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BY HEATING A TOROIDAL PLASMA

BY

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**PLASMA PHYSICS
LABORATORY**

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Methods of Driving Current by Heating a Toroidal Plasma*

Nathaniel J. Fisch

Abstract

We survey the possibilities that abound in driving toroidal currents in tokamaks by means of heating mechanisms. In addition to the usual mechanism which utilizes the Ohmic transformer current, which is necessarily pulsed, there exist several steady-state mechanisms. Heating mechanisms which can lend themselves efficiently to continuous current generation include neutral beams, Alfvén waves, ion-cyclotron waves, lower-hybrid waves and electron-cyclotron waves.

I. Introduction

The operation of a tokamak is dependent upon the maintenance of a toroidal electric current. For a fusion reactor based upon the tokamak concept to become an economic reality, this toroidal current must be produced both cheaply and in long pulses. Long pulses are required in order to limit the metal fatigue arising from the heat stress to which the structural components of the tokamak are subjected in a pulsed device. In this paper we survey the methods that have been proposed to produce this current, particularly the steady-state methods, and we assess the relative attractiveness of these schemes in a reactor environment.

In discussing the schemes for current-drive, we have categorized them according to whether the current is carried by the whole electron distribution, by a small number of superthermal electrons, or through the outflow of electrons from the magnetic axis.

II. Thermal Current Carriers

The method originally envisioned for driving the toroidal current is the inducement of a static toroidal electric field, which, since it is not curl-free, occurs by means of a time-varying magnetic field. This method suffers primarily in that it is inherently pulsed, since confinement is maintained only so long as the magnetic field varies monotonically. An advantage of this method, however, is that the power dissipated in the plasma is quite small or, in other words, the current is produced cheaply. The reason for this is that the electric field pushes electrons as though they were a fluid with a parallel velocity equal to the average electron velocity, v_d , which in practical situations is a very small velocity. Thus, it is easy for the field to push the electron fluid, since (in one dimension) it is far easier to push a slow particle than a fast particle as the ratio of expended energy to imparted momentum is the particle velocity.

The principle of pushing slow particles guided the earliest attempts at

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improving upon inductively driven currents through the use of acceleration mechanisms that could operate continuously. One suggestion¹ is to employ traveling Alfvén waves to impart momentum to resonant electrons, i.e., those with parallel velocity $v_{\parallel}$ equal to the wave parallel phase velocity $\omega/k_{\parallel}$. Such waves could be excited with relatively small $\omega/k_{\parallel}$ indicative of a high content of parallel momentum per unit energy (since the wave energy is proportional to its frequency ω , whereas the wave parallel momentum is proportional to its parallel wavenumber $k_{\parallel}$). The idea is to impart momentum with as little as possible energy expenditure to the resonant electrons and thence, by collisions, to produce a drift of the electron fluid in a manner similar to that produced by a dc electric field. If the power dissipated by ohmic currents is given by

$$P_d = \eta_{\parallel} J^2, \quad (1)$$

then the power dissipated by the Alfvén wave driven current would be given approximately by

$$P_d = \eta_{\parallel} J^2 (v_{\parallel}/v_d), \quad (2)$$

where J is the current and $\eta_{\parallel}$ is the Spitzer resistivity. (A more exact derivation of the power dissipated is given in Ref. 2.)

The factor $v_{\parallel}/v_d$, which is usually large, occurs as an inefficiency arising from pushing individual electrons with velocity $v_{\parallel}$ rather than pushing a fluid with velocity v_d . These electrons are faster and hence harder to push. To avoid ion Landau damping, $v_{\parallel}$ must be substantially greater than v_{Ti} , the ion thermal velocity, but still could be small compared to, say, v_{Te} , the electron thermal velocity.

An alternative suggestion³ that similarly employs a high-momentum "pusher" is to inject counter-streaming ion beams, which may enter the plasma as neutrals, of disparate ion charge states. Although the total injected ion current may vanish, the electrons will collide preferentially with the ions with the higher charge state and consequently will drift in the streaming direction of those ions, producing net current. The ions with the higher charge state must, however, be injected at superthermal velocities, so that the injected ions will collide mainly with electrons before losing their directed momentum to the other ion species. This implies that the power requirements for driving currents by beams is approximately the same as those for driving currents by Alfvén waves, since the momentum content per unit energy of the beam is roughly equivalent to that of the wave.

The brute-force injection of counter-streaming neutral beams may be technologically inferior to other means of producing counter-streaming ions of disparate charge states. Addressing this point is the recent proposal⁴ to drive currents by minority species heating using ion cyclotron waves. The idea here is to increase the gyromotion of minority species ions that travel in one direction parallel to the magnetic field. The increased energy of these ions does not affect their collision frequency with electrons, which in

any case are much faster, but does decrease the collision frequency with the majority ions which are slower and hence sensitive to the energy of the minority ions if they are superthermal. The result then of the minority heating is to alter the majority ion drag only on minority ions with one sign of parallel velocity so that the drag retards these minority ions less than counter-streaming ones. Consequently, the two ion species tend to move in opposite directions and, should they have disparate charge states, a current develops as with neutral beam current-drive. The power requirements are similar to those for neutral beam injection, though possibly technologically easier to fulfill.

The above three methods of producing steady-state currents with high-momentum-content drivers all face the same limitation, namely, the energy/momentum of the driver must be somewhat greater than an ion thermal velocity. Thus, the power dissipated in any of these schemes obeys Eq.(2) with $v_{\parallel} > v_{Ti}$. An estimate of the dissipated power may be obtained by assuming that $\beta_p = R/a$ is attained, where R and a are the major and minor radii, and where β_p is the ratio of plasma pressure to poloidal magnetic field pressure. It may then be calculated, assuming $v_{\parallel} > v_{Ti}$, that

$$\frac{v_{\parallel}}{v_d} \approx \left(\frac{m_e}{m_i}\right)^{1/2} \frac{(aR)^{1/2}}{\delta} \approx 10^{-2} a_1 n_{14}^{1/2}, \quad (3)$$

where $\delta \equiv c/\omega_{pe}$ is the plasma skin depth, n_{14} is the density normalized to 10^{14} cm^{-3} and a_1 is the minor radius in meters. Using Eqs. (2) and (3), it can be seen that, for reactor parameters, the three proposed steady-state current-drive schemes dissipate two to three orders of magnitude more power than the conventional inductive means dissipates. Although this appears to be a large dissipated power, for purposes of appreciating economic feasibility the proper comparison is to the fusion power output, of which this power is only a few percent. Allowing for inefficiencies in producing and delivering this power to the tokamak, this implies a tolerable level of circulating power to sustain the steady state. Yet, an even lower level of circulating power to sustain steady-state currents would be highly desirable and is an especially tantalizing ambition in view of the remarkably smaller power level required to sustain the ohmic current.

III. Superthermal Current Carriers

In all the above schemes of driving current, including the inductive means, the electrons are treated as a single fluid which, by one mechanism or another, flows against a retarding background of ions. A basically different approach⁵ distinguishes that superthermal electrons are far less collisional than the thermal electrons, so that it would be desirable, even if they are harder to push, to have the current carried exclusively by these fast electrons. To examine schemes which achieve reduced ion drag by producing currents of this nature, consider first the general question of pushing these fast electrons in the arbitrary velocity direction $\hat{s}$. For the pushing to occur by means of waves, which diffuse resonant electrons in energy, obviously $\hat{s}$ must

point to higher energy. It may be shown⁶ that the current produced per power dissipated as a result of such a push is given by

$$\frac{J}{P_d} = \left(\frac{4}{5 + Z_i} \right) \frac{\hat{s} \cdot \hat{w} u^3}{\hat{s} \cdot \hat{w} u^2}, \quad (4)$$

where w is the resonant electron parallel velocity and u is the resonant electron speed both normalized to v_{Te} , J is normalized to $-en_0 v_{Te}$ and P_d is normalized to $v_0 n_0 e v_{Te}^2$, where $v_0 = \omega_p^4 \ln \Lambda / (2\pi n_0 v_{Te}^3)$ and Z_i is the ion charge state. Equation (4) enjoys substantial numerical verification.⁷

Consider now the case in which $\hat{s}$ is parallel to w , which describes the pushing of superthermal electrons by lower-hybrid waves.⁵ Since $w \gg 1$, most resonant electrons have $u \approx w$, so that $J/P_d \sim w^2$, which scales as w^3 times the J/P_d associated with the previously considered steady-state current-drive schemes. This is as expected since the resonant electrons here are w^3 times less collisional than thermal electrons. For reactor parameters, where typically $w \approx 4$, the power requirements here are comparable to those for the other schemes.

Note that lower-hybrid waves have little momentum content since $w \gg 1$. Thus, whereas previously a high-momentum-content pusher was employed at the expense of pushing collisional electrons, here relatively collisionless electrons are pushed by forgoing the advantage of a pusher with high momentum content. The advantages of both schemes would happily accrue were a wave with high momentum content (low $\omega/k_{\parallel}$) allowed to impart its momentum to a superthermal electron. In principle, this can be achieved with a low-phase-velocity cyclotron wave with $\omega \ll \omega_{ce}$, where ω_{ce} is the electron cyclotron frequency, but with the Doppler shifted phase velocities, $(\omega + \omega_{ce})/k_{\parallel}$, several times the electron thermal velocity. Thus, the resonant electrons are collisionless, although the wave has abundant parallel momentum. The effect of such a wave is to diffuse the resonant electrons along paths of nearly constant energy. Assuming a normalized wave parallel phase velocity w_1 , the diffusion direction is given by $\hat{s} = x\hat{w} - (w - w_1)\hat{x}$, where x is the normalized perpendicular velocity and the hatted quantities are unit vectors. From Eq. (4) we get, for $w_1 \rightarrow 0$,

$$J/P_d = \left(\frac{2}{5 + Z_i} \right) \frac{u^3}{w_1}, \quad (5)$$

which is seen to be far greater than that attainable by other steady-state schemes since it is simultaneously allowable to have $u \gg 1$, but $w_1 \ll 1$. Unfortunately, although the plasma supports waves with the necessary characteristics for achieving this exceptionally efficient means of current-drive, it appears that these waves are impossible to excite efficiently in a fusion environment. This is because suitable waves would have $\omega_{ce}/k_{\parallel} = v_{Te}$, which, in fusion reactors, implies a wave with a one-millimeter parallel wavelength, and an efficient launching of such a wave appears to be an insurmountable technological problem.

Finally, note that it is not necessary to impart any parallel momentum at all to fast electrons by waves in order to drive a current.⁶ This can be seen

from Eq. (4) by taking $\vec{k}$ perpendicular to $\vec{w}$ and noting that J/P_d does not vanish. The current arises because electrons traveling in only one direction absorb the wave energy and hence become more collisionless. The ions then drag less on these electrons than those traveling in the opposite direction, resulting in a current. This scheme can make advantageous use of electron cyclotron waves with super-relativistic parallel phase velocities and little momentum content.

IV. Conversion of Vector Potential

All the schemes surveyed thus far can be used to generate current in a homogeneous plasma. In a tokamak, however, the magnetic field is not homogeneous, and other effects come into play. The particle vector potential, for example, is a function of radial position. Note that the toroidal canonical angular momentum has two components, mechanical momentum and vector potential, and only the sum of the two components is a constant of single particle motion in an axisymmetric geometry. Thus, a mechanism that converts vector potential to angular velocity need not impart toroidal momentum and yet may still directly generate, or destroy, the toroidal current. The generation (destruction) of current is always accompanied by charged particles streaming away from (to) the magnetic axis.

Large radial excursions, with resulting variation in current, occur only for trapped particles. Since these particles occur mainly on the tokamak periphery, the effects that are described in this section occur near the periphery rather than near the magnetic axis.

The only previously discussed scheme that could be significantly affected by trapped particles is current generation by Alfvén waves, because the waves interact specifically with electrons with low $v_{||}$, which are mostly trapped. Since these electrons cannot absorb mechanical momentum, they must instead drift towards the magnetic axis. In the steady state, if it is achieved, a compensating outward flow of electrons must, however, counterbalance the inward flow. Accompanying the outward flow will be the same mechanical momentum (and current) that was lost by the inward flow. Thus, the Alfvén wave momentum is used, essentially, to provide a particle source for the bootstrap current.

Alternate mechanisms for particle sources near the magnetic axis may be envisioned. One example is the injection of neutral pellets which ionize near the magnetic axis. The ionization is tantamount to the production of vector potential which is converted into current as the charged particles leave the magnetic axis.

The question is how to achieve the steady state or, in other words, how to induce the outward flow of charged particle from the magnetic axis, granted that a mechanism (e.g., Alfvén waves or pellet injection) was found to bring them there in the first place. It is not clear whether the plasma itself will find means of expelling these particles from the magnetic axis as β_p rises. At any rate, these particles may be expelled by external means. This may be done, for example, by perpendicularly heating untrapped electrons that carry current in the wrong direction.⁸ The perpendicular heating traps these

electrons so that they no longer carry the counter-current. Since the external source imparted no momentum to the electrons, an outward electron flow must accompany the current production.

V. Relative Merits

Several steady-state mechanisms for driving current in tokamaks have been proposed in order to improve upon pulsed tokamak operation. The assessment of the relative merits of these schemes must address both their power requirements and technological feasibility, including the survival probability of the apparatus in a fusion environment. A thorough assessment is obviously beyond the scope of this section; instead, here some of the relevant issues are merely brought to light.

It should be noted that current generation by conversion of vector potential results in a hollow current profile, since the conversion cannot occur on axis. The hollow current profile is unstable, so that this scheme cannot exist by itself, although it may be useful as an assist to other schemes.

The other schemes utilize a variety of devices in stages of varying technological advancement. Powerful and efficient neutral beam sources would need to be developed, as would suitable shielding, enabling the sources to be placed in the proximity of the reactor. Singly charged heavy ion beams, which produce the same effect in the plasma, may be preferred to neutral beams.⁹

For transporting rf energy, waveguides may be preferred over coils, and for that reason the lower-hybrid wave may be an especially attractive candidate for driving current. On the other hand, to date, lower-hybrid heating has not been proved experimentally as efficient as minority species heating. In theory, the most efficient scheme utilizes selective electron heating by electron cyclotron waves, since these waves can resonate with the most collisionless electrons, although how this can be achieved in practice has yet to be examined in detail.

In conclusion, it may be noted that although definitive assurances cannot be given that any one scheme is likely to work, there is a certain comfort to be taken in the number and variety of schemes that have been proposed to maintain steady-state toroidal current for tokamak reactors.

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