Bootstrap Tokamak Reactor Driven by Fusion-Produced Alpha Particles

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A new possibility for steady-state current drive based on the use of neoclassical transport processes in tokamak reactors is considered. It is found that the existence of a steady-state self-sustaining plasma current can be ensured with a bootstrap current generated on the magnetic axis by fusion-produced alpha particles. The radial distribution of the driving current turns out to be peaked at a radius close to the magnetic axis.

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A key problem in realizing steady-state operation of a tokamak reactor is the generation and sustainment of a continuous toroidal current. During the last years, a variety of non-Ohmic methods have been proposed to maintain a steady-state current by using externally supplied power sources, e.g., various rf fields or neutral beams. Although there have been several experiments that have established the possibility of driving currents with rf waves or neutral beams, one should note that the prospects of incorporating these methods in a thermonuclear reactor are connected with severe disadvantages. First and foremost, it should be necessary to give up the regime of self-sustaining thermonuclear burning and, second, there is a need for development and application of powerful steady-state sources of rf fields and/or neutral beams. In addition, present-day experiments indicate a strong deterioration of the efficiency of the current drive when the plasma density is increased to values which are required for a fusion reactor. Thus it is not clear whether a sufficiently large reactor multiplication factor (ratio of fusion power to the power introduced into the plasma), $Q > 15$, can be obtained.

In this context, there is motivation, therefore, to explore the possibility of new current-drive methods which are characterized by a high efficiency and, especially, which are based on the use of internal plasma processes only. The prediction by Galeev and Sagdeev[1] of enhanced radial diffusion in the banana regime and the associated diffusion-driven toroidal current prepared the ground for works in this direction. Kadomtsev and Shafranov,[2] and independently, Bickerton, Connor, and Taylor,[3] were the first who considered the possibility of a steady-state tokamak using neoclassical transport process. They concluded that such a tokamak is possible only provided that a seed current is generated in the near-axis region by external sources. A more detailed treatment of the "bootstrap tokamak" with neutral injection was carried out by Sigmar[4] and Sigmar and Rutherford.[5]

A new approach to the problem of sustaining a steady-state current in a tokamak plasma was given by Kolesnichenko, Reznik, and Yavorskij.[6] They realized that for reactor conditions the role of a generator of a high-energy ion beam may be played by the thermonuclear reaction producing the high-energy alpha particles which, because of the presence of pitch-angle–dependent prompt losses, have an anisotropic distribution. The possible use of alpha particles for the currrent drive in tokamaks with $I < 5.4\sqrt{A}$ (I is the plasma current in megamperes; A is the aspect ratio of the torus), in which the driving-current region includes the magnetic axis, was considered by the same authors together with Chuyanov and Putvinskii.[7] Recently, Goloborod'ko, Kolesnichenko, and Yavorskij[8] have developed the neoclassical theory of alpha-particle transport in the central region of a tokamak plasma with $I > 5.4\sqrt{A}$ and shown that in the neighborhood of the magnetic axis (and on the axis itself) the alpha-particle bootstrap current is nonzero.

Since the potential of the bootstrap current for generating a steady-state tokamak is of substantial practical importance it should be pointed out that the question of experimental verification of the bootstrap current in tokamaks remains open.[9] Hogan[10] has investigated the experimental data from the ISX-B tokamak and concluded that the beam-induced bootstrap current, if present, must be less than 25% of its theoretically predicted value. This conclusion seems to be supported by the theory of Molvig *et al.*[11] who argue that the nonobservance of the bootstrap current in fusion devices may be a consequence of deviations from perfect symmetry caused by fine-scale turbulence which can weaken the bootstrap current. On the other hand, Zarnstorff and Prager[12] have recently observed the bootstrap current in a toroidal ocotopole experiment and found that the detailed measurements of the parallel plasma currents agree with the neoclassical-transport-theory predictions.

In this paper we wish to draw attention to the fact that the presence of an alpha-particle–generated bootstrap current makes it possible to reconsider the problem of the bootstrap tokamak. The present analysis is the first effort in this direction. We show that, even in the absence of a seed current driven with neutral injection, a self-sustaining plasma current exists. Its radial distribution is nonmonotonic and peaked at a radius close to the magnetic axis.

We consider plasma parameters similar to those of an INTOR-type tokamak reactor: $I \sim 5$–7 MA, $B \sim 50$ kG, $R \sim 500$ cm, and $A \sim 3$–5, where B is the toroidal magnetic field and R is the major radius. In this case the current condition $I > 5.4/\sqrt{A}$ MA for confinement of the alpha particles produced in the magnetic-axis region is well fulfilled and the results of the neoclassical theory developed in Ref. 8 are applicable. Because of considerable radial excursions of the alpha particles the expression for the alpha bootstrap current[8] is approximately valid in a sufficiently large plasma region $r/a < A\delta^{2/3} \sim 0.3$, where $\delta = 2q_0\rho_\alpha/R$, q_0 is the tokamak safety factor at the magnetic axis, and ρ_α is the Larmor radius of the high-energy alpha particles. On the other hand, the limits of validity of the neoclassical theory[13] for bulk plasma include the region with $r/a < 0.3$, but the theory is violated for very small r. Thus, there exists a common plasma region $(r/a < 0.3)$ where neoclassical theory for alpha particles as well as for bulk plasma may be applied.

Assuming that in the vicinity of $r \rightarrow 0$ the density of current generated by the alpha particles significantly exceeds the density of the bootstrap current of bulk plasma, we can approximate the plasma current in the region $r/a < 0.3$ by the expression

$$J(r) = J_p + J_{\alpha e}, \tag{1}$$

where J_p and $J_{\alpha e}$ are the bootstrap currents generated by bulk plasma and alpha particles, respectively. Using Eq. (1) and the particle balance equations,[3,4], we can write the equation for the total plasma current within radius r as

$$dI/dr = [S(r)/c^2\eta n r]I + 2\pi r J_{\alpha e}. \tag{2}$$

Here $I(r) = 2\pi\int_0^r J(r')dr'$, $S(r)$ is the particle source strength per unit length within radius r, η is the classical resistivity of the plasma, and n is the plasma density. It can be readily seen that the presence of the term connected with the alpha particles ensures a nontrivial solution of Eq. (2). Actually, for $r \rightarrow 0$ we have $dI/dr = 2\pi r J_{\alpha e}$ and consequently $I(r)$ is a monotonically growing function of the radius. Thus, because of the alphas a steady-state self-sustaining plasma current should exist (provided that the plasma parameters are kept constant).

In order to determine the radial distribution of the current one should solve the set of equations governing the radial profiles of the current, temperature, and density taking into consideration the results of neoclassical theory for the bulk plasma and the alpha-particle transport processes. This problem is more complicated than the one investigated in Refs. 3–5 because the seed current generated by alpha particles in the near axis region depends on the plasma parameters which in turn are determined by the plasma current. Moreover, the simple model used in Refs. 3–5 in which the seed current is localized within a radius r_s is hardly justified. However, a qualitative picture of the radial dependence of the driving current may easily by obtained.

For this purpose we represent the current generated by the alpha particles as

$$J_{\alpha e} = J_\alpha(1 - Z_\alpha/Z_{i0}), \tag{3}$$

where the alpha bootstrap current J_α is given by[8]

$$J_\alpha = -0.34 e_\alpha v_\alpha q_0^2 \rho_\alpha^2 (\partial^2 n_\alpha/\partial r^2)_{r=0}. \tag{4}$$

Here e_α, Z_α, and $v_\alpha = 1.3\times 10^9$ cm s^{-1} are the alpha-particle charge, charge number, and velocity, respectively; $Z_{i0} = Z_{\rm eff}(r=0)$ is the effective charge number of the plasma at the magnetic axis; $n_\alpha = n\tau_s/\tau_f$ is the density of nonthermalized alpha particles; $\tau_f = 4/n\langle\sigma v\rangle$ is the characteristic time of the thermonuclear reaction and τ_s is the alpha-particle slowing down time.

Let us take into account that the safety factor q_0 at the magnetic axis is given by

$$q_0 = cB_0/2\pi R J_0, \tag{5}$$

where $J_0 = J(r=0)$. Then assuming that $J_0 = J_{\alpha e}$ and $\partial^2 n_\alpha/\partial r^2 = -\nu_\alpha n_\alpha/a^2$, where ν_α is a numerical factor depending on the alpha-particle density profile, we find from Eqs. (3)–(5)

$$J_0 = \frac{c v_\alpha}{a}\left[\frac{0.34 m_\alpha^2 c}{(2\pi)^2 e_\alpha}\,\frac{\nu_\alpha n_0}{RA}\,\frac{\tau_{s0}}{\tau_{f0}}\left(1 - \frac{Z_\alpha}{Z_{i0}}\right)\right]^{1/3}, \tag{6}$$

where τ_{f0}, τ_{s0}, and n_0 denote the values calculated at $r=0$. For a numerical estimate of the magnitude of the current density J_0 we take, for example, $a = 120$ cm, $R = 500$ cm, $n_0 = 3\times 10^{14}$ cm^{-3}, $T_0 = 20$ keV, $Z_{i0} = 3$, $\nu_\alpha = 8$, and obtain $J_0 \sim 40$ A/cm^2. For this current density we find from Eq. (5) that $q_0 = 4$. However, from the equilibrium condition for the tokamak plasma, $\beta_p < A$ ($\beta_p = 8\pi/B_p^2$, p is the averaged plasma pressure, B_p

is the poloidal magnetic field), it follows that, for the tokamak parameters used, the required value of the safety factor at the plasma edge is $q_a \approx 2$. This means that to satisfy the equilibrium condition the plasma current density beyond the near-axis region has to be significantly higher than that determined by Eq. (6) and the current close to $J_{\alpha e}$ should be localized in a sufficiently narrow region. Note that a tokamak reactor with a nonmonotonic radial distribution of the plasma current ("hollow current profile") was discussed in connection with the problem of maintaining the steady-state currents driven by rf fields.[14] In some experiments it has also been observed that hollow current profiles occurred without indications of enhanced magnetohydrodynamical activity.[15–17]

Let us finally estimate the radius of the flux surface r_s where the current density produced by the alpha particles is comparable to the bootstrap current of the bulk plasma. Taking into consideration the facts that J_p essentially exceeds $J_{\alpha e}(r=0)$ for $dn/dr \sim n/a$ and consequently that the radius r_s should be close to the magnetic axis, we can approximate the bulk plasma density by $n(r) \sim n_0'' + \frac{1}{2}n_0''r^2$, where $n_0'' = (d^2n/dr^2)_{r=0}$. Then, using the expression for the bulk plasma bootstrap current,[13] we obtain

$$J_p(r_s) \cong 5(c/B_p)(r_s/R)^{1/2}T_0 n_0'' r_s. \tag{7}$$

The poloidal magnetic field entering into Eq. (7) is mainly determined by the alpha-generated current, i.e.,

$$B_p = (2\pi/c)\kappa r J_{\alpha e}, \tag{8}$$

where $\kappa > 1$ is a numerical coefficient taking into account the presence of the bulk plasma current for $r < r_s$. Assuming now that $J_p(r_s) = J_{\alpha e}$, we find from Eqs. (7) and (8) that

$$r_s/a \cong 4\pi^2\kappa^2 A J_{\alpha e}^4/25 T_0^2 n_0''^2 c^4, \tag{9}$$

where $J_{\alpha e}$ is determined by Eq. (6). For the tokamak parameters used above and for $n_0''/\kappa \sim n_0''/a^2$ it follows from Eq. (9) that $r_s/a \sim 5\times10^{-3}$. However, the banana regime for the bulk plasma is not realized in a region which is so close to the magnetic axis. We can expect that the value of r_s is rather determined from the existence condition for the bulk plasma banana regime, which gives $r_s/a \sim 0.1$. For $r > r_s$ the current density is expected to have a maximum value ensuring that the condition $q(r) \sim 1$ is satisfied.

In summary, we have presented the idea of a steady-state tokamak reactor with a toroidal current which is maintained by neoclassical processes connected with both the bulk plasma and the thermonuclear reaction products. Our work is the first approach concerning this important problem. Detailed analysis of the radial distribution of the toroidal current and plasma parameters should be carried out by taking into account the particle and energy balance. Also the stability of the alpha-driven bootstrap tokamak merits careful investigation.

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