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PINCH REACTOR

MASTER

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SUBMITTED TO: For the Proceedings of the 2nd Joint Grenoble-Varenn
International Symposium on Heating in Toroidal Plasmas

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STABLE HEATING AND BURN SIMULATIONS OF A REVERSED-FIELD PINCH REACTOR*

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ABSTRACT

The reversed-field pinch provides three significant advantages as a fusion reactor: it can be ohmically heated, it operates at high β , and it is not restricted to a small aspect ratio. Experimentally, the best understood startup scenarios are self reversal, aided reversal and fast-field programming. On the basis of results from a one-dimensional transport and stability code, an ideal MHD stable startup and burn procedure is described in this paper. Pitch programming and a gas feed at the wall are used. This adiabatic startup is characterized by a high pitch near the minor axis and hollow current and pressure profiles. Ideally, it would be possible to have a reactor startup and burn without highly turbulent processes to deposit excessive amounts of energy on the wall. Potential problems of resistive instabilities and plasma-wall interactions are discussed.

INTRODUCTION

One of the most important unsolved problems for the reversed-field pinch (RFP) is how to initially set up the required field profiles. Baker and Phillips¹ have shown that diffusive startup processes generally require large energy losses to reach an equilibrium in the post-compression phase. Also, this approach generally results in a high β post-compression plasma which does not have enough current to significantly heat the plasma further.

*Supported by DOE Contracts DE-AS02-76ET52040 and W-7405-ENG-36.

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It is desirable to find a non-diffusive startup technique which maintains MHD stability to insure minimal energy loss and low β . Newton² originally suggested such an approach based on a convective startup technique. This procedure satisfied the necessary stability criterion that the pitch ($P \equiv rB_\phi/B_\theta$) of the field lines does not have a minimum.³ We have extended Newton's technique using RFPBRN⁴ (a transport and stability code) and have found a startup scenario that theoretically maintains ideal MHD stability to global and local modes during the startup, heating, and burn phases.

Technique

It is easily shown that for an ideal plasma, conservation of toroidal and poloidal magnetic flux implies that pitch is also conserved. Consequently, if plasma is fed in at the wall and the fields are simultaneously programmed, the pitch initially present in the plasma will be conserved as the plasma is compressed. This condition is also approximately true for a resistive plasma and consequently, the shape of the pitch profile can be controlled externally.

A natural boundary condition for a Lagrangian code like RFPBRN is the placement of the plasma boundary. Since convective startup involves a plasma compression, we have chosen to model it by moving a virtual plasma boundary inward as the simulation evolves in time. The fields and gas feed rate at the wall are then monitored to determine what programming would be required to do this on an experiment. the equation chosen for the boundary is:

$$r_p = \begin{cases} 10a(0.9[(\tau_R - t)/\tau_R]^4 + .1), & t < \tau_R \\ a, & t > \tau_R \end{cases} \quad (1)$$

where a is the vessel radius, τ_R is the rise time, and t is the present time in the simulation.

Profiles sufficient to maintain stability during the heating and burn phases are known, so the question is how to properly program the fields to arrive at these desired profiles. Since startup is approximately an adiabatic compression, the initial profiles (when the virtual plasma boundary is at ten times the vessel boundary) are arrived at by adiabatically expanding the desired post-compression profiles to ten times the vessel radius. This insures that the final profiles will be near the desired ones.

Results

Using the programming procedure described above, a start-up scenario has been found which has ideal MHD stability to both local (Suydam)⁵ and gross modes during the start-up and burn phases. The gas feed rate and toroidal and poloidal fields at the wall sufficient for stability are shown in Figure 1. Startup is achieved in 1 msec. although slower times are possible.

Figure 1. Gas feed rate and magnetic fields at the wall during startup.

Maintenance of stability during startup and burn requires peaking both the toroidal current density and the particle density off axis. Peaking the particle density off axis leads to an off-axis pressure peak which stabilizes interchange modes in the weakly sheared central plasma region. Peaking the current density off axis stabilizes gross current driven kinks in the pre-reversed state.

Figure 2 shows the initial, startup termination, and final (end of burn) current profiles for the RFP. Note that the toroidal current does diffuse into the central plasma region, but not fast enough to spoil the plasma stability characteristics. However, the toroidal current remains slightly peaked off axis during the entire burn.

Since the toroidal current profile is not an input parameter to RFPBRN, peaking the current density off axis was accomplished by flattening the

Figure 2. Current density profiles initially, at the end of startup, and at the end of the burn.

toroidal field on axis. The post-compression toroidal field profile sufficient to do this is

$$\begin{aligned} B_{\phi}(r) &= B_{\phi 0} J_0(\alpha(r)r), \\ \alpha(r) &= 3.12a^{-1}[1 - 0.6 \exp(-r^2/0.16a^2)] \end{aligned} \quad (2)$$

Bessel function fields alone were found to be violently unstable.

Flattening the toroidal field is a stabilizing influence on the plasma since it decreases the poloidal field near the axis which drives the instability. Even though the Bessel function profile satisfies the necessary criterion of not having a pitch minimum, the relatively large poloidal field during early stages of compression makes it unstable. Consequently, this is a more stringent stability criterion than just maintaining a minimum-free pitch profile.

It is not unlikely that the ideal MHD stable plasmas described here will be resistively unstable. Perhaps this can be mitigated by observations made during this work that RFP plasmas evolve towards greater stability under compression. Even if resistive instabilities cause some redistribution of the plasma during early stages of compression, chances are still good that it will evolve to a stable post-compression state. A study of resistive instabilities during startup is currently underway.

Summary

A startup scenario which theoretically predicts ideal MHD stability for both local and global modes during the startup and burn phases for an RFP reactor has been found. Toroidal current density must be peaked off axis in the pre-reversed phase in order to maintain stability. Density and pressure are peaked off axis in order to stabilize Suydam modes in the weakly sheared plasma interior during the burn phase.

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