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

J.K. Anderson[1], D.R. Burke[1], M. Cengher[1], W.A. Cox[1], C.B. Forest[1], J.A. Goetz[1], M.C. Kaufman[1], S.M. McMahon[1], M.A. Thomas[1], J.L. Waksman[1]

[1] *Department of Physics, University of Wisconsin, Madison WI 53706, USA*

Abstract Auxiliary heating and current drive using rf waves promise to advance the performance of the reversed field pinch (RFP). Edge-localized current drive has been shown to suppress tearing mode activity that is responsible for much of the energy transport in the RFP. There are two rf experiments on the Madison Symmetric Torus with aspirations to non-inductively drive parallel current in the plasma edge. The electron Bernstein wave (EBW) is an attractive heating and current drive scheme, similar to standard ECCD as there is strong absorption at the electron cyclotron resonance, but the EBW propagates with no upper bound on density. Thus it can deposit energy into the overdense RFP plasma where electromagnetic waves are cutoff well outside the cyclotron resonance. Studies performed at low power (< 10 watts) have shown that a significant fraction of launched electromagnetic power at 3.6 GHz successfully couples to the electron Bernstein mode and there is an optimized launch angle with finite perpendicular wavenumber. A 130kW experiment (roughly 25% of the Ohmic input power of target discharges) shows a slight increase in soft x-ray emission during EBW injection. A new antenna capable of delivering 250kW is installed and initial experiments underway. The lower hybrid (LH) wave is being studied as a current drive technique in the RFP. An antenna with 300kW capacity is installed and operates at 800 MHz. The power flowing through the antenna has been measured with pickup loops installed in the antenna backplane. The measured power damping length of 2-4 parallel wavelengths is sufficiently long to prevent diffraction of the launched $n_{//}$ spectrum. Hard x-ray emission is observed from the plasma with up to 80 kW of LH power injection. Advancement toward full power (250 - 300kW) operation of the antenna is underway. This work is supported by the USDOE.

Dynamo is required to maintain the high beta equilibrium in a conventional reversed field pinch (RFP), as a flat parallel current profile results from relaxation of a centrally-peaked force (electric field) profile.(1) The magnetic fluctuations associated with the dynamo activity lead to magnetic stochasticity and corresponding parallel transport over much of the plasma volume. 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 to drive the necessary poloidal current, although transient and non-localized, is a well-established way to increase energy confinement in the RFP.(2) 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 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. A reflectometer-based study of EBW coupling compared with simulations indicates a reasonable understanding of physics at the coupling layer(3) but a direct measurement of the Bernstein wave propagating in the RFP plasma is yet unachieved.

Measurements of blackbody levels of cyclotron emission from the core of the RFP(4) have established that efficient mode-conversion from EBWs to electromagnetic waves can occur at the plasma boundary and by reciprocity that EBWs can be launched from the edge. A two-waveguide grill antenna capable of launching waves at a few GHz has been used for low power (1 Watt) coupling studies and has been conditioned to deliver about 130 kW (limited by transmitter output). Slight perturbations to SXR emission are measured at this level, shown in Fig. 1. In order to increase transmitter power and improve the antenna directionality, a four-waveguide grill (to be driven by 4 microwave tubes instead of two) has been constructed and installed on MST, and is pictured in Fig. 2a.

The engineering of the LH antenna presents the biggest unknown in the LHCD scheme. An interdigital antenna (pictured in Fig. 2b) has been successfully tested to 80kW (limited by transmitter output). The antenna is a slow wave structure in which a resonant array of conducting rods is alternately grounded to opposite

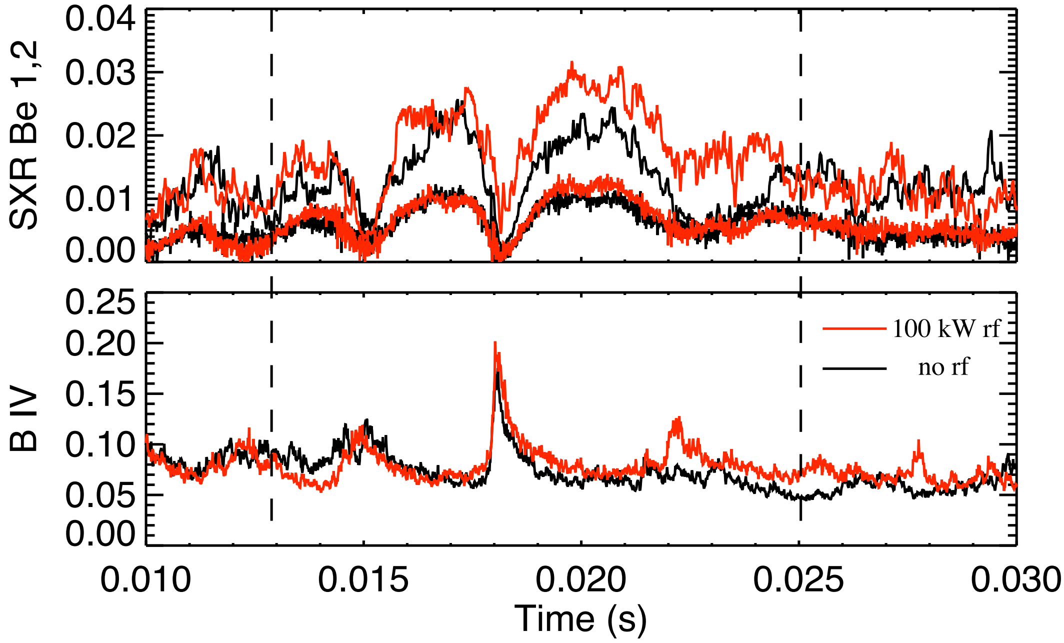

Figure 1: Measurable increase in soft x-ray emission during EBW injection (between vertical dashed lines). Emission is measured through two different thickness beryllium filters. There is a slight increase in boron IV emission during the same period, likely due to the boron-nitride construction of plasma facing components of the antenna.

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 $n_{\|} \sim 7.5$ in the presence of plasma.(5)

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 4-20 cm has been measured with plasma. The plasma loading can be controlled with the edge electron density and the most recent antenna is outfitted with a pair of triple Langmuir probes for diagnosis.

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.

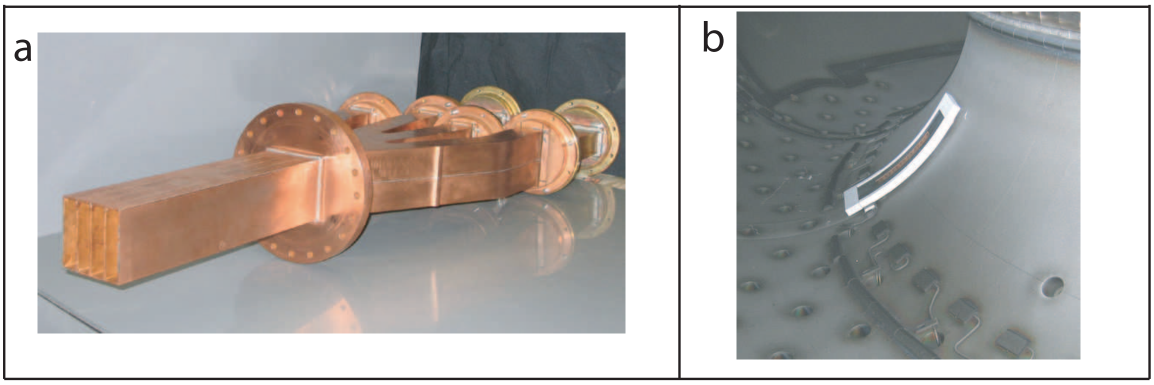

Figure 2: Left: photograph of four-guide EBW antenna, now installed on MST. Right: photograph of lower hybrid antenna installed in MST.

The measured energy is about ten times the estimated rf potential in front of the antenna rods and also greater than that of the ∼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. Source development is underway to extend the transmitter output to 300 kW.

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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