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START-UP AND RAMP-UP OF THE PLT TOKAMAK BY LOWER HYBRID WAVES

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ABSTRACT

Lower hybrid waves have been used on the PLT tokamak both to start the plasma current and to ramp it up from pre-existing levels. The waves, at 800 MHz, were launched from a 6-waveguide grill. The phasing between adjacent guides could be selected electronically, and thus the launched spectrum could be set and changed at will. For start-up, the waveguide phase difference was initially set at 0° in order to create a plasma, then switched to 90° to drive the current. Over 100 kA of plasma current, at a density of 0.5-1 x 10^{12} cm^{-3}, was generated in this manner. Ramp-up experiments were performed under a wide variety of conditions. The most efficient ramp-up was found at the lowest plasma densities and with the fastest launched spectrum ($n_e \sim 2 \times 10^{12}$ cm^{-3}, $N_{\parallel} \sim 1.6$ peak); ~ 20% of the launched RF power was converted to (increased) poloidal field energy. All of the ramp-up results are in excellent agreement with a theory which determines the efficiency of ramp-up from the consideration of the relative energy losses of the superthermal current-carrying electrons to collisions and to the opposing inductive E-field.

INTRODUCTION

In a tokamak fusion reactor, as in all tokamaks, the confinement of the reacting plasma will be provided by two orthogonal magnetic fields, the toroidal and poloidal fields. The toroidal field is generated by a system of coils external to the plasma. Whereas in most present day tokamaks these coils are resistive, in a reactor they will presumably be superconducting. For present devices, the duration of the toroidal field, at least at the highest fields these machines can produce, is limited by coil heating; for the reactor, on the other hand, the field will be on for unlimited duration. Because of the pulsed nature of the toroidal field, among other reasons, present tokamaks are pulsed devices, and thus rapid start-up is a necessary part of their operation.

Unlike the toroidal field, the poloidal field of a tokamak is generated mainly by a current internal to the plasma. In a reactor, furthermore, the energy in the poloidal field is enormous, ~ 1 GJ. This field, however, is not lossless, and there is no prospect of making it lossless. At present, this is of little consequence, because the poloidal field can generally be maintained with a transformer for as long as the duration of the toroidal field, with the poloidal field being restarted by the transformer near the beginning of each toroidal field pulse. However, in a reactor with a transformer as the source of the poloidal field the discharge would again need to be pulsed, and repetitive start-up would be a routine part of the reactor operation. On the other hand, if the poloidal field were to be maintained steady state, like the toroidal field, then start-up of the confining fields would be an occasional event which could be performed slowly and under conditions most suitable to it. In this case, the fusion burn might or might not be pulsed; if it were, burn start-up would be a simpler process with a much lower power consumption than it would be if the poloidal field also needed to be started up. The large, repetitive mechanical stresses of inductive start-up would also be eliminated by the slow start-up and steady-state maintenance of the poloidal field.

Even if a true steady-state poloidal field were *not* to be utilized, these advantages might be retained if most of the field were conserved between fusion burns. One possible method of conserving poloidal field would be to allow the current to decay (with ~ 1 hr time constant) during the burn and then to restore the current with a current drive scheme for a short time between burns.[1] A variant would be to maintain the current during the burn with a transformer, and then recharge the transformer between burns, while maintaining the poloidal field with current drive. In this latter scheme, the transformer would need to have less than 10% of the drive capability of a full tokamak transformer (or, alternatively, the burn time could be extended by a factor of 10). Also, the vacuum vessel could be made very robust because the flux would penetrate the vacuum vessel extremely slowly.

Lower hybrid current drive (LHCD) is an inherently steady state means of maintaining the poloidal field of a tokamak. However, the energy losses of LHCD, which are proportional to density, are projected to be too great in a fusion reactor for LHCD to be economically feasible during the burn state of the reaction cycle.[2] Nevertheless, LHCD could be extremely useful in restoring poloidal field energy between burns, since the density during this time could be significantly lower than during the burn. Like all current drive schemes, the rate at which LHCD can build up the poloidal field is limited by the power available at the RF source; magnetic energy cannot be stored up in advance and transferred to the poloidal field rapidly, as is done by a transformer. In situations not requiring a rapid build up, LHCD appears, by extrapolation from present experiments, to be capable of supplying the full required poloidal field energy.

Experiments have been performed on PLT and other tokamaks to examine the role of LHCD in start-up[3-5] and ramp-up,[6,7] as well as to examine the efficiency of steady-state current drive.[8-11] Both the start-up and the ramp-up experiments on PLT were quite successful, with the start-up experiment obtaining currents up to 20% of full current for PLT, and the ramp-up experiments obtaining ramp-up efficiencies of ~ 20% (efficiency meaning the ratio of the increase in magnetic field energy to the RF energy expended).

START-UP

Both the start-up and the ramp-up experiments reported here were carried out on the PLT tokamak, a torus with a major radius of 1.32 m and a minor radius of 0.4 m, at toroidal fields of 20 to 30 kG. The LHCD apparatus on PLT for these experiments consisted of a 6-waveguide grill on an outside port, with each waveguide independently driven by a 160 kW, 800 MHz source.[3,8,12] For start-up, two different grills were used: a narrow one, with each waveguide 2 cm wide, and a wide one, 3.55 cm; both were 22 cm high. The couplers are shown in Figs. 1 and 2. The parallel phase velocity v_{ph} of the wave was determined by the relative phasing of the individual waveguides, which was set electronically at the inputs to the sources. For the experiments reported here, $\Delta\phi$ was 60°, 90°, and 135°, corresponding to an average $N_{\parallel}$ ($= c/v_{ph}$) of 2.7, 4.1, and 6.1 for the narrow grill, and 1.5, 2.3, and 3.4 for the wide one; the spectral width (at half maximum) was 2.7 for the narrow grill, and 1.5 for the wide one.

With either coupler, the background gas, which was deuterium at 1-2 × 10^{-5} Torr, was broken down by the injection of up to 200 kW of RF power, and a plasma of line average density of (0.5-1) 10^{12} cm^{-3} was formed. The phase angle between waveguides during this 10-30 msec initial stage was set to 0° to minimize wave reflection in the mouth of the waveguides prior to plasma formation. Following the breakdown stage, the waveguide phasing was electronically switched to 90° or 135° so that the waves would propagate toroidally and drive an electron current.

In the experiments with the narrow grill, the launched spectrum was both relatively slow and also wide. This grill was found to be relatively poor both at ramping up current and at handling high power, but it was capable of starting up the current by itself. Successful discharges up to 28 kA (5% of full current for PLT) were created by this grill, as shown in Fig. 3. The density was not controlled, except by the initial gas fill; however, it increased as the current increased, possibly as the result of better particle containment accompanying the current. No temperature or X-ray measurements were made with the narrow grill start-up experiments, and after this experiment it was removed from PLT and has never been replaced.

In order to achieve the initial start-up of the current, the equilibrium field (EF) had to be adjusted so as to cancel out the small net vertical field of the toroidal field coils. With the narrow grill, once this bias field had been found, the current would start up, and the PLT feedback control system would then add in extra EF as needed to maintain the plasma column centered in the vacuum vessel.

With the wide grill, on the other hand, the current did not start up by itself. Instead, careful programming of the EF, in addition to the bias field, proved necessary prior to the start-up. After the RF had been turned on at 0° phasing, to establish a plasma, the EF was decreased in magnitude for ~ 20 msec, and then returned rapidly to the bias level; this gave a flux change of about 0.01 V_{sec}. Simultaneously, the phasing of the grill was changed from 0° to 90° or 135°, and the current started up.

The wide grill was significantly better than the narrow grill at driving currents and at ramping them up. Thus, in the start-up with this grill, the current rose quickly to 30 kA at a rate of $\sim$ 200 kA/sec, followed by a 2 sec rise to over 100 kA at a 35 kA/sec rate, as shown in Fig. 4. The density in this case remained about constant at $\sim 10^{12}$ cm^{-3}; again there was no gas puffing.

Soft X-ray emission (< 10 keV) from the main body of electrons shows that the central electron temperature rose to 300 eV in 50 msec and then slowly rose to 400 eV during the remainder of the pulse. At a 10 cm radius, carbon ion CV emission indicates that T_e was > 200 eV, while the very soft X-ray temperature shows it as varying from 250 to 350 eV. Hard X-ray measurements indicate that the current was carried in an energetic electron tail, as has also been shown for steady-state current drive. Soft X-ray emission (10-30 keV) shows that the fast electrons were centered on axis and had a radial extent of about 12 cm.

In this experiment, about 500 kJ of RF energy was launched into the tokamak (P_{rf} = 200 kW for 2.5 sec). Of this, approximately 20 kJ was converted into poloidal field energy, with $\sim$ 4 kJ going into the internal poloidal field energy. The kinetic energy was less than 1/4 of the internal field energy, that is, less than 1 kJ ($\beta_\theta + \ell_i/2 = 0.4$; $\beta_\theta < 0.1$). Collisional dissipation should have absorbed no more than 12 kJ, if such absorption was in keeping with our steady-state measurements. Thus we are able to account for only 33 kJ: more than 90% of the RF energy must have flowed out of the plasma unmonitored. However, for these low density and current conditions, both the tail and the bulk electron energy confinement might be poor. It should be noted that conversion efficiencies of about five times better than this have been measured in the ramp-up experiments.

RAMP-UP

Poloidal field start-up is really an initiation of plasma current followed by a long current ramp-up. In order to study more fully the effectiveness of the whole start-up process, a detailed study has been made of the ramping up of the plasma current in PLT. To do this, a data base was generated from the results of many days of run time, during which much, but not all, of the effort was directed toward ramp-up. The data include both ramp-up and ramp-down; this discussion will emphasize the ramp-up aspects. Because the narrow grill rarely, if ever, achieved ramp-up, the data base includes data only from the wide grill; this section, and the remainder of the paper, will be concerned only with the wide grill.

The principal quantity used in this study was the power flow, $\dot{W}$, into (or out of) the energy W of the poloidal field. $\dot{W}$ was considered a dependent variable in this study, with RF power and phase, and plasma density and current as independent variables. The inductive energy $W = I_p^2 L/2$ can be determined from the equation for the inductance of a torus:

$$L = \mu_o R_M [\ell n(8R_M/a) - 2 + \ell_i/2] \quad , \qquad (1)$$

where I_p is the net plasma current, R_M and a are the major and minor radii of the plasma column (in meters), and $\ell_i/2$ is the (unitless) internal inductance of the plasma column. $\ell_i/2$ can be determined from the Shafranov equilibrium equation:

$$4\pi B_{eq} R_M = \mu_o I_p [\ell n(8R_M/a) - 3/2 + \ell_i/2 + \beta_\theta] \ , \tag{2}$$

where B_{eq} is the equilibrium magnetic field required to maintain the plasma column centered in the vacuum vessel and $\beta_\theta = 1/2\ (\beta_\perp + \beta_\parallel)$ is the plasma internal pressure. β_θ is not well-known in PLT; we estimate the component of β_θ resulting from the energetic electron tail to be ~ 0.1-0.2. In most of the calculations presented here we assume $\beta_\theta = 0.15$.

The power flow into the inductive energy is not by itself an adequate measure of the RF ramp-up effectiveness because there is also flow into W from the ohmic heating (OH) and equilibrium field (EF) coils. Instead, the power flow equation is used:

$$P_{ex} + \eta P_{rf} = \dot{W} + D \ , \tag{3}$$

where P_{ex} is the external inductive power flowing into W from the OH and EF coils, P_{rf} the RF power, η the fraction of P_{rf} absorbed in the ramp-up process (that is, current drive), and D is the dissipation of the current in the plasma. D in turn consists of two parts, the collisional dissipation of the RF driven current, which is not resistive, but which is voltage-like, and the resistive dissipation resulting from any electric fields in the plasma:

$$D = I_d V_c + V^2/R \ , \tag{4}$$

where I_d is the driven current and V_c its dissipation term normalized to an effective one turn loop voltage, V is the axial loop voltage of the electric fields, and R is the effective resistance of both the superthermal current-carrying electrons and the bulk background plasma. A theoretical expression for V_c, derived from the work of Fisch,[13,14] is:

$$V_c = 6.2\ 10^{-5}\ n_e \bar{N}_{\parallel} N_{\parallel}'\ R_M (Z+5)\ \text{Volts}, \tag{5}$$

where n_e is in units of 10^{12} cm^{-3}, $\bar{N}_{\parallel}$ is the average $N_{\parallel}$ in the spectrum of the waves, and $N_{\parallel}'$ the largest $N_{\parallel}$ (that is, the slowest electron velocity to which the wave can match). Z is the effective ionic charge.

Equation (3) can be rewritten:

$$P_a + \eta P_{rf} = D\ , \tag{6}$$

where $P_a = P_{ex} - \dot{W} = V\ I_p$,

and also $I_p = I_d + V/R$,

P_a, the axial inductive power, is completely known, and is an important quantity; in the absence of current drive ($P_{rf} = 0$) P_a is equal to the dissipation in the plasma. In ramp-up, P_{ex} is usually rather small, so that P_a is generally a negative quantity: it is therefore useful to define $\dot{W}' = -P_a$ for discussions of ramp-up. $\dot{W}'$ can be thought of as being the power $\dot{W}$ flowing into W, corrected for a small P_{ex}. Then a form of Eq. (3) which is most useful is:

$$\dot{W}' = \eta P_{rf} - D\ . \tag{7}$$

If D were to remain constant, then W' should increase linearly with P_{rf}.

For the purposes of the data base, all relevant waveforms, including calculated quantities such as P_a and V, were averaged over the duration of the RF pulse, but beginning 50 msec after the start of the RF. However, if the density varied during the RF pulse, averaging was done only over the time during which the density remained within 0.5 x 10^{12} cm^{-3} of the minimum density within the pulse. The 50 msec delay was utilized so that changes in β_θ from the build up of the superthermal electron tail would not affect the calculations. Some key parameters were also averaged over the whole RF duration. The RF system was equipped with arc protection circuitry which would shut the RF off briefly if reflections were too high. Such shots were rejected from the data base if the RF had not been on for 99% of the time.

For the experiments which generated this database, the tokamak was run with deuterium plasmas. The density of the target plasmas ranged from 1.5 to 6×10^{12} cm^{-3}, and the current from 150 to 400 kA. Typically, the OH transformer was precharged to ~ 5 kA, and then reversed, as in normal PLT operation, but then the primary current was clamped. Thus the plasmas were initiated, but not maintained, by the OH system. This resulted in a plasma with a central electron temperature $T_e \sim 1$ keV. $\Delta\phi$ was 60°, 90°, and 135°, corresponding to an average $N_\parallel$ of 1.5, 2.3, and 3.4.

RF ramp-up is illustrated in Fig. 5, which shows the I_p waveform for several different RF powers, along with a no RF case. The lowest RF power shown, 40 kW, was the equilibrium power for plasma conditions of this particular scan, $\Delta\phi = 60°$, $I_p = \sim 200$ kA, $n_e = 2.2 \times 10^{12}$ cm^{-3}. At the highest power shown, the current ramps up at 120 kA/sec during the time the density was constant. This corresponds to $\dot{W} = 89$ kW; however, since P_{ex} was about 19 kW, $\dot{W}'$ was 70 kW. The ramp-up efficiency ε, defined as $\dot{W}'/P_{rf}$, then was 23%.

At and above 260 kW, a subsidiary effect limited the ramp-up process. A small hot spot (< 1 cm^2) appeared on the limiters; subsequently, an uncontrolled increase in density (possibly caused by out-gassing from the hot spot) then curtailed further ramp-up. The density increase was accompanied by a large increase in carbon V emission. The density trace for the 260 kW case is shown in Fig. 6, *illustrating this effect. Because of this hot spot, the* higher power pulses were restricted to 300 msec, whereas the lower power pulses were 350 msec. The data base program, however, limited the analysis of the ramp-up to the part of the discharge in which the density remained near the minimum density during RF on time (2.2×10^{12} for Figs. 5 and 6). All these times are short compared to the L/R time (> 1 sec) of the plasma column.

The time-averaged $\dot{W}'$ as a function of RF power is shown in Fig. 7, along with many other data points taken at the same *plasma* conditions; these are the x's. Also shown are similar data taken at three other conditions: $N_\parallel = 2.25$ and 3.40, and for $N_\parallel = 2.25$, $n_e = 2.25$, and 3.0×10^{12} cm^{-3}; I_p was 200 kA in all four cases. These data can be seen to fall on four distinct, more or less straight lines. If straight lines are indeed fitted to these four data sets, the slopes of the lines range from about 23% for the top line to 10% for the bottom set. Roughly, this is an indication of what the ramp-up efficiency is. The lines are separated both because of the differing slopes and because the intercepts are also different. These intercepts can be interpreted as the steady-state dissipation. As such, they are in rough agreement with the theoretical dissipations calculated *using* V_c *from Eq. (5). It should be noted* that the total dissipation should be close to D_c ($= I_d V_c$) only for $\dot{W}' \sim 0$ (no ramp-up). For $\dot{W}' \neq 0$, the data points should tend to drop below the lines; the further $\dot{W}'$ is from zero, the more this should happen.

The *ramp-up efficiency,* ϵ, is shown in Fig. 8 for the most efficient case, the top line (X's) of Fig. 7. The maximum efficiency obtained was about 20%. For the calculations used to obtain Figs. 7 and 8, $\dot{W}'$ was averaged after 50 msec, and β_θ of 0.15 was assumed based on X-ray measurements of the tail distribution for similar discharges.[15-18] During the first 50 msec of the RF pulse, β_{eq} [(of Eq. (2)] increases because of the buildup of the superthermal tail, and hence of β_θ. In the absence of a waveform for β_θ, there is no way to correct B_{eq} for the β_θ portion of its change. After 50 msec, it is sufficient to assume β_θ is a constant.

Another simplified analysis, which lumps all the data together, can be derived by dividing Eq. (7) by D_c:

$$\dot{W}'/D_c = \eta P_{rf}/D_c - \alpha \quad , \qquad (8)$$

with $\alpha \equiv D/D_c$.

If the dissipation of each shot is closely related to the theoretical steady-state current drive dissipation D_c, then α should be a global constant for the whole data base. If the fraction of the RF power going into ramp-up is also the same for all conditions, then Eq. (8) is a straight line with slope η and intercept $-\alpha$. That is, if these assumptions are correct, and if the quantity $\dot{W}'/D_c$ is plotted versus P_{rf}/D_c for each shot in the data base, then the plotted points should fall on a straight line with slope η and intercept $-\alpha$. Figure 9 is such a plot, and it can be clearly seen that the points do indeed cluster near to the straight line plotted, which is $\eta = 0.275$, $\alpha = 1.23$. This graph supports the concept that the dissipation of the driven current is close to the theoretical value; it also suggests that over all about 25% of the wave energy was absorbed in current drive. It should be noted that the data points shown in this graph and also Fig. 10 were not corrected for β_θ, and the averaging was done over the whole duration of the RF pulse (unless the density was not constant). Also, as can be seen in Fig. 7, there is some variability in the slope, and hence in η, as a function of plasma conditions (or, perhaps, of ramp-up rate).

THEORY

A theory of current drive in the presence of a DC electric field has been developed to explain these ramp-up results.[19,20] This theory is much more thorough than the empirical explanations given in the preceding section. In essence, the theory divides the current-carrying electrons into two categories; those with parallel velocities less than and those greater than the runaway velocity v_R associated with the E-field and the plasma density. Because the E-field is opposed to the velocity of these electrons, it does not cause them to run away, but rather acts to slow them down. In so doing, they give up energy to the E-field, which means putting energy into the associated poloidal field. Collisions, too, slow down the electrons, and, simultaneously with both slowing down processes, the electrons also regain energy from the RF wave. Electrons with velocities greater than v_R are more likely to lose energy to the E-field than to collisions, whereas the slower electrons are more likely to slow down by collisions. Thus ramp-up with electrons faster than v_R should be more efficient than with slower electrons. The theory determines the fraction of RF power which is converted into electric field energy.

The useful output of this theory is a relationship between a corrected ramp-up efficiency and the ratio u of the wave phase velocity to v_R. In this case, the corrected ramp-up efficiency, ϵ^*, is the ratio of $(\dot{W}' + V^2/R)$ to P_{rf}, not the simpler and somewhat more useful $\epsilon = \dot{W}'/P_{rf}$. Here R is the resistance of the bulk plasma and not the net resistance of the bulk and the superthermal electrons because the effects of the superthermal conductivity are already accounted for in the theory. The runaway velocity used in this theory is proportional to, but not the same as, the Dreicer runaway velocity;

specifically, it does not include a Z scaling which Dreicer did use. v_R, as used here, is directly related to the dissipation of the superthermal electrons. Specifically:

$$u^2 = (v_{ph}/v_R)^2 = 2/3\ (V/V_c)\ . \qquad (9)$$

Theory and experiment can be matched, then, if e* and u can be calculated for each point in the data base, and compared with the e*(u) curve given by the theory. Unfortunately, to do this, individual values of R are needed, and R is generally unknown. However, R can be estimated from the few Thomson scattering T_e measurements that were taken during current drive (although during steady-state current drive and at a somewhat higher density than most of the data base), and using Z_{eff} = 4 estimated from X-ray measurements.[15-18] Typically, T_e was about 1 keV (peak) for which R = 9)X. If a power balance model is used to estimate T_e, taking both the containment time (15 msec) and the temperature profile $[1 - (r/a)^2]^m$, m = 4 from an average of the Thomson scattering measurements, then electron temperatures of less than 1 keV would be expected for the lower power shots of the data base, but higher than 1 keV at the higher powers. For the 260 kW case of Fig. 5, for instance, the calculated T_e is 1.35 keV, the bulk back current V/R is 70 kA, and power dissipated in this back current is 28 kW.

The match between theory and experiment can be seen in Fig. 10. For this plot, a value of N approximately 10% greater than the launched spectral peak was used, to compensate for an expected up-shift in N in the plasma because of toroidal effects. As in Fig. 9, all the points in the data base, both ramp-up and ramp-down, are plotted, and no correction made for b_r. Also, the theoretical curve has been normalized by a factor ζ representing the fraction of the wave power absorbed in current drive. In Fig. 10, $\zeta = 0.425$. It can be seen that, with this normalization, the match is very good indeed. The curve for ε^* increases monotonically as u increases, eventually saturating at ζ for large u. This is not true of ε, the ratio of poloidal input power to RF power. ε is less than ε^* by V^2/RP_{rf}, which increases with u; for the data in this data base, V^2/RP_{rf} can be fairly well approximated by a u^4 curve. Using this approximation, the ratio of poloidal input power to RF power, ε, can be calculated, and is shown as the dashed lines in Figs. 9 and 10.

DISCUSSION

In start-up, the initiation of the current by RF alone proceeded well, once the proper equilibrium magnetic field had been found. This was true with both grills, even though the wide grill needed a very small amount of assistance from the EF field. Thereafter, the ramp-up proceeded at the rates of about 100 and 200 kA/sec for the narrow and wide grills, respectively (see Figs. 3 and 4), until about 30 kA was reached. This was an efficiency of about 5 and 10% for the two grills at that current. For the wide grill, this was about half the best efficiency obtained.

Although the narrow grill did not go above this level, the wide one did, but at a much reduced ramp-up rate. The overall ramp-up efficiency was 4%, which is only 1/5 of the best ramp-up rate (20%) produced with this grill. The reason for this low efficiency during start-up is unknown: arcing in the grill and in the transmission lines made the system inoperable just after the ramp-up to over 100 kA had been obtained, and further experimentation was not possible. Unfortunately, the experiments have not been repeated yet. One possible explanation of the low efficiency is the arcing itself. One or two of the waveguides may have had very little power. Besides reducing the net power, this would have completely altered the launched spectrum, and thereby reduced the usable current drive power even further. If the arc started at the time the current reached ~ 30 kA, then this could explain the sudden change in the ramp-up rate.

Another possible explanation is that the plasma was somehow different than during the ramp-up experiments. There are three obvious differences, and all three may have degraded the efficiency. The density, the current, and the temperature were all lower. The confinement of the bulk and tail electrons was probably also low. We would have expected the low density to have caused the efficiency to be better. However, at these low densities the discharges may have consisted of a relatively dense core detached from the limiters (and the grill). In this case, the coupling of the wave to the current-carrying core of the plasma could have been quite different than in the other current drive experiments.

The low electron temperature, on the other hand, would be expected to reduce the efficiency. In general, there is a gap between the slowest phase velocity of the launched waves and the fastest electrons in the thermal distribution of the plasma. (Here "fastest electrons" means the fastest velocity at which there is a sufficient number of electrons to carry the driven current when these electrons are accelerated up to the average velocity *of the wave. This velocity is generally taken to be three times* the *thermal* velocity.) With a colder plasma, the gap is bigger, and whatever mechanism fills the gap is very likely to work less well. Since electron tempeatures are generally lower in lower current (OH driven) discharges, the lower current in the start-up experiments might have led to the reduced temperature, which in turn may have reduced the efficiency. By itself, however, the lower current probably would not have reduced efficiency, except for poor electron confinement.

For ramp-up, this gap argument can be used the other way. The best ramp-up efficiency ($\sim$ 20%) was obtained at very low density, $\sim 2 \times 10^{12}$ cm^{-3}. While this density is much too low for the Thomson scattering system on PLT to measure T_e, it is thought to be about 1 keV. At this temperature, the gap is still large, and there is very little overlap between the electron velocity distribution and the wave spectrum. If the plasma were hotter, however, the gap would go away. A wave with some reasonable power at $N_\parallel = 2.5$ should sufficiently overlap a 4.5 keV plasma so that the wave by itself could accelerate electrons up to the fastest wave velocity (and hence the best current drive) without any gap-filling mechanism. This opens the possibility that ramp-up in hotter plasmas might be more efficient. The hope then exists that efficiencies of 50-60% might be possible.

Countering such possible improvement in efficiency with increased electron temperatures is the increased back current V/R that would occur as R decreases with temperature (assuming no anomalous resistance occurs). The only way to reduce this current in a tokamak with a given temperature is to reduce the ramp-up rate. This would have to be done anyway since the L/R time is longer in a hotter tokamak, and it is very difficult to increase substantially poloidal field energy in a time shorter than L/R. Thus, even if there is better ramp-up efficiency at higher temperatures, it would not result in a quicker buildup of the current. Instead, less RF power would be needed to achieve the same results.

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[17] S. von Goeler *et al.*, in *Proceedings of the Fifth Topical Conference on Radio Frequency Plasma Heating* (University of Wisconsin, Madison, Wisconsin, 1983), p. 96.

[18] J. Stevens *et al.*, in *Proceedings of the Fifth Topical Conference on Radio Frequency Plasma Heating* (University of Wisconsin, Madison, Wisconsin, 1983), p. 164.

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FIGURE CAPTIONS

Fig. 1 The narrow 6-waveguide grill for 800 MHz lower hybrid waves. The individual guides are 2.0 cm wide and 22 cm high. With a 90° phase difference between waveguides, the peak of the launched spectrum is at $N_\parallel = 4.1$.

Fig. 2 The wide grill. The individual guides are 3.55 cm wide and 22 cm deep. The peak of the launched spectrum is at $N_\parallel = 2.25$ for a phase difference of 90° between waveguides.

Fig. 3 Start-up with narrow grill. Waveforms of plasma current and density. The grill was phased at 0° for 30 msec to generate a plasma and then the phase changed to 90° to start-up the current. $P_{rf} = 200$ kW.

Fig. 4 Start-up with wide grill: current waveform. $P_{rf} = 200$ kW, N_e was $\sim 1 \times 10^{12}$ cm^{-3} throughout, and $T_e \sim 250$ to 350 eV.

Fig. 5 Current ramp-up for various RF powers, $N_e = 2.2 \times 10^{12}$ cm^{-3} and $N_\parallel = 1.5$.

Fig. 6 Density, loop voltage, and internal inductance parameter $(\beta_\theta + \ell_i/2)$ waveforms for the 260 kW case of Fig. 5.

Fig. 7 Corrected inductive power $\dot{W}' = \dot{W} - P_{ext}$ as a function of RF power for the four different conditions shown in the table. For all conditions, the plasma current was 200 kA. β_θ of 0.15 was assumed in calculating $\dot{W}'$.

Fig. 8 The ratio of corrected poloidal energy flow $\dot{W}'$ to net RF power P_{rf} as a function of P_{rf} for the condition shown in X's in Fig. 7.

Fig. 9 Inductive power vs RF power, both normalized to DC. The line shown corresponds to a dissipation 1.23 D_c and to a power utilization η of 27.5%. The dashed curve is calculated from the theory of Fisch and Karney.[19]

Fig. 10 Corrected efficiency, ε^*, vs u for 240 PLT shots. The RF power P_{rf} varied from 0 to 300 kW, the density from 1.5×10^{12} to 6.0×10^{12} cm^{-3}, the plasma current from 150 to 400 kA, launched $N_\parallel$ of 1.5(*), 2.25(+), and 3.4(#). The solid curve ist the theoretical curve, with a normalizing factor of 0.425. The dashed curve is the efficiency, ε, calculated from ε^* using a simple model of the correction factor as a function of u.

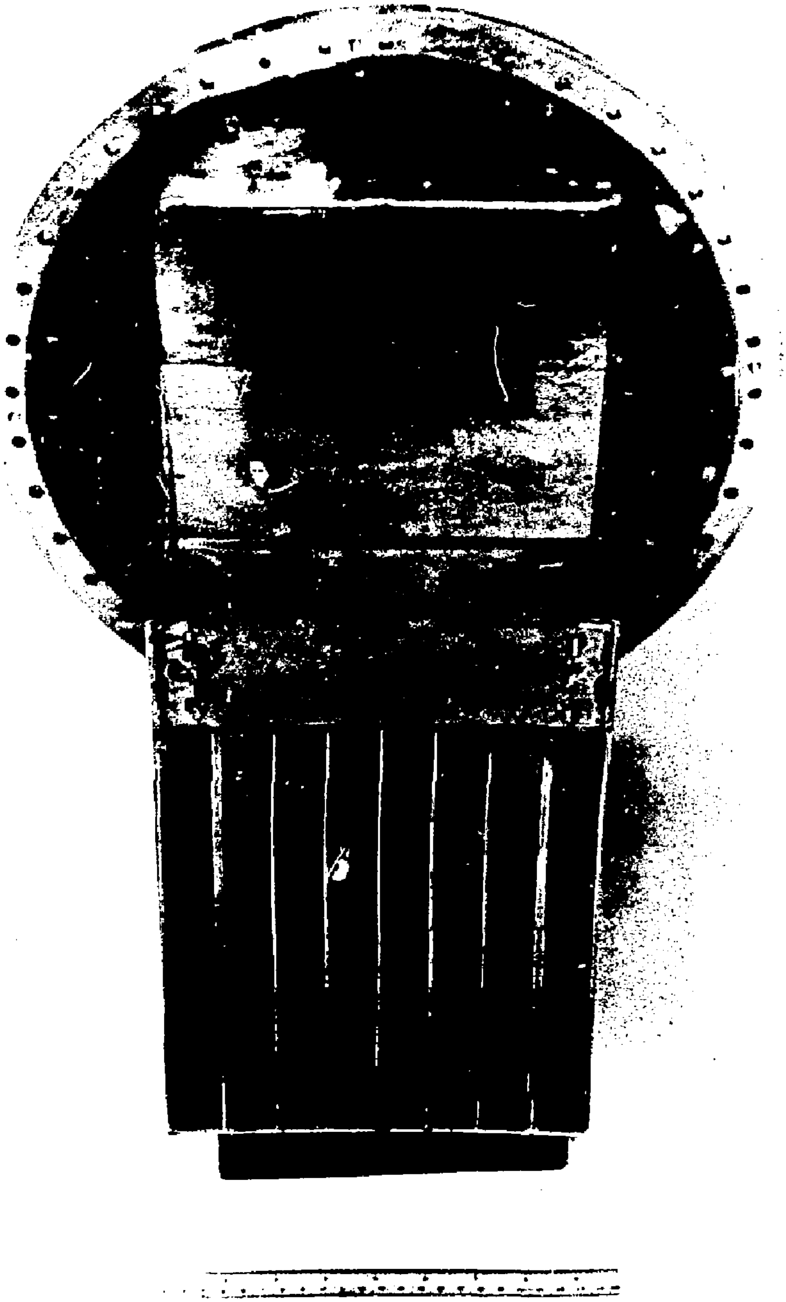

Fig. 1

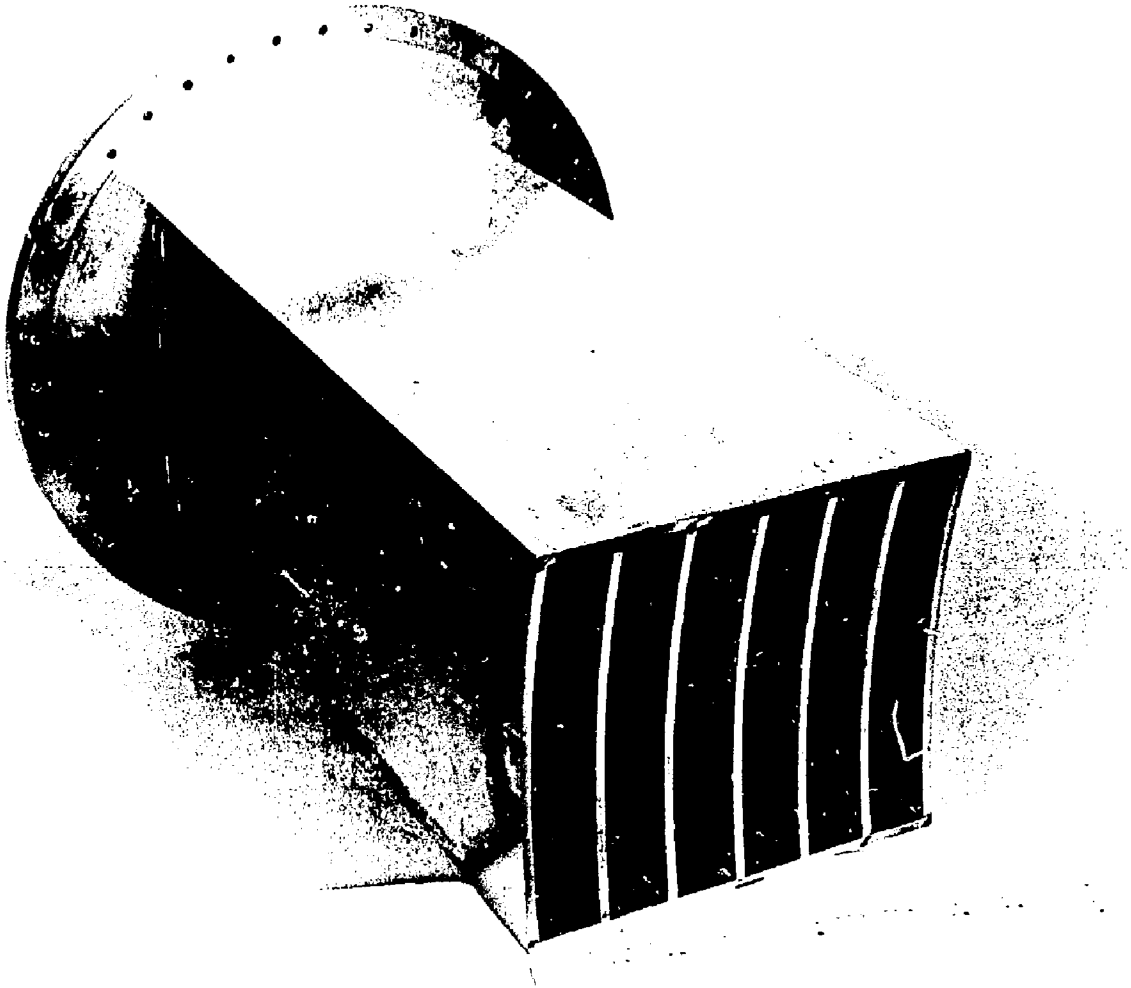

Fig. 2

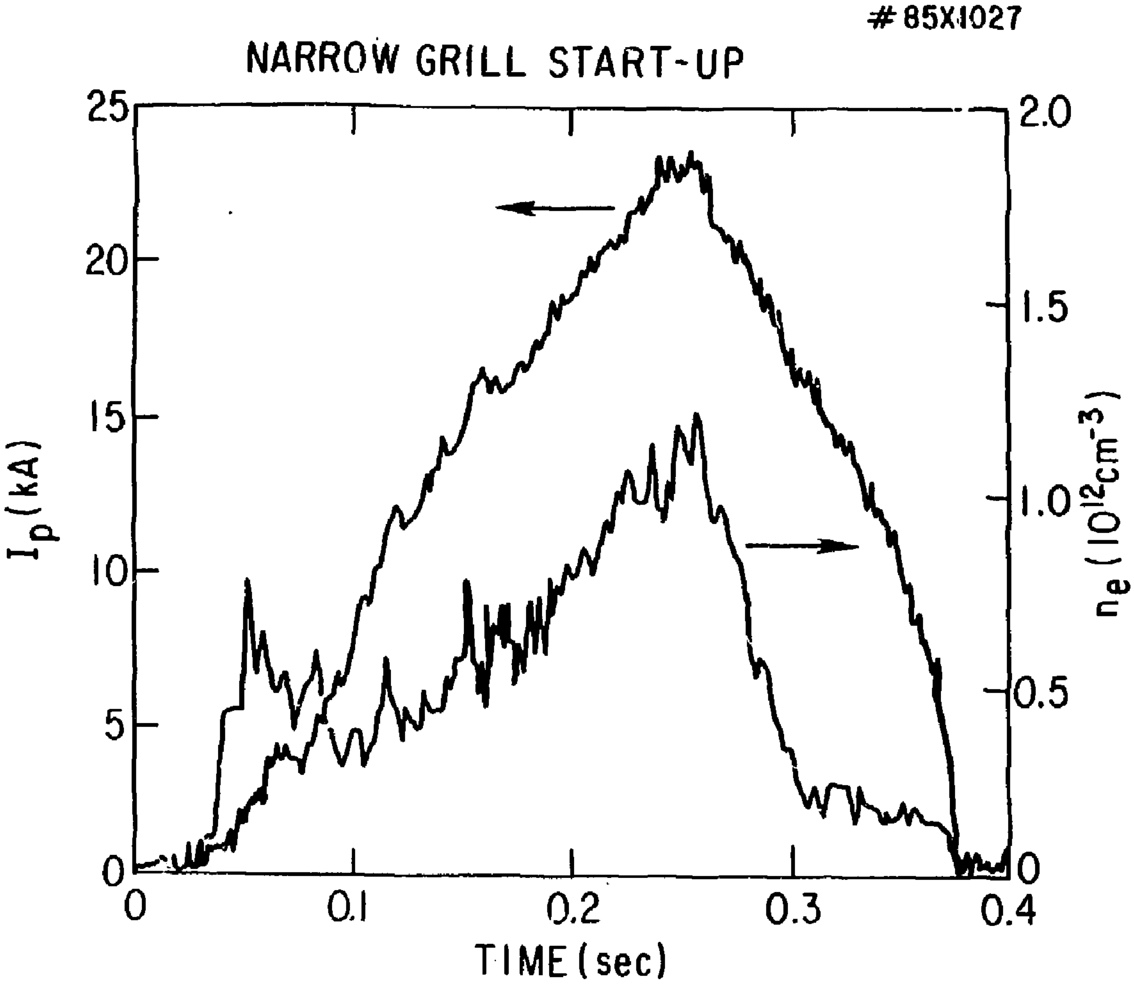
#85X1027
NARROW GRILL START-UP
I_p (kA)
n_e (10^{12}cm^{-3})
TIME (sec)
0
5
10
15
20
25
0
0.5
1.0
1.5
2.0
0
0.1
0.2
0.3
0.4

Fig. 3

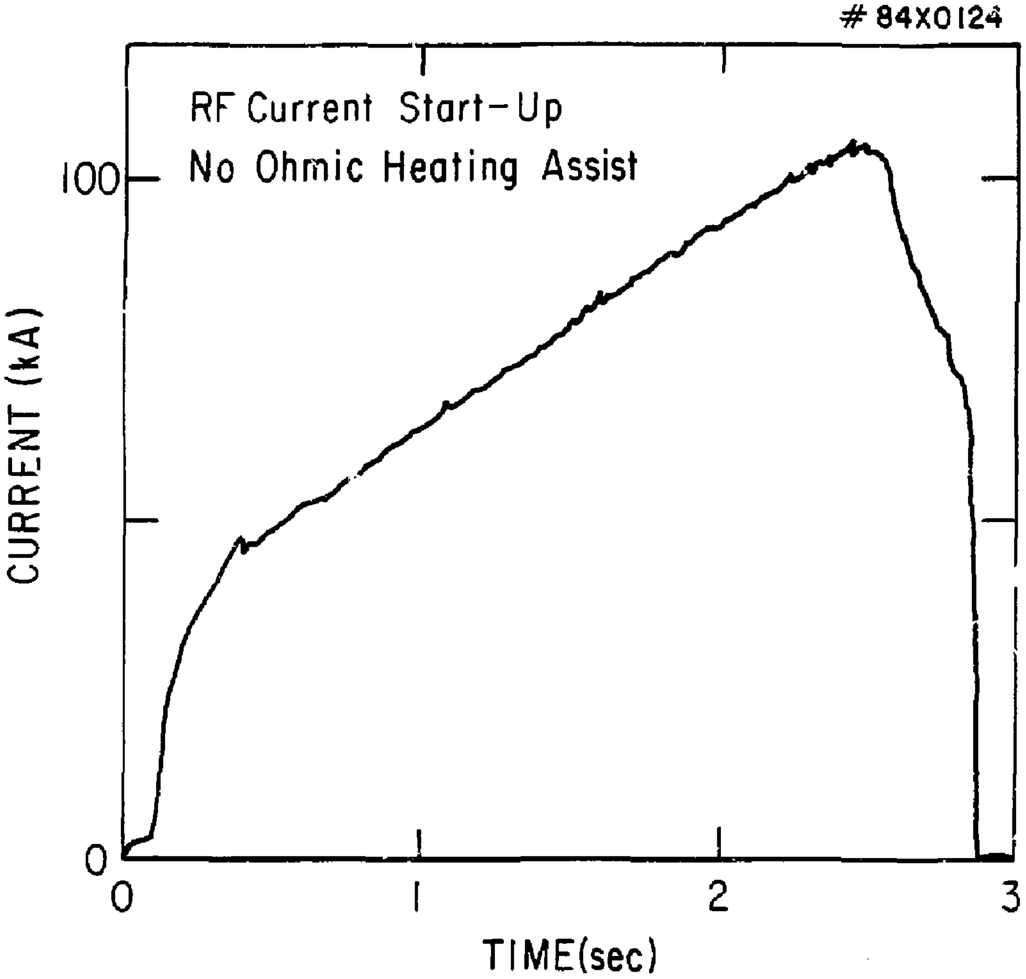
84X0124
RF Current Start-Up
No Ohmic Heating Assist
CURRENT (kA)
100
0
0
1
2
3
TIME(sec)

Fig. 4

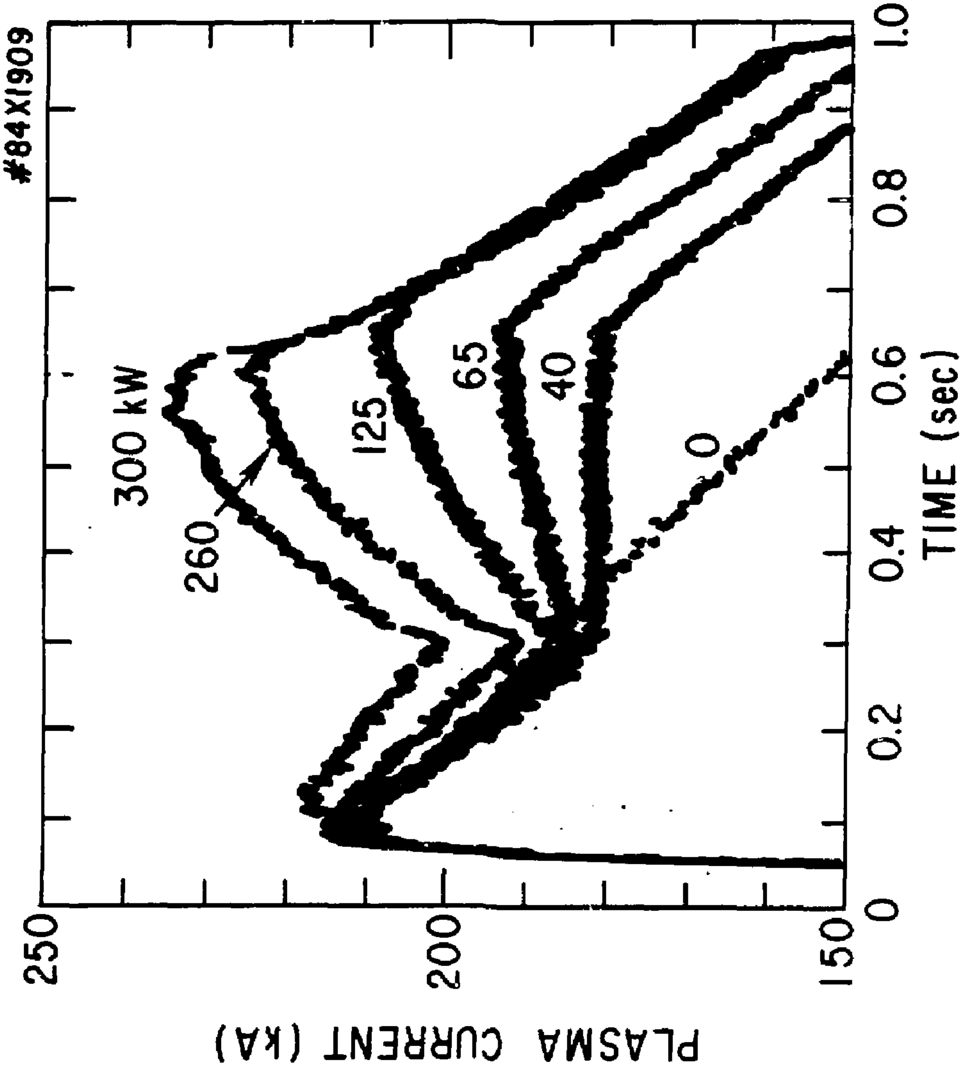
#84X1909
300 kW
260
125
65
40
0
PLASMA CURRENT (kA)
250
200
150
TIME (sec)
0
0.2
0.4
0.6
0.8
1.0

Fig. 5

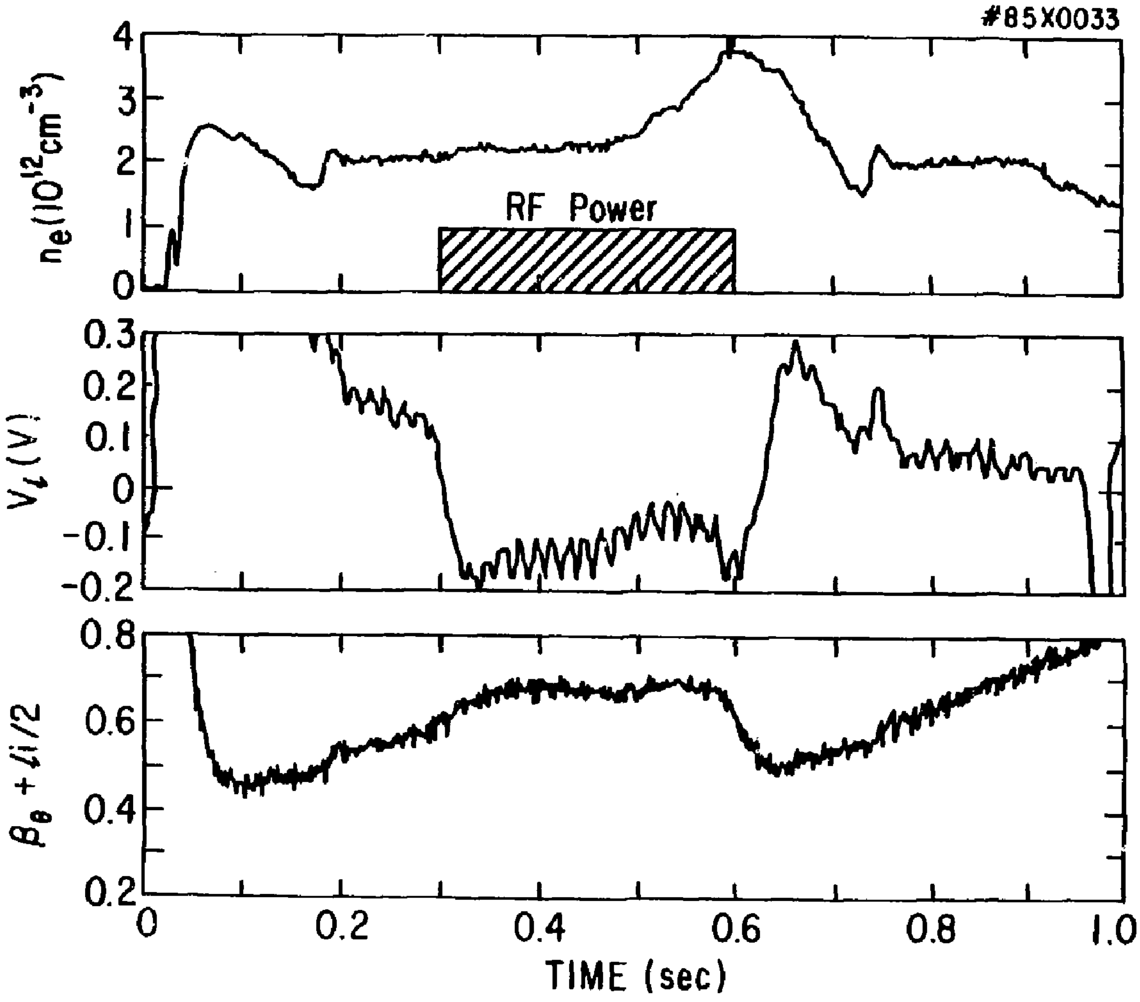
#85X0033
$n_e(10^{12}cm^{-3})$
4
3
2
1
0
RF Power
$V_\ell(V)$
0.3
0.2
0.1
0
-0.1
-0.2
$\beta_\theta + \ell i/2$
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
1.0
TIME (sec)

Fig. 6

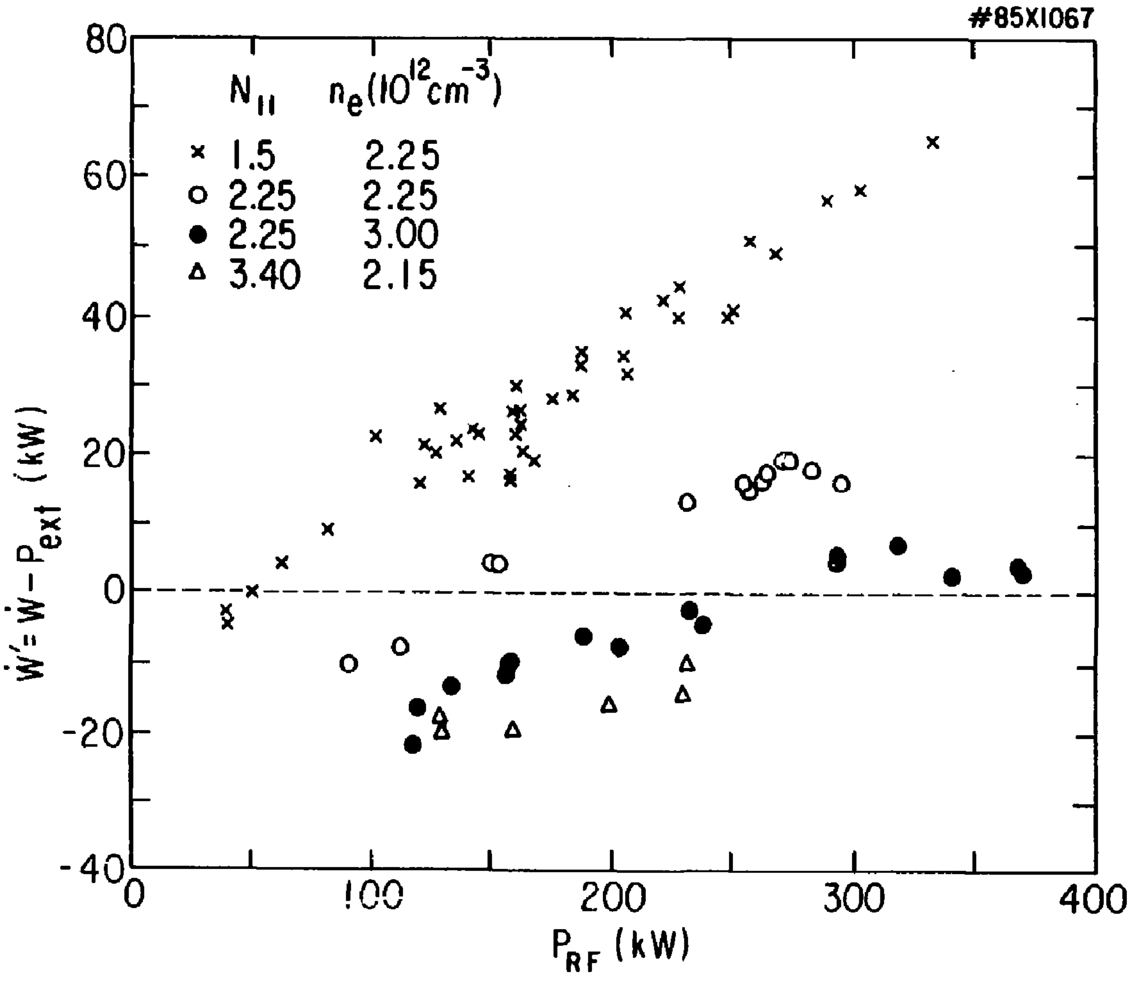
#85X1067
$N_{\parallel}$
$n_e(10^{12}cm^{-3})$
× 1.5 2.25
○ 2.25 2.25
● 2.25 3.00
△ 3.40 2.15
80
60
40
20
0
-20
-40
$\dot{W}' = \dot{W} - P_{ext}$ (kW)
0
100
200
300
400
P_{RF} (kW)

Fig. 7

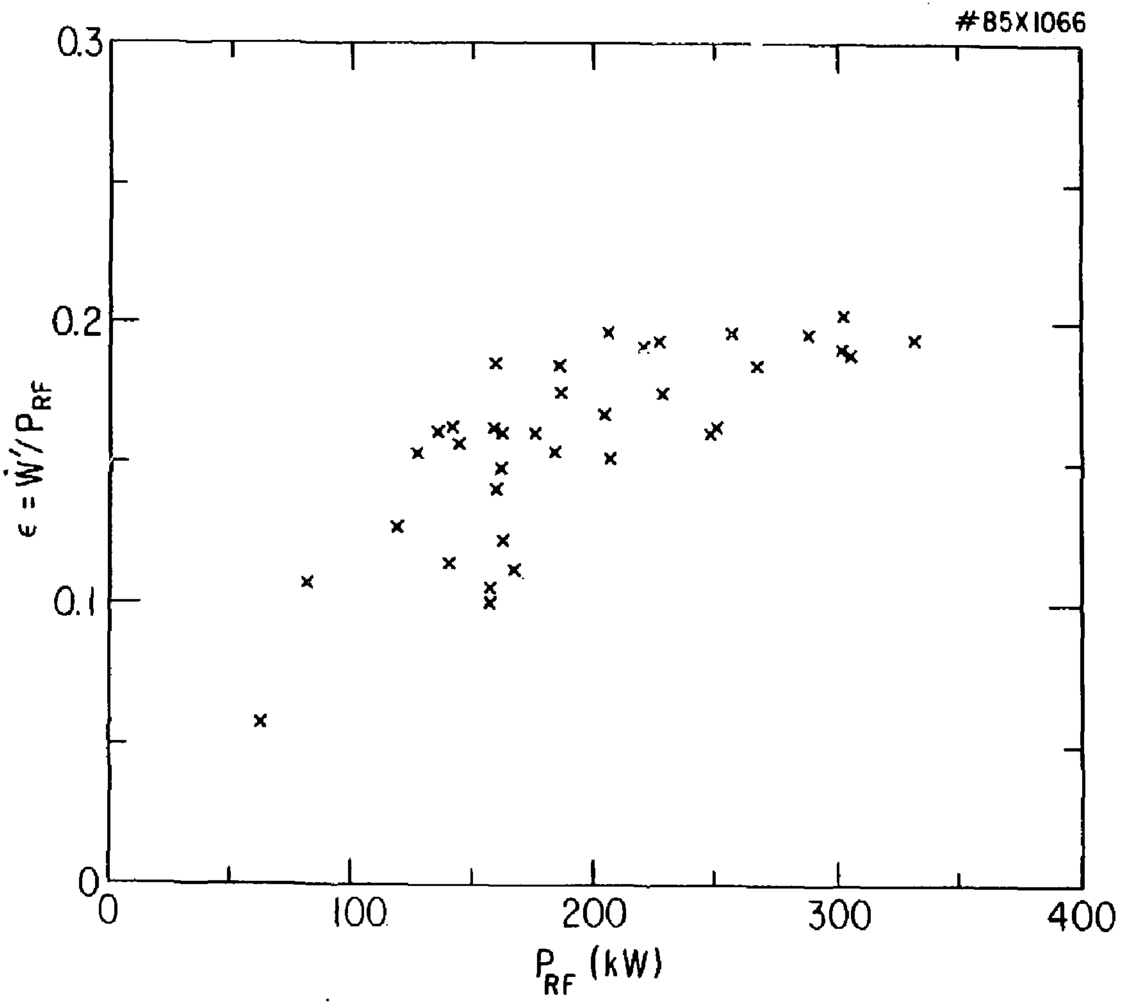

Fig. 8

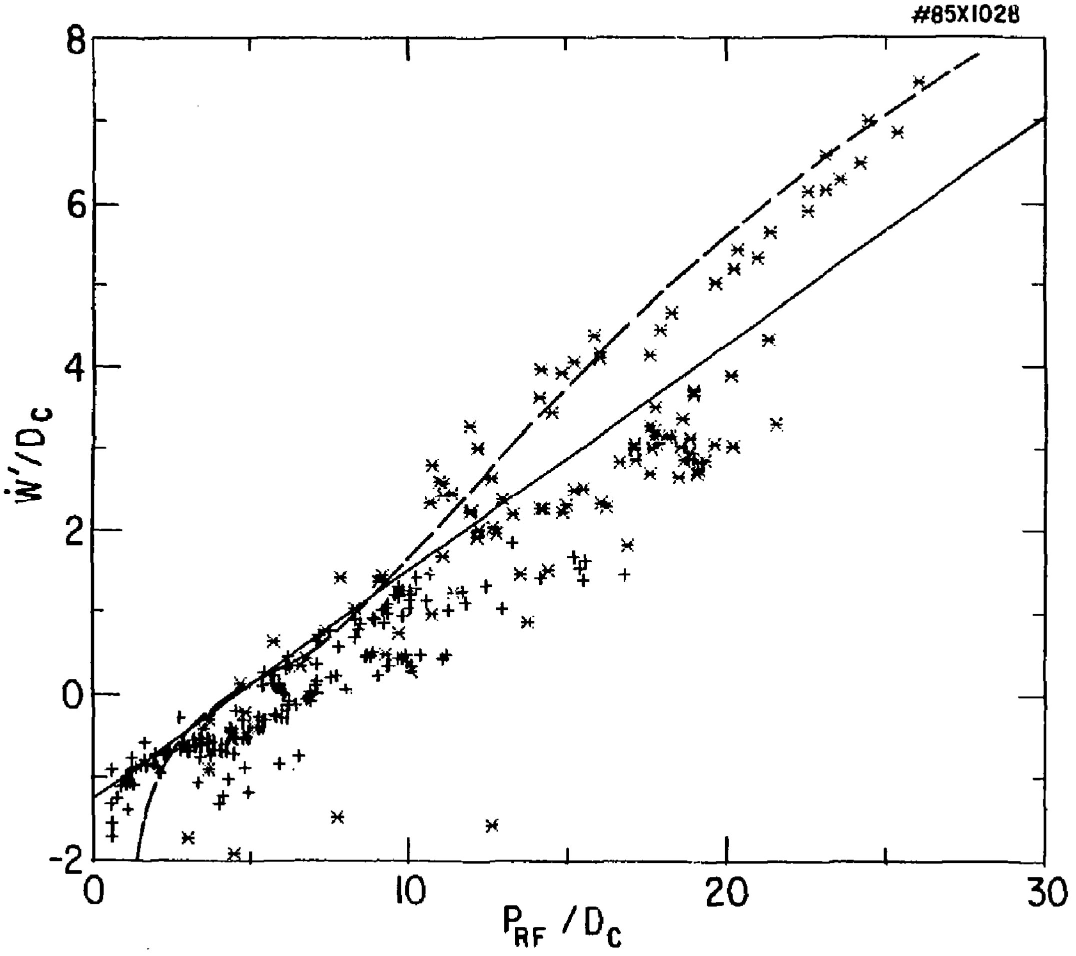

Fig. 9

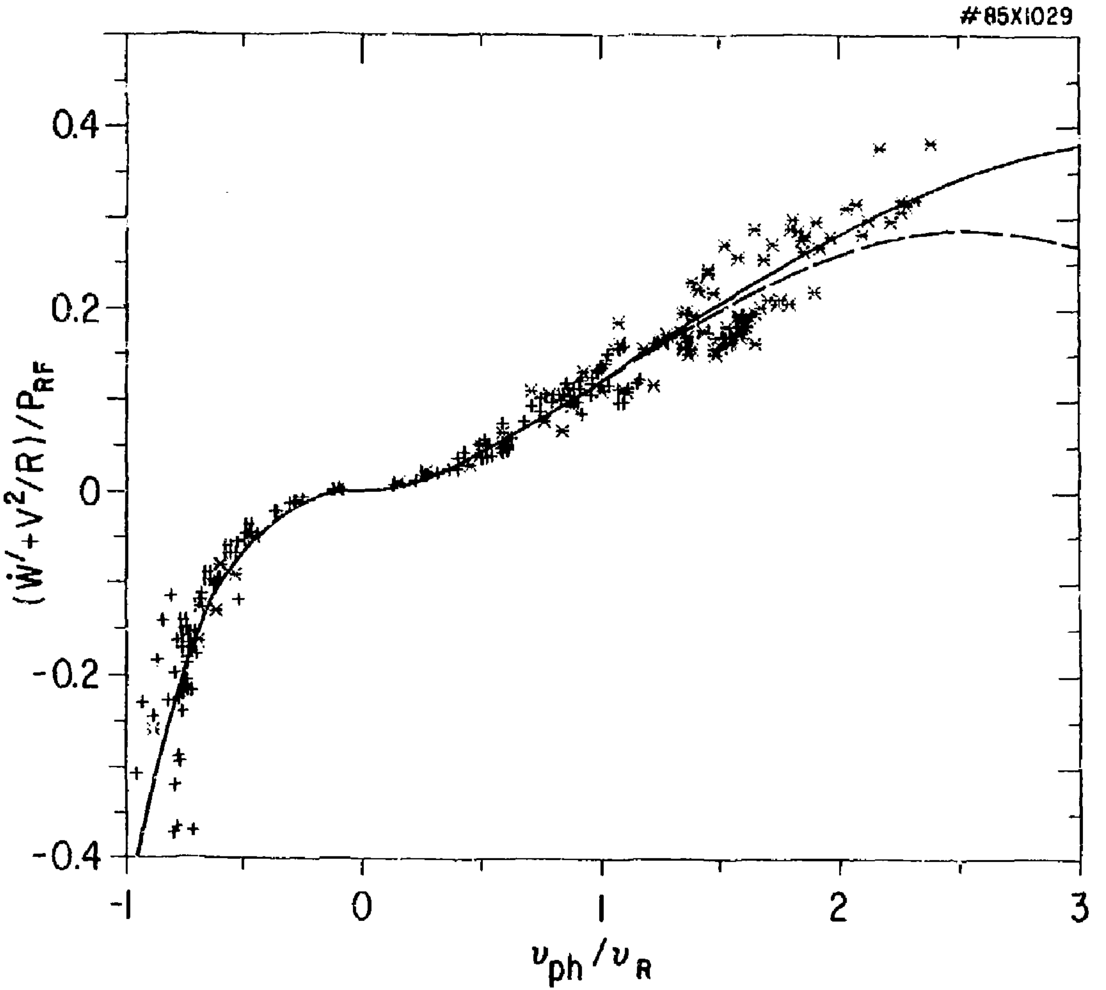

Fig. 10

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