# UTILITY OF EXTRACTING $\alpha$ PARTICLE ENERGY BY WAVES

N.J. FISCH, M.C. HERRMANN
Princeton Plasma Physics Laboratory,
Princeton University,
Princeton, New Jersey,
United States of America

ABSTRACT. The utility of extracting $\alpha$ particle power, and then diverting this power to fast fuel ions, is investigated. As power is diverted to fast ions and then to ions, a number of effects come into play, as the relative amounts of pressure taken up by electrons, fuel ions and fast $\alpha$ particles shift. In addition, if the $\alpha$ particle power is diverted to fast fuel ions, there is an enhanced fusion reactivity because of the non-thermal component of the ion distribution. Some useful expressions for describing these effects are derived, and it is shown that fusion reactors with power density about twice what otherwise might be obtained can be contemplated, so long as a substantial amount of the $\alpha$ particle power can be diverted. Interestingly, in this mode of operation, once the electron heat is sufficiently confined, further improvement in confinement is actually not desirable. A similar improvement in fusion power density can be obtained for advanced fuel mixtures such as D–$^3$He, where the power of both the energetic $\alpha$ particles and the energetic protons might be diverted advantageously.

## 1. INTRODUCTION

If the energy from energetic $\alpha$ particles could be extracted by waves and diverted to the tail of the fuel distribution in a tokamak reactor, there are a number of benefits: first, the energetic $\alpha$ particle pressure is suppressed, allowing for more fuel ion pressure. Second, the electron temperature is suppressed while the ion temperature is enhanced, possibly giving rise to the so-called 'hot ion mode'. Third, there is a non-thermal fuel ion component that may lead to increased reactivity at a given pressure. On the other hand, there are costs: to divert $\alpha$ particle power may require external catalytic heating, and, in any event, the increased reactivity leads to more $\alpha$ particle pressure, which also must be taken into account. What this paper attempts to do is to quantify these benefits and costs.

It has been recognized that there are advantages in attempting to operate fusion reactors in regimes in which there is a significant hot, non-Maxwellian component to the fuel ions [1–3] or in which the fuel ion temperature can be much greater than the electron temperature [4, 5]. Noting a number of experiments [6–8] exhibiting the hot ion mode, Clarke [5] pointed out that the hot ion mode regime could be reached if the ion energy confinement time exceeds the electron energy confinement time, assuming velocity space instabilities that diverted $\alpha$ particle power to the fuel ions. Such instabilities have been considered [9–12] in the context envisioned by Clarke, but the amount of free energy is limited. Recently, it has been recognized that the free energy in the $\alpha$ particles might be more completely tapped by injecting waves that diffuse the $\alpha$ particles both in space and in energy, rather than just in energy [13–15]. In fact, it appears that, at least in principle, eventually all of the $\alpha$ particle power could be diverted to the ions.

In view of the added element that there are now at hand definite ways [13–17] of tapping the $\alpha$ particle power by waves, and that these waves might then damp resonantly on the fast energy tail of the fuel ions, this paper builds upon the work of Clarke. Thus, not only is the hot ion mode realized through the diversion of $\alpha$ particle power, as envisioned by Clarke, but a significant non-Maxwellian fusion component is realized simultaneously, as envisioned by Furth, Dawson and co-workers.

The approach adopted in this paper is to solve self-consistently the heat balance equations in 0-D for electrons and ions, including the heating from both the Maxwellian and the non-Maxwellian contributions to the fusion power. This simple 0-D model demonstrates the possible improvement in power density, although 1-D considerations would be required to quantify the benefits of channelling the $\alpha$ particle power with realistic plasma profiles. In 0-D, heat is lost from electrons or ions either through collisional equilibration with another plasma species or to the outside. Heat lost to the outside, whether by radiation, conduction or convection, is lumped into an electron or ion heat confinement time. Importantly, the electron heat and the ion heat confinement times are distinguished as separate quantities. This is a point worth brief elaboration, in view of the importance of this distinction in achieving the hot ion mode.

In order to attain ion temperatures that are far in excess of electron temperatures, it is not only important

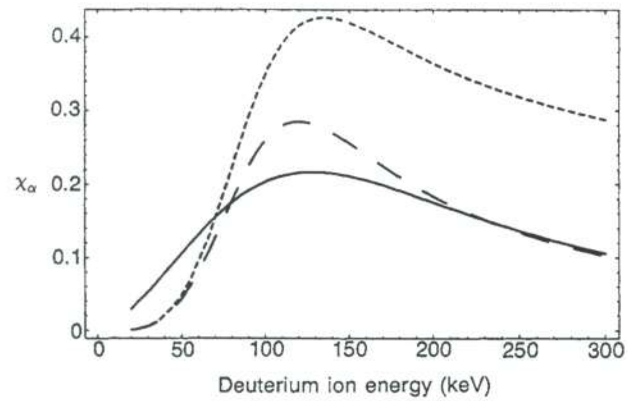


*FIG. 3. $\chi_\alpha$ versus deuterium ion energy (keV) for a 50:50 DT mixture, for $T_e \to \infty$, $T_T = 0$ keV (short dashed line); for $T_e = 10$ keV, $T_T = 0$ keV (long dashed line); and for $T_e = 10$ keV, $T_T = 20$ keV (solid line).*

In Fig. 3 we show how $\chi_\alpha$ depends on both the energy of the fast ions and the background ion and electron temperatures; note, however, that $\chi_\alpha$ is independent of the background density. The values given in this figure are for a 50:50 DT mixture; for a tritium-rich mixture, these values could be about doubled.

The extra pressure taken up by the fast ion distribution is just $u_{fi} = n_f E_d$, or, in terms of the power diverted, $u_{fi} = P_{input}/\nu_e(v)$. Note that the fast ions represent added deuterium to the plasma, so that it is only the ratio now of thermal deuterium to thermal tritium that is 50:50. Together with the added fast deuterium, to maintain charge neutrality, there must also be additional electrons added. These additional electrons, maintained at the electron temperature, cost in plasma pressure. This added electron pressure has been neglected in our calculations, since it is small compared with the extra fast ion pressure which, in turn, is small compared with the overall pressure in the reactor.

It is worth pointing out that in practice it is not a $\delta$ function distribution of particles that is maintained, rather there is a slowing down distribution that is maintained. The calculation of $\chi_\alpha$ can also be posed in an incremental way [15], in which the incremental effect of heating on the slowing down distribution is calculated. However, it turns out that, because this distribution arises from the constant heating of ions at a specified energy that then slow down, both calculations yield the same result.

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