Thermal Dike Concept for Plasma Confinement

Tihiro Ohkawa

General Atomics, P.O. Box 85608, San Diego, CA, USA 92186-9784

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Abstract

The concept of a thermal dike for the reduction of electron heat loss parallel to the magnetic field from magnetically confined plasma to the material wall or divertor plates is discussed. The ponderomotive pressure of the rf field or the combination of the magnetic mirror and rf heating pushes the cold plasma towards the divertor plate. The influx of cold electrons is prevented by a thermal dike and the parallel heat loss which takes the form of exchange between hot and cold electrons in the long mean free path regime is reduced.

Keywords :

Plasma confinement, parallel heat conduction, rf pressure, ECH heating, magnetic mirror, tokamak,

1. Introduction

There are two types of heat transport in plasma, convective and conductive. Magnetically confined plasma isolated in vacuum will suffer only the convective heat loss. However, plasma in the laboratory is surrounded by a material wall and cold plasma is produced between the wall and hot plasma as a result of convective particle loss. The hot plasma can lose heat via conduction to the cold plasma that in turn transports the heat to the wall. In diverted tokamak plasma, a major portion of the heat appears on the divertor plates. The heat is conducted parallel to the magnetic field line from the edge of the plasma to the divertor plate. The parallel heat flux has different characteristics depending on the relative size of the electron collision mean free path and the scale length. In the collisional regime, i.e. short mean free path, the heat flux is proportional to $7/2$ power of the electron temperature. In the collisionless, i.e. long mean free path, the electron heat transport between hot and cold regions takes the form of the exchange of hot electrons with cold electrons. This case has been calculated in reference 1 where an electrostatic potential is used as a barrier reducing the parallel heat flux. Forces other than the electrostatic force would be just as effective as a barrier.

The loss of hot electrons has two components. One is to match the loss of the ions and represents the convective loss. The other is to match the influx of cold electrons and represents the conductive loss in the limit of the long mean free path. The barrier reduces the influx of cold electrons and thus reduces the conductive heat flux. The barrier acts as a dike against a sea of cold electrons.

Two types of thermal dike are considered in this paper. The first kind used the pressure of the rf field to push back the cold plasma towards the divertor plate. The rf dike is possible because the rf field pressure must exceed only the pressure of cold, tenuous plasma while rf confinement of hot plasma is impractical because obtainable rf field pressure is much too small compared to the pressure of hot plasma. The cold plasma faces the dike on one side and the divertor plate on the other. The cooling by the divertor plate and the pumping of the divertor region are essential for keeping the plasma cold and tenuous. This is in contrast to the thermal barrier concept of mirror confinement. Both sides of the thermal barrier are magnetically confined hot plasmas. The pressure of rf alone can not create a thermal barrier.

The second kind of dike utilizes magnetic confinement of mirror magnetic field in conjunction with rf heating. The pressure of the cold plasma is made anisotropic by rf heating and the gradient of the magnetic field strength exerts pressure on the cold plasma.

In both kinds of dike, the required rf power is the crucial question. Unless the required power is much smaller than the conductive heat outflow, the concept of a thermal dike is meaningless. We shall calculate the power requirement for both kinds of thermal dike in the following.

2. Force of rf Field on Plasma

Plasma can reflect or absorb photons. In either case, photons exert a force on plasma. The power requirements for a given force are quite different in the cases of reflection and absorption. We demonstrate the difference using a simple model where the response of the plasma can be described by scalar real dielectric constant ϵ and conductivity σ . We consider transverse electromagnetic waves traveling in a z-direction. The wave quantities are proportional to $\exp[-i\omega t + ikz]$, where ω is the frequency and k is the wave number. It is convenient to define $E_{\perp}$ by

$$E_{\perp} \equiv E_x + i E_y \quad (1)$$

The induction equation gives

$$B_{\perp} \equiv B_x + i B_y = -\frac{k}{\omega} E_{\perp} \quad (2)$$

The current density $j_{\perp}$ induced in the plasma is given by

$$j_{\perp} \equiv j_x + i j_y = [-i\omega(\epsilon - \epsilon_0) + \sigma] E_{\perp} \quad (3)$$

The dispersion equation is given by

$$k^2 = \mu_0 \omega^2 \epsilon + i\omega \mu_0 \sigma \quad (4)$$

The dissipated power P_d per unit volume is

$$\begin{aligned} P_d &= R_e(j_{\perp}^* E_{\perp}) \\ &= \frac{1}{2} \sigma |E_{\perp}|^2 \end{aligned} \quad (5)$$

and the force F acting on plasma per unit volume is

$$F = R_e(-i j_{\perp}^* B_{\perp})$$

$$= -\frac{R_e(k)}{\omega} P_d - \frac{1}{2} I_m(k) (\epsilon - \epsilon_0) |E_{\perp}|^2 \quad (6)$$

The first term on the right-hand side represents the force due to the absorption. If this force is to balance the gradient of the plasma pressure p , the required power is given by

$$P_d = \nabla p \frac{\omega}{R_e(k)} \quad (7)$$

and is too large to be practical. The second term represents the force due to reflection. In the absence of dissipation, the imaginary part of the wave number is made finite by the negative dielectric constant of the plasma. The wave becomes evanescent in the plasma and is reflected at the vacuum-plasma interface. The pressure p_r acting on the plasma at the interface is obtained by integrating F with respect to z . We obtain

$$p_r = \frac{1}{4} (\epsilon_0 - \epsilon) |E_p|^2 \quad (8)$$

where E_p is the electric field at the interface. The amplitude of the incident wave E_i and the reflected wave E_r are given in terms of E_p by

$$|E_i|^2 = |E_r|^2 = \frac{\epsilon_0 - \epsilon}{4 \epsilon_0} |E_p|^2 \quad (9)$$

The pressure on the plasma can be written as

$$p_r = \frac{\epsilon_0}{2} (|E_i|^2 + |E_r|^2) \quad (10)$$

3. Response of Magnetized Plasma

The response of the magnetized plasma can not be expressed by scalar dielectric. We shall calculate the force acting on the plasma in the absence of dissipation. The plasma is placed in static magnetic field B_0 in the z -direction. We consider circularly polarized waves evanescent in the plasma. The electric fields are given by

$$E_x = E \exp[-\beta z] \cos \omega t \quad (11)$$

$$E_y = \pm E \exp[-\beta z] \sin \omega t \quad (12)$$

where $\mp$ corresponds to the right- and left-handed waves. The equations of motion of a charged particle are given by

$$m \frac{dv_x}{dt} = e E_x + e v_y B_0 \quad (13)$$

$$m \frac{d v_y}{dt} = e E_y - e v_x B_0 \quad (14)$$

$$m \frac{d v_z}{dt} = e (v_x B_y - v_y B_x) \quad (15)$$

By neglecting thermal motion, we obtain

$$v_x = \left(\frac{e}{m} \right) \frac{\exp(-\beta z) E \sin \omega t}{(\mp \Omega + \omega)} \quad (16)$$

$$v_y = \left(\frac{e}{m} \right) \frac{\exp(-\beta z) E \cos \omega t}{(-\Omega \pm \omega)} \quad (17)$$

where $\Omega = eB_0/m$ including the polarity of e .

The magnetic fields are given by

$$B_x = \mp \left(\frac{\beta}{\omega} \right) E \exp(-\beta z) \cos \omega t \quad (18)$$

$$B_y = \left(\frac{\beta}{\omega} \right) E \exp(-\beta z) \sin \omega t \quad (19)$$

The force acting on the particle in the z -direction becomes

$$m \frac{d v_z}{dt} = \frac{e^2}{m} \frac{E^2 \exp(-2\beta z)}{(\mp \Omega + \omega)} \left(\frac{\beta}{\omega} \right) \quad (20)$$

When the frequency is much lower than the ion cyclotron frequency, the forces acting on the electrons and the ions are almost equal and in opposite direction. As a result, the plasma receives very little net force. This phenomenon is utilized in the current drive concept⁽²⁾ by the injection of wave helicity. If the frequency is much larger than the ion cyclotron frequency but smaller than the electron cyclotron frequency, the ion response and the force acting on ions are small and neglected.

By considering only the electron response, the dispersion equation becomes

$$\beta^2 = \frac{\omega^2}{c^2} \left(-1 + \frac{\omega_p^2}{\omega(\mp \Omega_e + \omega)} \right) \quad (21)$$

where ω_p is the plasma frequency. We select a right-handed or an ordinary wave and the condition for evanescence is

$$\frac{\omega_p^2}{\omega(|\Omega_e| + \omega)} - 1 > 0 \quad (22)$$

The force acting on the plasma is given by

$$F = \frac{\omega_p^2 \epsilon_0 E^2 \exp(-2\beta z) \beta}{\omega(|\Omega_e| + \omega)} \quad (23)$$

By integrating over z , the pressure exerted on the plasma at the interface is given by

$$\begin{aligned} p_r &= \int_0^\infty F dz = \frac{\epsilon_0 E^2}{2} \frac{\omega_p^2}{\omega(|\Omega_e| + \omega)} \\ &= \frac{\epsilon_0 E^2}{2} \left(1 + \frac{c^2 \beta^2}{\omega^2} \right) \end{aligned} \quad (24)$$

By matching the boundary condition, the standing cavity electric field strength E_v is given by

$$E_v^2 = E^2 \left(1 + \frac{c^2 \beta^2}{\omega^2} \right) \quad (25)$$

The pressure exerted on the plasma in terms of the cavity electric field becomes

$$p_r = \frac{\epsilon_0}{2} E_v^2 \quad (26)$$

4. Cylindrical Thermal Dike with Ordinary Wave

If the hot plasma and the cold plasma are connected through a cylindrical bundle of magnetic flux, a cylindrical cavity with circularly polarized wave can be used as a thermal dike. A schematic is shown in Fig. 1.

Fig. 1

A rotating TE_{11} mode is excited in the cavity. The size of the channel through the cavity is small enough so that the wave is cut off. Generation of electric field E_c in the cavity requires the power P_c given by

$$P_c = \epsilon_0 E_c^2 \frac{\omega}{2\pi Q} S_c d_c \quad (27)$$

where Q is the cavity Q , S_c is the cross section and d_c is the length of the cavity. By using the calculation of the previous section, the required power is given by

$$P_c = \frac{n(T_e + T_i) \omega}{\pi Q} S_c d_c \quad (28)$$

The conductive heat-loss P_L in the long mean free path limit is given by

$$P_L = n v_e (T_e^h - T_e) S \quad (29)$$

where S is the cross-sectional area of the channel and the superscript denotes the quantities of the hot plasma. The ratio of the required rf power and the heat loss becomes

$$P_c/P_L = \left(\frac{T_e + T_i}{T_e^h - T_e} \right) \left(\frac{S_c}{S} \right) \frac{\omega d_c}{\pi v_e Q} \quad (30)$$

By using an example set of parameters: $T_e = T_i = 10$ eV, $T_e^h = 200$ eV, $S_c/S = 10$, $\omega = 10^9$ Hertz and $d_c = 0.2$ m, we obtain $P_c/P_L \sim 30/Q$. The condition $P_c/P_L \ll 1$ is satisfied if $Q > 300$. The required power is proportional to the plasma density. Densities much above 10^{18} m^{-3} requires too large rf power to be practical.

The plasma density in the divertor region with the thermal dike has two regimes. At a low density, the dike will eliminate the conduction heat into the region. The small heat input keeps the density low. When the density is high, the dike is overwhelmed by the plasma pressure and the conduction heat flows into the region. The large heat input will keep the density high. Therefore the dike should be turned on before the density and the temperature of the main plasma reach large values.

5. Mirror Field and ECRH Heating

An example of the second kind of thermal dike can be constructed by combining a static mirror field and ECRH (electron cyclotron resonance heating). The arrangement is shown in Fig. 2. The hot ions are confined in the mirror. Since the collision frequency of electrons is greater than that

Fig. 2. A dike placed at the end of a mirror configuration

of ions, the electrons are confined by electrostatic potential. The plasma develops the potential to equalize the losses of ions and electrons. These losses represent the convective energy loss. When cold plasma is generated by the interaction of escaping particles with the end plate, two plasmas can exchange particles. The ion flow velocity is much smaller than the electron flow velocity and we consider only the exchange of electrons.

We assume that the plasma electrons are in a long mean free path regime. The flux Γ of cold electrons flowing into the hot plasma overcoming the mirror field is given by

$$\Gamma = n v_e S \left[1 - \left(\frac{R-1}{R} \right)^{1/2} \right] \quad (31)$$

where n is the density, v_e is the thermal velocity of cold plasma, S is the cross-sectional area and R is the mirror ratio. The net heat outflow Q from the hot plasma due to the exchange of hot and cold electrons is given by

$$Q = (T_e^h - T_e) \Gamma. \quad (32)$$

We choose ECRH as the rf field for the dike. The ECRH increases the electron energy perpendicular to the magnetic field $w_\perp$ and the electron pressure becomes anisotropic. The gain in $w_\perp$ per single transit is given by

$$\Delta w_\perp = P_{\text{ECH}} (d / n v_e) (Sd)^{-1} \quad (33)$$

where P_{ECH} is the ECRH heating power and d is the thickness of the dike. The increased $w_\perp$ results in smaller electron flux because of the mirror field. We obtain

$$\begin{aligned} \Gamma &= n_e v_e S \left[1 - \left(\frac{R-1}{R} \right)^{1/2} \left(1 + \frac{\Delta w_\perp}{T_e} \right) \right] \\ &= n_e v_e S \left[1 - \left(\frac{R-1}{R} \right)^{1/2} \right] - \left(\frac{R-1}{R} \right)^{1/2} \frac{P_{\text{ECH}}}{T_e} \end{aligned} \quad (34)$$

and

$$Q = (T_e^h - T_e) n_e v_e S \left[1 - \left(\frac{R-1}{R} \right)^{1/2} \right] - \frac{T_e^h - T_e}{T_e} \left(\frac{R-1}{R} \right)^{1/2} P_{\text{ECH}}. \quad (35)$$

The ECRH power necessary to eliminate the exchange of hot and cold electrons is given by

$$P_{\text{ECH}} \geq n_e v_e T_e S \left[\left(\frac{R}{R-1} \right)^{1/2} - 1 \right] \quad (36)$$

In terms of the heat flux Q_0 in the absence of the dike, the above condition becomes

$$P_{\text{ECH}} \geq Q_0 \left(\frac{R}{R-1} \right)^{1/2} \left(\frac{T_e}{T_e^h - T_e} \right) \quad (37)$$

When $T_e^h \gg T_e$, the condition $P_{\text{ECH}} \ll Q_0$ is readily satisfied.

6. Application to Tokamak Configuration

In diverted tokamak configurations, heat is exhausted on the divertor plates through the magnetic flux lines near the separatrix. An example of D-III-D⁽³⁾ is shown in Fig. 3. The magnetic flux lines intersect the divertor plate with a shallow angle typically 3° . A thermal dike may be placed between the plasma and the divertor plates either axisymmetrically or azimuthally localized, provided that all magnetic flux lines intersecting the divertor plates are intercepted by the dike at least once.

The toroidal geometry makes it awkward to use the cavity mode described in Section 4. The ECRH heating method discussed in Section 5 is more amenable to the toroidal geometry. However, the outboard side and the inboard side of the diverted flux lines behave quite differently for this method. Since the magnetic field strength decreases with major radius, the electrons leaving the outboard divertor see increasing magnetic field towards the null points, while the opposite is true for the inboard divertor. When ECRH heating is applied between the outboard divertor plates and the null point, a thermal dike is created. For the inboard side, the magnetic configuration must be modified in such a way that the divertor plates are placed where the major radius is larger than of the null point. The configuration is shown in Fig. 4.

Fig. 3

Fig. 4

The mirror ratio R is given roughly by

$$R = 1 + \epsilon \quad (38)$$

where ϵ is the inverse aspect ratio. The ratio of the ECRH power and the plasma thermal throughput is given by

$$\frac{P_{\text{ECH}}}{Q_0} = \left(\frac{T_e}{T_e^h - T_e} \right) (1 + \epsilon^{-1})^{1/2} \quad (39)$$

where long electron mean free path is assumed.

It is crucial to keep the electron mean free path longer than the flux line length between the divertor plate and the main plasma for the reflection by the magnetic mirror to be effective. Also, the required ECRH heating power is proportional to the plasma density. Therefore, the density of the cold plasma must be kept low for the thermal dike to work. In the present experiments⁽⁴⁾ in D-III-D, the plasma density near the divertor is encouraged to be high to reduce the heat load on the divertor plates. Typical plasma parameters are plasma density of $2 \times 10^{19} \text{ m}^{-3}$ and electron temperature of $10 \sim 20 \text{ eV}$. About one-half of heat flowing into the divertor region is radiated before reaching the divertor plate. For the thermal dike experiment, a large pumping speed should be provided in the divertor region to keep the neutral gas pressure and the plasma density low.

The condition that the mean free path is longer than the distance between the main plasma and the divertor plate parallel to the magnetic field is given by

$$n \leq 2.5 \times 10^{16} \left(\frac{T_e}{e} \right)^2 (R_0 q) \quad (40)$$

where R_0 is the major radius and q is the safety factor. By taking $T_e = 20 \text{ eV}$ and $R_0 q = 10 \text{ m}$, we obtain $n \leq 10^{18} \text{ m}^{-3}$. One way of maintaining a low density in the divertor region is to establish the thermal dike while the

density and the temperature of the main plasma are still low, i.e. in Ohmic heating phase. The subsequent heating and fueling increase the temperature and the density of the main plasma. The action of the thermal dike prevents the increased thermal throughput of the main plasma from coming into the divertor region. With a reduced power input into the divertor region, it may be possible to maintain a low density. Phenomena like the ELM (edge localized mode) may overpower the thermal dike by dumping plasma particles into the divertor region if the pumping speed is not high enough. Only experimental tests will give the answer.

The configuration shown in Fig.4 requires not so trivial modification of existing tokamaks. We may take advantage of the fact that the heat flux on the outboard divertor plates is 2~4 times greater than the heat flux on the inboard plates and perform experimental tests only at the outboard side to assess the practicability of the concept.

The thermal dike created by the combination of the mirror field and ECRH heating can be used for ignition control. The thermal dike is fully turned on before the plasma reaches ignition. The ECRH power in the thermal dike is reduced upon ignition so that the fusion power is taken out conductively to the divertor plates. It should be possible to maintain a constant level of fusion power by a feedback control.

7. Summary

The concept of a thermal dike is proposed. By using the pressure of the rf field or the combination of a magnetic mirror and rf heating, the thermal contact between the main plasma and the cold plasma near the divertor plates are interrupted. The key assumption is that the electrons in the dike region are collisionless. The characteristics of the cold plasma near the divertor plates or the scrape-off layer plasma are rather complicated because of the interaction with the material wall and the divertor plates. More analyses and test experiments on the existing tokamaks are needed for an assessment of the concept. If successful, the thermal dike will improve the confinement greatly by reducing the parallel conductive heat loss to the divertor plates and by reducing the convective loss at the edge by virtue of higher edge temperature.

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