MASTER

THE USE OF FIELD RIPPLE FOR BURN PHASE
CONTROL IN SHORT-PULSE TOKAMAK REACTORS

by

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I. Introduction

In a tokamak fusion power reactor, the plasma will of necessity be subjected to many kinds of controls. Some of these controls may be passive or preprogrammed. This mode is the dominant one for present day, pulsed tokamak experiments. However, since the total burn cycle of a tokamak will last much longer than the time scales for energy and particle confinement, for positional instabilities, or for thermal instabilities, many of these control functions must be active, i.e., they must involve some rapid feedback mechanism. An example is the need to exercise control over the total plasma thermal energy content during the burn phase of the cycle. In reference to this problem, the object of the work described in the present paper was to determine the magnitude of the control necessary to maintain a constant ion temperature in a beta limited tokamak plasma and to investigate the possibility of effecting that control by means of a variation in the toroidal magnetic field ripple.

Once a plasma is heated to the desired operating temperature, it will not in general remain at that point during the subsequent burn without some form of active control. The accumulation of impurities with its concomitant plasma cooling by enhanced radiation losses and the unstable nature of the operating point associated with the strong sensitivity of the fusion reaction cross section and transport losses to ion temperature are but two of the well known effects that necessitate such control. This problem of thermal stability has been addressed in a number of previous works, represented by Refs. 1-4, in which the rate of departure from the equilibrium point has been calculated under a variety of assumptions concerning

the plasma. The mechanism most commonly suggested for the control of the thermal instability has been variation of the particle input rate either by controlling the total particle flow or by varying the D-T ratio for a constant fuel feed rate.^{1,4} Computer simulation indicates that these mechanisms may be effective, but very little is known about how tokamaks will indeed be fueled or how cold fuel will actually interact with a hot fusion plasma.

Recently the use of adiabatic compression and expansion was suggested as a means of plasma temperature control.⁵ However, in order to obviate significant changes in the toroidal field strength, the compressions and expansions must be effected by changes in the major radius of the plasma. The need for gross plasma motions implies an inefficient use of the plasma chamber which may be incompatible with the requirements of an effective divertor.

Temperature control in fusion plasma is a space dependent as well as a global problem. The degree of thermal stability or instability may change drastically over the plasma cross section since the transport regimes depend strongly on local temperature and the fuel density, temperature, and impurity density profiles will differ greatly. The efficacies of the various control mechanisms generally have spatial variations also and it is important to match the profile of the solution to that of the problem. Some initial studies on density and temperature profile control by pellet injection have been reported,⁶ but the difficulty and high cost of performing numerical analyses on the dynamics of a spatially dependent plasma have inhibited the development of this work. The experimental implementation of any control mechanism should

not proceed, however, until space dependent analyses have been performed.

In the work reported herein, the possible use of toroidal field ripple to control temperature excursions was investigated. In particular, the magnitude of the power savings necessary to control the ion temperature for about 120 seconds during the burn phase of an ETF tokamak was determined through the use of a global dynamics code. Then the amount of field ripple necessary to effect that control was calculated for each case. In the next section the basic properties of the simulation code are given and the various plasma cases investigated are described in some detail. There follows a discussion of the field ripple control mechanisms and their application to the problem at hand. Finally, the results of the study are presented along with the conclusions drawn from them.

II. Simulation of the Plasma Burn Cycle

The burn cycle simulations were performed with a point dynamics plasma particle and energy balance code⁷ which treats the full plasma cycle including start-up, burn, and shut-down. Both self-sustaining ignited plasmas and subignition burns can be modeled. The basic equations in the code follow the evolution of the spatially averaged densities and temperatures or average energies of fuel ions, alpha particles, electrons, and two species of impurities, a prescribed amount of oxygen and sputtered wall material. All particle densities are allowed to evolve as the code dictates with the exception of fuel ions, the density of which is maintained by a cold ion source. Energy losses by bremsstrahlung, line and recombination radiation, and synchrotron radiation are included in

the model.

Particle and energy losses resulting from spatial transport are determined from a multi-regime transport model used to calculate the confinement parameter, τ_E .⁸ Typically, for large electron-ion collision frequency, the ion energy transport follows neoclassical scaling and the electrons, pseudoclassical scaling. For very low collisionality all confinement is determined by trapped ion mode theory. For intermediate values of the collision frequency, trapped electron mode scaling is invoked for the electron energy losses. However, the code chooses at any time step the mechanism which gives the largest loss, of both particles and energy, and the magnitude of the loss associated with each process is determined in part by an arbitrary multiplicative constant called a confinement parameter. The values of these confinement parameters are part of the input to the code. Hence, the transition frequencies and the relative magnitudes of the transport losses associated with these different regimes can be arbitrarily varied in the code, thereby allowing simulation of plasma burns in which one or more of the transport mechanisms is suppressed. This feature of the code was very useful in the work reported herein since the thermal stability of the plasma is extremely sensitive to the temperature scaling of the transport losses and each mechanism has its own scaling. Therefore, the control requirements are dependent on the transport regime in which the plasma operates during a burn.

Although the code is zero dimensional, the essential effects of the spatial variation in temperature and density are included by solving the balance equations for quantities which are averaged over the plasma

cross section. These averages are calculated under the assumption that during the cycle the density and temperature profiles are fixed with respect to flux surfaces. The position of these surfaces and the differential volume contained between flux surfaces is calculated along with the safety factors and poloidal beta at each time step by use of a MHD equilibrium solver.

During the simulation impurity control is effected by a subroutine which models both wall interaction resulting from neutrons and ions flowing from the plasma and the action of a divertor.⁹ Appropriate sputtering coefficients, divertor efficiencies, and charge exchange coefficients are used in this model to calculate the reflux of impurity and fuel ions to the plasma from beyond the limiting flux surface. The impurity material can be chosen arbitrarily.

The reactor and plasma parameters chosen for this investigation are similar to those found in typical ETF tokamak designs.^{10,17} The plasma has a major radius of five meters and an aspect ratio of three. The toroidal magnetic field is 3.4 tesla and the plasma current during the burn is 6.75 mA. These parameters are consistent with the plasma having an average particle density of about 2×10^{20} particles/m³, an average ion temperature of 10 keV, and a total beta of approximately 8%.

In each of the simulation runs to be described below, the start-up phase of the burn cycle is similar. The plasma is struck and heated by the plasma current alone until one second into the cycle at which time a 40 Mw beam of 180 keV neutral particles is injected for supplemental heating. The plasma ignites and the average temperature reaches the

the vicinity of 10 keV at the time the beam is turned off, about five seconds after it is started. The plasma continues to burn for varying lengths of time thereafter depending on the impurity buildup and degree of control exercised.

To establish a base case for the control studies, the various confinement parameters were set equal to the same value, and that value was chosen so that a plasma in which both impurity influx and alpha particle accumulation were suppressed would burn uncontrolled for approximately 120 seconds at an average plasma ion temperature of about 10 keV. The resulting ion temperature during such a burn is shown on the curve labeled No Impurities in Fig. 1. Thermal runaway to higher temperature is naturally controlled during this burn simulation by the inverse temperature scaling of trapped particle mode energy confinement.

To demonstrate the necessity of temperature control, several uncontrolled burn cycle simulations were run in which alpha particles and wall sputtered impurities were allowed to accumulate in the plasma. The ion temperature during two such runs is also illustrated in Fig. 1. All of the relevant input parameters are the same in these runs as in the uncontrolled base case.

The addition of impurities to the plasma changes the evolution of the burn in many ways, but there are three major effects. First the addition of ions with high charge states and the associated increase in the electron density leads to greatly enhanced energy losses due to bremsstrahlung as well as line and recombination radiation. Secondly, the increase in the average ion charge, Z_{eff} , that accompanies impurity addition increases the collisionality of the plasma. Qualitatively, this has the same effect

Fig. 1. The Ion Temperature for Uncontrolled Burns

on the transport losses as a decrease in plasma temperature. It causes a decrease in trapped ion mode loss rates and if large enough can lead to a transition to trapped electron, pseudoclassical, or neoclassical confinement regimes. Finally, the impurity ions and their electrons displace fuel ions in beta limited systems and thereby indirectly reduce fusion power production.

When the wall sputtered impurity is the light element Be, the enhanced radiation losses are very nearly balanced by the reduction in the trapped ion mode transport losses. As shown in Fig. 1, the uncontrolled burn lasts for about 60 seconds after the neutral beam heating is removed before the ion temperature begins to fall and the burn is terminated. However, when the wall is composed of the relatively high-Z material SiC, the burn is almost immediately extinguished by impurity accumulation. In fact, after about ten seconds Z_{eff} has increased enough to cause a transition from the trapped ion mode transport regime which characterizes a clean plasma at a temperature of 10 keV to the pseudoclassical-neoclassical regimes for which the plasma is thermally unstable. This fact, coupled with the large radiation power losses, causes a precipitous drop in ion temperature leading to the end of the burn.

Temperature control of the burn cycle is implemented in the simulations by simply forcing the ion temperature to remain at a predetermined value, 10 keV in the cases discussed here. Of course, this procedure prevents the energy balance equations from being satisfied; but the discrepancy, ΔP , between total power into the plasma and total power out serves as a measure of the control necessary to achieve constant ion temperature. The quantity ΔP is calculated as

$$\Delta P = P_L + P_\gamma - P_\alpha \quad (1)$$

where P_α is the total fusion power that goes into the alpha particles P_γ is the power lost through all forms of radiation, and P_L is the power lost from all particle species by energy and particle transport. If one were to add just ΔP to the ions by a supplemental heating method or to reduce the ion energy transport losses by that amount, the ion temperature would be held at the desired value. Figures 2, 3, and 4 show the power discrepancy, ΔP , as a function of time during a two minute burn phase of three simulation runs. Figures 2 and 3 show the silicon carbide wall and beryllium wall cases corresponding to the uncontrolled burns illustrated in Fig. 1. The result shown in Fig. 4 is the same beryllium wall case with the exception that all trapped-particle mode transport is suppressed. In each figure, the total alpha power, P_α , produced by fusion reactions during the burn is also plotted.

The amount of power necessary to maintain the ion temperature varies greatly in these three cases. For a silicon carbide wall, Fig. 2 shows that the power discrepancy ΔP is nearly an order of magnitude greater than the alpha particle power at the end of the burn phase. Almost all of this extra power is necessary to make up for the severe radiation losses that result from the high Z impurity. In the beryllium wall case illustrated in Fig. 3, the power requirements for a steady state burn are relatively modest and, if trapped ion mode transport losses are suppressed, Fig. 4 shows that ΔP is negative at the early stages of the burn phase, i.e., power must be removed to prevent thermal runaway to a higher temperature.

Fig. 2. Control Power and Alpha Power for a Burn with SiC Impurity.

Fig. 3. Control Power with a Be Impurity

Fig. 4. Control Power with a Be Impurity and without Trapped Particle Modes

As far as thermal control is concerned, the average value of the power discrepancy over the burn phase has no real meaning. In the first place, the confinement parameters were set in an arbitrary manner and could easily be adjusted to give simulations with very different average ΔP . Furthermore, if ΔP is positive over the burn, a constant injection of neutral beam power would shift it to smaller or negative values. The important quantity for thermal control is the range of ΔP over the burn phase or, more accurately, the range of the chosen control parameter necessary to produce the required variation in ΔP .

III. Toroidal Field Ripple as a Control Mechanism

One possible mechanism for producing the power swings necessary for thermal control is variable toroidal field ripple. In general, very small asymmetries in tokamaks are known to have significant effects on the confinement of the plasma and of the high energy alpha particles. This ability of a small change in field ripple to cause large changes in energy confinement gives this process its attraction as a control mechanism. Since field ripple increases plasma energy losses and the imbalance, ΔP , between power out and power in reaches its maximum at the end of the burn phase of the cycle, control will be exercised by decreasing the ripple from some non-zero initial value to zero at the beginning of shut down. In other words, it is assumed that the transport losses are small enough or the supplementary power input is large enough that in the absence of ripple effect the power discrepancy ΔP , would be negative throughout the burn, reaching zero only at the end of this phase of the cycle.

The toroidal field ripple affects the motion of the plasma particles, and hence causes changes in particle transport, in two basic ways. First, particles with very large pitch angles with respect to the magnetic field can be trapped between the local field maxima of the ripple. For particles so trapped, motion in the poloidal direction is impossible and the rotational transform associated with the poloidal field is defeated. For extremely collisionless particles such as high energy alphas, that fraction trapped in the ripple wells simply drifts out of the plasma with the $\underline{B} \times \nabla \underline{B}$ drift velocity. For more collisional species like the fuel ions, the motion is the same, but the rate of loss is governed by the collisionality of the plasma.¹²

The ripples in the toroidal field also affect the collisional diffusion of those particles trapped in the magnetic wall associated with the toroidicity of the tokamak; the banana particles.¹³ In this process, the ripple causes a certain fraction of the banana trapped particles to undergo large radial excursions in orbits that are sometimes called super-bananas or banana drifts. These radial motions lead to an enhanced radial diffusion of particles and energy when the collisionality of the plasma is very low. The size of the losses by the banana drift mechanism are the subject of some controversy¹⁴ and consequently, the value of ripple as a control process was assessed both with and without a banana drift contribution.

For a tokamak with N toroidal field coils, there is a natural ripple in the magnitude of the toroidal field. In terms of the usual r , θ , and ϕ coordinate system shown in Fig. 5, the variation in magnetic field strength along a field line can be written as

$$|B| \approx B_0 (1 - \epsilon \cos \theta + \delta \cos N\phi)$$

where ϵ is the inverse aspect ratio r/R . The parameter δ indicates the amplitude of the ripple as a fraction of the field strength on the magnetic axis and is used as a convenient measure of ripple magnitude when discussing control. It is assumed that appropriately designed coils can provide a method of varying this parameter without changing its periodicity.

The plasma power losses, P_R , that accompany a given amount of ripple can be written as:

$$P_R = f_R P_\alpha + \frac{3}{2} \left(\frac{n_i T_i}{\tau_r} \right) V \quad (2)$$

where the first term accounts for the fraction, f_R , of the alpha particles that are lost by ripple trapping before they slow down, and the second term represents the loss of ion energy by the enhanced diffusion that results from ripple trapping or the banana drift process. The quantities N_i and T_i are the average ion density and temperature, respectively, V is the plasma volume, and τ_R is the ion energy confinement time associated with field ripple diffusion. This last parameter can be calculated from the expression:

$$\frac{1}{\tau_R} \approx \frac{4}{a^2} \left(\chi_{i_{RT}} + \chi_{i_{BD}} \right) \quad (3)$$

where a is the minor radius of the plasma, and $\chi_{i_{RT}}$ and $\chi_{i_{BD}}$ are the ion heat transport coefficients for ripple trapped diffusion and banana drift diffusion, respectively. These two quantities are in turn given by the equations¹³

$$\chi_{i_{RT}} \approx (0.06) \frac{\delta^{3/2}}{\nu_{ei}} \left[\frac{T_e}{eBR} \right]^2 \left(\frac{m_i}{m_e} \right)^{1/2} \times \left(\frac{T_i}{T_e} \right)^{3/2} \quad (4)$$

and

$$\chi_{i_{BD}} \approx \chi_{i_{RT}} \left\{ \frac{(qN)^2}{20} \delta^{1/2} e^{3/2} \right\}^\gamma \quad (5)$$

where δ is expressed in %, R is the major radius of the plasma, e is the electronic charge, T_e is the average electron temperature, m_e and m_i are the electron and average ion mass, respectively, and q is the safety factor at the minor radius. The quantity ν_{ei} is the usual electron ion collision frequency in the plasma

$$\nu_{ei} = \frac{4(2\pi)^{1/2} n_e e^4 \ln \Lambda}{3(m_e)^{1/2} T_e^{3/2}} \quad (6)$$

The parameter γ is put in the expression for the banana drift heat transport in order to allow the magnitude of this effect to be varied arbitrarily. Banana drift losses are completely suppressed when γ is zero. The section of alpha particles lost, f_R , becomes for the geometry considered here,¹⁵

$$f_R \approx (0.02) \delta^{1/2}$$

where again δ is given in percent.

To estimate the amount of ripple necessary for thermal control of the three cases illustrated in Figs. 2, 3, and 4, Eq. (2) was solved for δ when P_R was equated to the power removal necessary for holding the ion temperature constant during the burn phase of the cycle. As discussed

previously, the control power was made negative by assuming that ΔP became zero at the end of the burn. Hence, at any time during the burn, P_R was equated to the difference between the value of ΔP at that time and its value at the end of the burn phase. For each simulation, the maximum value of δ resulting from this calculation was accepted as the amount of ripple necessary to control that case.

IV. Results and Conclusions

The amounts of ripple necessary to control the burn phase of several simulations were determined as described in the previous section and are displayed in Table 1. The three rows labeled SiC, Be, and Be without trapped particle modes correspond to the controlled burns illustrated in Figs. 2, 3 and 4. The columns correspond to three separate calculations of the ripple magnitude, δ . The results in the left column were determined with the assumption that the ripple losses included the full effects of banana drift diffusion, i.e., γ in Eq. (5) was set equal to one. In the center and right hand columns, the ripple magnitude was calculated with γ equal to 1/10 and zero, respectively.

The fact that the banana drift diffusion accounts for a large part of the control effect of field ripple is obvious from Table 1., in which the necessary ripple increases by a factor of from 5 to 10 as this process is suppressed. Not so clear from these results is the fact that banana drift diffusion is the most sensitive control mechanism associated with field ripple since this process scales like δ^2 while ripple trapped diffusion and alpha particle losses scale like $\delta^{3/2}$ and $\delta^{1/2}$, respectively. Consequently, if field ripple proves to be a useful control variable, the banana drift process will probably play an important part in its success.

TABLE 1

RIPPLE CONTROL

Amplitude of Ripple at the Plasma Edge
as a Percentage of the Total B-Field

CASE	W/ Full BD Losses	W/ 1/10 BD Losses	W/0 BD Losses
SiC	1.7	5.0	6.7
Be	0.3	0.8	1.4
Be W/0 TIM or TEM	0.9	2.6	6.7

The increased amount of ripple necessary to control the case with silicon carbide walls over the case of beryllium walls is simply a reflection of the size of the effects associated with the buildup of the higher Z impurity.

Since the temperature scaling of the trapped particle modes is such that increased ion temperature leads to increased losses, this transport mechanism gives a high degree of thermal stability when transport losses are relatively important to the energy balance. Consequently, the suppression of these modes generates the need for more control as shown in the third row of Table 1.

Overall, it appears that the thermal stability of the burn phase can be assured by a modest amount of variable toroidal field ripple if the plasma is fairly clean, and the impurities have a low Z, and if banana drift diffusion is an important part of the transport losses associated with the ripple effects. The numbers given in Table 1. should be viewed as representative of the ripple necessary for control. The actual magnitudes must be determined by more sophisticated calculations and eventually experimentally measured. In deriving the results given here, this spatial variation in the ripple effects and its importance in the determination of the transport losses was included only in the sense that spatially averaged values of the parameter were used in the calculations. Questions on the stability of temperature and density profiles in the presence of field ripple can only be answered by performing one dimensional analyses. However, these initial results are encouraging. They indicate that variable field ripple is potentially a solution to an important control problem in the development of fusion power.

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