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TOKAMAK START-UP WITH ELECTRON-CYCLOTRON HEATING

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ABSTRACT. Experiments are described in which the start-up voltage in a tokamak is reduced by about a factor of two by the use of a modest amount of electron cyclotron resonance heating power for pre-ionization. The solution of the zero-dimensional start-up equations indicates that the effect is due to the high initial density which increases the rate at which the conductivity increases in the neutral-dominated initial plasma. The effect extrapolates favourably to larger tokamaks. A 50% reduction in the start-up volt-second requirement and impurity reflux is also observed.

One important technological difficulty with a tokamak fusion reactor is the high toroidal voltage required to initiate the discharge when the temperature, density and conductivity are low and energy losses are dominated by line radiation from low-Z, partially-stripped impurities [1]. One possible means for reducing the loop voltage is the use of electron cyclotron resonance heating (ECRH) to produce a plasma of modest conductivity before the onset of Ohmic heating [2]. ECRH has the added advantage of initiating the discharge in a local region away from the walls so that one might expect reduced impurity reflux from the walls during the early stages of the discharge when the plasma is poorly confined.

ECRH has been used previously for plasma production in a purely toroidal field. Anisimov et al. [3] injected microwave power from the high-magnetic-field side and observed absorption at the upper hybrid layer. ECRH bulk heating in tokamaks with high power (100 kW) gyrotrons has also been performed [4, 5]. A comparison of pre-ionization techniques was performed by Bulyginskii et al. [6] in FT-1. Main-electric-field breakdown and initial-reverse-field breakdown were carried out at roughly twice the loop voltage which was recorded for the 50 kW of the ECRH pre-ionization discharge. It is noteworthy that the 50 kW were launched from the low-field side. Cho et al. [7] launched about 20 kW into WT-1 in the vertical plane. WT-1 exhibited an initial-loop-voltage reduction of about 40% with this ECRH. Gilgenbach et al. [8] used 80 kW from the high-field side of ISX-B and observed pre-ionized densities of 5×10^{12} cm^{-3} and electron temperatures of about 10 eV. It was suggested that the 40% reduction in loop voltage was due to the initially low resistivity of the pre-ionized plasma. Our work differs from other published work in that the voltage reduction is achieved with lower ECRH power (10 kW) and hence lower initial densities. In addition, we have injected both from the low-field side and the vertical plane with similar results. Furthermore, we provide a zero-dimensional start-up code which indicates that the effect (1) arises from the ECRH-induced start-up density which raises the time derivative of the conductivity of the neutral-dominated plasma and (2) scales favourably with machine size (proportional to a^2).

The experiments were performed on the Tokapole II device [9], a tokamak with a four-node poloidal divertor (Fig. 1). The device was operated at toroidal fields of ~ 3 to 6 kG on axis so that readily available microwave sources at 9 and 16 GHz with nominal output powers of ~ 10 kW for ~ 500 μs could be used. The ECRH pre-ionization is applied before the Ohmic heating voltage (Fig. 2) when the magnetic field is purely toroidal; thus the ECRH resonance zone is a vertical cylinder with radius adjustable via the toroidal field strength. The wave is launched from the low-field side or vertically from the midcylinder. The observation of loop voltage reduction is independent of the launch sites. A previous report [7] described ion saturation current measurements and visible light measurements made on this ECRH plasma alone with no Ohmic heating ($n \sim 10^{10}$ cm^{-3}, $kT_e \sim 10$ eV); the plasma density profile is strongly peaked at the electron cyclotron resonance position, but extends to the outer wall, consistent with the fact that no equilibrium exists with a purely toroidal field. Electric-field measurements show a vertical electric field which gives rise to an outward $\vec{E} \times \vec{B}$ drift, consistent with the observed outward motion of the plasma. An X-ray detector consisting of a thin aluminium-coated plastic scintillator with a photomultiplier located on the midcylinder shows a dramatic increase in X-rays when the cyclotron resonance lies exactly on the midcylinder.

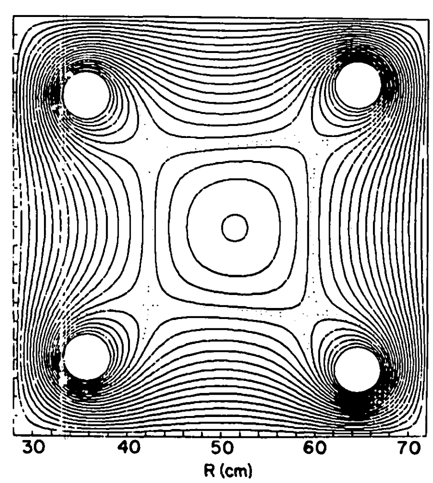

FIG. 1. Poloidal magnetic flux plot as calculated by an MHD equilibrium code. The four current-carrying internal rings provide the divertor field. The flux plot has been experimentally verified through internal magnetic probe measurements.

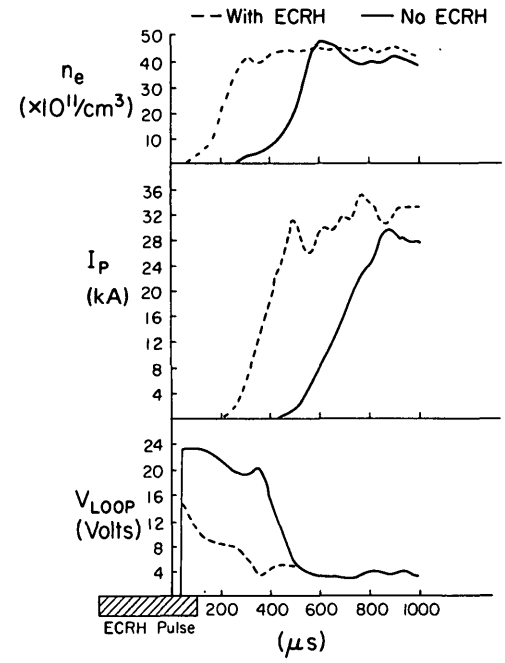

FIG. 2. Loop voltage on minor axis, current and electron density versus time during start-up with and without ECRH pre-ionization.

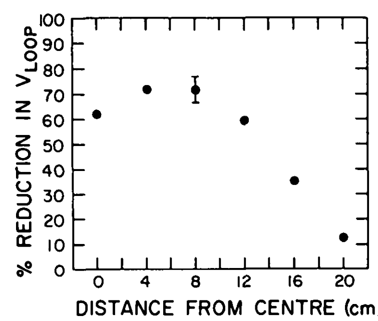

FIG. 3. Percentage by which loop voltage is reduced by ECRH versus position. Resonance held fixed at 4 cm from axis. Data are taken at 200 s.

The effect of present interest is the reduction in the start-up toroidal loop voltage. ECRH is observed to reduce the voltage at the machine centre by almost a factor of two (24 V to ~ 15 V) as is shown in Fig. 2. The reduction lasts for about 400 μs with negligible effect on plasma parameters after ~ 1 ms. Measurements of the spatial profile of the loop voltage using a probe (described in Ref. [9]) indicates that the voltage reduction decreases gradually with radius, and monotonically goes to zero at the wall (Fig. 3). The ECRH does not change the voltage at the wall (the gap voltage) simply because it is fixed by the external circuitry. The gap

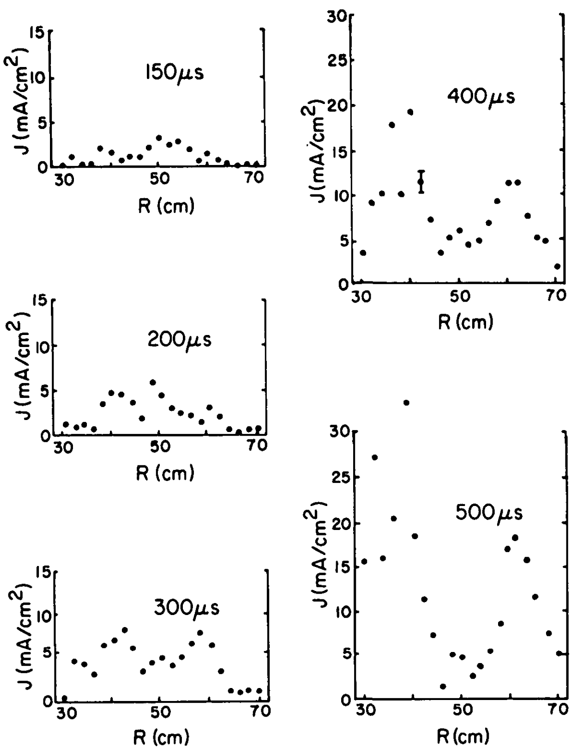

FIG.4. Spatial profiles of plasma current density during tokamak start-up, taken with a small Rogowski coil.

voltage decays sinusoidally in time; thus the same gap voltage is applied with and without ECRH in order to obtain the same plasma parameters late in time in both cases. Alternatively, the beneficial effect of ECRH pre-ionization can also be demonstrated by reducing the applied gap voltage to the lowest value for which a normal long-duration discharge is able to form. Without ECRH a vacuum loop voltage on axis of 16 V (2.5 $V \cdot m^{-1}$) is required, but, in the presence of ECRH, this value drops to 10 V (1.6 $V \cdot m^{-1}$). Thus the reduction in start-up voltage obtained with ECRH is roughly the same whether it is lowered by the external circuit (at the wall) or by the plasma.

It is instructive to evaluate voltage reduction where the plasma current flows. Spatial profiles of plasma current measured with a small Rogowski coil (2 cm diameter) show that for the first 200 μs the plasma has a very broad peak at the minor axis (Fig. 4). Measurements made with a 0.63-cm-diam. paddle probe [10] are almost identical. Thus the start-up loop voltage has, on the average, been reduced by roughly a factor of two at the location of the plasma.

At about 300 μs after the Ohmic heating has been applied, the current profile develops a distinct peak roughly midway between the minor axis and the wall. This is most likely caused by the inhomogeneity of the applied electric field which rises monotonically from the centre to the wall. By about 1.5 ms the central current channel has fully evolved, and the plasma current has a maximum on the central magnetic axis. This behaviour is virtually identical with and without ECRH pre-ionization, except for earlier start-up with pre-ionization.

As the ECRH power is only a small fraction ($\lesssim 1\%$) of the Ohmic input power, the loop voltage decrease is *not* due to replacing Ohmic power for an equivalent amount of ECRH power. Furthermore, the loop voltage reduction is not a sensitive function of the ECRH power level (in the range ~ 1–10 kW). The following set of zero-dimensional equations is used to model the start-up phase and to reveal the cause for the loop voltage reduction:

$$V_\ell = IR = V_v - L\frac{dI}{dt} \qquad (1)$$

$$\frac{d}{dt}\left(\frac{3}{2}nT_e\right) = \frac{I^2R(n, n_0, T_e)}{Vol} - \frac{3/2\, nT_e}{\tau_i} - P_{rad} \qquad (2)$$

$$\frac{dn}{dt} = \frac{n}{\tau_i} \qquad (3)$$

where $V_\ell = IR$ represents the toroidal loop voltage at the plasma centre, I is the toroidal current, V_v is the loop voltage that appears in the vacuum without plasma, $L \sim \mu_0 R_0 (\ln(8R_0/a) - 7/4)$ is the plasma inductance, a and R_0 are the minor and major radii, $\tau_i = n_0 \langle\sigma v\rangle$ is the ionization time, P_{rad} is the radiated power density, n and n_0 are the plasma and neutral density, and T_e is the electron temperature. The plasma resistance $R(n, n_0, T_e)$ consists of a Spitzer term and a contribution from electron-neutral collisions:

$$R(n, n_0, T_e) = \frac{10^{-5}R_0}{a^2}\left[\frac{160}{T_e^{3/2}} + \frac{1.3n_0}{n}\right] \qquad (4)$$

where all units are MKS except T_e which is in eV. Since the experimental microwave power input is small it is neglected in Eq. (2). Its pre-ionizing effect appears through the initial conditions for n and T_e. Plasma density losses are neglected since they are small relative to the ionization gain. Energy loss to the ions is neglected.

The equations evolve n, T_e and I (or V = IR). Figure 5 displays the predicted loop voltage for the

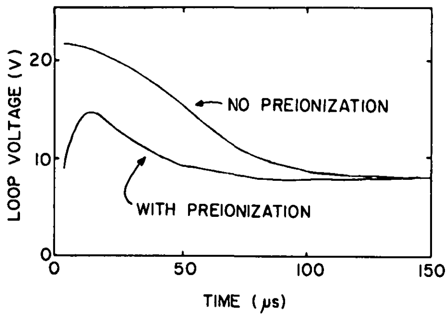

FIG.5. Loop voltage versus time, with and without pre-ionization, as predicted by a zero-dimensional code which models the start-up for Tokapole II parameters.

ECRH-assisted and unassisted cases, which are distinguished by initial conditions only. The numerical results for Tokapole II parameters exhibit loop voltage reductions similar to that seen experimentally. The effect is rather insensitive to the initial temperature. Since the start-up plasma is neutral-dominated, in that the second term is the main contributor to the plasma resistance in Eq. (4), an increase in the start-up plasma density through ECRH pre-ionization significantly raises the plasma conductivity and its time derivative and thereby reduces the loop voltage, as will be described below.

Similar benefit is derived from pre-ionization in reactor-sized tokamaks. If we assume that we can fill a volume 100 times that of Tokapole II with the required density by simply adding power, the microwave power required is ~ 1 MW. The power requirement will, however, always be negligible compared to the bulk heating needs.

The maximum loop voltage during start-up can be obtained analytically by differentiating $V_\ell = IR$ in Eq. (1) with respect to time and setting the result equal to zero to give:

$$V_{\ell,\max} = \frac{V_v}{1 + (L/R)(-\dot{R}/R)} \text{ (at the extremum)} \qquad (5)$$

This equation illustrates that it is the rate of change of the plasma resistance ($\dot{R}$) that produces the voltage reduction and not just the low initial resistance. When ($\dot{R}/R$) is comparable to or greater than R/L, the plasma current rises more rapidly than it would otherwise, and the plasma produces a back emf = LdI/dt that reduces V_ℓ. Since L/R is proportional to a^2, the result extrapolates favourably to larger devices.

For a neutral-dominated start-up one can ignore Eq. (2) and the Spitzer contribution to Eq. (4). An analytic expression for the maximum value of the loop voltage V_{max} is then easily obtained as

$$V_{\ell,\max} = \frac{V_v}{1 + \alpha} \qquad (6)$$

where $\alpha \cong 0.1\,(\ln(8R_0/a) - 7/4)\, na^2 \langle\sigma v\rangle$; and all quantities are evaluated at the time when V_ℓ is a maximum. Thus for maximum V_ℓ reduction, α (and thus na^2) should be maximized during start-up. This requirement ensures that the ionization time is comparable to the plasma L/R time in order that the density rise (or resistance drop) time is comparable to the rise time of V_ℓ to its vacuum value. In fact, both the experiment and code results indicate that the peak loop voltage during a discharge decreases with increasing pre-ionized plasma density, as shown in Fig. 6. The effect will saturate as the density becomes much higher because the resistivity is eventually dominated by the Spitzer term. It is for this reason that we are able to achieve the same factor-of-two reduction in loop voltage at 10^{10} to 10^{11} cm^{-3} as was obtained in ISX at 10^{12} cm^{-3}. If one considers a start-up density sufficiently high that the Spitzer term dominates, then similar reduction will be allowed through a high initial temperature, provided the temperature is not held at a constant value by radiation so that R is small.

In conclusion, we may state that a modest amount of ECRH power applied just before the onset of Ohmic heating in a tokamak can significantly reduce the

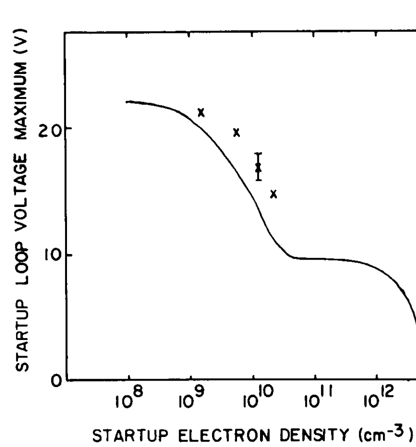

FIG.6. Maximum loop voltage during start-up versus density of the pre-ionized plasma, comparing the numerical prediction (solid line) and experimental results (X).

required loop voltage. Comparison with a zero-dimensional code describing the start-up indicates that the effect arises from the increased initial density which enhances the initial plasma conductivity (and the subsequent conductivity time derivative) in the neutral-dominated start-up plasma. The effect extrapolates favourably with machine size. However, this effect of lowering the start-up loop voltage as the plasma becomes fully ionized is to be distinguished from the separate concern of Ohmical heating to temperatures (> 20 eV) beyond which low-Z inpurity radiation is negligible. The total volt-seconds consumed up to the time of peak plasma current (~ 1 ms) are reduced by about 50%. Application of a comparable amount of second-harmonic ICRH power during start-up was observed not to have the same effect. ICRH did assist the breakdown allowing the plasma to start up earlier and hence reduce the duration of the high start-up voltage [11]. Similar, but more detailed studies of the feasibility of ICRH pre-ionization have since been done on PRETEXT [12]. Decrease in impurity radiation during start-up is sometimes observed with pre-ionization [9] and will be further studied, along with the possibility of localizing the plasma initiation with localized wave injection.

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