THE ICRH TOKAMAK FUSION TEST REACTOR

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ABSTRACT

A Tokamak Fusion Test Reactor where the ions are maintained at $T_i \approx 20$ keV $> T_e \approx 7$ keV by ion-cyclotron resonance heating is shown to produce an energy amplification of $Q > 2$ provided the principal ion energy loss channel is via collisional transfer to the electrons. Such a reactor produces 19 MW of fusion power and requires a 50 MHz radio-frequency generator capable of 50 MW peak power; it is otherwise compatible with the conceptual design for the Princeton TFTR. The required $n\tau_E$ values for electrons and ions are respectively $n\tau_{Ee} > 1.5\cdot10^{13}$ cm^{-3}-sec and $n\tau_{Ei} > 4\cdot10^{13}$ cm^{-3}-sec . The principal areas where research is needed to establish this concept are: tokamak transport calculations, ICRH physics, trapped-particle instability energy losses, tokamak equilibria with high values of β_θ , and, of course, impurities.

INTRODUCTION

John Dawson[1] has recently argued that substantial energy amplification can occur in plasmas where the ion temperature is maintained approximately a factor-of-two above the electron temperature. The purpose of this work is to show that this concept makes an attractive alternative to the injection-driven TFTR[2-4] and to point out the areas where research is needed to establish whether the ICRH Tokamak Fusion Test Reactor has important basic difficulties.

The overview picture of how the ICRH/TFTR would operate proceeds as follows: A tokamak discharge with a minor radius $a = 50$ cm, major radius $R = 250$ cm, and current $I = 1.3$ MA is initiated in a 50% - 50% DT plasma. A cold deuterium blanket is added to increase the radius to $a = 70$ cm, while the current is increased to $I = 1.7$ MA (See Fig. 1). The central electron density is approximately $7 \cdot 10^{13}$ cm^{-3}. The initial properties of this discharge are comparable to the "Weak Compression with Blanket" discharge studied for the injection-driven TFTR.[5] At this point, a preheat phase commences operating at the second harmonic of the tritium gyrofrequency, $\nu \approx 50$ MHz, and with a power of 50 MW. The ICRH scheme has the advantage that all the rf power is delivered to the tritons in the central regions of the plasma. In roughly 100 ms, the ions within the volume containing tritons reach a temperature of 20 keV, while the electrons remain at 7 keV due to their greater energy losses. At an ion temperature of 20 keV, the thermonuclear energy production has reached a level of 19 MW, while the steady-state ion temperature can be maintained by only 8 MW of ICRH power; the overall steady-state energy gain is $Q = 2.4$. The net radio frequency

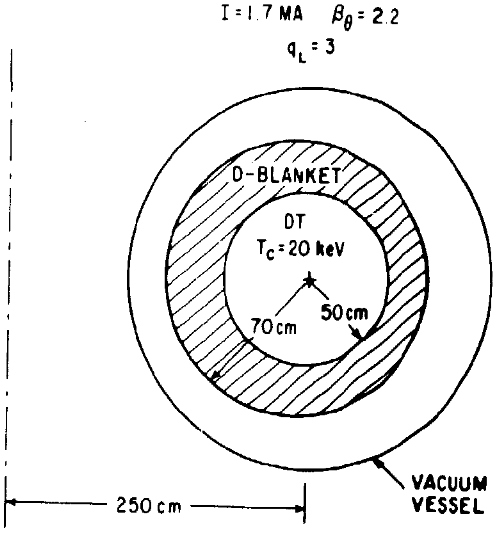

Fig. 1. Sketch of the plasma properties envisioned for an ICRH-driven TFTR confined by the planned[5] TFTR confinement fields. The central, hot-ion region has $T_i = 20$ keV, $T_e = 7$ keV, and $n \simeq 7 \cdot 10^{13}$ cm^{-3}.

energy delivered in one second is 14 MJ , which, combined with a 50% generating efficiency (the planned efficiency of the PLT ICRH proposal), requires an overall energy supply of 28 MJ . Indeed, the ICRH system could run at 20 MW in the steady-state portion of a one-second pulse without exceeding the 55 MJ capacity planned for neutral beam injection power supply.

The ICRH Tokamak Test Reactor differs from the Injection-Driven Reactor in a number of important ways: First, its energy content is higher--roughly by a factor of four. The value $\beta_\theta \simeq 2.2 \simeq 0.6\ (R/a)$ corresponds more closely to the high-β_θ plasma that is desirable in an eventual Tokamak Power Reactor. Second, the thermonuclear power produced--about 15 MJ--is also higher and could be maintained for periods substantially in excess of the planned one-second toroidal field pulse provided that the toroidal field could be so maintained (by far the largest energy expenditure). Lastly, its demands on an ion energy confinement, the value of $n\tau_{Ei}$--the ion energy loss excluding collisional transfer to the electrons--are great; $n\tau_{Ei}$ must exceed $4 \cdot 10^{13}$ cm^{-3} sec. This is mildly incompatible with the rough theoretical estimates[6] for the trapped ion mode which gives $n\tau_{Ei} \simeq 1.5 \cdot 10^{13}$ cm^{-3}/sec. But these estimates are based only on the crudest theory, and an inverse density gradient due to the cold plasma blanket might well stabilize trapped-particle instabilities. In any event, the ICRH Tokamak Test Reactor will provide a good environment in which to test the physics of both trapped-ion instabilities and plasma equilibria in which β_θ is an appreciable fraction of the aspect ratio. An ICRH-driven TFTR could either follow an injection-driven TFTR (there being basic compatibility in the power demands and confinement fields) or replace it if neutral beam injection development does not meet its goals. But it is also clear that a vigorous ICRH experimental program on PLT must be pursued so that many of the concepts used in estimating the effects of ICRH become experimentally established realities.

CALCULATIONS OF $n\tau$, β_θ , ETC.

The equations governing the ion and electron heat losses in the central DT plasma region are

$$\frac{3}{2}\, n \frac{dT_i}{dT} = nS - \frac{n}{\tau_s}\frac{3}{2}(T_i - T_e) - \frac{3}{2}\frac{n^2 T_i}{(n\tau_{Ei})} \qquad (1)$$

$$\frac{3}{2} n \frac{dT_e}{dT} = \frac{n}{\tau_s} \frac{3}{2} (T_i - T_e) - \frac{3}{2} \frac{n^2 T_e}{(n\tau_{Ee})} \qquad (2)$$

where S is the rate of energy input per particle from ICRH, τ_s the energy interchange time,

$$\frac{1}{\tau_s} = \left(\frac{8\sqrt{2\pi}}{3}\right) \frac{n_e e^4 \ell n m^{1/2}}{M_H T_e^{3/2}} \left(\frac{q_D}{A_D} + \frac{q_T}{A_T}\right)$$

$$\tau_s = (6 \text{ ms}) \frac{T_{keV}^{3/2}}{n_{14}} \frac{1}{\left(\frac{q_D}{A_D} + \frac{q_T}{A_T}\right)} , \qquad (3)$$

where T_{keV} is the electron temperature in keV and n_{14} the electron density in units of 10^{14} cm^{-3} . Ion energy loss through channels other than transfer to electrons is represented by $n\tau_{Ei}$.

Let us, for the moment, suppose that the ICRH power is sufficient to maintain the ion temperature at a steady-state value of $T_i = 20$ keV , and that ion energy losses, other than collisional energy interchange with electrons, are negligible. The energy amplification Q is then given by

$$Q_o = \frac{(n\tau_E)_e W_o (\overline{\sigma v})_{DT}}{6 T_e} \qquad (4)$$

where $(\overline{\sigma v})_{DT} = 4.2 \times 10^{-16}$ at $T_i = 20$ keV and $W_o = 17.6$ MeV . Table I gives the electron temperature, $n\tau_{Ee}$, Q_o , and two ion quantities: $(n\tau_{Ei})_o$, the $n\tau$ for ion energy interchange with electrons, and P_o , the rate at which ICRH power must be supplied to maintain the ion temperature in a plasma volume of $1.3 \cdot 10^7$ cm^3 containing an ion density of $7 \cdot 10^{13}$ cm^{-3} . The appropriate plasma volume is that containing tritium and has a minor radius a = 50 cm and major radius R = 250 cm. ICRH heating does not interact with the cold deuterium blanket.

Table I

Parameters for a Steady-State ICRH Driven TFTR with $T_i = 20$ keV

T_e-keV	$\frac{n\tau_{Ee}}{10^{14}\ \mathrm{cm}^{-3}\text{-sec}}$	Q_o	$\frac{(n\tau_{Ei})_o}{10^{14}\ \mathrm{cm}^{-3}\text{-sec}}$	P_o-MW
15	2.5	19.0	$3.3 \cdot 10^{14}$	1.0
12	0.9	9.0	1.5	2.1
10	0.45	5.4	0.90	3.5
8	0.21	3.1	0.53	6.0
7	0.14	2.4	0.40	8.0
5	0.051	1.2	0.20	16.0

If additional ion energy loss channels occur, then

$$Q = \frac{Q_o}{1 + \frac{(n\tau_{Ei})_o}{n\tau_{Ei}}} \tag{5}$$

$$P = P_o\left(1 + \frac{(n\tau_{Ei})_o}{n\tau_{Ei}}\right) . \tag{6}$$

Concentrating on the case where $T_e = 7$ keV , one sees that energy breakeven will be obtained if $(n\tau_{Ei})$ exceeds $4 \cdot 10^{13}$ cm^{-3}-sec with an electron $(n\tau_{Ee})$ of only $1.4 \cdot 10^{13}$ cm^{-3}-sec.

The ICRH-driven TFTR produces large values of β_θ . Let us employ the definition

$$\beta_\theta = \frac{4\pi c^2}{I^2} \int P(r)\, r dr \cong \frac{4\pi \bar{P} c^2 a^2}{3I^2}$$

where $\bar{P}$ is the average pressure in the central, hot-ion region. One then computes (for a = 70 cm)

$$\beta_\theta = 3.3 \frac{n_{14}}{I_{MA}^2}\left(\frac{T_e + T_i}{10\ \mathrm{keV}}\right) = 2.2$$

which is not all that much less than the aspect ratio $R/a = 3.6$. This indicates that perhaps a noncircular cross section would be preferable.[7]

Ion confinement will be strongly into the trapped ion regime where the dissipative trapped ion mode[8] is expected to govern plasma transport. Applying the currently utilized Kadomtsev-Pogutse scaling laws,[6] one finds the $n\tau_{Ei}$ value for the trapped ion instability to be

$$n\tau_{Ei} = 1.5 \cdot 10^{13}$$

faster than Table I permits. But only crude nonlinear theory has been used to obtain this estimate, and the mode may be localized by magnetic shear[9] or stabilized by inverted density gradients. On the other hand, a recent[10] nonlinear (but local) theory predicts that the diffusion coefficient may be even larger than the Kadomtsev-Pogutse value at high temperatures. Evidently more work is needed. The ICRH/TFTR will be clearly in the trapped-ion regime and hence an interesting environment for reactor-level plasma physics.

On the positive side, the calculations which lead to Table I neglect two effects which will enhance Q : electron heating by fusion-produced α-particles and the enhancement of the thermonuclear burning rate resulting from the high energy tail associated with second harmonic ICRH heating.

FUTURE RESEARCH

Most of the research problems characteristic of reactor-grade plasma devices[4,5] are found in the ICRH/TFTR and we will not enumerate them again here. The unique problems of this device center on the ICRH method of plasma heating and the high value of β_θ.

In the ICRH regime, we have assumed that one can successfully heat a particular ion--tritium--with close to 100% efficiency when that ion is shielded from the surface by a layer of nonresonant ions. The physics of this process could be investigated by second harmonic heating of He^3 embedded in a PLT discharge using the proposed 55 MHz radiofrequency generator and a toroidal field of about 27 kG . Hydrogen-deuterium plasmas are not appropriate because the gyrofrequencies are commensurate. Because second harmonic heating proceeds via formation of a high energy tail, the thermonuclear reaction rates in an ICRH/TFTR experiment may well exceed those predicted from the Maxwellian-averaged $\langle\sigma v\rangle_{DT}$.

A Fokker-Planck computation is called for, as well as experimental work on D-D neutrons in the PLT.

The second area is how to confine and control a high-β_θ tokamak equilibrium.[11,12] Very little work has been done on actual equilibria with arbitrary pressure profiles, and on how to adjust the vertical and radial fields during the rapid thermal evolution of the preheat phase.

CONCLUSION

The principal difference between an ICRH-driven and an injection-driven TFTR is that the ICRH technique permits penetration of the auxiliary heating power to the center of the discharge where it can be deposited with high efficiency solely in the ions. Neutral beams with sufficient energy to penetrate to the center of a hot plasma produce substantial electron heating as well. Thus, a true thermonuclear burning plasma can be established, which begins to simulate an experimental power reactor.

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