

Radio-frequency Wave Experiments on the MST Reversed Field Pinch

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Experiments, simulations, and theory all indicate that the magnetic fluctuations responsible for the poor confinement in the reversed field pinch (RFP) can be controlled by altering the radial profile of the current density. The magnetic fluctuations in the RFP are due to MHD instabilities caused by current profile peaking; thus confinement in the RFP is ultimately the result of a misalignment between inductively driven current profiles and the stable current profiles characteristic of the Taylor state. If a technique such as rf current drive can be developed to non-inductively sustain a Taylor state, the confinement of the RFP and its potential as a reactor concept are likely to increase.

Two rf experiments, high- n_{\parallel} lower hybrid (LH) waves and electron Bernstein waves (EBWs), have been shown to be theoretically feasible and are being initiated to investigate current drive and heating on the Madison Symmetric Torus (MST)[1].

AN EXPERIMENT TO TEST THE VIABILITY OF HIGH- n_{\parallel} LOWER HYBRID HEATING AND CURRENT DRIVE IN THE RFP

For frequencies above the lower hybrid resonance the lower hybrid wave propagates[2] only if the parallel index of refraction satisfies $n_{\parallel}^2 > 1 + 2\frac{\omega_{pe}^2}{\Omega_{ce}^2} - \frac{\omega_{pi}^2}{\omega_{rf}^2}$. In high field tokamaks, the second term on the right hand side is small, which implies that lower hybrid waves with $n_{\parallel} \approx 1.5$ and thus high parallel phase velocities can be launched (the last term on the right hand side depends only upon density). For MST parameters ($f_{lh} \approx 250$ MHz in the core) this second term dominates (as seen in Figure 1) and requires that propagating lower hybrid waves will have relatively slow parallel phase velocities.¹ This restriction implies that the power will be absorbed by electrons at lower velocities than otherwise possible which impacts the current drive efficiency.

Ray-tracing studies using the code GENRAY have confirmed that waves with $n_{\parallel} > 7$ can propagate and be absorbed in the core or edge of the MST plasmas. Absorption and current drive are computed using the Fokker-Planck code CQL3D. An example of a propagating wave is shown in Figure 2. The wave propagates predominantly parallel to the magnetic field (which is poloidal in the RFP) in the edge region, spiraling in until it is absorbed. Also shown is the

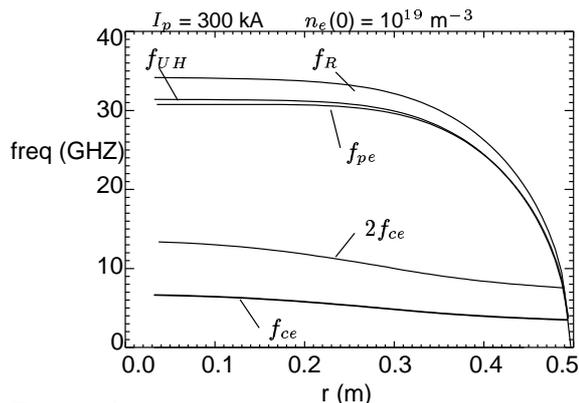


Figure 1: Characteristic frequencies in the the electron cyclotron range of frequencies on MST. This corresponds to an RFP plasma current in MST ($R = 1.5$ m, $a = 0.5$ m).

¹The magnetic field strength in the RFP is to lowest order in aspect ratio only a function of minor radius.

driven current profile which is mostly in the poloidal direction. The simulations indicate that the current drive figure of merit $\eta_{cd} \equiv \frac{nI_\phi RB}{P_{rf} B_\phi} = \frac{nI_\theta r B}{P_{rf} B_\theta}$ is low compared to tokamaks, typically $\eta \approx 5 \times 10^{17} \text{ A/Watt} \cdot \text{m}^2$, a result of the low electron temperatures in the RFP[3, 4].

The first experimental goal will be to demonstrate that the power can be coupled to the LH wave, and that the wave propagates according to the predictions of ray tracing theory. There are a number of limitations of the ray tracing theory, each of which can only be resolved through experimentation. Of primary concern are the issues of the LH density limit and the role of fast electron diffusion[1]. 800 MHz has been chosen for an initial experiment on MST primarily to be well above the lower hybrid frequency ($f_{lh} < 250 \text{ MHz}$) and to satisfy a criteria proposed by Sverdrup and Belan[5] for a density $n_e < 10^{19} \text{ m}^{-3}$.

An $n_{||} = 8$, inter-digital, comb-line antenna has been developed to launch a traveling, electrostatic LH wave. The close fitting vacuum vessel and conducting shell on MST renders a conventional phased array of waveguides like the ones used on tokamaks infeasible, while the low radial build of the comb-line antenna allows it to fit between the vessel and the plasma (as shown in Figure 3). It has the additional feature that only two coaxial penetrations through the vessel wall are required. The inter-digital comb-line is based upon well established microwave filter designs[6] and is motivated in part by experiments using a comb-line antenna for launching the fast wave on the JFT-2M tokamak.

The initial experiments will be performed with a $P_{rf} \approx 200 \text{ kW}$, $f = 800 \text{ MHz}$ klystron on loan from PPPL. The klystron has been tested and is ready for experiments to begin in the fall of 1999.

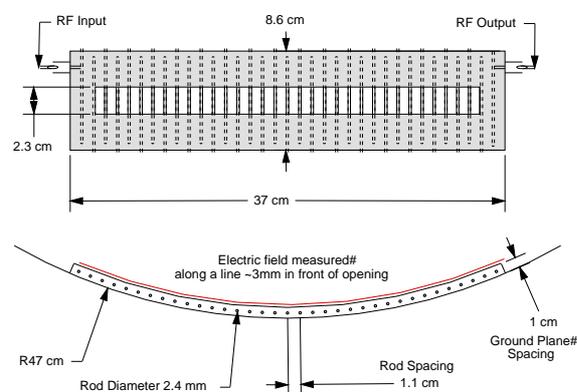


Figure 3: A prototype comb-line antenna which has been constructed and tested. The slow-wave structure consists of rods spaced $\approx 1 \text{ cm}$ apart, and grounded at alternating ends. The individual rods are resonant at 800 MHz, and support a propagating wave through their mutual capacitances and inductances. The measured $n_{||}$ spectrum at 800 MHz is shown on the right.

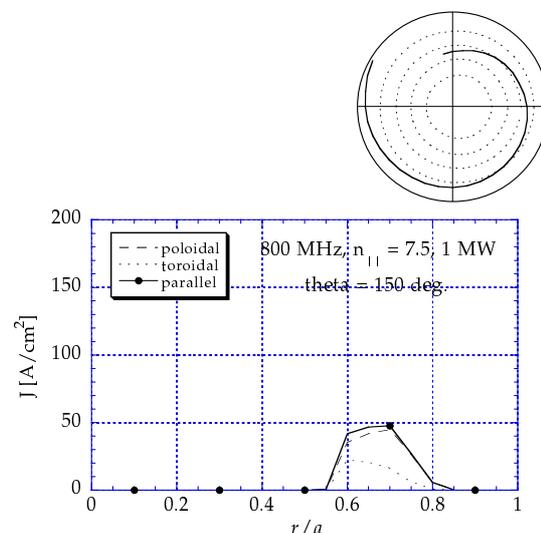
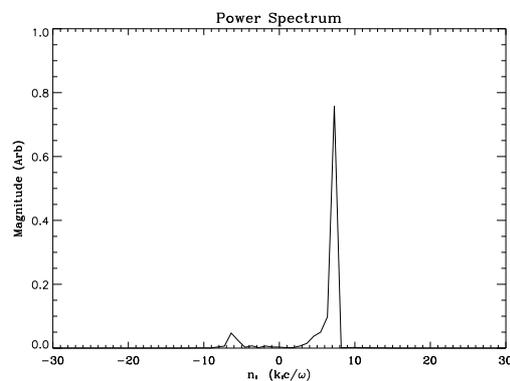


Figure 2: Top: poloidal projection of ray trajectories calculated for an 800 MHz LH wave with $n_{||} = 7.5$ in MST. Bottom: driven current deposition profile computed using the Fokker-Planck code CQL3D.



ELECTRON BERNSTEIN WAVE HEATING AND CURRENT DRIVE IN THE RFP

For current profile control, one would ideally choose a current drive scheme similar to ECRH in tokamaks, where the power deposition is determined largely by the magnetic equilibrium properties rather than details of the kinetic profiles. For ECRH, the power is absorbed where the wave frequency is equal to the local electron cyclotron frequency ($\omega_{rf} = \Omega_{ce}(r)$). Unfortunately, it is well known that conventional electromagnetic waves such as the X and the O mode do not propagate in the electron cyclotron range of frequencies when $\omega_{pe} \gg \Omega_{ce}$. However, the electrostatic electron Bernstein wave (EBW) does. Indeed, it has been shown both experimentally and theoretically possible to couple to these waves[7, 8].

The dispersion of the EBW is a complicated function of magnetic field, density and electron temperature, which can only be addressed numerically. For this purpose, a new hot plasma dispersion solver (non-relativistic) has been written to find roots for the EBW and coupled to the GENRAY ray-tracing code (previously used for LH waves). The rays are launched as electromagnetic O-modes from the outside of the plasma at the optimal angle for mode-conversion to the EBW; the ray naturally mode converts into the EBW as shown in Figure 4.

Interestingly, for rays launched from the mid-plane the n_{\parallel} of the wave undergoes oscillations about $n_{\parallel} = 0$, similar to the behavior of ion Bernstein waves[9]. This n_{\parallel} variation is disconcerting since it apparently destroys the directionality of the wave (which would be bad for current drive). However, following the IBW analog[10], we have discovered that for EBW rays launched above and below the mid-plane, the n_{\parallel} variation is unidirectional and the up-shift is determined by the launch position. The parallel index of refraction depends upon whether the ray is launched in the upper or lower half of the torus, thus the directionality of the wave for current drive can be controlled and depends upon the side of the torus from which the wave is launched.

The linear power deposition profile is determined by the location in the plasma at which Doppler shift cyclotron resonance occurs, i.e. $\frac{\Omega_{ce}(r)}{\omega_{rf}} \approx 1 - n_{\parallel} \frac{v_{Te}}{c}$; for low- n_{\parallel} the Doppler shift is only several cm for MST parameters, however the large n_{\parallel} up-shift for above and below mid-plane launch can lead to a shift of up to 10 cm. For core current drive and heating, accessibility depends critically upon the equilibrium magnetic field. Waves which are resonant at the core may have to pass through a second harmonic resonance at the edge (see Figure 1); the cyclotron damping of EBWs is strong at all harmonics and therefore the wave will not propagate beyond this point, effectively imposing an overlap criterion of $|B(a)| > 2|B(0)|$. The driven current has been estimated and is comparable to that found numerically for lower hybrid waves. Power deposition profiles and driven current profiles are well localized.

Two approaches are being investigated for launching power (and receiving power) into

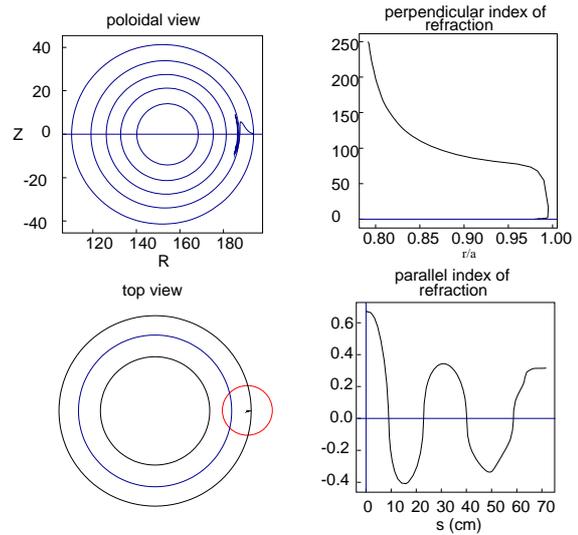


Figure 4: Ray trajectories for a 6 GHz EBW ray in MST, launched in a 500 kA, and cyclotron damped at $r/a = 0.6$. $T_e(0) = 1$ keV, $n_e(0) = 1.5 \times 10^{19} \text{ m}^{-3}$. GENRAY follows the O mode root onto the EBW root smoothly as predicted by the OXB theory.

(from) the EBW on MST. First, a direct launch using a small electrostatic probe, similar to that used in double plasma devices is being attempted[11]. This is essentially a low impedance co-axial line terminated to act as an electrostatic antenna. The probe is placed directly into the plasma and is designed with an impedance to match the wave impedance. Transmission studies will be used to determine the effective coupling to the EBW and then a radiometer will be installed to look for electron cyclotron emission. For heating, either OXB mode-conversion and/or X-mode resonant mode-conversion will be used. Initially, a two waveguide phased array antenna will be constructed in C-band, with the possibility of being rotated to launch either polarization.

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