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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 pre-fill 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, the 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 consumed owing 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, the 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 the order of 10–20%. Moreover, it is not clear that optimization of bootstrap current also implies optimization of fusion power per unit capital investment. This depends on constraints such as for example divertor heat load limitations and MHD stability. Thus, for designs that are optimized in terms of fusion power per unit capital investment, instead of bootstrap current, potentially the recirculating power for NICD is substantially larger.

The downtime of the burn in ICD schemes can be minimized 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 downtime is determined mainly by the sum of the plasma ramp-down and ramp-up times. In conventional tokamak operation with unidirectional plasma current, the recharging time of the central solenoid contributes significantly to the downtime, because of 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). Note that 'dwell time' in this paper always refers to the time between subsequent plasma discharges. The downtime of the burn, i.e. the time between ignited plasmas, is approximately given by the sum of the dwell time and the times required for current ramp-down and ramp-up.

2. CONFIGURATION

The AC discharges in JET [8] were performed in a 2 MA limiter configuration, without currents in the shaping coils. The modifications to the poloidal field power supplies and control systems are described in Ref. [9]. They can be summarized as follows. The AC operation requires a four-quadrant control (two polarities of both voltage and current) of the vertical field, compared with two-quadrant control for normal operation (two polarities of voltage and unidirectional current). To obtain two polarities in current, the power supply which normally drives the currents in the shaping coils was connected in anti-parallel to the vertical field power supply. There is thus no current in the shaping coils in this experiment. There were no hardware modifications to the Ohmic current drive (central solenoid) circuit. The only changes made were in the timing and control circuits. With the JET Ohmic current drive circuit, two types of plasma breakdown can be performed. First, plasma can be generated in a situation with zero pre-magnetization current in the solenoid, by high voltage excitation of the solenoid power supply (low voltage breakdown). Second, plasma can be generated by driving a pre-magnetization current through the solenoid and, in a switching action, redirecting this current through a load resistor parallel to the solenoid (pre-magnetization breakdown). The power supply, which is disconnected by the switching action at breakdown, is reconnected after about 1 s in reverse polarity to drive the plasma current. It is important to note that the switching actions (interruption and reconnection) can be executed only once per tokamak pulse. Hence, in the AC operation, the first plasma is generated by low voltage breakdown, and the second plasma by pre-magnetization breakdown at a pre-magnetization current of about 20 kA. The effect of the type of plasma breakdown on the subsequent plasma behaviour is very minor (for pre-magnetization currents less than about 30 kA). With low voltage breakdown, a slightly lower internal inductance may result for the first few seconds. Hence, to all intents and purposes, the first cycle of the AC discharges is identical with a standard 2 MA flat-top JET discharge of the same magnetic configuration.

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 pre-fill gas. The JET vacuum vessel is made of Inconel. The inner wall and the 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 ion cyclotron resonance heating (ICRH) antennas [10]. ICRH power is applied in the fast wave minority heating mode with hydrogen as the minority. The frequency is 42.6 MHz and the antenna phasing is dipole.

3. DEMONSTRATION

Figure 1 shows a typical full cycle AC discharge. 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 pre-magnetization 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

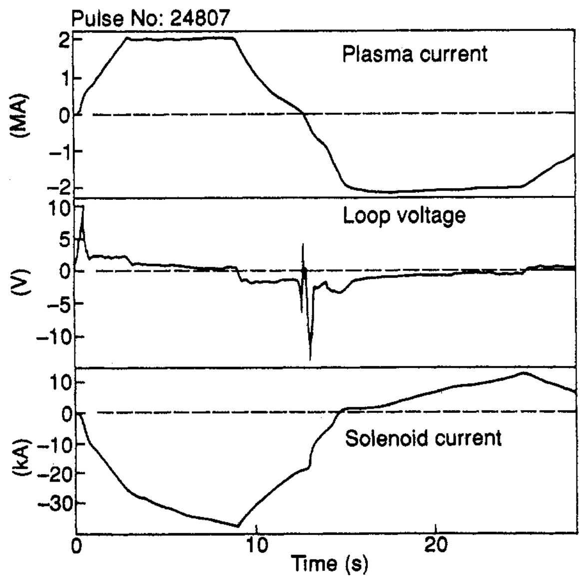

FIG. 1. Parameters of a full cycle AC discharge (shot No. 24807). Shown are the plasma current, the loop voltage and the current in the central solenoid as a function of time. The slow increase in the solenoid current at the beginning of the second plasma (15–17 s) is due to non-saturation of the iron core.

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 a pre-magnetization breakdown, redirecting the solenoid current of 20 kA through a parallel 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.

4. PLASMA PURITY

Figure 2 shows data pertaining to plasma purity for the discharge shown in Fig. 1. The electron density, measured by a multichannel far infrared interferometer, is under feedback control and is nearly equal in the two cycles (for example 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 ICRH). The density transient effects are induced by the switching of the ICRH power [11]. The electron temperature, measured by electron cyclotron emission

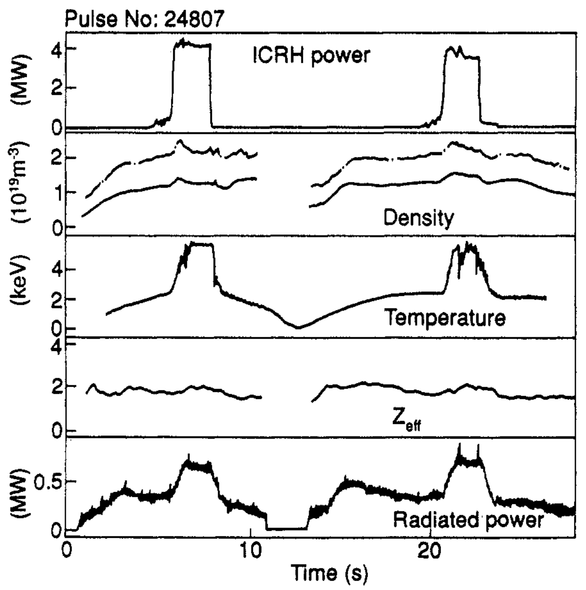

FIG. 2. Plasma purity of the two cycles (shot No. 24807). Shown are the ICRH input power, the electron density (volume average: solid trace; central: dashed trace), the electron temperature, the effective ion charge Z_{eff} and the total radiated power as a function of time for the discharge shown in Fig. 1. Some of the traces are not available during part of the ramp-up and ramp-down stages.

spectroscopy, is equal in the two cycles. A slight difference in the sawtooth behaviour during the ICRH phase is visible in the figure; there is a long (monster) sawtooth in the first phase. This is not significant, and is not reproducible in subsequent AC discharges. The effective ion charge Z_{eff}, measured by bremsstrahlung emission, is also equal in the two cycles (2.0 at 7 s and 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 the two cycles, the same neutron production rate 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 pre-fill 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 the first and the 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 pre-fill 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).

Figure 3 shows a successful second breakdown at a pre-fill 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 fuelling; this is a density limit disruption at high q. The current decay rate is low, but

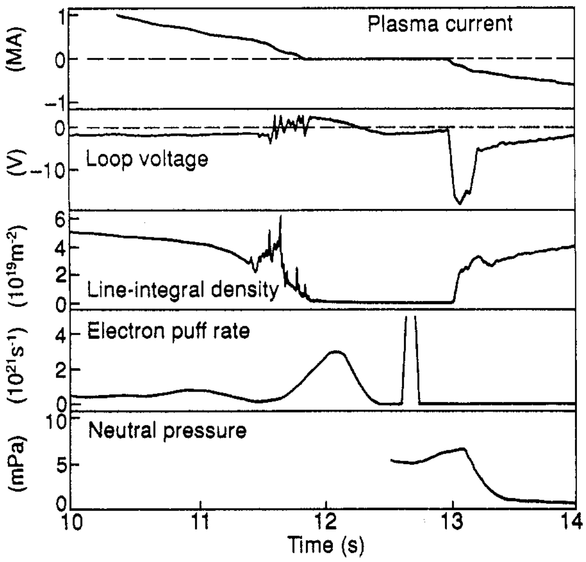

FIG. 3. Second breakdown after disruptive termination (shot No. 24835). Shown are the plasma current, the loop voltage, the line integrated density, the gas puff rate (in electrons per second) and the neutral pressure. The neutral pressure is not meaningful before 12.5 s because it is measured near the gas puff module.

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 pre-fill pressure for normal breakdown with the same loop voltage and stray field are not available for the present JET configuration (note that machine configuration changes with respect to that reported in Ref. [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 of two), 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.

Figure 4 shows a successful AC discharge 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 (9–13 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 time-scale 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 the order of 50 kA were obtained in the second plasma after correct programming of the vertical field and after delaying or

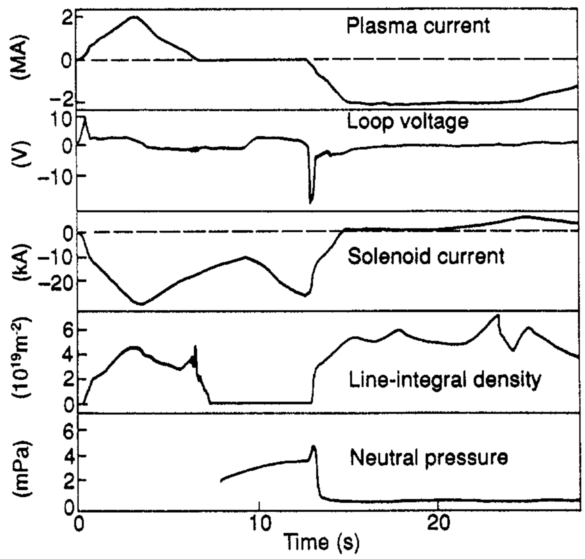

FIG. 4. AC discharge with 6 s dwell time (shot No. 24853). Shown are the plasma current, the loop voltage, the vertical line integrated density, the central solenoid current and the neutral pressure. The neutral pressure is not meaningful before 8 s because it is measured near the gas puff module.

eliminating the pre-fill gas puff (if the pre-fill 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 pre-fill gas puff resulted in failure due to a too low neutral pressure.

7. PLASMA FUELLING

Figure 5 shows the gas puff rate (in numbers 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 a factor of two (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. The curves of integrated gas input can be compared 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.

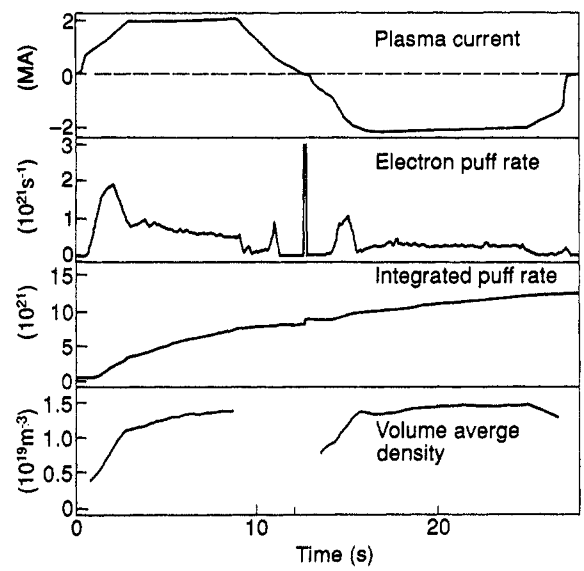

FIG. 5. Plasma fuelling in consecutive cycles in an AC discharge without additional heating (shot No. 24829). Shown are the plasma current, the gas puff rate (in electrons per second), the integrated gas puff rate and the volume averaged density. The plasma volume is about 80 m^3. The spike on the puff rate represents the introduction of the pre-fill gas puff.

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. A 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 one was observed. The range of pre-fill 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, without loss of ionization, cannot be ruled out as yet, we have so far been unable to demonstrate this. 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 NICD methods.

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