REACTOR APPLICATIONS
OF
TWO-COMPONENT TOKAMAK PLASMAS

BY

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PLASMA PHYSICS
LABORATORY

MASTER

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Reactor Applications of Two-Component Tokamak Plasmas

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ABSTRACT

The physics of two-energy-component toroidal plasmas (TCT) is reviewed. Energy "breakeven" using the TCT mode (deuteron beams on a triton-target plasma) can be attained at much smaller $n\tau$ and temperature than in thermal plasma operation. This result reflects the fact that the fusion power density in a TCT can be much larger than in a thermal DT plasma of the same pressure. The large fusion power density (i.e., large neutron flux) of a TCT may find practical use in a number of applications.

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Introduction

In the last year or so there has been, in some circles of the CTR community, a rising interest in what might be possible to do with a two-component plasma in a tokamak fusion reactor.^{1,2} A "two-component plasma" is characterized simply by a marked non-Maxwellian ion velocity distribution such as might be produced by the injection of a beam of very energetic ions into a thermal plasma. Although we will make our remarks in terms of injected beams, one should not overlook the possibility of creating two-component plasmas by rf techniques as well.^{3,4}

Fusion reactors will, by definition, use nuclear fusion events as their source of power. Hence to enhance the rate of fusion events should make a better reactor. The question we will discuss briefly is: how does one maximize the reaction rate?

The fusion cross sections of the likely candidates for fusion fuels are of a resonant nature and are peaked in the 100 to 1000 keV range. Consequently there is an optimal speed for colliding fuel ions that will maximize their rate of reaction, (σv) , where σ is the reaction cross section and v is the relative speed of the colliding particles.

Of the candidate reactions for a fusion reactor, the deuterium-tritium reaction has the largest peak cross section of about 5 barns at the lowest energy in the center

mass system of about 68 keV. We will use this reaction to illustrate our remarks. Thus the product (σv) maximizes for a 46.8 keV deuteron and a 20.8 keV triton in head-on collision. Colliding beams of particles⁵ might create this situation. On the other hand, if the triton were at rest, a 130 keV deuteron maximizes the reaction rate.

To produce and inject such beams of particles into a target plasma requires energy. Consequently a parameter of interest for a reactor is the ratio, Q_b , of the fusion power released to the injected beam power required. For an ignited plasma, one in which the charged products of the fusion reaction maintain the state of ignition, no injected power from external sources is required, there are no "beams", and hence Q_b becomes infinite. However, the reaction rate remains finite in a thermonuclear plasma no matter what the temperature. This limitation of the reaction rate is, of course, due to the peaked nature of the fusion cross section.

Rate of Reaction

1. Reaction rate per reacting particle.

Quite generally the reaction rate, R , of two reacting species of particles can be written as:

$$R = \int_{\underline{v}_1} \int_{\underline{v}_2} f_1(\underline{v}_1) f_2(\underline{v}_2) \sigma_{1,2} |\underline{v}_1 - \underline{v}_2| d\underline{v}_1 d\underline{v}_2 \quad (1)$$

$$\equiv n_1 n_2 \langle \sigma v \rangle .$$

Here $f(\underline{v})$ is a velocity distribution function and n is a spatial density given by:

$$n = \int_{\underline{v}} f(\underline{v}) d\underline{v} .$$

The reaction rate per reacting particle is just $\langle \sigma v \rangle$.

To evaluate R for a thermonuclear DT plasma one inserts Maxwellian velocity distributions for both the deuterium and the tritium ions. The resulting integrals are functions of the temperature and particle energy and do not depend on the densities of the reacting particles. Thus $\langle \sigma v \rangle$ for the DT reaction will be a function of the temperature alone and has a broad maximum with a peak value of $0.90 \times 10^{-15} \text{ cm}^3/\text{sec}$. at a temperature of about 70 keV. Of course not all the particles are colliding at optimal speeds to produce a maximum reaction rate.

How does this reaction rate compare with that of an injected deuteron? The 130 keV deuteron incident on a stationary triton, cited above, does better with a reaction rate of $1.67 \times 10^{-15} \text{ cm}^3/\text{sec}$, nearly a factor of two higher. However, this comparison is not quite fair since in a thermonuclear plasma the reaction rate will be sustained,

whereas a 130 keV deuteron injected into a tritium plasma will slow down in the course of time and hence its reaction rate will decrease. A better measure of the reaction rate for injected deuterons uses the total probability for fusion developed by the injected deuteron in the course of its slowing down in the target plasma. The fusion rate to be compared is given by this total probability for fusion divided by the time for the deuteron to slow down and by the density of target tritons.

We can write the following expression for the total probability of fusion of an injected deuteron:

$$\text{Prob}_{fu} = \int_0^{t_s} r(t) p(t) dt \quad (2)$$

Here $p(t)$ is the probability of the deuteron being in the target plasma at a time t after injection, $r(t)$ is the instantaneous rate of reaction of the deuteron with the population of target tritons in the plasma, and t_s is the slowing down time after which the deuteron is no longer to be considered part of an injected beam.

The probability of being in the target plasma will be influenced by the confinement time for particles in the plasma as well as the nuclear reactions that may take place. Consequently if we are to have the maximum total probability for fusion, the particle confinement time should exceed the slowing down time.

The instantaneous reaction rate is given by the integral

$$r(t) = \int_{\underline{v}_T} f_T(\underline{v}_T) \sigma |\underline{v}_T - \underline{v}_b(t)| d\underline{v}_T \quad (3)$$

We assume the velocity distribution function for the target tritons to be isotropic and hence $r(t)$ will depend on the magnitude but not the direction of the deuteron velocity. In Fig. 1 we show the instantaneous reaction rate of a deuteron with a unit density Maxwellian gas of pure tritium for various temperatures.

How $r(t)$ will vary with time depends on how the deuteron slows down and this, in turn, will depend on the composition of the plasma as well as temperature. To show this dependence more explicitly we can recast Eq. 2 in terms of the speed of the injected particle, $v_b(t)$. Thus we write:

$$\text{Prob} f u = \int_{v_0}^{v_{\min}} \frac{r(v_b) p(v_b) dv_b}{(dv_b/dt)} \quad (4)$$

Here v_0 is the initial speed of injection. This expression can be readily evaluated since we know (dv_b/dt) from the theory of the energy loss of fast particles in a plasma.⁶ In

Fig. 2 we show an example of the slowing down of a 200 keV deuteron in a tritium plasma at a temperature of 6 keV.

The expression for the probability of fusion can be cast in still a somewhat different form that utilizes the concept of the velocity distribution function of the injected beam particles. If we think of a steady injection of beam particles into a target plasma, a steady state velocity distribution of beam particles will be created in about the slowing down time. In steady state the loss of beam particles via either loss of confinement or nuclear reactions or simply slowing down and being lost through the background plasma must equal the injection rate of beam particles. Thus the density of beam particles, $f_b(v_b)$, in a speed interval Δv_b is related to the injection rate per unit volume, J , in the following manner:

$$f_b(v_b) \Delta v_b = J p(t) \Delta t \quad (5)$$

Here $Jp(t)$ is just the rate at which beam particles, after a time t , arrive at a speed v_b ; and Δt is the time required for them to slow down an amount Δv_b . Substituting from Eqs. 5 and 3 into Eq. 4 we have the following expression:

$$\text{Prob}fu = \frac{1}{J} \int_{v_b} \int_{v_T} f_b(v_b) f_T(v_T) \sigma |v_T - v_b| dv_T dv_b \quad (6)$$

$$\equiv \frac{1}{J} n_b n_T (\tilde{\sigma}v)_b \quad (6a)$$

where:

$$n_b = \int_{v_b} f_b(v_b) dv_b = J \int_0^{t_s} p(t) dt \equiv J \langle p \rangle t_s \quad (7)$$

and

$$n_T = \int_{v_T} f_T(v_T) dv_T$$

This form of the probability of fusion is more suitable for taking into account the statistical variations in slowing down of individual beam particles or for calculating the probability of fusion for any scheme that can create a non-Maxwellian velocity distribution. There is a clear analogy between Eq. 6 and Eq. 1.

The desired fusion rate per reacting particle for the injected deuteron is just $(\tilde{\sigma}v)_b$. This rate can be viewed as simply the reaction rate per reacting particle of the injected particle averaged over the time to slow down. It cannot exceed the maximum value of $r(v_b)$ associated with a particular plasma temperature. A plot of $(\tilde{\sigma}v)_b$ is shown in Fig. 3. The curves have been calculated for a perfectly confined pure tritium plasma at an electron density of 10^{14} cm^{-3} , but the results are rather insensitive to the density. The broad maxima result from the peaked nature of the DT cross section.

For a 200 keV deuteron injected into a tritium plasma at a temperature of 6 keV and a density of 10^{14} cm^{-3} , we have the result

$$(\tilde{\sigma}v)_b = 0.97 \times 10^{-15} \text{ cm}^3/\text{sec} .$$

This rate is to be compared to the value of $0.90 \times 10^{-15} \text{ cm}^3/\text{sec}$ cited above as the maximum value of $\langle \sigma v \rangle$ for a thermal DT plasma. Although somewhat higher values $(\tilde{\sigma}v)_b$ can be achieved, our conclusion here is that the maximum reaction rates per reacting particle are comparable for the thermal plasma and the beam injected plasma.

2. Reaction rate per unit volume.

For a fusion reactor one is interested in the reaction rate per unit volume of plasma and hence one is interested in how many reacting particles can be placed in a unit volume. What limits this density and how do thermal plasmas and beam injected plasmas compare?

The magnetically confined fusion reactors will be pressure limited devices. Thus the rate of fusion per unit volume of plasma will be limited by maximum plasma pressure

that, in turn, will be determined by other factors such as the magnetic field strength and configuration.

For a thermal DT plasma without "impurities" the pressure is simply the sum of the partial pressures of the electrons, the deuterons and the tritons, namely:

$$P = (n_e + n_D + n_T) T \quad .$$

Plasma neutrality requires $n_e = n_D + n_T$ and, assuming the optimal mixture of $n_D = n_T$, we have for the reaction rate per unit volume, R, the familiar expression:

$$R = n_D n_T \langle \sigma v \rangle = \frac{P^2}{16} \cdot \frac{\langle \sigma v \rangle}{T^2} \quad .$$

For fixed P, R is maximized at a temperature $T \approx 15$ keV for which $\langle \sigma v \rangle = 0.27 \times 10^{-15}$ cm³/sec. Note $\langle \sigma v \rangle$ is about one third of its theoretical maximum.

For the beam injected plasma we take the plasma pressure to be

$$P = (n_e + n_T) T_e + n_b \cdot \frac{2}{3} \bar{W}_b \quad . \quad (8)$$

where we have taken the effective temperature of the beam particles to be two-thirds of their average energy, $\bar{W}_b$, in

analogy to the definition of kinetic temperature. Plasma neutrality requires:

$$n_e = n_T + n_b \quad . \quad (9)$$

To fix the densities of the three different components of the plasma, we need one more relation. We chose a model whereby the plasma temperature is maintained by the energy delivered to the plasma by the slowing down of the injected particles. Equating the beam power to the energy loss from the plasma we write:

$$J W_0 = \frac{n_b}{\langle p \rangle t_s} \cdot W_0 = \frac{3}{2} \frac{(n_e + n_T) T_e}{\tau_E} \quad (10)$$

where W_0 is the injection energy and where the extreme right hand side of Eq. 10 represents the energy loss from the plasma and serves to define τ_E , the energy confinement time. Using Eqs. 8,9 and 10 to determine n_b and n_T , the reaction rate per unit volume for the beam injected plasma is:

$$R_b = n_b n_T (\tilde{\sigma}v)_b = \frac{p^2}{2} \frac{(X - 1)}{(\frac{2}{3} \frac{\bar{W}_b}{T_e} + X)^2} \cdot \frac{(\tilde{\sigma}v)_b}{T_e^2} \quad (11)$$

where:

$$X \equiv \frac{2}{3} \frac{W_o}{T_e} \cdot \frac{\tau_E}{\langle p \rangle t_s}$$

We chose the parameter, X , to optimize R_b . In doing so we anticipate that the density of the injected particles will remain small compared to the density of tritons. Under this assumption the ratio of the tritons to the electrons in the plasma will remain rather insensitive to X and hence we can treat $(\tilde{\sigma v})_b$ as insensitive to X as well. This is a subtle point involving the shape of the distribution function for the beam particles and is briefly discussed in Note 1.

We find $X = 2 + \frac{2}{3} \frac{\bar{W}_b}{T_e}$ optimizes R_b .

Thus:

$$(R_b)_{opt} = \frac{p^2}{16} \cdot \frac{2}{(\frac{2}{3} \frac{\bar{W}_b}{T_e} + 1)} \cdot \frac{(\tilde{\sigma v})_b}{T_e^2},$$

and hence comparing plasmas at the same pressure:

$$\frac{(R_b)_{opt}}{R_{max}} = \frac{2}{(\frac{2}{3} \frac{\bar{W}_b}{T_e} + 1)} \cdot \frac{(\tilde{\sigma v})_b}{T_e^2} \cdot \frac{1}{(\frac{\langle \sigma v \rangle}{T^2})_{max}} \quad (12)$$

For our example of a 200 keV deuteron injected into a tritium plasma at a temperature of 6 keV, and noting from

Fig. 2 that $\bar{W}_b \approx \frac{1}{2} W_o$, we find $X_{opt} \approx 13$ and

$$\frac{(R_b)_{opt}}{R_{max}} = \frac{2}{(\frac{2}{3} \cdot \frac{100}{6} + 1)} \times \frac{0.97 \times 10^{-15}}{0.265 \times 10^{-15}} \left(\frac{15}{6}\right)^2 = 3.78$$

This beam driven fusion rate is 3.78 times the maximum fusion rate per unit volume obtainable by a thermal DT plasma at any temperature!

We also note that

$$\frac{n_b}{n_e + n_T} = \frac{1}{X} \approx \frac{1}{13} \ll 1$$

and

$$n_T/n_e = \frac{1}{1 + \frac{2}{X-1}} \approx 1$$

which justify our above assumptions about the insensitivity of $(\tilde{\sigma}v)_b$ to X . Choosing the electron density of the tritium plasma to be 10^{14} cm^{-3} , we calculate for the 200 keV deuteron a slowing down time of 0.156 seconds and a probability of fusion of 0.0151. Thus the probable fusion energy released per injected deuteron is 288 keV or 1.33 times the injection energy. One can think of this

situation as demonstrating a kind of energy "break-even", but hardly a condition for producing net energy from a fusion reactor.

In addition we note that from the optimal value of X we have:

$$\frac{\tau_E}{\langle p \rangle t_s} = \frac{\bar{W}_b + 3T_e}{W_o} = 0.59$$

Hence we have:

$$n_e \tau_E = \langle p \rangle 0.92 \times 10^{13} \text{ sec/cm}^3$$

This value of $n_e \tau_E$ is viewed as a requirement on the plasma performance since we conceptually vary X by varying τ_E . Thus, in our example, to optimize the fusion rate per unit volume of a beam driven fusion reactor, there is an optimal value of $n_e \tau_E$ that is an order of magnitude lower than the usual value of 10^{14} sec/cm^3 associated with ignited thermal DT plasmas.

Conclusion

The result of the above remarks is the recognition of quite different optimal operating regimes for a fusion reactor depending on one's desires for a maximum of net power production or a maximum rate of fusion events.⁷ For power production the ignited plasma at high temperatures and

relatively long energy confinement times is required. However, for neutron production the beam-driven plasma at lower temperatures and relatively short energy confinement times is more optimal. These operating conditions seem to be within easier reach than those of an ignited plasma. Furthermore, 14 MeV neutrons can be put to use for materials testing, to breed fissile fuel and to burn fission waste products. Hence the prospect of a more immediate useful application of fusion technology within the next decade or so has met with great interest. Although the early practical "spin-off" from the CTR effort may be very useful, the two-component plasma conditions are not optimal for the production of net fusion power - the ultimate goal of the CTR effort.

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Note 1

If $(\tilde{\sigma v})_b$ were independent of n_b and n_T , then Probfu would depend on the ion densities only through the product $n_b n_T$ as indicated in Eq. 6a. However, from Eq. 6 it is clear that Probfu will depend on the shapes of the distribution functions for the ions as well as the magnitude of their spatial densities. Hence $(\tilde{\sigma v})_b$ will reflect this dependence as well.

The shape of the ion distribution functions will be determined by the interactions between the various species of particles that make up the target plasma and the injected beam. In particular, the shape of $f_b(v_b)$ will be determined by how the beam particles slow down in the plasma. The slowing down of a beam particle is clearly a function of the plasma composition as well as its density. Thus it is through the ratio n_T/n_e that the shape of f_b and hence $(\tilde{\sigma v})_b$ are rendered dependent on n_b and n_T and hence dependent on the parameter X.

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Fig. 1. Fusion reaction rate of an energetic deuteron with a tritium Maxwellian gas of unit density and temperature T .

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Fig. 2. Slowing down of a deuteron in a tritium plasma.

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Fig. 3. Average reaction rate of injected deuteron slowing down in a pure, well confined tritium plasma at temperature T.