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OPERATION OF THE TOKAMAK ISTTOK IN A MULTICYCLE ALTERNATING FLAT-TOP PLASMA CURRENT REGIME

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ABSTRACT. Operation of the tokamak ISTTOK in a multicycle alternating square wave plasma current regime is reported. Discharges with seven half-cycles without dwell times, over a total time span of about five times the maximum duration of a single DC discharge, were obtained by feeding the primary of the transformer with an electrolytic capacitor bank switched in polarity by a fast insulated gate bipolar transistor (IGBT) H bridge.

Alternating inductive plasma current (AC) operation has been referred to as a potential alternative conceptual scenario to that of a pure steady state fusion reactor [1–5]. In comparison with non-inductive current drive operation, AC discharges are technically simpler and have higher reliability and efficiency. A possible disadvantage of the AC regime could be mechanical fatigue of some tokamak components. However, the achievement of long flat-top plasma current AC discharges should reduce the importance of this effect [3].

AC operation was firstly demonstrated on STOR-1M, with a smooth variation of the plasma current (I_p) from 4 to -4 kA [6]. A full cycle of AC operation with reactor relevant plasma current (± 2 MA with 6 s flat-tops) has been demonstrated in JET although with dwell times between the two half-cycles varying from 50 ms to 6 s [7]. One cycle of sinusoidal (trapezoidal) plasma current without a dwell time has been recently obtained on STOR-M [8] (CT-6B [9]). Continuous sinusoidal discharges during about 20 s with peak currents of ± 0.5 kA, 2 ms flat-tops, a repetition time of 10 ms and finite dwell times were obtained on CSTN-AC [10]. Constant duration AC discharges (40 ms), with two, four and eight sinusoidal cycles of $\pm$(4–5) kA were obtained on CT-6B [9]. One and a half cycles of sinusoidal operation during about 55 ms was achieved on STOR-M with a smooth reversal of ± 18 kA and a dwell time of about 2 ms [11].

The above described results were obtained using:

(a) A flying wheel generator and thyrister bridges in JET;

(b) Insulated gate bipolar transistors (IGBTs) on CSTN-AC;

(c) A multistage capacitor bank system with ignitron switches on STOR-M;

(d) Two capacitor banks, power tubes for low frequency AC modulation and a digital pulse wave generator that controls the plasma current waveforms on CT-6B.

The operation of a tokamak reactor in an inductive AC regime would require the achievement of long duration, multicycle, trapezoidal plasma current discharges, if possible and convenient without dwell times. This article presents the results already obtained on ISTTOK aiming at the fulfilment of this objective.

ISTTOK is a small size ($R = 46$ cm, $a = 8.5$ cm), circular cross-section, iron core transformer ($\Delta\Phi = 0.22$ V $\cdot$ s), limiter tokamak [12]. It has an RF generator (1.7 MHz, 300 W) for the hydrogen preionization, a 1 MW direct current power supply for the toroidal magnetic coils (8 kA), a continuous and puffing gas injection system, a predischarge capacitor bank (1 mF, 5 kV) and an electrolytic one (3.8 F, 350 V), hereafter referred to, respectively, as PRECO and ELCO, for control of the loop voltage. For the work described in this article, we have used the following diagnostics: a Rogowski coil (I_p), a single vertical chord microwave interferometer ($\langle n_e \rangle$), a one turn loop (V_L), a specially filtered fast photodiode (H_α), sine and cosine coils (Δ_H and Δ_V), a soft X ray diagnostic (T_e) and a Langmuir probe ($n_e(a)$, $T_e(a)$).

The forward flat-top discharges, which are the most adequate for repetition in AC operation, were performed with the following external parameters: $p_H = 2 \times 10^{-4}$ torr, $B_T = 0.45$ T, $V_{PRECO} \sim 1300$ V, $V_{ELCO} \sim 250$ V, transformer ratio $N = 40$, vertical

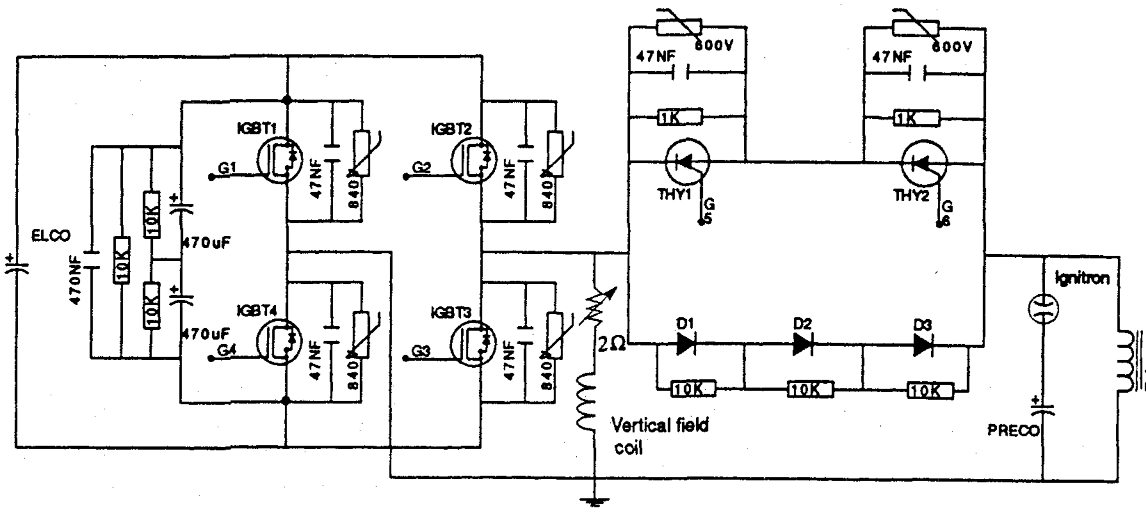

FIG. 1. Scheme of the IGBT H bridge power supply.

and horizontal B fields adjusted to maximum current flatness. These discharges were characterized by the following internal parameters: $I_p \sim$ 4–5 kA, duration $\tau_D \sim$ 40 ms, $n_e \sim 7 \times 10^{18}$ m^{-3}, $T_e \sim$ 180 eV, T_i (C III) $\sim$ 150 eV, energy confinement time, $\tau_E \sim$ 1.2 ms, central beta value $\beta(0) \sim 0.5\%$ and safety factor on-axis $q(0) \sim 1.2$ and on the edge $q(a) \sim 5$.

Aiming at identifying possible asymmetries in the ISTTOK operation due to the change of the plasma current direction, single DC discharges were made by applying symmetric voltages to the primary of the transformer. By reversing and varying the vertical field and slightly adjusting the horizontal field, discharges with I_p parallel and antiparallel to B_T could be made with similar durations and plasma current behaviours.

The ISTTOK alternating discharges were performed using a specially designed power supply

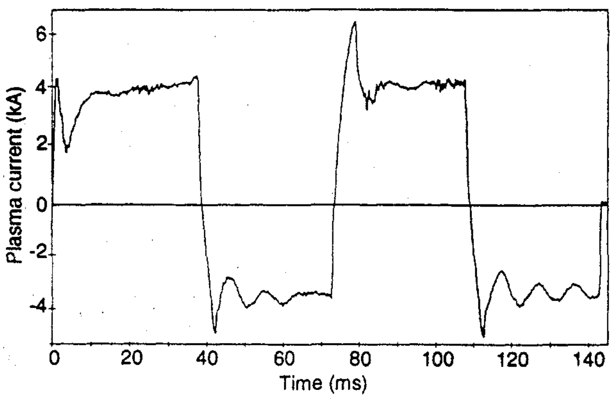

FIG. 2. Time variation of the plasma current in shot 5701.

(Fig. 1). This voltage reversible system relies on an H bridge of four IGBTs, where each pair drives the current in one direction. The IGBTs (MBN300A from Hitachi) can operate until 600 V and can drive currents of up to 400 A. The maximum values for rise, fall, turn-on and turn-off times are less than 1 μs. The IGBT controller circuit consists of a digital interpreter for the signals coming from the VME central timing unit [13] and the four drivers (HTK0030). Special care was taken to avoid simultaneous conduction of both pairs of IGBTs at reversal. The IGBT bridge is insulated from the PRECO by a series of three diodes in parallel with a series of two thyristors. These prevent free-wheeling of the IGBT diodes under the PRECO discharge. The IGBT gates (G1, ..., G4) are connected to the IGBT control unit. The safe operation of the high power devices is guaranteed by snubers composed of associations of resistors, capacitors and voltage dependent resistors.

The operation of this power supply is controlled by the ISTTOK central timing system, which provides signals for the control of the PRECO charge and discharge, the ELCO charge and the operation of the IGBT bridge. The interface between the VME timing unit and the IGBT control circuit consists of three optical signals (start, stop and clock) which drive, respectively, the beginning of the ELCO discharge over the primary of the transformer, the end of the ELCO discharge and the alternating period.

Laboratory tests have shown that this power supply works faultlessly, while feeding its load with an alternating square wave voltage, with a small risetime ($<$ 20 μs), programmable amplitude (0–300 V) and half-cycle duration (0–1 s) during a maximum of 5 s.

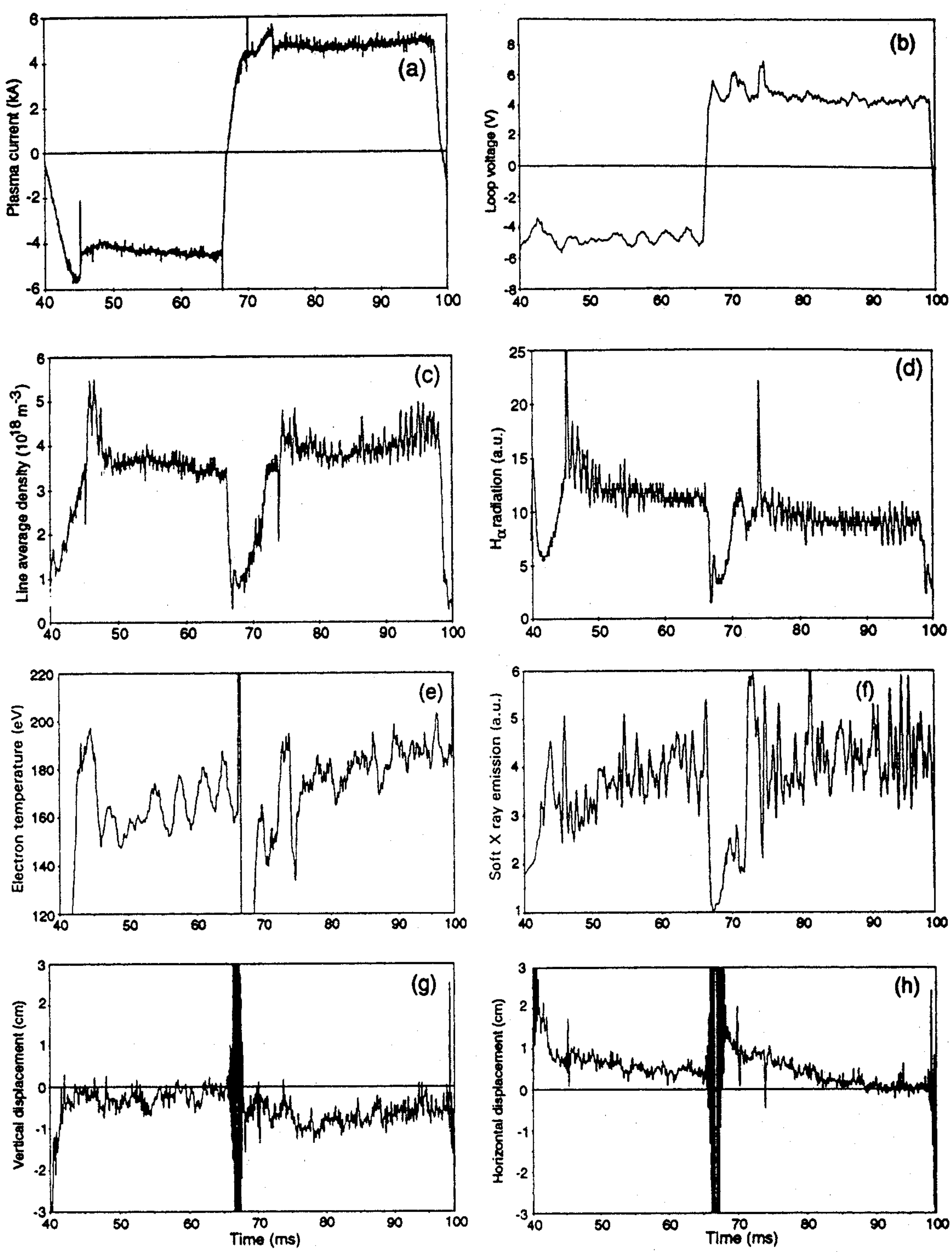

FIG. 3. Evolution of the main discharge parameters in shot 5671: (a) plasma current, (b) loop voltage, (c) line averaged electron density, (d) H_α radiation, (e) electron temperature, (f) soft X ray emission, (g) vertical current axis displacement, (h) horizontal current axis displacement.

The AC discharges analysed in this article were carried out using the above described parameters and with the power supply half-period limited to 35 ms in order to avoid iron core saturation.

After a series of preliminary discharges with only a few half-cycles of current reversal, we have attained a maximum of six half-cycles at $I_p = \pm 4$ kA, in a total time span of about 180 ms, with a triangular shaped flux swing of 0.15 V·s (a single DC discharge with $\Delta\Phi = 0.22$ V · s would only last for about 45 ms). These long duration discharges presented in some cases (shot 5663) a significant dwell time (4 ms) in the positive–negative plasma current transition. On the inverse transitions there was no dwell time and the average plasma density around $I_p = 0$ remained at a high value (1.7×10^{18} m^{-3}), when compared with its maximum (4.8×10^{18} m^{-3}).

The plasma column was formerly stabilized by the external horizontal B field (B_H) created by 2 × 6 windings and by the vertical B field (B_V) created by 4×6 windings, wrapped over the copper shell. For the optimization of the AC operation it was proved necessary to install a new set of more external symmetric windings for B_V to minimize the error fields, to feed the horizontal windings by an independent DC power supply and to develop feedback control systems for both B_V and the gas puffing.

With the new B_V coil consisting of 2×14 windings placed close to the inner surface of the toroidal coils and the fast switching of the B_H coil current between two prechosen values, one for each I_p direction, we have achieved a better plasma current evolution, with almost a square wave shape and a plateau in the positive current direction. Discharges with four half-cycles without a dwell time at ±4 kA were obtained (Fig. 2, shot 5701).

During the second and the third half-cycles shot 5671 reveals:

(a) Plasma current flat-tops in both directions, with an amplitude rising from −4.5 to +5 kA (Fig. 3(a));

(b) A loop voltage with a constant absolute amplitude ($|V_L| = 5$ V) (Fig. 3(b));

(c) A plateau line averaged density increasing from 3.5×10^{18} to 4×10^{18} m^{-3} and dropping to a minimum of 0.8×10^{18} m^{-3} at current reversal (Fig. 3(c));

(d) Continuous H_α emission with an intensity decreasing from 12 to 8 arbitrary units (Fig. 3(d));

(e) An increase of electron temperature from about 150 to 190 eV, determined using the ISTTOK scaling law $T_e = 175(I_p/V_L)^{2/3}$ with I_p in kiloamps and V_L in volts (Fig. 3(e));

(f) An increase of soft X ray emission (Fig. 3(f));

(g) Small current axis vertical displacements (Fig. 3(g));

(h) Slightly larger horizontal displacements (Fig. 3(h)).

We note that the ratio between $\langle n_e \rangle$ and the H_α radiation intensity increases by about 70%, suggesting that we have achieved in the third half-cycle a better particle confinement. Further, the soft X ray emission and T_e have, as expected, similar time variations.

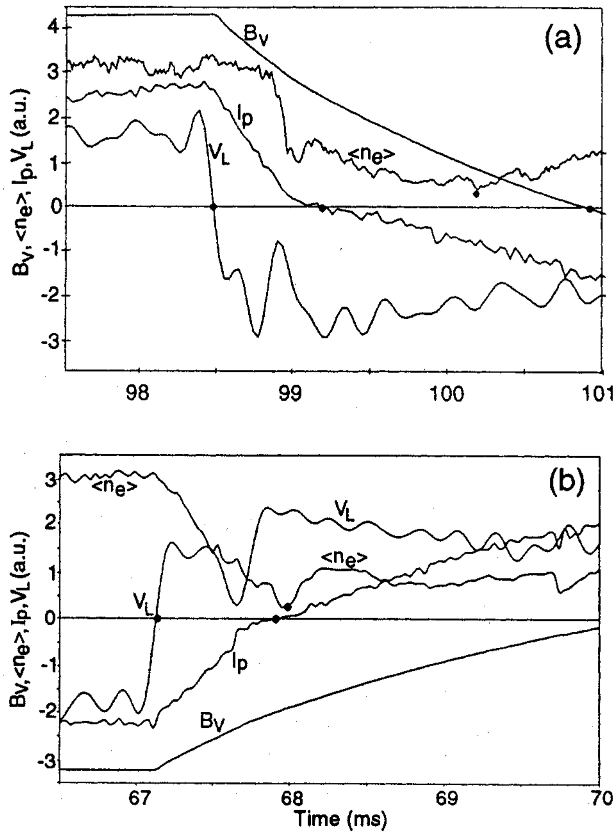

FIG. 4. Detailed time variation of the vertical magnetic field (B_V), line averaged plasma density ($\langle n_e \rangle$), plasma current (I_p) and loop voltage (V_L) around the instant of current reversal in (a) shot 5904 and (b) shot 5671.

Detailed analysis of the positive to negative current transition (Fig. 4(a)) reveals that, in shot 5904, the fastest reversal was that of the loop voltage (200 μs). The plasma current has also dropped to zero quickly (800 μs). B_V has decayed on a longer time-scale due to its coil inductance, reaching zero in 2.5 ms. In this shot $\langle n_e \rangle$ has remained, after loop voltage reversal, at a high value for about 400 μs and has then dropped rapidly (200 μs) to its first minimum. The lowest value of $\langle n_e \rangle$ was observed approximately at the midpoint between the instants at which $I_p = 0$ and $B_V = 0$. The rapid density decrease observed around $t = 99$ ms could suggest that a weak disruption might have occurred. However, analysis of many other current transitions, showing a smooth density decay, have proved that this occurrence was accidental. Inverse transitions have led to

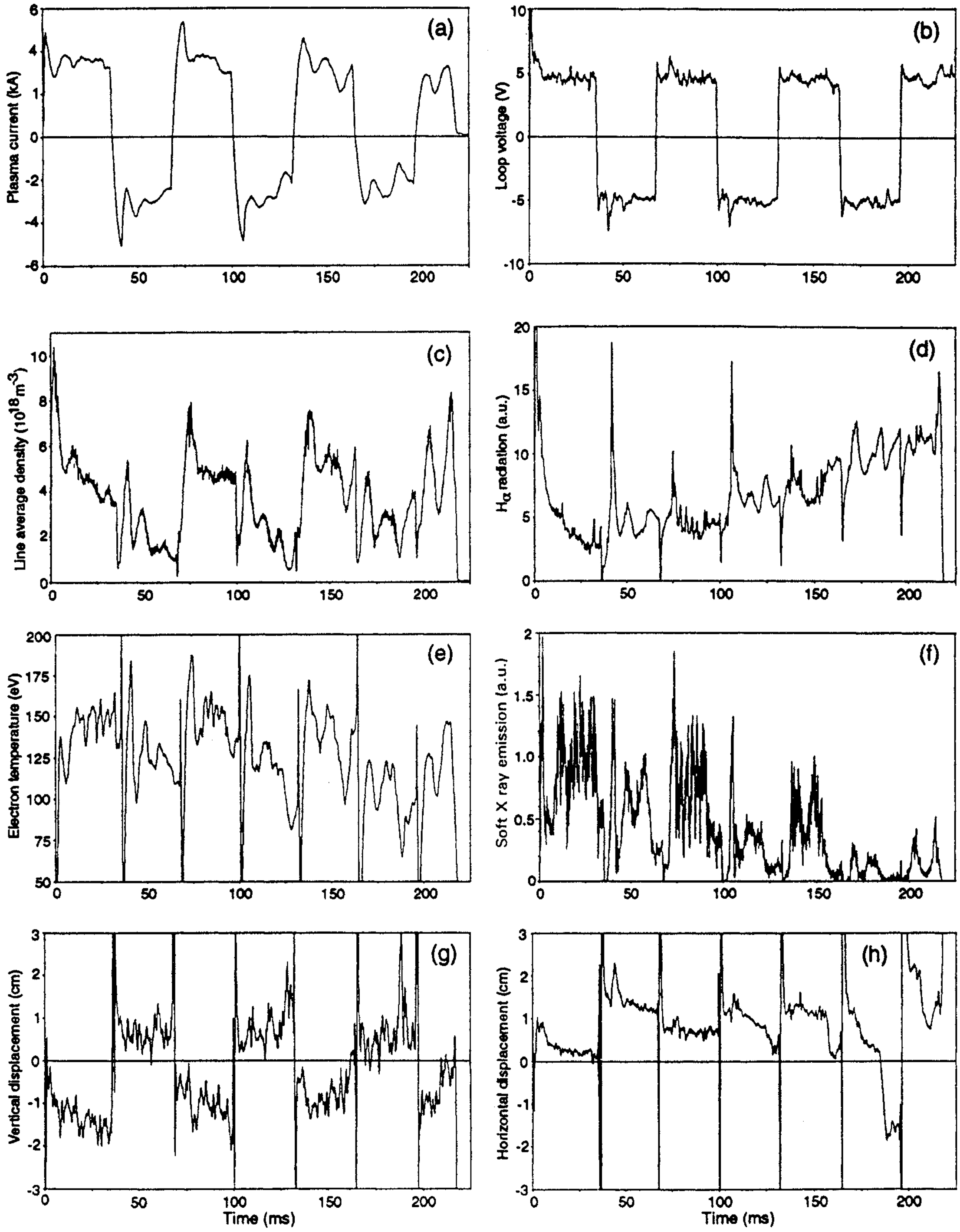

FIG. 5. Evolution of the main discharge parameters in shot 6043: (a) plasma current, (b) loop voltage, (c) line averaged electron density, (d) H_α radiation, (e) electron temperature, (f) soft X ray emission, (g) vertical current axis displacement, (h) horizontal current axis displacement.

similar parameter variations, with almost identical time-scales (Fig. 4(b), shot 5671), proving that the fact of I_p being parallel or antiparallel to B_T has no influence on the plasma behaviour under current reversal.

We have seen that, while I_p is approaching zero, $\langle n_e \rangle$ decreases rapidly towards its first minimum in some 200 μs. It is perhaps interesting to compare this time with that associated with the magnetic field gradient and curvature drifts, in the absence of any transverse B fields. The global drift velocity is given, in tokamak geometry, $B(r) = B_T R/(R+r)$, by $v_D = \pm m(v_\parallel^2 + v_\perp^2/2)/eRB_T$. For a Maxwellian distribution the average values of $v_\parallel^2$ and $v_\perp^2/2$ are both equal to kT/m. Therefore, the average drift velocity can be written as $2kT/eRB_T$, where T is the plasma temperature. The maximum drift time is attained at $r = 0$, where the particles, in our tokamak, have to travel upwards 8.5 cm to the vertical limiter or downwards 10 cm to the vessel wall. For $B_T = 0.45$ T the drift time is about 49 μs for $kT = 180$ eV. Therefore, these drift mechanisms suggest that at the first density minimum ($\Delta T \sim 200$ μs) only a residual plasma with a temperature below 44 eV could still exist, if we do not consider the creation of new charged particles by the induced E field.

With the Langmuir probe fed with a 50 Hz voltage (± 100 V), we have seen (shot 5904) that, at current reversal, the edge temperature decayed to 50% of its plateau value (11 eV) and that it increased afterwards to the same level, while the edge density has dropped to 65% of its former value ($4.2 \times 10^{17}\,\mathrm{m}^{-3}$) and has become higher afterwards ($5.8 \times 10^{17}\,\mathrm{m}^{-3}$), probably due to the lower value of I_p after the current transition.

Finally, by a careful adjustment of the gas puffing system (1 ms gas pulses with a period of 30 ms), we have obtained in shot 6043 a discharge with seven half-cycles without any dwell times in a total time span of about 220 ms (Fig. 5). This discharge shows:

(a) A clear decrease of I_p for $t > 130$ ms (Fig. 5(a));

(b) A loop voltage with a constant absolute value along the entire discharge (Fig. 5(b));

(c) A relatively high density ($\langle n_e \rangle = 8 \times 10^{18}$ m^{-3}) at the beginning of the positive current pulses, in which $\langle n_e \rangle$ is sustained at values above 4×10^{18} m^{-3}, while the negative I_p pulses present an oscillatory continuous decay from 5×10^{18} to 1×10^{18} m^{-3} (Fig. 5(c));

(d) An increasing H$_\alpha$ emission for $t > 50$ ms (Fig. 5(d));

(e) A strong decrease of T_e from 150 to about 100 eV for $t > 130$ ms, once more with the positive I_p pulses showing the highest values (Fig. 5(e));

(f) A similar variation of soft X ray emission (Fig. 5(f));

(g) A square wave current axis vertical displacement, most probably related to the two prechosen values for B_H (Fig. 5(g));

(h) Smaller horizontal displacements except for $t > 150$ ms.

The discharge is terminated by a disruption, occurring at $t = 217$ ms, since the loop voltage was sustained until $t = 228$ ms.

The constancy of the loop voltage along the entire discharge eliminates any malfunction of the AC power supply as a cause for the gradual I_p decrease.

We believe that this drop in the plasma current, which is associated not only with a decrease in both T_e and the X ray emission but also with an increase in both n_e and the H$_\alpha$ radiation, is due to an increasing neutral pressure inside the vessel. Indeed ISTTOK has a continuous gas feeding system together with a gas puffing unit. The lack of a baratron, presently under installation, makes it difficult to control the neutral pressure during the shot. Furthermore, the impact of consecutive pulsed thermal loads on the tokamak wall might liberate additional hydrogen together with impurities such as carbon and oxygen, which would also contribute to the drop in T_e, owing to enhanced plasma radiation.

Finally, we observe that the I_p, $\langle n_e \rangle$, T_e, H$_\alpha$ and soft X ray signals exhibit, especially during the later half-cycles, slow oscillations with a period varying between 9.5 and 13.5 ms. Figure 5 shows that these oscillations are not (or very poorly) correlated with $\Delta_H(\Delta_V)$. The exact cause of these slow fluctuations is still unknown and will be the object of future research.

Concluding, we may state that multicycle alternating inductive discharge operation with flat-tops in the plasma current and without dwell times was achieved on ISTTOK. A maximum of seven half-cycles was obtained, enlarging the duration of the discharges from 40 to 220 ms. The plasma density has remained finite during current reversal. Temporary increases of n_e and T_e were observed during a few half-cycles in some shots. Measurements have shown that the lowest density around current reversal is probably associated with the minimum of the total transverse B field. Therefore, the time variation of B_V may play a role in the behaviour of AC discharges.

The increase of the local memory of the VME transient recorder modules and the upgrade of the feedback control procedures for both the gas puffing and the vertical B field will most probably allow us to increase the discharge duration to one second (30 half-cycles) in the flat-top part of the 4 s toroidal magnetic field time variation. Under these conditions, it will be possible to act externally on the plasma column to try to raise both the plasma density and the electron and ion temperatures from half-cycle to half-cycle until a limit situation is reached. If this objective is fulfilled, the realization of AC discharges might be, not only an alternative operational scenario for steady state tokamak operation, but also a method of achieving a higher thermal power.

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REFERENCES

[1] REBUT, P.H., BOUCHER D., GORMEZANO, C., KEEN, B.E., WATKINS, M.L., Plasma Phys. Control. Fusion **35** (1993) 3.
[2] TUBBING, B.J.D., JET TEAM, Plasma Phys. Control. Fusion **35** (1993) B55.
[3] MITARAI, O., WOLFE, S.W., HIROSE, A., SKARSGARD, H.M., Fusion Technol. **15** (1989) 204.
[4] MITARAI, O., HIROSE, A., SKARSGARD, H.M., Fusion Technol. **20** (1991) 285.
[5] MITARAI, O., Fusion Eng. Des. **26** (1995) 605.
[6] MITARAI, O., WOLFE, S.W., HIROSE, A., SKARSGARD, H.M., Nucl. Fusion **27** (1987) 604.
[7] TUBBING, B.J.D., et al., Nucl. Fusion **32** (1992) 967.
[8] MITARAI, O., et al., Nucl. Fusion **36** (1996) 1335.
[9] YANG, Xuanzong, et al., Nucl. Fusion **36** (1996) 1669.
[10] HAYASHI, K., et al., in Plasma Physics (Proc. Int. Conf. Nagoya, 1996), Vol. 2, Fusion Research Association of Japan, Nagoya (1996) 1246.
[11] MITARAI, O., et al., Rev. Sci. Instrum. **68** (1997) 2711.
[12] VARANDAS, C.A.F., et al., Fusion Technol. **29** (1996) 105.
[13] VARANDAS, C.A.F., et al., Rev. Sci. Instrum. **66** (1995) 3382.

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