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Characterization of physics events in JET preceding disruptions

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The Sequence of Physics Events (SPE) that leads the plasma towards a disruption can be different in different discharges. An Event, in this framework, refers to the signature of a physical phenomenon (*e.g.* a peaked *ne* profile or bolometric peaking factor), whose duration may vary from few ms to several hundreds ms. The SPE have a direct influence on the evolution of the pulses. Then, it is reasonable to assume that their identification can provide relevant information to keep the discharges within a safe operational space. In this work, first, a set of Event detectors (each one targeting a distinctive disruption-related phenomenon) have been considered. These detectors have been applied to JET disruptive discharges in the range of #94152 to #97137 (June 2019 – March 2020, corresponding to Baseline scenario experiments). Each one of these disruptive shots has been characterized by its corresponding SPE. Once the main signatures of the disruptive behaviour have been determined, the last step of the work consists of the analysis of these SPEs. The objective is to identify which ones are more prone to occur and therefore useful to describe their impact on the discharge evolution. This first step opens the possibility of applying the method to a considerable larger database, including also non-disruptive discharges, in order to better understand when and why similar trajectories end (or not) in a disruption.

1. Introduction

In the perspective of ITER, it is necessary to achieve operational configurations stable enough to maintain the discharges running for more than 40 min [1]. This requires avoiding plasma instabilities, specially disruptions. In JET, one of the most studied scenarios is the so-called “Baseline”, mainly focused on pushing the operation towards the high current and field with a relaxed current profile [2].

The description of the disruption path can be defined by a Sequence of Physics Events (SPE). Some SPE influence the discharge trajectory by diverting it from the expected trail, finally pushing it into a disruption. The analysis of those paths can offer key clues for the avoidance of such events.

Following that premise, in the last years several works have been devoted to unweave the rainbow of possible disruptions tracks, mainly based on the recognition of early precursors, as the hollowing of the electronic temperature profiles [2–7], the plasma edge cooling [8], neoclassical tearing modes [4] or early radiation events [3,6,8].

Our research goes in the same direction of the abovementioned works aiming at characterising the disruption paths. In our case, it is oriented to an offline analysis and not to the online prediction of disruptions.

The main differences and contributions offered here are three. The first one is to take into account the intervention of the control system (PETRA [9]) in the analysis. This is a critical point, because in many cases, the course of the discharge is profoundly affected by control actions and posterior SPE do not occur in a natural way (but because of PETRA’s intervention). The identification of the recurrent SPE before and after the control actions are key questions answered in this analysis. To the authors’ knowledge, this kind of information has not been included in any published paper yet.

The second contribution is the inclusion of measurements derived from the fast operational visible cameras. This diagnostic has been rarely used for the characterization of disruptions [3] and, as it is mentioned in the following Sections of this paper, has a significant role in the identification of early instabilities (in some cases even before PETRA’s intervention).

Finally, a relevant aspect for the analysis is the computation of the Events’ duration. Our analysis not only takes into account their occurrence (e.g. the existence of a hollow Te profile) but also the time interval

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it remains in that state, which discriminate whether it is a fleeting phenomenon or one that persists for a long interval.

This article is structured as follows. In Section 2 the gathered database is detailed, as well as the time-traces, profiles and videos used for each discharge. Section 3 explains the way the Events are computed whereas Section 4 is devoted to the analysis performed over the database and to show the main plots that summarize the whole evolution of the discharges, including the computed SPEs and the PETRA interventions. Finally, in Section 5, the conclusions are discussed and insights for future improvements are suggested.

2. Database

The gathered database has 27 disruptive shots from JET's Baseline scenario experiments. These discharges are in the range of #94152 to #97137 (June 2019 – March 2020). A necessary prerequisite to this analysis was the availability of all the parameters required by the identification of SPEs.

For each one of the 27 pulses, the following data have been collected:

- Videos of the operational camera.
- Profiles from High Resolution Thomson Scattering (HRTS): both Te and ne profiles.
- Locked mode amplitude and time derivative of the stored diamagnetic energy.
- Radiation (Total radiated power).
- Bolometric diagnostic line integrals.

The abovementioned magnitudes are used to compute different Event detectors as it is explained in the following Section.

3. The events within the SPEs

3.1. Determination of the "disruptive zone" by a "first warning"

Every discharge transits through different phases (whether they disrupt or not) [10]. To focus the analysis on the shot's portions where disruptive precursors are likely to appear (instead of assessing the whole evolution of the discharge), a "disruptive-related" zone needed to be determined [5].

For that, a statistical method, based on the most essential signatures of disruptions, has been deployed. In very broad terms, it can be agreed that disruptions are linked to MHD modes, to an increase in the radiated power and to a decay in the plasma confinement [2]. Therefore, these signals (Locked mode, Total radiated power and plasma stored diamagnetic energy) have been analysed. The "disruptive zone" is set to start in case their magnitudes exceed a "reasonable" amplitude. "Reasonable", in this case, means exceeding two standard deviations of its mean value computed over the plasma current flat-top of the discharges (this is based on classical statistics and it is performed using the whole DB of 27 discharges). The above-mentioned statistical technique was using an "OR" logic: (i.e. the first event detected is the one considered). This first warning (**1W**) only depends on the statistical threshold set over radiation, locked mode and stored diamagnetic energy. Neither PETRA information nor extra signals are were included for its calculation.

As it will be discussed in posterior subsections, the **1W** is consistent with the Jump To Termination (**JTT**) activation of PETRA.

3.2. The events and their computation

This paragraph is devoted to listing and briefly explaining the specific Event detectors and how they are computed.

Radiation Shift Event (**RS**): a sudden movement in the visible Radiation (derived from the fast visible operational camera data, as it is explained in [3]). It may indicate a MARFE, a core cooling or even a Transient Impurity Event.

Hollow Te profile Event (**HTe**): a simple difference between inner (core) and outer (High Field Side) measurements from the High Resolution Thompson Scattering (HRTS) is computed as it is detailed in [3] and very similar to the one performed in other works [4].

Peaked ne profile Event (**Pne**): analogue computation to the Hollow Te profile, but using the electron density data [3].

Edge Cooling Event (**EC**): a robust statistical method, also using HRTS data and carefully explained in [8] is applied.

Bolometric Factor (**BF**): peaking factor described in [4] that considers the difference of measurements in the plasma core and Low Field Side.

These Events are tracked down over all the disruptive discharges in our database and analysed in the next Section.

4. Analysis and summary plots

PETRA [9] compiles a rich set of indicators optimized, among other tasks, to start the discharge shutdown in order to protect the device in case of possible danger. Once an alarm is activated, a so-called Jump To Termination (JTT) is programmed and a pre-set chain of actuators begin to intervene. In Fig. 1, two example discharges are described through their SPEs. The upper Figure corresponds to the pulse #94425 and the bottom one to #96384. In each Figure's title, the following information is shown: the shot under analysis, the 1st Warning (**1W**, see Section 3.1.) and PETRA's first trigger (JTT). Notice that Fig. 1, the reason why these 2 independent triggers (1W and JTT) are activated coincide: a radiation (RAD) peaking. This concurrence happens in the 77,77% of the shots in the database.

In Fig. 1 (top), even before the 1W (green vertical line) a Radiation Shift Event (RS, purple vertical line) is detected. Few milliseconds after that detection, an Edge Cooling Event (EC, light blue squares, fourth time-trace) takes place. As consequence, an MHD instability grows and it is detected by the 1W and, few milliseconds later, by PETRA (JTT, light blue vertical line) with a posterior EC. The disruption (D) occurs around 51,2s without any mitigation. Summarizing this case, the SPE can be expressed as RS→EC→1W→JTT→EC→D.

Fig. 1 (bottom) describes a very different trajectory. A Peaked ne profile (Pne, second time-trace) is detected in several occasions. This behaviour is then noticed by the Bolometric Factor Event detector (BF, third time-trace) to finally trigger the 1W and a posterior JTT. PETRA intervention results in the firing of the DMV, whose injection is very near to the beginning of the current quench.

In this case, the SPE can be written as Pne→BF→1W→JTT→DMV→D.

These 2 examples illustrate the utility of the compact notation that describes the disruption path. These trajectories can be searched in massive databases and even refined: not only the identified events are stored but also their duration.

It is also quite relevant to distinguish among the recognized Events *before* and *after* PETRA intervention. Before PETRA's trigger, a wide variety of SPEs occur. The most common ones are: RS→1W (4 cases in the 27 discharges of the database); only 1W (4/27); HTe→Pne→1W (3/27); BF→1W or 1W→BF (6/27); BF→Pne (4/27).

However, the landscape is quite different after JTT's intervention. This was expected, since the chain of posterior actions are pre-set and the natural evolution of the discharge is actively altered. In those cases, the protection system attempts to avoid or at least mitigate the impact of the expected disruption. The posterior Events, then, are conditioned by these control actions and they should not be taken into account as natural precursors. In these cases, the vast majority of SPEs after the JTT are these: JTT→BF→DMV (18/27). All this cases end in the DMV activation. Even more, the DMV is fired in 23 of the 27 discharges of the DB. The only 4 cases where the DMV was not activated were the ones without a clear radiation peak.

To provide more general statistics, in the case of this work, in 25 of

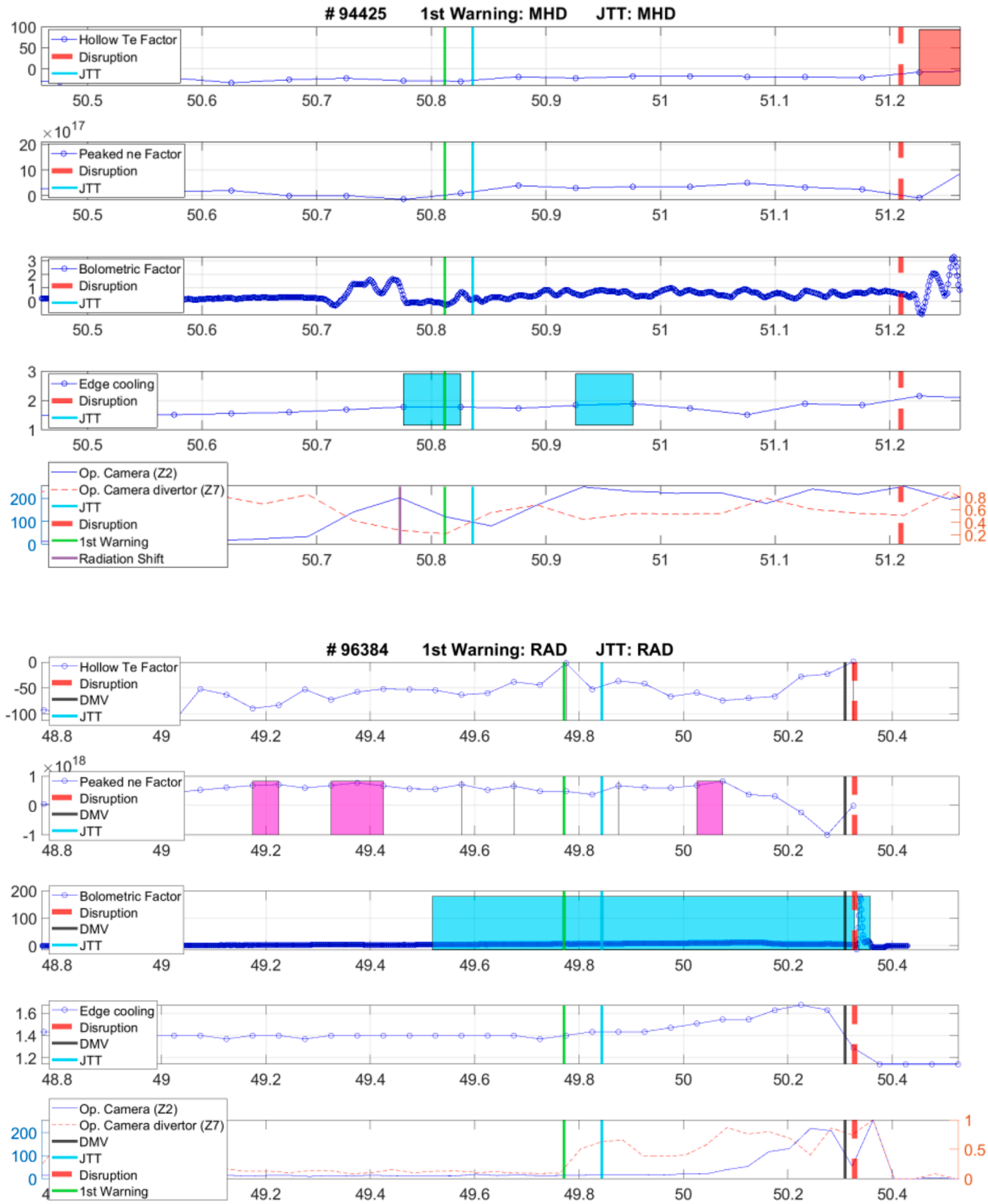

Fig. 1. SPEs describing the disruption paths for #94425 (top figure) and #96384 (bottom figure). Notice that not only the events are marked with a vertical line but also the time interval they remain active (e.g. purple and cyan boxes in the bottom figure). The dotted red line represents the disruption time. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the 27 shots of the database (92,59%) the 1W has been fired *before* JTT alarm.

PETRAs first alarm and the 1W were similar in the case of low current (<2MA) shots: the 1 W has a mean anticipation time of only 162 ms with respect to JTT.

In the case of discharges with a maximum Plasma Current (Ip) >=2,5MA (i.e. so potentially more dangerous) the average anticipation of the 1W *versus* the JTT is 320 ms

Regarding low Ip and excluding #96371 (JTT is very early triggered in a healthy plasma for a termination experiment), the 1 W has a mean anticipation time of 162 ms with respect to JTT.

5. Summary and conclusions

In this work, 27 JET Baseline scenario discharges have been investigated. Several “Physics Events” were computed by using a heterogenic set of diagnostics.

The Sequence of these Events (we called them "SPE") summarizes the trajectory of the pulses towards the disruption. Three clear utilities of these SPEs (specially thinking of massive fusion databases) arise.

To this end, several Event Detectors (most of them developed by different authors in previous works) have been replicated. These detectors were originally designed with a different goal (disruption prediction or avoidance) and tested over different databases.

In this work, instead, they have been used for the characterization of disruption paths.

One is its possible use for data retrieval and analysis. For example, all the SPEs defined by: "a Radiative Shifting instability followed by a Hollow Te profile, before any intervention of JET control system" could be tracked down in the whole database. The resulting list can be used to draw conclusions about their similarities and differences. Even more, that same set of characteristics defined by this example can be also searched upon non-disruptive discharges in order to better understand why in those cases the shot did not ended drastically.

This kind of analysis takes large amounts of time with a classic "visual inspection" (the manual tracking of these chains of Events in past discharges is considerably time consuming) and therefore it would be quite useful to have the technique here described helping with the task.

The second contribution is the use and analysis of visible cameras movies. This diagnostic can provide rich and different information than any other one, detecting early instabilities even before, in some cases, than any other diagnostic.

The third contribution is the inclusion of PETRA information and the duration of the Events. Of course, the most common disruption paths are well known, but the exact percentage of them that follow a specific SPE with (and without) a previous intervention of PETRA is, as far as the authors of this article know, not present in the available literature [11]. In this case, each Event is not only detected but also the duration of each one is stored, which can be useful for deeper studies.

This first step opens the possibility of applying the method to a considerable larger database, including also non-disruptive discharges, in order to better understand when and why similar trajectories end in a disruption (in disruptive discharges) and to quantify the successful control actions able to avoid them (in non-disruptive discharges).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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