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** See Appendix 1*

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AC PLASMA CURRENT OPERATION IN THE JET TOKAMAK

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ABSTRACT. A full cycle of AC tokamak operation, at a plasma current of ±2 MA, has been demonstrated in JET. The plasma purity in the two half–cycles was equal, with an effective ion charge of 2 at an average density of 1.2 10^{19} m^{-3}. Dwell times between the two plasmas of between 50 ms and 6 s were obtained. The range of prefill pressure for successful breakdown of the second plasma was between 1.5 and 6.0 mPa, comparable to that in normal JET breakdown. Within this range, second breakdown was not significantly affected by gas release from the vessel walls.

1. INTRODUCTION

The toroidal plasma current, required in a tokamak for plasma confinement, can be driven either inductively, or by various methods of non–inductive current drive (NICD) [1,2]. In the case of inductive current drive (ICD), the current is driven by transformer action. The flux increase in the primary winding, the central solenoid, provides both the inductive flux required for the magnetic configuration and the flux consumption due to plasma resistivity. Because the flux capability of the solenoid is limited, the ICD tokamak is a pulsed device. In a power generating reactor, there are disadvantages associated with pulsed burn [3]. An external thermal energy storage system is required in order to maintain a continuous electricity production, plasma facing components are subject to thermal cycling and some structural components are subject to stress modulation [4].

With NICD, steady–state operation can be obtained. The significant disadvantage of NICD is that with the presently available current drive efficiencies, high current drive powers are required. Even in reactor concepts that are optimized for NICD by utilizing a large fraction of bootstrap current [5,6], current drive powers of the order of 60 MW injected into the plasma are projected, leading to plant recirculating powers of order 10 to 20 %. For designs that are optimized in terms of fusion power per unit capital investment, the recirculating power for NICD is substantially larger.

The down time of the burn in ICD schemes can be minimised by using AC operation [4], in which the plasma current alternates in direction between subsequent burn periods. In AC operation, no recharging of the central solenoid between plasmas is required, so that the down time is determined mainly by the sum of the plasma ramp–down and ramp–up times. In conventional tokamak operation with uni–directional plasma current, the recharging time of the central solenoid contributes significantly to the down time, due to the large magnetic energy stored in the central solenoid.

AC operation was first demonstrated in the STOR–1M tokamak [7], at a plasma current level of 4 kA and a cycle time of 4 ms. It was found that a smooth transition through current zero could be made, without interruption of the ionization, by correct programming of the vertical field. No assessment of the relative purity of subsequent discharges could be made.

The motivation for the present work in JET was the necessity to demonstrate the feasibility of AC operation in conditions which can be considered relevant to a reactor. The issues of highest interest are first the relative purity of the consecutive discharges, second the possible effect of wall gas release on the conditions for obtaining a second plasma, and third the question as to whether the second plasma can be obtained without loss of ionization (zero dwell time), or whether a finite period without plasma is necessary (finite dwell time).

2. CONFIGURATION

The AC discharges in JET [8] were performed in a 2MA limiter configuration, without currents in the shaping coils. The modifications to the poloidal field power supplies and control systems have been summarised in [9]. The major radius is 3.0 m, the minor radius is 1.15 m, the elongation is 1.4, and the toroidal field is 2.5 T. The plasma current is 2 MA in both cycles, and the cylindrical safety factor q_{cyl} is 5.5. The plasma shape and position are the same for both cycles. The main plasma species is deuterium, although helium was used for the prefill gas. The JET vacuum vessel is made of inconel. The innerwall and top X–point areas are protected by carbon tiles, while the bottom X–point area is protected by carbon and beryllium tiles. The plasmas were limited on the carbon side protection of the eight ICRH antennas [10]. ICRH power is applied in fast wave minority heating mode with hydrogen as the minority. The frequency is 42.6 MHz and the antenna phasing is dipole.

3. DEMONSTRATION

In figure 1, a typical full cycle AC discharge is shown. The plasma current in the first cycle is 2 MA in the positive direction with a 6 s flat top. The first plasma is generated using a low voltage breakdown with no bias current in the central solenoid; the loop voltage is applied directly by the solenoid power supply. The electric field in the vacuum chamber is ramped up to a maximum of about 0.3 V/m, in about 300 ms. The current ramp–down of the first plasma is started when the current in the central solenoid nearly reaches its maximum permissible value of 40 kA. The plasma current decay is driven primarily by the resistance of the solenoid (zero voltage is applied across the solenoid) and the first plasma terminates at 12.8 s. At that time, the solenoid current is 20 kA, which corresponds to the resistive flux consumption of the first plasma. The second breakdown, at 13.0 s, is generated by interrupting the central solenoid power supply, and directing the solenoid current of 20 kA through a resistor. The corresponding electric field is 0.75 V/m, and is applied suddenly. It is maintained for 200 ms, and then reduced by switching additional resistors parallel to the central solenoid. In the second cycle the plasma current is 2 MA in the negative direction with a 10 s flat top. Both breakdown scenarios are equivalent to those used in normal JET operation.

4. PLASMA PURITY

In figure 2, data pertaining to plasma purity are shown for the discharge shown in figure 1. The electron density, measured by a multi–channel far infra–red interferometer is under feedback control, and is nearly equal in the two cycles (for example eg. 1.2 10^{19} m^{-3} at 7 s and 1.4 $10^{19} m^{-3}$ at 22 s, both times 1 s after the start of the ICRH). The density transient effects are induced by the switching of the ICRH power [11]. The electron temperature, measured by electron cyclotron emission spectroscopy, is equal in the two cycles. The effective ion charge Z_{eff}, measured by bremstrahlung emission, is also equal in the two cycles (2.0 at 7 s vs 2.0 at 22 s), indicating that there is no difference in impurity levels between the cycles (although there is an indication of a slight overshoot in Z_{eff} during the first 5 s of the second plasma). Furthermore, the total radiated power, measured by broad–band bolometers, and originating primarily from impurity line emission, remains the same for the two cycles. In similar discharges, but with equal ICRH power in both cycles, the same neutron production rate from to deuterium–deuterium fusion reactions was obtained, which is further evidence for the observation that there is no measurable difference in impurity contamination.

5. BREAKDOWN CONDITIONS

In normal operation, the JET pulse rate is about once per 20 minutes; the prefill gas pressure consists almost entirely of a deliberate deuterium or helium gas puff. The most common reason for failure of the breakdown is an impure condition of the vacuum vessel. This results in high impurity line radiation losses from the initial plasma and consequently the failure of the plasma to break through the radiation barrier [12].

All successful AC discharges in JET were obtained with a finite dwell time (50 ms to 6 s) between first and second plasma, during which ionization was lost (The reasons for failure of the attempts to obtain zero dwell time will be discussed below). The second breakdown is then equivalent to a normal JET breakdown, with the exception that the release of gases, including possibly impurity gases, from the walls may affect the prefill neutral pressure. Neutral pressure due to gas release from the vacuum vessel is low immediately after normal termination of a discharge and increases to a maximum value about 15 s later [13]. A typical maximum value is 15 mPa (150 10^{-9} bar), with a pumping capability in JET of 7000 l/s. Disruptive termination leads to a fast increase of the neutral pressure, to levels up to 30 mPa (300 10^{-9} bar).

In figure 3 we show a successful second breakdown at a prefill neutral pressure of 6 mPa. This pressure was obtained after disruptive termination of the first plasma at a current level of 400 kA. The disruption was caused deliberately by excess gas fueling; this is a density limit disruption at high q. The current decay rate is low, but the disruptive nature of the termination is visible on the traces of density and loop voltage. Some gas was still puffed in after the disruption. In a similar case, with a disruptive plasma current termination at 500 kA, and a pressure at breakdown of 8 mPa, second breakdown was not successful.

Detailed data on the window of prefill pressure for normal breakdown with the same loop voltage and stray field is not available for the present JET configuration (note that machine configuration changes with respect to [12] have been made). However, the maximum pressure of 6 mPa found here for second breakdown is not substantially different from that for normal breakdown (not more than a factor 2), despite the fact that part of the pressure originates from the disruptive termination of the first plasma. Hence there is no indication that impurity gases significantly affect the breakdown.

In figure 4 a successful AC discharge is shown with a 6 s dwell time, where second breakdown occurs well into the wall outgassing phase of the first discharge. For technical reasons, this dwell time had to be obtained by shortening the first plasma. The central solenoid is partly recharged just before the second breakdown (9 to 13 s, as seen also on the loop voltage trace), leading to a somewhat higher breakdown voltage than in the other cases. The neutral pressure at the time of second breakdown is about 4 mPa, and is dominated by the pressure from wall release, which rises steadily after termination of the first discharge. The gas puff, introduced at 12.6 s, makes only a minor contribution to the neutral pressure. Hence, at a neutral pressure below the maximum quoted above, there is again no indication that impurity gases, released from the walls over a period of several seconds, impair second breakdown.

We note that the highest wall release pressures after JET discharges are too high to allow second breakdown at the pressure maximum. However, second breakdown with a short dwell time should always be feasible after normal discharge termination, because advantage can be taken of the fact that the wall release pressure builds up on a timescale of 15 s. In extrapolating to reactor conditions, where the wall outgassing is assumed to be significantly stronger, it should be taken into consideration that reactors will have two to three orders of magnitude more pumping capability in view of the helium exhaust requirements [14]. In addition, additional heating systems may be used to assist breakdown.

6. ZERO DWELL TIME

It was attempted to start the second discharge without interruption of the ionization. Currents of order 50 kA were obtained in the second plasma after correct programming of the vertical field, and after delaying or eliminating the prefill gas puff (if the prefill puff was retained, it was impossible to sustain the first discharge). However, these plasmas could not be sustained. The reason for this is not clear, although we suspect that the delay or elimination of the prefill gas puff resulted in failure due to too low neutral pressure.

7. PLASMA FUELING

In figure 5 we show the gas puff rate (in number of electrons per second) and the integrated electron input, for a typical AC discharge with equal density in the two cycles. The second discharge requires less gas input by about a factor 2 (0.45 10^{22} compared with 0.8 10^{22} electrons). For both plasmas the integrated gas input exceeds the plasma particle inventory (0.11 10^{22} electrons), indicating that most of the gas input is absorbed by the walls. Partial saturation of the wall pumping leads to the smaller input in the second plasma. A comparison can be made of the curves of integrated gas input with similar curves for long pulse discharges (40 s pulse duration) under similar conditions. Apart from the modulation caused by the ramping down and up of the plasma current, there is no qualitative difference in the behaviour. Hence, in terms of saturation of the wall and the release of neutrals from the wall, there is no difference between the second cycle of an AC pulse and an uninterrupted long pulse.

8. CONCLUSIONS

It has been demonstrated for the first time in a large tokamak that AC operation is a feasible current drive mode for a tokamak fusion reactor. Plasma current of 2 MA in each direction has been achieved. No degradation of plasma purity in the second plasma with respect to the first was observed. The range of prefill pressure in which second breakdown can be achieved is not substantially different from that for normal breakdown, indicating that the possible presence of impurity gases in the wall gas release does not have a major effect. Although plasma sustainment through the plasma current zero can not yet be ruled out, we have so far been unable to sustain a second plasma above a very low plasma current. As regards the saturation of the wall pumping capability, there appears to be no substantial difference between the second cycle in an AC discharge and a long pulse without interruption.

The use of AC inductive current drive for a tokamak fusion reactor allows the reactor to operate with a minimum plant recirculating power. It further allows more flexibility in the optimization of the fusion power per unit capital investment. The machine parameters and the operating point are not restricted by the requirements posed by non–inductive current drive methods.

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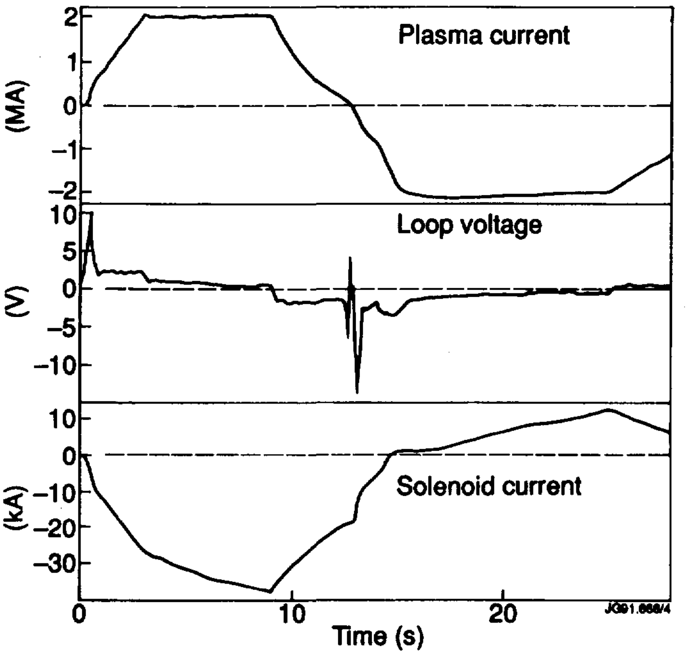

FIG. 1. Parameters of a full cycle AC discharge (shotnr. 24807). Shown are plasma current, loop voltage and current in the central solenoid as a function of time. The slow increase in the solenoid current at the beginning of the second plasma (55 to 57 s)is due to non—saturation of the iron core.

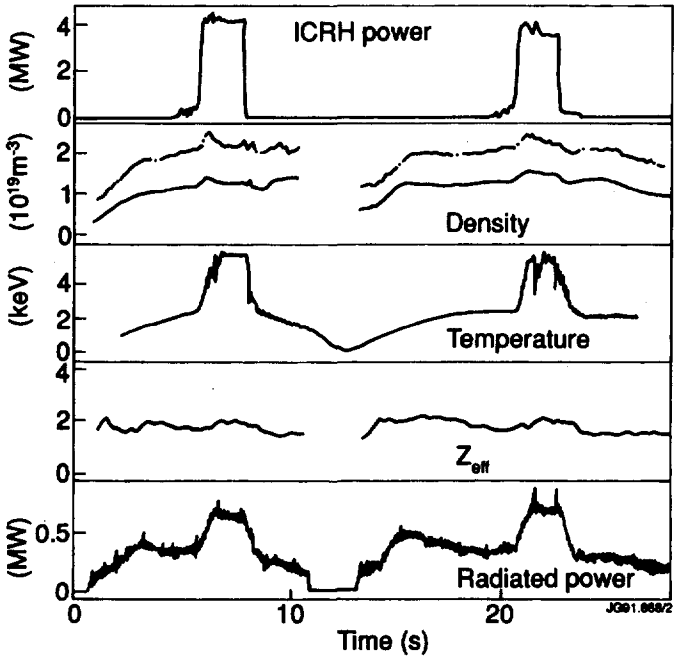

FIG. 2. Plasma purity of the two cycles (shotnr. 24807). Shown are ICRH input power, electron density (volume—average, solid trace and central, dashed trace), electron temperature, effective ion charge Z_{eff}, and total radiated power as a function of time for the same discharge shown in figure 2. Some of the traces are not available during part of the ramp—up and ramp—down.

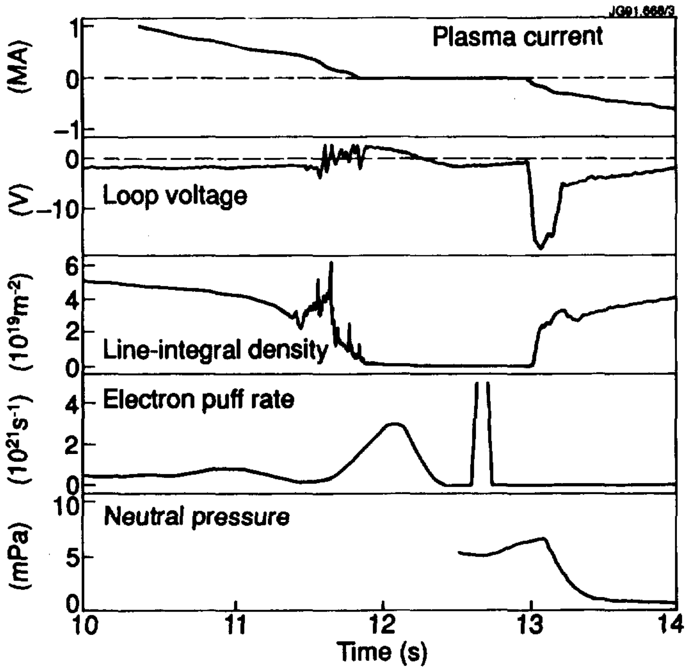

FIG. 3. Second breakdown after disruptive termination (shotnr. 24835). Shown are plasma current, loop voltage, line—integrated density, gas puff rate in electrons per second and neutral pressure. The neutral pressure is not meaningful before 52.5 s because it is measured near the gaspuff module.

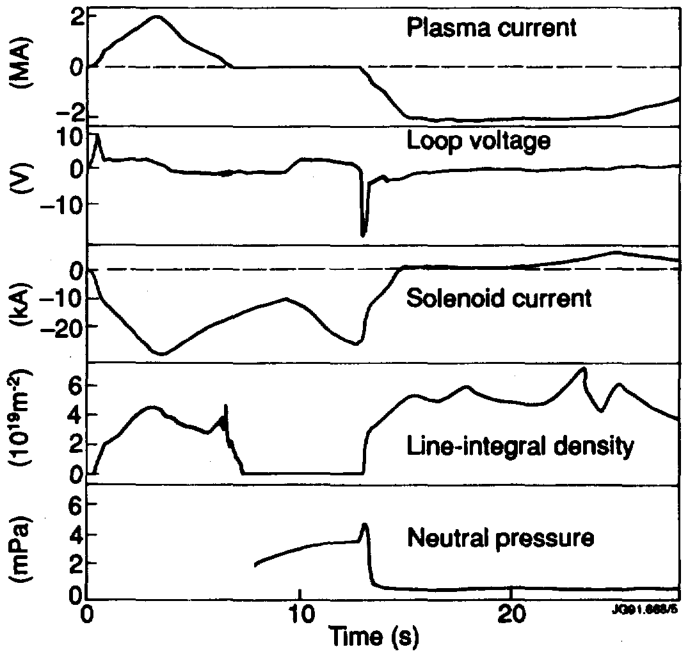

FIG. 4. AC discharge with 6 s dwell time (shotnr. 24853). Shown are plasma current, loop voltage, vertical line—integrated density, central solenoid current, and neutral pressure. The neutral pressure is not meaningful before 48 s because it is measured near the gaspuff module.

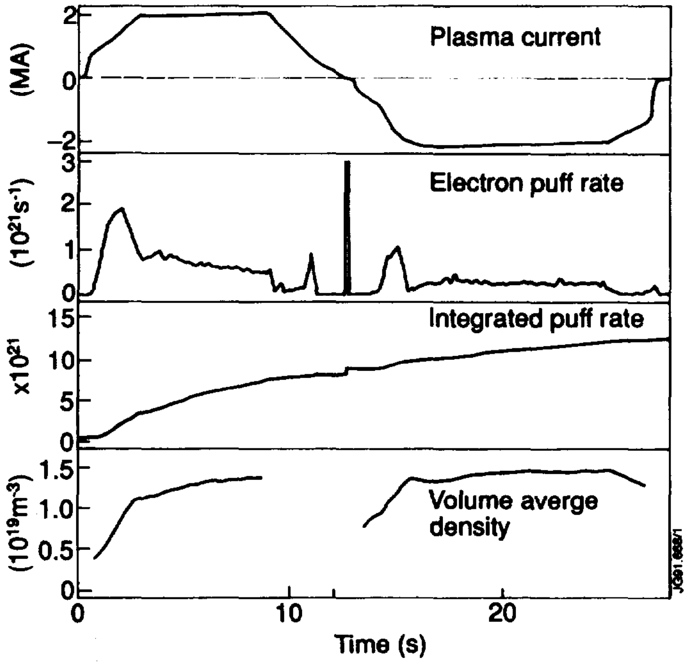

FIG. 5. Plasma fueling in consecutive cycles in an AC discharge without additional heating (shotnr. 24829). Shown are plasma current, gas puff rate in electrons per second, integrated gas puff rate and volume–average density. The plasma volume is about 80 m^3. The spike on the puff rate represents the introduction of the prefill gaspuff.

Appendix I

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