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By

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ABSTRACT

Recently a tokamak plasma was observed in TFTR that was not limited by a limiter or a divertor. A model is proposed to explain this equilibrium, which is called a detached plasma. The model consists of (1) the core plasma where ohmic heating power is lost by anomalous heat conduction and (2) the shell plasma where the heat from the core plasma is radiated away by the atomic processes of impurity ions. A simple scaling law is proposed to test the validity of this model.

In a tokamak, plasmas need not be bounded by a material limiter or a divertor, and may radiate away all input energy at the boundary. In fact, these "detached" plasmas are observed experimentally.[1-3] Detached plasmas in TFTR[3] last more than one second, or more than approximately three times the energy confinement times, which indicates that the plasma is in equilibrium. A simple model is proposed here to relate the plasma radii to the other plasma parameters. This model suggests that some aspects of tokamak plasma behavior connected with profile consistency also may be explained.

We take a circular tokamak not bounded by a limiter or divertor. If the temperature at the main plasma surface is zero or very small compared with the central temperature, closed magnetic surfaces will still be constructed.

We assume first that the plasma density is given as a function of the magnetic surface and is nonzero at the main plasma surface. It is possible that nonzero plasma density exists beyond the main plasma surface. Impurity ions are assumed to be present which emit radiation at a temperature of approximately 200 eV or less. The model is schematically shown in Fig. 1. Following Post <u>et al.</u>,[4] we assume that the radiation power density at the boundary is given by

$$S = n_e n_I L(T) \quad . \tag{1}$$

Further we let

$$L(T) = \text{const.}\ (\approx 10^{-32}\ \text{watt m}^3 \text{for oxygen impurity}) \qquad 0 \le T \le T_b (\approx 100\ \text{eV}) \tag{2}$$

$$L(T) = 0 \qquad T \geq T_b \ . \tag{3}$$

Thus we assume that the boundary layer starts at $T = T_b$.

In region I (where $T \geq T_b$), under the steady-state condition,

$$\frac{1}{r}\frac{d}{dr}\, r\, \kappa\, \frac{dT}{dr} + \sigma(0)\left(\frac{T}{T_o}\right)^{3/2} E^2 = 0, \; r \leq a_D \text{ and } T \geq T_b \ . \tag{4}$$

Here $\kappa(r)$ is the heat conductivity, $\sigma(0)$ is the electrical conductivity at $r = 0$, $T_o = T(0)$, and E is the applied toroidal electric field.

For $\kappa(r) = \kappa = \text{const}$, Eq. (4) will be simplified to give

$$\frac{1}{x}\frac{d}{dx}\, x\, \frac{dY}{dx} + \lambda\, Y^{3/2} = 0 \qquad o \leq x \leq 1 \tag{5}$$

with

$$Y(0) = 1, \; Y(1) = T_b/T_o, \tag{6}$$

$$\lambda \equiv \frac{\sigma(0)E^2}{T_o\kappa}\, a_D{}^2 \ . \tag{7}$$

To satisfy Eq. (5) with the boundary conditions (6), λ's have discrete eigen values. If $T_b/T_o \rightarrow 0$, the lowest λ is approximately 7.0.

Obviously, we have

$$J = \sigma E \tag{8}$$

or

$$I \equiv 2\pi \int_0^{a_D} r dr \, J = 2\pi \int r dr \, \sigma E \, . \tag{9}$$

The current, I, can be considered equal to the total current, if $T_o >> T_b$, which is valid for tokamaks such as TFTR.

At the radiative boundary, we have

$$\kappa \frac{d^2T}{d\xi^2} = S \qquad \xi > 0 \quad (\xi \equiv x - a_D) \quad . \tag{10}$$

Usually S is a function of both position and temperature. Assuming for simplicity that S as well as κ are constant, we get

$$T = T_b - A \xi + \frac{1}{2} \frac{S}{\kappa} \xi^2 \; , \tag{11}$$

where A is a constant to be determined. The heat flux at $\xi = 0$ $(r = a_D)$ is determined by

$$Q_o = -\kappa \frac{dT}{d\xi}\bigg|_{\xi = 0} = \kappa A \quad . \tag{12}$$

If there is no heat sink or source for $0 \leq \xi < \infty$ other than S, the heat flux $Q(\xi)$ must be non-negative, or

$$Q(\xi) = \kappa A - S \xi \geq 0 . \tag{13}$$

At $Q(\xi) = 0$, $T = 0$ and the reverse is also true.

Hence

$$\kappa A - S \xi_b = 0 , \tag{14}$$

$$T_b - A \xi_b + \frac{1}{2} \frac{S}{\kappa} \xi_b^2 = 0 . \tag{15}$$

Thus, Eq. (14) and (15) determine ξ_b (where the temperature becomes zero) and the temperature gradient A. They are

$$\xi_b = \frac{\kappa A}{S} = \sqrt{\frac{2 \kappa T_b}{S}} \tag{16}$$

$$A = \sqrt{\frac{2\ S T_b}{\kappa}} = \frac{Q_o}{\kappa} . \tag{17}$$

Therefore, in a detached tokamak plasma, the power P generated is

$$P = S_p Q_o = S_p \sqrt{2 \kappa S T_b} \quad , \tag{18}$$

where S_p is the plasma surface area.

Equation (4), which describes the temperature for $r \leq a_D$, is now combined with Eq. (11) to solve the heat diffusion of a detached plasma.

In view of Eq. (9), Eq. (4) can be integrated to give

$$2 \pi a_D \kappa \left.\frac{dT}{dr}\right|_{r = a_D} + I E = 0 \quad . \tag{19}$$

Since for $r \geq a_D$ we have the relation (12), we get

$$- 2 \pi a_D \sqrt{2 S \kappa T_b} + I E = 0 \ . \tag{20}$$

Equations (7), (19), and (20) determine three unknown quantities E, T_o, and a_D, once other parameters are given.

Alternatively, by eliminating E^2/κ between Eqs. (7) and (20), we obtain

$$\lambda = \frac{\sigma(0)}{T_o} \frac{8 \pi^2 a_D^4 S T_b}{I^2} \quad . \tag{21}$$

Thus a scaling law

$$a_D^2 \propto \frac{I}{S^{1/2} T_o^{1/4}} \propto \frac{I}{n_{edge}} \frac{1}{F^{1/2}} \frac{1}{T_o^{1/4}} \qquad (22)$$

is predicted. Here n_{edge} is the electron density at $r = a_D$ and F is the ratio of impurity ion density to the electron density at that point.

The relations (21) or (22) predict that the detached plasma radius will decrease with the impurity concentration, if the edge density and the total current are held constant. The radius a_D cannot be made arbitrarily small, however, for the fixed tokamak condition. As the safety factor q_D at $r = a_D$ proportional to

$$q_D \propto \frac{a_D^2}{I} \frac{B_t}{R} \propto \frac{B_t}{\bar{n}R} \frac{\bar{n}}{n_{edge}} \frac{1}{F^{1/2}} \frac{1}{T_o^{1/4}} , \qquad (23)$$

if Murakami parameters $\bar{n}R/B_t$ increase, at some point the plasma is expected to become unstable against the kink/tearing instability, as q_D approaches 2. A similar conclusion is found in Ref. 5.

The relation (23) further predicts that

(1) If the average density becomes large compared with the edge density, that is, if the density profile is peaked, the plasma is more stable, as q_D increases.

(2) The increase in the impurity fraction, F, leads to the disruption.

(3) If the peak temperature is increased, or equivalently, if the heat conductivity κ is decreased, the plasma is more likely to disrupt.

The ratio $\bar{n}/n_{edge}$ depends on the density profile. The density profiles are determined by how the neutrals are ionized. If neutrals are injected as pellets or neutral beams, the ratio increases, whereas the recycling from the limiter will certainly reduce the ratio. Experimental observations concerning the density limit supports this interpretation.

Data are recently available from TFTR discharges.[6] From the data of Ref. 6, we can deduce that $S \approx 0.1$ watt/cm^3, $T_o/T_b = 15$ (if T_b is chosen, then 100 eV), $Z_{eff} \approx 2$, $I = 0.6$ MA, $\sigma(0) = 4.2 \times 10^7$ mho - m^{-1} at $T_o = 1600$ eV and $\lambda = 7.0$. The calculated value of $a_D = 58$cm from Eq. (21) compares favorably with the observed radius. The scaling relation (22) appears also to agree well. However, more detailed numerical analysis is perhaps called for.

The energy loss, S, could be accounted for by radiation. At the radiation boundary, the plasma density was $\sim 2 \times 10^{19}$ m^{-3} (Fig. 4 of Ref. 6). Thus, assuming that L(T) is 10^{-32} watt m^3, we get an impurity density of 5×10^{17} m^{-3} or F = 2.5%.

The results of q vs. n (Fig. 6 of Ref. 6) agree reasonably well with the discussions leading to Eq. (23). At high average density, q at the plasma edge should decrease.

We must ask why the detached plasmas are not observed more often. If the plasma is relatively impurity free, the plasma expands until it is limited by the divertor or limiter. Then, if the impurities are not released, the input power is lost simply to the neutralizer plates of a limiter or divertor and no limiter, the plasma edge starts to radiate. The discussions here suggest that the plasma would shrink. However, as the plasma shrinks, the impurity level is reduced, therefore, the plasma reexpands. Thus, a stable equilibrium is reached whereby the plasma loses energy partly to the limiter and partly to radiation.

More analysis is needed to see whether this model explains the observation. It is quite probable that the observation is explained by an entirely different phenomenon such as MHD instability.

There are several problems left unanswered. The sink of particles is not clearly identified at present. The average density (volume averaged) is approximately constant in time. (See Fig. 1 of Ref. 6.) Thus, there must be some mechanism to remove plasma particles from the tokamak. The particles could diffuse across the magnetic field in the cool temperature zone between the radiation shell and the limiter, as the density in that zone is not zero. Alternatively, the temperature can be low enough locally (as in Marfe) to allow the plasma particles to recombine. Then the quasiequilibrium can be established where the plasma density is maintained by recombination and reionization.

The graph of Fig. 5 of Ref. 6 shows that the plasma radius stayed approximately constant for 250 msec while the radiation density S was declining (by a factor of 2). This time constant is comparable to the energy confinement time of the plasma. Thus the dynamical change of the plasma radius must be studied with the heat capacity of the plasma taken into consideration in ordinary tokamak discharges. Hitherto, it was assumed that the plasma radius remained constant. In view of the existence of detached plasmas, a new, different interpretation of radiation-dominated tokamak discharges may be required.

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FIGURE CAPTION

Fig. 1. Schematic Drawing of a Detached Plasma I Core Plasma, where plasma is heated; II Boundary plasma, where plasma radiates away the energy supplied from the region I; III Cold plasma blanket. Density here can be very small; IV Material Limiter.

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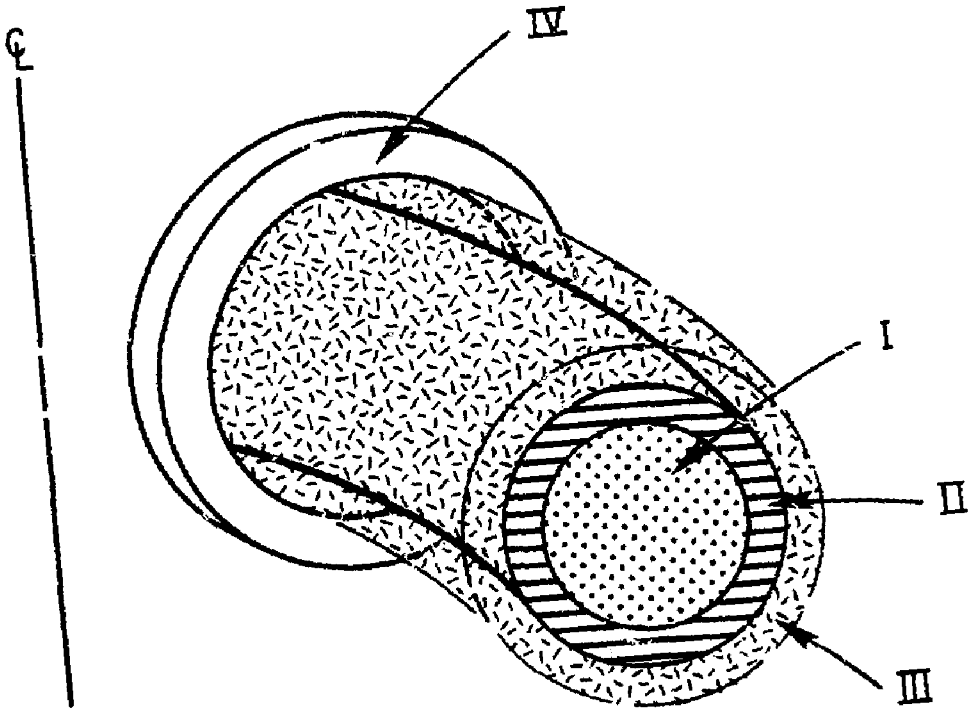

Fig. 1

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