The Reversed Magnetic Shear Experiments in the HL-1M Tokamak

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Abstract. An ohmic shear reversed configuration has been obtained in HL-1M by combined control of plasma current rise and supersonic molecular beam injection (MBI). An equilibrium reconstruction code has been applied to the HL-1M database, which stores data from 32 magnetic probes to derive the current density profile and safety factor q profile. The current density profile derived from the code is found to be hollow in the core plasma and q is nonmonotonic. A peaked density profile and hollow electron temperature profiles were formed. The hollow temperature profile leads to a hollow current density profile and reversed magnetic shear. Current profile control by LHCD was conducted in HL-1M. The sawtooth and m=1 mode instabilities were observed to be suppressed by LHCD. The current profile and q profile reconstructed by the equilibrium code show a hollow current profile during LHCD and they are related to the nonmonotonic q profile. In ECRH off-axis experiments the occurrence of the compound sawtooth observed by the soft X-ray diode array implies that hollow current density profiles were formed.

1. Introduction

In recent tokamak experiments, successful improvement of plasma performance in reversed magnetic shear discharges has been reported [1-3]. Here the magnetic shear, S, is defined as $S=(\rho/q)(dq/d\rho)$, q is the safety factor and $\rho=r/a$ is the normalized flux radius. A reversed magnetic shear configuration is characterized as a configuration in which S is negative in the inner region of the plasma and positive in the outer region. These results have emphasized the importance of current profile control in the tokamak plasma. In the HL-1M tokamak experiments were performed with supersonic molecular beam injection (MBI) during the ohmic current ramp phase, LHCD and ECRH to obtain a reversed magnetic shear configuration [4].

In recent HL-1M experiments, plasma performance was greatly improved through the use of boronization, siliconization, and lithiumization [5,6]. Typical parameters of ohmic heated hydrogen plasmas are:$n_e<8\times10^{19}$ m^{-3}, $I_p<320$ kA, $B_t<3$ T and a pulse duration of up to 4 s. ICRF at a power level of 0.3 MW, NBI at a power level of 0.4 MW, ECRH at a power level of 0.25 MW and LHCD at a power level of 1 MW have been initiated. New fueling techniques with pellet injection and supersonic MBI were also employed to significantly improve the energy confinement time and density limit [7].

2. Reversed magnetic shear in the HL-1M ohmic discharges

Well collimated hydrogen MBI with a velocity of about 500 m/s was injected into the HL-1M plasma. With a penetration depth of ~10 cm, the ramp-up rate of electron density dn_e/dt is as high as 2.9×10^{20} $m^{-3}s^{-1}$ without disruption and the resulting plasma density reaches n_e

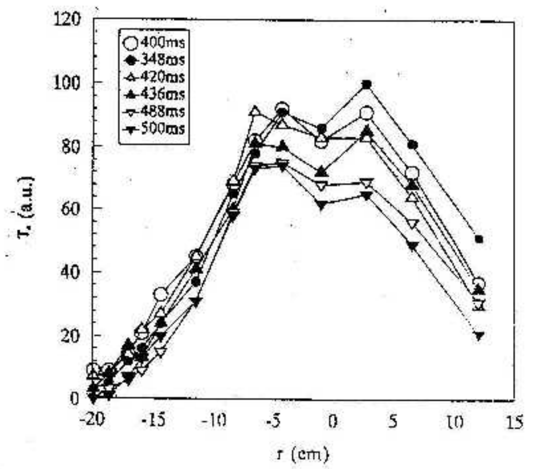

FIG. 1. *Hollow Te profiles appear in HL-1M by combined control of plasma current rise and supersonic MBI.*

$=8\text{x}10^{19}\text{m}^{-3}$ with a lower impurity concentration. The density peaking factor is about 1.7. The energy confinement time measured by diamagnetism is 10-30 % longer than that with gas puffing under the same discharge condition [8].

An ohmic shear reversed configuration has been obtained in HL-1M by combined control of plasma current rise and supersonic MBI. A peaked density profile and hollow electron temperature profile were formed, as shown in *FIG.1*. An equilibrium reconstruction code, which uses 32 magnetic probes, has been applied to the HL-1M database for deriving the current density profile and the safety factor q profile. For sawtooth discharges, the position of the q=1 surface determined by the code is in good agreement with the observed sawtooth inversion position [9]. The current density profile is found to appear hollow in the plasma core and the q profile in such discharges is nonmonotonic. Soft X-ray sawteeth become small in the center and large sawtooth crashes appear off-axis. They are related to a nonmonotonic q profile and hollow current density profiles.

3. Lower hybrid reversed shear discharges

Up to 0.85 MW of LH power has been applied to the HL-1M plasma. The dependence of the current drive efficiency on various plasma parameters was investigated. A significant density increase (up to a factor of two) has been observed in the HL-1M experiments during combined ohmic and LHCD discharges. The results indicate a decrease in the edge density fluctuations in improved particle confinement mode during lower hybrid wave injection. The HL-1M experiments have shown that the suppression of density fluctuations is related to the poloidal rotation produced by LHW injection. Changes in the poloidal rotation velocities during lower hybrid wave injection can be explained by the modification of the radial profiles of the radial electric field. It appears that the poloidal velocity is mainly determined by ExB drift [10]. The effects of LHCD on MHD activities (sawteeth, m=1 mode) are studied with the soft X-ray emission. The suppression of the sawteeth and m=1 mode instabilities by LHCD has been observed in the sawtoothing discharges (electron density n_e=(1-3)x10^{19} m^{-3})(see *FIG. 2*). A

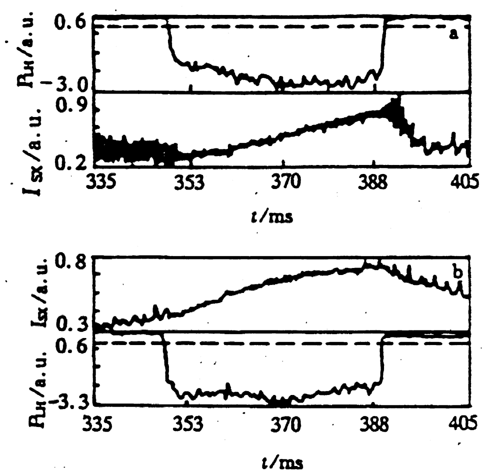

FIG. 2. Complete suppression of central sawteeth, (a) m=1 mode (b) sawteeth with LHCD.

decrease in internal inductance by LHCD has been observed during sawtooth and m=1 mode suppression, which suggests a flattened radial current profile and a safety q profile with q(r) higher than 1 everywhere in the plasma [11]. Figure 3 shows the reconstructed profiles of J and q for shot 4560, which has LHCD. At t=140 ms LHW has not been injected into the plasma, and the reconstruction current profile is peaked (see *FIG. 3a*). During LHW injection such as at t=180 ms and 220 ms hollow current profiles appear as shown in *FIG. 3b* and *FIG. 3c*. The reason for this may be power deposition of LHCD off-axis. After LHCD the current profile becomes peaked again (see *FIG. 3d*).

4. ECRH in HL-1M reversed magnetic shear discharges

In the HL-1M tokamak, sawtooth activities are observed to be strongly modified by localized election-cyclotron-resonance (ECR) heating near the q=1 surface. The compound sawteeth are observed erratically in some operating regimes, typically, at plasma currents 150 kA$<I_p<$210 kA , line averaged electron densities n_e=(0.8-2)x10^{19} m^{-3} and toroidal field B_t=2.50-2.65 T when ECR off-axis (r=1-6 cm) heating with microwave power P_{rf} from 200 to 230 kW on the high-field side (HFS) is applied.During ECRH both the period and amplitude of the soft X-ray are varied and some double sawteeth appear during ECRH on the high B field side. The complete double sawtooth cycle in the plasma center has four phases: a rise, a disruption with smaller relative amplitude, another rise and another disruption with greater relative amplitude. For chords far away from the plasma center, the direction of the sawtooth is reversed. The formation of the double sawtooth can be explained by the following physical picture: The current density profile or q profile has been changed due to the off axis ECRH. If there are two q=1 surfaces because of the hollow current density profile, the m=1/n=1 magnetic islands will develop in the two surfaces. When the reconnection and mixing of the magnetic island encompass the magnetic

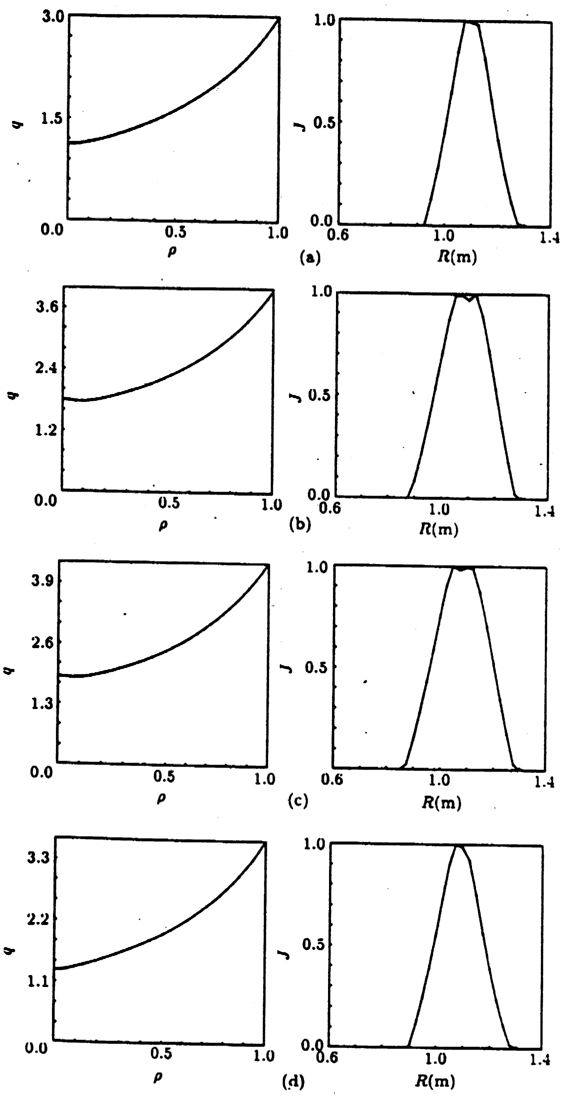

FIG. 3. Reconstructed profiles of J and q for shot 4560, (a) t=140 ms, (b) t=180 ms, (c) t=220 ms, (d) t=280 ms.

axis completely, the double sawteeth in the plasma center and the reversed double sawteeth outside of the q=1 surface can be observed [12]. Typical double sawteeth during ECRH are as shown in *FIG. 4*.Primary observation in HL-1M indicates that reversed magnetic shear can be formed with ECR off-axis heating on the HFS.

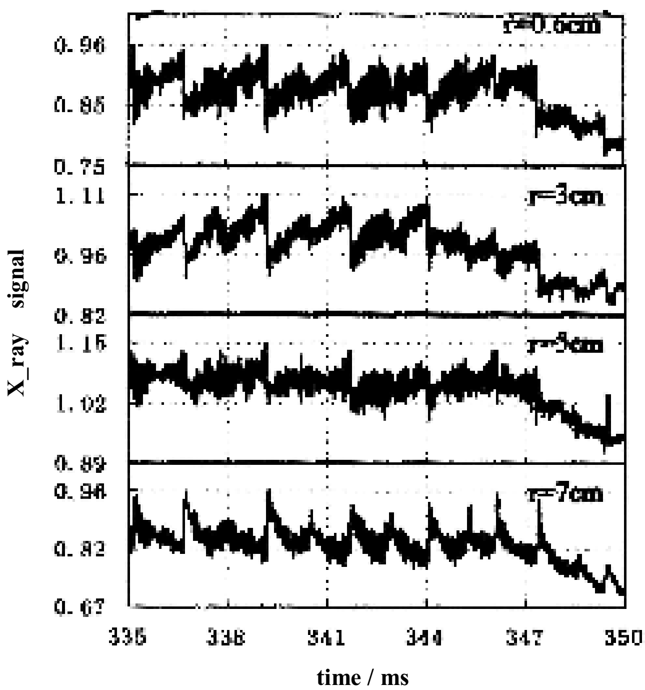

FIG. 4. The typical double sawtooth during ECRH

5. Conclutions

An ohmic shear reversed configuration was obtained in HL-1M by combined control of plasma current rise and supersonic molecular beam injection (MBI). The current profile and q profile reconstructed by the equilibrium code show a hollow current profile during LHCD and they are related to the nonmonotonic q profile. In ECRH off-axis experiments the occurrence of the compound sawtooth observed by the soft X-ray diode array implies that the hollow current density profiles were formed.

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