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INTRODUCTION

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 resistive 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 (a current profile linearly stable to all tearing modes), the confinement of the RFP and its potential as a reactor concept are likely to increase.

Until now, auxiliary heating and current drive experiments have not been performed on the RFP; most rf heating and current drive experiments have been performed on tokamaks. Interestingly, present day RFPs have plasma parameters and device geometries (for MST $T_e(0) \approx 1$ keV, $n_e(0) \approx 10^{19} \text{ m}^{-3}$, $R = 1.5$ m, $a = 0.5$ m, $I_p = 0.2$ to 0.5 MA) very similar to the plasma parameters of tokamaks such as PLT and ASDEX where rf current drive was first applied with great success[1]. From the view point of current drive, present day RFPs differ in two important ways when compared with these mid-size tokamaks: the total magnetic field is about 10 times smaller, and the energy confinement of the RFP is roughly 20 times worse. The low magnetic field means that $\omega_{pe}/\omega_{ce} \gg 1$ which places severe restrictions on accessibility for lower hybrid waves ($n_{\parallel} > 7$ for typical MST parameters) that limits the achievable current drive efficiency, and prohibits the use of electromagnetic waves in the ECRF. The high-density, low-field characteristic of the RFP, is shared by spherical tokamaks, and other high- β experiments. More serious perhaps, is the poor energy confinement of the RFP, a result of the break up of magnetic surfaces resulting from resistive tearing modes. The working hypothesis is that rf might produce a current profile which is stable to these resistive modes and therefore greatly improve the confinement of the RFP. Full sustainment of the current is desirable for a reactor, but it is not necessary to have an impact on the confinement; resistive MHD simulations have shown that partial non-inductive current drive applied in the edge region ($r/a \gtrsim 0.7$) can greatly reduce the magnetic fluctuations in the RFP [2].

Whether there is a self-consistent path from poor confinement to greatly improved confinement through current profile modification is an issue for future experiments to address *if and only if near term experiments* can demonstrate: (1) coupling to and the propagation of rf waves in RFP plasmas, (2) efficient current drive, and (3) control of the power deposition which will make it possible to control the current profile. In this paper, modeling results and experimental plans are presented for two rf experiments which have the potential of satisfying these three goals: high- $n_{\parallel}$ lower hybrid (LH) waves and electron Bernstein waves (EBWs).

PHYSICS ISSUES FOR LOWER HYBRID HEATING AND CURRENT DRIVE IN AN RFP

For frequencies above the lower hybrid resonance

$$\frac{1}{\omega_{lh}^2} = \frac{1}{\omega_{pi}^2 + \Omega_{ci}^2} + \frac{1}{\Omega_{ci}\Omega_{ce}} \quad (1)$$

the lower hybrid wave propagates[3] only if the parallel index of refraction satisfies

$$n_{||}^2 > 1 + 2 \frac{\omega_{pe}^2}{\Omega_{ce}^2} - \frac{\omega_{pi}^2}{\omega_{rf}^2}. \quad (2)$$

In high field tokamaks, the second term on the right hand side is small, which implies that lower hybrid waves with $n_{||} \approx 1.5$ 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 have confirmed that waves with $n_{||} > 7$ can propagate and be absorbed in the core or edge of the MST plasmas. The ray tracing code GENRAY is used, together with a cold plasma dispersion relationship to describe the LH waves. 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 driven current profile which is mostly in the poloidal direction. The simulations indicate that the current drive figure of merit $\eta_{cd} \equiv \frac{nI_{\phi}RB}{P_{rf}B_{\phi}} = \frac{nI_{\theta}rB}{P_{rf}B_{\theta}}$ is low compared to tokamaks, typically $\eta \approx 5 \times 10^{17}$ A/Watt $\cdot$ m², a result of the low electron temperatures in the RFP[4, 5]. Estimates based upon MHD simulations[2] indicate that to stabilize MHD fluctuations will require an rf driven poloidal current approximately equal to the toroidal current. Assuming a density of 10^{19} m⁻³ and a plasma current of 250 kA, the estimated efficiency implies that an rf power of 2 MW may significantly affect the magnetic fluctuations. Operating at lower density or higher electron temperature will presumably require less power. Other choices of $n_{||}$ and frequency can be made to provide more centrally peaked deposition profiles.

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. Two of these issues are outlined here.

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).

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.

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

(1) The Density Limit. Lower hybrid experiments in tokamaks exhibit an empirical density limit. Although there are differences between the RFP and the tokamak, it is reasonable to speculate that LHCD in the RFP will also be subject to a density limit. A primary goal of the first set of experiments will be to determine the density limit in MST. The density limit is a poorly understood phenomenon. Most explanations of the density limit invoke an interaction of the RF waves with ions. When the RF power is absorbed by the ions it is not available for current drive. This can only happen if the perpendicular wave number becomes sufficiently large for ions to appear unmagnetized, which does not occur if the wave propagation is governed by cold plasma dispersion relationship. If warm plasma effects are included, mode conversion of the LH wave into a warm plasma mode is predicted which has a sufficiently high perpendicular wave number to damp on ions. Sverdrup and Bellan[6] showed that a proper accounting of mode conversion along with an empirical up-shift in $n_{||}$ can explain the density limit for a wide range of tokamak parameters. 800 MHz has been chosen for an initial experiment on MST primarily to be well above the lower hybrid frequency ($f_{lh} < 250 MHz$) and to satisfy the Bellan constraint at a density $n_e < 10^{19} m^{-3}$.

Figure 3: Broadening of the rf current drive profile by particle diffusion. Typical radial thermal diffusivities are $10 m^2/s$ in MST.

(2) Fast Electron Transport. Fast electron transport can restrict our ability to localize current drive and also can modify the power deposition profile by modifying the plateau which is formed during the RF heating. The magnetic fluctuations which cause the poor energy confinement of the RFP, are also predicted to spatially diffuse fast electrons which might be produced by the RF waves. This effect will both limit the localization of driven current and reduce the overall current drive efficiency of the waves. A number of authors have considered the role of the fast electron transport on current drive[7–9].

Following Kesner[9], the radial profile of non-inductive current density has been estimated in the presence of magnetic fluctuation driven transport and found to lead to significant broadening of the driven current profiles as shown in Figure 3. It appears that localized current drive may only be possible if the the confinement can be further improved.

AN EXPERIMENT TO TEST LHCD IN THE RFP

A lower hybrid experiment is under construction to test the viability of heating and current drive using the lower hybrid wave in the MST plasma, with its primary objective to determine the density limit and study the role of fast electron transport on current drive.

An $n_{||} = 8$, inter-digital, comb-line antenna has been developed to launch a traveling, electrostatic LH

Figure 4: Inter-digital comb-line antenna developed for launching high $n_{||}$ lower hybrid waves in the reversed field pinch. The figure shows how the MST lower hybrid antenna (under construction) fits snugly against the MST vacuum vessel.

Figure 5: A prototype comb-line antenna which has been constructed and tested. The slow-wave structure consists of rods spaced ≈ 1 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.

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 4). 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[10] and is motivated in part by experiments using a comb-line antenna for launching the fast wave on the JFT-2M tokamak.

A prototype inter-digital antenna has been constructed to demonstrate that the structure can be built and operates as predicted by theory. The schematic and measured spectrum are shown in Figure 5. The antenna is a slow wave structure in which a number of radiating elements (conducting rods) are inductively and capacitively coupled to each other and the end elements are matched to coaxial transmission lines. Power is introduced through a coaxial feed, and then propagates along the resonant slow wave structure. In the absence of a plasma, there is little radiated power since waves with $n_{||}$ are attenuated strongly as they propagate away from the antenna aperture. With a plasma, on the other hand, power is radiated and it is meaningful to consider the attenuation of the power in the antenna along the slow-wave structure. We have estimated the damping length using the coupling theory of Golant[11] for a typical MST shot. This damping length of the radiation is determined by the proximity of the plasma to the antenna and the plasma density near the edge. The damping can be neither too weak nor too strong: if the coupling is strong, the wave is damped in a short distance and the narrow spectrum of the antenna can be significantly

Figure 6: Damping length of power propagating along slow wave structure in inter-digital antenna, $P_a(s) \propto e^{-s/L}$ where s is the distance along the antenna measured from the input feed, and L is the damping length as measured in cm for a 500 kA MST plasma with $n_e = 10^{19} \text{ m}^{-3}$ and a density scale length of 0.1 m at the plasma edge.

broadened; if the coupling is weak, little power is radiated into the plasma but is transmitted to the matched output feed and lost into a dummy load. For the MST antenna, the optimal antenna/plasma spacing is only 4 mm; thus, an important part of the planned experiment will be to vary the coupling in order to test the Golant coupling theory and optimize the antenna/plasma spacing for the spatial dimensions of the antenna.

The initial experiments will be performed with a $P_{rf} \approx 200$ kW, $f = 800$ MHz klystron on loan from PPPL. The klystron has been tested and is ready for experiments to begin in the spring of 1999. The first experiments will focus on determining coupling efficiency of the comb-line antenna, power deposition profiles, and the density limit for an electron interaction.

ELECTRON BERNSTEIN WAVE HEATING AND CURRENT DRIVE

Lower hybrid waves have been chosen for an RFP experiment since they have had the most success at efficiently driving current in medium size tokamaks. Although the LH waves appear promising, there are limitations which may restrict their applicability to the RFP current profile modification. Most importantly, the ray-tracing studies have shown that the power deposition is a sensitive function of wave frequency, electron temperature, equilibrium fields, density profiles, and choice of $n_{||}$. 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.

The potential of using the EBW for heating over dense plasmas was recognized early in the theoretical work of Preinhalter and Kopecký[12, 13], and recent experiments on W7-AS[14, 15] have clearly demonstrated its feasibility. Preinhalter and Kopecký elegantly showed that the electromagnetic radiation can couple power to EBWs through a double mode conversion from O-mode in vacuum into slow X-mode and then onto the EBW, which we denote by OXB mode-conversion. It has been shown that this only occurs for obliquely propagating O-modes for a modest range of $n_{||}$. An alternative coupling scenario based upon a resonant mode-conversion from X mode to EBW has recently been proposed by Ram[16]. The EBW has previously been proposed for heating the low aspect ratio tokamak[17]—this study shows it may also be suited for the RFP.

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 code solves for the ray trajectories of the waves and determines the wave damping based upon the non-hermitian part of the dielectric tensor. For OXB mode-conversion scheme, GENRAY

Figure 7: 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.

Figure 8: Ray trajectories for three 9 GHz EBW rays launched from 3 different poloidal positions.

can follow the proper root through the process if given the proper value of $n_{\parallel}$. 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 7. Although the WKB theory is not valid for describing the mode-conversion process, the ray tracing equations nevertheless describe the mode-conversion.

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[18]. 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[19], 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. $\frac{\Omega_{ce}(r)}{\omega_{rf}} = 1 - n_{\parallel} \frac{v_{Te}}{c}$; 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. The second harmonic overlap criteria imply that core heating of the RFP using EBWs will only be possible if $|B(a)| > 2|B(0)|$.

Figure 9: Power deposition and current drive profiles for two different frequencies chosen to deposit power in the periphery of MST.

Figure 10: Contours of the electron distribution function and the quasi-linear diffusion operator for mid-plane launch of a 9 GHz EBW in MST.

The driven current has been estimated using the relativistic current drive model of Cohen[20], and numerically the efficiency of current drive is comparable to that found numerically for lower hybrid waves. Power deposition profiles and driven current profiles are shown in Figure 9. The absorption of the EBW is strong and is strongly affected by relativistic resonance effects; the non-relativistic damping indicates that the wave is fully absorbed well before reaching the cyclotron resonance position. To properly assess the role of relativity and non-linearities in the presence of strong damping, studies using CQL3D have been started. CQL3D uses the polarizations determined by the hot plasma dielectric tensor and then self-consistently computes the damping and current drive using relativistic formulas. So far, only the mid-plane launch has been examined. Initial results indicate strong plateau formation as shown in Figure 10.

Two approaches are being investigated for launching power (and receiving power) into (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[21]. 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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