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Emissive Limiter Bias Experiment for Improved Confinement of Tokamaks

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Experiments have been performed in Ohmic discharges of the UCLA CCT tokamak with a LaB_6 biased limiter, capable of emitting energetic electrons as a technique to improve confinement in tokamaks. To study the effects of emitted electrons, the limiter position, bias voltage, and plasma position were varied. The results have shown that the plasma positioning with respect to the emissive limiter plays an important role in obtaining H-mode plasmas. The emissive cathode must be located close to the last closed flux surface in order to charge up the plasma. As the cathode is moved closer to the wall, the positioning of the plasma becomes more critical since the plasma can easily detach from the cathode and reattach to the wall, resulting in the termination of H-mode. The emissive capability appears to be important for operating at lower bias voltage and reducing impurity levels in the plasma. With a heated cathode, transition to H-mode was observed for $V_{bias} \leq -150$ V and $I_{inj} \geq 30$ A. At a lower cathode heater current, a higher bias voltage is required for the transition. Moreover, with a lower cathode heater current, the time delay for inducing H-mode becomes longer, which can be attributed to the required time for the self-heating of the cathode to reach the emissive temperature. From this result, we conclude that the capacity for emission can significantly improve the performance of limiter biasing for inducing H-mode transition. With L-mode plasmas, the injection current flowing out of the cathode was generally higher than 100 A (compared to $\sim$ 30 A for the H-mode case).

1. INTRODUCTION

Since the discovery of H-mode plasmas in ASDEX [1] about a decade ago, many devices have reproduced this improved confinement regime by biasing plasmas utilizing inserted probes or electrodes [2-5], divertor plates [6-8], limiters [9-13], to produce radial electric fields at the edge of the plasma. This electric field is believed to be correlated with the onset of H-mode and also influences the interaction between the plasma and the wall. At first the H-mode was considered to be accessible only in diverted plasmas but later it was observed in limiter plasmas. In PBX [9], a negative bias voltage up to −290 V was applied to the limiter with respect to the vessel wall. As a result of biasing, the averaged electron density increased by 10% at a constant rate of gas puffing and H_α emission at the wall decreased by a factor of two. The improvement of plasma energy confinement time was about 4%. The limiter current was 140 A when the bias voltage was less than −180 V but decreased to 50 A when V_{bias} increased to −290 V. In TEXTOR [10], TEXT [11], DIII-D [12], and Tokamak de Varennes [13], positive biasing as well as the negative biasing was attempted and better results were generally obtained with negative biasing. Results from DIII-D showed an improvement in plasma particle confinement time inferred by steeper density gradient and smaller particle flux at the edge region. Similarly, the global particle confinement time increased by 20% and the radial electric field was $\sim$ 100 V/cm in the TEXT experiments. In Tokamak de Varennes, the bias voltage was scanned to see how sensitive parameters such as density, H_α, neutral pressure and impurity flux were with respect to the applied voltage. They observed a simultaneous steepening of the density gradient at the edge and the reduction of Z_{eff}.

In contrast, the experiments presented here utilized a novel scheme of an emissive electrode both to charge up the plasma and to define the plasma as a limiter.

The CCT tokamak and the related LaB_6 cathode assembly is briefly described in Section II. In Section III, results are shown when the limiter is biased negatively without being heated. Section IV presents experimental results when the limiter is heated so that it emits electrons. Finally, conclusions and possible applications of this idea in future machines are described in Section V.

2. DESCRIPTION OF THE DEVICE

Fig. 1 depicts a cross-sectional view of the Continuous Current Tokamak (CCT) located at the University of California at Los Angeles. The CCT vacuum vessel is made of 1 cm thick stainless steel and has an insulating break to prevent eddy current from flowing in the toroidal direction. The loop voltage developed is measured across this insulating break. Inside the vacuum vessel, 3 mm thick copper panels line the vessel and this copper liner also has several breaks both toroidally and poloidally. The diameter of the liner is 80 cm so that the plasma can be as much as 40 cm in minor radius. The major radius of CCT is 1.5 m and it was operated with $I_p = (30-40)$ kA, $B_T = 0.3$ T, and $n_e = (1-6) \times 10^{18} m^{-3}$.

The cathode used as a limiter in this experiment was located at the top of the machine ($\theta = 90°$), at a single toroidal location as seen in Fig. 1. It was made of lanthanum hexaboride (LaB_6) and the description of its construction can be found in several references [14-16]. The cathode assembly is composed of 18 beads whose diameter is 1.9 cm and is strung onto a carbon rod. This carbon rod is heated electrically, and the beads are in turn heated by this rod to become sufficiently hot to emit electrons. As shown in Fig. 1(b), tungsten plates, of size 13 cm × 10 cm, are placed on both sides of the cathode with openings for the LaB_6 beads. Since the beads are open on both sides toroidally the electrons emitted follow field lines in both directions. The assembly is biased negatively with respect to the vacuum vessel, so that the vessel acts as an anode in this case.

3. LIMITER BIASING AND H-MODE TRANSITION

When the limiter bias exceeded a certain voltage, transition to H-mode could be obtained. Fig. 2 shows the temporal evolution of various plasma parameters when the limiter is located at 15 cm inside the wall and biased at -450 V. At 39 msec the bias voltage is applied to the cathode and at the same time injection current through the limiter begins to flow. I_{inj} continues to increase up to ~ 80 A and then suddenly drops to ~ 40 A at 72 msec (33 msec after biasing), implying that the transport of emitted electrons from the cathode to the copper liner has decreased and that the confinement of the plasma is improved. Line-integrated electron density also starts to increase at this time of transition to H-mode. The H-mode lasts for ~ 8 msec and then an abrupt rise in UV light due to impurities appears, thereafter leading to a plasma disruption. In this paper an H-mode transition is defined by the decrease of injection current and loop voltage, a drop of impurity line spectrum intensity, and a subsequent increase of plasma density.

In contrast, when the limiter was biased by -250 V, no H-mode transition was observed and the plasma remained in L-mode. This triggering of transition with high bias voltage may be explained by the plasma ion bombardment to the limiter. Initially the 'injected' current caused by the biased limiter is due to plasma ion flow to the limiter itself, but once the limiter surface is heated up due to these bombarding ions, the current can be attributed to thermionically emitted electrons from the limiter. At a higher bias voltage, ions collide with the limiter at a higher energy resulting in a more effective heating of the LaB_6 cathode and producing electrons sooner after the bias is applied.

In order to support this hypothesis, a simple numerical estimate of the time required for the LaB_6 surface to reach $\sim 1200\,^\circ C$ was made by solving the time dependent heat conduction equation assuming a slab geometry (since the heat conductivity of this material is relatively small compared to the heat transfer coefficient of the plasma ($B_i \gg 1$), the penetration depth of the heat flux from one side of the boundary is much shorter than the size of the cathode). According to this estimate, the time to get to $\sim 1200\ ^\circ C$ is about 60 msec, which is the same order of magnitude as the measured delay time (33 msec). Additional heating is expected from the plasma which would further reduce the required time.

Based on this explanation, -250 V is too low a potential to heat the cathode and provide the sufficient radial current. Therefore there is a threshold to induce the transition, which is between -250 V and -450 V. This suggests that a limiter with an emissive surface would initiate the bifurcation in a more effective way. The electrons emitted will charge up the plasma negatively, producing a local radial electric field layer at the edge region which is believed to play an important role in obtaining H-mode.

4. RESULTS WITH EMISSIVE LIMITER

In order to see the effect of electrons emitted from the limiter, the limiter was heated by a carbon rod which supported 18 LaB_6 beads as shown in Fig. 1(b) during an application of a negative bias voltage. The factor which determined the limiter temperature was the current flowing in the heater circuit.

(a) Location of the plasma edge

Finding out the location of the plasma edge is important in this experiment to confirm the role of the cathode as a limiter.

First, for the H-mode transition, it was important to position the plasma so that the cathode acts as the primary limiter. When the limiter was inserted into the vessel well away from the liner, the position control was relatively easy. As the limiter was moved closer to the liner, the plasma positioning became more critical in obtaining the H-mode transition since the plasma could easily touch the liner, causing the cathode current to flow directly into the liner and not able to charge up the plasma.

Second, with a fixed bias voltage ($V_{bias} = -220$ V) and the limiter temperature ($I_{heater} = 320$ A), a series of shots were taken by varying the physical locations of the limiter. Fig. 3 shows the contour plot of the electron density from the multi-tip Langmuir probe array. The probe array, having 10 tips which were 1 cm apart from each other, was inserted into the vessel to measure the floating potential and the electron density. It was located at the top of the machine ($\theta = 90°$), at a single toroidal location but not close to the cathode. The ordinate of the figure is the normal distance measured from the Cu liner. As shown in the figure, the electron density increased at 39 msec when the bias voltage was applied and there were regions of the steep density gradient. The position of the cathode bottom end is 9 cm and 13 cm for Fig. 3 (a) and (b), respectively. Since the diameter of a LaB_6 bead is 1.9 cm, the region of steep density gradient matches well with the location of the cathode, which means that the edge of the plasma can be identified by the position of the cathode.

(b) Typical H-mode shot with a fully heated cathode limiter

Fig. 4 shows the evolution of the plasma current, loop voltage, injection current, line-integrated density, and UV emission of a typical H-mode shot with the heated cathode limiter. For this shot, the limiter was located at 15 cm inside the liner and was heated with heater current of 300 A and biased by -250 V from 39 msec. As shown in the figure, UV spectrum decreased and simultaneously, the electron density measured by the 8 mm microwave interferometer began to increase, indicating the start of H-mode. The injection current was measured to be as low as 30 A, which was much less than $\sim$ 100 A for L-mode plasmas. After $t = 84$ msec, giant sawteeth began to develop which led to the disruption of the plasma. The loop voltage for a series of H-mode shots including the one in Fig. 4 remained at between 0.9 V and 1.1 V, which was less than that ($\sim$ 1.6 V) of L-mode plasmas, suggesting an improvement of the energy confinement time (beyond the usual improvement due to the density rise). One thing to notice here is that when the limiter is heated, the transition occurs immediately after the imposition of the bias voltage to get into the H-mode state. In Fig. 5, a time delay from the beginning of biasing to the onset of H-mode in three different cases is compared. With a limiter that was biased ($V_{bias} = -450$ V) but unheated ($I_{heater} = 0$ A), the observed time delay was $\sim$ 33 msec. When $V_{bias} = -250$ V and $I_{heater} = 250$ A, the delay time was less than 10 msec. This may be related again to the required time for the self-heating of the cathode to reach the emissive temperature.

As discussed previously, the H-mode transition could be seen at a lower bias voltage as long as the limiter was hot enough to emit electrons thermionically. The low bias voltage also probably helps to reduce the impurity content caused by sputtering due to the application of high voltages to the limiter.

Fig. 6 shows the time history of floating potentials at 4 probe tips that are located at 9, 11, 13, and 15 cm from the liner. The radial electric field is obtained from the plasma potentials, $V_p = V_f + 3kT_e$, of two probe tips located at 9 and 15 cm from the liner respectively, assuming a constant electron temperature around the plasma edge region. The floating potential which was measured by this probe array (Fig. 6 (a)) indicates that right after the negative bias is applied, the resulting electric field around where the limiter resides increases by a factor of 3 compared to that before biasing (Fig. 6 (b)).

The radial profile of the floating potential near the cathode from 4 different shots with different locations of the cathode is depicted in Fig. 7. For this series of shots, V_{bias} = -220 V, I_{heater} = 320 A, and other conditions were held fixed. The dotted line in the figure indicates the potential before the bias voltage was applied to the limiter and the others are potentials in the H-mode state. The abscissa is the distance from the liner and Δt represents the time after the H-mode transition occurs. The comparison between before and after biasing illustrates that the biasing steepens the slopes of the potential. Moreover, this increased radial electric field is found to be extended inward to ~ 2 or 3 cm from the lower boundary of the cathode as well as outside of it in the SOL region. The usual transport phenomena may not explain this inward extention of E-layer, and two possible explanations exist. One possibility is transport along stochastic magnetic field, i.e., the emitted electrons are not localized due to the field stochaticity so that electrons spread out radially around the cathode. The other possibility is the inward convective motion of emitted high energy electrons.

In the DC-helicity injection experiments of CDX [15, 17], a negative potential well inside the plasma was also observed. Because of the negative potential, a dc radial electric field was created, and as a result, poloidal rotation of the plasma with a typical rotation velocity of $\sim 1 \times 10^4$ m/sec was observed. Based on the measurements, the radial electric field scales as E_r (V/cm) $\approx 11 B_T$ (kG)$/\mu^{1/2}$, where μ is the ion mass number. This electric field may also be explained by the similar mechanisms.

Fig. 8 was obtained from 4 shots (Fig. 7) in the H-mode regime with different locations of the cathode. Even though the absolute value of the potentials are slightly different from each other, the slopes of the 4 potential traces are more or less same.

(c) Cathode limiter bias voltage scan

In order to see how sensitively the radial electric field changes at the edge of the plasma due to the bias voltage, several shots were taken with different voltages while the heater current of 300 A and other conditions remained fixed (Fig. 9). In this experiment, -150 V was the lowest bias voltage in which a transition was obtained. Due to the charging-up of the plasma by electrons emitted from the cathode limiter, a 100 V difference in the bias voltage change produces an increase of the electric field by a factor of 2.

5. CONCLUSIONS

The utilization of a limiter which is capable of injecting thermionic electrons has an important advantage of inducing H-mode plasmas. When the limiter was heated to reach a certain temperature ($\sim$ 1200 °C) and biased by -150 V to -260 V, the CCT Ohmic plasma moved to the H-mode regime showing line-integrated density rise, impurity light intensity drop, lower loop voltage, and a decrease of injection current, implying the drop of electron transport to the wall. The emissive capability of the limiter also improved the impurity influx from the wall since it could induce H-mode at a lower bias voltage. According to the limiter position scan, positioning of the plasma becomes more crucial as the cathode is moved closer to the wall since the plasma can easily detach from the cathode and reattach to the wall. When the limiter heater current was not sufficiently high, a higher bias voltage was required to induce H-mode, and a time delay to get into H-mode was observed. The maximum electric field after an H-mode transition is a linear function of the limiter bias voltage in the operating regime of this experiment (-150 V to -260 V), but it is unrelated to the limiter heater current (250 A to 300 A).

The radial profile of the plasma potential shows that the electric field at the edge of the plasma increases by a factor of 3 after the biasing of the electron-emitting limiter began. This increased electric field exists beyond 2-3 cm from the limiter bottom edge inside the plasma, and this may be attributed to the inward penetration of emitted electrons by an anomalous diffusion process.

An emissive limiter has the advantages that it is simple and reliable, inexpensive to operate, and the heated cathode may be able to reduce the impurity problem compared to using a cold limiter. The results shown in this experiment suggest that the performance of the limiter or divertor bias experiments can be significantly improved by simply adding emissive capability.

6. ACKNOWLEDGEMENTS

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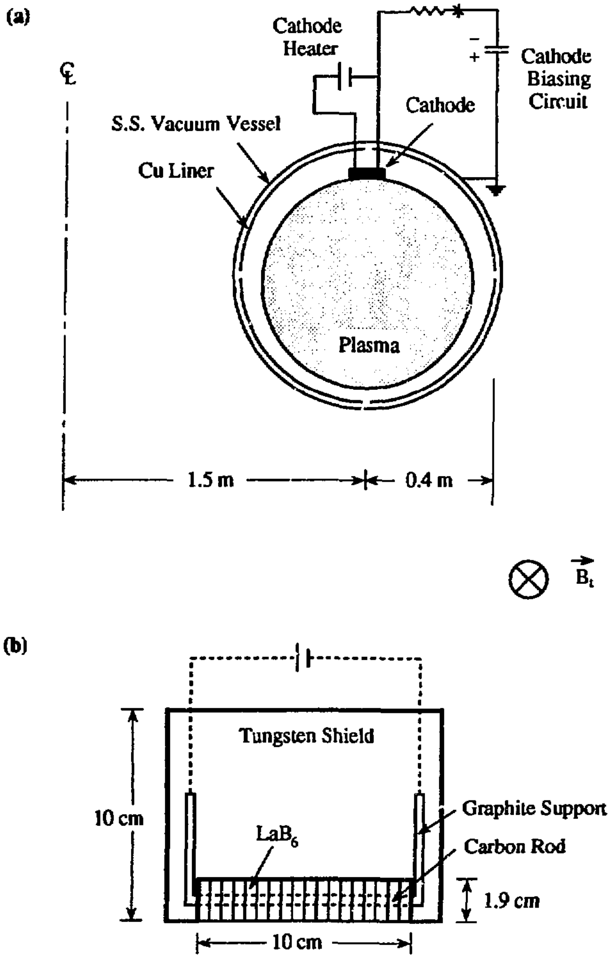

Figure 1: Cross-sectional view of CCT and the cathode system. (a) Cathode is located inside the Cu liner whose minor radius is 40 cm. In this experiment the cathode was inserted up to 15 cm from the liner. (b) 18 LaB$_6$ beads are open in the toroidal direction and are heated by a carbon rod.

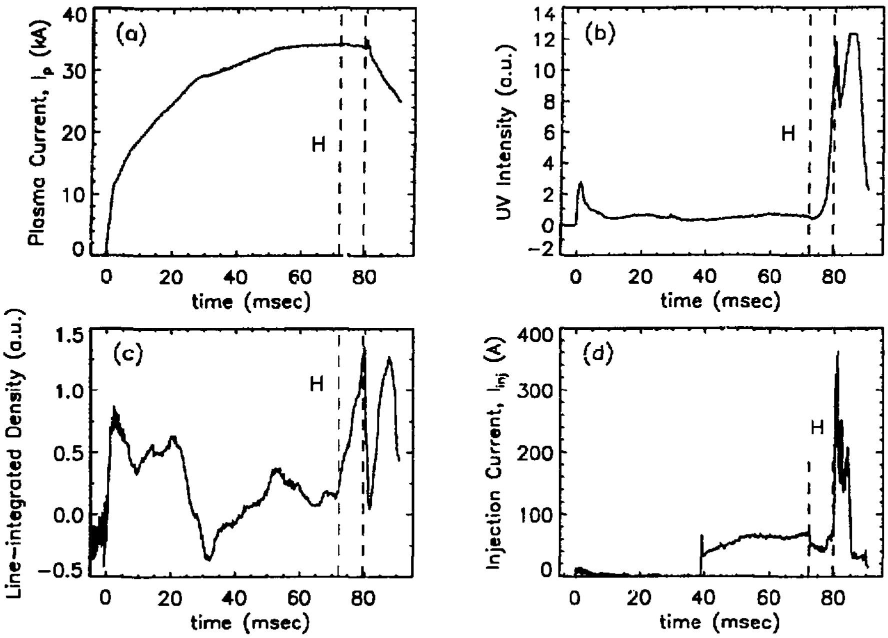

Figure 2: Time trace of main plasma parameters when the limiter was biased at -450 V and was not heated. Ohmic discharge began at 0 msec and the bias was applied at 39 msec. The bifurcation was observed at 72 msec when the line-integrated density increased and the injection current decreased.

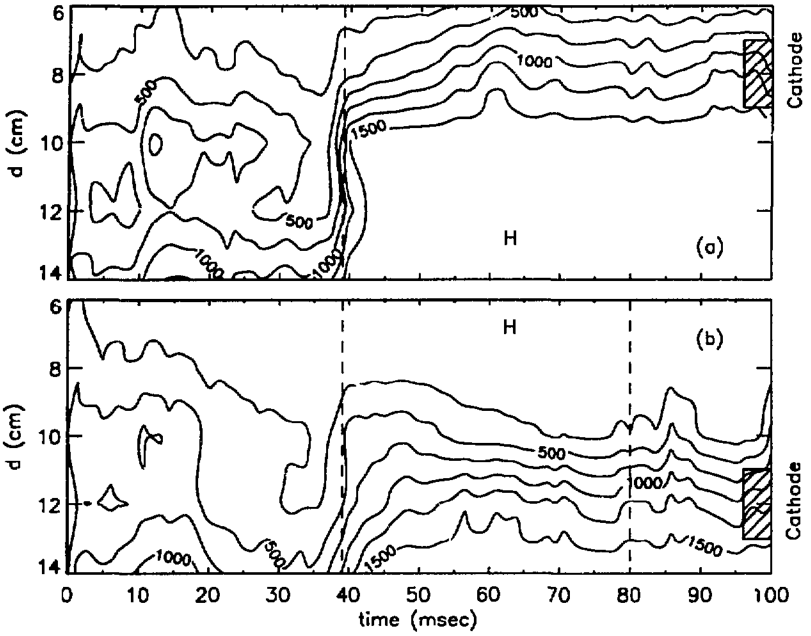

Figure 3: Contour plot of electron density (a.u.) from the multi-tip Langmuir probe array. The ordinate indicates the distance from the Cu liner. The cathode is placed (a) from d=9 cm to 7 cm, and (b) from 13 cm to 11 cm in the plot. For these shots, V_{bias} = -220 V, and I_{heater} = 320 A. H-mode occurs from 39 msec for (a) and from 39 msec to 80 msec for (b).

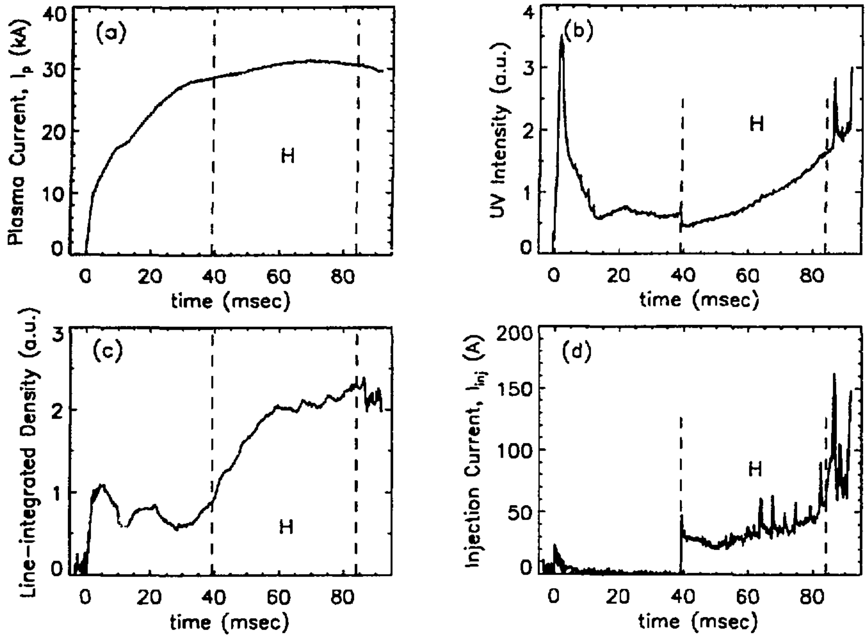

Figure 4: Evolution of plasma parameters of a typical H-mode when the limiter was heated (I_{heater} = 300A) and biased by -250 V. Biasing began at 39 msec and the transition followed immediately after the biasing.

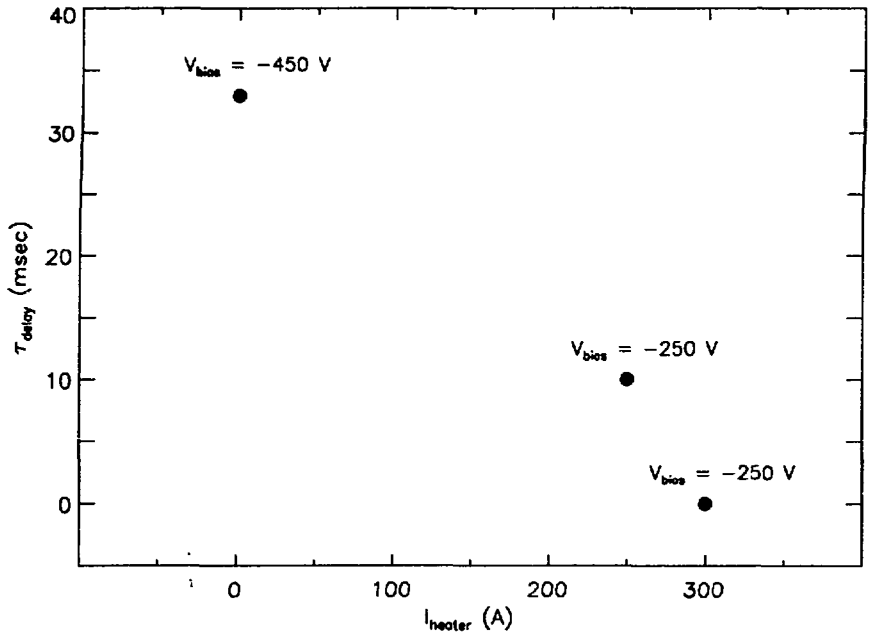

Figure 5: Time delay to get to H-mode after biasing begins.

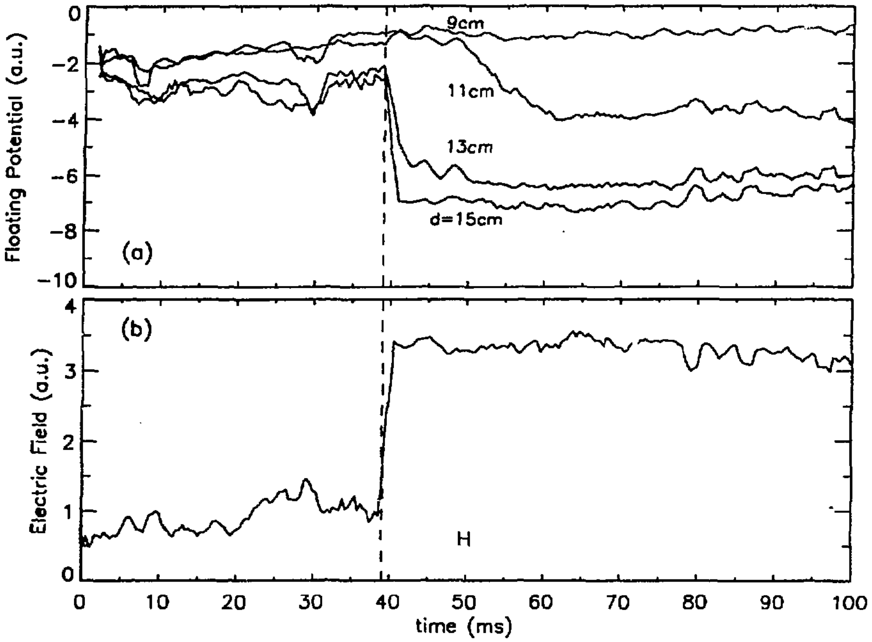

Figure 6: Time history of (a) floating potentials at 4 locations and (b) the corresponding electric field from 2 probe tips. The tips are located at 9, 11, 13, 15 cm from the Cu liner, respectively. As soon as the bias voltage is applied at t = 39 msec, the electric field between probe tips at d =15 cm and d = 9 cm increases by 3 times compared to that before biasing. The cathode is located at 15 cm from the liner and V_{bias} = -250 V, I_{heater} = 300 A.

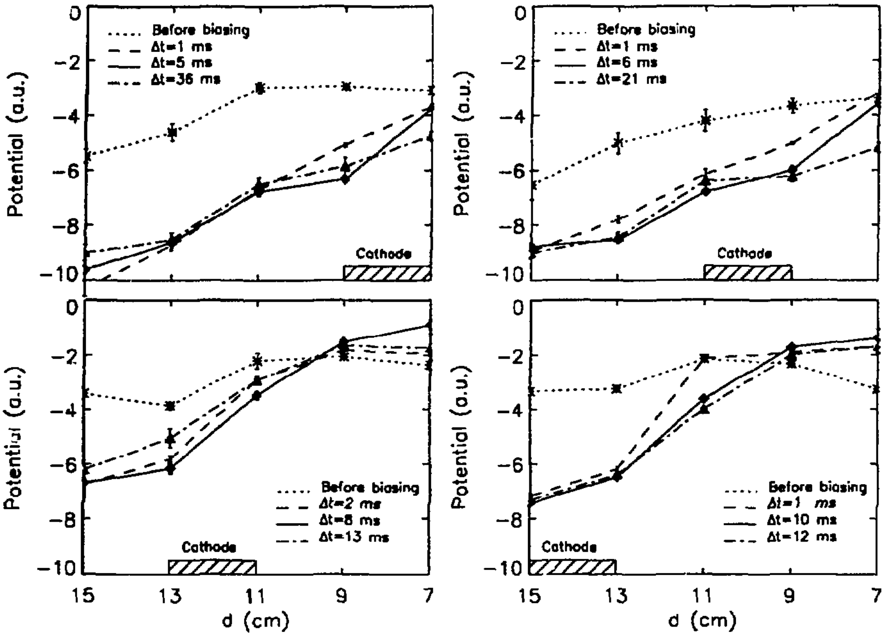

Figure 7: Radial profile of the floating potential inside and outside the cathode from four different shots. Δt indicates the time after the H-mode transition and the abscissa is the distance measured from the Cu liner. V_{bias} = -220 V and I_{heater} = 320 A for these shots. Potential in the H-mode increased noticeably compared to that before cathode bias was applied.

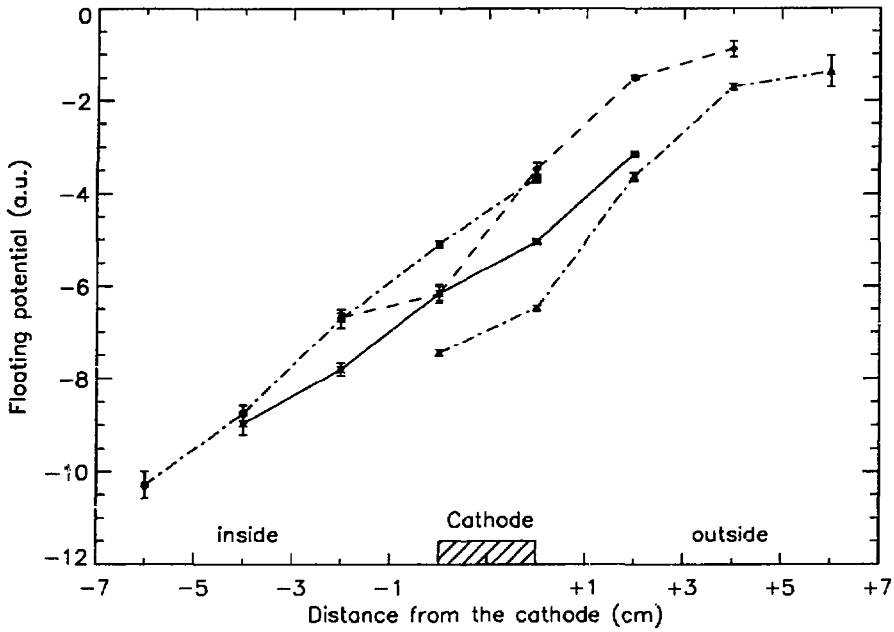

Figure 8: Radial profile of the typical floating potential in the H-mode inside and outside the cathode from four different shots. In the plot, inside means plasma region and outside means scrape-off-layer region. V_{bias} = -220 V and I_{heater} = 320 A for these shots.

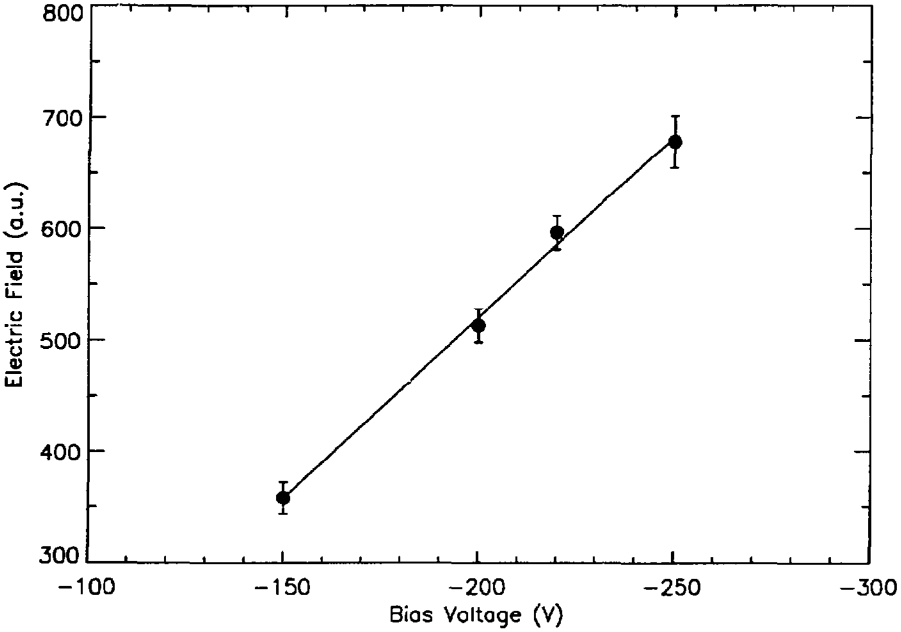

Figure 9: Maximum electric field as a function of limiter bias voltage after H-mode transition. The cathode limiter was placed at 15 cm inside the liner and heated with $I_{heater} = 300A$.