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RF Heating and Current Drive Experiments in the Madison Symmetric Torus Reversed Field Pinch

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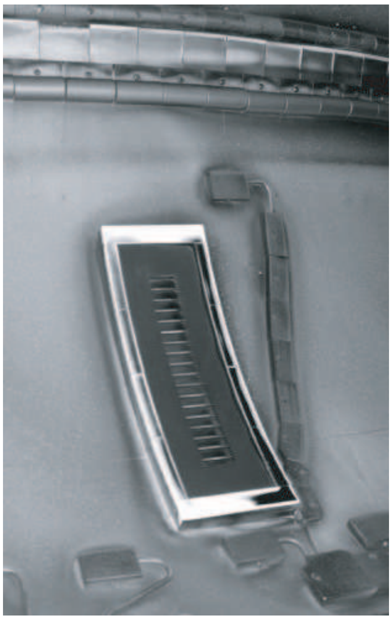
Energy transport in conventional reversed field pinch (RFP) plasmas results from a mismatch between the current drive and the actual current profile. Dynamo activity is required to balance the difference between toroidal induction and the nearly poloidal edge current density. Large magnetic fluctuations associated with dynamo activity lead to magnetic stochasticity and corresponding parallel transport over much of the plasma volume.(1)

Altering the current drive scenario allows for sustainment of the equilibrium with dramatically reduced transport. In particular, an increase in parallel (poloidal) current drive in the outer region of the plasma is desired. Inductive application of a poloidal emf (which takes the place of the parallel edge dynamo emf) to drive the necessary poloidal current is a well-established way to greatly increase energy confinement in the RFP.(2; 3) Although inductive current profile control has been highly successful in reducing transport, it is transient and non-localized. The optimal current profile control technique for RFP plasmas is expected to be rf current drive as it offers the possibility of steady and more precise control. Feasibility studies for two rf approaches are underway on the Madison Symmetric Torus (MST); 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.

Here we report progress on the two rf current drive schemes in the MST, directed toward the major open questions for each. The LH and EBW approaches have complementary strengths. The physics and application of LHCD are well established



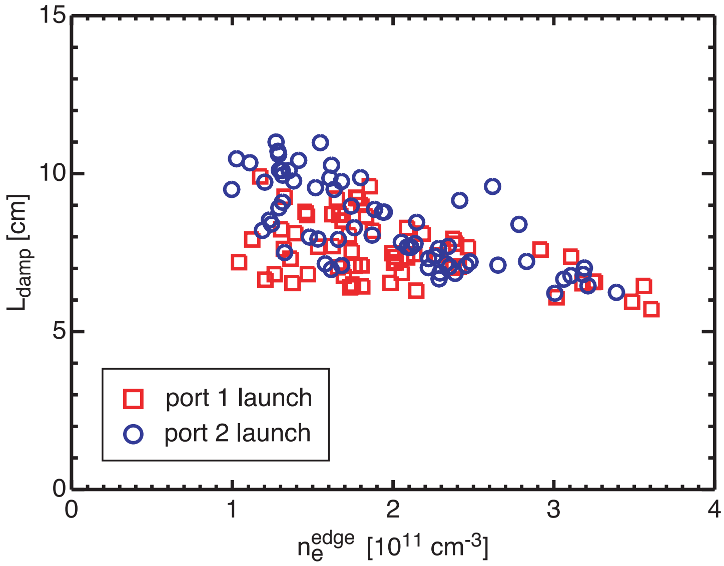


Figure 1: Left: photograph of lower hybrid antenna installed on MST. Right: measured power damping length along antenna versus edge density. Antenna loading is clearly controllable through edge density.

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 any high beta fusion plasma.

The engineering of the LH antenna presents the biggest unknown in the LHCD scheme. An interdigital antenna (pictured in Fig. 1) has been successfully tested to 60kW. The antenna is a slow wave structure 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. Rf power (at 800 MHz) enters the structure at one end and then propagates to the other end; along the way some power is radiated. The electric field between elements fringing through an aperture in the cavity couples to the lower hybrid wave. The fields are evanescent in vacuum but couple to the slow wave at $n_{\|}$= 7.5 in the presence of plasma.(4)

A measure of the power at various stages along the slow wave structure shows the expected decrease, and the power damping scale length (L_D) is defined by fitting an exponential curve to the measured power along the antenna. In vacuum, the L_D is about 56 cm, but L_D of 5-15 cm has been measured with plasma. The plasma loading can be controlled with the edge electron density, as shown in Fig. 1. It has

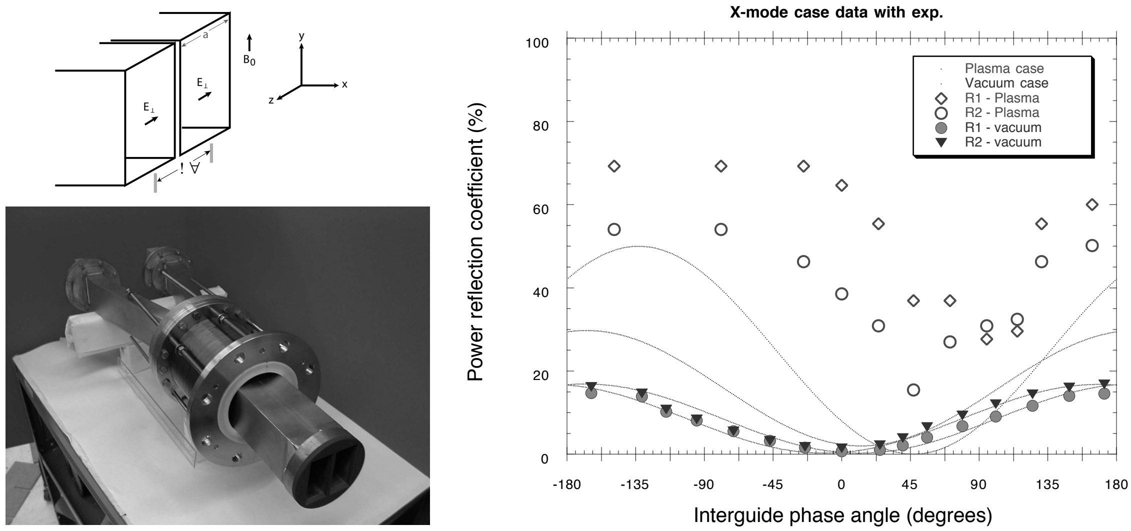


Figure 2: Left: photograph of twin-waveguide EBW antenna installed on MST. Right: Preliminary data compared to simulation (solid lines) for fraction of power reflected into each arm of the antenna for vacuum and plasma cases.

also been observed that L_D varies with magnetic field line pitch: L_D is lowest when **B** is parallel (to within 5^o) of the antenna electric field.

Hard x-rays are generated (10 - 25 keV) when lower hybrid waves are launched into MST. HXRs have been generated when power is fed in either direction through the antenna and the flux correlates closely with rf propagation along the antenna. The measured energy is about ten times the estimated rf potential in front of the antenna rods and also greater than that of the $\sim$4 keV electrons resonant with the wave at $n_{||} = 8$. Therefore the generation mechanism for these x-rays is still unclear and is under further investigation.

The EBW presents a second opportunity for RF current drive in the RFP. The primary area of interest in our current EBW research is the study of physics involved in coupling an externally launched electromagnetic wave to the electrostatic warm plasma electron Bernstein mode. Measurements of blackbody levels of cyclotron emission from the core of the RFP(5) have established that efficient mode-conversion from EBWs to electromagnetic waves can occur at the plasma boundary and by reciprocity that the EBWs can be launched from the edge. A full wave coupling theory has been incorporated into a computer simulation(6) which 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. Ray propagation studies have shown that the launched EBW can be used to drive a net current in either the parallel or antiparallel direction based on launch angle.(7)

A waveguide antenna capable of launching waves at a few GHz is shown in Fig. 2. This two waveguide grill can be used to launch waves with a finite toroidal mode number by externally imposing a phase shift. Several such antennas have been constructed; one has the capability of rotating 90^o to launch X-mode, O-mode or any linearly polarized combination of the two. Preliminary experiments at low power ($\sim$1 W) show that there is an optimal launch angle different from zero degrees, as shown in Fig. 2, in rough agreement with theory. A moderate-power transmitter has been built and tested with the antenna at power as high as 120 kW; experiments at the higher power level will utilize the results of the coupling studies.

In summary, the need for auxiliary poloidal current drive is evident for advanced RFP operation. Two schemes based on RF current drive are in progress on the MST. Lower hybrid current drive and electron Berstein wave current drive are both being studied, and plans to advance to higher power are in place for each scheme. If successful, either scheme could serve as a steady-state way to maintain the transiently realized high-confinement regime in the RFP.

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