

SAWTOOTH-FREE PLASMAS IN HL-1M

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1. INTRODUCTION

Sawtooth stabilization is one of the attractive topics in tokamak research because sawtooth oscillations always lead to central confinement degradation although it can eject impurity particles from the plasma center. The sawtooth-free, e. g. sawtooth-stabilized, plasma have been obtained in ASDEX with LHCD [1], in JET with ICRH and pellet injection [2]. Earlier than these, sawtooth-free plasmas have been observed in Doublet III 'O' type discharge [3] and then in ASDEX Ohmic discharge [4], correlated with impurity and density peaking respectively. Similar results have been obtained in Ohmic and pellet injection hydrogen discharges on the HL-1M tokamak.

2. OHMIC DISCHARGE

In Ohmic hydrogen discharge the sawtooth-free can survive the current ramp-up phase, part of the current plateau phase, or whole discharge, not only in the low density range but also in the higher density range of $\bar{n}_e \leq 6.0 \times 10^{13}/\text{cm}^3$, realized by steadily and appropriate density increase with gas puffing or super-sonic molecular beam injection[5], combining with slow ramp-up ($dI_p/dt=0.5-1\text{MA/s}$) or secondary ramp-up ($dI_p/dt=0.5-2.5\text{MA/s}$) of the plasma current at $B_t=2.2-2.5\text{T}$ after wall siliconization but not fresh one on the HL-1M tokamak. This means that the sawtooth-free is related to the current density profile and impurity accumulation.

A typical sawtooth-free (STF) discharge #4882 is shown in Fig. 1, in which the sawtooth is free in the whole discharge but strong MHD oscillation ($\tilde{I}_{SX}/\bar{I}_{SX} \approx 10-40\%$) is superimposed on the central soft X-ray signals. The neighboring sawtoothing (ST) discharge #4883 is shown in Fig.2, in which the central intensities of the soft X-ray radiation (SXR) and the plasma radiation (P_r) are much lower than in the STF discharge #4882. The current waveform and the wall status are almost same in these two discharges, only the density waveforms are difference as shown in Fig.3. The density \bar{n}_e in #4882 is increased steadily and has a lower increasing rate than in #4883. This implies that the density increase rate has an important role on the realization of the STF plasma in the HL-1M Ohmic

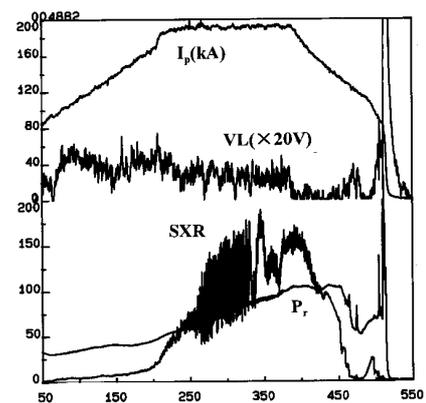


Fig.1 sawtooth-free discharge #4882

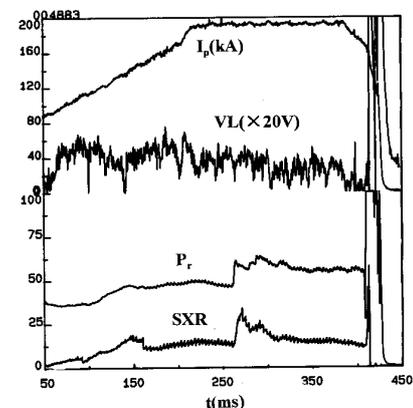


Fig. 2 sawtoothing discharge #4883

discharge, but it has to be combined with a certain current increase rate under a certain wall condition. In more detailed comparison of the STF plasma with the ST plasma it has been observed that the central electron temperature $T_e(0)$ is higher and the profile $T_e(r)$ is more peaking in the STF plasma than in the ST plasma, and also the central ion temperature T_i is higher in the STF plasma than in the ST plasma, but no apparent difference between the density profiles $n_e(r)$ in the STF and ST plasmas has been observed. With the measured $T_e(r)$ and $n_e(r)$ the electron pressure profile $P_e(r)$ can be derived, resulting in that the central electron pressure $P_e(0)$ is higher and the profile $P_e(r)$ is peaking in STF plasma. All these observations related above indicate that the heat diffusivity is reduced and the confinement is improved in the central region of the STF plasma compared with the ST plasma.

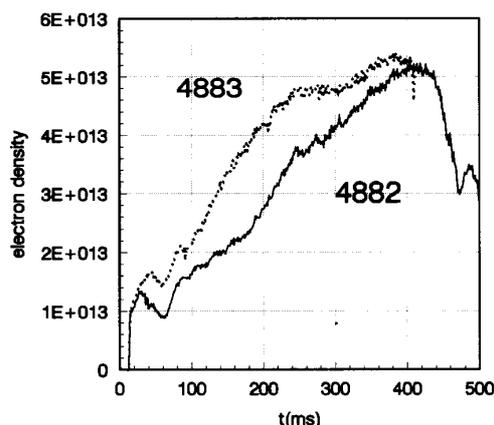


Fig.3 \bar{n}_e of #4882 & #4883

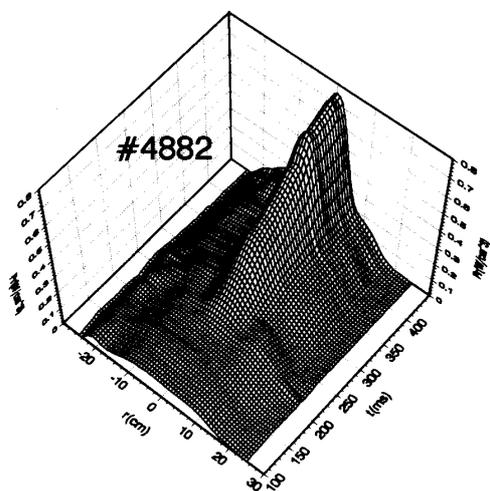


Fig.4 peaking P_r in sawtooth-free Ohmic discharge #4882

This improvement has been validated by the diamagnetic measurement in which the diamagnetic flux begins to reduce at the transition from the STF plasma to the ST plasma. The measurements of the 16-channel bolometer and the 3×20 SXR detectors show that the plasma radiation profile $P_r(r)$ is peaking in STF plasma, as shown in Fig. 4 for the typical STF discharge #4882, which indicates that the impurity is accumulated in the plasma center and also indicates that the particle confinement is improved in the central region of the STF plasma. In ST plasma, however, the plasma radiation profile $P_r(r)$ is hollow as shown in Fig. 5 for the typical ST discharge

profile is peaking in the STF plasma and flattening in the ST plasma, similar to the observation on Doublet III [3]. The measurements of the VUV spectroscopy and the SXR energy spectrum show that there is little metal impurity and the dominant impurities are C and O in the STF plasma. The symmetry of the $P_r(r)$ in the STF and ST plasmas is also difference. The $P_r(r)$ is always symmetric in all density range of the STF plasma. In the ST plasma there are two possibilities: the $P_r(r)$ is symmetric only in lower density range of $\bar{n}_e < 5 \times 10^{13}/\text{cm}^3$ but strongly asymmetric in higher density range of $\bar{n}_e > 5-8 \times 10^{13}/\text{cm}^3$ and in this case the MARFE can be taken place. However, no MARFE has been observed in the STF plasma. The

discharge #4883, and the SXR

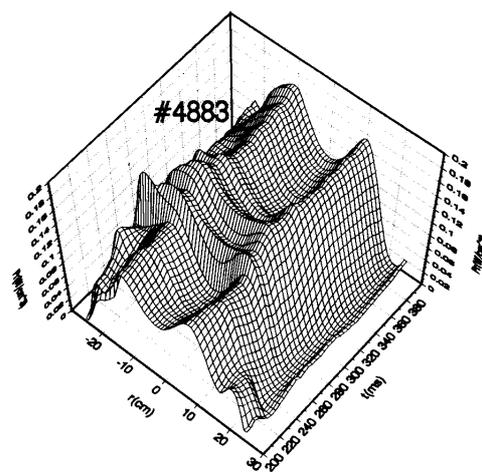


Fig.5 hollow P_r in sawtooth discharge #4883

STF discharge can be ended normally without disruption in the lower density range of $\bar{n}_e \leq 4.0 \times 10^{13}/\text{cm}^3$, but disrupted in higher density of $\bar{n}_e = 5.0-6.0 \times 10^{13}/\text{cm}^3$. The achieved maximum density for the hydrogen plasma is $\bar{n}_e^{\text{stf}}(\text{max}) = 6.0 \times 10^{13}/\text{cm}^3$ in the STF discharges and $\bar{n}_e^{\text{st}}(\text{max}) = 8.0 \times 10^{13}/\text{cm}^3$ in the ST discharges, indicating that the STF plasma is not of benefit for achieving higher density limit although the confinement is better in STF plasma than in the ST plasma.

The central SXR signals of the STF plasma are always superimposed by strong or weak MHD oscillations, which can be supposed to be $m=1/2$ mode. The $m=1$ mode oscillation can be ended by a fast crash ($\sim 100-200 \mu\text{s}$) which triggers the normal sawtooth, implying that the $q_0 < 1$. The $m=2$ mode oscillation can persist very long time, as shown in Fig. 1, and normally the annular crash can be triggered and the off-axis sawtooth is developed [6], as shown in Fig. 6 for the STF discharge #4882, from which it can be found that at 449.5ms the SXR signals on the central channels (outside 60mm, 39mm, 17mm and inside 6mm at the mid-plane) have no crash, only have no or some weak oscillations, but on the channels at outside 100mm and inside 50mm the clear

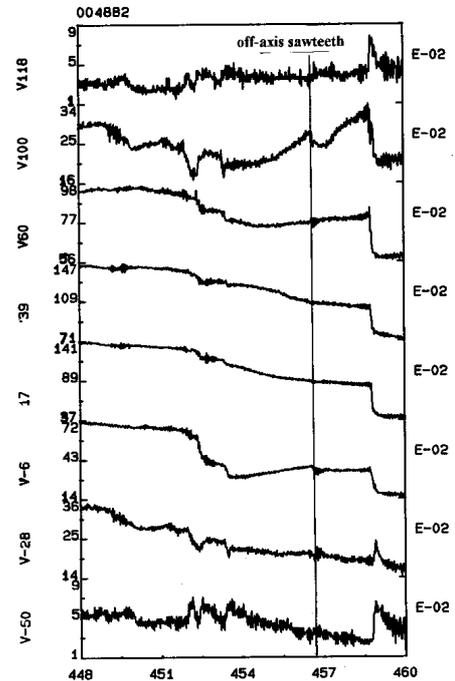


Fig.6 off-axis sawtooth in Ohmic discharge #4882

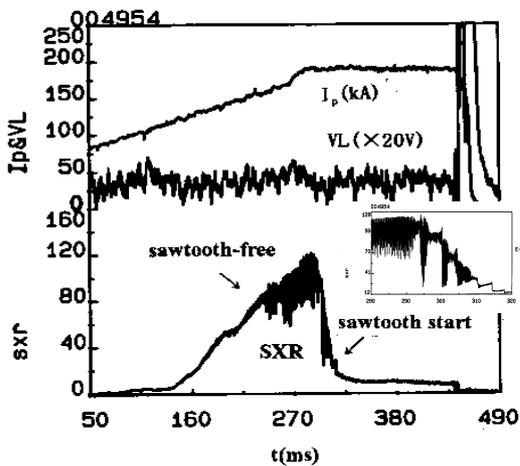


Fig.7 sawtooth-free to sawtooth transition with irregular oscillations

crash can be observed at 456.8ms at which no any crash or oscillations on the central channels of V17 and V39 can be observed. At the little far channels of V100 and V-6 from the plasma center the clear crash can be observed and the inverted sawteeth can be observed at the more far channels of V118 and V-28. This off-axis sawtooth

can be observed, indicating that the first annular crash has been taken place and the first off-axis sawtooth is formed. At 453.2ms the crash can be observed on the all SXR signals, but the amplitudes of the crash on the central channels is

smaller than that on the outside and inside channels. More standard off-axis sawteeth

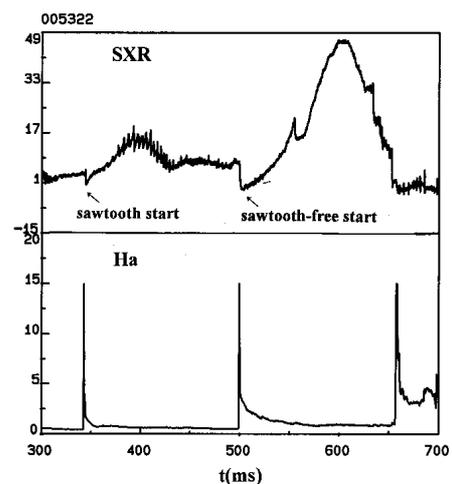


Fig.8 sawtooth-free in pellet fuelling discharge #5322

is an evidence of that the current profile is hollow and the magnetic shear is reversed. In fact in the off-axis sawtooth phase the hollow or flattening $T_e(r)$ and very peaking $P_r(r)$ are observed, which is caused by the impurity accumulation in the plasma center. In some discharges the $m=2$ mode oscillation can be developed to the normally sawtooth oscillation after a few irregular oscillation, as shown in Fig. 7, implying that the current profile changes from hollow to peaking after the impurity is ejected from the plasma center during the irregular oscillation phase. In another some discharges the MHD oscillations also can be free, implying that $q>1$ everywhere, and always developed to trigger the annular crash and lead to the appearance of the off-axis sawtooth, implying that the current profile is hollow too.

3. DISCHARGE WITH PELLETT INJECTION

After pellet injection the sawtooth can be suppressed and always the superimposed MHD oscillations can be observed, as shown in Fig. 8, and when the density is higher enough the MHD oscillation can be free, as observed in the Ohmic discharges. Some times in this case the annular crash can be triggered and off-axis sawtooth can be occurred shown in Fig.9, indicating that the magnetic shear is reversed. Comparison of the pellet injection discharge with the ohmic discharge, we have observed that the behaviour of the STF plasma in these two cases is same and the annular crash is more commonly observed in the pellet fuelling plasma than in Ohmic plasma. Similar STF plasmas also have been obtained in the discharges with LHCD, impurity injection with laser blow-off.

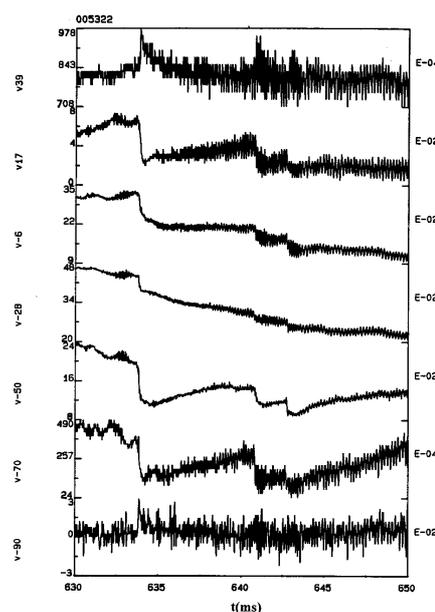


Fig.9 off-axis sawtooth in pellet fuelling discharge #5322

4. CONCLUSION

Sawtooth-free plasma has been obtained in the Ohmic and pellet injection high q_a hydrogen discharges on the HL-1M tokamak in which the central confinement is improved and the impurity distribution is more peaked than in sawtoothing plasma. In these sawtooth-free plasmas the annular crash can be triggered and the off-axis sawtooth has been developed, implying that the magnetic shear is reversed, caused by the impurity accumulation in the plasma center.

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