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Experimental Results of Real-Time Protection System for Plasma Facing Components in Wendelstein 7-X at GLADIS

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Abstract

One of the aims of stellarator Wendelstein 7-X (W7-X), is to investigate steady state operation, for which power exhaust is an important issue. The predominant fraction of the energy lost from the confined plasma region will be absorbed by an island divertors, which is designed for $10\,\mathrm{MWm}^{-2}$ steady state operation. In order to protect the divertor targets from overheating, 10 state-of-the-art infrared endoscopes will be installed at W7-X.

In this work, we present the experimental results obtained at high heat flux test facility GLADIS (**G**arching **LA**rge **DI**vertor **S**ample test facility in IPP Garching) [2] during tests of a new plasma facing components (PFCs) protection algorithm designed for W7-X. It contains two ion beams which can generate a heat load from $3\,\mathrm{MWm}^{-2}$ to $55\,\mathrm{MWm}^{-2}$. The algorithms developed at W7-X to detect defects and hot spots are based on surface temperature evolution and are adapted to work in real-time. The aim of this work was to test the real-time algorithms in conditions close to those expected in W7-X. The experiments were performed on W7-X pre-series tiles to detect delaminations. For detection of surface layers, graphite tiles from Wendelstein 7-AS stellarator divertor were used to observe temporal behavior of fully developed amorphous carbon-hydrogen (a-C:H) surface layers. In order to simulate realistic scenarios for W7-X, different heat loads were applied. The experiments indicate that the automatic detection of critical events works according to W7-X PFC protection requirements.

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I. INTRODUCTION

W7-X is an optimized stellarator, designed for steady state operation of up to 30 minutes. The PFCs which are subject to largest power loads include divertors and first wall. During steady state operation, these components have to be actively water cooled. The overheating of PFCs, which may lead to development of the defects in their structure, of which the most critical are those appearing between the CFC-layer and the cooling structure [7]. Thus it is required to detect the defects in real-time during plasma operation in order to modify the power loads to PFCs if necessary to remain within material limits.

This paper provides a detailed explanation of the RTPS (Real Time Protection System) framework and its test implementation at GLADIS. Section II provides a description of the CFC which is used in the divertor target element. Section III describes the RTPS framework and its integration with the main central control system. Section IV explains the experimetal setup at GLADIS. Section V explains the results obtained from the experiments conducted in GLADIS. Section VI gives a short description of the outlook and a summary.

II. CARBON FIBER COMPOSITE (CFC)

The divertor in W7-X is separated in then units which are composed of about 890 PFCs covered with flat tiles of CFC NB31[1]. These CFC tiles are bonded via a copper interlayer by Active Metal Casting (AMC) to an copper chromium zirconium (CuCrZr) cooling structure. The basic structure of the target elements can be seen in Figure 1.

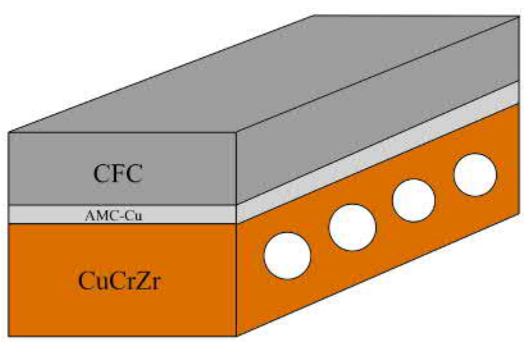


FIG. 1: Schematic structure of W7-X divertor target element

These target elements are designed to withstand a steady state heat flux of upto 10 $\mathrm{MWm^{-2}}$ for long term plasma operations of W7-X [1]. Each divertor module consists of up to 250 mm to 500 mm long and 50 mm to 61.5 mm wide individual target elements which are covered with an on average 6 mm thick CFC top tile.

In the past, experiments were conducted at GLADIS in order to analyze the performance of W7-X tiles during high heat loads. In general three different types of defects (corner, enclosed and band defect) were detected during the post analysis of the prototype target elements. All defects occurred at the interface between the CFC and AMC interlayer and are named delaminations. Further details regarding the formation of these defects is discussed in [3].

In order to detect these defects, a method [7] was developed based on the surface temperature decay time defined as

$$\tau = \frac{T(t)}{\partial_t T(t)} \tag{1}$$

A so called τ criterion ($\tau_{\text{crit}} > \tau_{\text{mean}} + 4\sigma$) was evaluated by observing behavior of the target elements under different heat loads with an infrared diagnostic.

III. RTPS FRAME WORK

The primary goal of W7-X is to maintain a steady-state plasma for 30 minutes. On such longer time scales, defects can be formed during plasma operation as mentioned in [[3] , [7]]. Although surface layers created by deposition of eroded surface material are not defects, they lead to false temperature measurements of the graphite tiles and resulting in higher values of heat flux calculations. This was already observed e.g. in W7-AS and described in [4]. This would lead to false positive alarms by the RTPS. A prerequisite for safe steady state operation is to detect these abnormal features in real-time. For this reason, an RTPS is designed to create an early response system to provide feedback information to the W7-X central safety system (CSS). The block diagram of the system can be seen in Figure 2.

For parallel processing, an NVIDIA Quadro graphics processing unit (GPU) is used. A data acquisition card (DAQ) is used to send/receive trigger signals. A camlink interface card is used to acquire data from IR cameras. Advanced GPU computation techniques were used to achieve higher performance.

The data is then in parallel assigned to different units i.e. for visualizing IR data, sending the data to GPU for computation and saving the data in a storage device in HDF5 format. The video saving during the discharge is controlled using DAQ card. As the experiments

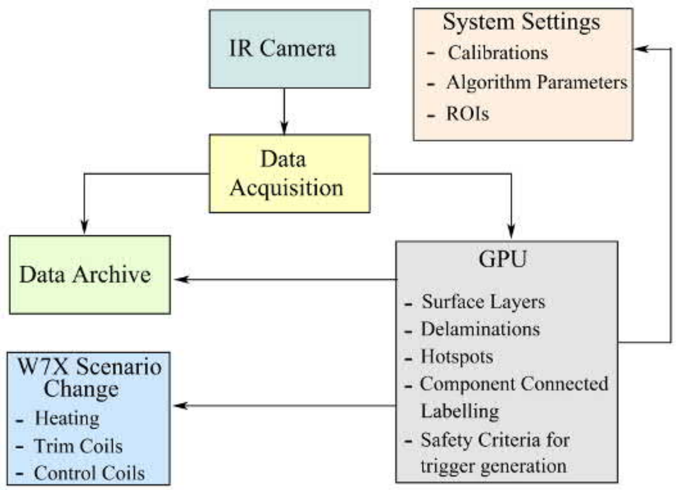


FIG. 2: Block diagram of the RTPS designed for the protection of PFCs in W7-X by detecting thermal events in the infrared images.

were performed at GLADIS, the Trig IN signal in Figure 3 is generated by the GLADIS DAQ system approximately 500 ms before the beam starts.

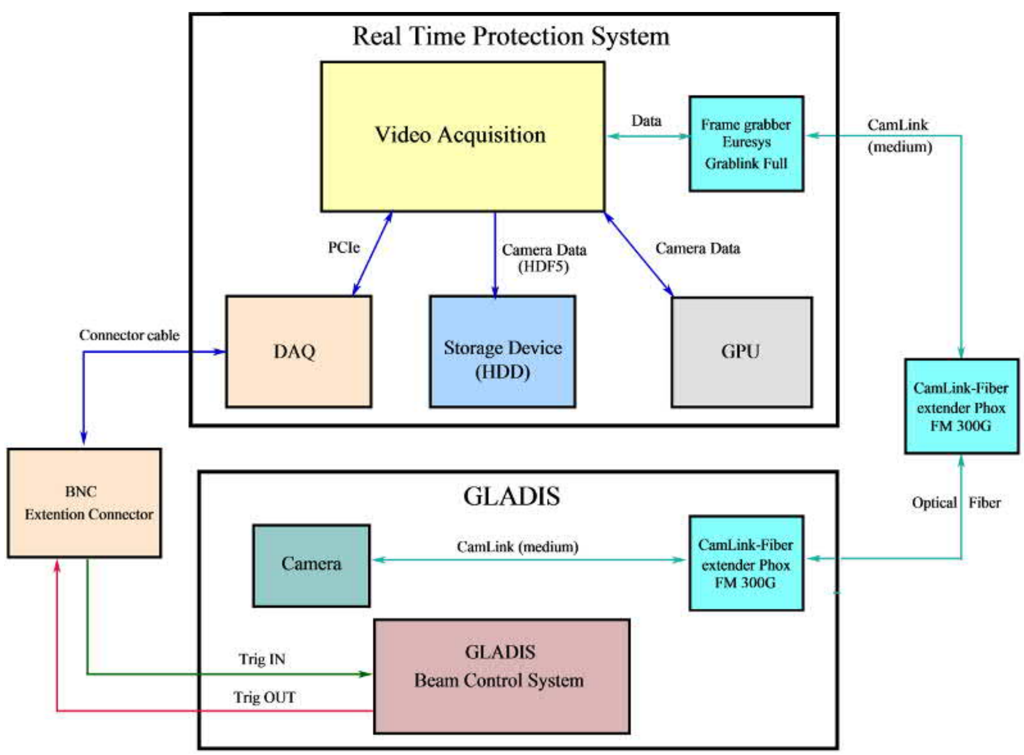


FIG. 3: Hardware setup of the RTPS at GLADIS

The same signal is used to start the video recording of infrared diagnostic. During the experiment, the system classifies the data to detect thermal events during plasma discharge.

If the system detects that the threshold i.e. $\text{size}_{\text{defect}} > \text{size}_{\text{critical}}$ where $\text{size}_{\text{critical}}$ is defined by the user, a trigger signal from RTPS is generated which is send to the GLADIS DAQ system.

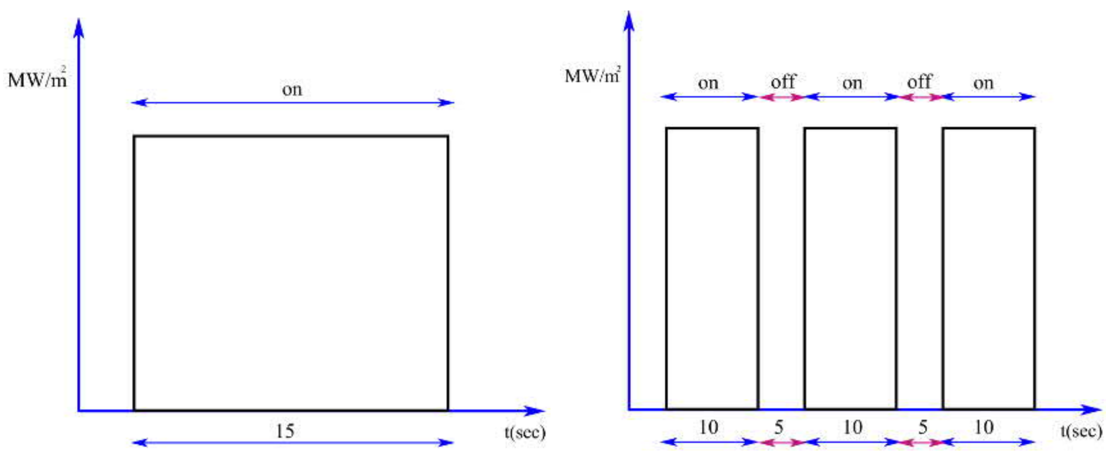
The method defined in [7] was also implemented using the GPU. However, we focused our efforts on significantly improving the efficiency of the parallel computing, which allowed us to process 100 times more data at the same time. The cameras send the raw data to the data acquisition system which then generates the parallelized tasks for the CPU and GPU. The probability of sending false positive alarms increases if the criterion of sending alarms depends on the evaluation of a single detected pixel on the defected area. Although the defects are being detected in the system using the method described in [7], determining the size of the defects on the material is also an important requirement to reduce the amount of false positive alarms.

For this reason, an additional method based on the concept of component connected labeling (CCL) is developed, similar to the one described in [6]. CCL is a fast search algorithm where a 4 or 8 point search (up, down, left, right and diagonal elements) is applied. Initially all pixels are assigned index labels with respect to their location. Then the minimum label value between current pixel and its neighboring pixels replaces the current label value. In this way all the pixels which are connected to each other are assigned to a single label value. However, the method described in [6] is modified to be compatible with the binary results obtained from the GPU. It also calculates the size of each label value which is used to determine the safety criterion for generating trigger signals.

After the size of each label value is calculated, it is compared with the safety criterion threshold defined by the user. The next step for W7-X safety requirements would be that if the size of any label is greater than the threshold, a trigger signal will be generated which is then sent to CSS to take an early reaction e.g. by changing the strike line position using the control coils or reduce heating power. The operator of the system can also modify the algorithm parameters that are used to detect surface layers, delaminations, hotspots and safety thresholds at run time. After each plasma discharge, the calibrated and raw data will be saved in the archive in standard HDF5 format for post analysis.

IV. EXPERIMENTAL SETUP AT GLADIS

In order to qualify if the RTPS is compatible with the safety requirements of W7-X, HHF experiments on W7-X prototype divertor target elements were conducted at GLADIS [2]. To investigate if the RTPS system is able to detect hotspots, surface layers and delaminations in real-time, a prototype target element (pre-series 4S-032) was tested under different heating scenarios. Graphite tiles used as a part of the divertor at Wendelstein 7-AS stellerator similar to those mentioned in [4] and [5] were used to detect surface layers formed by a-CH deposition. The RTPS system used for GLADIS experiments consists of a workstation connected to an infrared diagnostic. The main part of the system is a IR camera measuring in the wavelength range of 3 µm to 5 µm with InSb intrinsic semiconductor sensor. During experiments at GLADIS it was mounted on one of the ports to observe the divertor target elements. The samples were observed through a sapphire filter with high transmittance in the infrared spectrum. In order to simulate a realistic scenario for W7-X, the heating power was varied between 3, 5, 8 and 10 $\mathrm{MWm^{-2}}$. Two different types of beam discharges (constant beam and modulated) were used as seen in figure 4. The beam focus on the W7-X target element was also varied between tile 4, 6 and 8 to detect the defects with direct and indirect beam focus on the defected tiles .

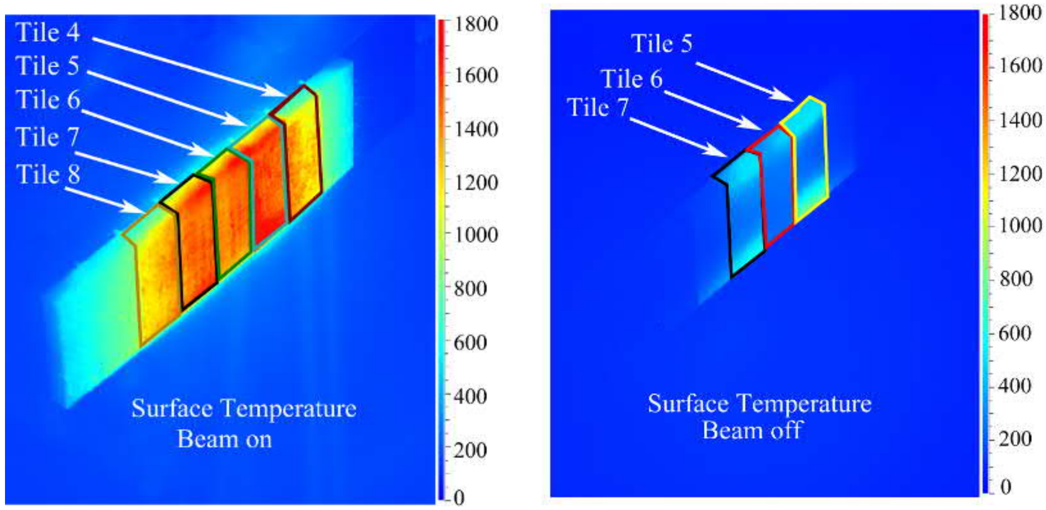


(a) Constant beam discharge (b) Modulated discharge

FIG. 4: The input power and duration were varied to have different temperature profiles on the target element.

V. EXPERIMENTAL RESULTS

The detection of delaminations is difficult if the heat load is less than 8 $\mathrm{MWm^{-2}}$ as mentioned in [7]. Maximum number of pixels detected as delaminated occurs when applying a beam power of 10 $\mathrm{MWm^{-2}}$. An example representing surface temperature on CFC tiles during and after the plasma beam discharge can be seen in Figure 5.



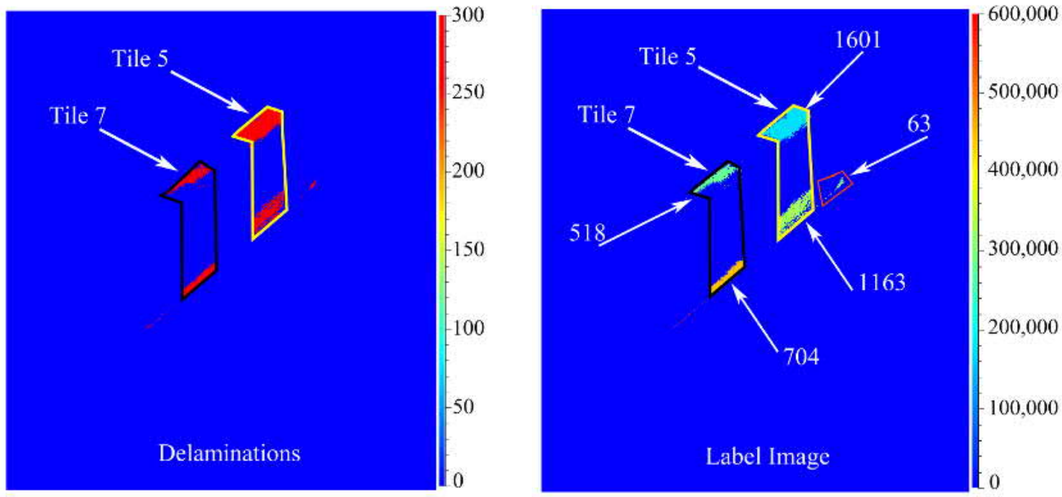
(a) Surface Temperature Beam on

(b) Surface Temperature Beam off

FIG. 5: False color image of W7-X divertor target element. Regions of interest(ROIs) in yellow, red and black represent the areas of tile 5, 6 and 7.

The surface temperatures at the edge of tiles 5 and 7 can be seen at higher temperatures compared to other tiles. Tile 5 shows similar features of band defect whereas tile 7 shows enclosed and corner defects. The system creates 5 independent arrays of data which are visualize as images of surface layers, delaminations , hotspots. The 4th array labels the resultant connected component pixels. The 5th array calculates the size of the corresponding labels. The calibrated image from the IR camera is then passed through an image processing algorithm to create a binary output arrays which can be seen in Figure 6.

The yellow and black regions of interest (ROIs) indicate the areas of two tiles. The number of pixels within each label can also be seen in Figure 6. After calculating the size of each label value, it is compared with the threshold value. If the calculated value exceeds the threshold, a trigger signal is generated by RTPS and send to GLADIS beam control system where it is recorded.



(a) Delaminations (b) Label image

FIG. 6: ROIs in yellow and black represent the area of tile 5 and 7. The numbers on label image represent the size of each label calculated by 5th data array.

As mentioned in IV, W7-AS divertor tiles were used to provide realistic conditions for the detection of surface layers. After visual inspection of W7-AS divertor modules, tiles with maximum deposition were selected (Tile 5, 12 and 13, for details on deposits see [5] and [4]).

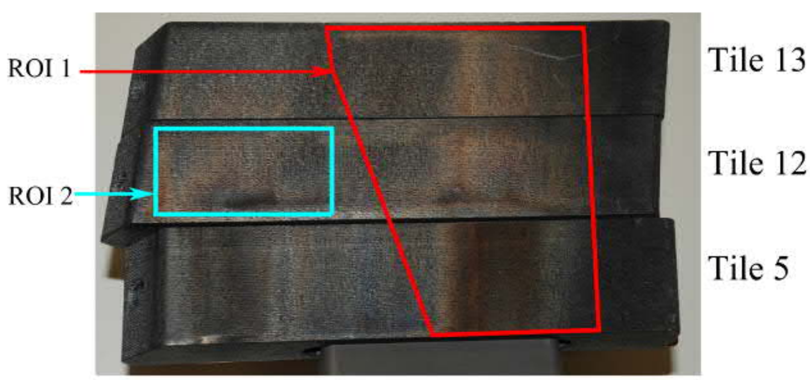
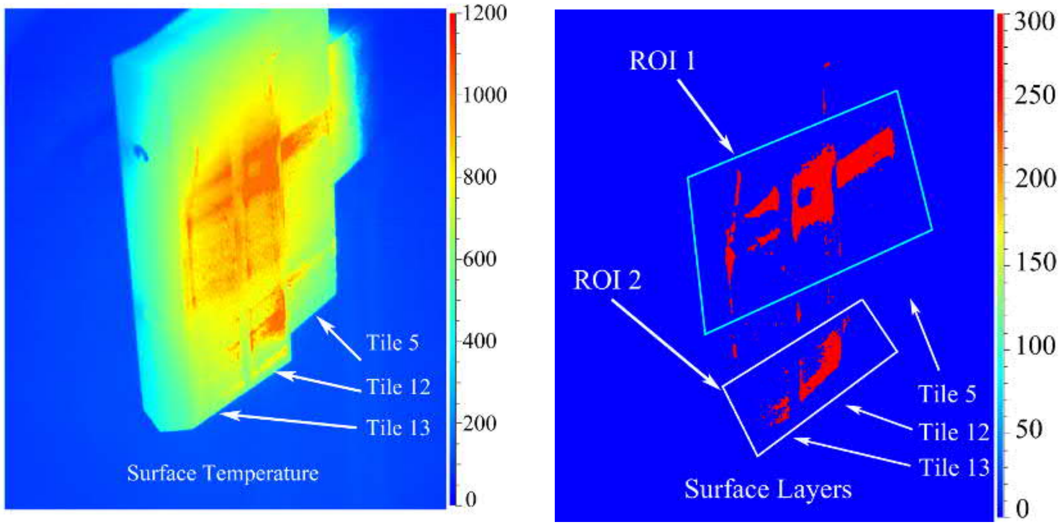


FIG. 7: W7-AS divertor target elements. The numbers indicate tiles position on the entire divertor module. The ROIs show the areas where the surface layers are present.

Different heat loads of 3, 5, 7 and 10 $\mathrm{MWm^{-2}}$ were applied with constant and modulated beam discharges. Most prominent results of surface layers detected by the RTPS when the input power was 10 $\mathrm{MWm^{-2}}$ with a modulation beam discharge of 500ms was applied which can be seen in Figure 8.



(a) Surface Temperature

(b) Surface Layers

FIG. 8: False color image of W7-AS divertor target element. ROIs in blue and white represents areas with expected deposition of surface layers.

The blue and white regions of interest (ROIs) in Figure 7 correspond to areas that are compared with the surface layers results obtained from the system. As seen in Figure 8, the areas where the expected surface layers are found comparatively match with the results obtained from the system. Similar results are expected at W7-X, with corresponding measurements during the next experimental campaign starting in 2017.

VI. OUTLOOK AND SUMMARY

In this work, we presented the experimental performance of the RTPS at GLADIS for detection of surface layers, delaminations and hotspots of different origins. Algorithms are developed to detect these defects in real-time based on the infrared diagnostic. The results presented in the paper clearly show that the system was able to detect these defects in real-time and is ready for implementation within the CSS of W7-X. Surface layers and hotspots are expected to be detected in the next experimental campaign when inertially cooled divertors are used. However, delaminations will be detected when water-cooled high-heat-flux divertors are installed during experimental campaign in 2020.

VII. ACKNOWLEDGEMENT

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