The plasma current profile during current reversal in AC operation of the CT-6B tokamak

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The plasma current profile during current reversal in AC operation of the CT-6B tokamak

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Abstract. Alternating current operation with one full cycle at a plasma current level of 2.5 kA has been achieved in the CT-6B tokamak. The poloidal magnetic field in the plasma is measured with two internal magnetic probes in repeated discharges. The plasma current distribution is reconstructed with an inversion algorithm. The reversed plasma current first appears on the low field side due to decreasing poloidal beta. Two plasma current components flow in opposite directions when the net current vanishes. The existence of the magnetic surfaces and rotational transform provides particle confinement in the current reversal phase.

1. Introduction

Alternating current operation could be an alternative method for producing a steady state power output in a tokamak fusion reactor with a small thermal energy storage system and a low recirculating power in comparison with RF non-inductive current drive. Alternating current operation experiments have been performed in a number of tokamak devices in the past decade. [1–9]. The method has been demonstrated to be feasible and free from secular degradation in performance.

A puzzle arising from these experiments is the finite plasma density observed during the time in which the current reverses its polarity [1, 7]. The particle confinement time is found to be about 0.5 ms during current reversal in the CT-6B tokamak [7], which is much longer than the 'free fall' time of particles in a simple toroidal magnetic field when the plasma current and the poloidal field vanish.

In order to answer this question and check if any local plasma currents and magnetic surfaces still exist during net current reversal, an experiment has been designed and then conducted in CT-6B.

In Section 2 the experimental device and measurement technique are presented. In Section 3 experimental results are presented and discussed. Conclusions are drawn in Section 4.

2. Experimental set-up and data processing

CT-6B is a small sized tokamak with an iron core transformer. Its major radius is 45 cm and the minor radius of the plasma is 12.5 cm. In normal tokamak discharges [10], the toroidal field is 6–13 kG, the plasma current is 10–30 kA and the plasma duration is 40–50 ms.

The AC experiment has been performed at a plasma current level of 2.5 kA and a toroidal field of 4.5 kG, as the magnetic probes immersed in the plasma used in such an experiment could work only for low values of the plasma parameters. The plasma current is also limited by the capacity of the current generator, which is now described. In the primary circuit of the transformer, two capacitor banks of energy storage are connected in parallel and in opposite polarities for the discharges in the positive and negative directions, respectively. Two power electronic tubes (modulators) control the discharge current in the primary circuit. The details of the experimental set-up and procedure are discussed in Ref. [7]. After a sufficient discharge precondition, AC operation with a smooth current transition can be achieved with suitable gas puffing during the current reversal phase, which guarantees the first half cycle of the plasma current 'soft landing'. The vertical field for equilibrium of the plasma is controlled by a programming signal with the same sinusoidal waveform as that of the plasma current and a feedback signal from the horizontal displacement multiplied by the plasma current. The measurement method of plasma position with cosine coils is still considered to be applicable during current reversal. In addition to conventional electromagnetic diagnostic terms, an HCN far infrared laser interferometer is used for measurement of the line averaged plasma density.

The key technique in this experiment involves the internal magnetic probes (coils) immersed in the

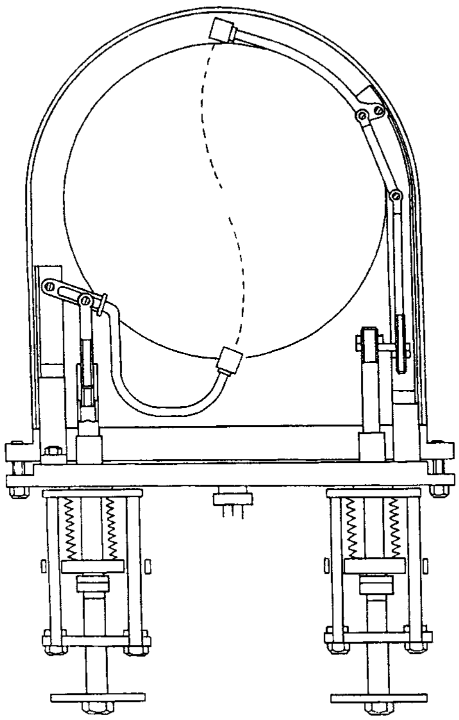

Figure 1. Adjustment mechanism of the internal magnetic probe system.

plasma for measurements of the poloidal magnetic field. In particular, since the plasma equilibrium may lose cylindrical symmetry during current reversal, the fields on the low and high field sides have to be measured simultaneously. We have designed two internal magnetic probes located on both sides, and their radial positions can be changed from discharge to discharge.

The coils are wound with wire of 0.01 mm^2 cross-sectional area. The total effective area nS of the coils is 126 cm^2 (No. 1, on the low field side) and 208 cm^2 (No. 2, on the high field side). They are placed inside two shielding stainless steel boxes of 8 and 10 mm in diameter, and 12 and 8 mm in length, respectively. The boxes are coated with Al_2O_3 by means of plasma spraying for protection from plasma bombardment. The adjustment mechanism for the radial positions of the coils is shown in Fig. 1. It is found that the discharges at a current level of a few kiloamperes are not obviously affected by the existence of the internal probes, even 2–3 cm away from the toroidal axis. Then we suppose that the discharges are reproducible and that the magnetic configuration of the plasma can be reconstructed on the basis of shot to shot measurements with the probes.

The output signals from the internal coils are integrated and digitized. The field measured with the coils is composed of the poloidal field caused by the plasma current, the externally applied vertical field and the toroidal field due to orientation deviations of the coils. The component of the signal from the toroidal field can be found through the discharges of the toroidal field alone and is removed from the signal before the integration. The vertical field can be deduced from the currents in the coils of the programming and vertical feedback fields. Its value is also subtracted from the measured result. The field produced by eddy currents in the saddle loops on the vacuum vessel walls is ignored due to its short decay time of 0.2 ms. Therefore, we have obtained the poloidal field caused by the plasma current, including the field produced by the current induced in the iron core of the transformer.

An inversion technique is adopted to process the data obtained with the internal probes. The cross-section of the plasma column, which is assumed to be circular during current reversal, is partitioned into n coaxial zones with equal widths. The toroidal plasma current in the kth zone can be expressed as

$$j_k = a_k + b_k \cos\theta \tag{1}$$

where θ is the poloidal angle, and a_k and b_k are constant coefficients, which compose a one dimensional matrix $\mathbf{I} = (a_k, b_k)$. Here terms of higher order than second are ignored, and the plasma current distribution is considered to be symmetric to the equatorial plane. Then if the poloidal fields are measured at $2n$ different locations, the fields can be expressed as

$$\boldsymbol{B} = \mathbf{T} \cdot \mathbf{I} \tag{2}$$

where $\mathbf{T}$ is a $2n \times 2n$ matrix. The linear dependence should be valid for non-saturated iron cores. The current coefficient matrix and the current distribution can be obtained from

$$\mathbf{I} = \mathbf{T}^{-1} \cdot \boldsymbol{B}. \tag{3}$$

The matrix $\mathbf{T}$ can be obtained by calculation of the magnetic fields produced by each current component at each measurement position and the related induced current in the iron core. For the purpose of simplification, the iron core is assumed to be an infinite cylinder with infinite magnetoconductivity.

3. Experimental results

In the experiment an AC discharge with one full sinusoidal cycle is achieved with a total duration of

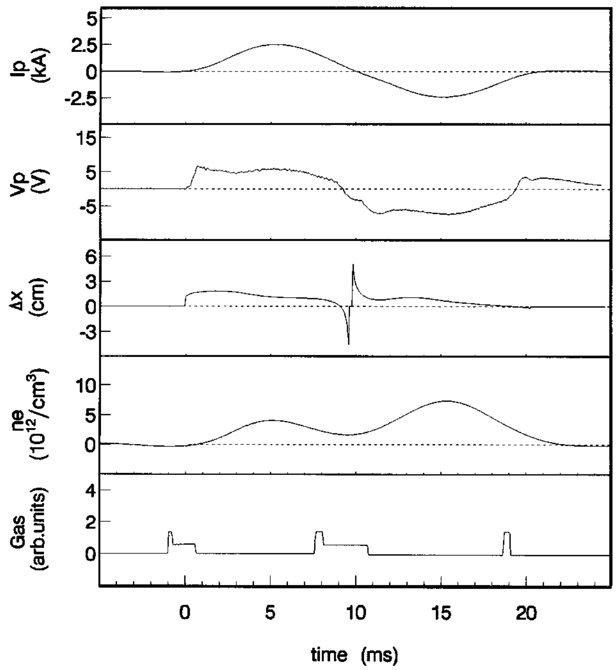

Figure 2. Set of typical waveforms of plasma current, loop voltage, horizontal displacement, line averaged electron density and gas puffing.

20 ms. The waveforms of plasma current, loop voltage, horizontal plasma displacement, line averaged electron density and gas puffing are shown in Fig. 2. The measurement of horizontal displacement in the current reversal phase is no longer valid as its value is calculated from the data of the displacement multiplied by the plasma current and this would be divergent for small current values. The electron density in the second half-cycle is higher than that in the first half-cycle due to the different gas recycling rates for discharges in opposite directions, as discussed in Ref. [7]. Figure 2 shows that the plasma current has a peak value of 2.5 kA in the positive half-cycle and changes polarity at $t = 10$ ms, then attains a negative peak at the same absolute value. The loop voltage passes zero about 0.5 ms before the plasma current reversal. The electron density attains its minimum at almost the same time as the current reversal. The current in the primary circuit of the transformer also passes through zero about 0.5 ms earlier and the vertical field 0.7 ms later than the current (not shown in Fig. 2).

In the experiment, we measured the poloidal field at ten radial positions for each probe; eight of these are inside the plasma and two outside the plasma. Naturally, the zone number is taken to be $n = 10$ in the inversion calculation.

A set of typical measurement results of plasma current profiles from $t = 8$ ms to $t = 11.5$ ms in the current reversal phase is shown in Fig. 3. As the plasma current drops, the current peak and its centre of weight shift towards the high field side and then the negative plasma current first appears on the low field side at $t = 9$ ms. As the total plasma current drops further, the negative plasma current increases, and then the second magnetic axis and magnetic surface system corresponding to the negative plasma current appear at $t = 9.5$ ms, as shown in Fig. 4. At the total plasma current reversal point, both positive and negative currents coexist at absolute current values of about 300 A. The first magnetic axis and the positive plasma current disappear at $t = 10.5$ and 11.5 ms, respectively. Two plasma current components flowing in opposite directions, obtained from the current distribution obtained, as functions of time are shown in Fig. 5, in which the total plasma current measured with a Rogowski coil is also shown.

The measurement of current distribution in the plasma with internal probes has answered the question why the plasma density remains finite during current reversal. There are two local currents flowing in opposite directions in the plasma when the net plasma current passes through zero. The magnetic surfaces and rotational transform still exist, so that the particle drift in the curved magnetic field can be cancelled and the particles be confined.

The safety factor of a plasma column is defined as

$$q(r) = \frac{B_\phi r}{B_p R} \tag{4}$$

where B_ϕ and B_p are the toroidal and poloidal fields, respectively, and r and R are the minor and major radii of the plasma column, respectively. The safety factor at the first current peak ($t = 5$ ms) is calculated from the above expression as a function of minor radius, and the result is shown in Fig. 6. The safety factor for the positive current component at the net current reversal ($t = 10$ ms) is also shown in Fig. 6, where the argument r is the averaged minor radius of the magnetic surfaces. This shows that the safety factor on the surface of the current component ranges up to 180. A similar result has been obtained for the negative current component at that moment.

The question is: How large a rotational transform and safety factor are needed to confine particles against drift losses? If an electron rotates through an angle π in the poloidal direction along the resultant

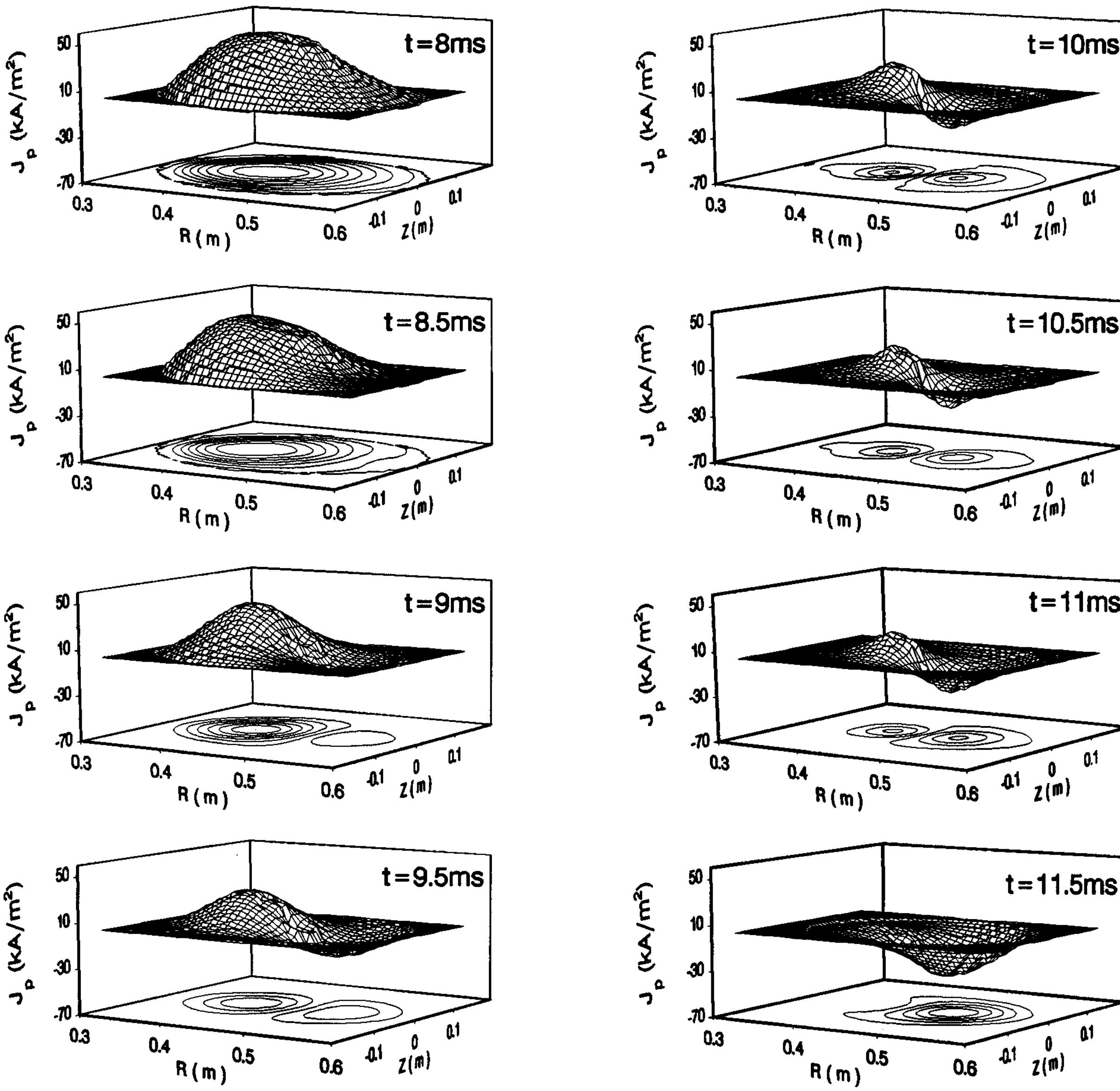

Figure 3. Plasma current distributions and magnetic surface structure during the total plasma current reversal from $t = 8$ ms to $t = 11.5$ ms; the increment of the contours is 6 kA/m^2.

magnetic field before it drifts to the plasma edge, the drift can be cancelled. Therefore, an effective rotational transform or safety factor should satisfy

$$\frac{\pi R}{v_\parallel} q(r) < \frac{r}{v_{dB}} \tag{5}$$

where $v_\parallel$ is the parallel velocity of the electron and v_{dB} is the magnetic drift velocity of the electron. For the electron temperature at current reversal $T_e \simeq 12$ eV, the critical value of safety factor for an effective rotational transform is about 1000. Therefore, the particles are still confined by the magnetic surfaces during current reversal except in the region with open force lines between two plasma current components.

However, a proper high q cannot provide charged particles with complete confinement in such a toroidal configuration. The particle drifts would greatly deviate from the closed magnetic surface, and then introduce a considerable radial diffusion. In fact, the transport of a toroidal plasma in the collisional regime follows Pfirsch–Schlüter diffusion which is $1 + 2q^2$ larger than classical diffusion [11]. The above measurements would result in a radial

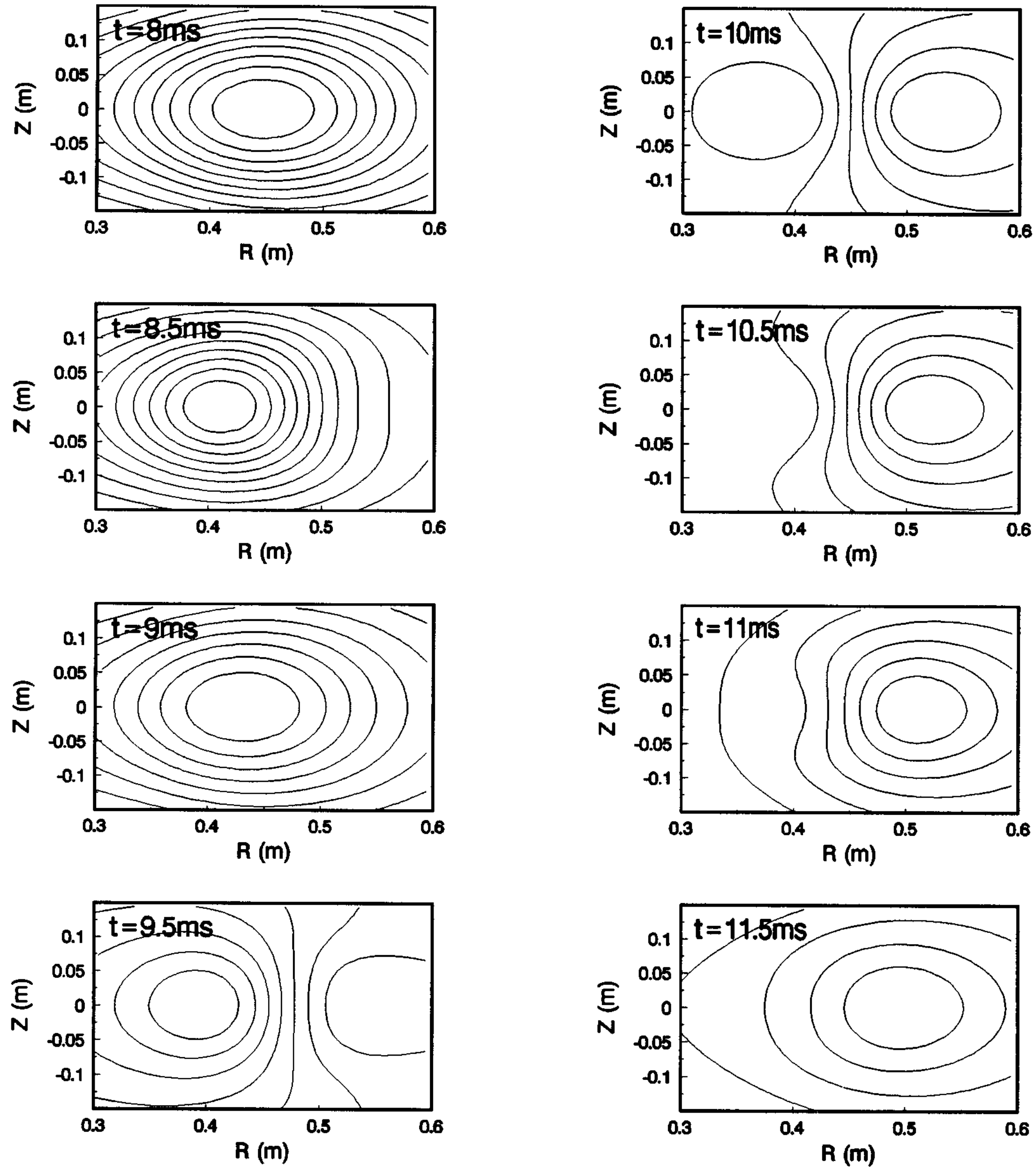

Figure 4. Poloidal magnetic surface structures during the total plasma current reversal from $t = 8$ ms to $t = 11.5$ ms; the increment between contours is 6×10^{-4} Wb.

plasma diffusion enhanced by four orders of magnitude and particle and energy confinement times less than one microsecond during plasma current reversal. The deduction is inconsistent with the measured result of particle confinement time during this period [7]. In addition, no other observable effects of very high radial diffusion are found during the period of about 3 ms when the two plasma current components coexist. The phenomenon is certainly interesting and worthy of further study.

Another important result obtained in the present experiment is that the negative plasma current first appears on the low field side rather than on the high field side, as predicted by some numerical simulations [12, 13] and observed in an experiment [14]. In the simulations [12, 13], a temperature profile and a finite rate of change during current reversal phase are arbitrarily assumed. Obviously, as the plasma current and the poloidal field decrease, the poloidal beta value increases for a certain plasma temperature.

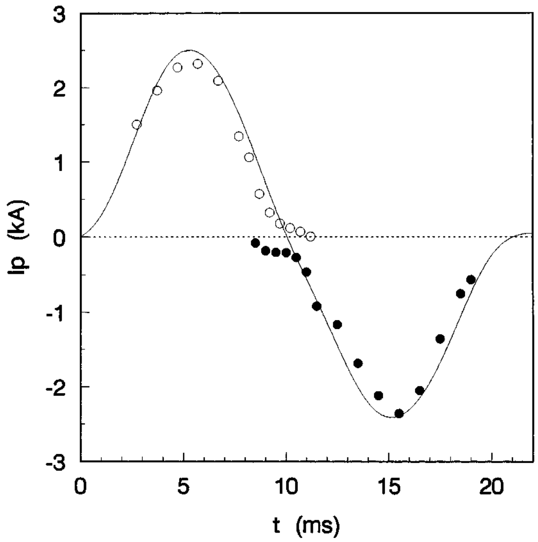

Figure 5. Positive plasma current (open circles) and negative plasma current (solid circles) obtained from the inversion calculation, and the total plasma current (curve) from the measurement with a Rogowski coil, as functions of time.

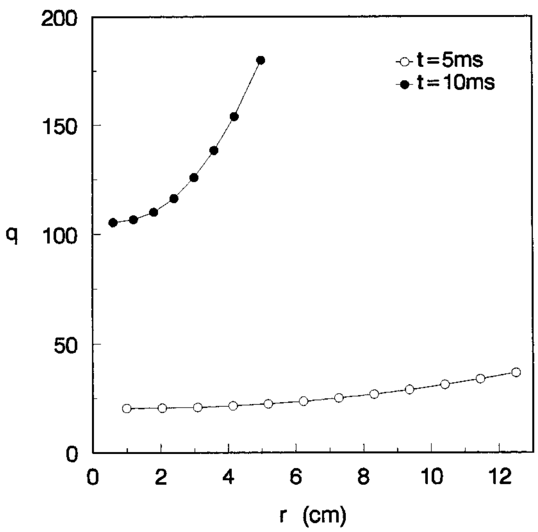

Figure 6. Safety factors at the first plasma current peak (t = 5 ms) and at plasma current reversal (t = 10 ms, for the positive current component) as functions of minor radius.

When it approaches its limit, namely the aspect ratio R/a, a poloidal separatrix and a negative plasma current appear on the high field side. In the experiment performed in a small device, the total plasma current quickly changes polarity in a few microseconds, which may be much less than the energy confinement time [14]. In this case, poloidal beta increases and a similar process occurs during current reversal. However, in the present experiment, the plasma current changes polarity slowly in comparison with energy confinement time (0.1–0.5 ms), the electron temperature is estimated to be about 15 eV and the plasma pressure is sufficiently low in the current reversal phase [7]. Therefore, the poloidal beta value decreases, and the equilibrium equation determines that the negative plasma current appears on the low field side when the total current drops. In Fig. 3 no skin current is observed during current reversal. This phenomenon indicates that the field diffusion time is much shorter than the current reversal timescale due to low plasma temperature. The result is also different from that obtained in a numerical simulation [12]. Moreover, as the poloidal beta does not attain its limit, no serious MHD instabilities are observed in the experiment.

4. Conclusions

The experiment shows the existence of two plasma current components flowing in opposite directions and an effective rotational transform at total current reversal, a situation which may lead to particle confinement during the current reversal phase. When the plasma current drops, the reversed current first appears on the low field side as the poloidal beta decreases, a situation which is apparently different from the results of some earlier simulations and an earlier experiment. The presented scenario of current reversal is free from the poloidal beta limit and related MHD instabilities and provides a stable and smooth transition between opposite phases of plasma current in AC tokamak operations.

It should be pointed out that the present experiment and measurements are still very preliminary. Only zeroth (axially symmetric) and first order (dipole) current components are considered in our simplifying model (expression (1)). More accurate measurements are needed for further analyses of plasma equilibrium and instabilities.

The experiment should be repeated at high plasma current levels. In this case fast action movable magnetic probes would be needed.

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