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THERMONUCLEAR REACTIONS DURING
ION-BEAM HEATING TO IGNITION

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Effects of Beam-Plasma Thermonuclear
Reactions During Ion-Beam Heating to Ignition

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ABSTRACT

If a 1:1 D-T tokamak plasma is heated to ignition by D beams with injected energy in the range 150-300 keV, the total energy of fusion products formed by reactions between beam deuterons and plasma tritons is 0.33 to 0.90 times the total injected beam energy, depending on the ignition temperature. Plasma heating by the alphas generated by these reactions reduces the total required injected neutral-beam capacity by as much as 18%.

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1. INTRODUCTION

In the two-energy-component tokamak reactor,¹ high energy deuterons injected at energy W_0 into a low-energy tritium target plasma undergo fusion reactions with the cold tritons. The energy multiplication factor is defined:

$$F = \frac{\text{fusion energy produced per injected ion}}{W_0} \quad (1)$$

The variation of F with T_e and W_0 is described in Ref. 1. F may be as large as 3.9, the value increasing with T_e , while the plasma ion temperature is arbitrary.

Here we wish to point out that in heating a tokamak plasma to ignition temperature, it is advantageous to use neutral D beams with energy in the optimum range for two-component thermonuclear reactions; that is, $W_0 \approx 150\text{-}300$ keV. In the following, we use a plasma composition of 50% tritium (T) and 50% deuterium (D). In evaluating the thermonuclear energy production, we do not include the 4.8 MeV per neutron that may be generated in a blanket. Hence, in using the values of F in Ref. 1, we must divide the thermonuclear output by the factor $2 \times (22.4/17.6) = 2.55$.

It should be emphasized that beams with energy in the optimum range can be utilized only if the plasma density is adjusted for complete beam trapping and favorable spatial energy deposition. For tangential injection of 200 keV beams, the requirement is $n_e a \approx 10^{16}/(2A)^{1/2} \text{ cm}^{-2}$, where a is the plasma radius and A is the aspect ratio.²

2. ENERGY MULTIPLICATION

Consider a tokamak plasma heated by neutral beams from $T_e = T_0$ to $T_e = T_f$, where T_0 is the temperature maintained by Ohmic heating, and T_f is the ignition temperature. If $P_b(t)$ is the injected beam power per unit volume, then the beam multiplication factor is

$$Q_b = \frac{\text{thermonuclear energy production}}{\text{injected energy}} = \frac{1}{2.55} \frac{\int_0^{\tau_h} F(T_e) P_b(t) dt}{\int_0^{\tau_h} P_b(t) dt} \quad (2)$$

where τ_h is the total heating time.

For any reactor whose ignition temperature is in the range 5 to 20 keV, $\tau_E \gg \tau_s$, where τ_E is the energy confinement time, and τ_s is the slowing-down time of suprathermal ions. The latter quantity is also approximately equal to the thermalization time of ions and electrons. Then if $\tau_h \lesssim \tau_E$, $T_i \approx T_e$ during the heating. Thus the rate of plasma heating is

$$3n_e \frac{dT_e}{dt} = P_b(t) - bn_e^2 T_e^{1/2} - 3n_e \frac{T_e}{\tau_E} \quad (3)$$

where b is the bremsstrahlung coefficient. Here we have ignored the contribution to plasma heating of alphas produced in the two-component reactions as well as in the reactions among thermal plasma ions. Furthermore, we now consider only the case of fast heating, where $P_b(t) \gg bn_e^2 T_e^{1/2} + 3n_e T_e / \tau_E$, until ignition temperature is attained. Then $dt = (3n_e / P_b) dT_e$. If n_e is constant, Eq. (2) becomes

$$Q_b = \frac{1}{2.55} \frac{\int_{T_o}^{T_f} F(T_e) dT_e}{(T_f - T_o)} \quad (4)$$

Figure 1 shows Q_b as a function of T_f and W_o , for $T_o = 2.0$ keV. (The values of F were taken from Ref. 1.) Evidently, Q_b as large as 0.9 is attainable, for $W_o = 200$ keV. In fact, even larger values of Q_b can be realized by appropriately varying W_o during the heating process, as well as the relative proportions of tritium and deuterium in the plasma. Although these results are independent of n_e , we note again that n_e must be in the range that allows complete trapping and favorable spatial deposition of the incident neutral beams.²

It should be noted that if we had not considered the case of fast heating, but instead, for example, had taken P_b as the value necessary to maintain ignition temperature (in the absence of alphas), then the heating rate, given by Eq. (3), would decrease with increasing T_e . Thus, for a given T_f , relatively greater time would be spent heating at the upper range of T_e , where F is larger, and Q_b would be greater than given by Eq. (4). However, this enhancement would be lessened if P_b is lowered to accommodate the contribution of alpha-particle heating at large T_i .

3. HEATING BY BEAM-PRODUCED ALPHAS

The alpha particles generated by fusion reactions between the beam deuterons and plasma tritons are, of course, confined in a plasma capable of attaining ignition, and these alphas will aid the neutral beam in heating the plasma to ignition. Since the

alpha energy is 3.5 MeV, the ratio of alpha power density to beam power density is $0.078 F(T_e)$. Then if $E_p = 3n_e(T_f - T_o)$ is the supplementary (i.e., non-Ohmic) energy required to heat the plasma to ignition, the required injected beam capacity is E_b , where

$$E_b = E_p - \int_0^{\tau_h} 0.078 F(T_e) P_b(t) dt \quad (5)$$

and

$$\begin{aligned} \frac{E_b}{E_p} &= 1 - \frac{\int_{T_o}^{T_f} 0.078 F(T_e) dT_e}{T_f - T_o} \\ &= 1 - 0.20 Q_b. \end{aligned} \quad (6)$$

[As in the derivation of Eq. (4), we have ignored radiation and transport losses during the heating.] Evidently, the reduction in the injected energy requirement can be as large as 18% (cf. Fig. 1).

4. CONCLUSIONS

Neutral D beams with energy in the optimum range for two-component power multiplication (150-300 keV) can heat a 1:1 D-T reactor plasma to ignition temperature with 33 to 90% of the injected beam energy reproduced by beam-plasma fusion reactions. Furthermore, the total injected energy is reduced by 6.6 to 18%, because of the heating effect of alphas generated by the two-component reactions. Assuming a thermal conversion efficiency of

40% for the neutron energy, which now includes the usual 4.8 MeV generated in the blanket, the net electrical energy required for heating is reduced by 21 to 49%. These advantages are apparently not shared by other proposed supplementary heating methods; this consideration is particularly important for pulsed reactors with energy multiplication factors of order 10 or less.

ACKNOWLEDGMENT

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 Fig. 1. Beam thermonuclear energy multiplication factor versus final plasma temperature T_f . Injection energies are indicated.

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