

INFLUENCE OF THE PLASMA SHAPE ON MODE LOCKING DURING THE PLASMA RAMP-UP IN TCV

Y. Martin, J.B. Lister and A. Pochelon

*Centre de Recherches en Physique des Plasmas,
Association EURATOM - Confédération Suisse,
Ecole Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland*

1. Introduction

Disruptions have to be avoided as much as possible in tokamaks, because of the huge mechanical constraints that disruptions impose on the machine design through magnetic forces. In a device like ITER, only a small number of disruptions will be allowed. It is therefore important to know where the dangerous operational regions are, in order to avoid them. Since all causes of disruptions are not yet clearly understood, a statistical approach can be useful. In this paper, we present the location of one type of disruptions, those induced by locking modes (LM), in the TCV operational diagram, as well as the technique established for TCV to prevent a repetition of shots already known as disruptive because of these modes.

2. Locking modes in TCV

TCV is a medium sized tokamak ($R=0.88\text{m}$, $a=0.25\text{m}$, $I_p \leq 1\text{MA}$, $B_\phi \leq 1.5\text{T}$) devoted to the investigation of the influence of the plasma shape on plasma characteristics such as transport, confinement and stability. This tokamak has 18 independent poloidal field coils to shape the plasma up to a design elongation of 3 (achieved: 2.56) and with a triangularity between -1 and 1 (achieved -.5 and .8).

In the beginning of TCV operation, locking modes often appeared during the plasma current ramp-up. Some empirical knowledge was gained and the rate of locking mode induced disruptions dropped considerably. Plasma shaping and density programming were found to be the key parameters to avoid these disruptions.

The locking modes are characterised by an oscillation increasing in amplitude and slowing down in frequency, as shown in Fig. 1. The typical duration of the locking phase is 50 ms, with a frequency starting around 5kHz. These modes are either visible in the soft X-ray emission signal or in the magnetics measurements. Their structure is usually $m=2$ and $n=1$. Once the mode is locked, the plasma exhibits a succession of internal disruptions before a final complete crash. This disruptive phase can last from 10 ms to 50 ms. Because of their fatal issue, which is the case in more than 95 % of the onsets, the region of the operational domain to be avoided is the one crossed at the beginning of the locking mode. In order to determine this time of birth, we calculated the spectrogram of the soft X-ray emission signal, as shown in Fig. 1b. The time of the birth, t_{birth} , is determined by eye as the beginning of the frequency decrease as soon as its amplitude is significant.

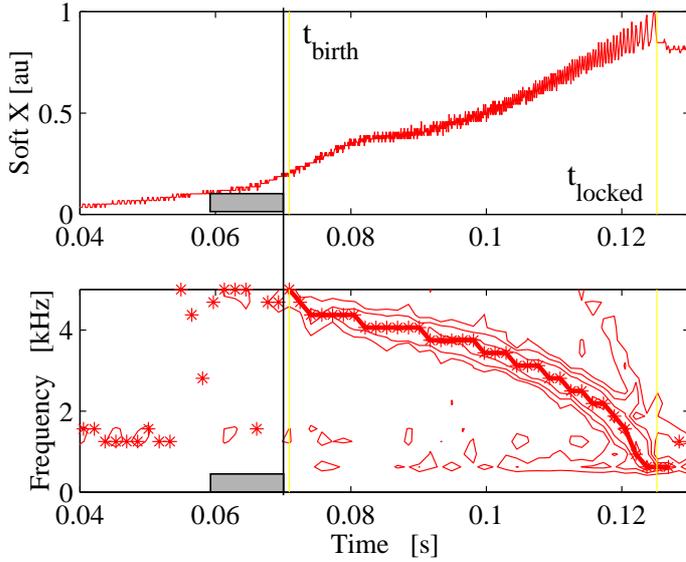


Figure 1: Soft X ray signal with its spectrogram. The time used for the analysis is t_{birth} , the time when the mode starts to brake.

Over 8000 shots have been examined, locking modes occurring during the plasma ramp-up were identified and the time of birth was extracted. About 100 cases of locking modes were found and put in a database together with points in the current ramp-up for all shots reaching q_{edge} below 3.3. For these ~ 1500 shots, data have been sampled every 10 ms during the plasma formation, i.e. in limiter configuration and with only ohmic heating. All basic plasma parameters such as plasma current, density, shape and position were calculated at these times. Examining

the database, we find that locking modes occurred in a small range of: a) the plasma density and b) a shape parameter, defined as $\delta^2 + (\kappa - 1)^2$, in agreement with our experience. This highly localised distribution is shown in Fig. 2.

Since locking modes originate in MHD phenomena, it is interesting to check whether they appear preferentially at given values of the safety factor. Some locking modes clearly start when the value of the safety factor at the edge crosses an integer value. These are usually observed in discharges located in the upper part of the vessel. In contrast, the locking modes growing in the lower part of the vessel seem to start at any value of q_{edge} , possibly indicating the presence of a stronger error field in the bottom of the tokamak.

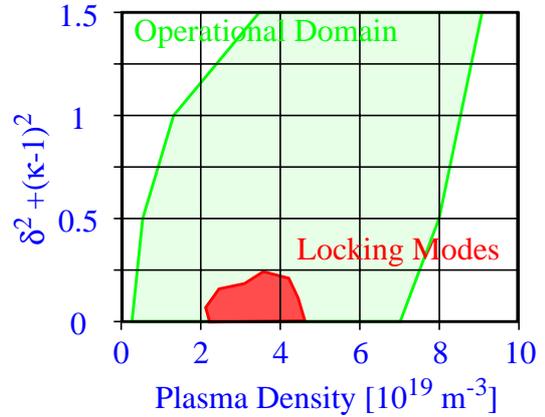


Figure 2: Locking modes locations in the plasma density and shaping domain.

The locking modes starting around $q_{\text{edge}}=3$ have been avoided by increasing the plasma shape parameter. Figure 3 shows the location of the locking modes as a function of the plasma shape and the rate of change of q_{edge} . It clearly shows that the locking modes which usually initiate at $q_{\text{edge}}=3$ appear in circular plasma cross-section with any rate of change in q and that stationary operation around $q_{\text{edge}}=3$ can be achieved with shaped plasmas.

3. Distance to locking modes

In order to describe the dangerous regions where LM have their birth location, all the parameters presented above must be considered simultaneously. Since the representation of such regions in a multi-dimensional space is quite difficult, a simpler representation must be chosen: after a

normalisation of the parameter space (I_p , n_e , κ , δ and z_{mag}), the euclidian distance to the n closest LM, n being equal to 1 to 5, has been calculated for every point along the trajectory of a discharge. This distance decreases as long as one or more LM are approached. Fatal trajectories exhibit distances close to zero at the time of the LM birth, as shown in Fig. 4a. This LM started in conjunction with the crossing of an integer value of q_{edge} . Figure 4b presents a case where the distance diminished drastically around $q_{edge}=4$, but was not too close to disrupt and then, thanks to the shaping as shown in the inset, the distance to any LM increased to a large value even for $q_{edge}=3$.

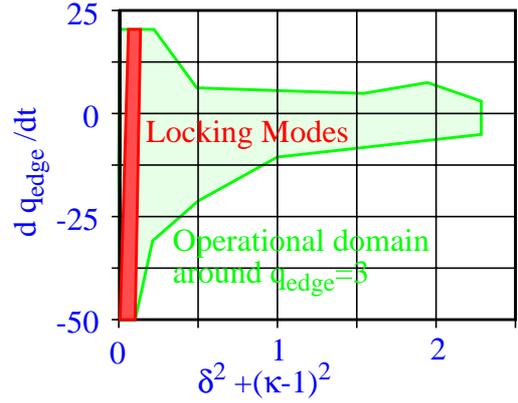


Figure 3: Operational domain covered by time slices having $2.9 < q_{edge} < 3.1$.

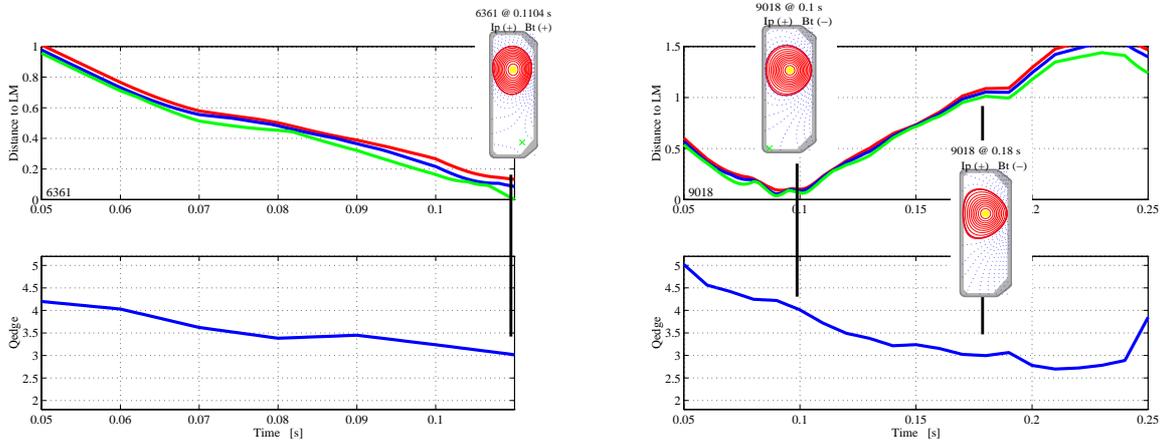


Figure 4: Time evolution of the distance to the n closest locking modes, $n=1, 3$ and 5 , shown together with the evolution of q_{edge} . On the left, the discharge entered locking modes at 0.11 s. On the right, the shaping prevented the discharge to have these modes.

This distance to the n closest LM has been calculated for all time slices in the database. A critical distance has been defined as the distance above which the point is considered as safe. Smaller distances are considered as too dangerous and the plasma is supposed to be lost in a LM. A confusion matrix has been estimated for many values of this critical distance as well as for many values of the number n , representing the number of closest LM to account for. The best distance is found to be 0.1 , with the confusion matrix expressed in table 1.

| | No disruption | Disruption |
|----------|---------------|------------|
| No Alarm | 1180 | 28 |
| Alarm | 65 | 174 |

Table 1: Confusion matrix

This table indicates that in 90% of the cases, the estimation of the distance is good enough to declare a trajectory as being dangerous somewhere. Although these calculations have been performed on existing data, the distance to locking modes can be calculated during the preparation of a new discharge, since all the parameters used in the distance estimation are

chosen, within the uncertainty of the control system, during this preparation. This step has been implemented on TCV and tests of the system are under way.

In order to improve the description of the regions where locking modes are born, a clustering technique has been applied to the database: when two locking modes are separated by a distance smaller than a given value, they are considered as belonging to the same cluster. One after the other the LM are attributed to clusters. Since the number of clusters is not known a priori, an algorithm scans the value of the distance. Starting at a very low value, the clusterisation finds as many clusters as starting points. With a larger distance LM start to aggregate and, finally, with a too large distance, there is only one cluster. The optimum is reached when most of the points are attributed to the maximum number of clusters. Figure 5 shows the clusters in a "multi2D" representation, in the lower part. In the upper part, the clusters are plotted as a function of the safety factor, showing that the clustering automatically grouped the LM appearing at the same q_{edge} value. This clustering technique provides a nice tool to represent the most dangerous regions. These clusters can also be used during the preparation of a discharge since they represent the dangerous regions.

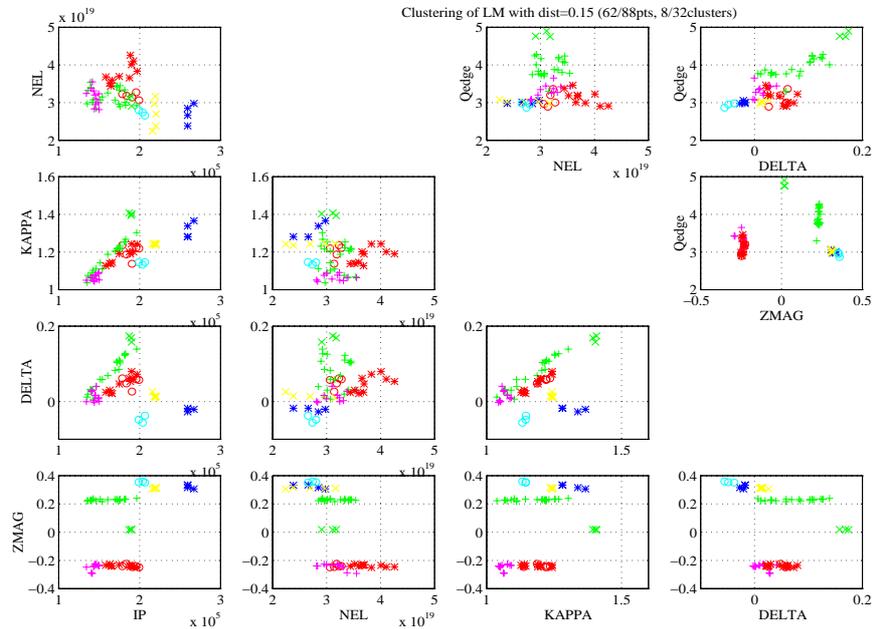


Figure 5: The clustering with a distance of 0.15.

4. Conclusion

Locking modes have been observed during the plasma ramp-up in TCV. The empirical knowledge, stipulating that the plasma shape, density and safety factor are the parameters governing the birth of LM, have been verified statistically. The distance to the closest locking modes has been calculated on a large TCV dataset. This distance has been shown to adequately characterise the danger of LM creation and therefore can be used during the preparation of a discharge, in order to avoid the repetition of a locking mode induced disruption already experienced.

Acknowledgements

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