Lower Hybrid Antenna Design for MST

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Abstract. Inter-digital line antennas are being used to test the feasibility of lower hybrid current drive in MST. The antennas use λ/4 resonators and launch slow waves at 800 MHz with $n_{\|} \sim 7.5$. Routine operation has been achieved with a good impedance match between antenna and plasma. High power antenna design improvements include larger vacuum feed-throughs, better impedance matching, and rf instrumentation on all resonators. The antenna and feed-through modeling was performed with CST Microwave Studio^{TM}. The pulse-forming network that powers the klystron is being upgraded to a 50 kV – 30 ms pulse. The goal for the LHCD system on MST is a modular design that can handle 300 kW per antenna.

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INTRODUCTION

Inductive current profile control has been highly successful in reducing transport in the Madison Symmetric Torus (MST) RFP [1], but it is transient and non-localized [2]. Current profile control with rf waves offers the possibility of steady and more precise control. Theoretical feasibility and optimization studies have identified the lower hybrid slow wave as a good candidate for current density profile control in the RFP [3]. Other studies have focused on fast wave current drive, which could also drive poloidal current in the outer region as well as toroidal current in the central region [4]. Ray tracing and Fokker-Planck calculations have identified suitable propagating waves that can provide localized current drive with relatively high current drive efficiency. To meet the goals of improving transport in an RFP, antennas have been designed and built to launch lower hybrid slow waves into MST.

MST LH ANTENNA DESIGN

The traveling wave antenna concept [5] is well suited for MST. It overcomes many of the inherent technical difficulties for the RFP, requiring only two coaxial feeds through the vacuum vessel, having a small radial height (<3 cm), and can be mounted on the inner wall of MST. The inter-digital line is an electrostatic variant of the comb-line antenna used successfully for launching fast waves on JFT-2M [6]. It behaves electrically like a microwave band-pass filter [7], and has been designed to produce the desired $k_{\|}$ spectrum at 800 MHz. The antenna is a slow wave structure

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in which a resonant array of conducting rods is alternately grounded to opposite sides of a rectangular cavity. The rods are coupled to each other both inductively and capacitively, and are matched to 50 Ω coaxial feeds at each end of the array. Coupling to the lower hybrid wave is accomplished by the electric field between elements fringing though an aperture in the cavity. The fields are evanescent in vacuum but couple to the slow wave at $n_{||} = 7.5$ in the presence of plasma.

The first LHCD antenna for MST was designed using the SPICE circuit simulation code [8]. The antenna was modeled as an array of coupled transmission lines using analytic impedance estimates. Initial experiments investigated coupling and loading issues from 10 W to 10 kW. These experiments showed that one feed had a power limit of 2-3 kW, above which the antenna was fully reflecting. The other feed was fully reflecting at all power levels. This antenna had 1 cm diameter vacuum feed-throughs and the impedance match between the feeds and the traveling wave structure was not very good, resulting in a VSWR ~ 6. Bench measurements of the wave spectrum showed that the desired $n_{||} = 7.5$ was being produced but also indicated that external circuit tuning is an important parameter in the antenna behavior. With these limitations on the power flow in the antenna identified, a second antenna was designed, built, and installed in MST.

In designing the second MST LH antenna, a finite-element method was used to refine the impedance values that are input to the SPICE model [9]. This led to better impedance matching, a lower VSWR ~2, and lower Ohmic losses inside the structure. In addition, a larger diameter (2 cm) vacuum feed-through was designed in order to achieve a better impedance match at the coaxial feed and to obtain better power handling. Instrumentation was added to the antenna backplane to measure power density near the center of the antenna. Experiments designed to investigate coupling and loading issues were carried out with the second antenna [10]. This antenna can handle up to 80 kW, which is the limit of the klystron given the capabilities of the pulse-forming network power supply. The impedance match to the antenna is good over a wide range of plasma parameters and input power when fed from both ports.

The behavior of the antenna phasing and $n_{||}$ spectrum during plasma operation has been investigated. Vector network analyzers are used to measure the power amplitude and phase on the central five elements of the antenna. As shown in Figure 1, the phase between elements remains near the $\pi/2$ design value. The $n_{||}$ can be calculated from the measured phase data, ϕ, by $<n_{||}> = \frac{<k>}{|k_0|} = \frac{<\phi>/d}{2\pi/\lambda_0}$, where d = 1.2 cm, the element spacing, and $\lambda_0 = 37.5$ cm, the vacuum wavelength. The antenna phasing and hence $n_{||}$ are quite robust to plasma loading and show only slight changes over a wide range of parameters. An example of this behavior versus plasma density is shown in Figure 2. The measured value of $n_{||}$ is near the design value of 7.5. The variation of $n_{||}$ with respect to wave launch direction is under further investigation.

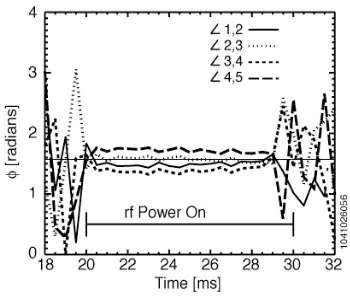

FIGURE 1. Phase between the central five elements of the antenna measured with a vector network analyzer phase-locked to the transmitter. Each line represents the phase difference between adjacent antenna elements. The design value for the phase is $\pi/2$ radians.

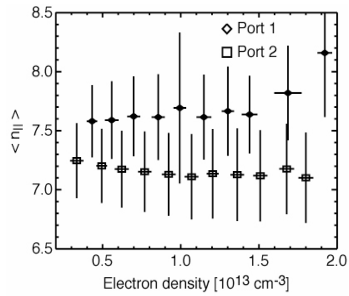

FIGURE 2. The parallel index of refraction is robust to plasma loading. The index is calculated from the phase data of Figure 1. The discrepancy between the different launch directions persists over a wide range of plasma parameters.

In order to carry the MST lower hybrid program forward there will be several upgrades performed to the transmitter system and antenna. The pulse-forming network that powers the klystron will be upgraded to a 50 kV, 30 ms long pulse. This should allow for 300 kW tube operation. To handle this increased power, the antenna is being redesigned. The CST MicroWave Studio^{TM} package for full 3D electromagnetic computer modeling is being used to design the new antenna. The model of the antenna used as input to the code is shown in Figure 3.

To handle the increased power, larger diameter feed-throughs (4 cm) have been fabricated in-house. This will keep the power density at the vacuum interface similar to that of the present antenna (~250 MW/m^2). In addition, a longer impedance matching section is needed to accommodate the larger feeds (see Fig. 3). It is desirable to lower the VSWR to less than 1.4. This will remove the need for external tuning and achieve better directivity. Modeling with Microwave Studio^{TM} has resulted in a design with good impedance matching of the antenna to the feeds, a VSWR < 1.1, and a reflection coefficient of less than –30 dB over the frequency range of interest (see Figure 4). The third generation antenna will have improved instrumentation. Vector power measurements of each antenna element will characterize the power flow along the structure. Phase and amplitude electronics are under construction and will be used to look for changes in the antenna dispersion with plasma loading. In addition, Langmuir probes will be installed on the antenna to characterize the edge plasma.

EXPERIMENTAL PLAN FOR MST LHCD PROGRAM

A 300 kW lower hybrid system will be operational in MST by the summer of 2005. A new pulse-forming network to power the klystron is being constructed and the third generation antenna is being built. Testing and experiments will then proceed in stages. First, coupling and loading measurements will be performed at powers up to

300 kW. Wave propagation and rf-plasma interaction will be studied in detail to confirm that the antenna is coupling to the desired wave. The power flow and loading along the structure will be measured and power handling limits investigated in order to produce an optimized design for higher power experiments. Second, the program will be expanded to 600 kW by adding another 300 kW klystron-antenna module. It is expected that this power should be sufficient to estimate the current drive efficiency. Ultimately, a high power (1–2 MW) LHCD experiment will be designed and implemented with fluctuation and transport reduction as the goals.

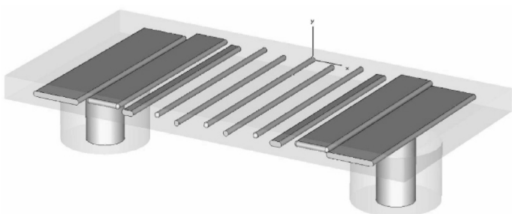

FIGURE 3. Model of the antenna used for input to the CST Microwave Studio™ 3D electromagnetic simulation code. Note the larger coaxial feed-through and the longer impedance matching section.

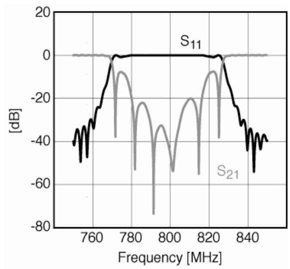

FIGURE 4. The S-parameters resulting from the simulation are shown over the frequency range of interest. S_{11} is the black line and S_{21} is the gray line.

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