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STEADY-STATE TOROIDAL CURRENT

BY

N. J. FISCH

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Operating Tokamaks with Steady-State Toroidal Current

Nathaniel J. Fisch
 Plasma Physics Laboratory, Princeton University
 Princeton, New Jersey 08544

Abstract

Continuous operation of a tokamak requires, among other things, a means of continuously providing the toroidal current. Various methods have been proposed to provide this current including methods which utilize radio-frequency waves in any of several frequency regimes. Here we elaborate on the prospects of incorporating these current-drive techniques in tokamak reactors, concentrating on the theoretical minimization of the power requirements.

The quest for methods of operating tokamaks in the steady-state by providing non-ohmic toroidal current is motivated by several considerations which impinge upon very different aspects of what is boldly envisioned as the economical tokamak reactor. First and foremost, the continuously operating tokamak is presumed to be less susceptible to the metal fatigue that arises from the heat stress to which the structural components are brutally subjected in the pulsed device. It is considered that only continuously operating the reactor can provide the requisite uniform heat load; other means of doing so have been considered but discounted as technologically undesirable. A second complaint against the pulsed tokamak relates to the premium location in the doughnut center that the cumbersome transformer coils occupy. The simpler geometry of several of the non-ohmic schemes of generating current allows the option of employing other systems in this valuable space or of shrinking the tokamak to a smaller aspect ratio. Thirdly, if superconducting coils are to provide the toroidal magnetic field, a steady-state poloidal magnetic field is desirable in order to avoid more severe requirements on the cooling of the superconductor.

In addition to the above, several other reasons for steady-state operation have also been invoked. The down time is less, so the plant efficiency is higher. It may also be supposed that a truly steady-state tokamak is less vulnerable to disruptions, since the plasma need not negotiate as often through hazardous parameter regimes. Nevertheless, the cure of steady-state operation also presents new problems and despite the appearance of many advantages of steady-state operation, the assessment of these advantages is almost impossible at this stage. It is worthwhile, therefore, to examine whether or not by forgoing some of these advantages, different, possibly preferable, solutions might be found.

A variety of methods have been proposed to drive steady-state current,¹⁻⁵ and among them there are several rf methods. A comparison of these methods and an explanation of their underlying physical mechanisms are given elsewhere.⁶ Here we focus upon a common drawback of the non-ohmic methods of

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driving current which is that they are all, although to a varying extent, power-intensive methods. Typically, a large fraction of the fusion power output must be recirculated, although the fraction of recirculated power is less in large, hot, and underdense reactors. For concreteness, we present two extreme examples of reactor parameters in the following table.

Design 1, small and cold

$$\begin{aligned} T_{10} &= 1 \\ n_{14} &= 1 \\ a_1 &= 3 \\ R_1 &= 8 \\ P_d/P_f &= \frac{15}{J/P_d} \text{ 20\%} \\ H &= 1.5 \text{ MW/m}^2 \\ P_f &= 1.8 \text{ GW} \end{aligned}$$

Design 2, large and hot

$$\begin{aligned} T_{10} &= 2 \\ n_{14} &= 1/3 \\ a_1 &= 5 \\ R_1 &= 13 \\ P_d/P_f &= \left(\frac{15}{J/P_d}\right) \text{ 3\%} \\ H &= 1 \text{ MW/m}^2 \\ P_f &= 3.3 \text{ GW} \end{aligned}$$

In this table, T_{10} is the temperature normalized to 10 keV, n_{14} is the plasma density normalized to 10^{14} cc^{-3} , a_1 and R_1 are the minor and major radii in meters, P_d is the power dissipated in driving the current, P_f is the fusion power, H is the wall loading, and J/P_d is a dimensionless parameter that ranges roughly between 15-30 depending on the current-drive scheme. The point of this table is that for intermediate designs it would be preferred to decrease P_d/P_f .

We present now a method that minimizes P_d/P_f for all the non-ohmic current-drive schemes. Mark that P_f increases as n^2 whereas P_d/J increases as n . Thus, the idea is to drive current non-ohmically while n is low and then to convert in a collision time of the non-ohmic current carriers to an ohmic type of current. Then the density is increased for higher fusion power while the plasma retains its current for an L/R time, which is fortuitously independent of density. To see how this happens, consider that

$$dJ_\phi/dt + J_\phi/\tau = J_{in}/\tau, \quad (1)$$

where J_ϕ is the toroidal current, J_{in} is the current produced non-ohmically, and $\tau = L/R$, where L is the plasma inductance and R its resistivity. The non-ohmic current is turned on instantly and obeys the decay $J_{in} = J_0 \exp(-\nu_{ct})$, where ν_c is a collisional frequency, so that solving (1) we get

$$J_{\phi} = J_0 (e^{-t/\tau} - e^{-v_c t}) / (v_c \tau - 1). \quad (2)$$

For $v_c \tau \gg 1$, we have $J_{\phi} = (J_0/v_c \tau) \exp(-t/\tau)$. Note that the time integral of J_{ϕ} is independent of τ , indicating that inductive effects have no average effect here on J/P_d , the current generated per power dissipated.

Consider instead that after a time t_0 , we increase the density from n to n' so that the non-ohmic current decays in a time v_c' instead of v_c , where we intend that $v_c' \gg v_c$. If $t_0 v_c \gg 1$, it is easily found that $J_{\phi} \approx (J_0/v_c \tau) \exp(-t/\tau)$ as before. Thus, for $\tau \ll t_0 \ll v_c^{-1}$, which is easily achieved, it follows that the efficiency of non-ohmic current generation is not decreased by raising the density at a sufficiently later time.

There are immediate implications for reactors: Consider a cyclic reactor where the plasma density is lowered for a short time t_0 to a value n each cycle of period $\tau = L/R$. A number of trade-offs now become available. The average P_d/P_f is certainly reduced; $n'/n = 1/10$ implies that P_d/P_f is about 1/10 of its value without the density oscillation so long as $t_0/\tau \ll 1$. However, for t_0/τ small, the capital cost of the rf (or other means of non-ohmic current generation) equipment, which is determined largely by the peak power requirements, increases. For $t_0/\tau = n'/n$, the capital costs remain constant.

While n'/n small decreases the average circulating power, it must be noted that true steady-state operation is certainly not achieved and some advantages are forfeited. Oscillating the density increases the likelihood of disruptions that might have been absent in a more quiescent mode of operation. The heat load now varies too, and thermal stresses may develop. However, certain advantages of the steady state are retained: the poloidal fields are constant and the ohmic coils may be removed.

At the expense of higher capital costs, the heat load on the first wall might be made constant by taking t_0/τ small enough that the input power to sustain current during the low-density phase matches the α -particle heating power during the high-density phase. For example, the average P_d/P_f might be 1%, with $n'/n = 1/5$ and $t_0/\tau = 1/20$. The heat load in the blanket, which is due to neutron heating, cannot be kept constant at the lower density. However, the longer thermal time constant of the blanket might imply that this is less severe a problem than for the first wall. Finally, note that by sacrificing even the constant heat load on the first wall, it is possible to take n'/n less than t_0/τ , which would reduce both the capital cost and the average circulating power of the non-ohmic drive. This might be most attractive; it retains the advantages of geometry, of constant magnetic field, and is economically most viable. The fact that the tokamak is still operable, and possibly ignited, in the low-density phase could alleviate stresses on the first wall, especially in combination with a pulsed divertor.

The possibilities outlined above allow for small oscillations in J_{ϕ} , because J_{ϕ} increases somewhat in the low- n phase and decays somewhat in the high- n phase. These small oscillations in J_{ϕ} may, if desired, be removed by employing a very small ohmic transformer coil at small cost. This coil would drive a small amount of additive current during the high- n phase but would be run in reverse during the low- n phase. There is an antecedent, with somewhat

different emphasis, for this hybrid type of ohmic and non-ohmic system in Ref. 7.

Recently, there have been several experiments that have established the possibility of driving current with high-phase-velocity lower hybrid waves^{8,9} or with neutral beams.¹⁰ There are also plans of testing out these and other schemes of current generation, including by means of minority species heating and electron cyclotron heating, on several tokamaks including PLT, PDX, ISX, Versator, and JFT-2. Once the underlying mechanisms and feasibility of the current-drive schemes are established, it is proposed that, in principle, the same equipment might be used to explore the possibility of maximizing the current generated per power dissipated in the manner envisioned here.

In conclusion, the oscillation of plasma parameters, especially the density, opens up the possibility of more efficient, if not steady-state non-ohmic current generation. Some advantages of the completely steady-state operation are retained.

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