RF-DRIVEN TOKAMAK REACTOR WITH SUB-IGNITED,
THERMALLY STABLE OPERATION*

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A Radio-Frequency Driven Tokamak Reactor (RFDTR) can use RF-power, programmed by a delayed temperature measurement, to thermally stabilize a power equilibrium below ignition[1], and to drive a steady state current[2]. We propose the parameters for such a device generating $\approx$ 1600 MW thermal power and operating with $Q \approx 40$ (= power out / power in). A one temperature zero-dimensional model allows simple analytical formulation of the problem. The relevance of injected impurities for locating the equilibrium is discussed. We present the results of a one-dimensional (radial) code which includes the deposition of the supplementary power, and compare with our zero-dimensional model.

The one dimensional equations for a plasma are modeled by:

$$\frac{3}{2}\frac{\partial(nT_i)}{\partial t} = f_i P_\alpha - P_{diff}^{(i)} + P_{exch} + g_i P_{supp} \tag{1a}$$

$$\frac{3}{2}\frac{\partial(nT_e)}{\partial t} = f_e P_\alpha - P_{diff}^{(e)} - P_{exch} - P_{rad} + P_{ohm} + g_e P_{supp} \tag{1b}$$

$$\frac{\partial n}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}(-rD\frac{\partial n}{\partial r}) + S \tag{1c}$$

where: $f_{i,e}$ ($f_i + f_e = 1$) represent the fractions of the α heating, P_α, going to ions and electrons; $g_{i,e}$ ($g_e + g_i = 1$) represent the fractions of the supplemental heating, P_{supp}, going to ions and electrons; $P_{diff}^{(i,e)}$ represent the diffusion operators for ions and electrons acting on their respective temperature profiles; P_{exch} is the Spitzer form of the ion-electron exchange heating; P_{rad} is the Bremsstrahlung and the impurity line radiation losses; P_{ohm} is the Spitzer form of the Ohmic heating; D is the diffusion coefficient; and S is the plasma density source controlled in a manner to reach a given central value. The supplemental heating is also controlled, specifically as a function of central temperature T_0, in a manner to obtain a thermally stable equilibrium.

We tested this method of control of tokamak heating using the one dimensional model of Eq. (1) in the following case: $n_0 = 2. \times 10^{20}/m^3$, $T_e = 9.5$ keV, and $T_i = 9.0$ keV, with a supplemental heating of 100 MW which is reduced to 30 MW at the equilibrium. This equilibrium power can be used at the same time to maintain a steady state current. The analysis of the thermal stability about such an equilibrium in this model is a formidable task; we instead consider the contribution to such an analysis which a zero dimensional model can make.

We thus examine Eq. (1) at the center of the plasma, taking $n = n_0$ (constant), and $T_e = T_i = T_0$ (time-dependent), and with the diffusion terms $P_{diff}^{(e,i)}$ replaced by $(\frac{3}{2}nT)/\tau_{e,i}$, where $\tau_{e,i}$ are the neoclassical (ions) and anomalous (electron) energy confinement times. P_{supp} is large compared to P_{ohm}. Summing Eq. (1 a) and Eq. (1 b), and using $2/\tau = 1/\tau_e + 1/\tau_i \approx 1/\tau_e$, yields

$$3n_0 \frac{dT_0}{dt} = P_\alpha - 3n_0 T_0/\tau - P_{rad} + P_{supp} \equiv F(n_0, T_0) \tag{2}$$

Now P_α and P_{rad} scale as n_0^2, so we write them as $n_0^2 \, p_{(\alpha,rad)}(T_0)$, and the equilibria of Eq. (2) are thus

$$n_0^2 = \frac{\frac{3n_0 T_0}{\tau} - P_{supp}}{p_\alpha - p_{rad}} \tag{3}$$

The equilibria of Eq. (2) are thermally stable if and only if

$$\left. \frac{\partial F(n_0, T_0)}{\partial T_0} \right|_{F=0} < 0 \Leftrightarrow \left. \frac{dn_0}{dT_0} \right|_{F=0} > 0 \text{ if } T > T_{asym}. \tag{4}$$

This can be achieved by gradually turning off the supplemental heating in the vicinity of the anticipated operating point. The turn–off stage maps in the n–T plane as a positive slope transition between the 0–contour and the contour given by the actual value of $P_{supp}(T_0)$. The steady operation materializes on the transition segment as shown in Fig. 1. Heating will occur for $T_0 < T_{asym}$ when the density is below the solid curve and for $T > T_{asym}$ when the density is above the solid curve. We thus take $n \approx 1 \times 10^{20}/\text{m}^3$ while $T < T_{asym}$ and then add fuel to the plasma when T exceeds T_{asym}; and follow the thermally stable curve in Fig. 1 until we reach the desired operating point by decreasing the supplemental heating in the controlled manner.

We are also able to consider the further problem of delayed control by writing the system

$$3n_0 \frac{dT_0}{dt} = P_\alpha - 3n_0 T_0/\tau - P_{rad} + P_{supp}(T_d) \tag{5a}$$

$$\frac{dT_d}{dt} = (T_0 - T_d)/\tau_d \tag{5b}$$

where T_d represents the temperature measured at a time delayed by τ_d. We find that simple control functions for P_{supp} allow $\tau_d \approx 1$ second. Thermal stability of the plasma center can therefore be achieved with a supplemental heating based on feedback measurement of the peak temperature.

To determine the power output which can be generated from such operation, we now consider the global power balance obtained by performing a volume average of Eq. (2), assuming simple density and temperature profiles, with a fixed central density n and a time–dependent central temperature $T(t)$. Fitting a cubic polynomial $f(T)$ to the average of $(P_\alpha - P_{rad})/n^2$ leads to the simple form

$$\left\langle 3n \frac{dT}{dt} \right\rangle = n^2 f(T) - bT/a^2 + P_{supp}(T) \equiv F(n, T) \tag{6}$$

where a is the plasma minor radius and b is a constant.

The thermal power density P_{th} is taken equal to the sum of the neutron energy and the radiation $(5P_\alpha + P_{rad})$, since the walls will ultimately absorb all of the power carried by the neutron and radiation fluxes. We now define Q as the ratio of the thermal power output to the supplemental heating input at equilibrium, $T = T_{eq}$:

$$Q \equiv P_{th}/P_{supp}(T_{eq}) = n_{eq}^2(5p_\alpha(T_{eq}) + p_{rad}(T_{eq}))/P_{supp}(T_{eq}). \tag{7}$$

It is desirable to operate a tokamak in a region of the n–T plane where several criteria are satisfied: the neutron wall loading is in the range 2–4 MW/m^2; the thermal power is on the order of 1600 MW; and the plasma has an average $\beta < 10\%$. The plasma should have a minor radius $a \approx 1$ m, and a major radius $R > 3$ m in order to to confine the α particles. The magnetic field must be in the range 40–80 KG to provide plasma confinement and have a safety factor $q(a) = 3$. These constraints can be imposed on the contours of Eqs. (2) and (6) in order to select compatible parameters.

We select the equilibrium temperature and density from the 0 contour of Eq. (2) so that the core will be in equilibrium for a given supplemental power input. The thermal power, Q, and β contours are shown in Fig. 2.

It is found that the criteria admit of a range of solutions, and we propose the following parameters as a suitable choice: $R = 8$ m and $a = 1$ m with a shape factor of $S = 1.6$ for improved MHD stability and additional cross sectional area; $B_0 = 55$ KG and $I = 3$ MA with $q(a) = 3$; supplemental power is 40 MW at the equilibrium, having been programmed as a function of temperature.

There is a tradeoff for Q and τ_d in that as we approach the ignition curve, in order to use only a little power to control the plasma, the time over which we must respond to positive thermal fluctuations to avoid thermal runaway is reduced. Fig. 3 shows a sample case in which the there is a .2 keV positive thermal fluctuation in T at $t = 0$; with $\tau_d = .8$ sec we find that the thermal stability is preserved.

We note that the addition of impurities to the plasma causes the line radiation to increase, and thus requires that the α production rate be increased in order to achieve equilibrium; since both terms scale as n_0^2, the temperature T_0 must rise to make P_α compensate for P_{rad}. This has the effect of causing a larger neutron production rate so that the overall thermal power output increases.

The RFDTR tokamak is taken to have an initial plasma density $n_0 = 1.75 \times 10^{20}/m^3$, and an impurity of Mo with a profile of $10^{-2}\%$ of the plasma density. After the supplemental heating raises the temperature above T_{asym}, we add additional fuel and also $10^{-2}\%$ Xe to cause further line radiation, thus pushing upward the ignition curve of Fig. 1. The controlled supplemental heating reduces to 40 MW, and the density approaches $3 \times 10^{20}/m^3$, as the temperature approaches 9 keV at the operating point. We find that the thermal power output is 1620 MW, and thus $Q = 40$ at this thermally stable equilibrium. The neutron wall loading is 3 MW/m^2 for this case, and $\beta = 3.4\%$.

The time dependence of the supplemental heating indicates that the power must be cycled on a short time scale to control the positive thermal fluctuations, so that RF power appears to be a very attractive candidate for such a source. The use of phased RF waves with a spectrum in 2–5 thermal velocity range can drive the current and thus eliminate bulky transformer equipment[2]. This design concept of the Radio Frequency Driven Tokamak Reactor is for a medium size (600 MW electric) generating plant.
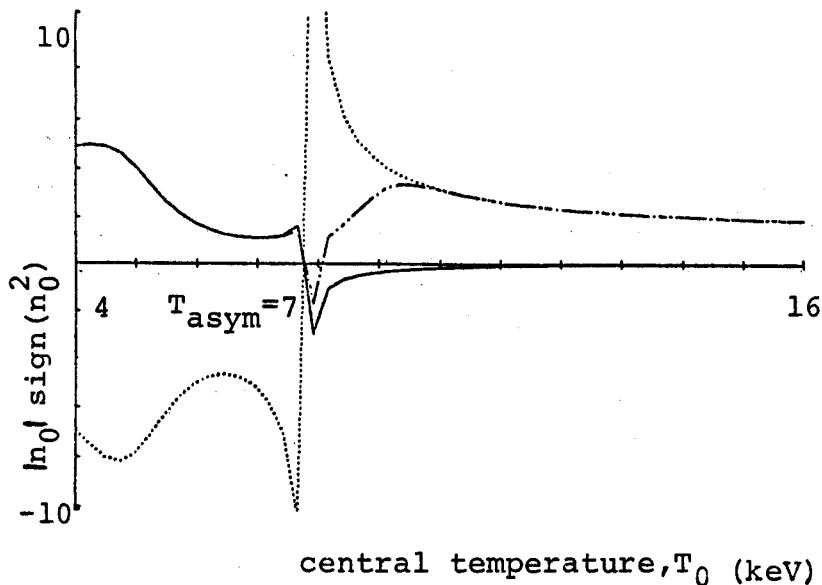
Figure 1. Equilibrium of plasma core; central density n_0 ($10^{20}/m^3$) vs central temperature T_0. Dotted curve is the ignition case of $P_{supp}=0$. Solid curve is for $P_{supp} \gtrsim P_{diff}$. Dash-dot curve is for the previous P_{supp}, with thermal control (slow turnoff) making a thermally stable transition to the ignition curve.
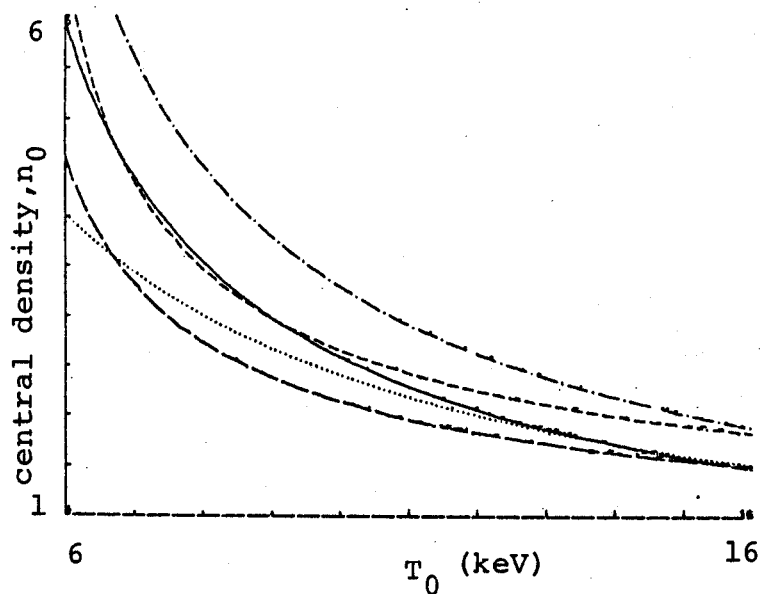

Figure 2. Plot of P_{th} (MW), Q, and β contours.

Solid: $P_{th} = 1600$ MW
Dash-dot: $P_{th} = 2100$ MW
Dot: $\beta = 3$ %
Long dash: $Q = 10$
Short dash: $Q = 40$

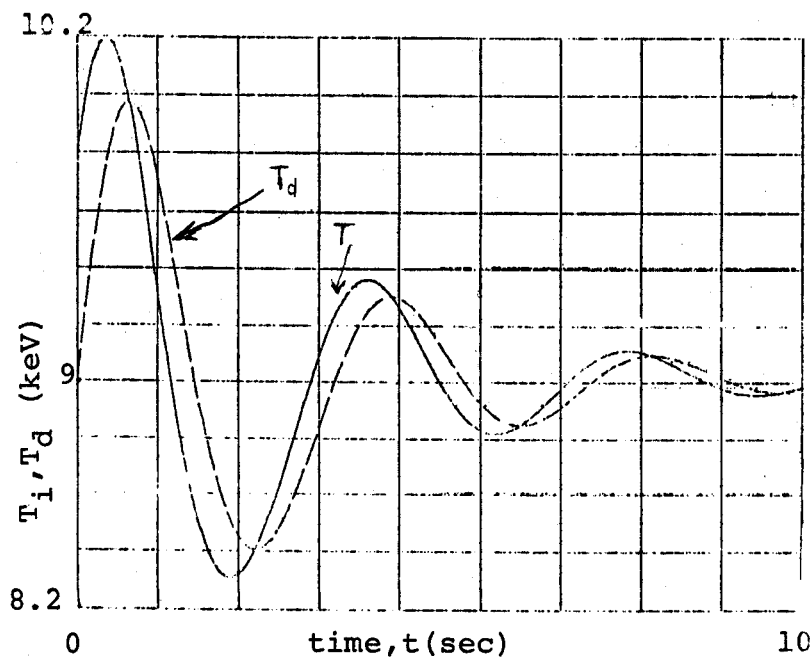Contours in the n_0 ($10^{20}/m^3$) vs T_0 plane, using RFDTR parameters.

Figure 3. Temporal evolution of $T(t)$, and of the delayed measurement $T_d(t)$, under thermally controlled conditions, illustrating the return to thermally stable operating point when a .2 keV positive thermal fluctuation makes $T>T_d$ at $t=0$.

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References

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Karney, C. F. F., and Fisch, N. J., *Phys. Fluids* <u>22</u>, 1817 (1979); and

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