HOW TEMPERATURE GRADIENTS ARE DETERMINED IN TOROIDAL PLASMAS

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ABSTRACT

It is commonly assumed in modern-day toroidal plasmas that the edge ion or electron temperature is sufficiently low so that the edge temperature can be neglected with respect to the center temperature. For example in a detached plasma, where the boundary condition is understood reasonably well, it is both theoretically and experimentally justified to say that the edge temperature can be approximately zero.

Now in a toroidal plasma bounded by a divertor, it is theoretically possible to design a divertor such that each pair of electron and hydrogen ion can carry, on average, $3/2(kT_e + kT_i)$. Then, in the absence of recycling, the temperature gradients in the scrape-off layer can be made zero or at least, less than $1/a$, where a is the plasma radius. Under that boundary condition, the temperature gradient inside the plasma vanishes. Realizing this in practice is difficult but not impossible. The problem is discussed in this paper.

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1. Introduction

In a toroidal plasma, usually there exists the scrape-off layer at the edge of the plasma. There the plasma flows along the magnetic field lines to be collected at the limiter plate or end plates in a divertor. The balance of the outward anomalous diffusion, D , and the parallel flow determines the scrape-off distance, which is given as

$$\lambda \approx \sqrt{DL/v_s} \quad (1)$$

Here L is the distance measured along the field lines and v_s is the sound velocity. In the absence of recycling, the density profile inside the scrape-off layer must satisfy the boundary condition at $r = a$:

$$-(dn/dr)/n = \lambda^{-1}, \quad r = a \quad (2)$$

This condition and $dn/dr = 0$ at $r = 0$ is generally sufficient to determine $n(r)$, if the expression for D is given and if the neoclassical or anomalous toroidal pinch effect can be estimated.

The temperature gradient in the scrape-off layer is equally important for determination of the temperature profile within the plasma. If $(dT/dr)/T$ in the scrape-off layer is $-\lambda_T^{-1}$, the boundary condition

$$-(dT/dr)/T = \lambda_T^{-1} \text{ as } r \rightarrow a - 0 \quad (3)$$

along with $dT/dr = 0$ at $r = 0$ is sufficient. To the author's knowledge, it is customary to assign a fixed (ion or electron) low temperature at $r = a$ and

solve for the temperature distribution. The procedure is justified if $\lambda_T^{-1} \gg 1/a$.

Here we shall estimate λ_T for a toroidal plasma that is bounded by a divertor and is radiation-free within the main plasma. This case is the opposite of the case of a detached plasma.

Then we shall explore the method to increase λ_T . In particular, if we can increase λ_T such that $\lambda_T^{-1} \leq 1/a$, we may be able to increase the energy confinement by (i) reducing temperature gradients, (ii) eliminating ion temperature gradient instabilities, and/or (iii) more speculatively generating the H-mode condition.

2. The temperature gradient in the scrape-off layer.

We shall assume that both ion and electron temperatures are equal in the scrape-off layer. (If not, the problem is still solvable but more complicated.) Also, as noted in the introduction, there is no radiation energy loss. Then the equation to determine the temperature gradient may be expressed (similar to the density gradient)¹

$$\kappa \frac{\partial^2 T}{\partial r^2} = (\alpha - \frac{3}{2}) T \frac{v_s}{L} \quad (4)$$

Here κ is the perpendicular heat conductivity in the unit of m^2/sec and 2α is the average energy of the ion-electron pair impinging on the neutralizer plate of a divertor. (α cannot normally be less than $3/2$.)

If the divertor is replaced by a limiter and if the temperature drop along the

field line is negligible due to the high parallel electron thermal conductivity,

$$2\alpha = \frac{1}{2} \ln \left(\frac{M}{m} \right) + \frac{5}{2} \text{ (for limiter)} \quad (5)$$

Here M and m are ion and electron mass, respectively.

If, on the other hand, there are neutral gas particles in the divertor which can be excited by plasma electrons, the temperature in the divertor can be lowered with respect to the scrape-off layer temperature in the main chamber. Furthermore, if we assume that the electron heat conductivity (parallel) is small, then $\alpha \rightarrow 3/2$.

Hence,

$$\kappa \frac{\partial^2 T}{\partial r^2} \approx 0 \quad (6)$$

In practice, a divertor with a long throat may approximate this condition.

Thirdly, the magnetic field lines in the divertor section could be made to fan out (as in Doublet type tokamaks). Then the plasmas which flow into the divertor become supersonic. The random thermal energy turns into the directed energy and the plasma temperature in the flow decreases. Under that circumstance, the parallel heat conduction (in addition to the convected energy by the plasma flow) may approach zero. If so, Eq. (6) is approximately true, $\lambda_T^{-1} \ll 1/a$. Then what kind of consequence can one expect?

3. Small temperature gradient in the scrape-off layer.

For the sake of simplicity we assume that the temperature gradient is zero in the scrape-off layer. Then provided that the heat conductivity is not infinite at the plasma edge, the heat conduction (in addition to the heat convection) becomes zero. Then the total energy loss is equal to

$$P = \frac{3}{2} (kT_i + kT_e) \text{ edge } \Gamma S_p, \quad (7)$$

where Γ is the flux of the particles and S_p is the surface area of the toroidal plasma.

The solution of $\lambda_T^{-1} \approx 0$ is not so obvious, if we suppose that the plasma is heated by the neutral beam injection whose particle has the constant energy W . As previously, we assume that the plasma can be thermalized so that $T_e = T_i$. Then the steady solution exists if

$$T = \frac{1}{3} W = \text{independent of } r. \quad (8)$$

To show this, we note that $T = \text{const.}$ satisfies the boundary conditions at $r = 0$ and $r = a$.

Further, the particle transport equation may be written as

$$\frac{1}{r} \frac{d}{dr} \left(D \frac{dn}{dr} + nV \right) = \frac{F}{W}, \quad (9)$$

where V is the (inward) velocity due to the pinch effect and F is the neutral beam energy flux. The boundary condition at $r = a$ yields Γ , the flux, is

defined in Eq. (7). If T is constant, the energy transport equation is Eq. (9) multiplied by T . Hence, if Eq. (9) is satisfied, the heat transport equation is also satisfied. Since Eq. (7) must be also satisfied, T is equal to $W/3$.

4. Conclusions.

The ion and electron temperature gradients in the scrape-off layer may be reduced by adequately designing a divertor. If, in the future, recycling-free toroidal plasmas can be produced, the experiments to lengthen the temperature gradient distance may be tried.

Some surprising conclusions can be drawn. A steady solution of the $\lambda_T^{-1} = 0$ condition has no temperature gradient within the plasma. The plasma temperature reaches $1/3$ of the injected neutral energy. In rf or ohmic heating discharges, the plasma density decreases in time. If the rate of decrease is sufficiently small, the plasma temperature confinement time equals the particle confinement time.

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Reference

¹S. Yoshikawa, W. L. Harries, and R. M. Sinclair, Phys. Fluids 6, 1506 (1963).