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## ABSTRACT

It is shown that the fusion of two counter-streaming beams of deuterium and tritium ions, slowing down in a toroidal background plasma, can give rise to a significant energy amplification factor Q. The Q of this 'three-component system' is found to be greater than the Q of the single beam-plasma system (two-component scheme) for beam injection energies in the range 40-100 keV.

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It has been shown by Dawson, Furth and Tenney(1) that the fusion of an injected beam of energetic deuterons with a cold trituim toroidal plasma gives a net energy gain. This type of energy amplifier will be referred to in future as the two component scheme. In this paper we show that fusion between counter-streaming beams of deuterium and tritium ions slowing down in a DT background plasma can give a larger energy amplification factor (Q) particularly for low energy injection. This three-component scheme has several additional advantages: first, beams at the required injection energy 40-60 keV have already been developed, second the neutralisation efficiency at this energy is much higher than at the 100-200 keV injection energy of the two-component scheme, and finally the present generation of Tokamaks (P.L.T, DITE etc) could test this concept.

To calculate the Q of the three component system, the distribution functions for the two fast ion species are required; these have been previously derived by Cordey and Core(2). Assuming the deuterons are injected in the co-direction ($\xi = 1$) and the tritons in the counter direction ($\xi = -1$), then the distributions are

$$f_D(v,\xi) = S_D \, \tau_D \, \delta(\xi-1) / \left\{ v^3 + v_{CB}^3(1-\rho) + 0.5\rho v_{CT}^3 v^2/(v+u_T)^2 \right\} \qquad \ldots (1)$$

and

$$f_T(v,\xi) = S_T \, \tau_T \, \delta(\xi+1) / \left\{ v^3 + v_{CB}^3(1-\rho) + 0.5\rho v_{CD}^3 v^2/(v+u_D)^2 \right\} \qquad \ldots (2)$$

respectively, where $v=(v_{\parallel}^2+v_{\perp}^2)^{\frac{1}{2}}$, $\xi=v_{\parallel}/v$, the slowing down time $\tau_j = 3v_e^3 \, m_e \, m_j/16\pi^{\frac{1}{2}}e^4 \, Z_j^2 \, n_e \mathrm{Ln}\,\Lambda$, $v_c = (.75 \, \pi^{\frac{1}{2}} \, m_e/m_i)^{1/3} \, v_e$, S is the source rate of injected particles, and $\rho = n_f/n$ where $n_f$ is the total number of fast ions and n is the electron density, $u_D$ and $u_T$ are the mean velocities of the fast ions ($u_j \approx 0.75 \, v_{cj}$) the subscripts B, T and D stand for background, tritons and deuterons respectively.

The first term in the denominator of Eqs (1) and (2) is from friction with the electrons, the second term is from friction with the background ions and the third term is due to friction between the two fast ion species. In deriving this last term the fast ion distribution used in the Rosenbluth potentials h and g(3) were taken as delta functions with mean velocity $u_D$ and $u_T$. This approximation may be justified as follows; fast-fast ion collisions are unimportant if either $n_f/n \ll 1$ or when electron friction dominates the slowing of the fast ions ie $|u_T + u_D| \gg v_c$, and this latter condition is satisfied for the parameters considered in this paper. For large electron temperatures ($T_e > 20$ keV), fast-fast ion collisions dominate the slowing of the fast ions and then a self-consistent solution of the two non-linear fast ion Fokker-Planck equations is required.

Ion-ion scattering has also been ignored in Eqs (1) and (2); by inspection of the complete solution with scattering, it can be shown that this approximation is good for velocities

$$v > v_{min} = \min(v_c,\ v_o/2^{m_f/m_i Z_{eff}}).$$

That is, scattering is only important for velocities below $v_{min}$. As a result the lower limits of all the integrals in the expression for Q (Eq (3)) are taken as $v_{min}$, and fusion arising from particles with velocities less than $v_{min}$ is neglected.

The Q for the three component system is

$$Q = \frac{S_D\ S_T\ \tau_D\ \tau_T\ Y}{S_D\ \varepsilon_D + S_T\ \varepsilon_T} \int_{v_{min}}^{v_D} \int_{v_{min}}^{v_T} \sigma(v+\acute{v})\,(v+\acute{v})\,f_D(v)\,f_T(\acute{v})\,v^2\acute{v}^2\,dv\,d\acute{v} \quad + Q_o \quad \ldots (3)$$

where $v_D$ and $v_T$ are the injection velocities of the deuterons and tritons, $\varepsilon_D$ and $\varepsilon_T$ their injection energy; Y is the thermonuclear yield per fusion event. The first term is from fusion between the two species of fast ions, the second term $Q_o = (Q_D S_D \varepsilon_D + Q_T S_T \varepsilon_T)/(S_D \varepsilon_D + S_T \varepsilon_T)$ is the fusion of the fast ion distributions with the background ions, $Q_D$ and $Q_T$ are the energy amplification factors of the two-component schemes with the appropriate injection energy; in the results of Figs 1 and 2 $Q_D$ and $Q_T$ were obtained from Dawson et al$^{(1)}$.

The expression for Q is a function of variables $S_D$, $S_T$, $v_D$ and $v_T$; these are not independent, since it has been tacitly assumed in deriving Eqs (1) and (2) that the background plasma has zero toroidal velocity, thus the total injected momentum must be zero, and this gives the constraint

$$S_D A_D v_D = S_T A_T v_T \ . \qquad \ldots (4)$$

If the expression for Q, Eq (3), is then maximised subject to the further constraint that the injected power is prescribed we find that $v_D = v_T$. This latter condition is most simply obtained by transforming variables in Eq (3) to $\alpha = v_D + v_T$ and $\eta = v_D - v_T$ then differentiating w.r.t. $\eta$ . The condition $v_D = v_T$ is equivalent to the injection energy of the triton beam being 1.5 times that of the deuteron beam, and using Eq (4) the triton injection current is ⅔ that of the deuterons.

Evaluating Eq (3) numerically using $n_f = \int_{v_{min}}^{v_D} (f_D + f_T)\, v^2 dv$ to eliminate $S_D$, and the condition $v_D = v_T$, the maximal value of Q is then obtained as a function of $n_f/n$ (the ratio of the fast ion number density to the electron density). In Fig 1 Q is plotted against the deuteron beam energy for an electron temperature of 5 keV. Shown dotted for comparison is the Q of the two-component scheme. Clearly the three-component scheme has a substantial Q for deuteron injection energies in the range 40-100 keV and even when the injection currents are small $n_f/n \sim 0.2$ there is gain in Q over the two-component approach for energies in the range 20-60 keV.

The case of $n_f/n = 1$, that is no background ions, has recently been discussed by Kulsrud and Jassby(4); using a different treatment these authors appear to obtain similar Q values for this particular value of $n_f/n$.

Figure 2 gives the dependence on Q for a series of different electron temperatures. For values of $T_e > 20$ keV and $n_f \sim n$, fast-fast ion collisions dominate, and as mentioned earlier the theory given here is no longer valid; however one would expect values of Q to be at least double that of the two-component scheme, that is for large $T_e$ the Q of the three-component scheme should be around 8 with injection energies of 60 keV for the deuterons, 90 keV for the tritons. The physical reason for the factor of two, is that when ion-ion collisions dominate, the fusion cross-section of two colliding DT beams each of, say, energy $\epsilon_o$ and current S (hence total injected power $2 S \epsilon_o$), is approximately the same as that of one beam of deuterons of energy $4 \epsilon_o$ and current S (hence power $4 S \epsilon_o$) colliding with a cold tritium plasma.

To give a few concrete examples of three - component operation : in a present-generation Tokamak with parameters $R = 110$ cm, $r = 23$ cm, $n = 4 \times 10^{13}$ $cm^{-3}$, $T_e \simeq 5$ keV, injecting 1.2 MW of D at 60 keV and 1.2 MW of T at 90 keV gives $n_f/n \sim 0.6$ and $Q \sim 0.4$ with $\Gamma = \overline{n_f \epsilon}/3n\ kT \sim 2$ ; increasing the injection power of the beams to around 3 MW gives $Q > 1$. To study alpha particle physics, the injection of counter-streaming 3 MW beams of 120 keV D and 180 keV $^3H_e$ into a hydrogen background plasma with the above parameters gives a $Q \sim 0.02$ and a total $\Gamma_\alpha$ of the fusion reaction products (3.6 MeV $\alpha$ plus 14.5 MeV protons) of 0.1, which is of the same order of magnitude as $\Gamma_\alpha$ in a reactor; using this technique one avoids the problems associated with tritium and neutrons.

To summarise it has been shown that fusion between two counter-streaming beams of deuterons and tritons slowing down in a DT plasma gives a large energy amplification factor for injection energies in the range 40-100 keV. The effects of energy diffusion$^{(5)}$ and alpha particle heating have been neglected in this analysis and both will increase the Q value (in the case of energy diffusion by ~ 30%).

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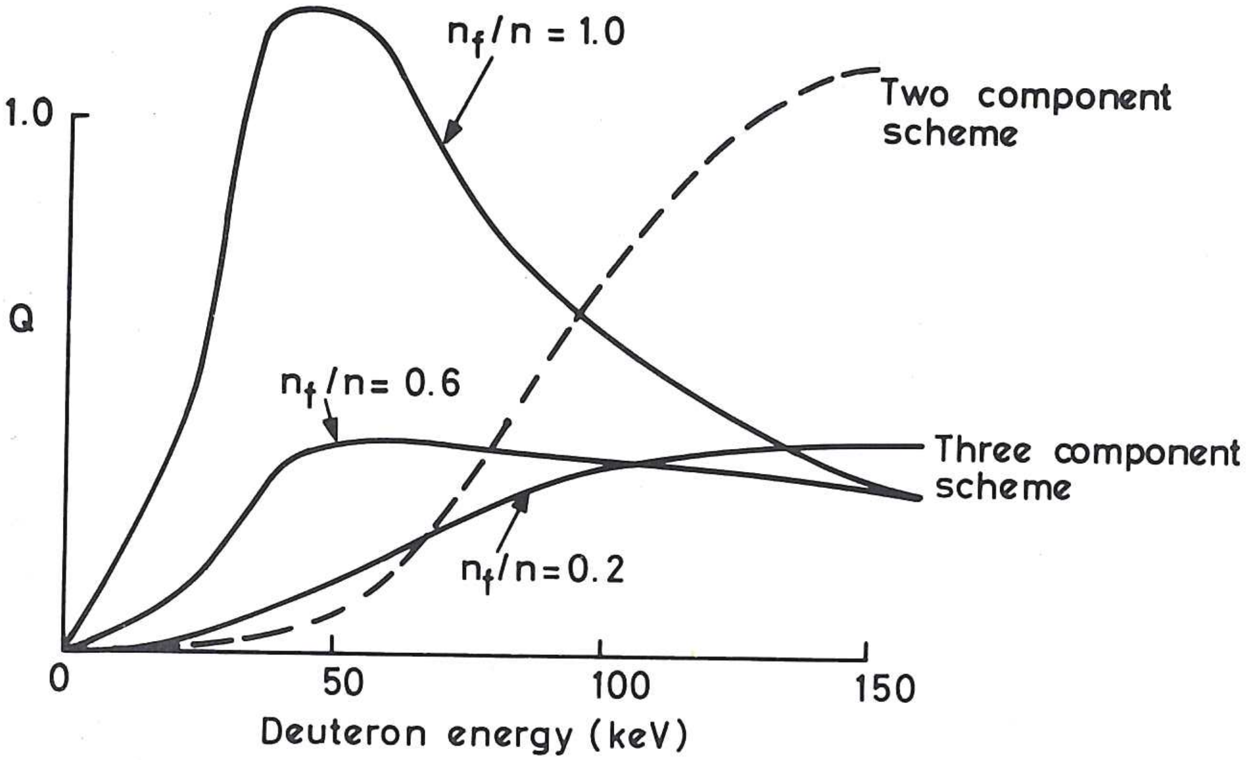

Fig.1 Q versus the deuterium injection energy (the tritium injection energy is 1.5 that of the deuterium) for three values of the fast ion to background electron density ratio. The dotted curve is for the two-component scheme. The electron temperature is 5 keV.

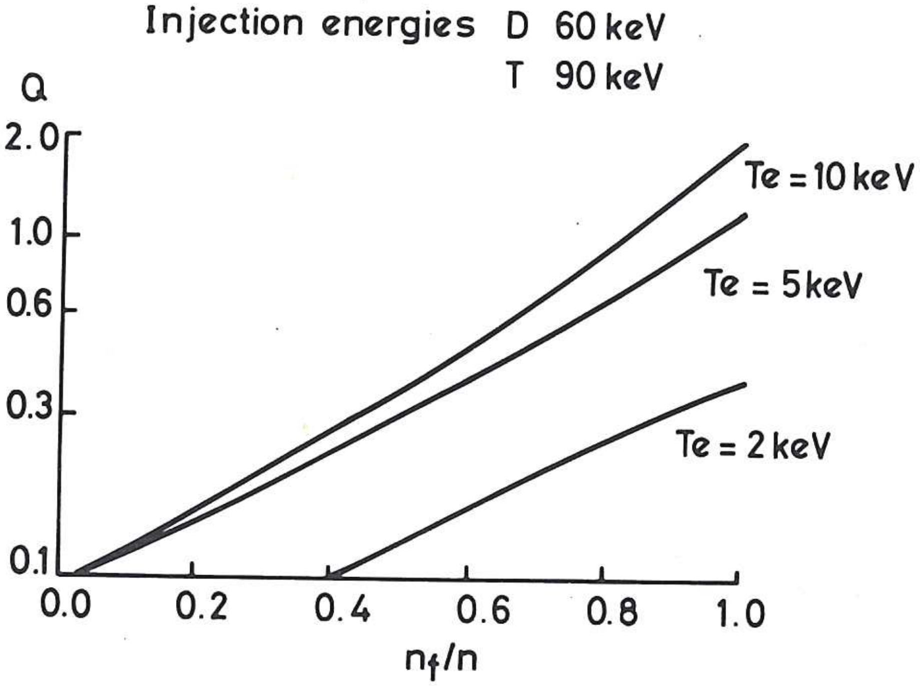

Fig.2 Q versus the fast ion to background electron density ratio for different electron temperatures.