# ELMing H-mode Accessibility in Shaped TCV Plasmas

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**Abstract**. The H-mode regime is easily reached with ohmic heating only in a wide range of TCV plasma parameters. However, the plasma usually enters an ELM free H-mode phase after the LH transition, leading to a high density disruption. Therefore, the access to a stable ELMy regime requires an LH transition directly leading to an ELMy phase. A “gateway” to the ELMy regime was found in TCV ohmic discharges. Although small in terms of plasma control parameter ranges, this “gateway” is well defined and robust against changes in wall conditioning for instance. Once in the ELMing regime, the plasma was successfully driven in a much wider range of plasma parameters, whilst remaining in this better confinement mode.

## 1. Introduction

Future fusion reactors like ITER are planned to operate in the ELMy H-mode regime. The H-mode is desired because of its high confinement properties and ELMs are necessary to control the plasma density and plasma impurities. ELMs, however, represent a threat to the divertor plates because of the deposited heat flux if the delay between ELMs becomes too large. Therefore, the identification of the plasma parameters which can control the ELM frequency is necessary. The strong shaping capabilities of TCV can be used to investigate the effect of plasma shape and position with plasma parameters on the ELM activity. On TCV, additional heating can not, as in other machines [1, 2 and references therein], be used to access a desired ELMing regime. Thus, other machine or plasma parameters must be found.

H-mode have already been obtained in ohmic TCV discharges with a large variety of plasma shapes, currents and densities. A large number of these discharges had an ELM free H-mode phase while some, seemingly similar discharges, exhibited ELMs. The goal of this study was to determine the conditions necessary for the production of a stable ELMy H-mode. These discharges could subsequently be used to study the plasma behaviour and ELM dynamics in an ELMing regime.

In this investigation, the plasma current, density, elongation, triangularity, plasma to wall gaps, divertor geometry and toroidal magnetic field were scanned. A single null divertor with the ion grad B drift directed away from the X point was chosen for these experiments. This configuration has been extensively used in previous experiments and led to most of the ELMy discharges previously observed on TCV. An ELM free H-mode period on TCV results in the plasma density increasing until the discharge terminates by a high density disruption. Since many such discharges had already been obtained, plasma parameters leading to this regime could be avoided. In the same way, discharges in this configuration which remained in L-mode were also avoided. From database studies of TCV discharges, ELMs were expected for plasma parameters between these limits.

It was found that an ELMy regime could be obtained by passing through a small but well defined region of the operational domain. Surprisingly, large changes in the machine conditioning, (including a boronisation) did not significantly affect the position of this "gateway" which was used to reliably access an ELMy TCV regime, as described in next section. Once in the ELMy regime, the plasma was found to be relatively robust to changes in the current, shape and density. It was thus possible to access a wider range of plasma parameters whilst remaining in an ELMy regime. A subsequent section describes the operational boundaries of the established ELMy regime and the limiting operational parameters.

## 2. The "Gateway" to the Ohmic ELMing Regime

This section first presents how the boundaries of the ELMy "gateway" were determined. The plasma discharges in this study were tagged with one of the labels: ELMY for stationary ELMy discharges, LMODE for discharges remaining in L-mode, ELMFREE for discharges which transited to an ELM free phase, ELMYL and ELMYELMFREE were attributed to discharges alternating between the two modes and ELMYFAIL was attributed to discharges disrupting shortly after the transition, for which the mode was unknown. Example discharges for these labels are shown in Fig. 1. The non stationary ELMing discharges were classified in two categories: discharges which ceased to be ELMy soon after the L-H transition and discharges whose ELM frequency became irregular as a result of programmed changes in some of the plasma parameters.

To pass the "gateway" to the ELMy regime, three parameters must simultaneously exceed a threshold value to obtain an H-mode: a) the plasma current has to be greater than 350kA or equivalently $q_{95}$ must be lower than 3.0 with $\kappa$=1.6-1.7 and $\delta$=0.5-0.6 as shown in Fig. 2a; b) the plasma line average density must exceed $4.5 10^{19} m^{-3}$,as shown in Fig. 2b; c) the distance between the plasma and the tiles must be greater than 1cm. The inter-dependencies between these limits were small. With the same plasma shape parameters, the plasma current must not

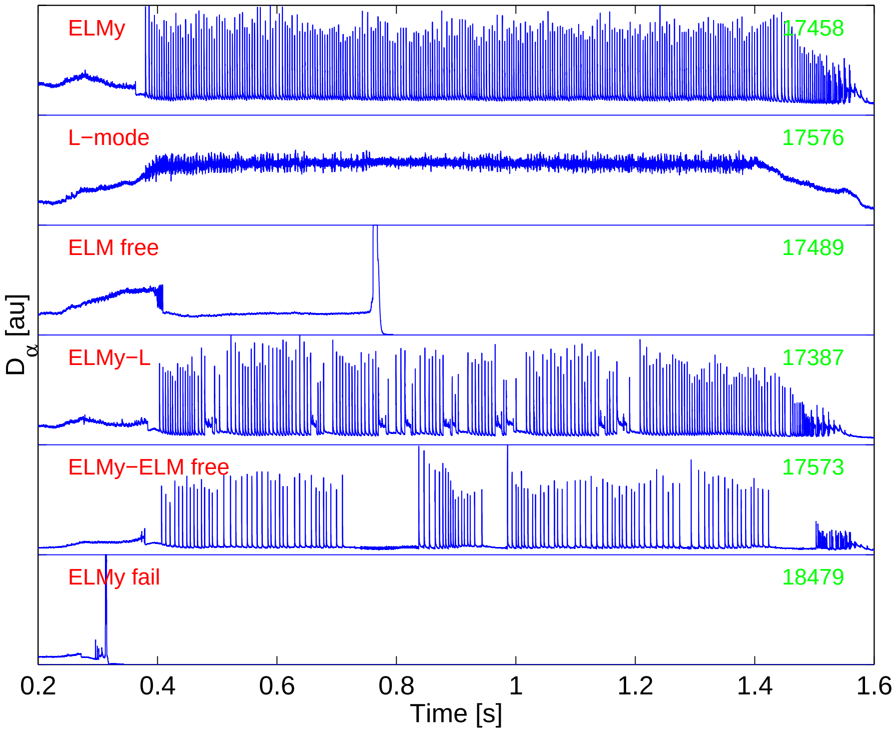

***FIG. 1**. Time evolution of the $D_\alpha$ emission from different type of discharges as indicated on the left.*

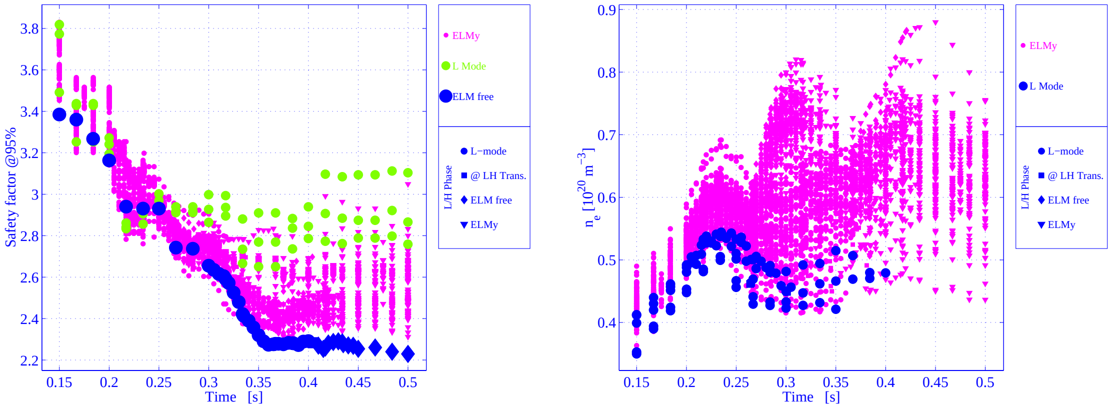

***FIG. 2**. a) Time evolution of the safety factor for L-mode, ELMy and ELM free shots indicating the available range in $q_{95}$ to access the ELMy regime. b) Time evolution of the plasma density for L-mode and ELMy shots indicating the lower boundary to access the ELMy regime.*

exceed 430kA (or $q_{95}$<2.3) otherwise the transition leads to an ELM free phase. A high density (> $6.10^{19}m^{-3}$) at the transition also led to an ELM free phase.

LH transitions were also provoked at higher plasma elongation (in the range 1.7 to 2.1) by retarding the formation of the SND configuration. In otherwise similarly shaped plasmas with similar densities, the L-H transition was obtained at higher $q_{95}$, with roughly equal values of plasma current. However, these transitions led to ELM free H-modes. A reduction in the plasma density at the L-H transition time resulted in L-mode discharges. Minor changes in the plasma shape at higher $q_{95}$ sometimes resulted in ELMs but with low frequency and high amplitude. The resulting perturbation in the control system was sufficient to lose vertical plasma position control and a disruption (VDE) ended the discharge. Changes in the control observers are being developed to improve this situation [3] which, for this paper, limited the maximum plasma elongation.

In summary, the “gateway” to the ohmic ELMy is bounded by the following limits in the operational parameters:

|  | $I_p$ [MA] | $n_e[10^{19}m^{-3}]$ | $\kappa$ | $\delta$ | $gap_{pl-w}$[m] |
|---|---|---|---|---|---|
| Min | 0.35 | 5.0 | 1.6 | 0.5 | 0.01 |
| Max | 0.43 | 6.5 | 1.7 | 0.6 | 0.03 |

## 3. The Operational Domain of the Ohmic ELMy Regime

Once in the ELMy regime, it was then possible to modify certain plasma parameters while preserving the ELMs. The plasma elongation was increased to κ=2.1, with $q_{95}$ approximately constant, as shown in Fig. 3a. Changes in $q_{95}$ during the elongation ramp resulted in vertical stability problems. Decreases in $q_{95}$ lowered the ELM frequency, as mentioned above, where-

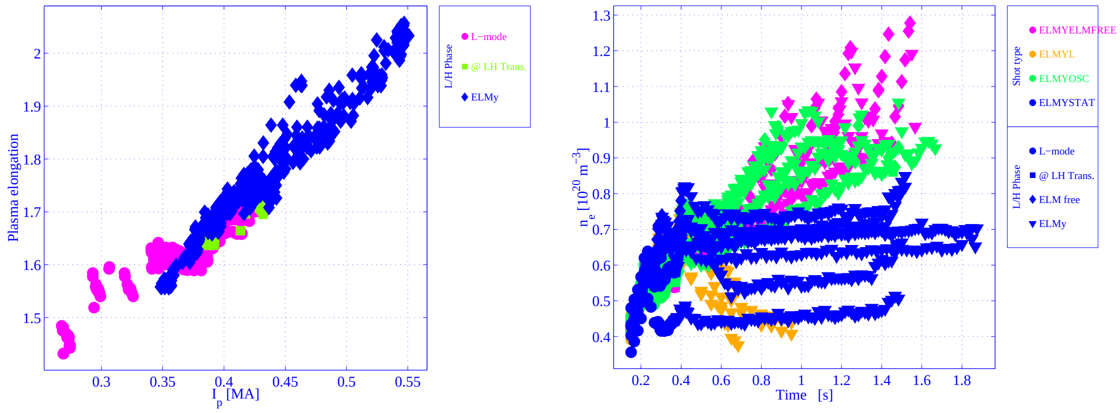

***FIG. 3**. a) Time evolution of the ELMy discharges in the $I_p/\kappa$ plan. The first stages of the discharges are in L-mode in the lower left corner and at the LH transitions in the centre of FIG. Then it was possible either to increase or decrease the plasma elongation at constant $q_{95}$. whilst remaining in the ELMy regime. b) Time evolution of the plasma density for ELMy shots. Stable ELMy shots are accessible in a limited range of plasma densities. A strong increasing density leads to oscillations in the ELM frequency or even to appearance of ELM free phases. Reduction of plasma density below a threshold at $4.10^{19}m^{-3}$ leads to a return in L-mode regime.*

as increases in $q_{95}$ made the plasma less vertically stable. Moreover, the plasma current must be ramped sufficiently slowly, or the discharge showed spontaneous H-L-H transitions regime or even returned to L-mode for higher values of $dI_p/dt$. The ELMing regime was also kept while the plasma elongation was reduced down to k=1.55. It is worth noting that no $L\text{-}H_{ELMy}$ transition was observed at this elongation exhibiting the hysteresis behaviour of the H-mode accessibility.

Once in ELMy H-mode, the plasma density can be decreased or increased in the range between $4\text{-}10.10^{19}m^{-3}$, as shown in Fig. 3b. A strong gas puff led to either oscillation in the ELM frequency or to alternating ELM free and ELMy phases. Trials to reduce the density below $4.10^{19}m^{-3}$ finally led to returns in L-mode.

Modifications in the plasma triangularity were also performed on ELMing plasmas whilst keeping other parameters fixed, see Fig. 4a. Discharges remained in stationary ELMing regime in a short range of plasma triangularity. At a triangularity higher than 0.65, the discharge shows oscillations in the ELM frequency or even the appearance of short ELM free phases. Contrarily, at low triangularity, $\delta<0.45$, the plasma suffers a back transition and returns in L-mode. LH transitions to ELMy or ELM free H-mode occur much more easily when the plasma wall distance is larger than 1 cm. However, this plasma wall distance can be reduced to values below 1cm, again without losing the ELMing regime, as shown in Fig. 4b.

Finally, the toroidal field was reduced during the ELMy phase. In one scenario, the safety factor was kept constant during the $B_t$ ramps. In the other, the plasma current was maintained. Small reduction of $B_t$ did not affect the ELMing regime for both scenarios. Stronger toroidal field decrease led to plasma disruptions for unclear reasons in case of constant q95 and to an oscillation between ELMy, ELM free and L-mode phases in the constant plasma current case.

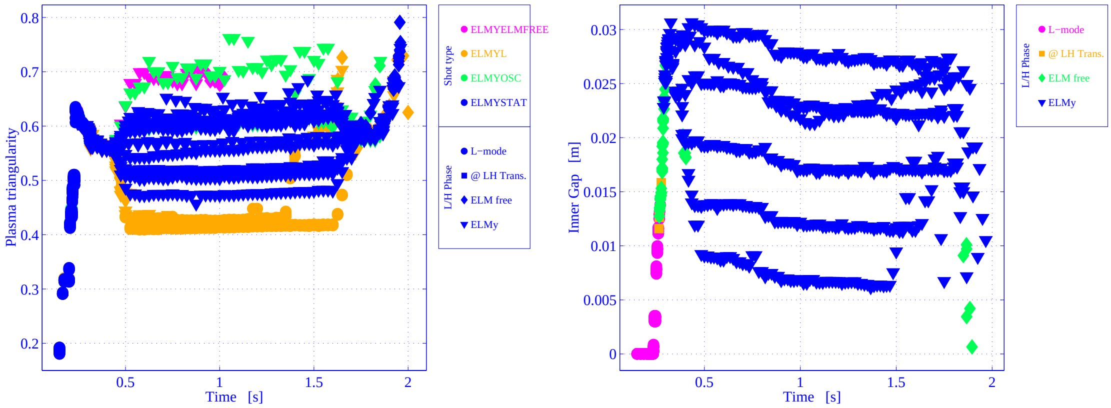

***FIG. 4**. a) Time evolution of the plasma triangularity for ELMy discharges. An increase of the triangularity leads to an oscillating ELM frequency or even to the appearance of ELM free phases. A reduction of the triangularity leads to a back transition to the L-mode. b) Time evolution of the plasma wall distance for ELMy shots. The gap was reduced to values below the threshold value without any deterioration of the ELMy regime.*

## 4 Conclusion

A reliable ELMy H-mode regime was successfully obtained in TCV. Access to ELMy discharges was only possible for a small region of the operational domain. Once this “gateway” is traversed, the ELMing state is stable to changes in the operational parameters. Plasma elongations from 1.55->2.1, triangularities from 0.45->0.65, plasma wall distances from .5->3cm and densities from 4->10.10$^{19}$m$^{-3}$ were successfully attained by passing the L-H transition with the “gateway” parameters and then programming plasma control changes. Although the ELM frequency was modified for these discharges, the ELMy regime characteristics were conserved.

Since the parameters under investigation in this paper were changed one at a time, it may be possible to extend even more theses ranges by compensating the effects of one parameter with changes in the other plasma parameters. The reliable access to the ELMy regime on TCV, together with the systematic changes in ELMing phases characteristics within parameter scans, open the way for the study of ELM dynamics and plasma confinement in this regime, both with and without ECH as a function of the plasma shape.

**Acknowledgement**: This work was partly supported by the Fonds National Suisse de la Recherche Scientifique. This work would not have been possible without the support of the entire TCV team.

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