Thermal Instability of a Thermonuclear Plasma in a DD Fusion Reactor. III. Inhomogeneous Temperature

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Abstract

A thermal thermonuclear instability of a deuterium plasma with an inhomogeneous temperature in a strong magnetic field is studied theoretically. The growth rate of the instability is obtained. The plasmas with an inhomogeneous temperature in a DD fusion reactor and in a catalyzed DD fusion reactor are unstable for the thermal instability.

§ 1. Introduction

In Paper I,¹⁾ a thermal thermonuclear instability of a homogeneous deuterium plasma in a strong magnetic field was studied. In Paper II,²⁾ the instability in a catalyzed DD fusion reactor was discussed.

In this paper, we present an analysis of the instability of a deuterium plasma with an inhomogeneous temperature. The thermal instability of an inhomogeneous plasma in DT fusion reactors has been discussed by some authors.³⁻⁴⁾

Kolesnichenko, Reznik and Yavorskij³⁾ have developed the method for investigating the stability of a steady-state thermonuclear reaction in an inhomogeneous deuterium-tritium plasma. They have analyzed the differential equation of the second order in partial derivatives which describes the instabilities of the energy balance in a thermonuclear DT Plasma.

We want to know the stability of a DD fusion reactor. In this paper, we will use the method developed in ref. 3) for analyzing the stability of a thermonuclear deuterium plasma.

In § 2, the instability in a DD fusion reactor is studied. The instability in a catalyzed DD fusion reactor is discussed in § 3.

§ 2. DD fusion reactor

First, we discuss the instability in a DD fusion reactor. We assume that (1) the

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deuterium plasma is isothermal ($T_e = T_i = T$), (2) the plasma energy losses are due only to heat conduction across a magnetic field and bremsstrahlung, (3) the number density n and the Coulomb logarithm λ are constant in space and time, and (4) the magnetic field B is uniform in space and constant in time.

For simplicity, we discuss the plasma of a plane layer. Then, we have the following equation for the energy balance: ¹⁾

$$3n \frac{\partial T(x, t)}{\partial t} = \frac{\partial}{\partial x} \left(\frac{An^2}{T^{1/2}(x, t)} \frac{\partial T(x, t)}{\partial x} \right) + P(T), \quad (1)$$

where

$$P(T) = Cn^2 T^{1.37} - Dn^2 T^{1/2}, \quad (2)$$

$$A = 4.48 \times 10^{-4} \frac{(\lambda/10)}{B^2}, \quad (3)$$

$$C = 1.21 \times 10^{-16}, \quad (4)$$

$$D = 3.34 \times 10^{-15}, \quad (5)$$

$$\lambda = 33.48 + \frac{1}{0.8686} \log_{10} \frac{T^3}{n}, \quad (6)$$

($T(\text{keV})$, $n(\text{cm}^{-3})$, $B(\text{G})$, $t(\text{sec})$, $x(\text{cm})$).

The x -axis is perpendicular to B and to the surface of the layer.

We assume that the temperature of the 0-th order T_0 depends only on x . Then, we obtain the equation of the 0-th order from eq. (1):

$$\frac{d}{dx} \left(\frac{An^2}{T_0^{1/2}(x)} \frac{dT_0(x)}{dx} \right) + P(T_0) = 0. \quad (7)$$

Putting

$$T(x, t) = T_0(x) + T_1(x, t); \quad T_0 \gg T_1,$$

and using eq. (7), we have the first order equation from eq. (1):

$$3n \frac{\partial T_1(x, t)}{\partial t} = An^2 \frac{\partial^2}{\partial x^2} \left(\frac{T_1(x, t)}{T_0^{1/2}(x)} \right) + \frac{dP(T_0)}{dT_0} T_1(x, t). \quad (8)$$

If we put

$$T_1(x, t) = T_1(x) e^{st}, \quad (9)$$

we obtain the following equation from eq. (8):

$$An^2 \frac{d^2}{dx^2} \left(\frac{T_1(x)}{T_0^{1/2}(x)} \right) + \frac{dP(T_0)}{dT_0} T_1(x) = 3ns T_1(x). \quad (10)$$

We assume that the perturbation $T_I(x)$ of the temperature is symmetric with respect to $x=0$:

$$\frac{dT_I(x)}{dx} = 0 \quad \text{at} \quad x=0, \quad (11)$$

and vanishes at the plasma boundaries $x=\pm L$:

$$T_I(x)=0 \quad \text{at} \quad x=\pm L. \quad (12)$$

When $s=0$, the differential equation (10) was solved by Kolesnichenko, Reznik and Yavorskij,³⁾ who obtained the following solutions:

$$T_I^{(1)}(x) = \frac{\partial T_0(x)}{\partial T(0)}, \quad (13)$$

$$T_I^{(2)}(x) = \frac{dT_0(x)}{dx}, \quad (14)$$

where $T(0)$ is the temperature at the center $x=0$. As easily seen, the first solution $T_I^{(1)}(x)$ satisfies the boundary condition (11), but the second solution $T_I^{(2)}(x)$ does not. The function $T_0(x)$ is the solution of the 0-th order equation (7) under the following boundary conditions: $dT_0(x)/dx=0$ at $x=0$ and $T_0(x)=0$ at $x=\pm L$. Here, the value of L depends on the temperature at the center $T(0)$: $L=L(T(0))$.

As done in ref. 3), we can express the boundary value problem (10), (11) and (12) in an integral form. If we put in eq. (10)

$$u(x) = \alpha(x) T_I(x), \quad (15)$$

where

$$\alpha(x) = \frac{An}{3T_0^{1/2}(x)}, \quad (16)$$

we have the following equation:

$$\frac{d^2 u(x)}{dx^2} + \frac{\nu(x)}{\alpha(x)} u(x) = \frac{s}{\alpha(x)} u(x), \quad (17)$$

where

$$\nu(x) = \frac{1}{3n} \frac{dP(T_0)}{dT_0}. \quad (18)$$

The solutions of eq. (17) with $s=0$ are given by

$$u_1(x) = \alpha(x) T_I^{(1)}(x), \quad (19)$$

$$u_2(x) = \alpha(x) T_I^{(2)}(x). \quad (20)$$

We assume that a Green's function $G(x, \xi)$ satisfies the following equation:

$$\frac{d^2}{dx^2} G(x, \xi) + \frac{\nu(x)}{\alpha(x)} G(x, \xi) = \delta(x - \xi). \quad (21)$$

Then, the solution $u(x)$ of eq. (17) satisfies the following integral equation :

$$u(x) = c_1 u_1(x) + s \int_0^L d\xi G(x, \xi) \frac{u(\xi)}{\alpha(\xi)}, \quad (22)$$

where c_1 is a constant. Putting

$$G(x, \xi) = \begin{cases} a u_1(x) u_2(\xi), & \text{for } 0 \leq x < \xi, \\ a u_1(\xi) u_2(x), & \text{for } \xi < x \leq L, \end{cases} \quad (23)$$

and using the condition that is derived from the integration of both sides of eq. (21) with respect to x for the small interval $\xi - \varepsilon \leq x \leq \xi + \varepsilon$:

$$\lim_{\varepsilon \rightarrow 0} \left\{ \left. \frac{dG}{dx} \right|_{x=\xi+\varepsilon} - \left. \frac{dG}{dx} \right|_{x=\xi-\varepsilon} \right\} = I, \quad (24)$$

we have

$$\frac{I}{a} = u_1(\xi) u_2'(\xi) - u_1'(\xi) u_2(\xi). \quad (25)$$

Substituting eqs. (19) and (20) into the above equation (25), we obtain

$$\frac{I}{a} = \alpha^2(\xi) \left\{ \frac{\partial T_0(\xi)}{\partial T(0)} \frac{d^2 T_0(\xi)}{d\xi^2} - \frac{1}{2} \frac{\partial}{\partial T(0)} \left(\frac{dT_0(\xi)}{d\xi} \right)^2 \right\}. \quad (26)$$

Now, from the equation (7) of the 0-th order, we have⁵⁾

$$\frac{d^2 T_0(x)}{dx^2} = T_0^{1/2}(x) \left\{ \frac{I}{2 T_0^{3/2}(x)} \left(\frac{dT_0(x)}{dx} \right)^2 - \frac{P(T_0)}{A n^2} \right\}, \quad (27)$$

and

$$\frac{dT_0(x)}{dx} = - \left\{ \frac{2}{A} T_0(x) \left(F - \frac{C}{1.87} T_0^{1.87}(x) + D T_0(x) \right) \right\}^{1/2}, \quad (28)$$

where

$$F = \frac{C}{1.87} T^{1.87}(0) - D T(0), \quad (29)$$

and we used the condition

$$\frac{dT_0(x)}{dx} = 0 \quad \text{at } x = 0. \quad (30)$$

Substituting eqs. (27) and (28) into eq. (26), we obtain

$$\frac{I}{a} = - \frac{A}{9 T^{1/2}(0)} P(T(0)). \quad (31)$$

Now, substituting eq. (23) into eq. (22), we have

$$u(x) = c_1 u_1(x) + sa \left[\int_0^x d\xi u_1(\xi) u_2(x) T_1(\xi) + \int_x^L d\xi u_1(x) u_2(\xi) T_1(\xi) \right]. \quad (32)$$

Using eqs. (15), (19) and (20), we can write eq. (32) as follows :

$$T_1(x) = c_1 T_1^{(1)}(x) + sa \left[\int_0^x d\xi \alpha(\xi) T_1^{(1)}(\xi) T_1^{(2)}(x) T_1(\xi) + \int_x^L d\xi \alpha(\xi) T_1^{(1)}(x) T_1^{(2)}(\xi) T_1(\xi) \right]. \quad (33)$$

Transforming the integral of the second term in the square brackets in eq. (33) as follows

$$\int_x^L d\xi = \int_0^L d\xi - \int_0^x d\xi, \quad (34)$$

we obtain

$$T_1(x) = a_1 T_1^{(1)}(x) + sa \int_0^x d\xi \alpha(\xi) \left(T_1^{(1)}(\xi) T_1^{(2)}(x) - T_1^{(1)}(x) T_1^{(2)}(\xi) \right) T_1(\xi), \quad (35)$$

where a_1 is a constant. Substituting eqs. (16) and (31) into eq. (35), we have the following integral equation :

$$T_1(x) = a_1 T_1^{(1)}(x) + s \int_0^x d\xi K(x, \xi) T_1(\xi), \quad (36)$$

where

$$K(x, \xi) = \frac{3n T^{1/2}(0)}{P(T(0)) T_0^{1/2}(\xi)} \left[T_1^{(1)}(x) T_1^{(2)}(\xi) - T_1^{(1)}(\xi) T_1^{(2)}(x) \right]. \quad (37)$$

The growth rate s is obtained from the boundary condition (12) at $x=L$:

$$T_1(L) = a_1 T_1^{(1)}(L) + s \int_0^L d\xi K(L, \xi) T_1(\xi) = 0. \quad (38)$$

Then, we have

$$s = - \frac{a_1 T_1^{(1)}(L)}{\int_0^L d\xi K(L, \xi) T_1(\xi)}. \quad (39)$$

If we put

$$T_1(x) = a_1 \rho(x), \quad (40)$$

where

$$\rho(0) = 1 \quad \text{and} \quad \rho(L) = 0, \quad (41)$$

we obtain

$$s = - \frac{T_I^{(I)}(L)}{\int_0^L d\xi K(L, \xi) \rho(\xi)}. \quad (42)$$

Now, we have the quadrature of the equation of the 0-th order (7):

$$L - x = \left(\frac{A}{2} \right)^{1/2} \int_0^{T_0(x)} dT_0 \frac{1}{T_0^{1/2} \left(F - \frac{C}{1.87} T_0^{1.87} + D T_0 \right)^{1/2}}, \quad (43)$$

where we used the condition

$$T_0(x) = 0 \quad \text{at} \quad x = L. \quad (44)$$

Differentiating both sides of the above equation (43) with respect to $T(0)$ for fixed x , we have

$$\begin{aligned} \frac{\partial T_0(x)}{\partial T(0)} = & \left[\frac{2}{A} T_0(x) \left(F - \frac{C}{1.87} T_0^{1.87}(x) + D T_0(x) \right) \right]^{1/2} \left\{ \frac{dL}{dT(0)} \right. \\ & \left. + \frac{(CT_0^{0.87}(0) - D)}{2} \left(\frac{A}{2} \right)^{1/2} \int_0^{T_0(x)} dT_0 \frac{1}{T_0^{1/2} \left(F - \frac{CT_0^{1.87}}{1.87} + D T_0 \right)^{3/2}} \right\}. \end{aligned} \quad (45)$$

From the above equation (45), we obtain

$$T_I^{(I)}(L) = \left(\frac{\partial T_0(x)}{\partial T(0)} \right)_{x=L} = \left(\frac{2}{A} T_0(L) F \right)^{1/2} \frac{dL}{dT(0)}. \quad (46)$$

The kernel $K(L, \xi)$ is given by

$$\begin{aligned} K(L, \xi) = & \frac{3n T^{1/2}(0)}{P(T(0)) T_0^{1/2}(\xi)} \left[\left(\frac{\partial T_0(x)}{\partial T(0)} \right)_{x=L} \frac{dT_0(\xi)}{d\xi} \right. \\ & \left. - \frac{\partial T_0(\xi)}{\partial T(0)} \left(\frac{dT_0(x)}{dx} \right)_{x=L} \right]. \end{aligned} \quad (47)$$

Substituting eqs. (46), (28) and (45) into the above equation (47), we obtain

$$\begin{aligned} K(L, \xi) = & \frac{3}{2n} \left(\frac{2}{A} T_0(L) F \right)^{1/2} \left(F - \frac{CT_0^{1.87}(\xi)}{1.87} \right. \\ & \left. + D T_0(\xi) \right)^{1/2} \int_0^{T_0(\xi)} dT_0 \frac{1}{T_0^{1/2} \left(F - \frac{CT_0^{1.87}}{1.87} + D T_0 \right)^{3/2}}. \end{aligned} \quad (48)$$

Substituting eqs. (46) and (48) into eq. (42), we obtain the growth rate

$$s = - \left[\frac{3}{2n} \int_0^L d\xi \rho(\xi) \left(F - \frac{C T_0^{1.87}(\xi)}{1.87} + D T_0(\xi) \right)^{1/2} \cdot \int_0^{T_0(\xi)} \frac{1}{dT_0} \frac{1}{T_0^{1/2} \left(F - \frac{C T_0^{1.87}}{1.87} + D T_0 \right)^{3/2}} \right]^{-1} \frac{dL}{dT(0)}. \quad (49)$$

The sign of s is determined by that of $dL/dT(0)$ since we may consider only the case $\rho(x) > 0$.

If we assume that the growth rate s is small, we have an approximate solution of the integral equation (36) as follows :

$$T_I(x) \approx a_I T_I^{(I)}(x) \quad (50)$$

Substituting

$$\rho(x) = T_I^{(I)}(x) = \frac{\partial T_0(x)}{\partial T(0)}, \quad (51)$$

into eq. (49) and using the approximation

$$\frac{\partial T_0(x)}{\partial T(0)} \approx \frac{T_0(x)}{T(0)}, \quad (52)$$

we have an estimate of s :

$$s = - \frac{2P(T(0))}{3nL} \cdot \frac{dL}{dT(0)}. \quad (53)$$

In order to see the $T(0)$ -dependence of L analytically, we use the following approximation

$$P_{fc} = C' n^2 T^{3/2}, \quad (54)$$

in place of the first term in the r. h. s. of eq. (2). Determining the constant C' from the following condition

$$C T^{1.37} = C' T^{3/2} \quad \text{at} \quad T = 100 \text{ keV}, \quad (55)$$

we have

$$C' = 6.65 \times 10^{-17}. \quad (56)$$

When we use the approximation (54), we have the equation of the 0-th order in place of eq. (7) :

$$\frac{d}{dx} \left(\frac{A n^2}{T_0^{1/2}(x)} \frac{dT_0(x)}{dx} \right) + C' n^2 T_0^{3/2}(x) - D n^2 T_0^{1/2}(x) = 0. \quad (57)$$

Then, we have the quadrature of the above equation (57) :

$$x = \left(\frac{A}{2} \right)^{1/2} \int_{T_0(x)}^{T(0)} dT_0 \frac{1}{T_0^{1/2} \left(F' - \frac{C'}{2} T_0^2 + D T_0 \right)^{1/2}}, \quad (58)$$

where

$$F' = \frac{C'}{2} T^2(0) - D T(0). \quad (59)$$

Using the boundary condition (44) in eq. (58), we have

$$L = \left(\frac{A}{2} \right)^{1/2} \int_0^{T(0)} dT_0 \frac{1}{T_0^{1/2} \left(F' - \frac{C'}{2} T_0^2 + D T_0 \right)^{1/2}}. \quad (60)$$

If we put $\xi = T_0/T(0)$ in eq. (60), we have

$$L = \left(\frac{A}{C' T(0)} \right)^{1/2} \int_0^1 d\xi \frac{1}{[\xi(1-\xi)(\xi + 1 - b)]^{1/2}}, \quad (61)$$

where

$$b = \frac{2D}{C' T(0)} = \frac{100}{T(0)}. \quad (62)$$

Putting $\xi = 1 - u^2$ in eq. (61), we obtain

$$L = 2 \left(\frac{A}{C' T(0)} \right)^{1/2} k K(k), \quad (63)$$

where $K(k)$ is the complete elliptic integral of the first kind

$$K(k) = \int_0^1 du \frac{1}{[(1-u^2)(1-k^2 u^2)]^{1/2}}, \quad (64)$$

$$k = \frac{1}{(2-b)^{1/2}} = \frac{1}{\left(2 - \frac{100}{T(0)}\right)^{1/2}}. \quad (65)$$

Substituting eqs. (3), (56) and (65) into eq. (63), we obtain

$$L = \frac{3.67 \times 10^6 (\lambda/10)^{1/2}}{B(T(0) - 50)^{1/2}} K(k). \quad (66)$$

Differentiating both sides of the above equation (66) with respect to $T(0)$, we have

$$\begin{aligned} \frac{dL}{dT(0)} = & - \frac{3.67 \times 10^6 (\lambda/10)^{1/2}}{2B(T(0) - 50)^{3/2}} \left\{ K(k) \right. \\ & \left. + \frac{50}{T(0) - 50} \cdot \frac{dK(k)}{d(k^2)} \right\}. \end{aligned} \quad (67)$$

Since

$$K(k) > 0 \quad \text{and} \quad \frac{dK}{d(k^2)} > 0, \quad (68)$$

we obtain

$$\frac{dL}{dT(0)} < 0. \quad (69)$$

Therefore, the sign of the growth rate s is positive :

$$s \sim - \frac{dL}{dT(0)} > 0. \quad (70)$$

We conclude that the plasma is unstable for the thermal instability.

The $T(0)$ -dependence of L for $B = 10^5 \text{ G}$ and $\lambda \approx 22$ is given in Fig. 1. In this case, for $T(0) = 150 \text{ keV}$, we have from Fig. 1

$$\frac{dL}{dT(0)} \approx -8.5 \times 10^{-2} \text{ cm/keV},$$

$$L \approx 11.7 \text{ cm}.$$

Fig. 1. A half plasma length L as a function of temperature $T(0)$ at the center for $B = 10^5 \text{ G}$ and $\lambda = 22$ in a DD fusion reactor.

Using eq. (53), we obtain the order of the growth rate s for $T(0) = 150 \text{ keV}$, $B = 10^5 \text{ G}$ and $\lambda \approx 22$:

$$s \approx 3.6 \times 10^{-16} n \text{ 1/sec}.$$

When $n \approx 10^{16} \text{ 1/cm}^3$, we have

$$s = 3.6 \text{ 1/sec}.$$

Similarly, for $T(0) = 200 \text{ keV}$, $B = 10^5 \text{ G}$, and $\lambda \approx 22$, we have

$$\frac{dL}{dT(0)} \approx -3.5 \times 10^{-2} \text{ cm/keV},$$

$$L \approx 9.01 \text{ cm},$$

$$s \approx 4.9 \times 10^{-16} n \text{ 1/sec}.$$

§ 3. Catalyzed DD fusion reactor

Secondly, we discuss the instability in a catalyzed DD fusion reactor. The growth rate s in a catalyzed DD fusion reactor is obtained similarly by the method done in § 2. Using eqs. (I. 2. 13) and (II. 6), we have

$$P_{fc} = C_I n^2 T^{1.37}, \quad (71)$$

where

$$C_I = 6.68 \times 10^{-16}. \quad (72)$$

Using C_I in place of C in § 2, we obtain the growth rate

$$s = - \left[\frac{3}{2n} \int_0^L d\xi \rho(\xi) \left(F_I - \frac{C_I T_0^{1.87}(\xi)}{1.87} + D T_0(\xi) \right)^{1/2} \cdot \int_0^{T_0(\xi)} \frac{1}{dT_0} \frac{1}{T_0^{1/2} \left(F_I - \frac{C_I T_0^{1.87}}{1.87} + D T_0 \right)^{3/2}} \right]^{-1} \frac{dL}{dT(0)}, \quad (73)$$

where

$$F_I = \frac{C_I T^{1.87}(0)}{1.87} - D T(0), \quad (74)$$

$$L = \left(\frac{A}{2} \right)^{1/2} \int_0^{T(0)} \frac{1}{dT_0} \frac{1}{T_0^{1/2} \left(F_I - \frac{C_I T_0^{1.87}}{1.87} + D T_0 \right)^{1/2}}. \quad (75)$$

Now, we have an estimate of

$$s \approx - \frac{2P(T(0))}{3nL} \cdot \frac{dL}{dT(0)}, \quad (76)$$

where

$$P(T(0)) = C_I n^2 T^{1.37}(0) - D n^2 T^{1/2}(0). \quad (77)$$

When we use the approximation

$$P_{fc} = C'_I n^2 T^{3/2}, \quad (78)$$

we have

$$C'_I = 3.67 \times 10^{-16}, \quad (79)$$

in place of C' in § 2. In place of b in § 2, we have

$$b_I = \frac{2D}{C'_I T(0)} = \frac{18.2}{T(0)}. \quad (80)$$

Then, we have

$$L = \frac{1.56 \times 10^6 (\lambda/10)^{1/2}}{B(T(0) - 9.1)^{1/2}} K(k_I), \quad (81)$$

where

$$k_I = \frac{1}{\left(2 - \frac{18.2}{T(0)} \right)^{1/2}}. \quad (82)$$

We conclude that the plasma in the catalyzed DD fusion reactor is also unstable for the thermal instability.

The $T(0)$ -dependence of L for $B = 10^5 \text{ G}$ and $\lambda \approx 22$ is given in Fig. 2. In this case, for $T(0) = 50 \text{ keV}$, we have from Fig. 2

Fig. 2. A half plasma length L as a function of temperature $T(0)$ at the center for $B = 10^5 \text{ G}$ and $\lambda = 22$ in a catalyzed DD fusion reactor.

$$\frac{dL}{dT(0)} \approx -1.0 \times 10^{-1} \text{ cm/keV},$$

$$L \approx 7.12 \text{ cm}$$

$$s \approx 1.1 \times 10^{-15} n \text{ 1/sec}.$$

When $n \approx 10^{15} \text{ 1/cm}^3$, we have

$$s \approx 1.1 \text{ 1/sec}.$$

Similarly, for $T(0) = 100 \text{ keV}$, $B = 10^5 \text{ G}$ and $\lambda \approx 22$, we have

$$\frac{dL}{dT(0)} \approx -2.8 \times 10^{-2} \text{ cm/keV}$$

$$L \approx 4.62 \text{ cm},$$

$$s \approx 1.3 \times 10^{-15} n \text{ 1/sec}.$$

§ 4. Conclusions

We have obtained the growth rates for the thermal thermonuclear instability of the deuterium plasma with an inhomogeneous temperature in a strong magnetic field. The growth rate s in a DD fusion reactor is given by

$$s = - \frac{2n}{3L} \left\{ 1.21 \times 10^{-16} (T(0))^{1.37} - 3.34 \times 10^{-15} (T(0))^{1/2} \right\} \cdot \frac{dL}{dT(0)} \text{ 1/sec}, \quad (83)$$

where $n(\text{cm}^{-3})$ is the ion number density, $L(\text{cm})$ a half thickness of the plane plasma layer and $T(0)(\text{keV})$ the temperature at the center. In a catalyzed DD fusion reactor, the growth rate s is given by

$$s = - \frac{2n}{3L} \left\{ 6.68 \times 10^{-16} (T(0))^{1.37} - 3.34 \times 10^{-15} (T(0))^{1/2} \right\} \cdot \frac{dL}{dT(0)} \text{ 1/sec}. \quad (84)$$

The $T(0)$ -dependence of L for the strength of the magnetic field $B = 10^5 \text{ G}$ and the Coulomb logarithm $\lambda \approx 22$ is given in Fig. 1 (DD fusion reactor) and Fig. 2 (catalyzed DD fusion reactor).

Since $s > 0$ because of $dL/dT(0) < 0$ in the temperature region considered in this paper, the plasmas with an inhomogeneous temperature in a DD fusion reactor and in a catalyzed DD fusion reactor are unstable for the thermal instability.

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