HOT-ION-MODE IGNITION IN A TOKAMAK REACTOR

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ABSTRACT. Presently observed scaling laws in tokamak experiments allow ignition of tokamak reactors with $n\tau_e$ possibly as low as $4.5 \times 10^{13}\,\mathrm{cm^{-3}\cdot s}$. These reactors operate in the hot-ion ignition mode with $T_i > T_e$ and are a direct extension of the hot-ion-mode operation observed in present tokamaks and expected in TFTR. They require MHD stability similar to conventional tokamak reactors and microstability at collisionality ten times lower than that observed on PLT. All physics issues associated with hot-ion ignited reactors, short of complete ignition, can be addressed in existing facilities and TFTR.

INTRODUCTION

It is the purpose of this paper to describe a new mode of ignited tokamak reactor operation which has properties significantly different from those previously described. This mode of operation is a direct consequence of the neoclassical ion energy confinement law presently observed in tokamaks. Its unique properties include ignition at $n\tau$, possibly as low as $4.5 \times 10^{13}\,\mathrm{cm^{-3}\,s}$, natural thermal stability at $T_i/T_e \sim 2$, $T_i \sim 40$ keV and an ion collisionality an order of magnitude less than the more traditional ignited reactors. Moreover, because of the low $n\tau$ required, a non-circular plasma with about the same physical size and magnetic field as the TFTR plasma could be ignited with as little as 25 MW of auxiliary neutral-beam heating and burn with a beta of about 7 to 9%. This low ignition power results from the small plasma size as well as the significant effect of alpha heating during the driven hot-ion-mode operation before ignition. Since this new version of an ignited tokamak reactor is the natural extension to alpha-particle heating of the hot-ion-mode-driven reactor, it is in many ways more closely coupled to present-day experimental knowledge than the ignited reactors now being designed.

It is widely recognized that there exist three modes of operation of a tokamak confinement system which can lead to the production of useful quantities of fusion power. The first of these, the two-component tokamak (TCT) mode, is a power amplifier reactor in which energetic non-Maxwellian ions injected into a colder bulk plasma undergo fusion reactions during the process of their thermalization [1, 2]. The second mode of operation, the hot-ion mode, has usually been considered a power amplifier reactor in which external heating is used to maintain an ion distribution at a temperature higher than that of a Maxwellian electron distribution [3]. The third possibility is the ignited plasma mode in which internally generated alpha particles maintain the electron and ion distribution at fusion temperatures with no external energy input.

The TCT mode evolves naturally into a hot-ion reactor as the energy confinement time and the temperature of the electrons is raised if the energy confinement time of the bulk ions is much better than that of the electrons [4]. If the heating power is delivered directly to the plasma ions, their temperature will exceed that of the electrons and their major energy loss will be energy transfer to the electrons. Although requiring better energy confinement than the two-component reactors, this hot-ion mode has the potential for substantially higher energy gain. Since energy is lost from the system predominantly from the electrons, the energy gain Q will be enhanced by a factor of up to $2\,T_i/T_e$ relative to the traditional thermonuclear mode in which the electron and ion energy loss is considered equal. Energy gains of $Q = 2-5$ can be realized in this mode. Cordey has pointed out that when heating of the ions by reaction products is considered, the energy gain increases still further and it is possible to obtain ignition in the hot-ion mode [5].

The TCT mode was first demonstrated at the Culham, Princeton and Oak Ridge Laboratories [6–8]. The hot-ion mode, in which $T_i > T_e$, was demonstrated for the first time in the ORMAK experiment at Oak Ridge [9] and the TFR experiment at Fontenayaux-Roses [10], and more recently and dramatically in the PLT experiment at Princeton [11]. In these experiments the injected neutral beams were thermalized in accordance with classical predictions and produced thermonuclear reactions in the TCT mode. Moreover, the ion energy transport was found to be sufficiently close to neoclassical and the beam energy coupled directly to the ions was sufficiently large that T_i exceeded T_e by up to a factor of 2, yielding a greatly enhanced thermonuclear reaction rate. The PLT results are particularly significant since they took place at reactor level collisionality and thus constitute substantive evidence in favour of the existence of both the TCT and the hot-ion mode of tokamak reactor operation.

The traditional Lawson analysis [12] indicates that an ignited plasma would have to possess a density and energy confinement time product of $n\tau$ of order $2 \times 10^{14}\,\mathrm{cm^{-3}\cdot s}$. or greater for both the bulk ions and electrons. This traditional $n\tau$ criterion for ignition assumes that electron and ion losses are equal, as they would be if particle losses of ions and electrons at the same temperature were the dominant loss mechanism. For example, the traditional Lawson criteria should apply to ignited, inertially confined plasmas where electrons and ions have the same life-times. However, it is not valid for the presently observed empirical electron [13] and neoclassical ion energy confinement [14] scaling laws in a tokamak which allow $T_i > T_e$. In this paper, we point out that, compared to machines previously considered [15, 16], tokamak scaling laws permit operating at lower $n\tau_e < n\tau_i$ and reduced machine size. In addition, by operating at higher temperatures $T_i > T_e$, the tendency towards thermal instability upon ignition is reduced or eliminated.

1. REACTOR ENERGY BALANCE

The energy balance equations for ions and electrons in a steady-state reactor equilibrium are written:

$$\frac{3}{2}\frac{n\,T_i}{\tau_i} = \frac{n^2\langle\sigma v\rangle}{4} E_\alpha \left(1 - f_e + 5/Q\right) - K_{ei}\frac{n^2(T_i - T_e)}{T_e^{3/2}} \tag{1}$$

$$\frac{3}{2}\frac{n\,T_e}{\tau_e} = \frac{n^2\langle\sigma v\rangle}{4} E_\alpha f_e + K_{ei}\frac{n^2(T_i - T_e)}{T_e^{3/2}} - K_R\, n^2\, T_e^{1/2} \tag{2}$$

where, for simplicity, radial profiles are ignored, peak values are used for all quantities, thermal conduction losses, alpha heating, Coulomb coupling of the ions and electrons and bremsstrahlung radiation are included and a number of obvious simplifications have been made. One of these is neglect of synchrotron radiation on the grounds that reflecting walls make this loss process negligible. The factor f_e gives the fraction of alpha-particle heating to the electrons and note is taken of the fact that, at the higher temperatures of interest, $T_e \gtrsim 20$ keV's, a non-negligible fraction of the alpha power $(1-f_e)$ is coupled directly to the ion species. The function f_e depends on T_e as well as the energy and mass of the alpha particles. A useful approximation in the range of interest which allows an analytic solution of Eq.(1) is

$$f_e = (1 - T_e/150)^2 \tag{3}$$

where T_e is in keV.[1]

We also assume that all external heating power is delivered to the plasma ions as is roughly the case with moderate-energy neutral-beam injection or ion cyclotron heating. Since we shall be dealing with systems in which the product of density and plasma radius can be of moderate size, penetration of such beams seems possible [17]. The external heating power is expressed in terms of the reactor energy gain Q defined as the ratio of fusion power produced to heating power. When Q goes to infinity, the reactor is ignited.

An ignited tokamak must contain alpha particles. Detailed orbit calculations by many groups have shown that this confinement depends basically upon the poloidal flux in the machine. A convenient containment criterion which summarizes these computations for a variety of reasonably peaked current distributions is that a tokamak reactor, of aspect ratio A with an elliptical plasma specified by the ratio of the major and minor elliptical radii K, must have a plasma current I_p such that

$$I_p\, A/C > 7.5 \times 10^6 \text{ amperes} \tag{4}$$

where the circumference ratio C has been added to reflect the decrease of confining flux per unit current

[1] Units in practical equations are temperatures in keV and all other quantities in MKSA units.

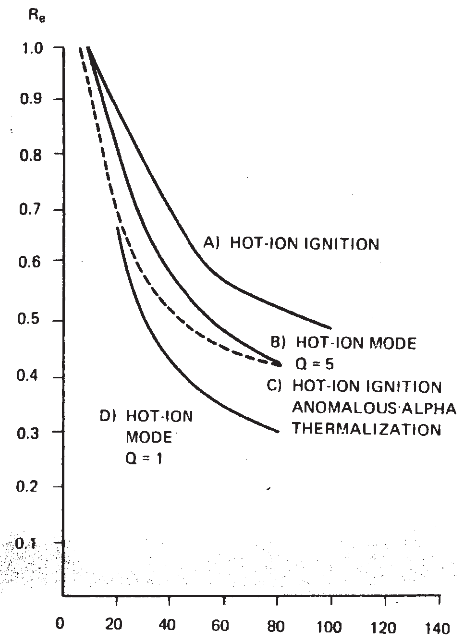

FIG.1. Ratio of electron to ion temperature R_e for ignited operation with classical and anomalous alpha-particle thermalization as well as driven operation for various ion temperatures in a tokamak.

as the plasma is elongated. If a reactor in which alpha particles are contained enjoys neoclassical ion heat conductivity in the collisionless regime given by

$$n\tau_i = 4.6 \times 10^7\, I_p^2\, A^{\frac{1}{2}}\, T_i^{\frac{1}{2}}/Z \ m^{-3} \ \text{seconds} \quad (5)$$

and empirical electron heat conductivity

$$n\tau_e = 7.6 \times 10^{-21}\, n^2 a^2 m^{-3} \ \text{seconds} \quad (6)$$

as inferred from present experiments, the ratio of ion to electron conductive power loss is simply

$$T_i\tau_e/T_e\tau_i < 2.94 \times 10^{-28}\, Z\, (naC)^2\, (T_i^{1/2}/T_e) A^{3/2} \quad (7)$$

For all ignition reactor designs except those at extremely high densities, this ratio is much less than one. Therefore, electron heat conductivity will dominate the energy loss. Indeed, examination of Eq. (1) with neoclassical ion heat conduction (Eq. (5)) shows that these neoclassical losses provide a small correction to the electron and ion temperature relationship established by balancing alpha power to the ions with Coulomb collisional energy transfer to the electrons.

Under these conditions, Eq. (1) shows that T_i must always exceed T_e. This conclusion is independent of density and, because of the weak effect of ion neoclassical losses, very nearly independent of machine size and current as long as Eq. (7) is satisfied. Solving Eq. (1) for the ratio $R \equiv (T_e/T_i)$ as a function of T_i and Q yields the nearly universal curves shown in Fig.1. Curve C, labelled anomalous alpha thermalization, in Fig.1 gives the function R if f_e were to go to zero. This will be discussed below. It is included here as a limiting case since it illustrates the most extreme separation of electron and ion temperature possible.

Having determined the electron ion temperature relationship, Eq. (1) can be added to Eq. (2) to solve for the ignition condition on $n\tau_e$. We obtain

$$n\tau_e = \frac{(6\ T_e)\,[1 + 1/R\ n\tau_e/n\tau_i]}{\langle\sigma v\rangle\ E_\alpha\ (1 + 5/Q) - 4\ K_R T_e^{\frac{1}{2}}} \quad (8)$$

where the ratio of ion and electron losses on the RHS of Eq. (8) is determined by the particular confinement system. For a tokamak with no anomalous ion losses, this is given by Eq. (7) and can be neglected. Ion losses such as direct ripple diffusion would serve to increase this ratio and consequently the required $n\tau_e$.

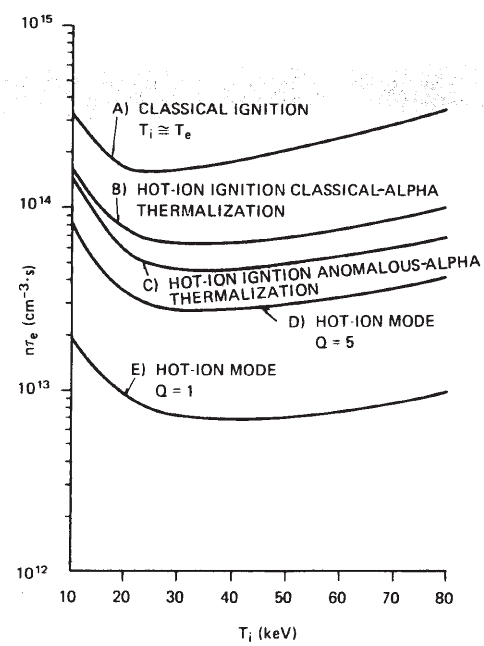

FIG.2. Required electron density and energy confinement time product for tokamak hot-ion-mode operation in a driven or ignited tokamak,along with classical ignition curve.

The ignition condition given by Eq. (8) with $Q = \infty$ differs from the traditional ignition condition because, under the scaling laws given in Eqs (5) and (6), the electron and ion losses are effectively in series whereas they are assumed to be of equal magnitude and, therefore, in parallel in the more conventional definition of ignition. Furthermore, we account for the fact that $T_i \neq T_e$ in a reactor dominated by neoclassical and empirical losses.

For comparison purposes, Fig. 2 shows the traditional ignition curve frequently used to measure progress in fusion research for $\tau_e = \tau_i$ and $T_i \cong T_e$ (curve A) and the ignition requirement for a hot-ion-mode reactor given by Eq. (8) with losses as given in Eq. (7) (curve B). The minimum $n\tau_e$ ignition point has been shifted to higher ion temperatures and significantly lowered relative to the traditional ignition curve.

We have emphasized the electron energy confinement time in Fig. 2 since in a tokamak the requirement to achieve this energy confinement time determines the minimum machine size. However, for completeness, we note that the total energy confinement time can be written

$$n\tau_E = (n\tau_e/(1 + n\tau_e/n\tau_i)) \tag{9}$$

From Eqs (7) and (8) we see that in a tokamak the average energy confinement time required for ignition is reduced by the temperature ratio R from the Lawson case of $T_i = T_e$, $\tau_i = \tau_e$. It should be emphasized, however, that the quantity of interest is the $n\tau_e$ which determines the minimum machine size.

Figure 2 also shows the hot-ion reactor $n\tau_e$ required if operated as an energy amplifier. Curves D and E show that the hot-ion mode can produce substantial energy gain at low $n\tau_e$ when operated below ignition.

If the fusion alpha-particle distribution function is subject to velocity space instabilities with frequencies between ω_{ci} and ω_{LH}, as has been suggested [18], there could be an enhanced direct coupling of alpha energy to the plasma ions via cyclotron damping. This follows since they have a velocity exceeding the Alfvén speed while particles in present devices do not. Therefore, it is possible that the minimum ignition point could be lowered still further. The limiting-case curve C, labelled alpha instability in Figs 1 and 2, shows T_i as a function of T_e and the ignition requirement on $n\tau_e$ calculated with the assumption that $f_e = 0$ due to direct instability coupling of all of the alpha power into the ions. The main effect is that the electron and ion temperature difference is increased and the minimum $n\tau_e$ for ignition now occurs at 4.5×10^{13} cm^{-3}·s.

It is well known [19] that the thermal stability of a reactor improves as its operating point approaches the minimum of the $n\tau_e$ ignition curve. In addition to the reduced absolute value of $n\tau_e$ associated with this minimum point in the hot-ion ignition mode, this improved thermal stability provides added incentive for exploring the feasibility of operation at temperatures in the 30–40 keV range.

2. CHARACTERISTICS OF A HOT-ION IGNITION REACTOR

The first point to consider with respect to such a reactor is whether one can achieve sufficient MHD stability. Because of the relationship between $n\tau_e$ and na given by Eq. (6), we can plot na on the abscissa of Fig. 3 and graphically display the beta of various reactors as a function of the ion temperature. The density can be expressed in terms of the magnetic field B and the plasma beta $\beta = 2\mu_0 (T_e + T_i) n/B^2$ as

$$n = 3.13 \times 10^{15} (\beta B^2/\mu_o I_i)(1/(1 + R_e)) \tag{10}$$

Then, using the definition $q = (a B_T/RB_p)$ for a tokamak, we can solve for the non-circular plasma radius

$$a = (\mu_o/2\pi)(q/B_t C)(IA/C) \tag{11}$$

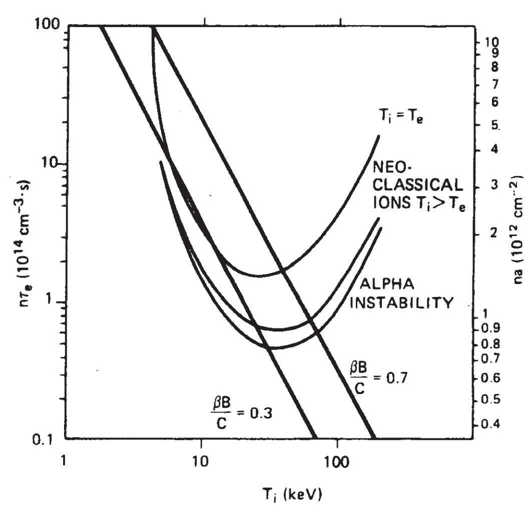

FIG.3. Relationship of required plasma beta, toroidal magnetic field and elongation to achieve hot-ion-mode or classical ignition shown by curves of constant $\beta B/C$.

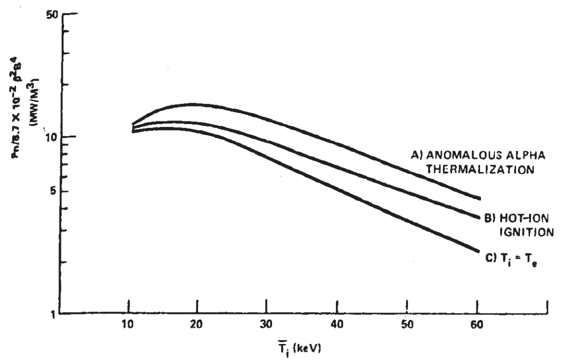

FIG.4. Fusion power density measured by neutron power per unit volume for hot-ion-mode ignition with either classical or anomalous thermalization, along with curve for classical ignition.

which gives the relationship

$$na = 4.97 \times 10^{14}\, 8(IA/C)(\beta B/C)(1/T_i(1 + R_e)) \quad (12)$$

Therefore, using the alpha-particle containment condition in Eq. (4) to eliminate the current, the product (na), or equivalently $n\tau_e$, can be written in terms of q, β, B, C and T_i. Assuming q = 2.5 and an aspect ratio A = 3, Fig. 3 shows two curves of constant $\beta B/C$ superimposed on the ignition curves. For example, in a toroidal field of 6 T and with a plasma elongation of 1.5, the curves shown are for plasma beta of 6.3 and 15 per cent, respectively. Thus, in this case, an ignited hot-ion-mode reactor should be able to operate with a reasonable beta at reasonable magnetic field between these curves.

As noted above, fusion alpha particles could be subject to a variety of instabilities not now seen in beam-injected ions in tokamaks. However, if the alpha particles thermalize classically, they could contribute a pressure of up to half of the thermal plasma pressure at the high temperatures of the hot-ion mode. Even so, it is an open question whether this pressure should be simply added to the bulk plasma pressure to determine the maximum stable beta which can be sustained in a hot-ion reactor. Both the alpha particles and the hot ions are quite collisionless and have much larger orbits than the ions in the traditional reactor. Therefore, they have significantly different dynamics. In general, the preliminary analysis which has been done shows that the fluid treatment, which is appropriate for the thermal plasma, gives a lower beta limit than the kinetic analysis more appropriate for the energetic particles in a hot-ion reactor [20]. Furthermore, finite-orbit effects might provide further stabilization in the hot-ion mode. More work needs to be done on this problem. We shall not include alpha pressure in the plasma beta shown in the figures because of these uncertainties. We simply note that if the alpha particles thermalize classically and one treats the hot alpha particles in the same manner as cold ions, the beta limit would have to increase by up to a factor of two to accommodate the alpha pressure. The alpha pressure can be easily estimated at a given temperature by use of the relationship between alpha and electron pressure $\beta_\alpha/\beta_e = n\tau_s/n\tau_e$ where τ_s is the alpha slowing-down time which increases as $T_e^{3/2}$.

Assuming that a beta of 5 to 10 percent with magnetic fields in the range of 4 to 6 T are possible, one can then ask if this reactor possesses an interesting fusion power density at the high operating temperatures of the hot-ion mode. Figure 4 shows the neutron power density at a given beta and magnetic field in a hot-ion reactor as compared to a traditional reactor with $T_i = T_e$. In a hot-ion reactor $T_i > T_e$, the power density curve broadens and the peak shifts to a higher temperature than in the traditional ignition reactor. This is shown in Fig.4 for the hot-ion reactor with $T_i > T_e$, with either neoclassical or anomalous alpha coupling to the ions. In the anomalous-alpha-coupling

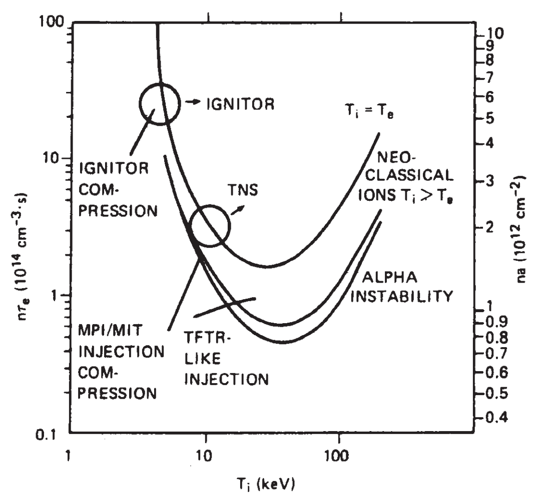

FIG.5. Heating requirements for hot-ion-mode ignition shown by injection of 25 MW into a TFTR-size plasma in comparison with those for several proposed ignition devices.

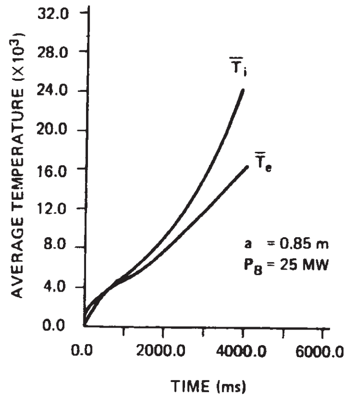

FIG.6. Average temperature evolution corresponding to TFTR curve in Fig.5 produced by injection into a TFTR-size plasma with ion neoclassical and Alcator electron scaling.

TABLE I. TEMPERATURE, ENERGY CONFINEMENT AND NORMALIZED COLLISIONALITY IN PLT, PROPOSED TOKAMAK REACTORS AND A HOT-ION-MODE REACTOR

	PLT	Ignitor	TNS	Hot-ion mode
T_i (keV)	4.5	5	10	35
$n\tau_e$ (10^{13} cm^{-3}·s)	0.1	250	30	6.5
ν^*/ν^*_{PLT}	1	40.5	3.51	0.13

TABLE II. TYPICAL THERMALLY STABLE HOT-ION REACTOR CHARACTERISTICS

	Classical alpha thermalization			Alpha instability thermalization
B(T)	6.0	5.0	4.0	5.0
K	1.5	1.5	1.5	1.5
β (%)	7	7	7	7
A	3	3	3	3
a (m)	0.73	1.2	1.64	0.68
p_W^N (MW·m^{-2})	1.78	1.20	0.79	1.12
P_T (MW)	225	410	502	123

case, the hot-ion reactor can have a power density as high as a reactor operating between 10 and 20 keV. Even for classical alpha slowing-down the ignited hot-ion reactor has a power density close to that of a thermally unstable reactor operating near the peak of its power density curve. As discussed below, if alpha-particle pressure contributes to the limiting plasma beta, the power density in the classical thermalization case could be reduced by a factor of up to two.

The next issue is whether one can heat a tokamak plasma to the hot-ion regime with a reasonable amount of auxiliary heating. Figure 5 shows the projected operating points of several proposed ignition experiments. The Ignitor [16] uses intense Ohmic heating and adiabatic compression to attempt ignition at high $n\tau_e$ and low T_i near the ideal ignition temperature. The TNS reactors use neutral injection heating to ignite at lower $n\tau_e$ and higher T_i [21]. Both reactors are thermally unstable at ignition, although the TNS reactors operating lower on the $n\tau_e$ curve are less so. These reactors typically use 35 to 60 MW of neutral-beam heating to ignite. A recent compact ignition experiment study [22] utilizing injection and compression to reach the TNS operating point, utilized 20 to 30 MW of compressional heating in addition to 16 MW of neutral-beam heating. The bar in the compression cases shown in Fig. 5 represents the $n\tau_e$, T_i trajectory during compression from the initial Ohmic- or neutral-beam-heated state and the ignition point.

For comparison, a typical $n\tau_e$, T_i trajectory for the heating of a TFTR-size plasma at B = 5 T with 25 MW of 140-keV neutral beams injected into a 1.2×10^{14} cm^{-3} plasma having the scaling of Eq. (6), is shown. After four seconds of heating, this plasma has clearly passed the ignition point. The corresponding behaviour of the ion and electron temperatures is shown in Fig. 6. This represents a typical ignition scenario for a hot-ion reactor or a sequence of operating points for a driven reactor.

Neutral-beam heating is particularly valuable in attaining hot-ion ignition since the ratio T_i/T_e is raised during the heating, thereby enhancing the pre-ignition production of alpha power. The neutral-beam injection naturally heats the ions in the hot-ion-driven reactor mode until enough alpha heating takes place to raise the ions and electrons into the hot-ion ignition mode. Because of this natural evolution, although limited to operating in the hot-ion-driven mode represented by the first 1.5 seconds of Fig. 6 by technological limits on sustainable beta and beam pulse length, TFTR should give valuable information on the ignition process for hot-ion reactors.

A final question is the collisionality which must be reached in a hot-ion reactor to take advantage of the above features. The collisionality parameter is

$$\nu^* \alpha \; A^{3/2} \; (na/T_i^{\,2}) \tag{13}$$

Therefore, for the same q and aspect ratio, and assuming that na is related to $n\tau_e$ by Eq. 6, we can relate the collisionality of the reactor types in Fig. 3 by the ratio $(n\tau_e)^{1/2}/T_i^2$. The result is shown in Table I, normalized to the results of PLT.

Thus, the collisionality of the thermally stable hot-ion reactor is up to ten times lower than that achieved in PLT and 26 times lower than that expected in the more traditional reactors represented by the TNS group. This lower collisionality may have a positive effect on the limiting plasma beta [20], however, it certainly leaves room for trapped-particle transport, which has no observable effect in PLT, to affect the ion transport in the hot-ion reactor. One other consequence of low collisionality, aside from the potential for enhanced transport which must be accounted for in the design of these reactors, is the sensitivity to magnetic-field-ripple losses.

Unlike the control of alpha-driven thermal excursion in the TNS or Ignitor reactors, the effect of lower collisionality on energy transport is subject to investigation on existing experiments. Should these studies reveal little or no increase in the ion transport rate at lower collisionality, the hot-ion reactor would seem to be acceptable on the grounds of transport as well as on thermal stability, beta, heating and power density grounds.

The characteristic parameters of several reactors operating near the thermally stable point are listed in Table II. The total output power P_t and neutron wall loading P_w^n should be higher in a real reactor than the values shown in the table since the zero-dimensional energy balance used in this paper tends to underestimate the actual power by 30 to 40 percent, because of neglect of the peaking of both density and temperature. This effect may also lower the $n\tau_e$ required for ignition. It is, however, clear that hot-ion reactors fit within reasonable bounds of both wall loading and total fusion power.

Table II shows that reactors ignited in this mode of operation can be smaller than standard reactors. It is also clear that reactors operating in this hot-ion ignition mode at higher $n\tau_e$, while not thermally stable, should be easier to control than those operating at the lower temperature of more conventional reactors. Finally, as has been shown by Cordey [5], the hot-ion ignition mode will also allow ignition of fuels other than deuterium/tritium at reduced $n\tau_e$.

CONCLUSIONS

It appears possible to operate a hot-ion tokamak reactor in the ignition mode at $n\tau$ values significantly lower than previously realized under reasonable engineering and physics constraints. This mode of operation could be thermally stable if operated near the minimum of the $n\tau$ curve. Given the existing data base, the largest uncertainty on the minus side seems to be with respect to the possibility of anomalous ion losses at collisionality ten times lower than achieved today. The largest uncertainty on the plus side appears to be the possible enhancement of MHD stability at low collisionality. The experimental basis for such a reactor can be established in near-term experiments, including TFTR, which provides a direct analogue of the hot-ion reactor ignition process.

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