Lower Hybrid and Electron Bernstein Wave Current Drive Experiments in MST

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Abstract. Inductive current profile modification in MST has been successful in reducing fluctuations and transport but is transient and radially non-localized. Current profile control with rf waves offers steady and more precise control. Studies of lower hybrid wave and electron Bernstein wave injection are underway. The lower hybrid antenna has coupled 125 kW to the plasma. Hard x-ray emission with energies as high as 50 keV has been observed and the emission is spatially localized to the antenna location. A 250 kW system designed to heat electrons and drive current via the electron Bernstein wave is in operation at 3.6 GHz. Coupling studies performed with a phased-waveguide antenna have shown that the total power reflection coefficient can be maintained near 10%. X-ray production studies are in progress.

1. Introduction

Inductive edge current profile modification in MST [1] has been highly successful in reducing fluctuations and transport and increasing confinement time, temperature, and beta [2]. However, these modifications are transient and non-localized. Current profile control with rf waves offers the possibility of steady and more precise control. Feasibility studies for two rf approaches are underway, one based on the (slow) lower hybrid (LH) wave and one based on the electron Bernstein wave (EBW). Ray tracing and Fokker-Planck calculations predict good absorption and directional control for both waves, as required for effective current drive [3]. The LH and EBW approaches have complementary strengths. The physics and application of LHCD are well established in tokamak research, but innovation in antenna design is required for MST use. In contrast, the EBW approach benefits from simpler antenna requirements, but the wave physics is not yet well established for the high-β plasma.

2. Lower Hybrid System

Poloidal current drive using lower hybrid waves has been proposed for several reasons. First, LHCD has proven to be an efficient rf method for non-inductive current drive in tokamaks. The physics of LHCD developed for the tokamak carries over to the RFP, with some modifications. Second, the slow wave trajectory can be localized in the outer region of the plasma where the current drive is desired by choice of parallel wave number and rf frequency. The fast wave is more weakly absorbed and tends to penetrate much deeper into the plasma.

This first application of rf to the high dielectric RFP presents challenges in rf physics, *e.g.*, confinement of fast electrons, and in antenna design. Stringent geometric constraints of the MST vacuum vessel (limited port holes, small radial extent, *etc.*) forced a novel interdigital line antenna to be chosen to assess the feasibility of this rf-based approach to current drive [4]. The third generation of this antenna is shown installed in MST in Figure 1. This traveling wave antenna operates at 800 MHz and $n_{||} \sim 7.5$; parameters chosen (through GENRAY and CQL3D modeling) to drive current in the edge ($r/a \sim 0.8$) with strong singlepass absorption. Extensive engineering testing and antenna loading studies have been performed to validate the antenna design in a variety of plasmas up to the present source power limit of 225 kW. At present, up to 125 kW have been coupled to the plasma.

Hard x-ray (HXR) emission from fast electron bremsstrahlung with energies up to 50 keV has been observed using CdZnTe detectors during lower hybrid wave injection [5]. This indicates that a region of good confinement for energetic electrons may exist. With co-current drive, the emission is spatially localized at the antenna location with a toroidal spread of about 60 degrees (see Figure 2). In contrast, for counter-current drive, the emission peaks ~15 degrees toroidally away from the antenna and the spread is ~two times greater. This interesting toroidal localization of the emission that occurs in the dominantly poloidal magnetic field of the RFP could result from the formation of a localized current structure.

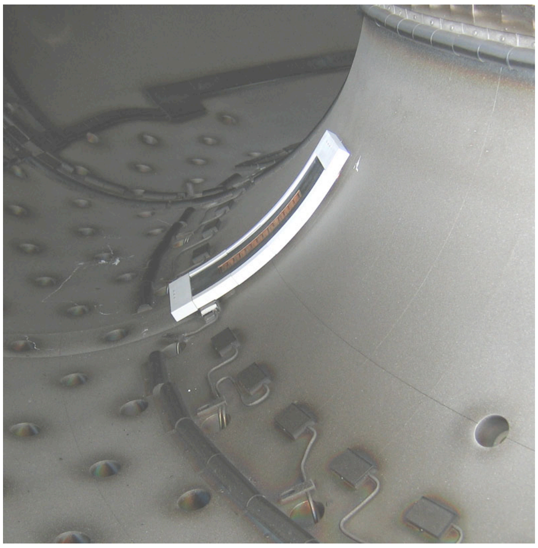

Figure 1. The interdigital-line traveling wave antenna used for lower hybrid wave injection experiments on MST.

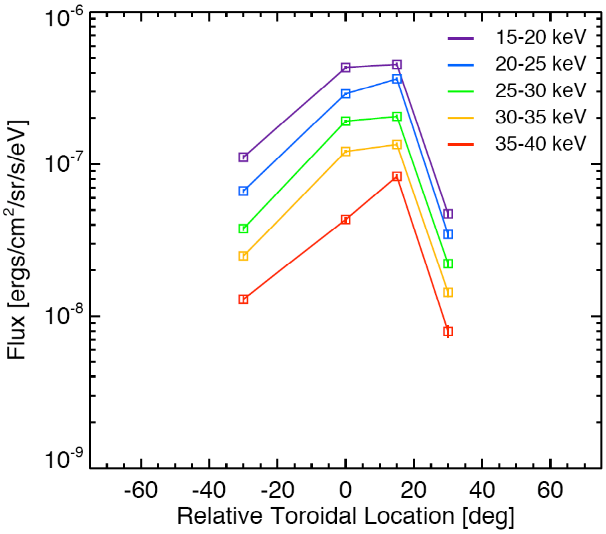

Figure 2. Profiles of HXR emission measured with CdZnTe detectors during LH wave injection. The toroidal angle is location relative to the antenna.

Two populations of fast electrons have been measured. One population is observed close to the antenna structure itself, “near-field”, and the other is seen away from the antenna in the “bulk”. The interaction of electrons with the electric fields in the “near-field” of the antenna has been modeled with a Monte Carlo code. It has been found that the “near-field” electron distribution can have a high-energy tail similar to that seen experimentally. This suggests that the “near-field” emission is due to prompt loss in the plasma edge. The HXRs observed from the “bulk” fast electrons are being modeled with the Fokker-Planck code CQL3D. Predicted HXR fluxes can be compared to the measured values and can be used to calculate the amount of driven current. However, the toroidal localization of the emission in the “bulk” makes comparisons difficult due to the flux-surface averaging used in CQL3D. Additionally, the high diffusion in the RFP makes modeling difficult but ultimately may be the cause of the localized “bulk” emission.

3. Electron Bernstein Wave System

RFP plasmas have high β and thus are inaccessible to electromagnetic heating or current drive at the electron cyclotron resonance. Unlike the tokamak, for which ECH and ECCD are routine, the plasma in the RFP is overdense: electromagnetic waves in the ECRF cannot propagate because the wave frequency is lower than the plasma frequency. The electron Bernstein wave (EBW), a nearly electrostatic solution of the hot plasma dielectric tensor, presents a different opportunity for heating and current drive at the electron cyclotron resonance [6]. Theory, simulations, and experiments show that EBWs convert to and from electromagnetic waves at the extreme edge of overdense plasma. It has also been found that the wave absorption is strong, a result of the electrostatic nature of the waves, giving efficient supra-thermal tail formation and current drive. If externally launched electromagnetic waves can be efficiently converted to the EBW, this could very well be the ideal current profile modification tool for the RFP. In addition, ray propagation studies have shown that the launched EBW can be used to drive a net current in either the parallel or anti-parallel direction based on choice of launch angle.

Significant advances have been made in EBW research on MST. Measurements of blackbody levels of cyclotron emission from the core of the RFP have been made [7]. The radiation temperatures for O- and X-mode polarizations are shown in Figure 3. These temperature profiles are also plotted together with the measured electron temperature in Fig. 3. The mode-conversion from EBWs to electromagnetic waves that occurs at the plasma boundary was measured to be 75% efficient. Reciprocity implies that if EBWs can be launched from the edge, efficient heating and current drive can occur.

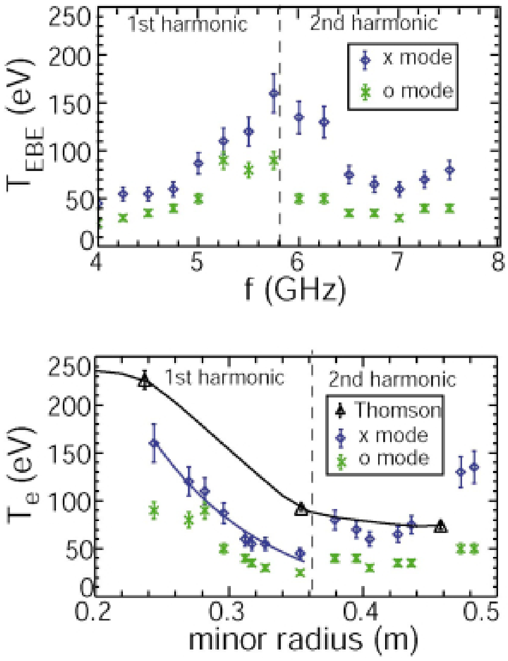

Figure 3. Profiles of electron Bernstein emission temperature measured with a radiometer in standard plasmas.

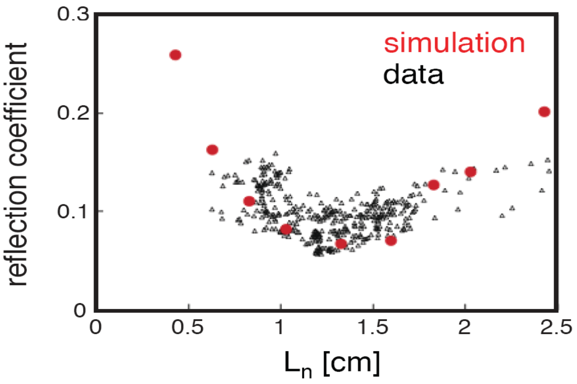

Figure 4. The reflection coefficient measured during EBW injection compares well with that calculated using full-wave theory. The density scale-lengths are typical of MST discharges.

A simple waveguide antenna for launching EBWs was designed, built and installed, and operated to study coupling at low power (< 10 W) [8]. A full wave coupling theory was incorporated into a computer simulation and tested against experiment. This aids in optimization of the launch structure and for interpretation of the experimentally measured phase and amplitude of the reflected portion of the incident electromagnetic wave. The simulations predict that coupling efficiency should depend strongly on the edge density gradient at the upper hybrid resonance (typically within 1-2 cm of the antenna). This is confirmed by experiment and is shown in Figure 4. The agreement between simulated and measured power reflection coefficient is good over a range of density scale lengths typical to the MST edge.

Presently, a 0.25 MW system designed to heat electrons and drive current via the electron Bernstein wave is in operation on the MST reversed field pinch. The antenna is a grill of four half-height S-band waveguides with each arm powered by a separate, phase controlled traveling wave tube amplifier at 3.6GHz. The X-mode polarization is being used to launch electromagnetic waves that mode convert to the EBWs in the edge plasma. Coupling to the plasma (as measured by ratio of reflected power) is very dependent on the relative phasing between adjacent waveguides and the total reflected power can be maintained near the 10% level.

Conditioning of the antenna is currently underway (near the 0.2MW level) and total system power is expected to reach 0.25MW, or roughly a fourth of the Ohmic input power in target plasmas. The x-ray spectrum (5-200 keV) is monitored as a way to detect modification to the electron distribution as full transmitter power is approached. Recent experiments using a 20-chord camera have noted toroidally localized soft x-ray emission between 4 and 10 keV.

Both rf current drive projects are proceeding as staged experiments. A power upgrade to the LH transmitter will be finished in the near future. This will allow for testing of the engineering limits of the compact antenna. The EBW project is exploring the possibility of operating at a higher frequency for which a high power (1 MW) tube already is available. The higher frequency means that smaller waveguide antennas can be used and thus allows for more flexibility in launch location. It is envisioned that 1-2 MW systems will be necessary to drive sufficient current to suppress fluctuations and improve transport.

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