Study of Plasma Equilibrium during the AC Current Reversal Phase on the STOR-M Tokamak*

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Abstract. This paper describes the newly employed hybrid digital/analog position feedback control system for alternating current operation on the STOR-M tokamak and addresses issues relating to the plasma equilibrium during the current-free phase without rotational transform. Smooth plasma current transition to the opposing current direction with a finite plasma density and H_α radiation levels during the current reversal phase has been consistently achieved. Direct measurement of finite limiter current during the current reversal phase suggests that the charge separation/accumulation arising from the grad-B and curvature drifts could be shorted out by the limiter and other conducting structures during the plasma current zero-crossing phase to maintain plasma equilibrium.

1. Introduction

Alternating current (AC) tokamak operation is an alternative reactor operation mode with various advantages including its technical simplicity and its high economical efficiency for plasma heating and current drive. Especially when a cleaner D-^{3}He tokamak reactor with a high density is conceived as the possible option, AC operation is the only known solution having a quasi-steady state operation due to the low efficiency of the non-inductive current drive methods [1]. Although AC tokamak discharges in some tokamaks experience the loss of discharge between currents with opposite polarities [2,3], smooth current transition without losing plasma in some other AC tokamaks has also been achieved [4,5,6]. Finite plasma confinement during the current reversal phase is beneficial for saving energy required to break down the gas and for reducing plasma-wall interactions and the associated impurity release from the wall.

It is well known that a rotational transform of the magnetic field in a toroidal magnetic confinement device (tokamaks, stellarators, reversed-field pinches) is essential for shorting out charge separation/accumulation induced by the grad-B and curvature drifts. In a tokamak, the plasma current induced poloidal field serves this purpose. However, the phase when the plasma current crosses zero to switch its polarity during AC operation represents a case without rotational transform. Delicate feedback control during this phase is usually required to achieve a smooth current transition without losing the plasma. However, the mechanism for finite plasma confinement without rotational transform has not been well studied.

Recently, central current holes extending up to radius $r/a=0.4$ have been observed in the JET and JT-60U tokamaks during conventional tokamak discharges with unidirectional currents [7,8]. Rotational transform

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disappearance in this plasma region resembles the zero-crossing phase in AC operation. Study of equilibrium and techniques to maintain plasma equilibrium without rotational transform is important for AC tokamak operation and may be also interesting, in general, for the equilibrium issues related to the current-free region of conventional tokamaks. In the CT-6B tokamak, direct insertion of magnetic probes into the AC discharge revealed localized positive and negative currents coexisting in different regions during the current reversal phase [9]. However, the scenario of opposing currents has been ruled out in the current-free region in JET within experimental uncertainties. Ideas to induce a strong poloidal rotation by off axis perpendicular neutral beam injection for a short-circuiting effect have also been proposed [10], but have not been experimentally confirmed.

In this paper, we describe an experiment to investigate the role of the limiter in providing the equilibrium during the current reversal phase, by short-circuiting the charge separation due to the grad-B and curvature drifts. In order to investigate the plasma equilibrium, it is necessary to achieve a smooth current transition during AC operation. We will also describe our new feedback position control system used in the present experiments. This system has simplified the adjusting procedure when the Ohmic heating circuit is converted from normal operation to AC operation and has also provided much needed flexibility to control the currents in the feedback vertical field windings.

2. Experimental Setup

STOR-M is a small tokamak ($R=0.46$ m, $a=0.12$ m) with an iron core transformer. It is equipped with a preprogrammed pulsed gas puffer for density control and a feedback plasma position controller. Three capacitor banks triggered consecutively were used to achieve *1.5*-cycle AC operation. The main diagnostics tools include a 4-mm interferometer to measure the line averaged electron density along the central chord, a spectrometer for monitoring H_α radiation levels, and Langmuir/Mach probes for monitoring plasma density in the edge region.

2.1. Feedback Position Control System

In order to study the plasma equilibrium, a smooth current reversal with zero dwell time must be achieved. In the previous STOR-M AC operation experiments, an analog circuit was used to determine the horizontal position signal ΔH and this signal was used to determine the required currents in the vertical field windings through a PID (proportional-integral-derivative) circuit. This system also provided different DC offsets to the ΔH signal for opposing current polarities to account for the difference in a correction term in the position determination circuit. Since the position was obtained using an analog divider (with plasma current as the denominator and a combination of magnetic pickup coil signals as the numerator), the position signal becames undefined during the current zero crossing phase and the ΔH signal often saturates randomly either at negative or positive levels depending on the polarity of the noise during the current reversal phase. To mitigate this problem, several square voltage pulses, marked as “dist” in Fig. 1, from a set of signal generators, were added to the ΔH signal during the current reversal phases based on our best guess of the polarity of the ΔH signal saturation and the required current in the feedback windings [3]. This improved feedback position control system, combined with careful control of gas puffing pulses, significantly reduced the adjusting time when the STOR-M tokamak is converted from the normal to the

AC operation. However, due to the increased stray fields from a new set of toroidal coils in STOR-M, smooth AC current reversal suffered a setback [3, 5].

More recently, a computer based digital data processing unit has been added to the existing analog feedback position controller. In this hybrid digital/analog system shown in Fig. 1, the plasma current, position signal, and a timing signal are converted to digital signals through the ADC converters on a multipurpose card and acquired by a personal computer. Based on this information and the preset conditions, the computer will make the following decisions: a) when to use the analog position signal ΔH, b) when to disable the analog ΔH signal and use a computer controlled waveform, and c) when to use both digital and analog controls. Alternatively, simple digital PID and more delicate fuzzy logic control algorithms may also be implemented to improve control qualities. After implementation of the new feedback control system, AC operation with zero dwell time and finite density has been restored.

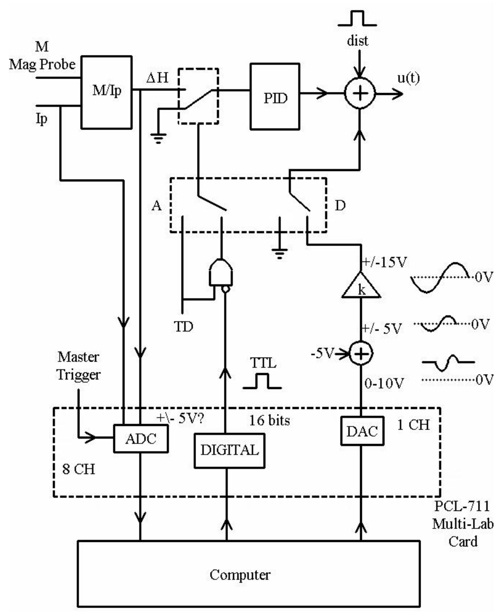

FIG. 1. Block diagram of the hybrid digital/analog feedback control circuit.

2.2. Segmented Limiter

To verify our hypothesis that the charge separation without rotational transform could be shorted out by the conducting structures surrounding the plasma column, a segmented limiter [11] has been used in STOR-M. Figure 2 shows the schematic diagram of the segmented limiter consisting of eight stainless steel segments with four segments mounted on each side of a ceramic supporting structure. Each plate is insulated from one another inside the vacuum vessel and is electrically connected to a feedthrough connector that is accessible outside the vessel. In our current experiments, the top two plates on both sides of the ceramic are connected together and then connected to two bottom plates through a conducting wire. The wire goes through a Pearson current probe for measuring the current flowing between the top and bottom plates. The same arrangement has also been made between the plates in the high field side and those in the low field side.

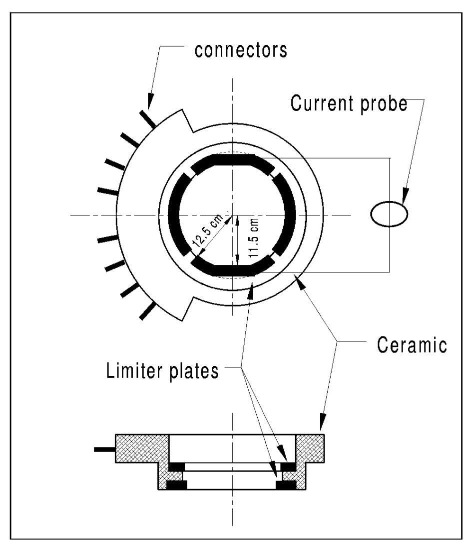

FIG. 2. Schematic diagram of the segmented limiter.

3. Experimental Results

Figure 3 (a) shows the discharge waveform during a full AC cycle discharge in STOR-M (shot number 135545) and Fig. 3 (b) depicts the expanded traces to emphasize the details of the same set of signals during the current reversal phase around *t=20.2* ms. Shown in the figure (from top) are plasma current, I_p , loop voltage, V_l , limiter current flowing from the top plates to the bottom plates, $I_{lim.}$, line averaged plasma density, n_e , H_α radiation level, and the horizontal displacement, ΔH. In this discharge, a smooth current transition from *+20* kA to *–12* kA has been obtained without losing the plasma. As a result, the loop voltage switched sign smoothly without any high voltage spikes. The line averaged density maintains above 4×10^{11} cm^{-3} during the plasma current reversal phase and the H_α radiation level stays above zero. The horizontal displacement is well controlled during the discharge, but saturates positively before the plasma current reversal and then saturates negatively after the reversal. The limiter current is about *-4* A and its direction is consistent with that determined from the grad-B and curvature drifts. Finite limiter current itself is also an indication that the plasma did not vanish during the current reversal phase.

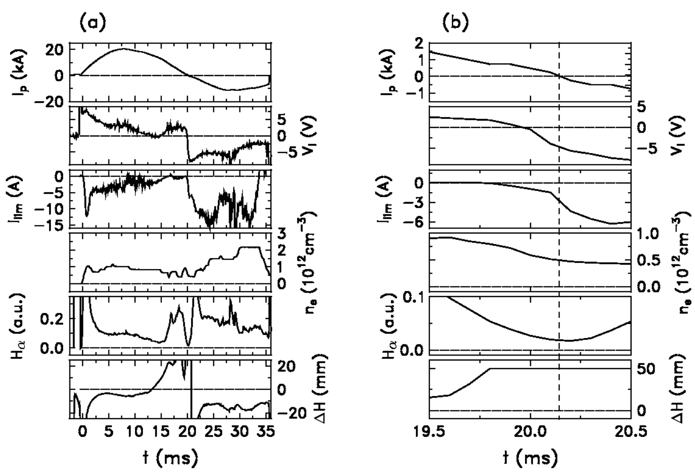

FIG. 3. Evolution of plasma discharge parameters (shot 135545).

Attempts have also been made to measure plasma rotations at the plasma edge using two sets of Mach probes, one set is oriented in the poloidal direction and the other in the toroidal direction. Figure 4 shows the reference plasma current trace and ion saturation currents collected by four Mach probe disks. The traces show that the ion saturation currents on all four probes remain finite during the current reversal phase, confirming the finite line averaged density and H_α radiation measurements. Flow velocity analysis is still underway.

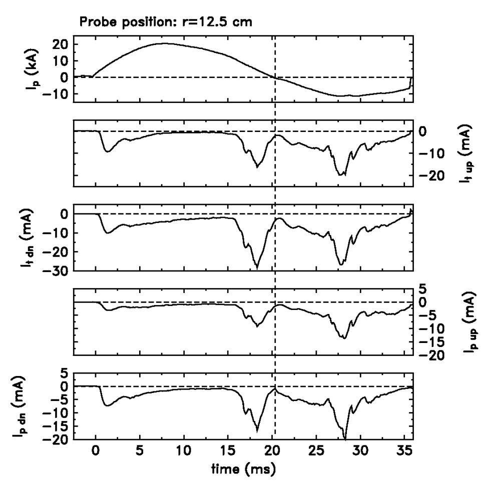

FIG. 4. Ion saturation currents on Mach probes at r=12.5 cm (shot 135545).

4. Conclusion and Discussions

The hybrid digital/analog feedback plasma position control system on STOR-M has significantly reduced the adjusting time and simplified the procedure to convert the Ohmic heating circuits from the normal operation to the AC operation and has also provided much needed flexibility to control the currents in the feedback vertical field windings. Finite particle confinement without rotational transform during the current reversal phase has been confirmed by finite line averaged plasma density, finite density measured by Mach probes in the plasma edge, and finite radiation levels. During the current reversal phase, the limiter current from the top plates to the bottom plates also remains finite and its direction is consistent with the grad-B and curvature drift direction, suggesting that the limiter and other conducting structure surrounding the plasma column could short out the charge separation and accumulation caused by grad-B and curvature drifts to maintain plasma equilibrium without rotational transform.

During the current reversal phase, the vertical field should have minimum effects on the equilibrium. However, flexible feedback control is still required during this phase to cancel stray fields and to ensure a smooth current reversal with zero dwell time.

In the current-hole modes, such as those observed in the JET and JT-60U tokamaks, the outer layers of plasma (with rotational transform) may also provide some if not all short-circuiting effect for the plasma in the current-free core region (without rotational transform). The interaction between the core plasma and the outer layer plasma in the current-hole mode is probably another set of problems compared with the possible force imbalance during the current reversal phase in AC operation. In the latter case, the result is the direct plasma-wall interaction that usually terminates the discharge and requires a new break down for the next half cycle. This represents not only an energy waste in the Ohmic heating circuit but also some mechanical stresses on the machine structures and thus should be avoided.

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