

# Diagnosis of Lower Hybrid on MST

D. R. Burke, J. A. Goetz, M. C. Kaufman, A. F. Almagri, J. K. Anderson,  
C. B. Forest and S. C. Prager

*University of Wisconsin - Madison, Madison WI 53706*

**Abstract.** RF driven current has never been demonstrated in a Reversed Field Pinch. Recently the lower hybrid system on the Madison Symmetric Torus reached a new operating regime. This upgrade allows RF powers of up to 5% of the Ohmic input power to be injected. It is therefore anticipated that the lower hybrid system is on the threshold of producing meaningful changes to the RFP equilibrium. A diagnostic set is under development to facilitate the study of such changes and lay the foundation for near megawatt operations. Many measurements are being studied for viability. These include electron cyclotron emission, examinations of bulk ion and electron heating, surface perturbation pickup coils, magnetic probe measurements, and Langmuir probe measurements. In addition, several x-ray diagnostics are in operation: pulse height analysis is performed on detector arrays to determine the 5-200 keV spectrum. An insertable target probe is available to create x-rays from fast electrons. Tomographic inversion of 2-D Soft x-ray detectors yields equilibrium information through island structure. Results from experiments with source power up to 225 kW will be presented. Preliminary results from CQL3D Fokker-Planck simulations will also be presented.

\*Work supported by US DOE Contract DE-FC02-05ER54814

## INTRODUCTION

A major obstacle to employing the Reversed Field Pinch (RFP) as a fusion reactor is stochastic transport, caused by overlapping magnetic islands. The gradient in parallel current density has been identified[1] as the free energy source for the tearing modes responsible for island formation. The most straightforward way to eliminate this current gradient is to drive current in the plasma. MHD simulations have shown that by driving current near the reversal surface ( $r/a \approx 0.7$ ), flux surfaces can be restored, reducing transport and improving global confinement[2].

Lower hybrid slow wave injection is an attractive candidate for a current drive technique. Unlike other, more established current drive methods in the RFP, LHCD is neither inherently pulsed [3], nor does it require an oscillatory equilibrium[4]. LHCD experiments on the MST have recently been upgraded to higher power. Source powers of 225 kW have been achieved. This corresponds to between 80 and 100 kW deposited in the plasma, compared with ohmic input power in the range of 2-10 MW. Because of the dynamo effect in the RFP, simple loop voltage is not necessarily an effective measurement of driven current. It has therefore become critical to develop a suite of diagnostics to assess the current drive efficiency.

## ELECTROMAGNETIC SPECTRUM DIAGNOSTICS

One of the principle expectations of lower hybrid current drive is that it will produce a high energy electron tail[5]. Many experiments have observed effects of this tail by looking at the X-ray spectra coming from the plasma[6, 7]. Additionally, diagnosis of the X-ray spectrum could indicate a competing absorption mechanism (for example bulk or edge heating of electrons) and how effective it is at diverting power.

One of the most important diagnostics we have for lower hybrid operations on MST is the x-ray spectrum. Currently, the portion from 10 keV to 300 keV is well diagnosed. Two systems are in place in this energy regime - a 16 channel CdZnTe camera and 12 independently movable CdZnTe detectors. These diagnostics reveal a high energy tail during lower hybrid operation that is completely absent during standard MST discharges. It is not currently known if these are emblematic of current drive since the radial location of emission has yet to be conclusively determined. Nonetheless these are considered important diagnostics because of their solidly reproducible effect which can be conclusively connected to lower hybrid wave injection.

Currently, work is being done in an attempt to expand the energy window that is being diagnosed. A preliminary study has begun using surface barrier detectors with beryllium filters, which produce an energy-integrated signal. By gating multiple detectors with different energy filters and comparing the outputs, a small number of low energy (1-10keV) bins can be produced. While this is not necessarily sufficient, success would provide the impetus for investing in a lower energy camera. An established diagnostic on MST is tomographic inversion of a 2-D soft x-ray array. This is of particular interest for RFP current drive as we anticipate driven current to restore flux surfaces. This structure has been seen with inductive current drive[8]. Observation has not yet been done at high power operation.

A second method of diagnosing the fast electron tail is to observe the cyclotron radiation. Electrons in MST have a cyclotron frequency near 4 GHz. Superthermal electrons are expected to emit cyclotron radiation that is doppler shifted by significant amounts. By examining higher frequency radiation, the doppler shift can be determined. This technique has been used on the PLT tokamak[6]. In order to measure this radiation, a 16 channel radiometer has been built and is awaiting calibration and installation. The viewing chord chosen for the radiometer's horn antenna is a toroidal chord which looks at the opposite side of MST relative to the antenna.

## BULK HEATING

Two conflicting absorption mechanisms for lower hybrid waves are bulk electron heating (if the wave damps on lower temperature electrons) and bulk ion heating through the lower hybrid resonance[9, 10]. Though it does not provide definitive evidence of current drive, well diagnosed species temperatures will indicate if the power is being diverted to bulk heating. Major temperature diagnostics on MST include a 21-channel Thompson Scattering System for diagnosing the electron temperature, Charge Emission Recombination Spectroscopy for impurity temperature, and Rutherford Scattering techniques for ion temperature, in addition to the soft x-ray tomography system for electron temper-

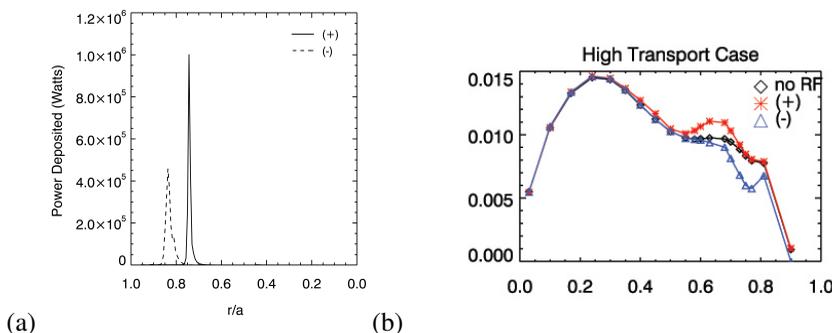
ature measurement. Preliminary measurements with the Rutherford Scattering system show that ion heating is not observed during lower hybrid operation over a range of densities.

## MAGNETIC PICKUP LOOPS

MST is equipped with magnetic pickup coils which are designed to detect plasma mode activity. There are 64 sets of 3 orthogonally arranged coils in the machine, equidistantly distributed toroidally around the machine. It has been observed that certain coils near the antenna pick up an 800 MHz signal during lower hybrid operations. This signal is measured to be around 100 mW, and is toroidally localized. Perhaps more interestingly the power is peaked at certain toroidal angles, much like our hard x-ray signals.

## FOKKER-PLANCK MODELING

Simulation work with GENRAY and CQL3D [11] is being done in parallel with diagnostic development. The aim is to identify at what powers macroscopic effects should be expected. Currently this study has been focusing on 2 MW waves in order to establish the kinetic impact of lower hybrid wave injection. The change in total parallel current expected is small, so modeling is done by setting the current drive profile back to its equilibrium value and allowing the parallel electric field to relax to an appropriate value, then applying the wave's contribution. One goal of this modeling is to produce an x-ray spectrum that could be compared with measurements. GENRAY is used to calculate wave trajectories and power absorption, shown in figure (1a). As expected, there is a narrow band of absorption near  $r/a \approx 0.8$ , which is near the reversal surface. CQL3D is then used to calculate the parallel electric field, and from that the parallel current. Typical results are shown in figure (1b). The plus sign indicates a positive  $n_{\parallel}$  spectrum and the minus sign corresponds to a negative  $n_{\parallel}$  spectrum.



**FIGURE 1.** (a) Power Absorption versus radius calculated by GENRAY (b) corresponding  $E_{\parallel}$  spectrum. Notice the relative peak and the valley for the two different wave injection directions. Here, (+) indicates a positive  $n_{\parallel}$  spectrum and (-) indicates a negative  $n_{\parallel}$  spectrum.

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