MHD signals as disruption precursors in FTU

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1. Aim of this work

The definition of suitable disruption precursors in order to trigger actions for avoiding or at least mitigating disruptions is currently being investigated in FTU, as in many other tokamaks. In particular we are exploring the possibility to build and implement a real-time algorithm for disruption prediction, based on the observation of plasma MHD activity through magnetic sensors.

2. Method overview

Typical FTU disruptions have a phase dominated by a strong *m=2, n=1* MHD activity preceding the Current Quench (CQ). We based our algorithm on the analysis of the evolution of such a mode using one Mirnov coil signal, sampled at 500 kHz. The MHD signal is integrated and zero-crossing processed in order to calculate the poloidal field perturbation's amplitude and phase (fig.1). Such an algorithm was chosen because it's fast and easily portable in real time. The resulting MHD amplitude is then compared with a preset threshold, and an Alert is issued (t_{AL}) whenever such a threshold is exceeded for at least 4 consecutive sampling times. Ideally, at this point a trigger could be issued by the real-time control system to perform disruption avoidance actions, for example based on localized ECRH injection as successfully demonstrated in FTU [1] [2] and ASDEX-Upgrade [2] [3]. Based on our experience, the time interval required for mitigation actions to be safely carried out should be no less than 5 ms. This value takes into account the response speed of the control system actuators (e.g. the ECRH gyrotrons switch-on time).

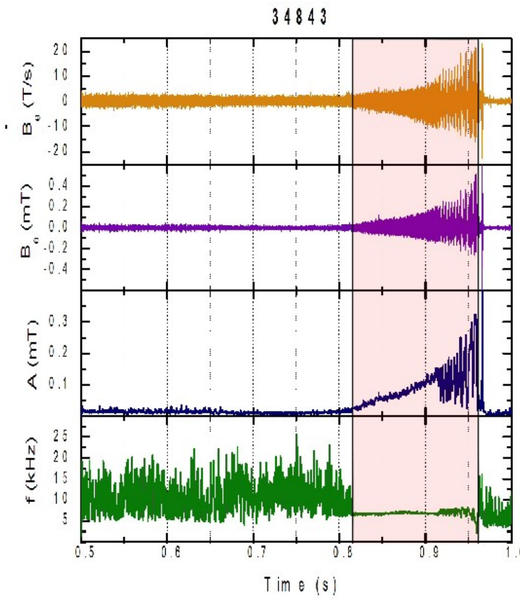

fig. 1: *MHD signal processing*

* See the appendix of P. Buratti et al., Proceedings of the 24th IAEA Fusion Energy Conf., San Diego, USA, 2012.

2.1 Assumptions

The choice to compare the MHD signal to a preset threshold is based on the fundamental hypothesis that a disruption occurs when the magnetic island's amplitude ***w*** reaches a critical value, assumed to be the same for all disruptions. It must be noticed, however, that the amplitude of the MHD signal is not only related to the island's width ***w*** but also to the distance of the resonant surface $q=2$ from the Mirnov coil itself. In the attempt to take this effect into account we considered various empirical threshold parametrizations, in particular based on expressions containing the safety factor at the edge (q_a). A good estimate of this quantity is easily obtainable by combining plasma current (I_P) and toroidal field (B_{tor}) measurements, which are available in real-time (see details in the following).

2.2 Choice of the sample

A particular care was taken in the choice of the sample to be analyzed: to ensure sufficient uniformity in initial conditions we considered all discharges that reached a stationary state characterized by a well defined current plateau. Each discharge was analysed starting from the beginning of such plateau. Discharges with particular behaviours, such as ramps in plasma current or in toroidal field (as produced in particular FTU experimental programs), or discharges with various problems, preventing them to reach the pre-programmed current plateau, were a priori excluded from the analysis. Finally, no attempt was made in this preliminary work to separately analyse the different types of disruptions.

2.3 Performance assessment

In order to assess the performances of the algorithm we needed a good definition of "disruption". For this purpose we decided to build a CQ detection algorithm. This algorithm is mainly based on the analysis of the plasma current derivative (dI_P /dt): when this value exceeds a preset threshold a disruption event is declared at that particular time (t_{CQ}). After running both the CQ and the Alert algorithms on all discharges, they are categorized according to their associated t_{AL} and t_{CQ} . Four classes and four corresponding numerical fractions are so defined:

- No Alert: CQ not found, Alert not found → N = (# NO Alerts) / (# NO CQ)
- False Alert: CQ not found, Alert found → F = (# Alerts) / (# NO CQ)
- Missed Alert: CQ found, Alert not found → M = (# NO Alerts) / (# CQ)
- Right Alert: CQ found, Alert found → R = (# Alerts) / (# CQ)

By definition: $N+F=1$ and $M+R=1$. A typical Right Alerts distribution is shown in fig. 2. It's evident that some Right Alerts are indeed declared too late, that is less than 5 ms before the CQ (solid red bin), so they must be moved into the Missed Alert category.

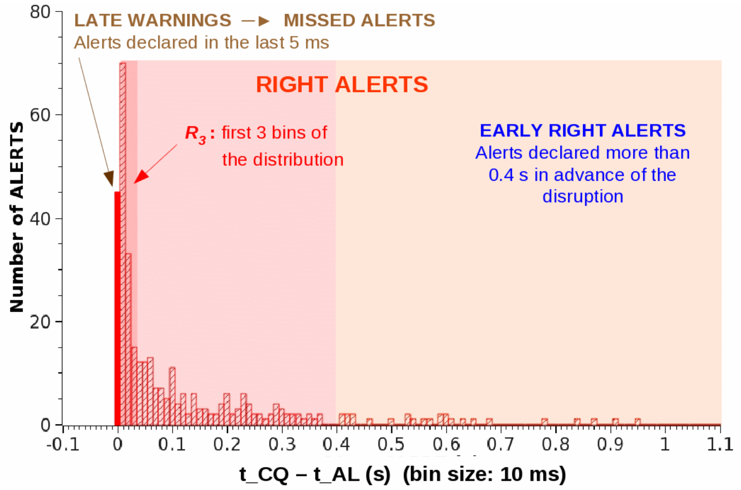

fig. 2: Right Alerts distribution

2.4 Optimization

Ideally one would like to maximize the *R* fraction, while minimizing the *F* fraction. To do so we defined a somewhat arbitrary family of Cost Functions (CF): $\boxed{C = \gamma M + \gamma^{-1} F - R_3}$,

where γ is a free parameter, while R_3 refers to the fraction of Right Alerts in the first three bins of the distribution, that's a time window spanning the range: 5 ms < $t_{CQ} - t_{AL}$ < 35 ms. This is, before the CQ, the maximum temporal window such that the number of Right Alerts falling in it is still strongly dependent on the chosen threshold parametrization.

3. Results

We analyzed a database of 2033 FTU discharges produced in the years 2009 ÷ 2012.

A total of 345 CQ were identified, covering a wide range of physical parameters:

B_{tor} = 2.5 ÷ 8 T, I_P = 250 ÷ 900 kA, n_{line} = 0.4 ÷ 4 x $10^{20}/m^3$, n_{line} / $n_{Greenwald}$ = 0.12 ÷ 2.00.

3.1 Constant Threshold

We first considered a constant threshold:

1) $Th = \alpha$

The best value α=1.78 G (table 1, first row) was found by requiring the CF to have an absolute minimum. Fig. 3 shows the integral of the Rights Alerts distribution. The integral's maximum corresponds to ***R* = 85%** (all Right Alerts farther than 5 ms from the CQ), while *50%* of Right Alerts fall within *Δt=62 ms* from the CQ. False Alerts are *F=12%*.

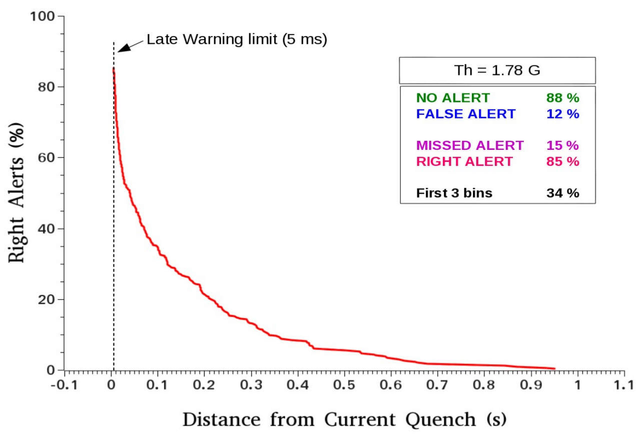

fig 3: Integral of Right Alerts distribution for constant threshold

The optimization process details are visible in fig. 4, where several calculations with different constant thresholds are shown. All fraction values (*N,F,R,M*) are plotted against the threshold value (in Gauss). Three CF are also calculated, corresponding to γ spanning the range 1÷3. It must be noticed that in this simple case each CF reaches its minimum approximately at the same threshold.

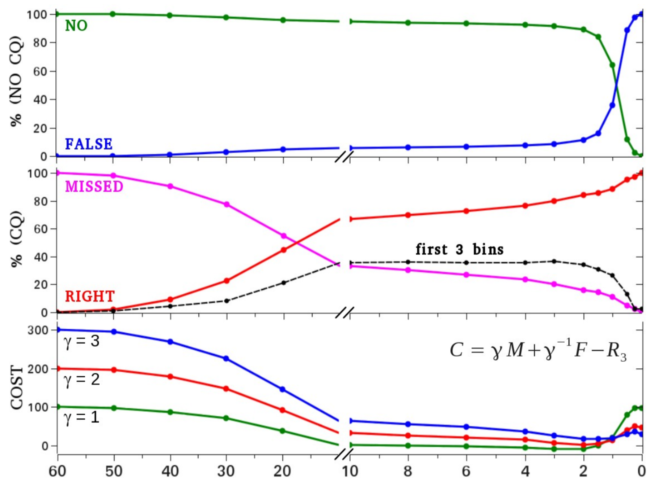

fig 4: *Results and optimization for constant threshold case*

3.2 Other parametrizations

To improve the aforementioned results, more complex parametrizations were considered:

2) $Th = \alpha - \beta q_a$; 3) $Th = \alpha B_{tor}$; 4) $Th = \frac{\alpha}{q_a - 1}$; 5) $Th = \alpha \frac{B_{tor}}{(q_a - q_0)^{\frac{m}{\beta}}}$

where *m=2* for FTU, and q_a is the safety factor at the edge, which was fixed by running a linear fit on FTU discharges, in the form $q_a = c B_{tor}/I_p$, yielding the value of *c*. For each case the best α, β, q_0 (i.e. those minimizing the CF) and the corresponding Alerts fractions are shown in table 1. The best parametrization tested so far is n°4 (in bold) which has both the lowest CF minimum and the highest R_3 .

case #	α	β	q_0	N %	F %	M %	R %	R_3 %	$C_{\gamma=2}$
1	1.78 G	-	-	88	12	15	85	34	1.87
2	3.95 G	0.31 G	-	88	12	15	85	36	-1.52
3	0.35	-	-	87	13	15	85	34	2.98
4	**9.5 G**	-	-	**88**	**12**	**15**	**85**	**38**	**-1.52**
5	1.6	2.0	1.0	86	14	14	86	36	-1.07

Table 1: *Optimized results vs. parametrizations* (γ=2)

4. Conclusions

A full real-time algorithm for disruption prediction and avoidance, based on one Mirnov coil signal, is being implemented in FTU. Preliminary results are encouraging. Possible future improvements and upgrades based on the use of multiple coils are also foreseen.

Acknowledgements

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References

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