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An arc control and protection system for the JET lower hybrid antenna based on an imaging system[a)]

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Arcs are the potentially most dangerous events related to Lower Hybrid (LH) antenna operation. If left uncontrolled they can produce damage and cause plasma disruption by impurity influx. To address this issue an arc real time control and protection imaging system for the Joint European Torus (JET) LH antenna has been implemented. The LH system is one of the additional heating systems at JET. It comprises 24 microwave generators (klystrons, operating at 3.7 GHz) providing up to 5 MW of heating and current drive to the JET plasma. This is done through an antenna composed of an array of waveguides facing the plasma. The protection system presented here is based primarily on an imaging arc detection and real time control system. It has adapted the ITER like wall hotspot protection system using an identical CCD camera and real time image processing unit. A filter has been installed to avoid saturation and spurious system triggers caused by ionization light. The antenna is divided in 24 Regions Of Interest (ROIs) each one corresponding to one klystron. If an arc precursor is detected in a ROI, power is reduced locally with subsequent potential damage and plasma disruption avoided. The power is subsequently reinstated if, during a defined interval of time, arcing is confirmed not to be present by image analysis. This system was successfully commissioned during the restart phase and beginning of the 2013 scientific campaign. Since its installation and commissioning, arcs and related phenomena have been prevented. In this contribution we briefly describe the camera, image processing, and real time control systems. Most importantly, we demonstrate that an LH antenna arc protection system based on CCD camera imaging systems works. Examples of both controlled and uncontrolled LH arc events and their consequences are shown. [http://dx.doi.org/10.1063/1.4889904]

I. INTRODUCTION

The Joint European Torus (JET) is equipped among other auxiliary heating systems with a LH (Lower Hybrid) antenna.[1] It provides 5 MW of heating and current drive to the JET plasma. This power is delivered by 24 klystrons (microwave generators) which can be controlled individually. A single klystron feeds a main wave guide which then feeds 2 multijunctions each of which is subdivided in 8 small plasma facing waveguides. It is this feature that creates the "grill" structure of the launcher (Fig. 1). To safely operate this antenna arc events must be mitigated. If left uncontrolled they can be the cause of damage to the antenna and of subsequent plasma disruption by Fe impurity influx coming from it as result of the mentioned damage. Two existing systems provide partial protection against these events. One of those is a fast protection system that relies on measurements of the reflected power. On one hand this system is relatively fast (~50 μs) and controls exclusively the klystrons for which the arc is detected. But on the other hand it assumes the power reflected to the two waveguides fed by a klystron follows an asymmetrical distribution in the presence of an arc. This is not always the case which means some arc events go undetected. A change to this asymmetry assumption would lead to a significant increase in false alarms.

Therefore, this system cannot be improved any further. The other protection system relies in the detection of iron in the plasma combined with bolometer radiation measurement in front of the launcher. If both values rise above a safety threshold limit all LH operation is inhibited. The drawbacks of such system are its relatively slowness (up to 100 s of ms after start of arc precursor), the halt of all LH operations and that the trigger only happens after damage to the "grill" has already occurred.

II. ARC IMAGING PROTECTION SYSTEM

To complement the existing protection systems an imaging protection system was assessed and implemented. This

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[c)]See the Appendix of F. Romanelli *et al.*, Proceedings of the 24th IAEA Fusion Energy Conference 2012, San Diego, CA, USA.

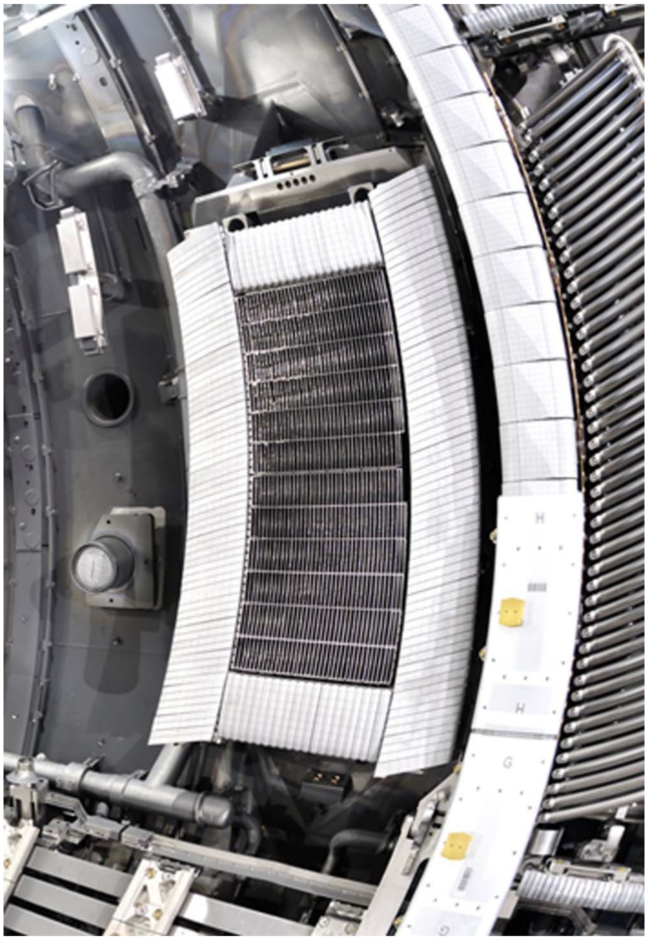

FIG. 1. JET LH antenna as imaged by visible camera. Low field side limiter is seen to the side of the antenna.

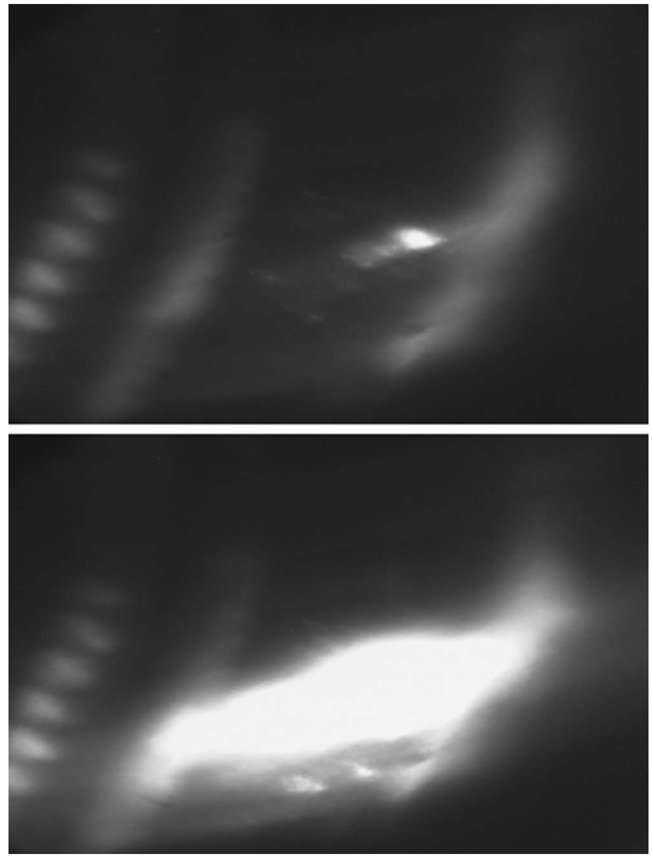

FIG. 2. Two consecutive frames (20 ms acquisition rate) of LH antenna protection camera show evolution of uncontrolled arc event. On the first frame an arc precursor is visible which develops into a flare on the second frame. In order for the protection system to act locally a grid of 24 ROIs was defined (Fig. 3). Each ROI covers one klystron.

system was developed by adapting the ITER Like Wall (ILW) hotspot protection system[2] using an identical camera and real time image processing unit. The camera in use is a HITACHI KP/M1AP analogue monochrome CCD camera. This type of camera has proved to be reliable despite JET's environment. In fact this kind of camera operates on JET without the need for magnetic shielding. The use of an imaging based approach allows for action to take place as soon as light from the arc precursor is visible (Fig. 2). This preempts both any significant damage and impurity influx into the plasma.

The Regions Of Interest (ROIs) grid (Fig. 3) was drawn taking in consideration a possible range of positions for the launcher. The system provides in real time the peak intensity for each ROI for every single frame. If the value provided surpasses a safety threshold the control system acts locally by reducing the power to the specific klystron(s). This control procedure avoids that the entire LH power input is inhibited while targeting the origin of the arc precursor (Fig. 4). After such process and if the latest camera data indicate that the arc event was successfully mitigated the power for the affected klystrons is ramped up again. If for a given pulse the same klystron is tripped more than a definable number of times it is turned off till the end of the pulse and the operator is alerted. The camera imaging the antenna uses a filter to block both Dα and BeII. By doing so saturation and subsequent non arc related spurious system triggers caused by ionization light are avoided. Nevertheless given that klystrons in the center of the antenna are less likely to be affected by spurious radiation the system allows for different thresholds to be set according to the different image characteristics for each klystron.

III. COMMISSIONING AND OPERATIONS

During the 2013 restart and experimental campaigns the arc imaging protection system was commissioned and made fully operational with positive results. Cases of arc precursors

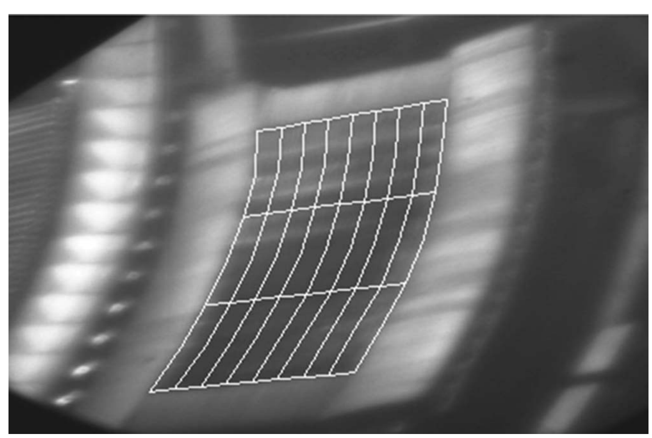

FIG. 3. JET LH antenna showing overlaid schematic representation of ROIs.

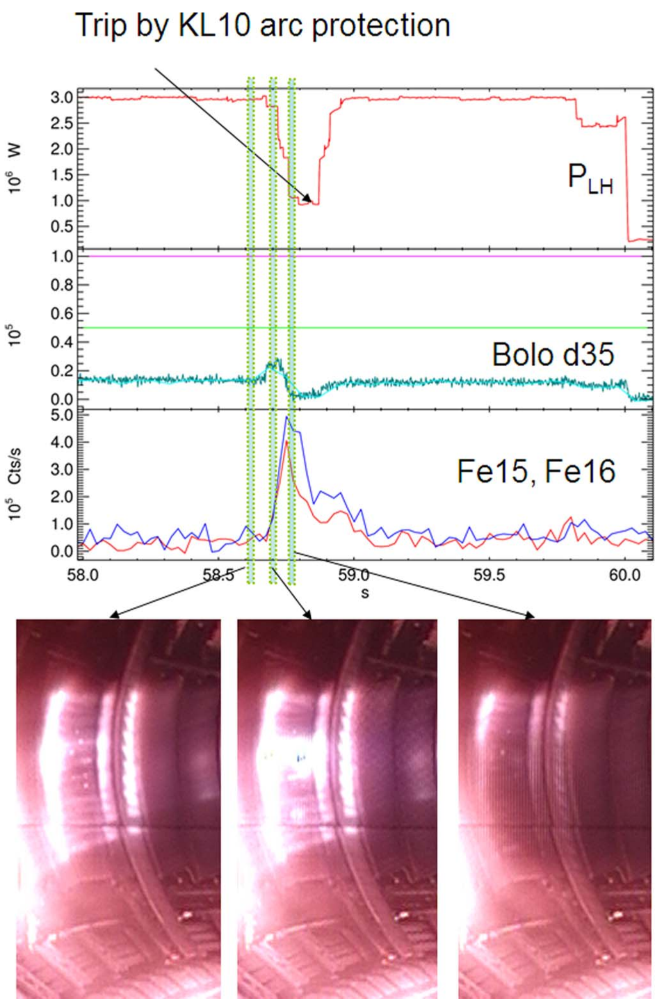

FIG. 4. LH antenna as viewed by wide angle visible camera. Consecutive frames show arc imaging protection system in operation. The detection of an arc precursor on the second frame leads to a local reduction in power and avoidance of arc event. 75% of the antenna being operated at the time is turned off as shown by the respective reduction in power output.

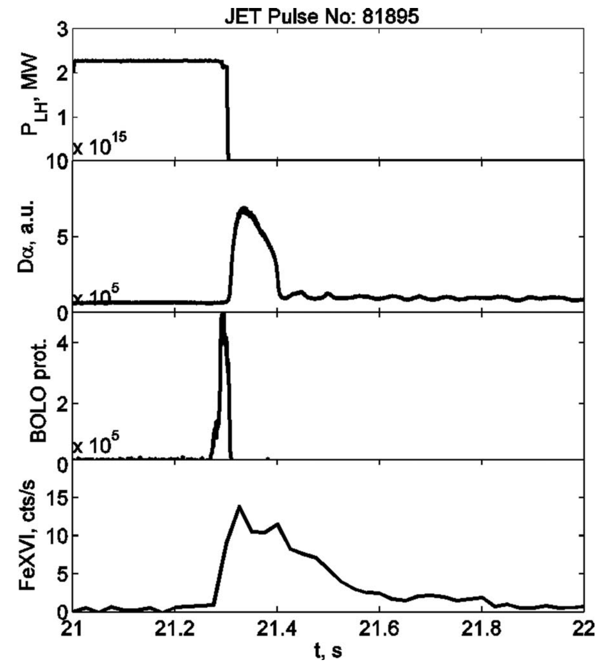

FIG. 5. Evolution of an arc event as seen from a visible camera in consecutive frames, acquired at 20 ms rate, showing how it develops into a flare. On the right, the time traces of the LH power, Dα signal, bolometer protection, and FeXVI line are shown.

during LH operations were successfully detected with the corresponding klystrons tripped. No plasma disruptions due to Fe impurity fluxes caused by arcs in the LH antenna occurred. An experimental example of full control cycle and response can be seen in Fig. 4. Upon detection of an arc precursor as imaged by a wide angle visible camera the power to the involved klystrons is reduced. The system is triggered and the power is locally reduced. From the second frame to the third it can indeed be immediately seen from the provided images that the arc precursor is completely and successfully controlled with any further consequences avoided. As explained it can be seen that the antenna power is only locally and partially switched off with ~1 MW of power still being provided. Immediately afterwards the system allow the power to be ramped up again to the initial value of approximately 3 MW.

By comparison on Fig. 5 the relevant parameters of an arc event before the implementation of the imaging protection system can be seen. Importantly it can be observed that the levels of FeXVI in the plasma are for this case approximately three times higher than for the mitigated case. Most strikingly the bolomoter signal is an order of magnitude higher than in the LH arc precursor event with the new protection system operational. The LH antenna operation was also inhibited totally and not partially and remained switched off till the end of the plasma discharge. This contrast shows several of the advantages of the protection system presented in this paper. The JET LH antenna has now an automatic control, protection and avoidance tool that if arc precursor is detected acts quickly enough so that the impact both the plasma in terms of influx of impurities and on the power output of the LH antenna is minimized.

IV. CONCLUSIONS

The implemented arc imaging protection and control system proved to be an important contribution for operations at JET with the LH antenna. It successfully addressed the problem of arcing and solved it. No significant impact on plasma operations due to arcing has been observed since the implementation of this system.

ACKNOWLEDGMENTS

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