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Study of Self-Generated Counter Current Flow in Tokamak Plasmas with Lower-Hybrid-Driven Current

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Abstract

We present a theoretical explanation for the counter-current flow observed in the Alcator C-Mod with Lower Hybrid Current Drive (LHCD). In non-overdrive regime, plasma spins up because counter-current momentum accumulates in plasma due to the improvement of electron momentum confinement during the launch of the lower hybrid wave. Simulations studies are carried out by applying a momentum transport model to the two-fluid equation system. Numerical results are consistent with experimental data. Co-current flow is predicted to occur in strong overdrive regime.

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The advantages of rotation on toroidal plasmas have been well addressed. Approaches other than neutral beam injection to drive rotation are needed for next generation tokamaks such as ITER [1, 2]. An alternative method to drive plasma rotation without direct external momentum input is to drive flow with RF waves, e.g. lower hybrid waves [3–6]. Recently, strong counter-current plasma rotation has been observed in discharges with LHCD[7–9]. However, the mechanism of the spinning-up of the plasma is still not clear. In this letter, we present a theoretical explanation for the flow in non-overdrive regime basing on the assumption that electron momentum confinement is improved by the lower hybrid waves. Here non-overdrive regime means toroidal electric field is in the same direction as plasma current. The lower hybrid waves interact with plasma globally [10–12] and it is reasonable to assume that strong lower hybrid waves can affect the transport features of plasma. Counter-current momentum is accumulated in the plasma because momentum confinement of electrons is improved by the lower hybrid waves. As a result plasma spins up counter-currently. The peak flow velocity can be estimated as $v_\varphi = -3E_\varphi a v_{ec}/4D_{i\varphi}\nu_{ei}$ [See Eq. (5)]. Radial profile and time scale of the flow are calculated by applying a momentum transport model to the two-fluid equation system. The numerical results are consistent with the experimental data of the Alcator C-Mod. This model also predicts that the lower hybrid waves can induce co-current flow in strong overdrive regime where toroidal electric field is opposite to plasma current.

To propose a mechanism for the counter-current flow, the question needs to be answered first is where the plasma gains the counter-current momentum in the discharges with LHCD. Any proposed momentum source has to be strong enough to drive a counter-current flow which is at least compatible with experimental data of flow speed and time-scale of spinning up. For a typical discharge of the Alcator C-Mod with LHCD the plasma density is $\rho \approx 10^{20}/m^3$, the maximum rotation speed is $v \approx 50km/s$ and the time-scale of spinning-up is $t \approx 200ms$. The magnitude of the momentum source to drive such a counter-current flow should be in the range of $-0.08kg \cdot m/s^2 \cdot m^{-3}$. Any proposed momentum source for the counter-current rotation in the Alcator C-Mod must be strong enough to produce this momentum.

Three plausible mechanisms for the counter-current momentum during LHCD had been proposed previously. However, we show here that none of these mechanisms can produce large enough momentum required. The first one is related to plasma non-neutrality. Plasma in tokamak is usually not exactly neutral, and it can be charged either positively or negatively. The lower hybrid wave might be able to cause orbit-pinch of resonant electrons [13–15]. Hence, electrons can be accumulated at the plasma core during discharges with LHCD, and the plasma core is charged negatively. Therefore the toroidal electric field in the toroidal direction is able to push the plasma counter-currently. The second plausible mechanism is related to possible non-zero radial current in tokamak. Just as discussed above, lower hybrid wave might be able to cause orbit-pinch of resonant electrons. Radial current can be non-zero if there is indeed such orbit-pinch. The Lorentz force induced by the radial current and the poloidal magnetic field will push the plasma counter-currently. The last one is that plasma gains counter-current momentum from the lower hybrid wave injected by antenna. We now show that these three mechanisms are not large enough to explain the experimental data.

For the first mechanism, the charge nonneutrality can be calculated using Poisson's equation from the radial electric field. The scale of radial electric field can be estimated from the radial force balance equation using experimental measured pressure, magnetic field and rotation velocity of the C-Mod [7]. The calculated radial electric field reaches its strongest magnitude at plasma core, which is on the scale of $400KV/m$, and charge density is on the scale of $-3.54 \times 10^{-6}C/m^3$. The inductive toroidal electric field of the Alcator C-Mod is typically around $0.24V/m$. Thus, the scale of momentum source that this mechanism can provide is $-8.5 \times 10^{-7}kg \cdot m/s^2 \cdot m^{-3}$, which is much less than what is required.

To see that the second mechanism is insufficient to explain the rotation, note that the orbital pinch caused by resonance with lower hybrid wave is a neo-classical effect. The pinch magnitudes of resonant trapped orbits and resonant transit orbits are different. The former is larger than the latter by an order of B_φ/B_θ, where B_φ and B_θ are toroidal and poloidal magnetic field respectively [13]. For distribution function of electrons close to the Maxwellian, the population of trapped electrons are less than that of transit electrons by an order of $exp[-R_0/2a]$, where R_0 and a are major and minor radius of tokamak respectively. The value of $exp[-R_0/2a]$ is much smaller than that of B_φ/B_θ, given typical experimental parameters. The radial particle flux should be calculated as resonant particle population times pinch velocity. Therefore the dominant radial current caused by the orbit-pinch of resonant electrons is from transit resonant electrons. The interaction between lower hybrid wave and resonant electrons can be modeled as random kicks when resonant velocity is reached. The orbit-averaged pinch distance Δr induced by one kick can be estimated as $\Delta r = q\Delta W/eB_0 V_{res}$ [13], where q is safety factor, ΔW is energy exchange between particle and wave during the kick, e is electron charge, B_0 is magnetic field at vacuum axis and V_{res} is resonant velocity. This estimate establishes a relation between radial current density caused by lower hybrid wave and power absorbed from lower hybrid wave by plasma, $j_r = qP_{abs}/B_0 V_{res}$, where j_r is the radial current density and P_{abs} is the power absorption. In terms of the LHCD efficiency $\eta = J_{LH}/P_{abs}$ [14], we have $j_r = qJ_{LH}/\eta B_0 V_{res}$, where J_{LH} is the current density driven by lower hybrid wave. Substituting the experimental data of the Alcator C-Mod into the equation above, we know that the radial current density driven by lower hybrid wave is in the order of $1.6mA/m^2$. Together with the poloidal magnetic field of the Alcator C-Mod, this mechanism is able to provide a momentum source on the scale of $-0.002kg \cdot m/s^2 \cdot m^{-3}$. It is much larger than momentum source provided by the first mechanism, but still far away from what is required. However, the spectrum of lower hybrid wave for the Alcator C-Mod contains a secondary branch carrying lower power but with phase velocity lower than primary branch, so that more electrons can resonate with the lower hybrid wave; Thus stronger radial current density might be generated. Although it seems like the approach described above is possible, a fundamental difficulty of this explanation is not resolved. The Lorentz force pointing at toroidal direction is caused by the interaction between radial current and poloidal magnetic field. Radial current is part of plasma current and poloidal magnetic field is generated by plasma current. Plasma cannot be pushed to rotate by itself according to Newton's Law. A similar mechanism has been presented recently [16]. However, there is no discussion regarding to any source where the counter-current momentum might come from.

The calculation for the third mechanism is straight forward. The total output power of the antenna of Alcator C-Mod is $W = 0.8MW$. The total momentum input by antenna is $P = W/c \sim 0.00267kg \cdot m/s^2$. To compare it with the minimum requirement of momentum source $-0.08kg \cdot m/s^2 \cdot m^{-3}$ we need to calculate the momentum density instead of the total momentum input by the lower hybrid wave. Considering the geometry parameters of Alcator C-Mod and plasma flow is localized at core, $r \leq 0.1m$ [7, 8], we know the momentum density is $p = P/V \sim 0.02kg \cdot m/s^2 \cdot m^{-3}$, which is about 4 times smaller than the minimum amount. The lower hybrid wave is never absorbed completely. Considering the efficiency of the absorbtion, the effective momentum injected by the lower hybrid wave is even smaller.

In this paper, we propose the following mechanism to explain the generation of counter-current flow during discharges with LHCD. The toroidal inductive electric field (loop voltage) acts as a momentum source for electrons and ions separately. In general, friction between electrons and ions consumes a portion of the momentum input by the inductive electric field. The rest of the momentum for both species is transported to the wall, and there is no net momentum accumulated. However, the launch of the lower hybrid wave might be able to tip the balance by improving the momentum confinement of electrons. Extra counter-current momentum is accumulated in the electrons. It causes higher electron fluid speed hence larger friction. The friction breaks the previous force balance of ions and drags ions to rotate counter-currently. A new balance is achieved by turning a static plasma into a counter-currently rotating plasma. The inductive electric field is a momentum source on a scale of $-4kg \cdot m/s^2 \cdot m^{-3}$ for electrons and $4kg \cdot m/s^2 \cdot m^{-3}$ for ions given the experimental parameters of the Alcator C-Mod. This value is 50 times larger than the required momentum source derived previously. Therefore, a slightly deviation away from the balance should be enough to drive a significant rotation.

In order to gain a more comprehensive understanding of the mechanism introduced above, we demonstrate it numerically by applying a simplified two-fluid plasma model. For simplicity, calculations in this paper is carried out using a tokamak model with circular concentric flux surfaces. In this geometry, we use the toroidal coordinate system (r, θ, φ), which are illustrated in Fig. 1. The three components of any given field are called radial, poloidal and toroidal component respectively. Sixteen equations are included in the standard two-fluid plasma model, which are continuity equations, momentum equations, equations of state for ions and electrons respectively, Ampere's Law and Faraday's Law. The unknowns are densities, pressures, velocities for ions and electrons respectively, electric field and magnetic field. The number of equations and unknowns can be reduced to seven by assuming that the spatial profiles of density n_i and n_e of ions and electrons, pressure p_i and p_e of ions and electrons, poloidal magnetic field B_θ, toroidal magnetic field B_φ, toroidal electric field E_φ, poloidal electric field E_θ, and the radial magnetic field B_r are given and temparally constant during the formation of the flow. The remaining seven unknowns are the radial component of electric field and velocities of ions and electrons. We keep seven equations which are radial component of Ampere's Law and momentum equations of ions and electrons. The toroidal component of the momentum equations can be decoupled from the rest by the following pro-

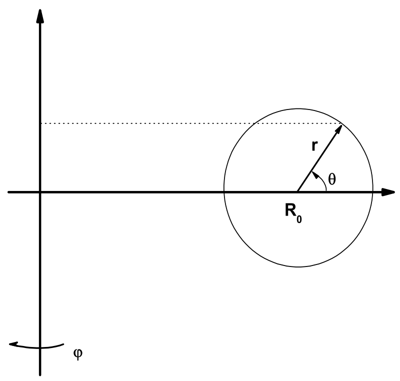

FIG. 1: 2D tokamak geometry with circular concentric flux surfaces.

cedure. The radial velocity of ions is smaller than the poloidal and toroidal rotation velocities by more than two orders of magnitude ($v_{ir} = 10m/s, v_{i\theta} = 10^3-10^4 m/s, v_{i\varphi} = 10^4-10^6 m/s$) and can be neglected [17]. The radial component of electron velocity is neglected assuming it is much smaller than the other components. Terms $v_{i\theta}\hat{\mathbf{e}}_\theta \cdot \nabla v_{i\varphi}$ and $v_{e\theta}\hat{\mathbf{e}}_\theta \cdot \nabla v_{e\varphi}$ are neglected because their averages over flux surfaces vanish, i.e., $\langle v_\theta \hat{\mathbf{e}}_\theta \cdot \nabla v_\varphi \rangle_{fluxaverage} = 0$ [17]. All the terms containing ∇_φ do not contribute because of the toroidal symmetry. The two decoupled momentum equations for toroidal velocities of ions and electrons are

$$n_i m_i \frac{\partial v_{i\varphi}}{\partial t} = -(\nabla \cdot \pi_i)_\varphi + e n_i E_\varphi - \nu_{ei} n_e m_e (v_{i\varphi} - v_{e\varphi}) \ , \tag{1}$$

$$n_e m_e \frac{\partial v_{e\varphi}}{\partial t} = -(\nabla \cdot \pi_e)_\varphi - e n_e E_\varphi - \nu_{ei} n_e m_e (v_{e\varphi} - v_{i\varphi}) \ . \tag{2}$$

Here, $(\nabla \cdot \pi_i)_\varphi$ and $(\nabla \cdot \pi_e)_\varphi$ are toroidal components of viscosity terms which represent the physics of toroidal momentum transport of ions and electrons. A toroidal component of viscosity term is composed of a neo-classical term $(\nabla \cdot \pi)_\varphi^{Neo}$ and an anomalous term $(\nabla \cdot \pi)_\varphi^{an}$. The neo-classical term can be ignored because it is much weaker than the anomalous term [17]. In the numerical calculation, we use the following expressions for anomalous viscosity terms [18, 19],

$$-(\nabla \cdot \pi_i)_\varphi^{an} = \frac{1}{r}\frac{\partial}{\partial r} r [D_{i\varphi} \frac{\partial n_i m_i v_{i\varphi}}{\partial r} + \frac{v_{ci} r n_i m_i v_{i\varphi}}{a}] \ , \tag{3}$$

$$-(\nabla\cdot\pi_e)^{an}_{\varphi}=\frac{1}{r}\frac{\partial}{\partial r}r[D_{e\varphi}\frac{\partial n_e m_e v_{e\varphi}}{\partial r}+\frac{v_{ce} r n_e m_e v_{e\varphi}}{a}]\ , \tag{4}$$

where a is the minor radius, $D_{i\varphi}$ and $D_{e\varphi}$ are momentum diffusivities of ions and electrons, and v_{ci} and v_{ce} are momentum convection velocity of ions and electrons. These four parameters are to be determined by experimental data.

Eqs. (1) and (2) are the key equations. An estimate of peak counter-current flow velocity can be made from the above equations by setting $\partial v_{i\varphi}/\partial t \sim \partial v_{e\varphi}/\partial t \sim 0$, $v_{i\varphi} \sim v^0_{i\varphi}$, $v_{e\varphi} \sim v^0_{e\varphi}$, $\partial v_{i\varphi}/\partial r \sim -v^0_{i\varphi}/a$, $\partial v_{e\varphi}/\partial r \sim -v^0_{e\varphi}/a$ and $\partial^2 v_{i\varphi}/\partial r^2 \sim \partial^2 v_{e\varphi}/\partial r^2 \sim 0$. The peak counter-current flow velocity is,

$$v_{\varphi}=-3E_{\varphi}av_{ec}/4D_{i\varphi}\nu_{ei}\ . \tag{5}$$

Subject to the boundary condition of no toroidal edge rotation, the evolution of toroidal rotation can be described by the solution of Eqs. (1) and (2). We will first simplify the parameters of Eqs. (1) and (2) before doing the calculation. Spatially uniform profiles are assumed for inductive electric field, densities, temperatures, momentum diffusivities of both species, and momentum convection velocity of ion in the numerical calculation. The improvement of momentum confinement of electrons induced by the lower hybrid wave is represented by an increment of v_{ce} from zero to a positive value. Larger increment means stronger improvement. According to previous studies of the Alcator C-Mod, the parameters are selected as follows in our numerical calculation, toroidal electric field $E_{\varphi} = 0.1V/m$, density $n_i = n_e = 10^{20}/m^3$, electron temperature $T_e = 2.5KeV$, momentum diffusivity of ion $D_{i\varphi} = 0.175m^2/s$, momentum convection velocity of ion $v_{ci} = 0m/s$ [18, 19]. The momentum diffusivity of electrons is assumed to be the same as that of ions. The profile of momentum convection velocity of electrons v_{ce} is chosen to fit the experiment data of plasma rotation profile of the Alcator C-Mod [7, 8].

Three different cases have been numerically studied. In the first case, we assume that the interaction between lower hybrid wave and resonant electrons happens spatially uniformly. Thus momentum confinement of electron is improved uniformly. We choose a flat profile for v_{ce}, i.e., $v_{ce} = v_{ce0}$ in our simulation correspondingly. For the second case, the lower hybrid wave and the resonant electrons have the strongest interaction near the plasma core. Hence the largest enhancement of momentum confinement of electrons is reached at the plasma core. As a result we choose the profile of v_{ce} to be $v_{ce} = v_{ce0}Exp[-(r/a)^2/0.5]$. In the last case, resonance between lower hybrid wave and electrons is mostly localized at position $r = a/2$. The momentum confinement of electron is improved mostly at position $r = a/2$ consequently. The profile of v_{ce} is chosen to be $v_{ce} = v_{ce0}Exp[-(r/a - 0.5)^2/0.1]$ in the calculation. Plasma rotation profiles for the three cases after reaching new steady states are plotted in Fig. 2. Maximum flow velocities of $-70km/s$, $-30km/s$ and $-40km/s$ are reached for the three cases respectively. The flow velocities for the three cases versus time are plotted in Fig. 3. We can see from Fig. 3 that the time scale of flow formation for the three cases are $100 \sim 200ms$. Both the magnitude and time scale of formation of counter-current flow in our model are compatible with the experimental data of the Alcator C-Mod [7, 8]. A more detailed investigation of simulation data shows that friction force is lower than electric force on ions initially. However, it exceeds the electric force by about 5 percent immediately after the launching of lower hybrid wave. Therefore, the spinning up of ions in our model is indeed caused by the increase of friction between ions and electrons. We have an estimate of peak flow velocity, $v_\varphi \sim -183km/s$, by applying parameters of the first case to Eq. (5). Though it is larger than what we have from the simulations, it is a useful expression for estimating flow velocity roughly.

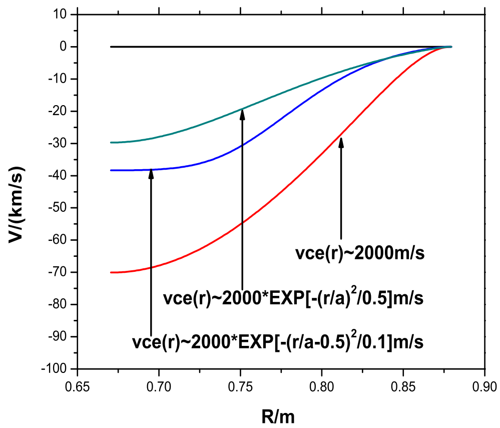

FIG. 2: The profiles of counter-current flow with different spatial resonant locations between lower hybrid wave and electrons.

There is indeed experimental evidence showing that electron momentum confinement is improved by launching a lower hybrid wave. A correlation between the peaking factor of electron density and velocity of plasma flow is plotted in Fig. 4. The peaking factor is defined

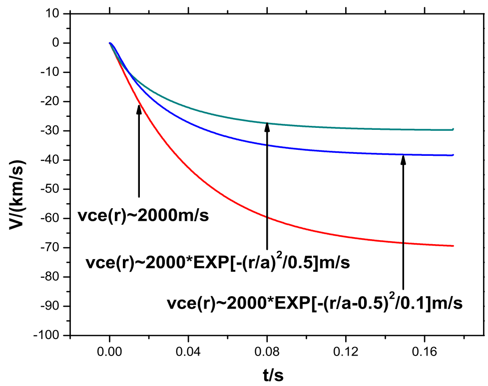

FIG. 3: Time evolution of toroidal velocities at core with different spatial resonant locations between lower hybrid wave and electrons.

as the ratio of densities at core and 0.7 minor radius, i.e., $n_e(0)/n_e(0.7a)$, where the data of the peaking factor and plasma flow is obtained from discharges of the Alcator C-Mod with LHCD. There is a strong correlation between the peaking factor and the velocity according to Fig. 4. Larger velocity is resulted from stronger interaction between lower hybrid wave and plasma. Higher peaking factor indicates better particle confinement of electron which can be a sign of better momentum confinement of electrons. Therefore stronger interaction of wave and electrons results in better electron momentum confinement. Unfortunately we are not able to show any more direct correlation due to lacking of experimental data related to electron momentum confinement.

The mechanism of the counter-current flow proposed is summarized as follows. The inductive electric field is the dominant momentum source for tokamak plasma. It provides the same amount of momentum to ions and electrons. The friction between electrons and ions consumes part of the momentum. The rest is transported to first wall through either the channel of electrons or that of ions. Whenever the momentum transport of electron is reduced by external factor, e.g., the injection of lower hybrid wave, extra counter-current momentum is accumulated in plasma. Therefore plasma spin up counter-currently. A non-zero toroidal electric field is important in the mechanism proposed above. Experiments suggest that toroidal electric field can be close to zero in some cases with LHCD. However, this discrepancy can be reconciled by realizing that first, a very weak toroidal electric field,

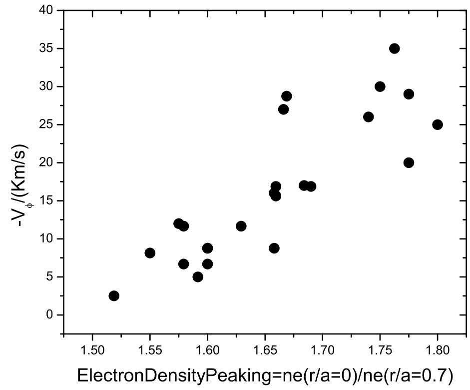

FIG. 4: Correlation between electron density peaking factor and peak velocity of plasma flow.

i.e., $V = 0.02V$, is strong enough to provide the required momentum source. In addition, toroidal electric filed is usually measured at the last closed flux surface, and its magnitude in plasma core is not necessarily zero. The difference between our approach and traditional momentum transport theory is the treatment of electrons. Electrons are usually not considered for the study of momentum confinement of tokamak plasma because of the negligible electron mass compared to ion mass. However, as we already discussed above, electrons gain the same amount of momentum from the electric field as ions because of quasi-neutrality of the plasma. Therefore, it is necessary to consider electrons in the study of plasma flow generation.

In addition, we can predict plasma flows in strong overdrive regime using our theoretical model. By strong overdrive regime it is meant that toroidal electric field is opposite to plasma current due to the LHCD. Overdrive regime is a necessary component in the currently envisioned tokamak operation mode with cyclic lower hybrid waves [20, 21]. If electron momentum confinement is improved by the lower hybrid wave as in the non-overdrive regime, then co-current momentum accumulates in plasma, and co-current flow should be observable.

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[1] S. A. Sabbagh et al, Phys. Rev. Lett. **97**, 045004 (2006).

[2] Y. Liu et al, Nuclear Fusion **44**, 232 (2004).

[3] J. Decker, Y. Peysson, J. Hillairet, J. F. Artaud, V. Basiuk, A. Becoulet, A. Ekedahl, M. Goniche, G. T. Hoang, F. Imbeaux, et al., Nucl. Fusion **51**, 073025 (2011).

[4] M. Murakami, J. M. Park, G. Giruzzi, and J. Garcia et al, Nucl. Fusion **51**, 103006 (2011).

[5] A. A. Tuccillo et al, Nucl. Fusion **47**, B363 (2005).

[6] F. Imbeaux et al, Nucl. Fusion **51**, 083026 (2011).

[7] J. E. Rice et al, Nuclear Fusion **49**, 025004 (2009).

[8] A. Ince-Cushman et al, Phys. Rev. Lett. **102**, 035002 (2009).

[9] A. Schmidt, P. T. Bonoli, O. Meneghini, R. R. Parker, M. Porkolab, S. Shiraiwa, G. Wallace, J. C. Wright, R. W. Harvey, and J. R. Wilson, Physics of Plasmas **18**, 056122 (2011).

[10] R. Cesario, L. Amicucci, C. Castaldo, M. Kempenaars, S. Jachmich, J. Mailloux, O. Tudisco, A. Galli, A. Krivska, and J.-E. contributors, Plasma Phys. Control Fusion **53**, 085011 (2011).

[11] J. Garcia, G. Giruzzi, X. Litaudon, J. Mailloux, J. F. Artaud, V. Basiuk, J. Decker, F. Imbeaux, Y. Peysson, M. Schneider, et al., Nucl. Fusion **51**, 073019 (2011).

[12] G. M. Wallace et al, Physics of Plasmas **17**, 082508 (2010).

[13] X. Guan, H. Qin, and N. Fisch, Physics of Plasma **17**, 092502 (2010).

[14] N. J. Fisch, Reviews of Modern PHysics **59**, 175 (1987).

[15] N. J. Fisch and C. Karney, Phys. Fluids **24**, 27 (1981).

[16] S. Wang, Physics of Plasmas **18**, 102502 (2011).

[17] K. Ida, Plasma Phys. Control. Fusion **40**, 1429 (1998).

[18] W. D. Lee et al, Phys. Rev. Lett. **91**, 205003 (2003).

[19] J. E. Rice et al, Nuclear Fusion **44**, 379 (2004).

[20] J. Garcia, G. Giruzzi, P. Maget, J. F. Artaud, V. Basiuk, J. Decker, G. Huysmans, F. Imbeaux, Y. Peysson, and M. Schneider, Nucl. Fusion **50**, 025025 (2010).

[21] N. J. Fsich, J. Plasma Physics **76**, 627 (2010).

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