LETTERS

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Lower-hybrid poloidal current drive for fluctuation reduction in a reversed field pinch

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Current drive using the lower-hybrid slow wave is shown to be a promising candidate for improving confinement properties of a reversed field pinch. Ray-tracing calculations indicate that the wave will make a few poloidal turns while spiraling radially into a target zone inside the reversal layer. The poloidal antenna wavelength of the lower hybrid wave can be chosen so that efficient parallel current drive will occur mostly in the poloidal direction in this outer region. Three-dimensional resistive magnetohydrodynamic computation demonstrates that an additive poloidal current in this region will reduce the magnetic fluctuations and magnetic stochasticity.

Recent experimental and computational results indicate that magnetic stochasticity arising from tearing-like fluctuations produces the anomalous energy and particle transport in the reversed field pinch (RFP). This has been established in the Madison Symmetric Torus (MST) RFP[1] through the direct measurement of energy and particle flux driven by magnetic fluctuations,[2,3] and through resistive magnetohydrodynamic (MHD) computation which evolves the plasma pressure.[4] The responsible tearing fluctuations, typically dominated by several helical modes,[5] are driven by current density gradients. Hence, through current profile control the fluctuations and transport can be reduced. Current drive in the outer region of the RFP (in the direction parallel to the magnetic field, which is dominantly poloidal at the edge) suppresses the gradients while supplying current to sustain reversal. Stabilization of the tearing fluctuations was first demonstrated in MHD computation in which current is injected electrostatically at the edge ("direct current helicity injection").[6] An encouraging experimental result has been obtained in MST in which the energy confinement time was doubled by modest edge current drive by a transient inductive poloidal electric field.[7]

To optimize and sustain an improved confinement state, however, it is desirable to effect this control using a nontransient method. One such method is radio-frequency current drive (RFCD) in the poloidal direction. The higher plasma beta in the RFP has stimulated interest in fast wave current drive. It has been shown that the fast wave can be used to drive a poloidal current in the outer region and a toroidal current in the central region.[8,9]

In this Letter, we show that the lower-hybrid (LH) slow wave is ideally suited for poloidal current drive in the outer region of the RFP. We examine accessibility, ray propagation, and current drive efficiency. The optimal radial location for RFCD to suppress fluctuations is established by incorporating auxiliary current drive in a nonlinear resistive MHD code.

To demonstrate auxiliary current drive suppression of magnetic fluctuations, a parallel electron force has been added to the three-dimensional (3-D), nonlinear, resistive MHD code DEBS (described in detail elsewhere[10]). This electron force reduces to a term in Ohm's law and a term in the single-fluid momentum equation. The force is assumed to be Gaussian in its radial profile, and it is directed to produce current parallel to the magnetic field. These simulations are in cylindrical geometry, with Lundquist number of 10^4 and effective aspect ratio of 3. Figure 1(a) shows the profile of $\mu_0 a j_\parallel / B$ with and without the auxiliary force centered at $0.8a$. Here, $j_\parallel$ is the mean parallel current density, B is the magnetic field, a is the minor radius, and μ_0 is the magnetic permeability of free space. The profile includes the Ohmic and fluctuation-driven current (the dynamo effect) as well as the auxiliary current. The profile flattening in the interior reduces the fluctuation energy by about an order of magnitude, as is evident in Fig. 1(b) which displays the axial mode n spectra for the azimuthal mode number $m=1$. The residual dominant modes are resonant in the outer half of the plasma radius. As seen in Fig. 2, reducing the fluctuation restores closed, nested flux surfaces in the core which are stochastic without auxiliary current drive. To effect these changes in this uniform resistivity case, about 25% of the total poloidal current is radio-frequency (RF) driven. The current drive efficiency is discussed later.

The optimal centering of the added current profile is roughly $0.1a$ inside the reversal layer. Added current profiles centered at smaller radii stabilize a smaller fraction of the region, while profiles centered at larger radii do not stabilize the core. This result is weakly dependent on variation of the

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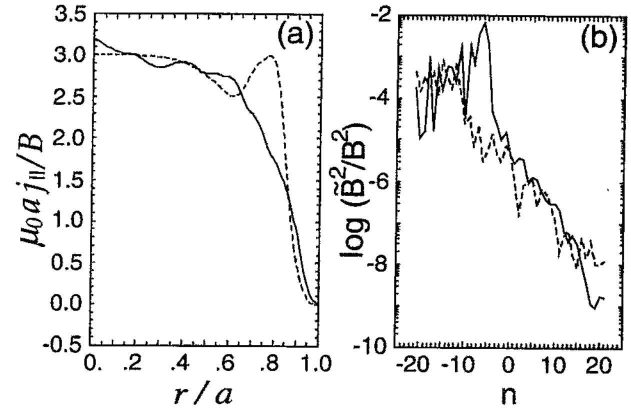

FIG. 1. (a) The $\mu_0 a j_{\|}/B$ profile and (b) the axial mode number spectrum of magnetic energy, for $m=1$ fluctuations before (solid line) and after (broken line) the addition of auxiliary current (the electron force). In a typical MST RFP discharge, the peak value of the auxiliary $j_{\|}$ required to effect this change is about 60 A/cm^2.

safety factor profile. Since the reversal surface is typically located near $0.8a$, the target radius for RFCD is typically $0.7a$.

Having established the RFCD target zone, we examine the feasibility of the LH wave. The distinguishing features of RFPs that affect lower hybrid current drive (LHCD) include (i) large ω_{pe}/ω_{ce} ranging from 3 to 10, (ii) large magnetic shear with a reversal layer, and (iii) small fraction of trapped particles. Here, ω_{pe} and ω_{ce} are electron plasma and electron cyclotron frequencies. In contrast, a comparably sized tokamak has $\omega_{pe}/\omega_{ce}<1$, a strong toroidal magnetic field with small shear, and a large fraction of trapped particles. The lower hybrid frequency $\omega_{\rm LH}\approx\omega_{pi}\omega_{ce}/(\omega_{pe}^2+\omega_{ce}^2)^{1/2}$ can be approximated by $(\omega_{ce}\omega_{ci})^{1/2}$ in the RFP. (The subscript i refers to ion quantities.) Our LHCD study is based on the theory developed for the tokamak[11–13] but appropriate conversions have been made to account for differences in magnetic topology and plasma parameters.

Because of a larger ω_{pe}/ω_{ce}, the parallel refractive index $n_{\|}$ of the LH slow wave must be chosen larger than that in a comparably sized tokamak to insure accessibility. In the frequency range $2-3\omega_{\rm LH}$, the slow wave branch of the cold plasma dispersion relation leads to an approximate inequality $n_{\|}^2\gtrsim[(1+\omega_{pe}^2/\omega_{ce}^2)^{1/2}+\omega_{pe}/\omega_{ce}]^2$ for a propagating wave. The LH wave satisfying this accessibility condition is predominantly electrostatic and the wave-vector **k** points almost perpendicular to the magnetic field. The direction of the group velocity is almost perpendicular to **k** and its magnitude is of order $c/n_{\|}$, where c is the speed of light in vacuum. The energy and momentum carried by the LH wave will be mostly in the poloidal direction, but a small radially inward component will cause the wave to spiral into the plasma.

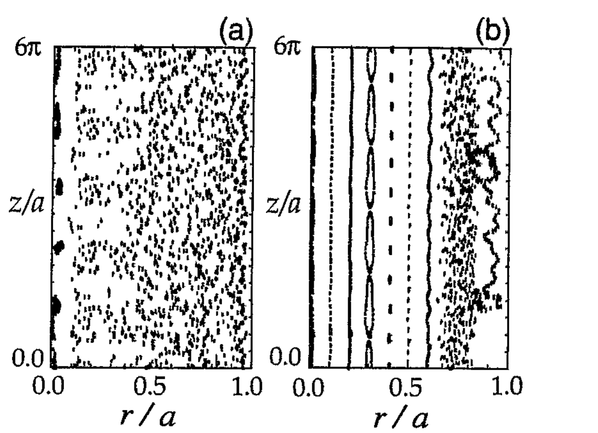

FIG. 2. Magnetic-field line puncture plots in the axial-radial plane (a) before and (b) after the addition of auxiliary current (the electron force).

As an example, we consider a typical MST RFP plasma (major radius $R=1.5$ m, minor radius $a=0.5$ m) with a toroidal current of 400 kA, a poloidal magnetic field strength of 1.6 kG at the plasma edge, and an electron density of 1.2×10^{19} m^{-3} on the magnetic axis. To permit penetration of the LH wave, we must choose $n_{\|}\gtrsim8$ at the edge. For example, this corresponds to a poloidal antenna wavelength of 19 cm at a frequency of 200 MHz ($\sim2f_{\rm LH}$). The radial penetration of the wave into a higher density region is facilitated by an upshifting of $k_{\|}=2\pi/\lambda_{\|}$, which is due to $1/r$ geometric reduction of $\lambda_{\|}$. Here, $\lambda_{\|}$ is the wavelength in the direction of the equilibrium magnetic field (predominantly poloidal in the outer region). For $n_{\|}<8$, $n_{\perp}$ is imaginary, even at the plasma edge, and the wave fails to penetrate.

The damping of the wave energy along a ray trajectory is estimated by calculating the imaginary part of the warm plasma dielectric tensor. To control the poloidal current profile by a traveling LH wave, we need to choose $n_{\|}$ such that the wave energy be mostly deposited in moderate to high energy electrons in the target zone. This can be accomplished by choosing $\lambda_{\|}$ at the edge such that $v_{\rm ph\|}/v_{\rm the}\sim2$ to 3 in the target zone, where $v_{\rm ph\|}$ is the parallel phase velocity of the wave and $v_{\rm the}$ is the electron thermal speed. This kinetic constraint imposes an upper limit on $n_{\|}$ for wave energy accessibility, precludes the possibility of traveling wave penetrating to the core of an RFP plasma, and makes the LH wave suitable for poloidal current drive in the outer plasma region.

For the typical MST discharge mentioned earlier the electron temperature in the target zone $0.7a$ is about 200 eV and electron density is about 8×10^{18} m^{-3}. The LH wave at $f=250$ MHz with $n_{\|}=10$ (or $\lambda_{\|}=12$ cm) at the plasma edge will complete about two poloidal turns before reaching the target zone where electron Landau damping is efficient.

The analytic estimates for the typical MST discharge have been confirmed by using an extended version of Brambilla's ray tracing code.[14] In the code we specify the values of f and $n_{\|}$ of the LH wave at the wall and launch a single ray from an outboard point on the equatorial plane. The magnetic-field structure is chosen to match an experimental profile in MST. The ray integration is carried out until the ray energy drops to 0.1% of the initial value. Figure 3(a) shows the ray trajectory projected on a constant toroidal angle plane.

The efficiency of RFCD can be characterized by a local quantity $\eta=j_{\|}^{\rm rf}/p^{\rm rf}$, where $j_{\|}^{\rm rf}$ is the RF-driven current density and $p^{\rm rf}$ is the RF power density deposited in the plasma. A useful but approximate formula for the total RF power re-

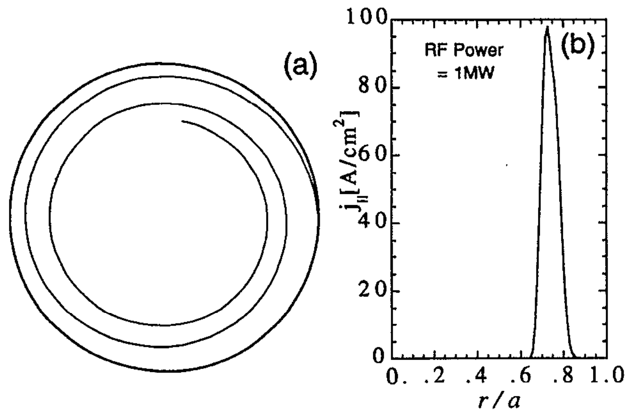

FIG. 3. (a) The ray trajectory of a LH wave (f=250 MHz and $n_\parallel$=10 at the wall) projected on a constant toroidal angle plane. (b) The profile of the RF driven current density for the case with 1 MW of RF power.

quirement is given by assuming that LHCD takes place uniformly within a cylindrical shell of inner radius r_1 and outer radius r_2. In this case, the RF-driven poloidal current I_θ^{rf} per total RF-power absorbed P is

$$I_\theta^{rf}/P \approx j_\parallel^{rf} 2\pi R(r_2 - r_1)/[p^{rf} 2\pi R(\pi r_2^2 - \pi r_1^2)]$$
$$= \eta/(2\pi r_{av}),$$

where $r_{av}=(r_1+r_2)/2$. In a tokamak, the RF-driven toroidal current per total RF-power absorbed is $I_\phi^{rf}/P \approx j_\parallel^{rf}\pi \times r^2/(p^{rf} 2\pi R \pi r^2) = \eta/(2\pi R)$. Hence, poloidal current drive in an RFP has a topological advantage of R/r_{av} over toroidal current drive in a tokamak. It is useful to note that for typical RFP equilibria,[15] $I_\theta \approx (3R/a\Theta)I_\phi$, where I_θ and I_ϕ are the total poloidal and toroidal plasma currents, respectively, and $\Theta \approx 2$ is the pinch parameter. Recall the MHD simulation predicted $I_\theta^{rf} \approx 0.25 I_\theta$ for stabilization.

The current drive efficiency is approximately given by $\eta = (38.4 \times 10^{18}/\ln \Lambda)(T_e/n_e)\eta_0$ [A-m/W], where $\ln \Lambda$ is the Coulomb logarithm, T_e is the electron temperature in keV, and n_e is the electron density in meter^{-3}. The dimensionless quantity η_0 is plotted in the paper by Ehst and Karney[16] as a function of $v_{ph\parallel}$ normalized to v_{the} and the fraction of trapped electrons. The poloidal magnetic field in the outer region of the RFP varies less than 10% on a flux surface, so the reduction in current drive efficiency due to particle trapping is small.

For the MST example above, we expect to achieve $\eta_0 \approx 10$ and $I_\theta^{rf}/P \approx 0.5$ A/W. The RF-driven current density peaks at around $r=0.7a$ [see Fig. 3(b)] as the LH wave is Landau damped mostly by the electrons with $v=2-3v_{the}$ in the target zone. The anticipated total RF power for stabilization is $P \approx 1$ MW. Magnetic fluctuations and anomalous particle losses may reduce the current drive efficiency. However, these effects might be avoided by preconditioning the target plasma with the aforementioned transient inductive current profile control.[7]

In summary, we have demonstrated that the LH slow wave is a promising candidate for efficient poloidal (parallel) current drive in the outer region of an RFP. Accessibility, energy absorption, and current drive have been evaluated through a combination of analytical calculations and computational ray tracing. To demonstrate the effect on magnetic fluctuations, auxiliary current drive in the outer region has been added to a nonlinear MHD code. The magnetic fluctuations are greatly reduced by the current profile flattening, and magnetic stochasticity in the core is essentially eliminated. Hence, we anticipate that LH current profile control is a suitable means to substantially improve confinement in the RFP.

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