Design of a Lower Hybrid Antenna for Current Drive Experiments on MST

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Abstract. RF current drive has been proposed as a mechanism for reducing the tearing fluctuations that are responsible for anomalous energy transport in the RFP. To this end, a system for launching lower hybrid slow waves at 800 MHz and $n_{\|} = 7.5$ has been designed and implemented in MST. The antenna is an enclosed interdigital line using 1/4 wavelength resonators with an opening in the cavity through which the wave is coupled to the plasma. The power handling capability of the present antenna design has been investigated. Presently, the power limit at which the antenna begins to reflect nearly all the launched power is ~ 3 kW. A boron nitride limiter assembly was added to the antenna and resulted in only a slight increase in the observed power limit. The antenna has been removed from the vacuum vessel and an inspection revealed no signs of damage after 16 months of operation inside of MST.

INTRODUCTION

Experimental and theoretical results indicate that anomalous energy and particle transport observed in the reversed field pinch (RFP) is due to tearing fluctuations. This transport has been observed directly [1,2] in the Madison Symmetric Torus (MST) RFP [3]. Tearing fluctuations are driven by current density gradients and thus, current profile control should affect transport. Indeed, reduced transport has been achieved by employing auxiliary inductive poloidal current drive in MST [4]. Recent experiments on MST have produced a nine-fold improvement in the energy confinement compared to a standard RFP plasma [5]. However, inductive current drive is an inherently transient technique and is non-local in nature.

RF poloidal current drive has been proposed [6] to provide steady control and more localized current deposition. Studies have indicated that the lower hybrid slow wave should be a good tool for current density profile control in the RFP [7]. Also, the predicted current drive efficiency should be sufficient to suppress the tearing fluctuations with RF power levels of less than 3 MW. To meet the goals of improving transport in an RFP, an antenna has been designed and built to launch lower hybrid slow waves into MST.

ANTENNA DESIGN

The prototype antenna designed for MST satisfies some very stringent constraints. The antenna is installed through the small portholes (<4.5" diameter) in MST so that vacuum vessel disassembly is not required. In addition, the antenna does not disturb the plasma that is surrounded by a close-fitting shell. The interdigital line concept [8] is very well suited to launching the lower hybrid wave in MST, requiring only two vacuum feed-thrus and having small radial extent. The initial prototype antenna is shown in Figure 1. The antenna is curved to match the radius of the vacuum vessel. Power can be fed to either the "inboard" or "outboard" side of the antenna with the other end being connected to a dummy load.

FIGURE 1. Pictures of the fully assembled antenna. The picture on the left shows the antenna on the bench with the flange and vacuum / power feed-thru. The longer of the two feed-thrus is located furthest to the inboard side of MST. The picture on the right shows the antenna installed in MST in October 1999 (the plasma facing components and rods are molybdenum; edge limiter is boron nitride).

The antenna is a slow wave structure in which a resonant array of quarter-wavelength 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 ohm coaxial feeds at each end of the array. RF power enters the structure at one end and then propagates to the other end; along the way some power is radiated as a lower hybrid slow wave [9]. It is important to make the structure long enough that most of the power is radiated before it reaches the opposite end as any remaining power is dissipated in an external dummy load.

The interdigital line behaves electrically like a microwave band-pass filter, and has been designed using SPICE circuit simulation to have the correct spacing and phase shift per element to produce the desired $k_{||}$ spectrum at 800 MHz. The frequency has been determined by the availability of klystrons and the desire to operate well above the theoretical density limit. 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 plasma.

INITIAL OPERATION IN MST

Initial experiments were designed to investigate coupling and loading issues. This antenna has been used in experiments from 10W to 10 kW as shown in Figure 2. As seen in Fig. 2(a), when the antenna is fed through the "inboard" port, the antenna is well behaved up to a power level of ~2-3 kW. At low power (<50 W), the antenna presumably undergoes a multipactor discharge, but as the input power is increased, the reflected power is decreased so that <10% of the input power is reflected. At >2-3 kW, the antenna suffers a breakdown and nearly 100% of the input power is reflected. The behavior of the antenna when the power is injected from the "outboard" port is quite different [Figure 2(b)]. Here, the antenna is never well behaved and the input power is nearly all reflected regardless of power level.

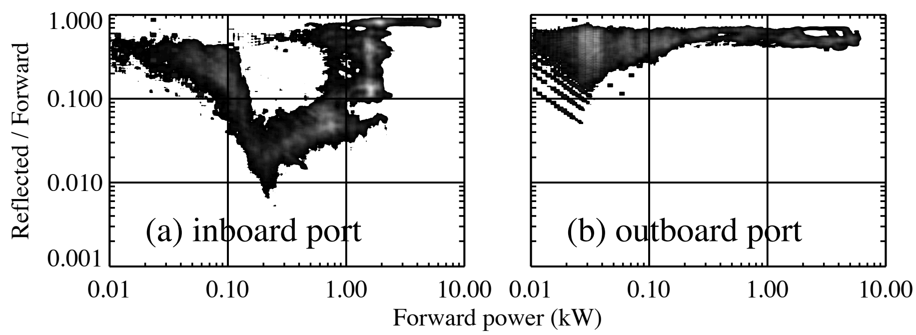

FIGURE 2. The antenna behavior in the presence of RFP plasma over many shots is displayed in a contour plot. When fed from the inboard port (a) the reflected power decreases until it reaches a level of < 10% and at a power level of ~2-3 kW it increases abruptly to nearly fully reflecting. When fed from the outboard port (b), the antenna is always nearly fully reflecting.

Scans of plasma parameters such as current and density were performed to improve the performance of the antenna. These scans were not successful in improving the antenna behavior. The antenna was observed with a CCD camera during RFP operation and no deleterious effects were noted. It was suspected that plasma might be interfering with antenna operation. So a boron nitride limiter assembly was added to the face of the antenna to change the density in front of the antenna. The behavior of the antenna was quite similar with or without the limiter.

The antenna was removed from the MST vacuum vessel for inspection in February of 2001. There were no indications of damage to the antenna despite being in a plasma environment for over a year. There are no visible clues as to why the "outboard feed" would not handle power. The occurrence of a multipactor discharge was verified in vacuum at low power. Bench measurements of the wave spectrum were then undertaken and showed that the desired $n_{||} = 7.5$ was being produced. However the directionality of the wave was very dependent on the external circuit tuning. For some external tuning, a standing wave results instead of a traveling wave. These measurements also indicate that better impedance matching is needed between the coaxial feed-lines and the antenna.

DISCUSSION

Through a combination of circuit modeling, finite element analysis and bench tests, an interdigital line antenna has been designed which produces the desired wave spectrum as measured on a test stand and has operated in MST for over a year at power levels up to several kilowatts. The impedance match to the antenna is good, with low reflected power over a range of plasma parameters and input power when fed from the "inboard" port. The power limit is presently ~3 kW and is not affected much by the presence of a limiter on the antenna face. The present antenna design is being upgraded with larger power feeds, better impedance matching, and better mechanical accuracy to address the power feed asymmetry issue. Diagnostics to measure wave fields are being incorporated into the antenna design. These changes will be tested up to ~50 kW.

Current profile control experiments on MST will proceed in three phases. The first phase includes the present coupling and loading measurements being made at low to medium power. The damping length along the structure will be measured and power-handling limits investigated in order to produce an optimized design for higher power experiments. The second phase will attempt to answer physics questions associated with lower hybrid current drive in an RFP. These topics include the density limit, fast electron transport, and wave scattering by density fluctuations. During this phase the antenna will be optimized for power $\leq$ 400kW in the plasma environment and the current drive efficiency will be estimated. The third phase consists of designing and implementing an experiment to reduce fluctuations and transport. This will only be attempted if the measured current drive efficiency is sufficiently high and the current can be localized in the proper region of the plasma for tearing fluctuation suppression.

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