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July 1973

UWFDM-53

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NEUTRAL BEAM HEATING AND ENERGY BALANCE STUDIES FOR CTR TOKAMAKS

by

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July, 1973

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Paper submitted to Winter Meeting of American Nuclear Society, Nov. 1973.

We report results of studies on the problem of plasma heating to ignition in a power producing, D-T fueled CTR Tokamak and the question of determining appropriate operating conditions for the plasma in such a reactor. Optimization considerations,[1] which will be discussed shortly, lead to the choice of plasma radius, a = 5 meters and major radius, R = 13 meters, giving an aspect ratio, A, of 2.6. With temperature profiles that are either flat, or weakly concave, such as $(1 - \frac{r^2}{a^2})^{\frac{1}{2}}$, the stability factor, q, chosen as 1.75 at r = a, will be greater than one over the entire plasma.[2] The basis of this assumption has been discussed previously.

In the heating analysis, gas breakdown and plasma formation are assumed complete, and we concentrate on the subsequent plasma heating by energetic neutral beams. A one-dimensional space and time resolved computer code is used to follow the evolution of the discharge. The code includes the two-fluid equations and Maxwell's equations. Ion energy transport is assumed to be neoclassical[3] and the election energy transport is assumed pseudoclassical.[4] Other energy transport processes considered include bremsstrahlung radiation, electron-ion energy transfer, synchrotron radiation with a reflectivity coefficient of 0.9, ohmic heating, injected energy and thermonuclear alpha particle energy. Convection losses are neglected due to the long particle confinement times predicted by both pseudoclassical and neoclassical theory.

After gas breakdown, the plasma conditions at the center of the discharge are assumed to be $T_{eo} = T_{io} = 500$ eV, $n_o = 3 \times 10^{13}$ cm^{-3},

B_T = 38.4 Kg and the plasma current I = 21 MA fully developed. At the plasma boundary, $T_i = T_e = 10$ eV, $n = 6 \times 10^{12}$ cm^{-3} and q = 1.75 are assumed. The initial radial profiles are assumed to be $T_{i,e} = T_{io,eo}$ $(1- r^2/a^2)^{1/3}$, $n = n_o\ (1 - r^2/a^2)^{\frac{1}{2}}$. The problem of neutral beam penetration into the plasma[5] is not considered. The injected energy is treated as a distributed power source with a radial profile the same as that of the plasma density. The increased density due to particle injection is accounted for and the neutral beam energy to the plasma by injection is assumed to be 100 keV. With these initial conditions and simulation model, the heating phase of reactor startup is examined.

We find no benefit to allowing the plasma to ohmically heat above 500 eV. Due to the decrease of plasma resistivity with increasing electron temperature ($\eta \propto T_e^{-3/2}$) ohmic heating is inefficient and in the present system requires 4 seconds to raise the plasma temperatures to 1500 eV. As a result, injection is initiated immediately after the initial conditions are established.

We find it is possible to ignite the plasma using 75 MW of neutral beam heating. Ignition occurs when the power delivered to the plasma by thermonuclear alpha particles exceeds the total plasma power losses. With 75 MW of injected power, 50% absorbed by each plasma species, ignition occurs over 50% of the plasma radius in ∿ 4 seconds, with T_{io} = 4910 eV and T_{eo} = 4920 eV at ignition. To establish a greater heat-up rate, injection is continued until t = 5.7 seconds when T_{io} = 6500 EV, T_{eo} = 6540 eV. Injection is then terminated. After 10 seconds, T_{io} = 7220 eV and T_{eo} = 7310 eV and the heat-up rate is ∿200 eV/second. $T_i \approx T_e$ throughout the heating phase of start-up. The sensitivity of the results to the distribution of injected power among the plasma species was tested by assuming 70% of the power is absorbed by the electrons, 30% by the ions. No appreciable change in the ignition parameters resulted.

Turning now to the question of plasma operating parameters in a CTR Tokamak, the plasma was sized by setting the power at 5000 MW_T($\sim$2000 MWe) and limiting the neutron wall loading to 1.25 MW/m^2. This latter value is set by radiation damage considerations and is the maximum loading possible due to embrittlement and swelling problems.[6] (Actually, gas production may cause embrittlement problems even at wall loadings of .1 MW/m^2.) With these two factors set, and using 20 MeV per fusion reaction, there is only a single value of $(a+\delta)R$, namely $71.5m^2$. Here, δ is the size of the vacuum gap from the plasma edge to the first wall. Optimization studies[1] indicate one should choose $R < 15$ m and $A = R/a$ between 2. and 2.5. Due to the need to have sufficient core space for a superconducting, air-core transformer, we set A at 2.6. This then sets a at 5 meters and R at 13 meters.

With these sizes, calculations were performed to evaluate the steady-state operating conditions. As previously reported,[2] both bremmstrahlung enhancement and confinement time spoiling (compared with neoclassical theory[3]) were required to achieve favorable power balances. β_θ was limited to $\sqrt{A}$, consistent with both the steady-state assumption based on the diffusion driven bootstrap current,[7] and the recent small A, MHD calculations of Callen and Dory.[8] We have found that there exists an optimum amount by which bremsstrahlung losses should be increased through the addition of impurities to obtain the optimum power balance at the thermally unstable equilibrium . For the system described, this enhancement of bremsstrahlung losses is 7.5 times such losses without impurities.

Typical parameters for the thermally unstable equilbrium are T_i = 11.1 KeV, T_e = 11.0 KeV, $<n_i>$ = .76 x $10^{14}/cm^3$, $<\tau_i>$ = 14.2 seconds and B_ϕ^{axis} = 38.2 KG. In contrast, typical parameters at the thermally stable point are T_i = 28 KeV, T_e = 21.0 KeV, $<n_i>$ = .35 x $10^{14}/cm^3$, $<\tau_i>$ = 67 sec, and B_ϕ^{axis} = 47.3 KG. The confinement times listed, based on the average density, are three orders of magnitude shorter than predicted using neoclassical theory. A more detailed listing of parameters will be given.

The important point to note regarding these parameters is that B_ϕ is ∿20% higher for the stable point, relative to B_ϕ at the unstable point. Since magnet costs scale as B_ϕ^2, this means ∿50% higher magnet costs at the stable equilibrium. For the recent University of Wisconsin CTR Tokamak design, this translates into approximately 50 million dollars in extra magnet costs. We argue therefore that there is considerable incentive for feedback control and operation at the thermally unstable point.

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