SHAFRANOV PARAMETER LIMITS FOR OHMIC AND R.F. HEATED PLASMAS IN TCA

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An ohmic study is presented to define the experimental dependence of the value of ($\beta + l_i/2$) derived from the Shafranov equation. The Alfvén Wave Heating pulse causes an increase in both ($\beta + l_i/2$) and density, and with R.F., the value of ($\beta + l_i/2$) is significantly greater than the ohmic scaling. However, the maximum R.F. values never exceed the maximum achieved ohmic values. As this limit is approached, the m=2 activity increases, as in the ohmic case, and we show that this increase correlates well with the increase in ($\beta + l_i/2$).

Results : This paper studies the increase in ($\beta + l_i/2$) measured during Alfvén Wave Heating (f~2.5 MHz) on the TCA tokamak (R, a = 0.61, 0.18 m, $B_\phi \leq 1.51$ T, $I_p < 135$ kA, D_2), and compares the results with ohmically heated discharges. When the R.F. pulse is applied, there is a significant and rapid increase in the value of the Shafranov ($\beta + l_i/2$) calculated from the vertical field and plasma current. The origins of this increase, whether mainly β, mainly $l_i/2$ or both, are discussed in a companion paper [1]. Figure 1 illustrates the changes in ($\beta + l_i/2$) when different R.F. power levels are applied, for a range of plasma currents and three excitation conditions (driving predominantly n=4, n=1 and n=2 waves). The increase in ($\beta + l_i/2$) is largest for low plasma currents and most effective for the n=4 modes. Since, under our standard conditions, the n=4 resonance surfaces are in the outer part of the plasma, this result is at first sight surprising. This whole issue is further complicated by the substantial increase in density which occurs during the R.F. pulse.

In order to proceed further, we have studied the values of ($\beta + l_i/2$) obtained in quasi-stationary ohmic discharges for three values of toroidal field (0.78, 1.16, 1.51 T) and plasma currents from 40-135 kA. The wide range of values obtained, Fig. 2a, can be reduced to an extremely good description of the density dependence by using the quantity $\Lambda^* \cdot (I_p/130\text{ kA})$ where $\Lambda^* = (\beta + l_i/2 - 0.7)$. The value 0.7 was selected to give the least deviation in the data. This quantity does not itself appear to have any absolute merit. However, we can redraw Fig. 2b scaled by $1/B_\phi$ in which $\Lambda^* \cdot (I_p/130\text{ kA}) \cdot (1.51\text{ T}/B_\phi)$ is a well defined function of $\overline{n_e}/B_\emptyset$, the Murakami parameter. That is to say the value of $\Lambda^*(\overline{n_e})$ divided by the value of β_p at the Troyon limit is determined by the fraction of the operational density range in ohmic conditions. The selected value 0.7 chosen to generate Λ^* corresponds to the minimum value of $(\beta + l_i/2)$ at high current (q_a=3), being roughly $l_i/2$ for q_a=3. At lower currents $(\beta + l_i/2 - 0.7)$ does not correspond to β, since the $l_i/2$ contribution is then larger (Fig. 1a).

When we look at non-stationary ohmic discharges, $(\beta + l_i/2)$ can be higher than predicted by the stationary scaling, for example during a rapid density ramp-up. An example is shown as a dashed line trajectory in Fig. 2b.

At the higher levels of R.F. power, the discharge evolution follows a much higher trajectory in the same plane and the maximum $(\beta + l_i/2)$ values achieved were shown in Fig. 1. Figure 2 shows the same results versus the plasma density and a certain alignment is already visible. With some hindsight we replot the data on the $\Lambda^* \cdot (I_p/130\ \text{kA})$: $\overline{n_e}$ plane, Fig. 4, with a typical trajectory shown as a dashed line. The R.F. accessed region is way above the quasi-stationary ohmic scaling, and exceeds the trajectory for hard gas-puffing. The different plasma currents and excitation modes are now indistinguishable. The most noticeable feature is that the maximum $\Lambda^* \cdot (I_p/130\ \text{kA})$ does not exceed the maximum ohmic value, that is, the ohmic value near the density limit ($\overline{n_e} \sim 8\text{x}10^{19}\text{m}^{-3}$). At the lowest densities the effect of the R.F. is most marked, that is, when the ohmic discharge is "weakest".

The data shown in Fig. 4 are those obtained in pulses which did not disrupt. On trying to exceed this experimentally observed limit, a disruption will ensue, characterised by a progressive increase in the $B_{\theta a}$(m=2) amplitude. This form of disruption is similar to the density limit disruption, but at a lower density, one at which there would be no significant m=2 activity in a quasi-stationary ohmic discharge. However, when we consider $\Lambda^* \cdot (I_p/130\ \text{kA})$ as the determining parameter the phenomenology of the two types of disruption is similar, Fig. 5. The details of the excited spectrum are, however, important as already noted [2], and can systematically alter the dependence of Fig. 5, but not by very much. The observation that the disruptions are most likely to occur near a mode threshold corresponds to the observation that the highest point in the $\Lambda^* \cdot (I_p/130\ \text{kA})$: $\overline{n_e}$ plane is also frequently close to a mode threshold.

The power levels in Fig. 1 (a,b,c) are much lower than the available R.F. power. It has always been considered that the n=2 excitation is preferable in that much more R.F. power can be delivered than for n=1, n=4. On reanalysing the highest power data, the trajectories of those shots do, nonetheless, lie within the distribution of Fig. 4. We had found a way of increasing the power acceptance in conditions in which the increase in $(\beta + l_i/2)$ had virtually saturated. In general, the longer R.F. pulses with lower ramp-rates produced less marked increases in $(\beta + l_i/2)$, and tolerated a greater level of R.F. power.

Discussion : These results show that all the quasi-stationary ohmic data can all be described by a simple law relating $(\beta + l_i/2)$ to the Troyon limit and the Murakami factor for a given density. In this parameterisation, the maximum achieved $(\beta + l_i/2)$ is simply studied for varying plasma conditions, and we find that, although we exceed the ohmic conditions for low density plasmas, we do not exceed the maximum value for $\overline{n_e}=8\times10^{19}m^{-3}$.

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References

[1] Th. Dudok de Wit at al., paper presented at this conference.
[2] K. Appert et al., 1987 Int. Conf. on Plasma Physics, Kiev, USSR, 1987. (LRP 321/87)

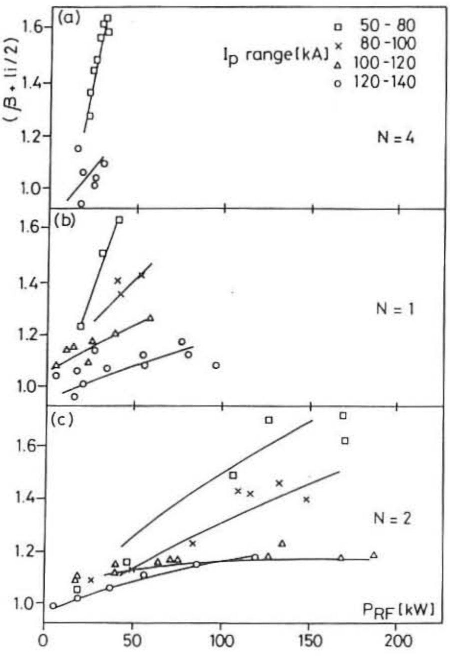

Fig. 1 $(\beta + l_i/2)$ achieved as a function of both delivered R.F. power and plasma current for a) n=4 b) n=1 c) n=2 [B_ϕ=1.51 T, f=2.5 MHz, D_2].

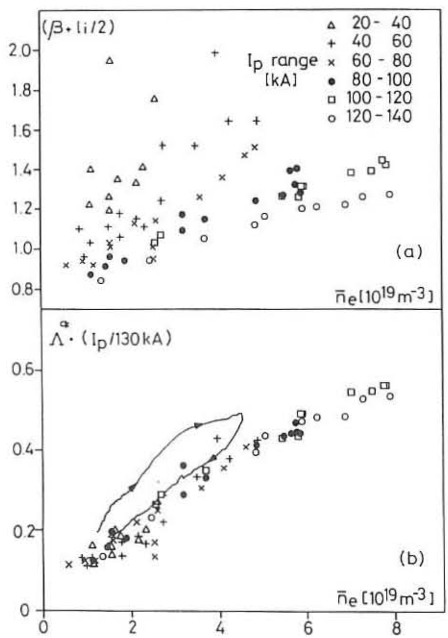

Fig. 2 a) $(\beta + l_i/2)$ as a function of n_e for ohmic discharges with different plasma currents b) $\Lambda^* \cdot (I_p/130\ kA)$ for the same data [B_ϕ=0.78, 1.16, 1.51 T, D_2].

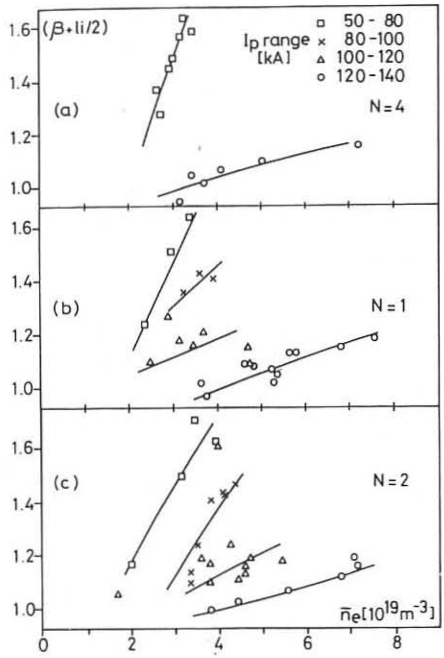

Fig. 3 The data of Fig. 1 replotted as a function of the maximum density reached.

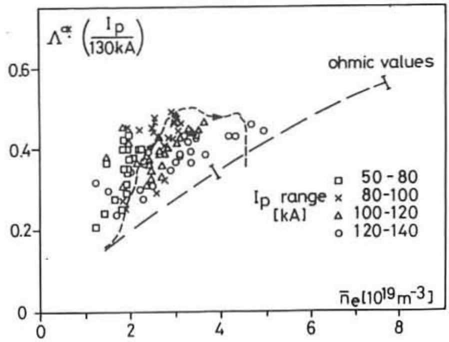

Fig. 4 R.F. discharges in the $\Lambda^* \cdot I_p : \bar{n}_e$ plane, for different plasma currents [B_ϕ=1.51 T, f=2.5 MHz, D_2].

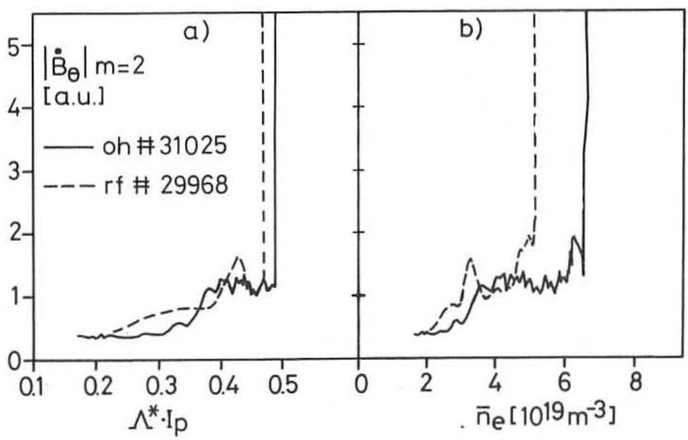

Fig. 5 Evolution of the m=2 amplitude as a function of a) $\Lambda^* \cdot I_p$ and b) $\bar{n}_e$ for ohmic and R.F. discharges.