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Localized Electron-Cyclotron Heating and Current Drive in the TIBER-II Reactor Study*

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ABSTRACT

A scenario is shown for launching 10 MW of 450 GHz extraordinary-mode electron-cyclotron waves into a TIBER-II equilibrium. Localized, high-efficiency current drive near but outside the $q = 2$ surface causes substantial reduction in the current gradients that may play a role in major disruptions and anomalous transport. The same launch geometry shows promise for heating the plasma core during startup.

INTRODUCTION

In a high-temperature tokamak reactor, broad electron-cyclotron resonances lead to constraints on current-drive efficiency at the peak T_e achieved during burn in the plasma core.¹ At lower T_e , however, the injection of electron-cyclotron power can serve two useful purposes. First, during plasma startup, localized heating of the core can help initiate the burn. Second, to minimize transport and suppress disruptions, one can control the radial profiles of T_e and plasma current near and outside of the $q = 2$ surface. This paper reports initial work towards these goals.

LOCALIZED, HIGH-EFFICIENCY CURRENT DRIVE

High-efficiency current drive by electron-cyclotron waves is achieved by selectively heating high-energy electrons that have parallel velocity of one sign. The relativistic, wave-particle resonance condition is satisfied for such electrons if the parallel index of refraction $|N_{\parallel}| = \mathcal{O}(1)$ and if $\ell\Omega/\omega < 1$, where ℓ is the harmonic number, Ω is the cyclotron frequency, and ω is the wave frequency. Typical values for these parameters are $|N_{\parallel}| = 0.6$ and $\ell\Omega/\omega = 0.9$.

Localization of power deposition and current drive to a small range of flux surfaces is accomplished by choice of the launch geometry and of the polarization. Wave absorption must be strong and occur where propagation

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Fig. 1. Poloidal projection of a ray trajectory that deposits power and drives current outside the $q = 2$ surface in a TIBER-II equilibrium. The dashed curve is the $\psi = 0.96$ flux contour. The chain-dot curve is the second-harmonic cyclotron resonance. The asterisks indicate the location of wave absorption.

is at a relatively small angle with respect to the flux surfaces. For any harmonic ℓ , the extraordinary mode has the stronger absorption.

An attractive launch geometry for the TIBER-II study is illustrated in Fig. 1. The launch location is just outside the separatrix of the diverted equilibrium. Extraordinary-mode power at 450 GHz is launched at polar angle $\theta = 50^\circ$ and at azimuthal angle $\phi = 285^\circ$ in a cylindrical coordinate system coaxial with the tokamak axis of symmetry. Power absorption is limited to the region outside the $q = 2$ flux surface and amounts to 99% of the incident power. Second-harmonic cyclotron resonance absorbs the waves in a region where magnetic-field and plasma parameters have the values $B \approx 7.2$ T,

$n \lesssim 0.46 \times 10^{20} \text{ m}^{-3}$, and $T_e \lesssim 10 \text{ keV}$. Third-harmonic absorption is not shown here but becomes significant farther along the ray, just after the second-harmonic absorption decreases; no power reaches the center of the plasma. These results are calculated with the TORAY ray-tracing code.^{2,3} Absorption is calculated for a Maxwellian electron distribution function.

Second-harmonic extraordinary-mode absorption is used here, but an alternative scenario for localized power deposition and current drive utilizes the ordinary-mode polarization and the fundamental cyclotron resonance with $\omega \approx 225 \text{ GHz}$. With either scenario, for accurate results the wave damping must include the warm-plasma effects on wave polarization. In this paper, cold-plasma polarization is used, and the results may be quantitatively inaccurate but are probably qualitatively correct.

The calculation of current-drive efficiency presented in Ref. 4 is used here to obtain the current driven in conjunction with second-harmonic power absorption. This calculation includes the effects of the relativistic resonance condition and of trapped electrons, both of which can alter current-drive efficiency significantly.

Figure 2 shows the effect of 10 MW of electron-cyclotron power on the current flowing in the TIBER-II plasma. The plots show the toroidal current enclosed within each flux surface, where the surfaces are parametrized by the normalized poloidal flux $\tilde{\psi} = (\psi - \psi_{\text{axis}})/(\psi_{\text{edge}} - \psi_{\text{axis}})$. The integrated equilibrium current I_p (dashed curve) is characterized for $0 < \tilde{\psi} < 0.6$ by nearly constant slope, which implies that $dI_p/d\tilde{\psi}$ is almost flat. For $\tilde{\psi} > 0.6$ and, in particular, near the $q = 2$ surface at $\tilde{\psi} = 0.73$, $dI_p/d\tilde{\psi}$ decreases with increasing $\tilde{\psi}$, indicating a gradient in the current profile that may be associated with major disruptions. The solid curve, which is calculated from the sum of the equilibrium and the driven currents, maintains the nearly constant slope to larger $\tilde{\psi}$. With electron-cyclotron current drive, therefore, the current gradient is reduced near the $q = 2$ surface, which may help to control disruptions and minimize transport.

HEATING DURING STARTUP

Ideally, the chosen launch geometry should also serve to heat the plasma core during startup and help to initiate the burn. Typical values at the magnetic axis for density and temperature are $\bar{n} = 5 \times 10^{20} \text{ m}^{-3}$ and $\bar{T}_e = 8 \text{ keV}$. The ray trajectory is similar to that shown in Fig. 1, because refraction is small both during startup and during steady state. Second-harmonic absorption is much reduced from that shown in Fig. 1, because the cooler plasma has very few electrons at the $\ell = 2$ resonance. The third-harmonic resonance occurs close to the magnetic axis, and localized absorption may occur there due to the strong T_e^2 dependence of third-harmonic damping. Future work will examine these questions quantitatively.

Fig. 2. Enclosed current as a function of normalized poloidal flux ψ . The solid curve differs from the dashed curve due to 10 MW of second-harmonic X-mode power.

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