Mechanism of H-mode Triggering by CT Injection in the STOR-M Tokamak

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Abstract. The H-mode like discharges induced by tangential compact torus (CT) injection in the STOR-M tokamak and by other techniques, such as by a short current pulse and electrode/limiter biasing, are commonly characterized by an increase in the electron density, significant reduction in the H_α radiation level, and steepening of the edge density profile. The H-modes induced by negative biasing and edge heating via a short current pulse result in large negative electric potential biasing, formation of a strong poloidal velocity shear, and slowdown of the toroidal flow. In contrast, in the H-modes induced by positive biasing and CT injection, only moderate positive electric potential biasing occurs. Formation of a strong poloidal velocity shear is absent, but the toroidal flow velocity increases. A plausible mechanism that does not require strong velocity shear itself to suppress the long wavelength turbulence is attributed to the stabilizing role of the curvature in the toroidal velocity profile.

1. Introduction

The University of Saskatchewan Compact Torus Injector was built to study the feasibility of central fueling of a magnetically confined fusion reactor [1, 2] and the interaction between the compact torus (CT) and the tokamak plasma in particular. Tangential CT injection into the STOR-M tokamak has induced H-mode like Ohmic discharges [3], similar to those previously induced in STOR-M by a short current pulse superposed on the ohmic current [4], and external plasma biasing via an electrode or a limiter [5, 6]. These H-modes are characterized by a rapid and sustained increase in the electron density, a sudden decrease in the H_α radiation level, and steepening of the edge density profile. In general, plasma density, potential and MHD fluctuations are suppressed in H-modes. However, strong electric field shear accompanying H-modes induced by a current pulse and negative biasing is absent in the H-modes induced by CT injection and positive biasing. This subtle difference prompted us to investigate the profiles of the radial electric field and plasma flow velocity in more details. A theoretical model, without resorting to the commonly accepted model based on fluctuation suppression (or decorrelation) due to $\mathbf{E} \times \mathbf{B}$ velocity shear, has been developed in an attempt to explain the mechanism triggering H-mode in STOR-M.

2. Experimental Observations

STOR-M is an iron-core tokamak with a major radius of 46 cm and a minor radius 12 cm. The nominal normal discharge parameters are: I_p(discharge current) $= 20 - 30$ kA, V_l(loop voltage) $= 3$ V, B_t(toroidal field) $= 0.7 - 0.8$ T, T_e(electron temperature) ~ 150 eV, and $\bar{n}_e$ (line averaged electron density) $= (0.5 - 2) \times 10^{13}$ cm^{-3}.

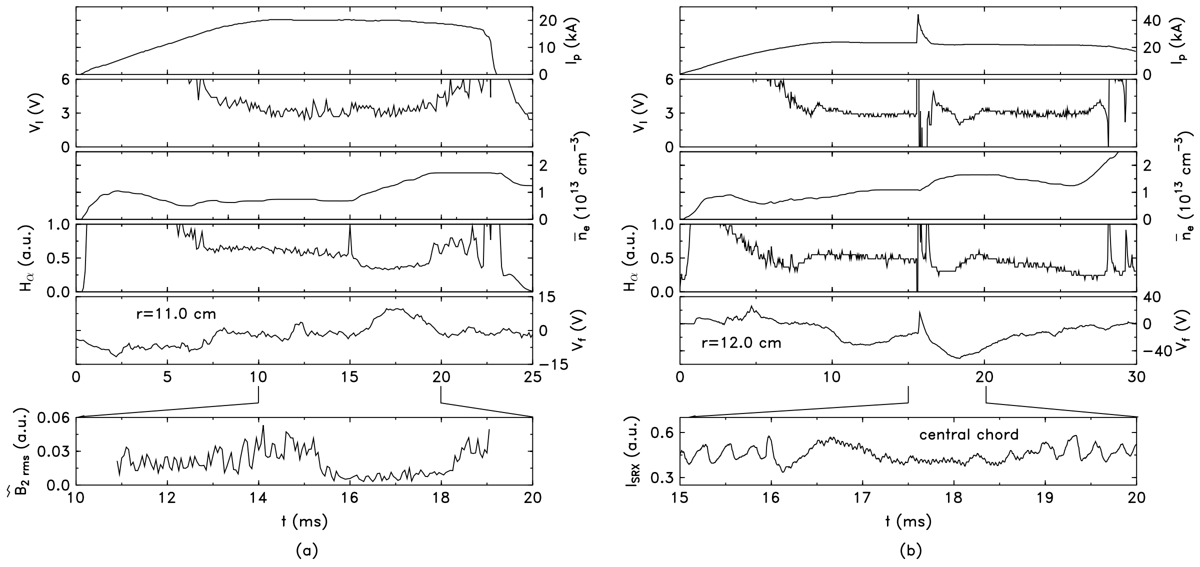

FIG. 1: H-modes induced by CT injection (a) and by a short current pulse (b).

Hydrogen CTs were formed and accelerated between coaxial electrodes in the University of Saskatchewan Compact Torus Injector. The inner and outer radii of the CT ring are 1.8 cm and 5 cm respectively. The estimated CT length is 15 cm. The typical CT parameters are electron density $\bar{n}_{\rm CT} = (1-2)\times 10^{15}$ cm^{-3}, CT velocity $v_{\rm CT} \sim 120-200$ km/sec. The CT mass is in the order of 1 μg, representing 50% the particle inventory in STOR-M. CTs were injected into STOR-M at 27° with respect to the major radial direction. This arrangement intends to transfer the CT momentum to the plasma discharge in the toroidal direction.

2.1 H-mode Like Phenomena

Figure 1(a) and Fig.1(b) show the plasma parameters with a CT injected at $t = 15$ msec and with a short current pulse applied at $t = 16$ msec respectively. In both Fig. 1(a) and Fig. 1(b), the first five traces are (from top): plasma current I_p, loop voltage V_l, average electron density $\bar{n}_e$ measured by a 4-mm microwave interferometer, H$_\alpha$ radiation level collected horizontally along the central diameter, and floating potential V_f at the edge. It has been noticed that the floating potential is significantly lowered after the current pulse and is only modestly increased after CT injection. The last panel in Fig.1(a) shows significant reduction of the RMS level of $m = 2$ Mirnov oscillations after CT injection, while that in Fig. 1(b) depicts prompt suppression of $m = 1$ sawtooth oscillations. Similar H-mode like discharges have also been induced by active electrode/limiter biasing. Again, large negative (small positive) plasma potential biasing have been achieved for negative (positive) biasing, consistent with auto-biasing associated with the current pulse (CT injection) induced H-mode.

2.2 Electric Potential and Flow Velocity Profiles

In order to investigate the role of the electric field and the flow velocity in triggering H-modes, Langmuir (rake) probes were used to measure, among other parameters, the

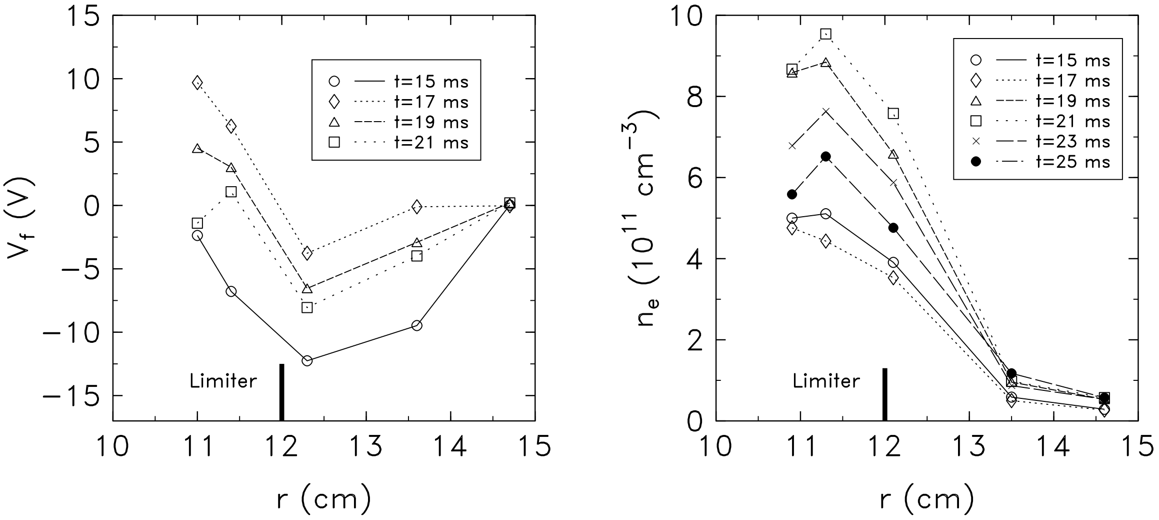

FIG. 2: Electric potential and density profiles during a discharge with a CT injected at $t = 15$ *msec.*

electric potential and electron density profiles. In addition, Mach probes were used to measure directly the plasma flow velocities. Figure 2 shows the electric potential and density profiles in the scrap-off-layer (SOL) and edge region. The electric field deduced from this profile is negligibly small. The density steepening during the improved confinement phase is evident. Based on this observation, it is not expected to have a significant change in the poloidal velocity shear which could be responsible for triggering the H-mode, at least not in the region where Langmuir probes are accessible. This is also supported by direct flow velocity measurements for the cases with active electrode biasing. Figure 3 shows the radial profiles of (a) the ratio between poloidal upstream and downstream Mach probe current (a measure of the poloidal flow velocity), (b) toroidal Mach number, and (c) plasma floating potential. In the cases shown in Fig. 3, the applied electrode voltages are $V = -350$ V, 0 V, and +150 V. In the H-modes induced by negative electrode biasing and application of a short current pulse, the edge potential decreases. Formation of poloidal velocity shear and slow down of the toroidal velocity have also been observed in these cases. In contrast, H-modes induced by positive biasing and CT injection do not indicate formation of velocity shear, but exhibit an increase in the toroidal rotation velocity. The apparent lack of a change in the radial electric field for H-modes induced by positive biasing and CT injection seems to indicate that there may be mechanism(s) at work other than the velocity shear which is commonly viewed as the ingredient in suppressing long wavelength plasma turbulence and transport.

3. Theoretical Interpretation

With these experimental observations in mind, a model has been developed based on the dissipative (resistive) drift-ballooning modes in the presence of parallel flow. The dissipative drift-ballooning modes have recently been identified as a plausible mechanism for anomalous transport in the tokamak edge [7, 8] and also appears to be the most appropriate candidate to get stabilized in the improved mode on STOR-M, because the

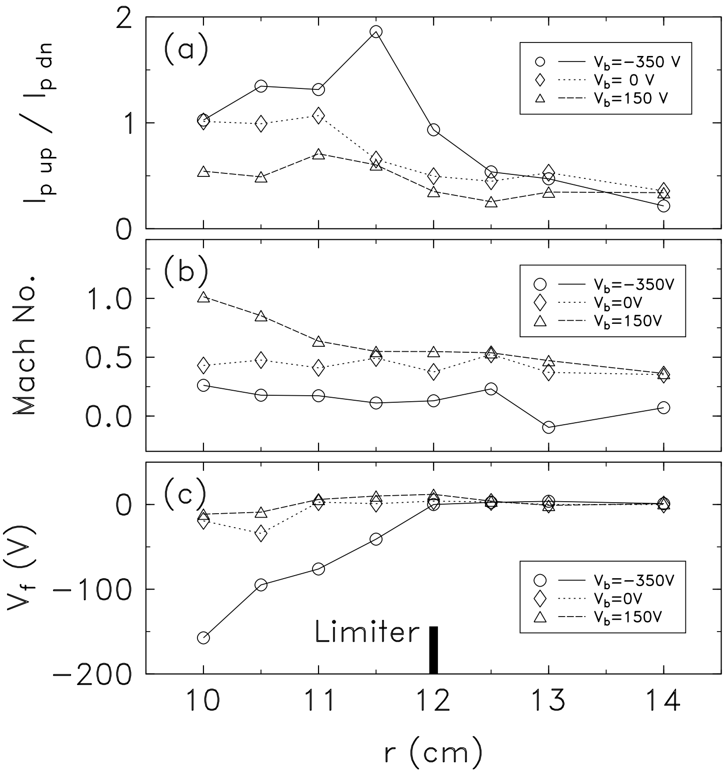

FIG. 3: (a) Ratio of poloidal upstream and downstream Mach probe currents, (b) toroidal Mach number, and (c) floating potential profile for electrode biasing voltages at $V_b = 0$ V, $V_b = +150$ V, and $V_b = -350$ V. The limiter is located at $r = 12$ cm.

experiments observe a sharp increase in the electron density in the edge of STOR-M, whereas the temperature does not change significantly (so temperature gradient driven instabilities are not likely to play a major role here). We consider the long-wavelength drift waves for a large aspect-ratio circular tokamak under the assumption that the ions are cold and the electron temperature gradient is negligible. Using the fluid model to analyze the ballooning mode in the presence of a velocity field, we find that the resultant eigenvalue depends on both the gradient (L_{v_1}) and curvature ($L_{v_2}^2$) of the radial profile of the equilibrium parallel velocity [9], where

$$\frac{dV_{\|o}}{d\rho} = \frac{V_{\|oo}}{L_{v1}}, \quad \frac{1}{2}\frac{d^2V_{\|o}}{d\rho^2} = \frac{V_{\|oo}}{L_{v2}^2}$$

are scale lengths associated with the usual Taylor expansion of the equilibrium flow velocity

$$V_{\|o}(\rho) \equiv V_{\|oo} - \left(\frac{\rho}{L_{v1}} + \frac{\rho^2}{L_{v2}^2}\right) V_{\|oo}.$$

It has been found that a velocity profile with a negative value of the curvature has a negative contribution to the imaginary part of the eigenvalue. Furthermore, analysis shuws that the radial flux reduces with the decrease of the scalelength of the parallel flow curvature, the lower limit of which will be determined by the threshold of excitation of the Kelvin-Helmholtz (KH) instability. The model clearly demonstrates that $L_{v_2}^2 < 0$ actually *stabilizes* resistive drift-ballooning modes which otherwise escape magnetic shear damping.

4. Summary and Conclusions

H-mode like discharges have been induced by tangential compact torus (CT) injection into the STOR-M tokamak. The global parameters and the edge electron density profiles of the STOR-M discharges during the improved confinement phases induced by CT injection are similar to those induced by a short current pulse and by electrode/limiter biasing. However, clear formation of edge electric field and poloidal flow velocity shear observed in the H-modes accompanied by negative biasing (spontaneously induced in the current pulse case and actively applied in the electrode/limiter biasing case) is absent in the H-modes accompanied by positive biasing (CT injection and positive biasing cases). Furthermore, the toroidal flow velocity increases during the H-modes with positive biasing and decreases during the H-modes with negative biasing. A theoretical model developed recently suggests that the dissipative drift-ballooning modes could be stabilized if the velocity profile has a negative value in its curvature. This model does not require a strong electric field shear and matches the observations during the CT injection induced H-mode.

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