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NUMERICAL SIMULATION OF NON-INDUCTIVE CURRENT DRIVE FOR TOKAMAK PLASMAS WITH TIME-VARYING ELECTRON TEMPERATURES

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A relatively simple computer simulation program has been developed for the investigation of plasma behaviour during pulsed heating and current drive experiments. The temporal evolution of various plasma parameters, including the internal electric and poloidal magnetic field distributions, as well as the surface loop voltage, can be simulated under a variety of conditions. The results show clearly the difficulty of using the observed loop voltage hebaviour alone as a measure of the RF-driven current, unless the plasma parameters have had sufficient time to approach equilibrium conditions during each distinct plasma phase.

Keywords: Tokamak, JFT-2M, Fast Wave, Current Drive, Heating, Computer Simulations, Loop Voltage

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トカマクプラズマの非誘導電流駆動のシミュレーション

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（１９８９年７月１８日受理）

パルス的に加熱されたり電流駆動されたプラズマの振る舞いを調べる為に，簡単な計算機シミュレーションコードが開発された。プラズマ表面におけるループ電圧同様にプラズマ内部の電場分布，ポルイダル磁場分布等のプラズマパラメーターの時間変化を多様な条件下でシュミレートすることが可能となった。計算結果によれば，高周波印加前，印加中，印加後のプラズマの各フェーズの間にプラズマパラメーターが充分に定常にならない場合は，観測されたループ電圧から駆動された電流値を推定することは困難である事が示された。

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1. Introduction

Attention has recently been directed to (non-inductive) fast wave current drive (FWCD), as this technique appears to be a promising one for sustaining currents in tokamak reactor plasmas[1]. Convincing evidence of non-inductive current drive generally takes the form of measurements showing that the plasma one-turn loop voltage falls essentially to zero while the plasma current is being maintained by non-inductive means[2]. In order to exclude the presence of currents driven by transient (and generally undetectable) internal electric fields caused by the rearrangement of plasma current profiles, the non-inductive current drive phase must last longer than this current rearrangement time[3], given approximately by the plasma "classical skin time". Alternatively, computer simulation of the dynamic loop voltage behaviour can be undertaken in order to infer the presence of wave-driven current when steady-state conditions have not had time to establish themselves[4].

Efficient coupling of fast waves requires plasma electron temperatures in the 1.5 - 3.0 keV range, values that cannot easily be achieved solely by ohmic heating in present-day tokamaks of modest size. FWCD experiments may thus have to make use of preheated target plasmas[5], produced by injecting heating pulses (electron cyclotron or ion cyclotron resonance) which are synchronized with the FWCD pulse. Given the relatively short pulse lengths often involved in these experiments, such preheated target plasmas are not necessarily in equilibrium as far as the internal distribution of electric fields and, consequently, the measured values of the surface voltage (one-turn loop voltage) are concerned. A straight-forward interpretation of loop voltage measurements to infer FW current generation is then precluded, unless unequivocal proof of the existence of equilibrium conditions can be obtained.

While powerful computer programs capable of simulating complex plasma conditions already exist[6], it is sometimes useful to be able to perform simplified partial simulations using programs of substantially more modest size and complexity. In an attempt to understand the nature of FWCD experiments involving pulsed additional heating, a simplified program applicable to plasmas undergoing rapid temporal and spatial electron temperature variations has been developed. This program is based on a previously-developed simulation[7] used for the numerical study of lower hybrid current drive (LHCD) in plasmas with temporally constant temperature profiles.

2. Simulation Model

The following model is used as the basis for the simulation.

i) The total plasma current, I_p, remains constant. This assumption corresponds to tokamak operation in the "constant current" mode, using a feedback control system with an instantaneous time response. The value of the RF-driven current, I_{RF}, can be chosen to lie anywhere in the range $0 \leq I_{RF} \leq I_p$.

ii) The RF-driven current profile is specified explicitly by a function supplied as input to the calculation. This current profile is constant in time. The onset of RF current drive is characterized by the instantaneous appearance of I_{RF} as specified by the RF current function.

iii) The Z_{eff} value is fixed and radially constant.

iv) The resistivity of the RF-driven current is zero. For the inductively-driven current, the resistivity is given by the Spitzer value.

v) The behaviour of the plasma temperature can be chosen to simulate the following three plasma conditions

a) "Ohmic" temperature profile , characteristic of the initial plasma phase,

b) "RF preheated" temperature profile, assumed to be established instantaneously when power from an auxiliary heating source is injected into the plasma,

c) "RFCD" temperature profile, assumed to establish itself instantaneously when the RF current drive source is turned on.

The above three temperature profiles are held constant throughout each corresponding plasma phase. An exception can be made for c), where the option of an exponentially-decaying temperature profile is provided. This feature is included for simulating the gradual decay of plasma electron temperature observed in some LHCD experiments[8].

A variety of temperature profiles can be chosen, including ones with an off-axis temperature peak. No provision is made, however, to ensure profiles consistent with sawtooth activity in the plasma central region, i.e. the magnitude of the safety factor is a free parameter, and is not limited to axial values of unity or greater.

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The tokamak plasma is approximated by a cylindrically-symmetric column, with the plasma current directed along the z-axis of a cylindrical co-ordinate system (r, θ, z). All variables are functions only of radial position,

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The plasma current density, poloidal magnetic field, and internal electric field distributions are governed by Maxwell's equations

$$\mathrm{div}\,\mathbf{B} = 0 \tag{1}$$

$$\mathrm{div}\,\mathbf{E} = \rho/\varepsilon \tag{2}$$

$$\mathrm{curl}\,\mathbf{B} = \mu_0\,\mathbf{j} \tag{3}$$

$$\mathrm{curl}\,\mathbf{E} = -\,\partial\mathbf{B}/\partial t \tag{4}$$

and by Ohm's law, which here takes the form

$$\mathbf{E} = \eta_{//}\,(\,\mathbf{j} - \mathbf{j}_{CD}\,) \tag{5}$$

as required by assumption iv.

Here

$\mathbf{j}$ is the density of the total plasma current flowing at radius r and time t

$\mathbf{j}_{CD}$ is the analogous quantity for the RF-driven current component only

$\eta_{//}$ is the (parallel) plasma resistivity at radius r and time t

and the other symbols have their usual meanings.

Combining Eq.'s (4) and (5), and then substituting for **j** from Eq. (3), yields the equation governing the evolution of **B** (r, t), which, for the geometry chosen here, takes the form

$$\partial\mathbf{B}/\partial t = \partial/\partial r\left\{(\,\eta_{//}\,/\,\mu_0\, r)\;\partial/\partial r\,(\,r\,\mathbf{B}\,)\right\} - \partial/\partial r\left\{\,\eta_{//}\,\mathbf{j}_{CD}\right\} \tag{6}$$

The boundary conditions on Eq. (6) are given by

$$B\,(\,0, t\,) = 0\ ; \qquad\qquad B\,(\,a, t\,) = \mu_0\, I_p\,/\;2\,\pi\, a$$

where a is the plasma minor radius.

The (one-turn) plasma loop voltage, $V_L(t)$, is given by the expression

$$V_L(t) = 2\pi R_p E(a, t) \qquad (7)$$

where R_p is the plasma major radius.

Eq. (4) states that the steady state is characterized by the condition

$$\mathrm{curl}\, \mathbf{E} = 0$$

i.e. that

$$\mathbf{E}(r) = \mathbf{E}_0 = \text{constant}.$$

An interesting special case of the above equations occurs when

$$j = j_{CD},$$

corresponding to the situation where the RF-driven current density profile is identical to that of the previously-established ohmic current density profile. Eq. (5) then states that the electric field inside the plasma falls immediately to zero everywhere, and, by Eq. (7), the loop voltage then also falls abruptly to zero.

4. Simulation Results

Although the results of simulation calculations will be qualitatively similar for all tokamak plasmas, the time scales involved depend strongly on the calculation parameters assumed. The results presented below were obtained for plasma parameters typical of the operation of the JFT-2M tokamak[9],

$$\begin{aligned} R_p &= 1.31\ \mathrm{m} \\ a &= 0.35\ \mathrm{m} \\ B_T &= 1.04\ \mathrm{T} \\ T_0 &= 700 - 1000\ \mathrm{eV} \\ I_p &\equiv 230\ \mathrm{kA} \\ Z_{eff} &= 2 \end{aligned}$$

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where T_0 is the axial plasma electron temperature during the ohmic phase
B_T is the toroidal magnetic field.

Fig. 1 shows an example of simulation results obtained for a combined plasma heating and current drive case. The plasma heating pulse, whose energy in this case is absorbed preferentially in the plasma axial region, is turned on at 0.60 s. In response to the resulting reduced resistivity in the central plasma region, the internal electric field (and ultimately also the one-turn loop voltage) begins to evolve towards a new equilibrium value. The current drive pulse (which also produces additional plasma heating) is applied between 0.70 and 0.85 s. The solid curve shows the result obtained when the RF source is assumed to drive 100 % of the plasma current (again concentrated in the axial region). The dotted portion of the curve corresponds to the case when the current drive pulse produces only plasma heating, with no driven current. New equilibrium conditions, as characterized by a radially constant value of the plasma electric field, do not have time to establish themselves before the current drive pulse, with its attendant plasma perturbations, is turned on. The heating pulse is turned off at 0.90 s, again before equilibrium conditions can be established.

Fig. 2 shows results obtained for the same experimental parameters, except that here the pulse lengths have been increased to allow new equilibrium conditions to be established before each distinct plasma phase begins. For the present plasma parameters, this requirement is met for pulse lengths of approximately 0.3 s or greater. (The loop voltage should vanish for late times. The residual value of about 40 mV gives an idea of the numerical accuracy which can be expected from this simulation.)

A potentially misleading case is shown in Fig. 3. In this example, the current drive pulse again is permitted to produce plasma heating. The consequences of this parasitic heating may be difficult to distinguish from that of the presumed current drive effect, since both wave absorption and current drive efficiency may vary simultaneously, for example as functions of the wave launching parameters. In this example, heating of the plasma edge region occurs (as well as heating of regions near the plasma axis) and the loop voltage changes occur promptly. The loop voltage decreases to about 65 % of its ohmic value for each of the three cases shown. By varying the amount of heating and of current drive assumed to accompany the fast wave pulse, approximately similar waveforms are obtained for RF-driven currents which vary from zero to 25 % of the ohmic value. Extreme caution is obviously required when interpreting loop voltage traces obtained under such conditions.

The most obvious measure of the approach to equilibrium conditions is provided by the radial profiles of the plasma internal electric field. For the simulations shown here, near-equilibrium conditions are established approximately 0.3 s after a change in plasma conditions. Assuming the evolution of the plasma parameters to follow an exponential law with an effective time constant τ_{eff}, approach to near-equilibrium should take place after a delay of approximately 3 x τ_{eff} (evolution to within 5 % of the asymptotic values). We then estimate

$$\tau_{eff} \approx 0.1 \text{ s}$$

(Note that the various portions of the loop voltage traces themselves are not necessarily well-characterized by the time constant τ_{eff}, as can be seen from Fig. 3.)

It may be of interest to compare this value of τ_{eff} with the result of a calculation of the magnetic diffusion time constant, τ_m (the classical skin time), as given by the expression

$$\tau_m = \mu_0 a^2 / \eta_{//} \tag{8}$$

The value of $\eta_{//}$ is a strong function of the plasma temperature, varying in this case from an axial value of about (2.0 - 6.8) x 10^{-8} Ω-m (depending on the plasma phase) to a value of about 3.5 x 10^{-6} Ω-m at the plasma periphery. An average value of $\eta_{//}$ is obviously required for use in Eq. (8). For equilibrium conditions inside the plasma column (E (r) = constant $\equiv E$) we have the general relation

$$j(r) = E\left\{1 / \eta_{//}(r)\right\}$$

which, upon integrating both sides from 0 to r, yields an expression for the average parallel resistivity, $<\eta_{//}>$, given by

$$<\eta_{//}> = \left[\int_0^a \left\{1 / \eta_{//}(r)\right\} 2\pi r \, dr\right]^{-1} \tag{9}$$

For the conditions of Fig. 2, Eq. (9) yields the result

$$< \eta_{//} > \approx 4.6 \times 10^{-7} \ \Omega\text{-m}$$

Substituting this value into Eq. (8) yields

$$\tau_m \approx 0.3 \text{ s},$$

a value in only qualitative agreement with the estimated value of τ_{eff}. A τ_m value of 0.1 s requires the use of an $\eta_{//}$ value of approximately 1.5×10^{-6} Ω-m in Eq. (8), a value characteristic of the outer zone ($r \approx 0.30$ m) of the plasma column. The appropriate value of $\eta_{//}$ to use when applying Eq. (8) to an arbitrary problem may thus not be immediately apparent, and must evidently be chosen with some care. It is interesting to note that the loop voltage traces themselves can sometimes give essentially no indication of the appropriate numerical value of τ_{eff}, as can be seen most clearly from a comparison of Fig. 2 and Fig. 3.

5. Conclusion

The simulation procedure described here reveals the complexity of the changes in the plasma internal parameters, and in the measured surface loop voltage, for RF current drive experiments involving pulsed heating of a target plasma. The simulation may be used to study heating effects induced by a separate auxiliary heating source, those resulting from parasitic effects provoked by the RF current drive pulse itself, or those arising from a combination of the two foregoing effects. The results clearly indicate the difficulty of making an unambiguous determination of RF-driven current when the existence of plasma equilibrium conditions cannot be confirmed.

This simulation procedure may be of use when choosing the parameter combinations required for producing a conclusive experimental demonstration of FWCD. It may also be of help for the interpretation of experimentally-obtained loop voltage measurements in cases where the RF-driven current component is relatively small, especially when the existence of steady-state plasma conditions is in doubt. The latter application, however, requires fairly detailed knowledge of the radial distributions of the heating and current drive profiles.

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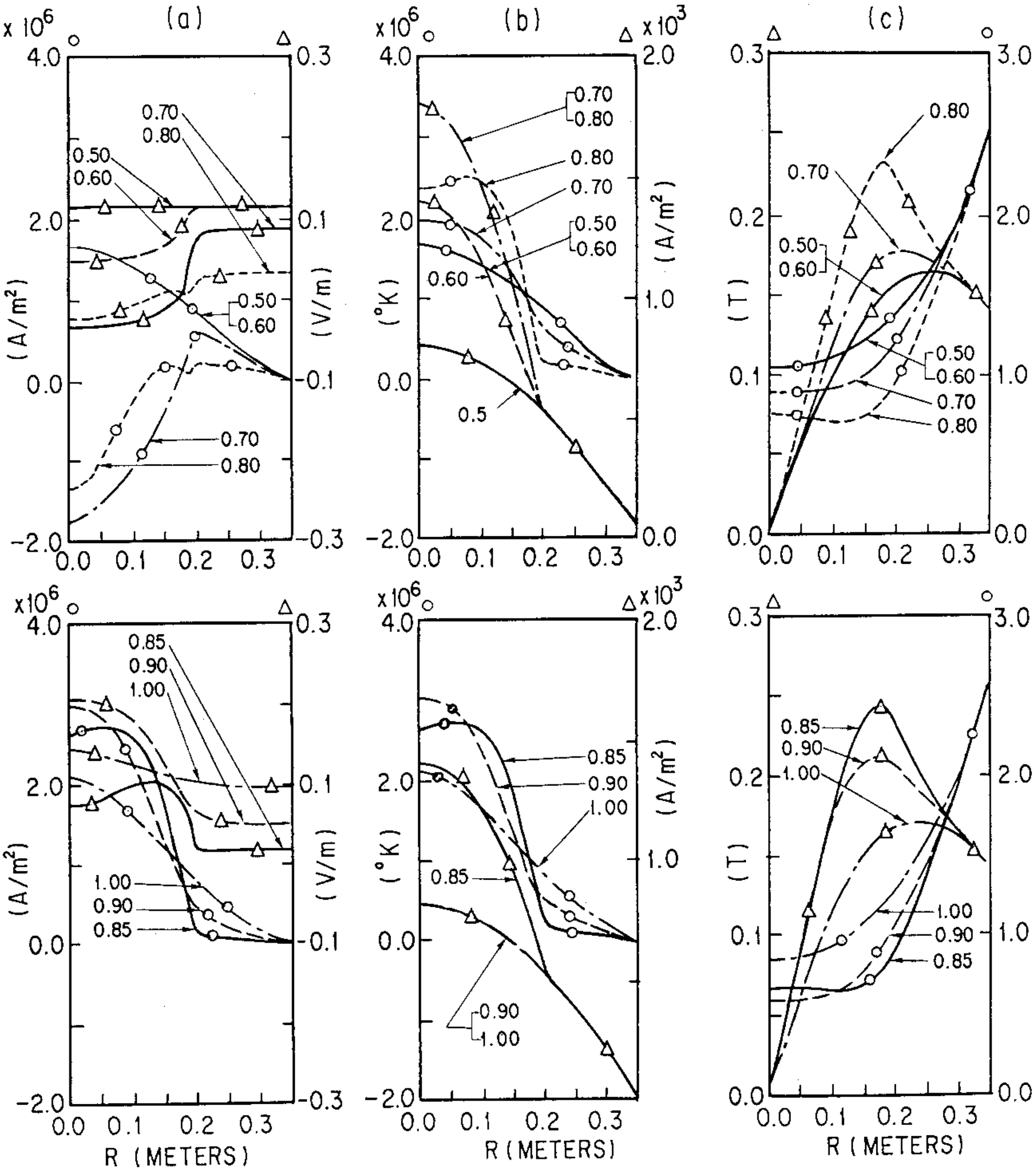

Fig. 1 Current drive simulation. Total plasma current : 245 kA; plasma axial temperatures : 0.85 keV (ohmic phase), 1.40 keV (heating phase), 1.80 keV (current drive phase). The heating phase begins at 0.6 s and ends at 0.9 s. The current drive phase begins at 0.7 s. and ends at 0.85 s. During the current drive phase, all the plasma current is RF-driven (net ohmic current vanishes). (a) Evolution of plasma internal electric field (—Δ—) and ohmic plasma current density (—o—) profiles, (b) Evolution of plasma temperature (—Δ—) and total plasma current density profiles (—o—), and (c) Evolution of poloidal magnetic field (—Δ—) and q (—o—) profiles.

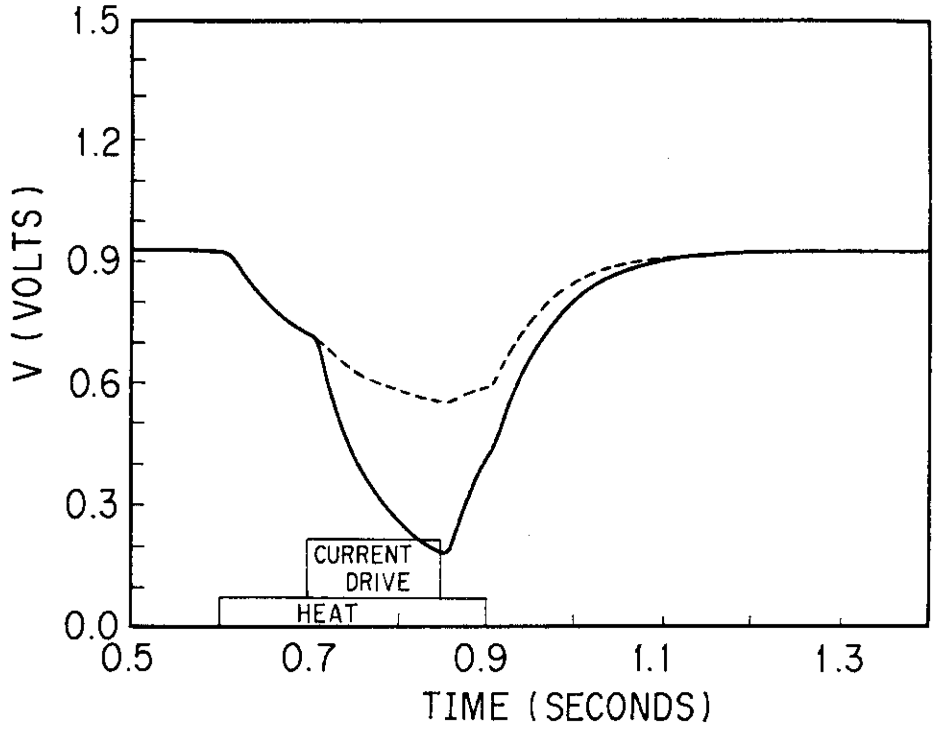

Fig. 1(d) Time behaviour of loop voltage. Solid curve : 100 % current drive, dotted curve : no current drive.

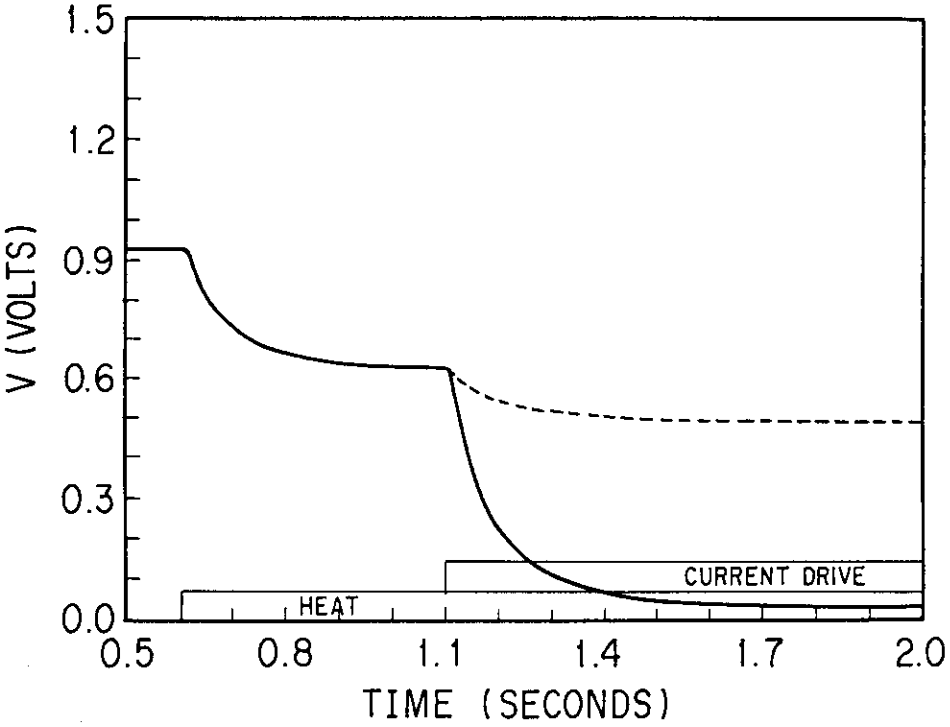

Fig. 2 Loop voltage traces obtained for long pulses (near-equilibrium conditions during the latter part of each plasma phase). Plasma conditions the same as for Fig. 1. Solid curve : 100 % current drive, dotted curve : no current drive.

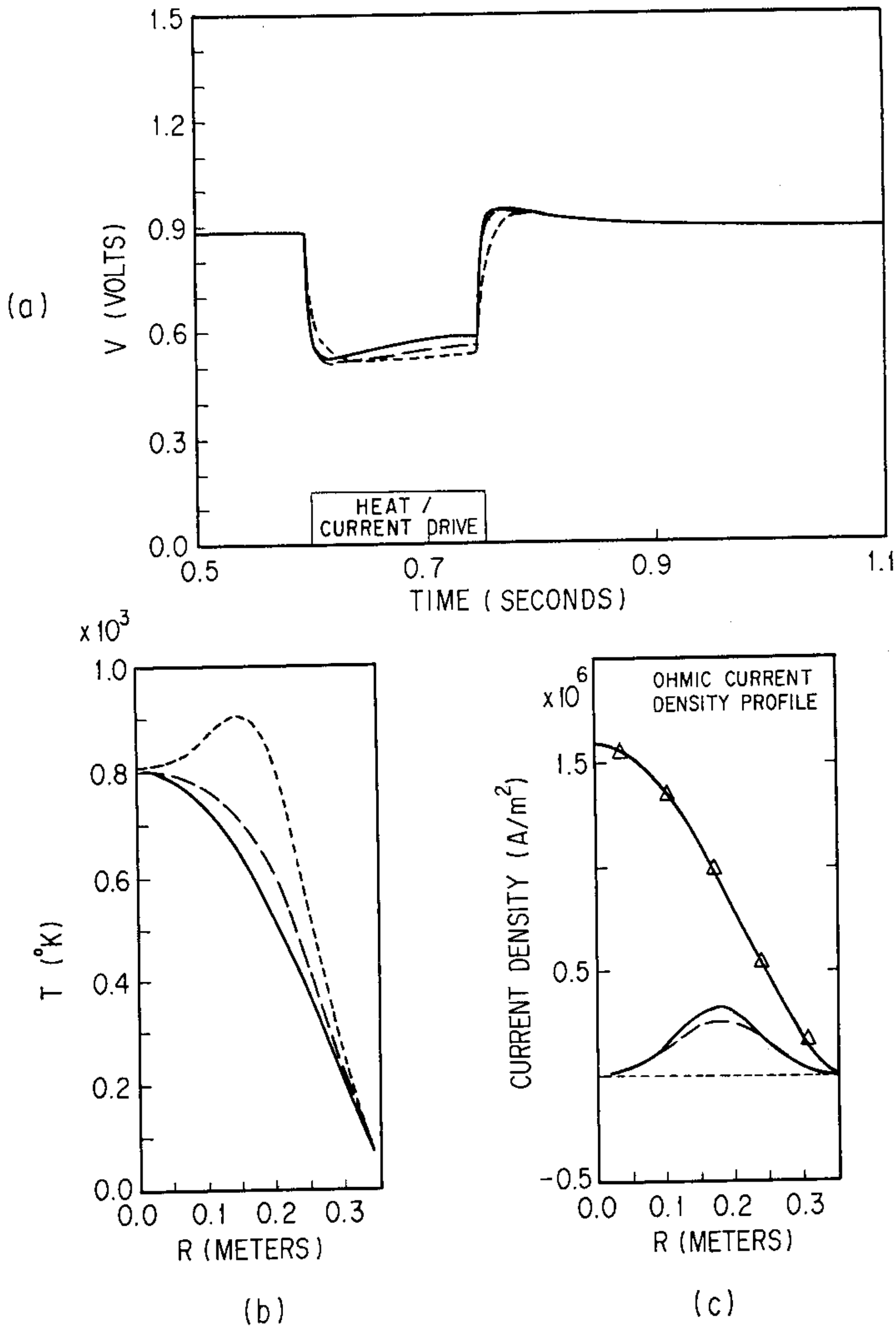

Fig. 3 Simulation results obtained when only a current drive pulse is present. This pulse produces varying amounts of heating and current drive. Loop voltage traces (a), assumed temperature profiles (b), and RF-driven current density profiles (c) for $I_{RF} = 0$ (-----), $I_{RF} = 0.20\ I_p$ (— —), $I_{RF} = 0.25\ I_p$ (———). The (initial) ohmic current density profile (—Δ—) is also shown in (c).