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FUSION TECHNOLOGY INSTITUTE

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Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

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G. A. Emmert, L. A. El-Guebaly, G. L. Kulcinski,
J. F. Santarius, and I. N. Sviatoslavsky
University of Wisconsin-Madison
Madison, WI 53706
(608) 263-1648

D. M. Meade
Princeton Plasma Physics Laboratory
Princeton University
Princeton, NJ 08544
(609) 243-3301

ABSTRACT

Ion channeling is a recent idea for improving the performance of fusion reactors by increasing the fraction of the fusion power deposited in the ions. In this paper we assess the effect of ion channeling on D-T and D-^{3}He reactors. The figures of merit used are the fusion power density and the cost of electricity. It is seen that significant ion channeling can lead to about a 50-65% increase in the fusion power density. For the Apollo D-^{3}He reactor concept the reduction in the cost of electricity can be as large as 30%.

I. INTRODUCTION

The high electron temperature typical of fusion reactors (both D-T and advanced fuels) has a strong degrading effect on reactor power density and performance. High electron temperature increases the electron pressure and thereby reduces the allowable ion pressure for a given beta and magnetic field strength. For advanced fuels, high electron temperature also increases the synchroton and bremsstrahlung radiation losses, which are the dominant loss channels for D-^{3}He plasmas in tokamaks. The high electron temperature results from three effects: 1) electron-ion rethermalization tending to keep $T_e = T_i$, 2) the fusion born fast ions give most of their energy to electrons during the slowing down phase, and 3) the (assumed) equality between electron and ion energy confinement times. Recent results on TFTR[1] indicate that the electron energy confinement time can be much less than the ion energy confinement time. The effect of this is to increase the transport of electron thermal energy across the magnetic field and reduce the electron temperature relative to the ion temperature, for a given total energy confinement time.

Fisch[2] has recently proposed increasing the fraction of energy of the fusion born ions going to the fuel ions by exciting waves in the plasma; these waves are amplified by their interaction with the fast ions and lose energy by damping on the thermal ions. The net effect is to enhance the transfer of fast ion energy to thermal ions at the expense of the transfer of fast ion energy to electrons. This process is known as ion channeling. A beneficial side-effect is that the pressure of the fast ions is reduced because of their increased slowing down rate due to interaction with the waves. A possible refinement is to select waves which damp predominantly on the tail of the fuel ion distribution so that they are heated relative to the bulk. This can increase the fusion reactivity and also increase the performance of the reactor. In addition, the slowing down process can cause the fast fusion products to diffuse out of the plasma during the slowing down phase; this decreases the concentration of "ash" in the plasma.

In this study we consider the significance of these effects for increasing the power density in tokamak fusion reactors. In Section II we present a model for fast ion slowing down due to wave interactions and the resulting effect on the fraction of energy transferred to the ions and the pressure of the fast ions. We also present a model for tail generation of fuel ions and the increase of fusion reactivity. In Section III we apply this model to the ARIES-I D-T reactor to estimate the increase in fusion power density that can result from ion channeling. In Section IV, we consider the effect of ion channeling on the performance of the Apollo D-^{3}He tokamak reactor.

II. MODEL FOR ION CHANNELING

The slowing down of the fusion products due to wave-particle interactions is modeled by a drag term. The extension of the Butler-Buckingham[3] slowing-down formula is

$$\frac{dE}{dt} = -\frac{2E}{\tau_s} - \frac{2E_c}{\tau_s}\sqrt{\frac{E_c}{E}} - 2\nu_w E\ . \qquad (1)$$

The first term on the right is the effect of electron drag, the second is the effect of ion drag, and the third is the term introduced to model the drag due to wave-particle interactions. The electron slowing down time is τ_s and E_c is the critical energy. Since the energy dependence of the drag coefficient ν_w is unknown, we take it to be a constant. We define an effective slowing down time by

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_s} + \nu_w \qquad (2)$$

and an effective critical energy by

$$E_* = E_c\left(\frac{\tau_{eff}}{\tau_s}\right)^{2/3}\ . \qquad (3)$$

With these substitutions, the analysis for the fraction of energy given to the ions and the pressure of the fast ions is formally identical with the usual analysis.[4] Consequently, the usual results can be applied with τ_s replaced by τ_{eff} and E_c replaced by E_*.

The enhanced reactivity due to generation of a hot tail of the fuel ions is modeled by assuming the damping of the waves on the fast fuel ions produces a distribution function of the form

$$f(E) = A\ \exp\left(-E / T_t\right)\ . \qquad (4)$$

We choose the temperature T_t of the tail ions and calculate their density by a balance between the power input due to wave damping and the power loss due to drag of the tail ions on the thermal ions. The fusion reaction rate between the tail ions and the other fuel species is calculated using the mass weighted mean temperature

$$T^* = \frac{m_2 T_t + m_1 T_2}{m_1 + m_2} \qquad (5)$$

where species 1 denotes deuterium and species 2 is the other fuel species. We assume that the tail is generated in the deuterium species.

The plasma physics portion of the Wisconsin systems code determines the plasma density from beta limits for an assumed ion temperature. The ion species included are D, T, and ^{3}He as fuel, ^{1}H and ^{4}He as ash, and a specified impurity species. Particle balance on the ash species determines their accumulation. The power generated by D-D, D-T, and D-^{3}He fusion reactions is included, as well as the pressure of the fast ions produced by these fusion reactions. The electron temperature is calculated from an electron power balance, which includes bremsstrahlung and synchrotron radiation losses as well as transport across the magnetic field. Spatial effects are incorporated by specifying radial density and temperature profiles and performing numerical integration of local power densities, etc.

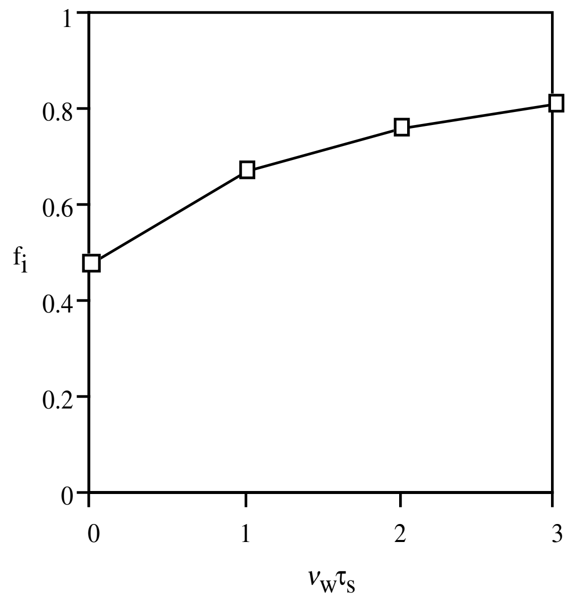

Fig. 1 Fraction of alpha energy given to the ions as a function of the ion channeling parameter, $\nu_w\tau_s$, for ARIES-I.

III. D-T REACTORS

The effect of ion channeling on the performance of D-T reactors has been studied using the ARIES-I parameters[5] as a reference design point (major radius = 6.75 m, plasma current = 10.2 MA, average ion temperature = 20 keV, fusion power = 1925 MW). We use the parameter $\nu_w\tau_s$ as a measure of the degree of ion channeling. Shown in Fig. 1 is the increase in the fraction, f_i, of the 3.5 MeV alpha particle energy given to the ions as ion channeling is increased. We see that without ion channeling the ions receive only 45% of the alpha particle energy, but the fraction can increase to about 80% for $\nu_w\tau_s = 3$.

Fig. 2 shows the effect of both ion channeling and the ratio of the ion to electron energy confinement time on the average electron temperature. In this calculation, the

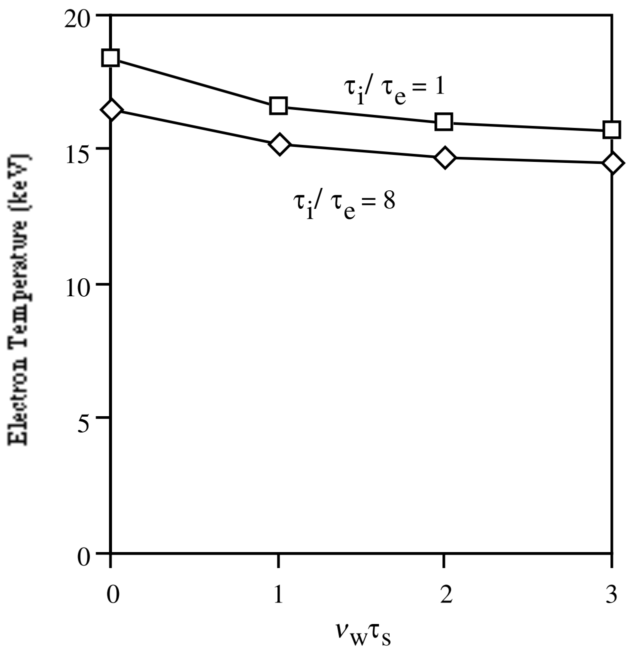

Fig. 2 Average electron temperature as a function of the ion channeling parameter, $\nu_w\tau_s$, for different ratios of τ_i/τ_e, for ARIES-I.

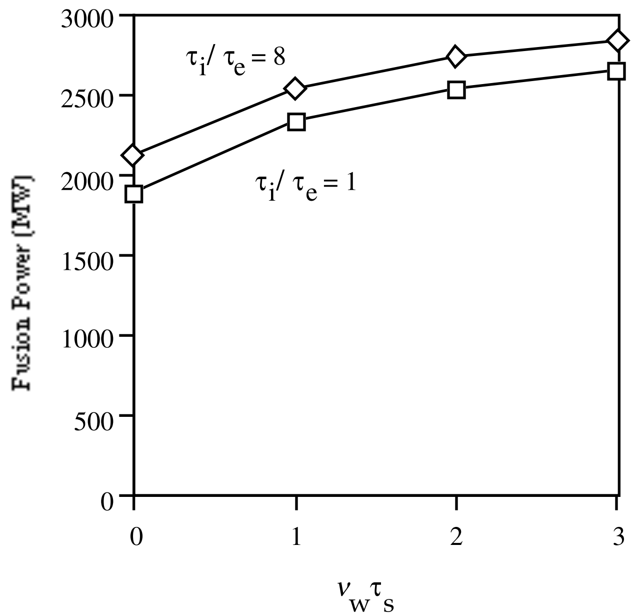

Fig. 3 Fusion power as a function of the ion channeling parameter, $\nu_w\tau_s$, for different ratios of τ_i/τ_e for ARIES-I.

global energy confinement time is kept fixed at the design value. Ratios of τ_i/τ_e up to about 8 have been observed in TFTR.[1]

The reduction in the electron temperature with increasing $\nu_w\tau_s$ and τ_i/τ_e increases the allowable ion beta for a given total beta. Ion channeling also reduces the fast fusion product beta. Since the fusion power scales as β^2, the fusion power is sensitive to modest changes in the ion beta. Shown in Fig. 3 is the variation of the fusion power with $\nu_w\tau_s$ and τ_i/τ_e. We see that the fus
ion power can increase from the nominal value of 1925 MW to about 2800 MW, which is about a 50% increase. Most of this increase is due to ion channeling rather than the increase of τ_i/τ_e. The increase in reactivity due to the generation of a fast deuteron tail is negligible in these calculations; because of the rapid slowing down on the bulk ions, the density of ions in the tail is small. Increasing the fusion power means that the design point is no longer self-consistent; the power deposited in the plasma exceeds the losses and the electrical power output is changing in this calculation. In practice, the benefit of ion channeling would mean a smaller and less expensive machine for a given electrical power output. Redesign of the machine for the higher power density would be required to determine the economic payoff from ion channeling, but the 50% increase in power density implies that the savings can be considerable.

IV. D-^{3}He REACTORS

The effect of ion channeling on the performance of D-^{3}He tokamak reactors has been studied using the Apollo design[6] as a reference point. This design is for a high magnetic field, first stability tokamak using a mixture of thermal conversion and direct conversion of synchrotron radiation to electricity. The major radius is 8.04 m, the magnetic field at the plasma is 11.2 T and the plasma current is 55.6 MA. The bootstrap current accounts for 43% of the current, synchrotron current drive provides 35% and an auxiliary current drive system is needed for the remaining 22%.

Shown in Fig. 4 is the effect of ion channeling on the fraction of the fast proton energy going to the ions. Without ion channeling only 11% of the proton energy goes to the ions; this is because the 14.7 MeV proton slows down primarily on the electrons. With ion channeling, as much as 75% of the proton energy is transferred to the ions. The other fusion product ions (e.g. 3.67 MeV alphas), which carry only 20% of the fusion energy, are assumed to be unaffected by ion channeling. Ion channeling results in less energy going to the electrons and a decreasing electron temperature, as shown in Fig. 5.

Figure 5 also illustrates that increasing the ratio of the ion to electron energy confinement time has little effect on the electron temperature in Apollo. This is because

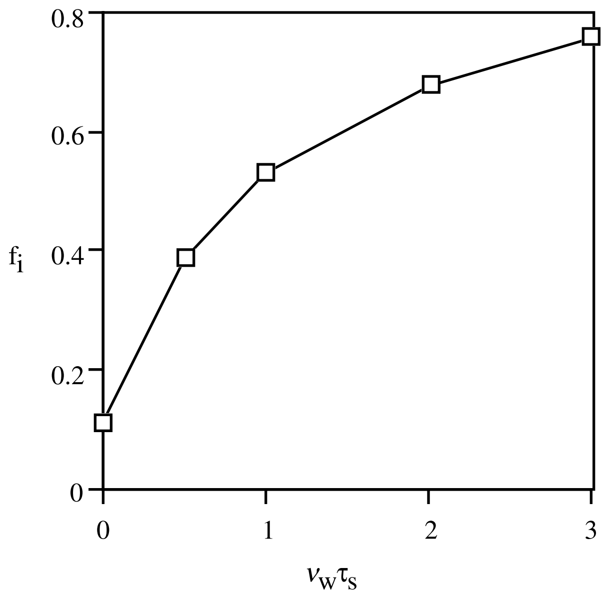

Fig. 4 Fraction of the fast proton energy given to the ions as a function of the ion channeling parameter, $\nu_w\tau_s$, for Apollo.

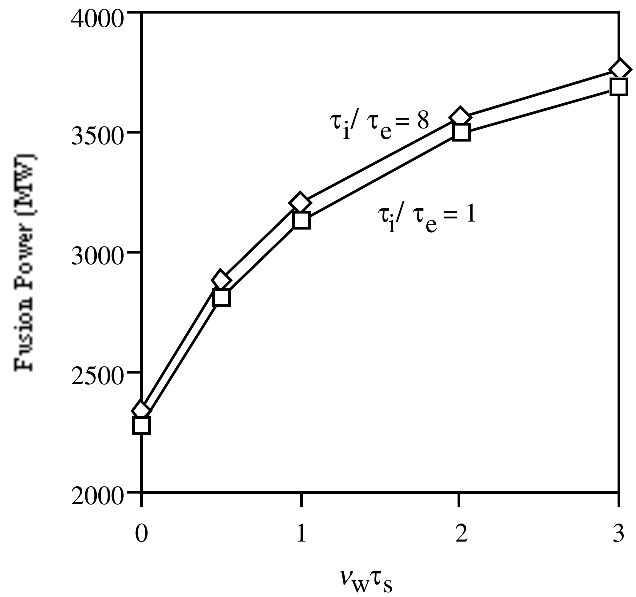

Fig. 6 Fusion power as a function of the ion channeling parameter, $\nu_w\tau_s$, for different ratios of τ_i/τ_e for Apollo.

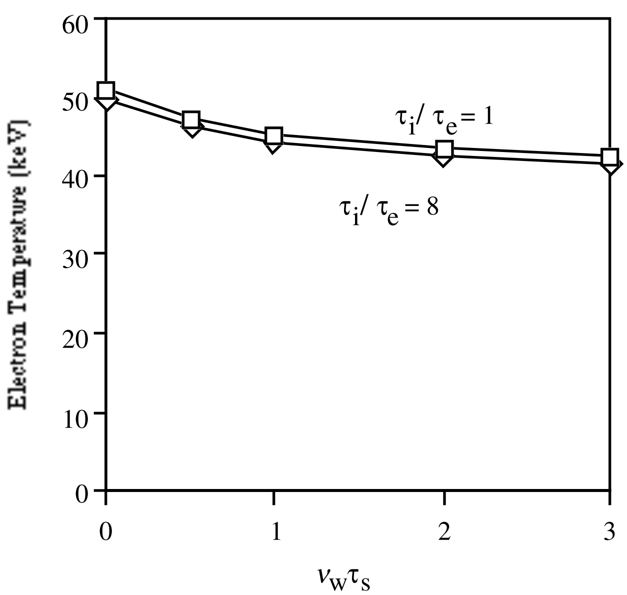

Fig. 5 Average electron temperature as a function of the ion channeling parameter, $\nu_w\tau_s$, for different ratios of τ_i/τ_e, for Apollo.

synchrotron and bremsstrahlung radiation losses are larger than energy transport across the magnetic field and thus reducing the electron energy confinement time has less effect on the electron power balance than it does in a D-T plasma.

The effect of ion channeling on the fusion power is shown in Fig. 6. The fusion power increases from about 2270 MW to over 3750 MW, a 65% increase, as the ion channeling parameter, $\nu_w\tau_s$, increases to about 3. Hence a considerable increase in D-^{3}He fusion power density can result from ion channeling.

It should be noted that, as in Fig. 3, the calculations used to generate Fig. 6 are not self-consistent. As the ion channeling increases, the fusion power deposited in the plasma becomes larger than the power required to sustain the plasma. The benefit of ion channeling leads to a smaller machine for a specified electrical power output. Furthermore, the design point has to be adjusted to maintain a power balance on the plasma. It can be expected, however, that ion channeling will lead to a less expensive fusion reactor.

The generation of a hot deuteron tail by wave-particle interactions increases the fusion power output by about 10% for the D-^{3}He case, whereas in the D-T case the fusion power due to the hot tail was negligible. This is because of two effects. First, in D-^{3}He, 80% of the fusion power is carried by the 14.7 MeV protons. Hence there is more power available to drive a hot deuteron tail. Second, the higher ion temperatures of D-^{3}He reduce the rate of energy loss of the tail by drag on the bulk ions.

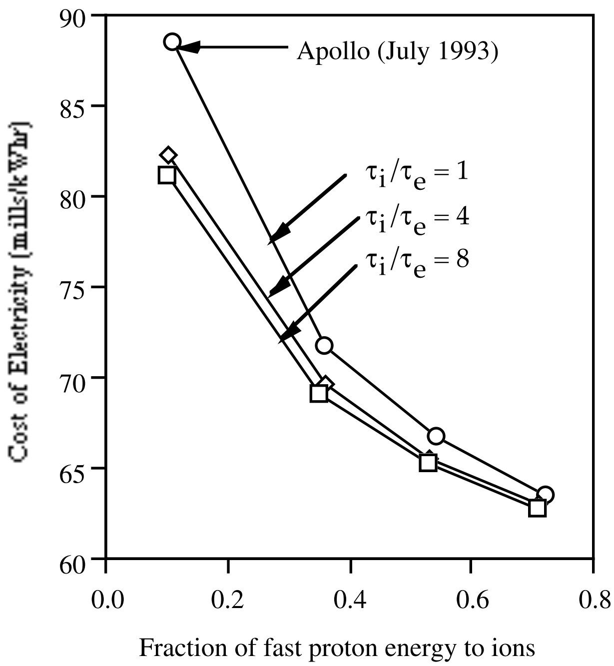

Fig. 7 Cost of electricity versus the fraction of the fast proton energy going to the ions.

Shown in Fig. 7 is the result of self-consistent plasma and systems calculations, combined with an economic analysis. In Fig. 7 the machine size is changing to hold the electrical power output constant at 1000 MW as the ion channeling parameter is increased. In addition, the fraction of synchrotron power fed to the rectennas is increased and the auxiliary current drive power required is decreased to satisfy the constraints of plasma power balance and current drive. The major radius of the plasma decreases from 8.04 m to 6.55 m as the fraction of fast proton energy going to the ions increases from 11% to 75%. The cost of electricity decreases by about 30% with ion channeling. This is partly due to the smaller machine size and partly due to the more favorable power balance and better utilization of the synchrotron radiation for direct energy conversion, which results in lower circulating power and higher system efficiency.

Not included in the calculation for Fig. 7 is the effect of hot deuteron tails increasing the fusion power output; these calculations were done prior to the development of the model for high energy tail formation. Consequently, further improvements in the economics can be expected.

It should be noted that the calculations for Fig. 7 have not considered a complete optimization of the system. In particular, only a single ion temperature and magnetic field strength have been considered. Thus the cost of electricity has not been fully optimized. It is conceivable that lower magnetic field strength may lead to more of a hot ion mode by reducing the density and thereby the rate of rethermalization between the ions and the electrons.

CONCLUSIONS

We have found in this preliminary study that ion channeling to increase the fraction of fusion power going to the ions can increase the fusion power density by as much as 50% in D-T and 65% in D-^{3}He. For the Apollo D-^{3}He reactor, ion channeling leads to as much as a 30% reduction in the cost of electricity. Several effects lead to these improvements: reduced electron temperature and radiation losses, reduced pressure of the electrons and the fast fusion products, increased pressure of the fuel for a given total pressure. Not included in this analysis is the power required to generate the ion channeling process since estimates for this are not yet available. The results of this preliminary study suggest that the ion channeling concept can have a significant impact on the performance of fusion reactors and thus warrants further study.

ACKNOWLEDGMENTS

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