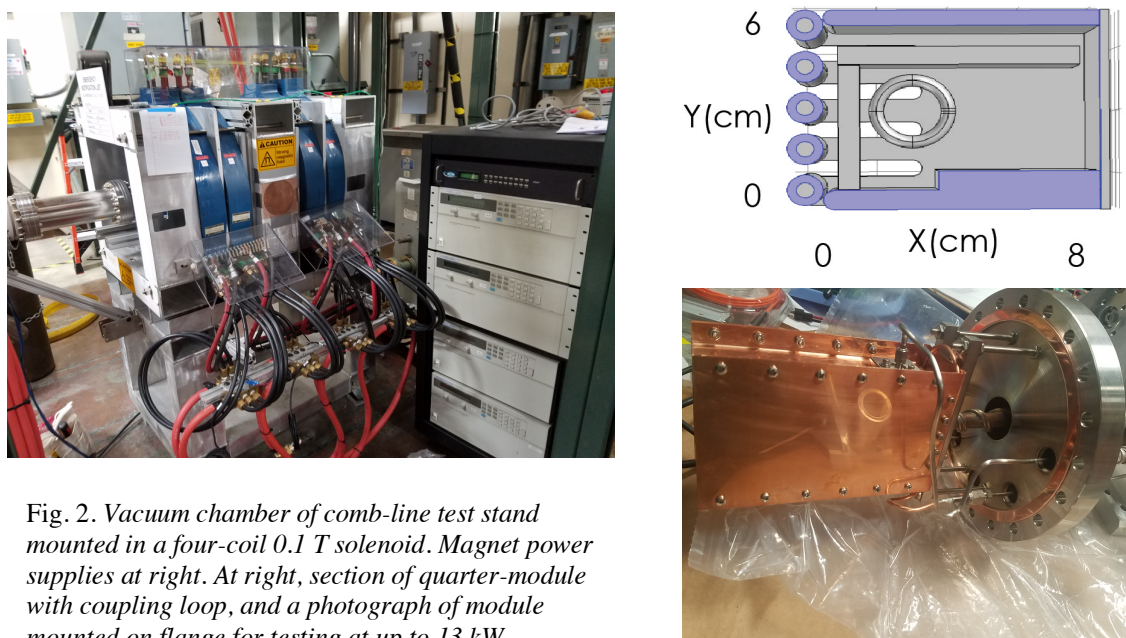
Fig. 2. *Vacuum chamber of comb-line test stand mounted in a four-coil 0.1 T solenoid. Magnet power supplies at right. At right, section of quarter-module with coupling loop, and a photograph of module mounted on flange for testing at up to 13 kW.*

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