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Development of a Monitoring System for Plasma Facing Components at Wendelstein 7-X

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Abstract

An important topic in plasma physics is the interactions between high temperature plasmas with in-vessel components, as it is crucial for a future reactor. The plasma facing components (PFCs) are designed to withstand heat flux densities originating from losses of the confined plasma. To increase the durability of the PFCs they need to be monitored and protected from too large heat loads. Even for short plasma pulses, real-time diagnostic may be needed to protect from overload. Considering that in future the duration of the plasma pulses will increase from seconds up to several minutes and eventually to continuous time scales, evaluation of these components is necessary to be conducted during a discharge in real-time.

Wendelstein 7-X (W7-X) is a state-of-the-art optimized stellarator that is designed to demonstrate high-power and high-density steady-state plasma operation. It is envisioned to show good confinement in an advanced stellarator for up to 30 minutes. In this work, the algorithms used for protection of W7-X divertors which are the main areas for particle and energy exhaust are investigated. This is required to be performed in real-time to avoid any fatigue damage during long pulse operation.

In order to do so, several steps are made to optimize the monitoring process. A near real-time image diagnostic system (NRT-IDS) has been created to detect thermal events on plasma facing components in W7-X. An in-house non-uniformity correction method was developed to attain uniform signal intensity on all the pixels of the infrared (IR) image. In addition, an in-house thermal calibration method based on the W7-X in-vessel field of view was created to convert the raw data from the IR cameras to temperature measurement. A thermal event detection algorithm has been developed and was applied to the IR images to detect thermal events during plasma operation. Events such as surface layers, delamination and hotspots are detected in near real-time using the temperature evolution of a PFC. Moreover, advanced computer vision techniques are applied to make the algorithms compatible with near real-time applications.

Initially, the NRT-IDS was tested and evaluated in GLADIS to mimicked the environment of W7-X during plasma operation. The experiments were conducted for the detection of thermal events like delamination in near real-time which were successfully identified by the system. Like the divertor, baffle and wall panels need to be monitored for any damage or cracks that may occur due to high thermal load. This was achieved by mounting the IR thermography diagnostic on different ports of W7-X. The system is capable of controlling all the IR cameras and monitoring the PFCs inside the W7-X from the central workstation. A trigger signal-based alarm protocol is defined to send signals to the W7-X central control system in case of any failure detected on any PFCs which can compromise the safety of the machine.
Abstract

operation. The system is now installed at W7-X for operating the IR diagnostic and routinely monitoring the status of the PFCs during plasma operation.
I would begin by thanking my family, especially my mother, father and brothers who have supported me throughout morally and financially during the difficult times and helped me overcome stressful times during every ordeal. Moreover, my wife, Alfiya has also been a great motivator for me as she stood by me during this period.

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Acronyms

ASDEX Axially Symmetric Divertor Experiment.
CCL Component Connected Labeling.
CFC Carbon Fiber Composite.
CPU Central Processing Unit.
CSS Central Safety System.
CUDA Compute Unified Device Architecture.
DAQ Data Acquisition.
EBW Electron Beam Welding.
ECRH Electron Cyclotron Resonance Heating.
GLADIS Garching Large Divertor Sample Test Facility.
HDD Hard drive.
HHF High Heat Flux.
HIP Hot Isostatic Pressing.
IR Infrared.
ITER International Thermonuclear Experimental Reactor.
LCFS Last Closed Flux Surface.
MIT Multi Integration Time.
MMU Memory Management Unit.
NRT-IDS Near Real Time Image Diagnostic System.
PCI Peripheral Component Interconnect.
PCIe Peripheral Component Interconnect Express.
PFCs Plasma Facing Components.
PFM Plasma Facing Material.
PS Pre-series.
THEODOR Thermal Energy Onto Divertor.
### Acronyms

<table>
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<td>TPL</td>
<td>Toroidal Pump Limiter.</td>
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1 Introduction

Nuclear fusion is a primary contender for future power generation for the energy-hungry consumers. This is due to its abundant fuel resources, no carbon emission, and no long-term radioactive waste. The nuclear reaction between deuterium $^2\text{D}$ and tritium $^3\text{T}$ which releases $^4\text{He}$ nuclei and a neutron $^1\text{n}$ seems to be the most promising case for net energy production in fusion reactor. The reaction (equation (1.1)) generates 17.6 MeV of kinetic energy. The neutrons carry most of it (14.1 MeV) leaving the plasma while the alpha particles, which remain inside the plasma carry 3.5 MeV. The later can be used to heat up the plasma.

$$^2\text{D} + ^3\text{T} \longrightarrow ^4\text{He} (3.5 \text{ MeV}) + ^1\text{n} (14.1 \text{ MeV}) \quad (1.1)$$

The early research of the controlled nuclear fusion in a thermonuclear reactor started in the last century when John. D. Lawson published the most renowned Lawson triple-product criteria [1]. It defines the plasma conditions required to create enough net power to generate electricity in a fusion reactor based on the following criteria.

$$P_\alpha \geq P_{\text{convloss}} + P_{\text{rad}} \quad (1.2)$$

Where $P_{\text{convloss}}$ is the convective loss and $P_{\text{rad}}$ is the radiation loss in a fusion reaction. The amount of energy that alpha particles have ($P_\alpha$) is only one-fifth of the total fusion reaction.

$$P_\alpha = \frac{1}{5} P_{\text{fusion}} \quad (1.3)$$

Assuming that the input heating power for igniting the fusion reaction is removed i.e.

$$P_{\text{heating}} = 0 \quad (1.4)$$

Lawson defined the figure of merit for the condition to reach ignition based on the following requirements:

- Cross-section (i.e. probability) for D-T reaction increases with ion temperature $T_i$. 

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- Rate at which fusion reaction takes place depends on the concentration of the reactants i.e. the density of ions $n_i$.

- Rate at which a reactor looses its energy is called confinement time $\tau_E$. It defines for how long plasma is able to keep energy in the core where D-T reaction takes place.

According to Lawson criterion (equation (1.2)) plasma ignites i.e. energy obtained via fusion reaction is higher than input energy at a sufficiently high product of ion density $n_i$, ion temperature $T_i$ and the energy confinement time $\tau_E$ of the plasma ($n_i T_i \tau_E > 4 \times 10^{21} \text{ keV s m}^{-3}$ with $T_i \approx 10 \text{ keV}$ which is equivalent to $\approx 10^8 \text{ K}$) [1]. To achieve and maintain an environment which fulfills the Lawson criterion for ignition, a hot plasma needs to be created. At such high temperatures (order of $10^8 \text{ K}$), it must be insulated from a plasma vessel. Two different ways are being investigated to confine high-temperature plasma: magnetic confinement and inertial confinement. As the scope of this work is only related to magnetic confinement devices, nuclear fusion using inertial confinement is not discussed here. In the case of magnetic confinement, the charged particles tend to follow the closed magnetic field lines and thus remain confined.

1.1 Devices for Magnetically Confined Fusion

As mentioned above, at high temperatures of order of $10^8 \text{ K}$, a working gas becomes fully ionized plasma, which needs to be insulated from the vessel. The charged particles are very efficiently confined with a magnetic field. Due to the Lorentz force, the charged particles propagate along the magnetic field lines in a spiral motion.

![Figure 1.1: Magnetic field topology where magnetic field lines can be seen in solid black lines and magnetic flux surfaces in red. The torus coordinates are labeled as: major radius $R$, minor radius $r$, height $Z$, toroidal angle $\varphi$ and poloidal angle $\theta$.](image_url)
1.1 Devices for Magnetically Confined Fusion

A toroidally shaped magnetic field is the most effective way to confine the charged particles. However, using only a toroidal field leads to charge separation caused by particle drifts of ions and electrons. As a result, instability occurs which leads to rapid loss of the plasma to the walls. The particle drifts are averaged out using poloidal magnetic field either generated by a toroidal current in the plasma [2] or using external field coils.

In a device with magnetic field consisting of toroidal and poloidal field, an infinite set of nested magnetic flux surfaces are created. One of such magnetic flux surface is presented in Figure 1.1. The field lines are described by their helicity, which results from the ratio of poloidal and toroidal field on the surface. The twist of magnetic field line is often described by so-called rotational transform $\iota$. The $\iota$ is defined as the ratio between the number of toroidal turns ($n_t$) and poloidal turns ($m_p$) of a field line on rational surface i.e. $\iota = m/n$. In simple words, $\iota$ indicates how many poloidal turns a field line makes during each toroidal turn on a given flux surface [3]. Magnetic fusion devices that operate with toroidally closed nested flux surfaces include stellarators, tokamaks, reverse field pinch (RFP), field reversed configuration (FRC) and spherical tokamaks (ST). Shot descriptions of a stellarator and a tokamak will be given in the next section.

### 1.1.1 Tokamak

Most of the research on magnetically confined fusion plasmas is conducted in tokamaks. The Tokamak (a Russian acronym for the toroidal chamber with an axial magnetic field [4]) was invented by Tamm and Sakharov. The main magnetic field in a tokamak is created by a solenoidal set of ring-like magnetic coils oriented in the form of a torus. The ring-like magnetic coils create the toroidal magnetic field which traps the plasma particles along the field lines. The current inside the tokamak produces the poloidal magnetic field. The resulting spiral of magnetic fields lines created together by poloidal and toroidal magnetic field around the torus creates closed magnetic flux surfaces.

A sketch of main components of a tokamak is shown in Figure 1.2. The largest tokamak called ITER (International Thermonuclear Experimental Reactor) is currently under construction to demonstrate the scientific and technical feasibility of fusion as an energy source. It is designed to produce a factor of 10 higher output of 500 MW of fusion power from an input heating power of 50 MW. However, it is not designed to produce electricity as it will guide the way for the next machine DEMO (DEMonstration power plant) [5] that will be designed as a power plant. In the past, tokamaks have been designed in various parts of the world. Among them, JET, Tore Supra, DIII-D, EAST and ASDEX Upgrade are the most popular devices in the fusion community. Tore Supra had a similar design structure of its plasma facing components (PFCs) as the ones that will be discussed in this thesis in Section 3.1.1.
1 Introduction

1.1.1.1 Tore Supra

Tore Supra (a French tokamak now called WEST) was a tokamak with a major radius of 2.3 m and minor radius of 0.7 m designed for extended pulse operation. Because of that it was equipped with the actively cooled carbon fiber composite (CFC) plasma facing components (PFCs). The toroidal pump limiter (TPL) as seen in Figure 1.3 located at the bottom of the vacuum vessel in Tore Supra was responsible for the power exhaust from the edge of the plasma. The strong ripple of magnetic field at the outer radius of the limiter impacts the heat flux on the limiter which creates a 3-D shaped heating pattern on the limiter as can be seen in Figure 1.3. The TPL consisted of 574 target elements composed of a finger-like shape of blocks of CFC with a copper chromium zirconium (CuCrZr) cooling channel.

Figure 1.2: Sketch of main components of a Tokamak [2].

Figure 1.3: Visible and thermographic view of Tore Supra Toroidal Pump Limiter (TPL). The temperature gradient between the hotter and colder region can be clearly seen from the image. Courtesy CEA Cadarache
1.1 Devices for Magnetically Confined Fusion

During operation, the TPL was exposed to the high-temperature plasma which caused a continuous erosion and depositions process [6] as can be seen Figure 1.3. The erosion mostly occurred in high loaded regions and the deposition on the low loaded regions. In Tore Supra, about 840 µm thick layers of amorphous carbon-hydrogen (a-C:H) depositions developed within 2.3 hours of plasma operation [7]. This led to a distortion in temperature measurements and surprisingly higher heat flux for protection of actively cooled components. Infrared (IR) cameras were placed to observe these target elements in case of any fatigue damage to them due to high heat loads. During operation, thermal events were detected by IR camera data when observing the surface temperature of PFCs [7–9]. The detection of the thermal events will be later discussed in detail in Section 3.2.1 and Section 3.2.2.

1.1.2 Stellarator

Tokamaks perform reliably under certain boundary conditions, e.g., density and current limitations. To achieve higher performance plasmas, it becomes necessary to go beyond the limits, which leads to disruptions due to internal plasma instabilities. Another kind of magnetic confinement device investigated is the stellarator which has non-axisymmetric toroidally closed magnetic flux surfaces. Lyman Spitzer introduced the concept of the stellarator in 1958 [10] where external superconducting coils produce the flux surfaces. Stellarators do not require any plasma currents. That is why they are free from most of the plasma disruption and instabilities. The main hurdle in designing the stellarator is its complex 3-D geometry. Also, the confinement in the early stellarator types was not good enough to extrapolate to an economic power plant. Since the 1980s, the computing power required to design such complex coils and the plasma theory for stellarator confinement has made tremendous progress. This allowed the design and development of Wendelstein 7-X.

1.1.2.1 Wendelstein 7-X

Wendelstein 7-X (W7-X) is a state of the art optimized stellarator, designed to demonstrate high-power and high-density steady-state plasma operation. It is located in Greifswald, Germany and it took 15 years of construction and commissioning before its first plasma operation. It is envisioned to show the good confinement in an advanced stellarator for generating steady-state plasma up to 30 minutes. The magnetic coil system as seen in Figure 1.4 required for the confinement of the particles consists of superconducting as well as non-superconducting coils. 70 (50 non-planar and 20 planar) superconducting magnetic coils form the main magnetic field. Different magnetic configurations at W7-X are used by changing the currents in the planar and non-planar coils.

Additional ten island control coils are used to sweep the position of the magnetic fields lines that are intersecting with the plasma facing components (PFCs). Five trim coils are installed to enable the correction of magnetic fields errors, shifting and tilting the plasma to provide a heat load balance on the PFCs [12, 13]. Several heating
systems like electron cyclotron resonance heating (ECRH), ion cyclotron resonance heating (ICRH) and neutral beam injection (NBI) will be used to reach an electron temperature $T_e$ upto 10 keV and ion temperature $T_i$ in the range of 2 keV to 5 keV. Ten gyrotrons capable of on average 0.8 MW of heating power and capable of being operated for the whole discharge duration will be used to provide a total input power of 8 MW. In addition to that, 8 MW of input power for a limited duration will be provided by NBI. The technical design parameters of W7-X for operating in a steady state regime are mentioned in Table 1.1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major radius</td>
<td>5.5 m</td>
</tr>
<tr>
<td>Minor radius</td>
<td>0.53 m</td>
</tr>
<tr>
<td>Magnetic field strength</td>
<td>2.5 T</td>
</tr>
<tr>
<td>Plasma volume</td>
<td>$30 \text{ m}^3$</td>
</tr>
<tr>
<td>ECRH power</td>
<td>8 MW</td>
</tr>
<tr>
<td>ICRH power</td>
<td>1 MW</td>
</tr>
<tr>
<td>NBI power</td>
<td>up to 10 MW</td>
</tr>
<tr>
<td>electron temperature</td>
<td>$T_{e,\text{core}} &lt; 10 \text{ keV}$</td>
</tr>
<tr>
<td></td>
<td>$T_{e,\text{edge}} \approx 10 \text{ eV}$</td>
</tr>
<tr>
<td>electron density $n_e$</td>
<td>$0.1 \times 10^{20} \text{ m}^{-3}$ to $3 \times 10^{20} \text{ m}^{-3}$</td>
</tr>
</tbody>
</table>

**Table 1.1:** W7-X technical design parameters for the steady-state operations [14].
For the reactor level performance of a stellarator type fusion device, it is important to design it in a way that the helium ash can be exhausted from the edge of the plasma. For that reason, the helium ions which are introduced by the fusion reaction in the plasma center must be transported to the edge and flushed out of the machine through the vacuum pump. A possible particle and energy exhaust system called divertor is investigated in the W7-X. The divertor PFCs are positioned such that they intersect so called magnetic islands at the plasma edge. An increase of turbulence at the edge would be beneficial since it would broaden the deposition profile to heat loads that can go beyond the divertor region onto the baffles and wall panels. Other PFCs are also mounted at locations where heat loads are predicted by modeling.

1.2 Island Divertors

1.2.1 Physics concept

In tokamaks, the poloidal divertor is considered to be the most promising design concept and is used mostly in the existing axis-symmetric devices. In an ideal case, the magnetic configuration consists of nested magnetic surfaces made up by the closed field lines. In reality, small deviations of the magnetic configuration due to the error in coil geometry can cause the flux surfaces to break into chains of magnetic islands [15]. The island allows parallel flows to go radially outward away from the hot core which causes a degradation in the temperature and density gradients. These magnetic field structures are intrinsically present in most of the devices. In a stellarator, the concept of magnetic island stems from the resonant perturbations of the radial magnetic field due to 3-D coil geometry, misaligned coils, and external perturbations.

Figure 1.5: A cross-section of the fields lines is vertically sliced to show magnetic islands at W7-X and the interaction with plasma facing components. Courtesy Daniel Böckenhoff.
1 Introduction

In an island divertor concept, these islands are intentionally used to divert the field lines to separate the hot plasma in the confinement region from the material surfaces. Figure 1.5 shows a Poincare plot (a technique to visualize magnetic flux surfaces in a 3-D structure by tracing field lines and marking where they intersect the poloidal plane) where the magnetic field lines are visible if a portion of a torus is vertically sliced. The shape and position of magnetic islands vary if the magnetic configuration changes. Since the island follows central magnetic field lines with the resonant rotational transform, it appears in poloidal cross sections at different locations depending on the toroidal angle ($\varphi$) which can be seen in Figure 1.9. The radial profile of the rotational transform can be varied with different current distributions in the planar and non-planar coils. Thus the radial position of the island and the order of the resonant mode can be varied creating, e.g., five separate islands or one connected island with 4 or 6 pass through in a poloidal cross section. The projection of magnetic field lines and the interaction with the divertor and baffle components in the standard magnetic configuration at W7-X can be seen in Figure 1.6.

![Figure 1.6: Projection of magnetic field lines (magenta) in the ideal standard magnetic configuration is visualized using W7-X Field Line Tracer [16]. The ten divertors (grey) are located toroidally in each upper and lower part of each sector. The field lines intersect the divertor components which creates strike-lines (red hit points) on the divertors. The field lines and the components data is generated using the web services of W7-X.](image-url)
1.2 Island Divertors

1.2.2 Power Loads

Depending on the magnetic configuration used, the PFCs at W7-X inherently cut different areas of the magnetic island. Thus the location of heat and particles exhaust varies with magnetic configuration as well. In W7-X, the energy lost from the confined plasma region will be deposited at the island divertors which are designed to sustain up to $10 \text{MWm}^{-2}$ heat flux densities for 30 minutes. W7-X consists of five identical modules each containing two island divertor units. Depending on the expected maximum heat flux on the plasma facing components, the selection of materials (e.g., graphite, CFC, stainless steel, copper) and the design of the PFCs were adjusted. Along with the divertor modules, baffle tiles and wall panels are placed at different locations of the vessel.

The divertor units are sub-divided into four areas based on the magnetic configuration and direct contact with the plasma. The sub-divided part are referred to as horizontal divertor and vertical divertor modules, the high iota and the low iota. In case of the water-cooled divertor which is going to be installed until 2020 for the steady-state plasma operation, the target modules TM1-4h (low iota region), TM7-9h (high iota region) and TM1-3v (low iota region) are designed to sustain heat flux up to $10 \text{MWm}^{-2}$. However, the central part (TM5-6h) of the divertor where the average predicted heat load is lower than the low and high iota region is designed to sustain only $1 \text{MWm}^{-2}$.

![Diagram of divertor units](image_url)

**Figure 1.7:** The divertor unit is subdivided into low iota (with a green contour) and high iota (with a black contour) modules. The center part of the divertor which receives lower heat load is the region marked by a red contour. Courtesy Marco Krause.

A single divertor unit (horizontal modules labeled as TM1-9h, verticle modules labeled as TM1-3v) consists of 137 fingers of target elements as seen in Figure 1.8. A finger is a group of target elements assembled to form a castellated vertical block that is connected to form a target module.

W7-X is planned to run in steady state for 30 minutes; however, the machine will go through a series of prior operation phases before the plasma is sustained for a longer duration. In the early stages, W7-X is equipped with more robust
plasma facing components. The primary objective is to mitigate risks and check heat load symmetrization on the divertor. The planned operation towards steady state operation is sub-divided into four phases in total, i.e., OP1.1, OP1.2a, OP1.2b, OP2. The maximum heat load and the temperature allowed for plasma facing components during these phases is given in Table 1.2.

<table>
<thead>
<tr>
<th>Plasma facing components</th>
<th>Operation phases</th>
<th>Material</th>
<th>Max. heat flux MWm$^{-2}$</th>
<th>Max. surface temperature $^\circ$C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limiter tiles</td>
<td>OP1.1</td>
<td>Graphite</td>
<td>10</td>
<td>1800 (IE)</td>
</tr>
<tr>
<td>Test divertor unit</td>
<td>OP1.2</td>
<td>Graphite</td>
<td>10</td>
<td>1800 (IE)</td>
</tr>
<tr>
<td>HHF divertor unit</td>
<td>OP 2</td>
<td>CFC</td>
<td>10</td>
<td>1000 (AC)</td>
</tr>
<tr>
<td>Divertor central part</td>
<td>OP1.2</td>
<td>Graphite</td>
<td>1</td>
<td>500 (AC)</td>
</tr>
<tr>
<td>Baffle</td>
<td>OP1.2</td>
<td>Graphite</td>
<td>0.5</td>
<td>500 (AC)</td>
</tr>
<tr>
<td>Heat Shields</td>
<td>OP1.1</td>
<td>Graphite</td>
<td>0.35</td>
<td>500 (AC)</td>
</tr>
<tr>
<td>Wall panels</td>
<td>OP1.1</td>
<td>Stainless Steel</td>
<td>0.1</td>
<td>200 (AC)</td>
</tr>
<tr>
<td>Pumping gap panels</td>
<td>OP1.1</td>
<td>Stainless Steel</td>
<td>0.2</td>
<td>150 (AC)</td>
</tr>
</tbody>
</table>

Table 1.2: Design parameters for plasma facing components installed during different phases at different areas of W7-X. IE stands for inertially cooling and AC stands for actively cooling.
In OP1.1 and OP1.2, the machine operating conditions (primarily pulse lengths) are limited due to inertially cooled components. In OP1.2, the inertially cooled test divertor unit (TDU) is installed. The TDU has a similar geometry as the high heat flux (HHF) divertor and is used to detect any error in the symmetrization of power loads on different divertor modules. Another advantage of using the TDU is that the graphite tiles are more resistant to high heat loads as the material will ablate rather than melt or develop cracks. However, the thermal conductivity is much smaller as compared to HHF divertor which leads to much faster rise in the surface temperature and reach up to the maximum surface temperature limit (see Table 1.2). Whereas in the case of HHF divertor, defects can appear with time which can affect the performance of the divertor heat exhaust. This will be explained in detail in Section 3.2.2.
Figure 1.9: Projection of the poincare plot at different toroidal angles with respect to the position of divertor where it touches. Courtesy Daniel Böckenhoff.
2 Thermography

2.1 Infrared Thermography

To measure the surface temperature evolution of the in-vessel components inside W7-X, the absolute calibration of the infrared cameras is required to get surface temperature measurements of different components with different material properties. In this section, the development of a classical method to measure surface temperature for different components is briefly explained. In the measurement setup, the IR emission from a blackbody at room temperature is measured. The blackbody temperature was varied to estimate the dynamic range of different neutral density filters for different exposure times. To measure the homogeneous temperature distribution of the black body as well as different grey bodies present inside the vessel, a non-uniformity correction method was developed.

2.1.1 Planck’s Radiation Law

In general, everything in the environment emits radiation. The amount of radiation a body emits depends on the temperature and surface properties of the body. The spectral radiance of a given black body that absorbs all electromagnetic radiation is described by Planck’s law as mentioned in equation 2.1. Where \( \lambda \) is the wavelength of the emitted photons at particular temperature (T) of the black body, h is the Planck constant, \( k_b \) is the Boltzmann constant, c is the speed of light and \( B_\lambda \) is the spectral radiance of a body emitted at a particular wavelength \( \lambda \) at temperature T.

\[
B_\lambda(\lambda, T) = \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} \frac{2hc^2}{\lambda^5} \exp\left(\frac{hc}{\lambda k_bT}\right) - 1 d\lambda \tag{2.1}
\]

As the IR cameras measure photons, it becomes logical to measure the photon flux, i.e., the number of photons received by the IR camera sensor for each pixel. This can be obtained by dividing the spectral radiance of a black body by emitted energy of a photon \( E_\gamma \) where \( E_\gamma = hc/\lambda \). Equation 2.2 gives the spectral radiance \( \Phi_{\lambda, \text{bb}} \) and Figure 2.1 show the spectral radiance per photon energy of a black body at different wavelengths and temperatures.

\[
\Phi_{\lambda, \text{bb}}(\lambda, T) = \frac{2c}{\lambda^4} \frac{1}{\exp\left(\frac{hc}{\lambda k_bT}\right) - 1} \tag{2.2}
\]
The ratio between radiation emitted by an object (grey body) with respect to the emission of an ideal black body is called emissivity $\epsilon$. If $\epsilon$ is 1, the object is an ideal black body, and if its zero, the surface has no emission. In case of ambient temperature, the amount of energy emitted by an object and the one received by IR camera is not the same because of optical characteristics of the lens. The radiation received by the IR camera is composed of thermal exposure from the environment (stray radiation), from the internal camera radiation (electronic heating) and radiation from the object. In a realistic scenario, everything in the optical path of emitted radiation can influence the measurements of photon flux until the sensor is receiving it. The degree of the amount of radiation emitted by a surface to the one received by an object (lens, window, air) is called transmissivity $\tau$. The optical components in a diagnostic and possible medium, e.g., air have finite transmissivity and distinctive thermal emission and contributes to the total radiation received by the sensor. In case of W7-X, the line of sight passes through a vacuum, so the influence of transmissivity of the optical setup corresponds to the transmission coefficient of the optical lens.

The photon flux $\Phi_{\lambda,bb}$ of a black body received by the IR camera sensor also depends on the optical setup and pitch size (i.e. number of photons received at each node) of the sensor receiving the incoming radiation at different wavelength region. If the emissivity of each object in the optical path is considered when measuring the photon flux $\Phi_{\lambda,\text{obj}}$ emitted by a grey body, then the equation 2.2 is replaced by

$$\Phi_{\lambda,\text{obj}}(\lambda, T) = \epsilon_{\lambda,\text{obj}}(\lambda, T) \cdot \frac{2c}{\lambda^4} \cdot \frac{1}{\exp\left(\frac{hc}{\lambda k_B T}\right) - 1}.$$  (2.3)
If the influence of tranmissivity from the optical lens is integrated in measurement setup then the total measured photon flux \( \Phi_{\lambda, \text{meas}} \) can be derived as mentioned in equation 2.4 where \( O_{\lambda, T_{\text{lens}}, T_{\text{window}}} \) is the offset caused by the thermal emission of optical window in front of the measurement setup.

\[
\Phi_{\lambda, \text{meas}}(\lambda, T) = \Phi_{\lambda, \text{obj}}(\lambda, T) \cdot \tau_{\lambda, \text{lens}}(\lambda, T_{\text{lens}}) \cdot \tau_{\lambda, \text{window}}(\lambda, T_{\text{window}}) + O_{\lambda, T_{\text{lens}}, T_{\text{window}}} (2.4)
\]

\[
O_{\lambda, T_{\text{lens}}, T_{\text{window}}} = \Phi_{\lambda, \text{window}} \cdot \tau_{\lambda, \text{lens}} + \Phi_{\lambda, \text{lens}} (2.5)
\]

### 2.1.2 Non Uniformity Correction

The signal intensity recorded by an IR camera depends on the sensitivity of the sensor, quantum efficiency (number of photons converted to electrons by the sensor) and signal amplification. A graphical scheme presenting the principle of data acquisition of IR camera receiving thermal radiation from a black body can be seen in figure 2.2. The IR radiation from a black body source passes through the optical setup which adds additional ambient radiation from the environment before it reaches to the IR camera. If the camera is observing uniform radiation and a homogeneous temperature object, the number of photons received at all the pixel nodes of the sensor and the output signal derived from those photons at all nodes should be the same. In reality, this might not be the case as the influence of dark current inside the sensor, ambient temperature variation, sensor internal temperature fluctuation and discrete signal amplification error may disturb the signal characteristics obtained at the output.

![Principle of radiation conversion to digital level](image)

**Figure 2.2:** Principle of radiation conversion to digital level. The cartoon shape diagram is showing how various effects contribute to the signal received at the output in the form of digital level (DL). Courtesy Peter Drewelow

Due to the vignetting effect and image distortion by the optical setup, the edge pixel nodes of the camera sensor may not receive the same radiation level as compared to the center nodes which results in a radial gradient in the intensity level at the different location of the sensor. As seen in Figure 2.3, there appears a radial gradient
from the center of the image to its corner edges. The vertical lines in the images emerge from the amplification error caused by the sensor electronics. Even if the same photon flux is transmitted equally at each end of the sensor node, the output signal generated by the sensor controller can have an in-homogeneous behavior leading to non-uniform structures in the resulting image.

A non-uniformity correction method (NUC) was developed to transform the signals of all pixels of the image $S(i)$ to the signal of reference pixel $r$ to present a uniform signal intensity level on all pixels of an image. In case of a linear response of the sensor, the signal intensity at the output of the sensor can be generalized as

$$S(i) = g(i) \cdot \Phi(T) + o(i)$$  \hspace{1cm} (2.6)

The signal intensity for a single reference pixel normally taken from the center of the image can be derived as

$$S(r) = g(r) \cdot \Phi(T) + o(r)$$  \hspace{1cm} (2.7)

In the above case, $g(i)$ is the gain at each pixel $i$ and $o(i)$ is the offset at each pixel and defined as the correction parameters. These correction parameters are calculated by applying a two-point NUC where two (hot and cold) images of a uniform source at two different temperatures are taken.

![Image](image_url)

**Figure 2.3:** Measured hot(a) and cold(b) images taken during the calibration process from an IRCam bolometric camera. The vertical lines in the images represent the amplification behavior of the camera sensor.

From equation 2.6, we can also classify the hot and cold images mathematically as mentioned in equation 2.8 and 2.9.

$$S_h(i) = g(i) \cdot \Phi(T_h) + o(i)$$  \hspace{1cm} (2.8)

$$S_c(i) = g(i) \cdot \Phi(T_c) + o(i)$$  \hspace{1cm} (2.9)
In case of company’s provided software, the gain $g(i)$ and offset $o(i)$ derived from the hot and cold images were automatically created by the software whenever a new NUC on raw images was applied. However, to create an in-house NUC method that is not dependent on company’s software, it became necessary to acquire new cold image at run time and generate the new hot image as the company’s hot and cold images could not be used. During the calibration process, it appeared that the difference in the intensity level of reference and the new cold image is the same as compared to the difference between the reference and new hot image. In this way, only the reference hot and cold images from the company were required to create a new hot image. The new cold image is taken during the NUC process by closing the shutter of the camera. In the end, the difference of the two cold images is added to the old reference hot image to generate the new hot image. When comparing the intensity level at each pixel of the hot and cold image, the gain value relative to reference pixel $r$ can be calculated using equation 2.10.

\[
\frac{S_h(r) - S_c(r)}{S_h(i) - S_c(i)} = \frac{g(r)}{g(i)} = G_r(i)
\]  

(2.10)

Considering the amount of flux coming from the hot and cold body is uniform, the signal flux can have an additional offset at each pixel because of the camera readout offset and the thermal radiation of the optical components in the line of sight. For setting the signal intensity of all the pixels $S(i)$ from equation 2.6 corresponding to the reference pixel intensity $S(r)$ in equation 2.7, the relative pixel intensity $S_r(i)$ such that $S_r(i) = S(r)$ can be derived as mentioned in 2.11.

\[
S_r(i) = S(i) \cdot G_r(i) + O_r(i)
\]  

(2.11)

Where $O_r(i)$ is the relative offset at each pixel $i$ of an image to reference pixel $r$. Substituting the values derived from equation 2.7 and 2.11, the resulting equation is transformed into equation

\[
S(i) \cdot G_r(i) + O_r(i) = g(r) \cdot \Phi(T) + o(r)
\]  

(2.12)

After substituting the values of $G_r(i)$ and $S(i)$, the $O_r(i)$ can be derived as

\[
O_r(i) = o(r) - o(i) \cdot \frac{g(r)}{g(i)} = o(r) - o(i) \cdot G_r(i)
\]  

(2.13)

The resultant image after the NUC process is applied with respect to the relative gain and offset images as mentioned in equation 2.11. Figure 2.5(a) and 2.5(b) show one of the results obtained from non uniformity correction. The vertical lines mostly caused by amplification error are removed, and the image appears uniform. The NUC
process does not work reliably at the very corners of the image. Because of vignetting, the quality of the NUC image suffers from the poor signal to noise ratio (SNR) of the hot and cold image. Vignetting can be caused by blocking light rays that image points at the edge of the sensor or by angular dependency of the light intensity of the image point at the center and edge of the sensor. Thus the values of gain and offset in the image corners is dominated by the signal noise in the hot and cold images. That is why the values of gain and offset can be largely over or underestimated at the corners of the image.

Figure 2.4: Calculated gain and offset images derived from the hot and cold images taken during the calibration process.
2.1 Infrared Thermography

Figure 2.5: Comparative results from the non-uniformity correction (NUC) method. Figure 2.5(a) shows the object with uniform temperature received from the IRCam bolometric camera without any NUC applied to it. It is not possible to gain any information as the image is heavily distorted. Figure 2.5(b) shows the image taken after the NUC process, where the noise levels are reduced, and a uniform image is visible. Due to poor signal to noise ratio (SNR), the border edges are covered with square blocks to get better contrast in the image.
If the NUC process is applied to an image, the corners pixels are dominated with fluctuations of extreme high and low values. Thus, for a better contrast in the image, the four corners of the image are covered with boxes.

### 2.1.3 Temperature Calibration

In the process of calibrating the IR cameras, the raw data measurements were taken by installing the immersion tube and endoscope in front of a blackbody radiating source. To remove the background intensities (at ambient temperature) from the original (raw) signal, an effective signal is calculated. As the IR camera placed inside the endoscope is equipped with different neutral density filters, it needs to be calibrated with each filter independently. The measurements were taken for different filters to find the dynamic temperature range for each filter covering most of the expected exposure times up to saturation of the camera response.

![Image of temperature calibration setup](image)

**Figure 2.6**: Schematic picture of the temperature calibration setup where a hot source (black body) placed in front of the optical tube (immersion tube or endoscope) to the optical axis of the front view of the tube at distance d. The temperature measurements from the hot source were varied in the range of 25 °C to 1200 °C at different integration times.

The IRCam cameras have a limited range of exposure times from 1 µs to 9 µs whereas InfraTec cameras can have exposure times up to 0.5 µs to 18 ms. However, due to a significant interest in measuring higher temperature the exposure times used for the InfraTec cameras are mostly in the range of 25 µs to 400 µs depending on the selection of neutral density filter. In case of the IRCams camera, the full range of exposure time i.e., from 1 µs to 9 µs is used as the camera is without any filter. The selection of exposure time depends on the desired temperature range the camera is expected to measure before it reaches saturation. The exposure time can be modified if the object temperature increases from the maximum limit set for that exposure time. Figure 2.7 shows the response of the InfraTec camera sensor for different temperature measurements at multiple exposure times using the filter designed to observe temperature in the range of 200 °C to 1200 °C.

The camera sensor saturates at longer exposure times if the object temperature (e.g., the black body temperature during the calibration process) exceeds the permitted
2.1 Infrared Thermography

Figure 2.7: Raw data in the form of digital level (DL) received by the camera with respect to different integration times at different temperatures.

The measured signal flux received by the IR camera sensor is obtained by removing the background signal and its dependency on exposure time.

\[
S_{\Phi,\text{meas}} = \frac{S_{\text{raw}}(\lambda, T) - S_{\text{back}}(\lambda, T)}{t_{\text{exp}}} \quad (2.14)
\]

If the measured signal flux from the camera sensor is known, and the response of the camera is expected to be linear, a linear model can be obtained that defines a relation between the sensor response of the IR camera, i.e., the amount of signal flux received by the camera with respect to the photon flux being emitted by the black body which can be derived using Planck’s law as mentioned in equation 2.3 and can be seen in Figure 2.8.

As both IR cameras (IRCam and InfraTec) have a linear response, a linear model fit \( S(\Phi) = A \cdot \Phi_{\text{meas}}(T) + B \) is obtained where \( A \) and \( B \) are the fitting parameters defined by the signal gain and offset of the sensor. In case of the NUCed images, these are the values of the reference pixel, i.e., \( A = g(r) \) and \( B = o(r) \). The expected photon flux emitted by an object can be obtained by the inverting the linear model i.e.

\[
\Phi(S) = \frac{1}{A} \cdot S + \frac{B}{A} \quad (2.15)
\]

The expected signal response \( T(\Phi) \) is obtained by interpolating the inverted Planck’s curve for a set of temperature points in the expected range. As the entire procedure is time-consuming and not realistic for runtime processing, Look-Up tables (LUTs) for the integration times of IR cameras and emissivity of different objects are created.
2 Thermography

Figure 2.8: Linear response of different neutral density filters of InfraTec camera placed inside the endoscope. A linear regression model is created which represents measured signal flux with respect to the photon flux emitted by a black body.

offline. For run-time processing, a two-index-step method is applied where the index of each pixel in the raw image corresponds to a 3-dimensional scene model (LUT Map) index from which the run-time system fetches the emissivity of the object. For each emissivity of an object and selected integration time of the IR camera, a LUT is selected. Each LUT consists of effective digital levels (after background subtraction) corresponding to the temperature of an object with a specific emissivity defined by the material properties and located to the 2-D coordinates of the scene model. The LUT also includes the uncertainty of how much deviation in temperature is expected at that digital level. The procedure for calculating the uncertainty for each digital level is mentioned in Section 2.1.4

2.1.4 Error Propagation

To get reliable temperature information from the infrared cameras, it is essential to estimate the errors that can influence the measurements. In general, there exist two primary sources of uncertainties known as measurement uncertainty and parameter uncertainty.

2.1.4.1 Measurement Uncertainty

In an ideal measurement setup, there will be no error in the data obtained. However, in reality, no measurement apparatus is without an error. Even if the data is obtained
2.1 Infrared Thermography

several times in the same environment, the outcome may differ by some factor. The measurement uncertainty in thermographic data collection procedure may come from the fluctuations in the calibration source. In case of a black body radiator, the uncertainties arise from multiple sources such as the amplifier voltage changes inside the camera, a change in the sensor temperature during measurements, movement of the camera during calibration process, optical properties of the imaging diagnostic (in this case the immersion tube and endoscope optical setup) and ambient thermal radiation from the environment.

To understand how such effects can influence the temperature evaluation, a measurement taken at a constant temperature of a black body is analyzed. Assuming that the black body has a homogeneous distribution, the temperature measurements at different points in the hot area are assumed to be of the same value. However, there are fluctuations in the value at different positions of the hot source. These fluctuations are due to camera sensor destabilization or unstable hot source (photon noise). These variations cause the uncertainty in the measurements and are taken into consideration during data acquisition in the calibration process.

For a quantitative analysis of the mentioned effect, a set of pixels $p_1, p_2, p_3... p_n$ is defined, where $n$ is the number of pixels observing the hot source area in one frame, and is kept the same for all the frames at that temperature. A relative background area with a set of pixels for the specific temperature measurement is analyzed similarly.

For each temperature measurement, the signal fluxes $S_1, S_2, S_3.... S_N$ are calculated by averaging over the set of pixels where $N$ is the index of frames taken for each measurement. The set of mean values of the signal flux received by the camera sensor at a specific temperature and integration time is computed. The total mean values for specific measurement is calculated as mentioned in equation 2.16

$$\mu_s = \frac{S_1 + S_2 + S_3 + ....... + S_N}{N}.$$  \hspace{1cm} (2.16)

The standard deviation of the measurements can be estimated as mentioned below where $n_s$ is total number of flux values observed in all the frames and $x_k$ is the average flux value from $n$ number of pixels in each frame at the specific location in hot source area.

$$\sigma_s = \sqrt{\sum_{k=1}^{n_s} (x_k - \mu_s)^2 \over n_s - 1}.$$  \hspace{1cm} (2.17)

Considering a linear model, the mean distribution of the photon flux at different measurement levels (fixed temperature with different integration times) can be estimated as linearized approximation of 1st-order Taylor Series expansion where $m$ is the total number of measurements taken.

$$\mu_{s,i} = \sum_{i=1}^{m} (\Delta S_i \frac{\partial \mu}{\partial S_i}) = \frac{1}{m} \sum_{i=1}^{m} \Delta S_i.$$  \hspace{1cm} (2.18)
2 Thermography

The estimated uncertainty in the measurements can then be generalized as sum of squares of the average mean distribution and standard deviation of the photon flux for each measurement taken at different exposure times.

\[ m_e = \sqrt{(\mu_{s,i})^2 + (\sigma_{s,i})^2} \]  

(2.19)

2.1.4.2 Parameter Uncertainty

In general, a measurement result can only be characterized as a meaningful information if it is accompanied with its associated uncertainty. Besides the propagation of error in the measurements, the uncertainty in the results obtained can be derived from the model that is used to estimate the results. As already mentioned in Section 2.1.3, the emitted photon flux from an object can be obtained using equation (2.15). In order to include the error propagation through the parameters of the model, equation (2.15) is transformed into equation (2.20) where \( A_{\text{error}} \) and \( B_{\text{error}} \) are the parameter errors derived from the linear model.

\[ \Phi(S) = \frac{1}{A \pm A_{\text{error}}} \cdot S + \frac{B \pm B_{\text{error}}}{A \pm A_{\text{error}}} \]  

(2.20)

Estimating the propagation of error using 1st order Taylor’s expansion, the photon flux error is mentioned below where \( \Delta A \) and \( \Delta B \) are the standard error in the linear model parameters A and B which are obtained from diagonal of the covariance matrix.

\[ \Phi_{\text{err}}(S) = (-\frac{1}{A^2} \Delta A) \cdot S + \frac{1}{A^2} (B \cdot \Delta A - A \cdot \Delta B) \]  

(2.21)

The total flux including the error propagated from the linear model can be defined as

\[ \Phi_{\text{tot}}(S) = \Phi_{\text{meas}}(S) \pm \Phi_{\text{err}}(S) \]  

(2.22)

2.1.5 Heat Flux calculation for analyzing Power Loads on Divertor

To obtain the heat flux on the divertor targets, information about surface temperature, spatial calibration and the material properties are necessary requirements. If these parameters are available, the heat flux can be calculated using the heat diffusion equation [17] as mentioned below

\[ \rho c_p \frac{\partial T}{\partial t} = \kappa \nabla_{\text{surf}} T \]  

(2.23)
2.1 Infrared Thermography

where $\rho$ is the density and $c_p$ is the specific heat capacity, $\kappa$ is the thermal conductivity of the material and $T$ is surface temperature on the top of the bulk surface. The heat diffusion equation and introduction of heat flux potential $u$ is mentioned as

$$ u = \int_{T_0}^{T} \kappa(T')dT' $$  \hspace{1cm} (2.24)

From the surface temperature evolution of the material, the heat flux ($q_s$) loaded onto the material surface can be evaluated using THEODOR (THermal Energy Onto DivetOR) code [17–20].

$$ q_s = -\nabla_{\text{surf}} u $$  \hspace{1cm} (2.25)

The most common known practice for refining the heat flux calculation in the presence of surface layers is by estimating the heat transmission coefficient $\alpha_{\text{top}}$ in $\text{W m}^{-2}\text{K}^{-1}$ which is defined in eq. (2.26) as

$$ \alpha_{\text{top}} = \frac{\lambda_{\text{layer}}}{d_{\text{layer}}} $$  \hspace{1cm} (2.26)

where $\lambda_{\text{layer}}$ is the heat conductivity of the layer and $d_{\text{layer}}$ is the thickness of the layer. Further details regarding the heat transmission coefficient $\alpha_{\text{top}}$ can be found in [21]. Small values of $\alpha_{\text{top}}$ reflect weakly coupled (small $\lambda_{\text{layer}}$) or thick (large $d_{\text{layer}}$) surface layers. As the layer thickness and its conductivity are unknown parameters, $\alpha$ is estimated iteratively. Too high values of $\alpha_{\text{top}}$ usually result in overestimated heat fluxes during the plasma discharge and negative heat fluxes at the end. The actual heat flux during an experiment is not known a priori, but the iterative procedure can be constrained sufficiently by the (physically obvious) requirement that the plasma heat flux is never negative. The iteration thus follows:

$$ \alpha_{\text{top},i+1}(s) = \alpha_{\text{top},i}(s) b_i^s, $$  \hspace{1cm} (2.27)

where $b_i = 1 + b/\sqrt{i}$ reduces after each step. The free parameter $b$ (here set to 0.5) controls the convergence speed and the resilience against the numerical fluctuations. How strong $\alpha_{\text{top}}$ is adjusted in the next iteration depends on $\epsilon(s)$ as the ratio between the minimal (negative) heat flux at this point and the absolute value of the most extreme minima along a profile. As a stop criteria for the iterations, it is assumed that the residual negative minima amount to less than 1 \% of the observed maximal heat flux.

$$ \frac{|q_{\text{min-low}}|}{\max(q_{\text{max-high}}(s))} < 1\%. $$  \hspace{1cm} (2.28)
The calculations are repeated until the ratio defined in eq. (2.28) is fulfilled or the number of iterations exceeds a predefined limit. In the current state, the limit is set to 200 iterations. The iterative method to find the $\alpha_{\text{top}}$ is computationally expensive as mentioned in [21]. This feature prevents the code’s usage in real-time applications and is one of the main reasons for adapting a faster method of estimation of the layers which is discussed in Section 3.2.1. The heat flux calculation results obtained from the W7-X test divertor experiments and the comparison of $\alpha_{\text{top}}$ correction with the numerical algorithm mentioned in Section 3.2.1 will be explained in detail in Section 5.5.4.

### 2.2 Infrared Camera Diagnostic

Infrared (IR) thermography is a non-destructive, non-contact analysis technique used to observe objects in a specific IR spectrum range from 700 nm up to 1 mm depending on the technology of the detector used. However, due to the influence of the atmospheric conditions, limitations on sensor’s radiation absorption and materials to be observed having different thermal characteristics, the suitable wavelength range to measure surface temperatures from $50^\circ\text{C}$ up to $2000^\circ\text{C}$ lies between 3 µm to 15 µm. In general, due to limited spectral region of interest, most of the industrial standard IR sensors can only receive radiation in specific wavelength sub-bands which are listed below.

1. 0.7 µm to 1.4 µm in the Near-infrared region (NIR)
2. 1.4 µm to 3 µm in the Short-wavelength infrared region (SWIR)
3. 3 µm to 8 µm in the Mid-wavelength infrared region (MWIR)
4. 8 µm to 15 µm in the Long wavelength infrared region (LWIR)
5. 15 µm to 1000 µm in the Far-infrared region (FIR)

The application of thermal cameras ranges from medicine, remote sensing, safety hazards detection, and material defects analysis. Depending on the observed wavelength range and application there are several types of IR detector:

1. InSb cooled sensors working in MWIR range. These sensors detect the radiation due to a change in photoelectric current generated by the photodetectors present inside the CCD chip.
2. Microbolometer cameras working in LWIR range. Each pixel of the sensor is a resistive bolometer that measures a temperature change by the impinging radiation.
3. Pyrometers use a single node to measure thermal radiation on one line of sight only instead of using a grid of sensor pixels.
2.2 Infrared Camera Diagnostic

W7-X divertors are designed to withstand continuous heat flux densities of up to 10 MWm$^{-2}$. After reaching thermal equilibrium it will lead to a surface temperature of about 800°C. After some exposure to plasma, due to impurities deposited on the surface of the materials and defects eventually appearing at the cooling channel or in the joining layer between the CFC and the Cu inter-layer of the divertor as mentioned in detail in Sections 3.2.1 and 3.2.2, it is expected that the surface temperature of the plasma facing components (PFCs) will increase significantly. To protect them from overheating during plasma operation inside the vessel, they need to be actively monitored so that in case of fatigue damage, they can be easily identified.

The primary measurement source for monitoring the surface temperature and to perform the heat flux calculation as mentioned in Section 2.1.5 on the PFCs at W7-X are the infrared cameras placed inside an immersion tube and endoscope. The development of diagnostic for steady state operation requires a lot of efforts and time. The reason for using two different types of the IR diagnostics at W7-X is due to different demands of pulse operations conducted at W7-X. In the initial phases of operation, short plasma pulses are performed with inertially cooled test divertors installed at W7-X. Immersion tube will be installed during these plasma operation for monitoring the divertor region, baffle and wall panels. During the quasi steady state plasma discharges, water-cooled divertors will be installed.

For the long plasma pulses, the front end of the immersion will be subjected to such high heat loads and cannot be used for longer duration. For this reason, all the immersion tube will be later replaced with endoscopes. They are optimized to view the full divertor region from the low iota to high iota (Section 1.2.2) resulting in a broad angle view. They also cover part of the wall to monitor heat overloads on them. The results obtained from these diagnostics will be explained in Section 5.5.

2.2.1 Immersion Tube

For the initial campaign of W7-X test divertor, the main observation system was a so called immersion tube with a design shown in Figure 2.9. It is inserted into 9 out of 10 AEF-ports and has the the ability to hold three cameras near the inner vacuum vessel wall. A LWIR camera is placed inside an immersion tube which provides a field of view of 116° in the horizontal direction and 100° in the vertical direction with an optical resolution of the order of 5 mm to 20 mm depending on the distance and view angle on the divertor. Due to extensive optical frame window very close to the inner vessel, the window itself and the inner tube requires an air cooling to keep the electrical equipment inside the tube work in a stable condition.

One of the disadvantages of using immersion tubes is its inability to protect the optical window from the neutrons especially during the deuterium plasma operation. The neutron flux at vessel walls during deuterium operation will increase which can damage the detectors near the plasma. Also due to high erosion rate in a carbon based machine, the optical windows gets covered with the carbon containing layers from the carbon eroded in the divertor [22]. This greatly changes the transmission ratio of the optics and will decrease the visibility at the field of view.
The IRCAM Caleo 768kL bolometric camera was placed inside the immersion tube measures the infrared radiation at the wavelength range between 8 µm to 10 µm and integration times ranging from 1 µs to 9 µs. This allowed to deduce surface temperatures from 30 °C up to 5000 °C. The sensor dimensions are 1024 x 768 pixels with a pixel pitch of 17 µm x 17 µm. Each pixel of the sensor is a resistive bolometer that measures a temperature rise by the incident radiation. The IR camera can operate with a maximum frame rate of 120 Hz. Different types of pneumatic valves control a calibration shutter in front of the camera lens and the internal cooling of these cameras.

Figure 2.9: Overview of CAD design of the immersion tube observing the divertor area by visible and IR cameras behind vacuum window inside W7-X [22].

Figure 2.10: Transmission curve of zinc selenide ZnSe window used in immersion tube. (Data taken from LEWVAC Company official website https://www.lewvac.co.uk/product/vacuum-optics-extended-range-viewports/).
These IR cameras are observing the inertially cooled test divertor unit installed at W7-X during the 2017 and 2018 campaigns. A scene model representing the field of view observed from the IR camera inside the immersion tube can be seen in figure 2.11.

Figure 2.11: Scene model of Module 5 upper divertor mapped to IR observation from the immersion tube. The horizontal divertor ranges from target module 1 to 9 (TM1-9h) and the vertical divertor ranges from 1-3 (TM1-3v).

2.2.2 Endoscope

During the steady-state operation, the amount of radiation from the plasma, the neutron bombardment, the diffusive transport of plasma particles and charge exchange neutrals will result in a too harsh environment for the application of immersion tubes. For this reason, state-of-the-art high resolution and wide optical view based endoscopes are being developed. A test prototype [22, 23] of these endoscopes has been installed and operated during the test divertor unit campaign.

The endoscopes observe 5 m long and 1 m wide divertor components with a field of view of 115° in the horizontal direction and 60° in the vertical direction. The radiation coming from the divertor enters the endoscope via pinhole at the front-end of the endoscope is transmitted to the camera sensor through complex system of mirrors and lenses. The photons are directed towards the sensor via two front-end mirrors (M1, M2) onto the off-axis Cassegrain optical system (M3,M4). From the M4 mirror, the photons are passed through window W2, where they are split by the dichronic beam splitter (B1) into visible and infrared radiation and are detected by the IR and visible camera sensors (C1 and C2) [22, 23].

The M5 mirror and W1 window provides additional optical access guiding divertor radiation towards spectroscopic diagnostic. The selection of pinhole instead of a window means that a constant influx of plasma impurities will enter inside the
endoscope which will result in a slow degradation of the optical system transmission due to deposition of a:C-H layers (especially on the surface of the first mirror M1) [22, 23].

Figure 2.12: Fundamental sketch of the IR/VIS prototype endoscope. The radiation emitted by the divertor surface is entering into the endoscope via a pinhole and is directed by first two mirrors (M1,M2) onto an off-axis Cassegrain system (M3, M4). After being reflected by the M4 mirror it passes through ZnS window (W2) and dichroic beam splitter (B1). A set of refractive optics in front of the camera helps to focus rays incoming from different parts of the divertor onto the camera sensor working in the spectral range of 3 µm to 5 µm [22, 23].

Figure 2.13: Snapshot of a CAD model of the high-resolution prototype endoscope designed by Thales SESO. The blue area shows the removable front head with two mirrors, shutter and a cold aperture in green color next to the front head. The green cylindrical shape tube shows the vacuum where all the water cooling pipes, shutter rod, heating cables and thermocouples are present. The orange area show the intermediate vacuum chamber where all the water cooling and cabling interface is connected. The purple and yellow part shows the location of the holder where IR and Visible cameras are mounted [22, 23].
Nevertheless, this loss is negligible as compared to loss in transmission of a window given the same coating. A shutter is placed in front of the pinhole, which closes the pinhole directly after the discharges to reduce carbon deposition on the mirrors [24]. Due to high magnetic field environment, electric relays cannot be used for the shutter control. A piezoelectric pressure valve changes the state of the pneumatic shutter at the front end of the endoscope.

Figure 2.14: Transmission curve of zinc sulfide ZnS window used in front of the endoscope. Courtesy Marcin Jakubowski.

The InfraTec ImageIR 9300 is an actively cooled IR camera which observes in the wavelength spectrum of 3 µm to 5 µm with an indium antimonide (InSb) intrinsic semiconductor sensor and is placed at the end of the endoscope to follow the broad angle view of the divertor. The camera has an internal filter wheel with three different kinds of neutral density filters and integration time ranging from 0.5 µs to 18 000 µs. It has a sensor dimension of 1280 x 1024 pixels and pitch size of 15 µm x 15 µm. The spatial resolution of the endoscope system is 4mm/pixel with a bit depth of 15-bit. The camera can be driven with a maximum frame rate of 106 Hz with full frame and can be run at a higher frame rate if the aspect of the image is reduced.
Figure 2.15: Scene model of Module 5 lower divertor mapped to IR observation from the endoscope view. The horizontal divertor ranges from target module 1 to 9 (TM1-9h) and vertical divertor ranges from 1 to 3 (TM1-3v).
3 Detection of Defects in Plasma Facing Components

3.1 Plasma Facing Components

The Plasma Facing Components (PFCs) which are subject to maximum heat loads include divertors, wall panels, and baffles. The wall panels are mostly exposed to energetic neutrals which increase the sources of impurities inside the machine. A higher impurity density increases the plasma radiation which is one of the limiting factor for longer plasma operation. Therefore, the total amount of impurities must be controlled, in a way that no radiation collapse occurs. The predominant fraction of the energy lost from the confined plasma region will be deposited in the divertors, which can sustain up to $10 \text{MWm}^{-2}$ (values expected also for ITER and DEMO [25, 26]) steady-state heat flux densities for 30 minutes. An essential requirement in manufacturing the PFCs is their high thermal conductivity to manage the fast heat removal from the surface in contact with the plasma and their durability under dynamic temperature changes.

For the selection of plasma facing material, its high thermal conductivity for fast heat removal plays an important role. Low-Z materials, e.g., carbon fiber composite (CFC) are used to minimize the impact of impurities on the energy confinement whereas high-Z materials, e.g., tungsten (W) is used to minimize erosion that in turn reduces the overall impurity content inside the machine. However, due to its high atomic number even a small amount of W in the plasma can lead to high radiation losses and consequently to cooling of the plasma centre. For W7-X, carbon fiber composite (CFC) NB31 [27] with a three-dimensional fiber structure is used as a material for PFCs. Another reason behind the decision to use it in W7-X is its high resistance against thermal shocks and fatigue. Also, it sublimates rather than melts which leads to lower surface distortion under overload [28]. Tungsten which is more durable and has a lower sputtering rate and is already used, as PFCs in ASDEX-Upgrade [29], JET, WEST, EAST, and ITER [25]. Also, considering a fusion power plant, the amount of tritium retention by carbon is very high as compared to tungsten, which leads to a high loss of fuel degradation required for a fusion reaction. As in W7-X, CFC is used therefore the later discussion concentrates on CFC material.
3 Detection of Defects in Plasma Facing Components

3.1.1 Carbon Fiber Composite

For W7-X, two different types of geometrical shapes of PFCs were investigated in the past, i.e., monoblock and flat tiles. In case of the monoblock design, a hollow cavity is created by drilling inside the carbon fiber composite (CFC). Then the copper (Cu) interlayer and copper chromium zirconium (CuCrZr) tube are placed inside and joined together. In case of flat tile, a CFC block is joined to a CuCrZr cooling structure with an Cu interlayer by laser welding and active metal casting (AMC) [28]. The Cu interlayer (so-called bi-layer) is used to reduce stresses and strains in both the CFC area as well as the metallic section [30]. Two methods used for bonding the connection are called hot isostatic pressing (HIP) and electron beam welding (EBW). The divertor tiles used during experiments in the current research work (Section 5.3) are from the PS II type of the design with a bi-layer interface using HIP and EBW technique.

![MONOBLOCK FLAT TILE](image)

**Figure 3.1:** PFC structural design for W7-X divertor. Two different design methods named as monoblock and flat tiles design [28].

To assess the quality of the joints between the CFC and the CuCrZr heat sink and the defects that may develop over time, they were tested with heat flux in GLADIS (Section 5.1) before installing them in the machine. The test were verified using thermographic analysis [31]. One of the critical requirements for water-cooled tiles is a uniform thermal conductivity since variations of the material conductivity can obscure defects in the thermographic analysis.

In general, using smaller blocks of the CFC tiles reduces the variation of thermal conductivity however it increases financial expenses and design complexity [32]. The divertor of W7-X is subdivided, into units which are composed of about 890 PFCs covered with about 14000 flat tiles of CFC NB31. The basic design of the target elements can be seen, in Figure 3.2. Each divertor module consists of up to 250 mm to 500 mm long and 50 mm to 61.5 mm wide individual target elements covered with an on average 8 mm thick CFC top tile.
3.2 Off-Normal Events on the Plasma Facing Components

Thermographic inspection of the inner vessel of the fusion machine plays a vital role in finding thermal events which could hinder to the safety of the machine. The most important event related to the safety of the component is delamination where the de-bonding in the inter-layer occurs between the cooling structure and the bulk surface. It can appear due to high thermal stresses on the material from the high heat loads on the bulk or due to manufacturing defects during the production process. In case of increase in the delamination size at the interlayer, the heat conduction from the bulk surface to the cooling channel will reduce which in turn increases the bulk surface temperature. Delamination can lead to in-homogeneous temperature distribution on the bulk surface and eventually can lead to high thermal stress in the CuCrZr cooling block.

Some of the events like surface layers (thin deposition of impurities on the top of the bulk surface) are of minor significance as far as the safety of the machine is concerned. However, they lead to false temperature measurements which in turn overestimates the total heat flux balance inside the machine. This overestimation increases the chance of generating a false alarm to stop the machine which can become a hurdle for steady-state plasma operation.

Other events like leading edges and hotspots caused by the misalignment of the tiles and overheating due to different heating sources can also decrease the durability of the PFCs performance. These off-normal events are necessary to be detected during
the plasma operation for avoiding any fatigue damages to the PFCs for more extended plasma operations. The detailed description and numerical method to detect them in run-time are discussed below.

### 3.2.1 Surface Layers

In all magnetically confined fusion experiments, classification and detection of surface defects is in-depth investigated [34, 35]. One of the processes that emerges during the plasma operations in a carbon machine is the erosion and deposition of impurities during the interaction of plasma with the material. A surface layer is a thin layer of deposited material with poor thermal conductivity to underlying bulk material. The identification of such layers is necessary as they can lead to uncertainties in the thermographic observation and heat flux calculation. This has been observed on many carbon devices including W7-AS [35, 36]. It was observed that because of surface layers the heat fluxes were partially overestimated up to a factor of 4 during the W7-AS operation [36]. In general, surface layers include the local distribution of deposition of impurities like carbon, hydrogen, oxygen, boron or iron. When the PFCs are exposed to the plasma from the last closed flux surface, a fraction of the upper surface of the bulk material is removed, due to the erosion of the material. These eroded materials eventually settle down at other areas.

**Figure 3.3:** Principle of erosion and deposition on PFCs [21]. The plasma ions along the field lines strike the surface of the material. Due to physical and chemical effects the upper surface is eroded, and the thin layers of impurities eroded are re-deposited to the nearby area.
3.2 Off-Normal Events on the Plasma Facing Components

If the deposited material which is not entirely bonded to the bulk surface is again exposed to the plasma, it will be eroded and re-deposited again at different areas of the machine vessel. In this way, erosion and deposition of wall material is a continuous process. Due to their lower contact with the bulk surface and their reduced thermal conductivity, the area where they are present appears to be at much higher temperature than in ordinary case (without any deposited layers). During the initial campaigns of W7-X, the areas observed with such high temperatures coincided with the surface depositions (surface layers) visible on the limiters [37, 38].

Although the expected location of these impurities inside a machine can be theoretically investigated using numerical simulation tools like ERO, still these tools do not give significant information about the evolution of the deposition during each plasma discharge. One of the methods that is used in plasma wall interaction studies for determining the amount of erosion and deposition of material is by artificially coating material like tungsten or carbon on the top of screws and tiles of the divertor and other plasma facing components. The amount of material eroded and other layers developed in that area is determined from the difference between the pre and post-exposure analysis [39]. However, this method is not suitable for runtime analysis as the depositions of layers may change within each plasma discharge. The presence of surface layers on the divertor tiles in W7-AS was validated in [35, 36] by analyzing thermographic data and observing the temperature variation on the thermocouples inside the divertor. Also, some of the selected tiles were analyzed in GLADIS by applying heat loads on the tiles and observing the variation of heat pattern before and after the removal of surface layers as mentioned in [36]. This method is useful but can be applied only in post-mortem analysis.

For detecting the location of surface layers in Tore Supra Toroidal Pump Limiter (TPL) tiles (Section 1.1.1.1), Finite Element Modelling (FEM) along with real thermographic image analysis was used [7]. In principle, this concept is useful for understanding the behavior of surface layers. However, the results from this method depend on the resolution of the optical setup as it compares two tiles showing different temperature characteristic. It is important to mention that insufficient research is conducted on this topic since the classification of surface layers at runtime is a challenging work. The offline analysis related to surface layers is mentioned in [34–36], however, all of these analyses have limited information about detecting the impurity distribution in a real-time environment.

For simulating the behavior of surface layers on the W7-X PFCs, FEM simulations were conducted, by overlaying an un-connected layer on top of the bulk surface. Similar results compared to the simulation analysis conducted in Tore Supra were achieved which can be seen in Figure 3.4. A numerical method based on the normalized derivative of the temperature evolution of PFCs is proposed in [40] as.

\[
\text{norm}_{[t,T]} = \frac{\partial_t T(t)}{T(t)}
\]  (3.1)
where $T(t)$ is the surface temperature of a tile and $\partial_t T(t)$ is the partial derivative of temperature during the initial and decay phase. The norm $\|T\|$ of a surface layer will be higher during the initial rise time and decay time as compared to a surface that is without any deposition of impurities. A user-defined threshold can be used to identify those areas by comparing them with the heat flux calculation during the plasma operation inside the machine which is discussed in detail Section 5.3. For replicating the behavior of surface layers inside W7-X, specific experiments were conducted, which will be discussed later in section Section 5.5.4.

![Temperature vs Time Diagram](image)

**Figure 3.4:** Schematic of a temperature evolution at a PFC show that the apparent temperature on the area where surface layers are present increases much faster as compared to a clean surface whereas during the cooling phase, the thermal capacity of the loosely bonded thin layers is much lower than the bulk surface which is why the surface layers cool down much faster as compared to a clean surface [33].

### 3.2.2 Delaminations

Using the experience from Tore Supra as explained in Section 1.1.1.1 and Section 5.4, high heat flux tests (HHF) on the W7-X pre-series tiles were conducted at the neutral beam facility GLADIS to verify an industrial scale process for manufacturing 890 target elements that comprise the W7-X divertor.

The primary focus of the previous test campaigns was to investigate the formation of cracks and its propagation over long plasma cycling discharges. During the test trials of the target blocks, no detachment or breakage of CFC tiles occurred, however, local degradation of the bonding at the free edges of CFC tiles, was observed [30]. The assumption in the FEM analysis of having a defected/de-bonded area is based on the condition of having an open crack without a direct thermal contact. In general,
three different types of defects appearing in the CFC-Cu interlayer are mentioned in [30], by taking into consideration the thermal radiation of the CFC surface by FEM analysis using ANSYS which are as follows.

- Corner Defect: The debonding appearing at the outer corner of the CFC/AMC edge.
- Enclosed Defect: A debonding enclosed at the outer edge of the CFC tile.
- Band Defect: Complete detachment of the outer edge of the CFC tile [30].

![Figure 3.5: Cross section of CFC/Cu interlayer. Due to different thermal coefficient of CFC and CuCrZr, a Cu interlayer was necessary to improve the heat transfer and to reduce the stresses and strain at the interface [30].](image)

The simulation results were later compared, with the IR data and similar results were achieved, i.e., some of the tiles showed corner defects at the outer corner of the tiles [30, 41]. It was observed that most of the growing defects were in the CFC-Cu bonding at the edge of a tile. In case of a crack formation by overload, the maximum temperature of 475°C at the AMC-Cu interlayer will be reached within six seconds [42]. Thus, it becomes necessary to avoid any harmful defects on these blocks before the critical time is reached to protect them from further damage. These cracks appearing at the joint between the CFC and heat sink interface where the heat conductivity reduces are referred, as delaminations.

The criteria for defining defects in the tile as mentioned above proved to be very successful for detecting the delaminations at the edges of the tiles after the experiment. However, to detect the defects online (during the exposure), each part of the tile is needed to be analyzed independently. For this purpose, a numerical method was developed based on the temporal evolution of the surface temperature of the PFCs [41] and tested in real-time scenario in GLADIS [43] which will be later discussed, in Section 5.3. The numerical method is based, on the temperature decay time which was derived, from the FEM analysis [41] where artificial de-bonding was created by
removing the thermal connection between the CFC block and the cooling channel. The temperature decay time during the turn off time (removal of heat flux from the tile surface) was observed, with different areas of delaminations which can be seen in Figure 3.6. Based on the FEM results, a temperature response of the CFC tile can be mapped to an exponential function $T(t) = Te^{\frac{t}{\tau}}$ for time $t$.

As seen in Figure 3.6, the area of the delaminations in the CFC tile dramatically influences the temperature response for related applied heat flux. During the rise time, the tile with the higher thickness of delamination reaches steady state temperature much later as compared to a standard tile. Due to lower heat transfer from the bulk to the cooling channel, the areas where delaminations are present cool down much slower than in case of intact tile.

![Normalised temperature curves](image)

**Figure 3.6**: FEM simulations with different areas of delaminations. The heating was turned off at 10 secs. The transient behaviour of the delaminations is clearly visible reproduced from [40].

To describe the behavior based on the temperature decay time of the surface of the material, a so-called tau criterion [41] was introduced where $\tau$ is defined as

$$\tau = \frac{T(t)}{\partial_t T(t)} \quad (3.2)$$
The criterion defines the critical state when \( \tau > \tau_{\text{crit}} \) where \( \tau_{\text{crit}} = \tau_{\text{mean}} + 4\sigma \) was evaluated by observing behavior of the target elements under different heat loads. To remove the uncertainty, due to the off-normal behavior of the material, a 4\( \sigma \) threshold is used as seen in Figure 3.7. It is also important to mention that the presence of the surface layers on top of the tile does not influence the detection of delamination which was mentioned in [40] and can be seen in Figures 3.6 and 3.7. As the decay time of area with a surface layer (blue curve) in Figure 3.6 is much shorter as compared to areas with delamination, they are not considered as defects in the evaluation of \( \tau \) criterion.

**Figure 3.7:** The decay time \( \tau \) for the edges and center of the tile is shown. The higher \( \tau \) values in the areas with defect confirmed that the presence of the surface layers does not affect the detection of delamination. Different thickness of layers was deposited on different tiles for quantitative analysis. The image is reproduced from [40].

For avoiding the effects of transient events which can cause abrupt temperature changes, the \( \tau \) value is compared at least three consecutive times (3 frames) within the timeframe of 300 ms to 600 ms after the system detects the decline in the temperature. The reduction in the temperature indicates a decrease in heating and the start of
the cooling of the surface of the tile. A change in the evolution of $\tau$ depends on the area of the delamination. The slower the heat conduction between the bulk and the cooling block is, the higher the value of $\tau$ will be. For safety reason, the temperature of the interlayer should not exceed more than 450°C. On longer time scales, the heat conduction from CFC to the CuCrZr cooling will reduce in the delamination area which further increases the CFC surface temperature and can affect the performance of the divertor. For that reason, $\tau$ must be calculated individually for each pixel observing the part of the water-cooled components and must be fast and reliable enough to detect the delaminated areas. However, per pixel evaluation depends on the spatial resolution of the imaging system and it will be difficult to detect delamination if the resolution is lower than millimeter range. The monitoring system mentioned in Section 4.1 must provide a rapid response to the central control system to avoid more significant damage to the machine.

The mathematical definition of $\tau$ defined in [41] was developed to detect off-normal thermal events like delaminations. However, in the current thesis work, the focus of the efforts lies on significantly improving the efficiency of the parallel computing algorithm using a fast graphics processing unit (GPU), which allows us to process 100 times more data at the same time. For this reason, advance parallel computation methods were developed using GPU to increase the performance of the processing of data. The experiments at GLADIS performed in this thesis work were the first of its kind where the defects inside a material (delaminations) were successfully detected using the IR data in near real-time. The enhancement in the performance of the system made it possible to reduce the total processing time of the algorithms so that they can be used in near real-time. This will be later discussed in Section 4.1.4. Although the computational algorithm designed to detect hotspots, surface layers and delaminations was successfully implemented and tested in GLADIS, the decision for risk analysis cannot be executed based on single pixel results. For risk analysis, it is necessary to observe the data in a broader perspective e.g., by defining the critical scenario based on the size of the delamination area on the divertor tile. By applying clustering on the binary results, the size of delamination as well as evolution of the defect (size increasing with time) can be evaluated.

### 3.3 Numerical method to detect and quantify defects

In modern data manipulation techniques, clustering is the most common method for evaluation of large data sets to find common or distinct features in the data. Clustering of data is widely used for object detection, pattern recognition, segmentation, features extraction and much more [44, 45]. As the numerical method for finding defects defined in [41] provides the pixel position of the defects in the form of binary arrays [43]. The next logical step leads to search the number of defects and the size of each area of defects, i.e., the number of defected points per area of the tile/tiles which are detected by the algorithm. The addition of the clustering algorithm will reduce sending false alarms to the central discharge control system in case of evaluating
individual points separately. This modification will strongly support the primary objective of the W7-X, i.e., to run the steady state machine for continuous 30 minutes.

For this reason, a clustering algorithm was developed and tested in GLADIS (Section 5.3) based on the concept of Connected Component Labeling (CCL) where a unique identifier is given to each non-zero element on a 2D grid in a way that all the non-zero neighbors are assigned the same identifier. CCL is a fast search algorithm where a 4 or 8 point search (up, down, left, right and diagonal elements) is applied. In general, two distinct concepts used for creating component labeling are Directional propagation and Label equivalence method.

![Flow chart explaining the working principle of CCL processes. Three primary processes are conducted. Initially, each index of the image is assigned a unique label. Then the 8 point scanning process is conducted to find the minimum label among its neighbors. The scanning continues until all the new labels are found. The process terminates if no new label is found.](image)

**Figure 3.8:** Flow chart explaining the working principle of CCL processes. Three primary processes are conducted. Initially, each index of the image is assigned a unique label. Then the 8 point scanning process is conducted to find the minimum label among its neighbors. The scanning continues until all the new labels are found. The process terminates if no new label is found.
In directional propagation, the main idea is the propagation of the label with the smallest value within its neighbors. In the case of Label equivalence method, three steps defined as scanning, analysis, and labeling are implemented iteratively in a loop as can be seen in Figure 3.8. A similar method was already being developed and is mentioned, in detail in [45]. In the framework of this thesis, the CCL method and in particular label equivalence method was implemented where initially all elements of the label array are assigned index labels to their location. For each group of connected pixels where defects were detected, a minimum label value is found among all the pixels within the group. The minimum label value is then assigned to all the connected pixels within the group. In this way, all the pixels that are connected to each other are assigned, to a single label value which can be seen in Figure 3.9. The scanning and analysis steps are processed in an iterative loop until all the new labels are founds. In scanning process, the 8-directional search is conducted where the minimum label of current location and its eight connecting neighbors (up, down, left, right, diagonal elements) is assigned to the index of the reference label image. The process is continued until all the new labels are found. In the analysis, the reference labels are passed to the original label image [43].

The next step was to calculate the size of the defect for risk analysis in case of generating alarm signals, i.e., send a warning signal if the defect size is greater than n number of pixels in a cluster. The relative size of the defect is determined based on the area of observation and the spatial resolution in that region. That is why determining the safety criteria of defect size is defined based on the experience gained during the initial plasma operations. In GLADIS experiments (Section 5.3), the safety criteria was defined based on the known delaminations results and calculating the size of the each cluster of pixels connected together. The trigger signal was generated based on the known size of the maximum area of delamination on the W7-X pre-series tiles. For faster computation of the numerical method, the entire process is performed on a GPU.

Figure 3.9: The resultant binary array for surface layers, delaminations and hotspots is mapped to label array and then size of each label is calculated in GPU computing [43].
4 Image Diagnostic System (IDS) for monitoring of plasma facing components

4.1 Near Real-Time Image Diagnostic System

The plasma facing components (PFCs) installed at W7-X are monitored using infrared diagnostic system (Section 2.2.1 and Section 2.2.2) observing the divertor, baffle and wall panels. The goal of the near real-time image diagnostic system (IDS) at W7-X is to monitor PFCs with a high risk of damage due to overheating during plasma operations and provide an early feedback response to the interlock system of W7-X. The thermal events such as surface layers, delaminations, and hot spots are detected using a graphics processing unit (GPU) based on computer vision techniques. The term near real-time (NRT) in the discussion is referred to a system which is not deterministic in a sense of nano-seconds precision, however the system processes the input on the pipeline within the timescales of several milliseconds. In the future, it is planned to transfer the current system in a real-time operating system which will enhance the system ability to provide deterministic response.

4.1.1 Architecture of the Monitoring System

The NRT-IDS architecture is based on ThermaVIP SDK (an upgrade version of WOLFF software platform [46]), which is an open source C++ framework initially developed at CEA and designed to process and display data for online and offline analysis. It consists of a set of plug-in modules that are used for data acquisition and storage, data visualization of heterogeneous signals (1-D to 3-D) and offline image processing.

The framework of ThermaVIP is further developed by ThermaDIAG company in collaboration with CEA and IPP and is aimed to provide an open source framework for controlling the cameras (visible and IR) and apply image vision techniques on the camera data. The open source version of the ThermaVIP SDK is expected to be accessible by the entire fusion community [47]. The system software works at different modules. These modules are interlinked and dependent on each other to perform a task as can be seen in Figure 4.1. The framework is based on Qt library which provides the development platform. The other modules consist of a software development kit (SDK) composed of shared libraries for logging, datatype, plotting, core, and graphical
The Image Diagnostic System (IDS) for monitoring of plasma facing components

Figure 4.1: Framework of ThermaVIP imaging SDK [47]. It provides different modules for video data visualization and analysis. Additional features like ROI, 3D visualization, GUI tools can be integrated using external libraries. The abbreviation of the libraries mentioned in the Figure are explained in the text below.

The user interface (GUI). The plug-in modules (dynamic libraries) contain user-defined functionalities based on the SDK. In addition to the tools mentioned above, it provides a multi-threaded processing pipeline that uses the multi-core CPU architecture.

Using ThermaVIP plug-in modules, the NRT-IDS interacts with hardware components to communicate, process and display the status of hardware on the GUI. It also interacts at a software level to communicate with the camera drivers, perform parallel processing on graphical user interface (GPU) using compute unified device architecture (CUDA) and on central processing unit (CPU) using Qt-C++ multi-threading.
4.1 Near Real-Time Image Diagnostic System

libraries. It creates plug-in modules based on the Qt-C++ framework. In the case of IR camera diagnostic, the pipeline structure consists of a set of interconnected processes each executing in an independent thread with circular buffer in each section.

In addition to these modules, it uses open source computer vision (OpenCV) library for applying image processing algorithm that are available in the OpenCV database. For visualization of three dimensional structures, it uses visualization toolkit (VTK) which is an open source toolkit for 3D computer graphics, modelling and scientific visualization of complex structures. It uses extensible markup language (XML) on the backend when creating pre-defined region of interests (ROI) on the thermographic images as when sending the metadata on the event detection system.

4.1.2 Network Communication of NRT-IDS

The NRT-IDS observation system designed for the monitoring of PFCs is subdivided into two distinct applications. They communicate through the network in a server-client topology as seen in Figure 4.2. The system comprises ten workstations acquiring and analyzing the IR camera data. The raw and temperature data is locally stored in the hard drive and streamed to the central workstation for visualization.

**Figure 4.2:** Overview of the image diagnostic system (IDS) with ten workstations acquiring and analyzing the thermographic images [47]. The IR acquisition streams the videos and sends alarms to the interlock system. The IR cameras are controlled by a main centralized workstation using server-client topology.
The infrared cameras data acquisition and the shutter in front of the cameras are controlled from the central workstation. The raw data is later uploaded on the W7-X Archive database (ArchiveDb) which can be accessed by any user of W7-X for further analysis. The metadata required to regenerate the temperature values from the raw data is also uploaded to ArchiveDb for offline analysis.

The NRT-IDS also provides the option to load the IR data directly from the ArchiveDb for visualization of the IR data. This provides the user an option to apply the post processing algorithms using NRT-IDS software. For synchronization among diagnostics, the local trigger time event (LTTE) signals generated from the W7-X CoDaC (control, data acquisition and communication) system were used. These trigger signals are synchronized with the W7-X control safety sytem which also controls the plasma conditions inside the vessel. The trigger signals are acquired by the data acquisition board installed at each thermographic acquisition workstation (TAC). The IR data is transmitted from the electronic box installed near the optical diagnostic (immersion tube or endoscope) through a CamLink-fiber channel and is received by the frame grabber.

The data is then transferred to the thermographic display workstation (TDC) (also referred as the central workstation) for visualization of the IR images. It also displays the thermal events detected during plasma operations. The central workstation can be accessed from the W7-X control room and is used for visualizing the IR cameras data. The central workstation display all the video streams downsampled in a $9 \times 9$ image grid at a frame rate of 25 Hz. The hardware setup of NRT-IDS system can be seen in Figure 4.3.
4.1 Near Real-Time Image Diagnostic System

Figure 4.3: NRT-IDS network communication system for acquiring infrared data from the cameras. The data is first received by the data acquisition module which then sends the data to the display module for visualization.
4.1.3 Pipeline structure in acquisition and analysis

In each acquisition and analysis workstation, a series of individual processes are created and connected through a pipeline at the software level. The frame grabber acquires the IR raw data and saves it in a local hard drive. The acquisition of the data occurs continuously; however, the saving of the raw data starts only when the system receives the input trigger from the W7-X LTTE trigger module. In a parallel thread, the raw data is processed for bad pixel correction (saturated or below background level pixels), and the Non-Uniformity Correction (NUC) for creating uniform signal intensity on all the pixel locations as mentioned in Section 2.1.2 is performed.

In order to convert the raw data to temperature, a Look-up table (LUT) is selected based on the camera model, integration time, and maps neutral density filter used during acquisition. As the camera observes different objects in the field of view, LUTs of emissivity for each object is selected. Using the LUT, the raw data is converted to temperature as earlier mentioned in Section 2.1.3. The temperature data is passed to multiple modules which display, analyze and transfer the data to the central workstation as can be seen in Figure 4.4. The central workstation can control one or all the acquisition systems.

![Figure 4.4: Processing pipeline structure at the software level for the acquisition and analysis workstation [47].](image-url)
4.1.4 Performance enhancement of the system

The temperature data is analyzed by GPU using advanced computer vision techniques to detect thermal events. The difference between a GPU and a standard CPU is that the GPU is designed for parallel computation and uses more transistors for computation rather than for data management. In general, GPUs are useful when computing the same instruction on a large number of dataset. In the current state of the NRT-IDS system, Nvidia Quadro M5000 of Maxwell architecture is used to process the thermal images and extract information from the images with high throughput. The Nvidia GPU architecture is based on an array of multi-threaded streaming multiprocessors (SMs) and a global memory. The SMs process the data based on Single-Instruction Multiple Thread (SIMT) architecture to manage a significant amount of threads. When a GPU program is executed on the CPU side, the CPU invokes a grid. The grid composes of series of blocks which are distributed to SMs. Each block in the grid has many threads and a block of threads are executed concurrently on a single SM as can be seen in Figure 4.5. However, multiple thread blocks can be executed concurrently on a single SM also. Each thread performs a specific task defined by the user.

![Figure 4.5: Structure of a grid inside the GPU. Depending on the model of the GPU, a grid is composed of several streaming multiprocessors (SM). The SM executes series of thread blocks where each blocks can have multiple threads executing in parallel inside the GPU.](image-url)
The SM executes, manages and schedules a group of 32 parallel threads called warps. A thread block consists of multiple warps each composed of 32 threads. When an SM processes a thread block, the threads are partitioned in a series of warps and are executed in parallel. In the current GPU architecture, a thread block can contain up to maximum number of 1024 threads and a SM can execute a maximum of 2048 number of threads. The limitation is because of shared memory resources within all the threads. The dimension of the block can be in 1-D, 2-D or 3-D thread blocks. The compute unified device architecture (CUDA) threads can access the memory at different levels. Each thread has a dedicated local memory. A group of threads in a thread block has a shared memory accessible by all the threads in that block. All the threads in different blocks can access the global memory. The size of each memory strongly depends on the GPU model used. The technical specification of the M5000 GPU that is currently installed in the IR diagnostic workstations is mentioned below.

<table>
<thead>
<tr>
<th>Technical Parameters</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device Model</td>
<td>Quadro M5000</td>
</tr>
<tr>
<td>System Interface</td>
<td>PCI Express 3.0</td>
</tr>
<tr>
<td>Streaming Multiprocessor (SM)</td>
<td>16</td>
</tr>
<tr>
<td>GPU max Clock rate</td>
<td>1.04 GHz</td>
</tr>
<tr>
<td>CUDA Cores</td>
<td>128 Cores/SM = 2048 Cores</td>
</tr>
<tr>
<td>CUDA Capability version</td>
<td>5.2</td>
</tr>
<tr>
<td>Max no of threads per SM</td>
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</tr>
<tr>
<td>Max no of threads per block</td>
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</tr>
<tr>
<td>Max dimension size of thread block (x,y,z)</td>
<td>(1024,1024,64)</td>
</tr>
<tr>
<td>GPU Memory</td>
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</tr>
<tr>
<td>Memory bus width</td>
<td>256 bit</td>
</tr>
<tr>
<td>Memory Clock rate</td>
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</tr>
<tr>
<td>total constant memory</td>
<td>65.536 kB</td>
</tr>
<tr>
<td>total shared memory per block</td>
<td>49.152 kB</td>
</tr>
</tbody>
</table>

Table 4.1: Nvidia Quadro M5000 GPU technical specification

As the GPUs are designed for higher throughput (amount of tasks completed per unit time), the main bottleneck in their performance is the data transfer between the host (CPU) and device (GPU). In general, the GPU must always call the global memory (DRAM) for direct memory access (DMA) to pinned memory inside the CPU. However, in the older version of CUDA, the data access was through non-pinned memory (pageable). The CUDA driver initially had to copy the data from pageable memory to an internal pinned (dedicated) memory in the CPU, and then the CPU to GPU memory transfer could be invoked. In the new version of CUDA, it is possible to directly process direct memory access (DMA) by initializing the data directly in the pinned/page-locked memory by-passing the pageable memory. The direct access dramatically reduces the transfer time of large images arrays and have increased the
performance of the system to limit the total processing time within the frame rate of the camera.

As the results obtained from the thermal event detection algorithm mentioned in Section 3.2.1 and Section 3.2.2 executed in GPU are of binary format, the data-type of these arrays were set to unsigned character (8-bit uchar). Although it may sound non-critical for the performance of the system, the data-type of the result arrays significantly influence the total processing time if there is a continuous transfer of data from CPU to GPU and vice versa. As the resultant binary arrays generated from the thermal event detection algorithm are independent of each other. For faster memory transfer between host and device, asynchronous memory transfer was possible using CUDA Streams which decreased the total data transfer time.

If a critical scenario, i.e., a thermal event of higher priority is reached, a trigger alarm is sent to the interlock system. The results of the thermal event detection algorithm (hotspots) and trigger alarm are also sent to the central workstation for visualization and are mapped on the simplified scene model (Figure 2.15). After the generation of the alarm, it depends on the interlock system of what kind of action it will perform. Possible solutions to avoid any further damage to the material are
4 Image Diagnostic System (IDS) for monitoring of plasma facing components

mentioned below; however, the decision of further action is beyond the scope of this discussion.

- Strike line sweeping by a change in planar and non-planar coil currents or using trim coils and control coils.
- Reduce the heating power in order to minimize the heat load on PFCs.
- Termination of the entire experiment.
5 Experimental Analysis

5.1 Experimental Setup at GLADIS

The simulation analysis for detection of surface layers and delaminations using Finite Element Model (FEM) analysis on water-cooled divertor was conducted before the start of this work [40]. The conceptual basis for the detection of anomalies is based on the temporal evolution of the surface temperature of the tile and observing the temperature behavior during the rise and decay time before it reaches thermal equilibrium. The heat flux and the corresponding surface temperature in the simulation analysis are assumed to be in an ideal case scenario (see [40] for further information).

As an initial proof that the detection of the off-normal events is achievable during plasma operation, high heat flux (HHF) tests on early series of divertor design blocks were carried out in GLADIS (Garching Large Divertor Sample Test Facility) [48] located at IPP Garching. An advanced test facility to perform HHF quality testing on plasma facing components to validate the performance of these components in a rigid environment. GLADIS is equipped with two independent H ion beam sources. Each beam is capable of operating in the heat flux density range from about 3 MW m$^{-2}$ to 40 MW m$^{-2}$. The schematic diagram of GLADIS is presented in Figure 5.1.

![GLADIS schematic diagram](image)

**Figure 5.1:** GLADIS cross-section shows the main components inside the chamber. The ion beam source of 1 MW is pointed on the target element placed along the target plane. The part of the beam passing the target is directed towards the beam dump [48].
The tested components can be installed at target plane 1 or 2 (see Figure 5.1) depending on the heat load requirements. The target element used during the experiments was placed at an inclined angle to target plane 1. The top H ion beam source at GLADIS was used for the experiments discussed in this thesis. The results presented in Section 5.3 were taken by IR camera placed at position 2 in Figure 5.2.

**Figure 5.2:** Schematic of the position of the IR Camera observing the divertor tile inside GLADIS. IR camera was mounted on position 2 for most of the experiments in GLADIS. Position 1 was also used to check if the system can detect defects mentioned in Sections 3.2.1 and 3.2.2 with lower spatial resolution.

### 5.1.1 Hardware Setup

One of the primary goals of W7-X is to maintain a high temperature and high-density steady-state plasma for 30 minutes. In such high performance plasmas, defects could form within a few seconds in a single discharge as mentioned in [30, 41]. For this reason, a near real-time image diagnostic system (NRT-IDS) as mentioned in Section 4.1 is designed to create an early response system to provide feedback information to the W7-X central safety system (CSS). Such a case can arise if an overheating or defect appears on any of the observed PFCs installed in W7-X.
5.1 Experimental Setup at GLADIS

During the experiments at GLADIS, an IR camera from InfraTec of model ImageIR 9300 was mounted on one of the top ports of the GLADIS (see Figure 5.2) to monitor the target element. The IR camera is actively cooled at 78 K and measures radiation in the spectral wavelength range of 3 µm to 5 µm with an indium antimonide (InSb) intrinsic semiconductor sensor. The camera has internal neutral density filters and an integration time ranging from 0.5 µs to 18,000 µs. The sensor dimension of the IR camera is 1280 x 1024 pixels and a pitch size of 15 µm with a maximum frame rate of 106 Hz in full resolution. For the GLADIS experiments, the default calibration files from the manufacturer were used for the temperature calibration. The calibration configuration was set to multi-integration time (MIT) i.e. fetching 2 images with different integration times of 260 µs (for lower temperatures) and 65 µs (for higher temperatures) and combining them together. The MIT enables to cover a dynamic temperature range from 300 °C to 1500 °C. The frame rate was set to 25 Hz.

Depending on the experiment day, the camera was mounted with either a lens with 25 mm focal length or with 50 mm for higher spatial resolution. The spatial resolution achieved from IR camera and the optical lens was 4 mm/pixel with 50 mm lens, which is of the same order as expected for thermographic systems built for W7-X. A sapphire window of transmission ratio \( \tau = 0.8 \) was installed in front of the IR camera lens to filter radiations (more than 50% of the radiation above 5 µm wavelength is blocked) outside the sensors range (i.e., 3 µm to 5 µm).

![Transmission curve of the sapphire window](image)

**Figure 5.3:** Transmission curve of the sapphire window used during the experiments in GLADIS. Courtesy Bernd Böswirth.

A prototype of the hardware setup of NRT-IDS used during the experiments in GLADIS is presented in Figure 5.4. The main components of the hardware setup of NRT-IDS are

- A data acquisition module which acquires the IR data from the camera
- Graphics processing unit (GPU) for analyzing and classifying the IR data
- A data acquisition card (DAQ) for acquiring and generating trigger signals.

The IR camera data is transferred to the acquisition module through a CamLink interface via fiber optics. The data is processed in parallel and assigned to different software modules, i.e., for visualization of the surface temperature of the material to be analyzed, processing the IR data with GPU for off-normal event detection and saving the data to a drive for offline analysis.

![Diagram of Real Time Protection System](image)

**Figure 5.4:** Hardware setup of the NRT-IDS at GLADIS. The IR camera sends the raw data to the data acquisition system where it performs the parallel task of recording and analyzing the IR data. The raw data is first converted to temperature using calibration files. The temperature is fed to the GPU to detect any off-normal event visible in the IR image. If the NRT-IDS detects critical events, a trigger OUT signal was generated by NRT-IDS which was sent to GLADIS data acquisition system [43].

The IR camera sends the raw data to the data acquisition module which then generates the parallel tasks for the CPU and GPU. During the irradiation with the H beam, the GPU classifies the data when it detects any thermal event. For parallel processing, an NVIDIA Quadro GPU card was used to achieve higher performance. Trigger signals for starting the acquisition of the data and send alarms to the GLADIS were generated using a DAQ card. Trig IN signal generated by the GLADIS DAQ system was used to start acquiring frames from the IR camera. It was generated.
5.2 Preparation of Experimental Scenario

For detecting delaminations in the water-cooled divertor, a pre-damaged prototype target element (4S-032) of the early pre-series designs of the W7-X divertor was tested under different heating scenarios. More than 50 pulses with different configurations (heating power and beam focus on different locations at the divertor tiles) were conducted. The ion beam at GLADIS has a gaussian-shaped heat flux profile covering the entire surface of the material loaded [48]. The H beam focus was varied in different experiments to apply maximum heat load at a different position of the installed targets within the line of sight of the IR camera. The W7-X divertor tiles are designed to sustain steady state heat flux densities of up to 10 MWm$^{-2}$. However, it is not necessary that all the parts of the divertor get exposed to similar heat loads. For the realistic scenario of heat loads on W7-X divertor, the heating power was varied between 5, 8 and 10 MWm$^{-2}$. The divertor tiles were loaded with different heating power to test whether the same results can be achieved if the heating is reduced. Two different types of operation (constant and modulated) were used as seen in Figure 5.5.

![Figure 5.5](image)

**Figure 5.5**: Two different types of beam time trace, i.e., constant and modulated beam loading were applied. The heating power and duration of the beam loads were varied to have different temperature evolution on the target elements of the divertor. In most cases the turn-on time was set to 10 s and turn-off set to 5 s for three consecutive pulses [43].

The primary reason for using modulated heating power was to detect delaminations in HHF divertor tiles during the temperature decay time (Section 3.2.2) before the
beam starts again. If comparing it with the W7-X conditions, a similar scenario can be obtained by either modulating electron cyclotron resonance heating (ECRH) power or by shifting the strike-line away from the investigated area (e.g., delamination, leading edges). The position of the strike-line can be moved using magnetic coils installed at W7-X (Section 1.1.2.1). The beam focus on the W7-X target element was also varied between tiles labeled as 4, 6 and 8 (see Figure 5.7(a)) to identify the location of the defects with direct and indirect beam focus on the damaged tiles.

In the current research work, a decision was made to use the W7-X divertor pre-series (4S-032) tiles which were mounted on target plane 1 with position 2 in Figure 5.2. A visible camera observing the divertor tiles was also mounted at a different location to take images as shown in Figure 5.6.

![Figure 5.6: Visible camera image observing the W7-X divertor pre-series tile (4S-032) inside GLADIS. The H\(^+\) beam in this case is focused on tile 4 from right at GLADIS as can be seen from the red color laser spot.](image)

Several interface defects were already detected in these tiles during the qualification experiments [40]. The information of known defects was beneficial during experiments as it was used to compare the results obtained from the numerical algorithm mentioned in Section 3.2.2. It is important to mention that some offline analysis was also conducted before the start of the work [40] which provided the basic concept for using temperature decay time as mentioned in Section 3.2.2 for finding internal material defects [40].

For surface layers detection, CFC blocks of Wendelstein 7-AS divertor similar to those discussed in [35, 36] were used to test the algorithm created to detect surface layers. The surface layers were composed of re-deposited materials, e.g., carbon, boron, oxygen or iron developed during the experiments conducted in W7-AS. Their surface was contaminated with deposits coming from plasma. These were mostly amorphous hydrocarbons, but also metallic coatings were present. These blocks served as proxy for surface layer coatings at W7-X. For testing the sensitivity of the imaging system, the modulation time during the experiments on the W7-AS inertially cooled tiles was changed to 500 ms.

In the current framework of the thesis, the primary focus of experiments in GLADIS was to test the near real-time analysis system that the material defects can be detected in near real-time using high-performance parallel computation.
5.3 Experimental Results

Using the NRT-IDS (Section 4.1), the IR data observing the divertor tiles was live streamed on the monitor screen during the experiments. The NRT-IDS system shows five independent binary output matrices with information on detected

- Surface layers
- Delaminations
- Hotspots
- Output of the CCL algorithm
- Size of the corresponding defects selected for the CCL output

The size of the clusters was compared to a threshold value defined by the user.

5.3.1 Detection of Delamination

The analysis mentioned below were conducted with the input power of the heating beam at either 8 MWm$^{-2}$ or 10 MWm$^{-2}$. As discussed in Section 5.2, intact and delamination tiles were exposed for 10 seconds to a heating beam. The test of the algorithm was performed in the cooling phase after 10.5 seconds from the beginning of the exposure. An example representing surface temperature on divertor tiles during and after the heating cycle is presented in Figure 5.7.

![Thermal image of surface temperature](image)

**Figure 5.7**: Thermal image of surface temperature on one of the W7-X pre-series (4S-032) divertor target elements tested in GLADIS. The rest of the tiles (1, 7, 8, 9 and 10) in Figure 5.7(b) are not visible because of lower heating. The black lines are used for marking the center and edges of the tile where the surface temperature is maximum.
5 Experimental Analysis

Figure 5.7(a) shows the surface temperature of the CFC tiles during the beam injection at 8.6 seconds with a heat load of up to 10 MW/m$^2$. Figure 5.7(b) shows the surface temperature 2.88 seconds after the beam was turned off. The parts of tile with defects show a higher temperature as compared to a normal area. The beam focus was adjusted to tile number 4 in Figure 5.7(a). The input power was set to 10 MWm$^{-2}$ with modulation sequence of 10:3 (on:off) seconds (see Section 5.2). The black lines numbered from tile 2 to 6 in Figure 5.7(a) and Figure 5.7(b) are used for analyzing temperature evolution and marking the areas where the surface temperature is maximum. The maximum temperature on the edges of the tiles reaches up to 1800 C° in the areas where delamination is formed. When the beam is switched off, the surface area at the edge of the tiles 3, 4 and 5 in Figure 5.7(b) has a higher temperature continuously as compared to the neighboring tiles 2 and 6 which are without any defects.

An example of temperature evolution on tile 5 and 6 during the cooling phase is shown in Figure 5.8. The blue curve shows the surface temperature, temperature decay time ($\tau$) and time derivative values on the top edge of delaminated tile 5. The green curve shows the same values on the top edge of intact tile 6. The $\tau$ values on the delamination area on tile 5 is much higher than the intact tile 6.

![Surface temperature and time derivative values on tile 5 and 6. The temperature of the delaminated part of tile 5 (blue) decreases slower due to weaker heat transport between the CFC and heat sink (CuCrZr).](image)

Figure 5.8: Surface temperature and time derivative values on tile 5 and 6. The temperature of the delaminated part of tile 5 (blue) decreases slower due to weaker heat transport between the CFC and heat sink (CuCrZr).

The relation between the time derivative and decay time as mentioned in equation (3.2) has to be taken into consideration as the entire analysis of the experiments depends on the proper evaluation of these quantities. The decay time $\tau$ indicates how efficient the cooling rate is or in simple terms how much time it takes for a tile to cool down. The higher the derivative values are, the faster the tile will cool down and vice versa. However, if the difference in the temperature between the delamination and intact area at a specific time is large, then the $\tau$ is dominated by the temperature
5.3 Experimental Results

difference. The temperature on tile 5 (blue curve in Figure 5.8) reduces much slower which can also be visually seen in Figure 5.7(b). As expected, the temperature decay time $\tau$ values in a delamination area on tile 5 are higher as compared to intact surface on tile 6 as seen in Figure 5.8. This indicates a slower cooling of the surface. The reason for such kind of behavior is because temperature decay depends on the cooling power either by radiation and heat conduction from tile top to bottom. If there is a delamination, the heat conduction drops which means that the temperature difference from top to bottom increases. Since the temperature difference between the delamination area and intact area is large, that is why the effect of the derivative has lower precedence on the $\tau$ values.

For quantitative analysis, a comparison of $\tau$ values for the delamination and intact area is performed in Figure 5.9. It shows $\tau$ versus surface temperature of delaminated and intact tile. A clear difference can be seen in $\tau$ values at temperatures higher than 600 $\degree$C in the performed experiment.

![Figure 5.9: Comparison of $\tau$ values with respect to surface temperature on delamination area on tile 5 and intact area on tile 6.](image)

A similar comparison is made between temperature versus time derivatives during the cooling phase (see Figure 5.10). In comparison to the intact tile the time derivative of the surface temperature for the delaminated tile is significantly lower as compared to a delaminated part for the temperatures above 800 $\degree$C. This is due to the fact that at higher temperatures, the radiation power dominates and the cooling efficiency of both intact tile and delaminated tile is reduced. At intermediate temperatures apparently, the cooling efficiency of the intact tile dominates and that is why it cools down much faster as compared to the delaminated tile. The missing thermal conduction in the delaminated tile causes a lower cooling and thus a lower derivative value.

It is important to mention that the behavior of $\tau$ with respect to temperature is also dependent on the applied heat load. The temperature range in which $\tau$ is
5 Experimental Analysis

**Figure 5.10:** Comparison of derivative values with respect to surface temperature on delamination area on tile 5 and intact area on tile 6.

Distinctly different between an intact and a delaminated tile shift towards lower temperatures and narrows down. This feature can be seen in Figure 5.11 where a comparison is made between the behavior of \( \tau \) with respect to temperature values when two different kinds of input power of 8 MWm\(^{-2}\) and 10 MWm\(^{-2}\) are applied. This will also depend on the size of the delamination, i.e., for larger delaminations the difference may also appear at lower temperatures. As shown further, this will also depend on the initial temperature.

**Figure 5.11:** Comparison of \( \tau \) values with respect to surface temperature on delamination area on tile 5 and intact area on tile 6 with different input power of 8 MWm\(^{-2}\) and 10 MWm\(^{-2}\).
5.3 Experimental Results

In the case of 8 MWm$^{-2}$ input power, the temperature range for comparing the $\tau$ value is reduced as the initial temperature from the start of cooling to 900°C. Still, it is marginally possible to differentiate the delamination and intact area within the limited temperature range. However, if the input power is further reduced, then it is not possible to detect precisely the areas where the delaminations are present. A black horizontal line shows the threshold value used in the detection of delamination during the experiments in GLADIS.

For automatic detection of the delamination on the thermal images, the measured surface temperature is processed through the image processing algorithm described in (Section 3.2.2). The algorithm is applied in the GPU which results in generating binary output array with the information of the position of delamination areas in a thermal image. The parameters used in the GPU algorithm are mentioned in Table 5.1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer heating threshold</td>
<td>10</td>
</tr>
<tr>
<td>Layer cooling threshold</td>
<td>-10</td>
</tr>
<tr>
<td>Minimum Temperature for IR observation</td>
<td>350°C</td>
</tr>
<tr>
<td>Delamination Threshold</td>
<td>2.3</td>
</tr>
<tr>
<td>Hotspots Threshold</td>
<td>1000°C</td>
</tr>
<tr>
<td>Safety Criteria for Cluster Value</td>
<td>1500 pixels</td>
</tr>
<tr>
<td>Heating State threshold</td>
<td>1.15</td>
</tr>
<tr>
<td>Cooling State threshold</td>
<td>-0.35</td>
</tr>
</tbody>
</table>

Table 5.1: Parameter values used in the algorithm mentioned in Sections 3.2.1 and 3.2.2 for detecting off-normal events like surface layers, delaminations and hot spots due to overheating. The purpose of these parameters is explained in the text below.

The values were kept fixed for all the GLADIS experiments. Heating and Cooling State values of the normalized derivative ($\text{norm}_{[t, T]}$) are used to detect the start of rising or fall of temperature. Layer Heating and Cooling thresholds of $\text{norm}_{[t, T]}$ are used for detecting surface layers during rising and fall of temperature. A minimum temperature threshold is required to remove any effect of noise level inside the image. Also, the temperature range for the camera calibration used during experiments was in the range of 300°C to 1500°C and temperature values below 300°C were cut off from the analysis. The hotspot temperature threshold was set to 1000°C and was detected only in the areas which were neither surface layers nor delamination but still had a surface temperature higher than 1000°C. The cluster value for the safety criteria is used to determine whether a trigger signal must be generated if the cluster value exceeds the threshold of 1500 pixels.

The GPU results processed for data presented in Figure 5.7 can be seen in Figure 5.12, where detected delaminations are marked in yellow in Figure 5.12(a). As the result shown in Figure 5.12(a) is binary, a data type of uchar (8-bit) was used to save
the data to reduce the memory transfer time. The delaminations results obtained from the GPU are then further processed to label index of each cluster of pixels to determine the size of the defects. The size of the cluster also helps in determining the evolution of the damaged area with time. Figure 5.12(b) shows the labeling results obtained from the method introduced in Section 3.3. Two large clusters formed on the tiles 4 and 5 are visible in green and brown color in Figure 5.12(b). The colors represent the label index value assigned to the cluster of pixels connected. The index values shown in Figure 5.12(b) are normalized for better visualization. The method of assigning index labels to each pixel and calculating the size of each cluster is explained in detail in Section 3.3.

Figure 5.12: Output arrays obtained from the algorithm applied on GPU. Figure 5.12(a) show the delaminations detected (255 value = delamination , 0 = not found) after the pulse ended. Figure 5.12(b) show Label image where colors in green and brown represent the cluster of delaminations areas of tile 3, 4 and 5. The numbers on the label image show the minimum label value assigned to each pixel in a cluster.

The beam focus was then changed to tile 6 to see whether the delamination in tile 5 is still visible if the magnitude of the heat flux changes. The surface temperature of the tiles can be seen in Figure 5.13(a) after 8.6 seconds of the beam turned on. Similar behavior of the delamination can be seen in Figure 5.13(b) during the cooling phase of the tiles after 2.88 seconds when the beam turned off. The area where delaminations are present appears at a higher temperature as compared to intact tiles. A new area of the delamination is visible as compared to Figure 5.7(b). Along with the large defect visible on tile 5, delamination is also detected on tile 7 which can be seen in Figure 5.14(a). The detection of a new delamination area on tile 7 with a change of beam focus is because the magnitude of the heat flux on tile 7 in the first case (10 MWm$^{-2}$ heat load with beam focus on tile 4) was less than 8 MWm$^{-2}$. With such
low heat flux, the surface temperature on tile 7 is not high enough and temperature decay time (τ) values lie below the threshold value mentioned in Table 5.1.

![Figure 5.13: False color image of surface temperature on W7-X divertor target elements tested in GLADIS. The beam was focused on tile 6 [43].](image1)

![Figure 5.14: Output arrays obtained from the algorithm applied on GPU. Figure 5.14(a) show the delaminations detected (255 value = delamination, 0 = not found) after the pulse ended. Figure 5.14(b) show Label image where different colors represent different clusters on tile 5 and 7. The numbers on the label image show the minimum label value assigned to each pixel in a cluster [43].](image2)

Whereas in the 2nd case (10 MWm$^{-2}$ heat load with beam focus on tile 6), the surface temperature on tile 7 is hot enough because of the high heat flux of 10 MWm$^{-2}$. That is why it was possible to identify the delamination on the edges of tile 7.
5 Experimental Analysis

The last change in the experiments in GLADIS was to align the beam focus to tile 8 and see a similar pattern appears if the magnitude of the heat flux is reduced. The surface temperature on the tiles during the rise and cooling phase can be seen in Figure 5.15(a) and Figure 5.15(b).

![Surface Temperature](image)

**Figure 5.15:** False color image of surface temperature on W7-X divertor target elements tested in GLADIS. The beam was focused on tile 8.

![Delaminations](image)

**Figure 5.16:** Binary output arrays obtained from the algorithm applied on GPU. Figure 5.16(a) show the delaminations detected (255 value = delamination, 0 = not found) on different tiles of divertor after the pulse ended. Figure 5.16(b) show Label image where colors in green and brown represent the large clusters of delaminations on tile 5, 7 and 8. The numbers on the label image show the minimum label value assigned to each pixel in a cluster.
5.3 Experimental Results

As expected, the number of perceived defected pixels on tile 5 reduces due to lower heat flux as seen in Figure 5.16(a) where the top edge delamination on tile 5 is not detectable anymore. Small edge defects are also visible on tile 10.

For quantitative analysis, the size of the largest cluster of defect on individual tiles in all the scenarios mentioned above was compared with an input power of $8 \text{ MWm}^{-2}$ and $10 \text{ MWm}^{-2}$. The difference in the size of the delamination on different tiles in both cases of input power can be seen in Table 5.2. In case of lower heat flux of $8 \text{ MWm}^{-2}$, the delaminations in the bottom edge on tile 5 and 8 are not visible. This feature must be considered in the future development of the system when operating inside W7-X.

<table>
<thead>
<tr>
<th>Beam Focus on Tile</th>
<th>$P_{in}$ $\text{MWm}^{-2}$</th>
<th>Max Delamination Label size</th>
<th>Tile 4</th>
<th>Tile 5</th>
<th>Tile 6</th>
<th>Tile 7</th>
<th>Tile 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>8</td>
<td>N.D</td>
<td>355TE, 301BE</td>
<td>N.D</td>
<td>N.D</td>
<td>N.D</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>con5</td>
<td>430TE, 368BE</td>
<td>N.D</td>
<td>81BE</td>
<td>N.D</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>8</td>
<td>N.D</td>
<td>265TE, 106BE</td>
<td>N.D</td>
<td>96BE</td>
<td>N.D</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>N.D</td>
<td>348T, 322B</td>
<td>N.D</td>
<td>50TE, 185BE</td>
<td>N.D</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>N.D</td>
<td>N.D</td>
<td>N.D</td>
<td>65BE</td>
<td>N.D</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td>N.D</td>
<td>62BE</td>
<td>N.D</td>
<td>281TE, 530BE</td>
<td>con7</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.2: Quantitative analysis of the delamination results after applying the CCL algorithm. The table shows the number of pixels within the maximum cluster size when the input power was $8 \text{ MWm}^{-2}$ and $10 \text{ MWm}^{-2}$ respectively. N.D means no detection of delamination. TE means the top edge of the tile and BE means bottom edge of the tile. con5 means delamination detected but cluster connected with tile5. con7 means delamination detected but cluster connected with tile7.

In this way, multiple delamination areas were detected on multiple tiles of the W7-X pre-series (4S-032) divertor tiles. The small difference in the delamination area was visible when applying a constant or modulated beam sequence. However, a clear difference can be identified by the size of the delamination area when applying the higher or lower input power on the divertor tiles.

5.3.2 Detection of Surface layers

Surface layers are formed by poorly attached thin (a few microns) layers of hydrocarbons on the surface of PFCs due to erosion and redeposition of the carbon together with hydrogen. Although they are not posing any danger to the machine, they lead to false surface temperature measurements by thermography and would trigger false positive alarms. Therefore, a prerequisite for steady-state operation in fusion devices with water-cooled carbon PFCs is to detect these surface layers and apply corrections.
regularly. After testing the NRT-IDS for detecting delamination on W7-X pre-series divertor tiles, the next experiment conducted in GLADIS was to detect surface layers on W7-AS divertor tiles. As mentioned in Section 5.2, W7-AS divertor tiles were used to provide realistic conditions for the detection of surface layers. After the visual inspection of the W7-AS divertor modules, three tiles labeled as 5, 12, and 13 with maximum deposition were selected (see Figure 5.17). All three tiles showed a significant amount of surface layers.

Visual observation showed a distinct color pattern on the tiles which developed because of deposition from different sources of impurities. Such layers consisting of carbon, iron, boron, and oxygen were formed during the W7-AS operation. For further details on deposits on W7-AS PFCs see [35, 36]. In order to test the detection of the surface layers by NRT-IDS, a modulated pulse sequence of 10 MWm\(^{-2}\) was applied. The maximum surface temperature on the W7-AS tiles was up to 1400 °C. As the tiles were inertially cooled, the beam had to be longer paused such that the tiles reach a state of thermal equilibrium.

Figure 5.17: W7-AS divertor target elements. The numbers indicate the tiles position on the entire divertor module. The ROIs show the areas where major surface layers are present [43].

The result of the algorithm for detection of surface layers in the form of binary output array is presented in Figure 5.18(b). The surface layers were detected on all the tiles and are marked in yellow color in Figure 5.18(b). ROIs in red and blue in Figure 5.18(b) represents the areas with expected deposition of surface layers visible in Figure 5.17. The successful detection of surface layers on W7-AS tile was used as a
5.4 Bench-marking with Tore Supra Limiter configuration

In order to test the algorithms with the water-cooled PFCs, several discharges from Tore Supra were analyzed. The thermographic data of Tore Supra (TS) looking at the Toroidal Pump Limiter (TPL) (Section 1.1.1.1) was used for the analysis. The TPL is composed of 6 mm thick CFC tiles assembled on CuCrZr actively cooled body (thus based on the similar technology as foreseen for the W7-X divertor modules). The TS-IR endoscopes used two IR cameras with a spectral wavelength range of 3 µm to 5 µm. It allowed the observation of three regions, i.e., two sections of the TPL located at the bottom of the machine and one at the ICRH antenna [49]. The spatial resolution on the TPL was between 7 mm to 10 mm in the center and outer

Figure 5.18: False color image of the W7-AS divertor target element [43]. Figure 5.18(a) shows the surface temperature on the CFC tiles during the heat loading. Figure 5.18(b) shows the surface layers detected (255 = during rise, 122 = during rise and decay, 64 = during decay and 0 = not found) by the system [43].

The results obtained from GLADIS experiments were the first successful attempt to detect surface layers and delaminations in near real-time. These results will contribute in the future as a reference for algorithms looking for overheated areas inside the W7-X during the steady-state plasma operation.
part of the image respectively. For a standard TS plasma discharge scenario (1.5 MW injected power, 1 MA plasma current), healthy PFCs located in a net erosion area (with no surface layer) have steady state surface temperatures of around 350°C. The discharge scenarios which were used to analyze the TS data are mentioned below in Table 5.3. The plasma pulse #37931 was taken before the cleaning of the limiter and pulse #41616 was taken after the cleaning with similar heating conditions.

<table>
<thead>
<tr>
<th>Plasma Pulse #</th>
<th>Plasma Current Ip</th>
<th>Total Power P_{\text{tot}}</th>
<th>Low Hybrid Power P_{\text{LH}}</th>
<th>Radiated Power P_{\text{rad}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>37931</td>
<td>1 MA</td>
<td>1.5 MW</td>
<td>1 MW</td>
<td>0.65 MW</td>
</tr>
<tr>
<td>41616</td>
<td>1 MA</td>
<td>1.5 MW</td>
<td>1 MW</td>
<td>0.5 MW</td>
</tr>
</tbody>
</table>

**Table 5.3:** Quantitative analysis of the delamination results after applying CCL algorithm. The table shows the number of pixels within the maximum cluster size when input power was 8 MW m^{-2} and 10 MW m^{-2}.

In case of plasma pulse #37931, the part of the limiter with surface layers located mainly at the periphery of the erosion areas shows higher surface temperatures of more than 750°C as seen in Figure 5.19.

![Figure 5.19: Surface temperature evolution of two different areas of TPL as shown in Figure 5.21. The blue curve shows the maximum temperature on the areas where surface layers are present. The green curve shows the area where no surface layers are present [33].](image)

The norm_{t, T} (Section 3.2.1) value on the areas where surface layers are present is higher during the initial temperature rise as compared to a normal surface area which can be seen in Figure 5.20. For TS-IR data analysis, the user-defined threshold of norm_{t, T} defined as layer heating and cooling in Table 5.1 for the areas with surface layers was set to a value of 7 with minimum temperature threshold of 180°C.
5.4 Bench-marking with Tore Supra Limiter configuration

Figure 5.20: \( \text{norm}[t, T] \) for areas where the surface layers are expected shown in the blue and normal surface in green. During the rise time, the \( \text{norm}[t, T] \) where surface layers are expected to be present is considerably higher as compared to the normal surface [33].

Figure 5.21: Surface Temperature on the Tore Supra limiter [33] visible from an IR image at 11.8 seconds. The part of the limiter with surface layers show higher temperature (red) as compared to a normal surface (light blue). The image is created by combining images from different field of views to overview the heating pattern on the larger area of the limiter. An IR image from one of the field of view is shown in Figure 5.23(a) and Figure 5.24(a).

The two ROIs used to extract the temperature evolution in Figure 5.19 of the limiter tiles are shown in Figure 5.21. The result of the surface layer detection algorithm from TS data can be seen in Figure 5.22(a). After detecting surface layers, the labeling
algorithm was applied. Different clusters of surface layers on different locations on the limiter are visible in Figure 5.22(b).

![Figure 5.22: Results from TS where Figure 5.22(a) show the surface layers detected (255 = during rise, 122 = during rise and decay, 64 = during decay and 0 = not found) by the algorithm [33]. Figure 5.22(b) shows the Label image where colors represent the clusters of surface layers on limiter tiles. The numbers on the label image show the minimum label value assigned to each pixel in a cluster.](image)

In order to test the algorithm before and after the cleaning of the Tore Supra limiter, two discharges mentioned in Table 5.3 are compared. In this case, surface temperature from high-resolution IR camera (see Figure 5.23(a)) focusing on a small area of limiter was analyzed.

![Figure 5.23: Tore Supra plasma discharges #37931 where the thermal image in Figure 5.23(a) was taken before the cleaning of the limiter tiles. Figure 5.23(b) show the surface layers detected (255 = during rise, 122 = during rise and decay, 64 = during decay and 0 = not found) by the algorithm. The field of view is the same as in Figure 5.21](image)

A significant change in the surface layers results can be seen in Figure 5.24(b) where the algorithm was able to detect only a very small area of surface layers. Even though
the tiles were cleaned up, still some amount of surface layers may have been stuck to some of the tiles which were detected by the algorithm. The surface layers detected by the algorithm show good agreement with visual inspection and previous IR data analysis [7, 34]. These observations prove the successful detection of surface layers inside a nuclear fusion experiment using the algorithm mentioned in Section 3.2.1.

Figure 5.24: Tore Supra plasma discharges #41616 where the thermal image in Figure 5.24(a) was taken after the cleaning of the limiter tiles. Figure 5.24(b) show the surface layers detected (255 = during rise, 122 = during rise and decay, 64 = during decay and 0 = not found) by the algorithm. The field of view is the same as in Figure 5.21.

5.5 Infrared Analyses at Wendelstein 7-X

The main aim of the IR analysis at W7-X is to measure and quantify power loads on the divertor. Therefore, in the 2017-18 campaign, inertially cooled test divertors (TDU) in each module (ten in total) were monitored by the infrared system.

5.5.1 IR System

The micro-bolometric cameras are installed inside the immersion tubes (see Section 2.2.1) and besides the divertor allowed to observe the part of the inner wall and baffles. Additionally, one of the prototype endoscopes (see Section 2.2.2) equipped with an IR camera (InSb semiconductor chip) was also placed in AEF50 port in module 5. The surface temperature on the divertor was deduced using the calibration method defined in Section 2.1.3. An example of an infrared view overlaid on a computer-aided design (CAD) model is shown in Figure 5.25. Main PFCs visible in the image are mentioned as:

- Low iota horizontal divertor (TM1-4h) is highlighted with orange.
- Low iota vertical divertor (TM1-3v) is highlighted with red.
5 Experimental Analysis

- Center horizontal divertor (TM5-6h) as well as baffle tiles are highlighted with yellow.
- High iota horizontal divertor (TM7-9h) is highlighted with brown.

The two elongated strike lines (one on horizontal and one on vertical divertor) originating from intersecting magnetic islands can be seen in Figure 5.25. Depending on the magnetic configuration used at W7-X, the shape and position of the strike line can appear at different parts in the divertor. However, in the majority of the plasma discharges the magnetic islands intersect the low iota part of the divertor (i.e., TM1-4h and TM1-3v).

Figure 5.25: Thermographic data from the IR camera placed at the end of the endoscope (see Section 2.2.2). The image is overlayed on the scene model to map the positions of the hot areas relative to W7-X geometry [33].

5.5.2 Leading edges on W7-X divertor

The leading edges appear due to misalignment between two target elements such that a step in height between the elements leads to a higher heat load on one of the target element as can be seen in Figure 5.26. Because of the various step heights at different positions of the divertor finger, some of the leading edges are loaded with higher heat loads as compared to the surrounding target surface. One of the reasons to use the TDU instead of the HHF divertor for the 2017-18 campaign is to identify the locations where leading edges cause higher erosion rate and power loads and fix them.
before installation of the HHF divertor for the steady state campaigns. However, the correction of leading edges is of limited scope as the location of leading edges will vary with each installation of PFCs and can still appear even after installing the HHF divertor.

Figure 5.26: Target elements with and without a step which causes leading edges when exposed to heat flux from the plasma along the magnetic field lines.

Due to different step heights on different fingers of the divertor module, the heating pattern changes along the divertor tiles. At some locations, the difference in the step height between modules was also measured. The hotspot areas on the horizontal divertor (low iota region) due to leading edges can be seen in Figure 5.27. Different steps were measured after the end of experiments in 2017 when an in-vessel inspection was performed.

Figure 5.27: IR image overlayed on the scene model of lower divertor in module 3. The numbers in green show the step height between the adjacent fingers. The step heights are taken from personal communication with Micheal Endler.

The location of the different steps was based on the manual measurement of the steps inside the vessel and the IR data observing the divertor region as shown in Figure 5.27. During the experiments in 2017, the surface temperature on the TDU exceeded more than 1000°C at the areas of leading edges. One of the examples is
shown in Figure 5.28 where hotspots appeared on the low iota part of the lower divertor in module 2. These leading edges serve as a good proxy for future hot spot analysis.

Figure 5.28: Surface temperature on the lower divertor in module 2. Some part of the low iota region of the divertor was overloaded with high heat loads leading to surface temperatures of more than 1000 °C in plasma discharge 20171207.039.

The hotspot detection system was able to detect high-temperature areas as seen in Figure 5.29. The yellow color on the low iota region in Figure 5.29 shows the hotspots areas of temperature higher than 1000 °C detected by the GPU.
5.5.3 Erosion and Deposition analysis at W7-X

In the 2017-18 plasma campaign at W7-X, different magnetic configurations were used. Each magnetic configuration generates a different island structure which in turn changes the strike line pattern and the area under load on the divertor. Different strike line patterns create different erosion and deposition patterns on the divertor area which can be seen in Figure 5.30. The darker areas show erosion of the carbon surface and a grey area shows deposition of different materials on the PFCs. However, determining the presence of erosion and deposition using the visible images may lead to uncertainties as the color in the image may change with the angle at which the image is taken.

![Erosion and Deposition Pattern](image)

**Figure 5.30:** Erosion and deposition pattern on the W7-X TDU fingers. Due to different magnetic field configurations, different deposition patterns were visible on the divertor.

More detailed analysis will be conducted in future to determine the location of erosion and deposition areas on the divertor fingers. The deposition of impurities on the surface of the PFCs leads to false temperature measurements from the IR diagnostic. Two different numerical algorithms mentioned in Sections 2.1.5 and 3.2.1 are used to detect surface layers. The numerical method based on the threshold criteria of norm$[t, T]$ to detect surface layers (as used in Section 5.3.2 and Section 5.4) is compared with the iterative method of heat transmission coefficient $\alpha_{\text{top}}$ values obtained from the heat flux calculation.

For the heat flux calculation on the W7-X divertor, THEODOR code (Section 2.1.5) was used. It uses one-dimensional temperature profiles evolving in time to calculate the heat flux onto the divertor. Line profiles i.e., 15 lines per each finger (as seen in Figure 1.8) were extracted from the thermal images. The values from the profiles
are extracted from IR image using bi-linear interpolation of the corresponding pixel value. Around 2055 line profiles were used to calculate the heat flux information per each divertor. An example of the heat flux on one of the lower divertor is presented in Figure 5.31. As the heat flux was calculated on the TDU tiles, the parameter values and the radiation level selected in THEODOR code for the tile is different as compared to a water cooled divertor.

![Figure 5.31](image_url)

**Figure 5.31**: Projection of the heat flux mapped on the horizontal and vertical divertor of W7-X. The maximum heat flux on the vertical divertor was more than 1 MW/m² for plasma discharge 20171101.012 [33].

The parameters used to calculate heat flux on TDU are shown in Table 5.4.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Temperature Dependency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Conductivity (W m⁻¹ K⁻¹)</td>
<td>165.58  87.88  58.89</td>
</tr>
<tr>
<td>Specific Heat (J kg⁻¹ K⁻¹)</td>
<td>680       1658   1926</td>
</tr>
<tr>
<td>density (kg m⁻³)</td>
<td>1830      1830   1830</td>
</tr>
<tr>
<td>Heat Diffusivity (m² s⁻¹)</td>
<td>145.07 × 10⁻⁶ 35.18 × 10⁻⁶ 18.58 × 10⁻⁶</td>
</tr>
<tr>
<td>Anisotropy factor</td>
<td>1.0       1.0    1.0</td>
</tr>
<tr>
<td>heat transmission coefficient top</td>
<td>1.0 × 10⁶  1.0 × 10⁶  1.0 × 10⁶</td>
</tr>
<tr>
<td>heat transmission coefficient bottom</td>
<td>200       200    200</td>
</tr>
<tr>
<td>Emissivity</td>
<td>0.82      0.82   0.82</td>
</tr>
</tbody>
</table>

**Table 5.4**: Material (graphite) parameter values used to calculate the heat flux on the W7-X TDU divertor tiles.
5.5.4 Comparison of surface layers detected by heat flux calculation and the threshold criteria of norm\([t, T]\).

The iterative method to find \(\alpha_{\text{top}}\) (Section 2.1.5) is computationally expensive [21]. This method cannot be used for real-time applications and a faster method for estimation of the layers is necessary. The results obtained from the numerical method to detect surface layers as mentioned in Section 3.2.1 were compared with the heat transmission coefficient \(\alpha_{\text{top}}\) values obtained from the heat flux calculation (Section 2.1.5). The \(\alpha_{\text{top}}\) values can be used to identify areas where surface layers affect the heat flux calculation. The values of \(\alpha_{\text{top}}\) obtained from the iterative method as mentioned in eq. (2.27) are projected on the 2D model of a W7-X divertor module as seen in Figure 5.32. The darker blue areas in Figure 5.32 show small values of \(\alpha_{\text{top}}\) where surface layers are detected, whereas the orange color shows normal surfaces where no deposition was detected.

![Figure 5.32: Projection of heat transmission coefficient \(\alpha_{\text{top}}\) on the horizontal and vertical divertor. The dark blue color shows lower values of \(\alpha_{\text{top}}\) which correspond to the location of surface layers. The values of \(\alpha_{\text{top}}\) below \(5 \times 10^5\) are linked to surface layers. The orange color shows the clean surface where no surface layers were detected.](image-url)

The surface layer results obtained from the numerical method (Section 3.2.1) which is processed in GPU is projected on a simplified 2D model of the W7-X divertor as seen in Figure 5.33. The NRT-IDS imaging software (Section 4.1) uses the numerical method and classifies the surface layers based on the state when they were detected. The yellow color show surface layers detected during the rise time, and brown areas
show surface layers detected during the rise and decay time. The green show layers detected only during the decay time. The results of the two numerical methods for detecting the surface layers as shown in Figures 5.32 and 5.33 are overlayed to find the matching areas. The overlaying provides meaningful information to find the best threshold for \( \text{norm}[t, T] \), which matches well with the regions of lower \( \alpha_{\text{top}} \) values.

**Figure 5.33:** Projection of surface layers detected on the W7-X horizontal and vertical divertor by the numerical method implemented in GPU. The yellow color shows the position of surface layers detected during the rise time. The brown color show areas where surface layers are detected during the rise and decay time. The green show layers detected only during the decay time [33].

The histogram of \( \alpha_{\text{top}} \) values on the areas where the numerical method detected surface layers can be seen in Figure 5.34. The majority (90\% to 99\% in most cases) of \( \alpha \) values lies below \( 5 \times 10^5 \), which is used as a cut-off range for the region with surface layers. The results achieved from the analysis prove that the numerical method can be used alternatively to find areas that have low \( \alpha \) values and by that indicates the presence of surface layers.

It is important to mention here that these results show the comparison of areas where the surface layers are detected by the numerical method which matches with the low \( \alpha \) values in those locations but the inverse is not proven yet. There can be areas where the \( \alpha \) correction method detected surface layers and the numerical method was not able to successfully detect them. However, this difference is still under analysis to find an optimal way to resolve this issue.

The numerical method depends on the relevant background offset level (more than 20 K above the background noise level) which may change during the day. Furthermore, in some cases, the numerical method is unable to detect surface layers; this requires further analysis. This failure can be either due to lower heating of the
5.5 Infrared Analyses at Wendelstein 7-X

**Figure 5.34:** Histogram showing the distribution of $\alpha_{\text{top}}$ values on the areas which match with the surface layers detected by the numerical algorithm for the shot number #20171101.012. The cutoff range for the minimum value of $\alpha_{\text{top}}$ for surface layers is set $5 \times 10^5$ [33].

divertor surface (temperature values lying below the offset level), the low thickness of the surface layers or due to norm$_{[t, T]}$ values lower than the criterion parameters. Lower values of norm$_{[t, T]}$ may be due to rise in the background temperature during the later half of an experimental day when the temperature on the divertor tiles is higher than the morning session. However, the influence of background temperature will reduce significantly in the future campaigns when water cooled PFCs will be installed.
6 Summary & Conclusion

For the steady-state operation of a magnetically confined high temperature plasma, the plasma facing components (PFCs) will be exposed to a high thermal load. The PFC called divertor is often responsible for main plasma exhaust at the edge of the plasma region. The HHF divertor at W7-X is composed of flat tiles of CFC NB31 and is designed to sustain a maximum heat load of $10 \text{ MWm}^{-2}$. These tiles are joined to the CuCrZr heat sink via an AMC-Cu interlayer which reduces stresses in both CFC and CuCrZr. Due to fatigue and aging, material defects such as delaminations can reduce the bonding between the CFC and the CuCrZr. The Delaminations can occur because of high thermal loads on the component or due to manufacturing faults at the interlayer during the fabrication process. If there is a delamination, less heat is transfered between the layers which further increases the surface temperature.

Another cause for observing high surface temperature are surface layers. The layers are formed because of redeposition of plasma impurities (e.g. eroded PFC materials) on the top of the bulk surface. Although not directly linked with the safety of the system, the surface layers are required to be detected in order to avoid overestimating the temperature measurement. This could otherwise lead to false alarms being sent to the central control system of W7-X. On the other hand, leading edges due to misalignment of the tiles and overloading by different heating sources can also lead to hotspots. It is necessary to detect these events during plasma operation to avoid any fatigue damages in the PFCs.

This work aimed at the creation of a near real-time image diagnostic system for protection of plasma facing components at W7-X. The system developed was divided into multiple sections based on the priority and available resources, and the work was organized along four targets.

- Create a characterization of the features to be included in a system
- Design the system based on the requirements for detecting thermal events.
- Test the system.
- Improve the system based on the response of the users.

Initially, the theoretical concepts on the identification of defects using temperature decay time were studied based on prior experience. The event identification algorithm developed prior to this work was developed in Python for post-analysis. For real-time processing, it was necessary to transform the algorithm and the entire image acquisition routines to generic C, C++ codes. Initially, the system was a stand-alone
tool with limited image vision techniques. In the framework of this thesis, it was embedded into ThermaVIP to include more image processing tools for runtime and offline analysis. The transformation dramatically enhanced the performance of the system and for the first time a near real-time system capable of the video monitoring of the PFC and analysis was created at W7-X.

The event detection algorithm for surface layers and delaminations was previously programmed in CUDA to use GPU processing of the thermal images. However, because of limited GPU resources (older version) and non-refined high-level programming, the processing time of the images with lower dimensions was only possible in the offline analysis. For detecting defects on the PFCs inside W7-X, the image dimensions of the IR camera must be maximum to cover as much as possible of the area of the vessel. For the real-time capability of the system, the algorithm was modified to make it as generic as possible so that it can be installed in any system with little modifications. Advanced parallel computation techniques were applied to achieve a processing time within the inter-frame time of the IR camera. As the results obtained from the algorithm are of a binary nature, the datatype of the result images was reduced to unsigned character (uchar) to reduce memory transfer time. Also, asynchronous memory transfer using CUDA streams was possible as the binary results are independent of each other. Parallel processing on the CPU using multi-threading processes was applied for faster data processing.

The performance of the system was validated in experiments performed at GLADIS using pre-series water cooled divertor tiles similar to those will be installed in the future at W7-X. The defects on these tiles were already known and were used to compare with the event detection algorithm results. The primary aim of the GLADIS experiments was to test the feasibility of the system and prove that it is possible to detect material defects such as delaminations in near real-time. For the experiments in GLADIS, an IR camera operating in the spectral range of 3 µm to 5 µm was mounted on one of the ports of GLADIS. The data was transmitted through optical fibers to the workstation where it was evaluated. A defective prototype target element of early pre-series design (4S-032) of the W7-X high heat flux divertor was used to detect delaminations in near real-time by the image diagnostic system. It could be shown that the algorithm detects delaminations based on the characteristic temperature decay time $\tau$ for a healthy tile and a tile with a defect. The $\tau$ value of the area with delamination is found to be much higher as compared to a normal surface area. A so called $\tau$ criterion was introduced to define a critical state when $\tau > \tau_{\text{crit}}$ with a characteristic threshold $\tau_{\text{crit}}$ measured from well-defined surface samples. If the critical state arised on any area of the tile, the area was labeled as delamination.

The heat load on the tiles was applied covering the entire surface of the component. The heating power was varied to check whether the system is capable of detecting delaminations even at lower heat loads. For realistic scenarios of heat loads on the W7-X divertor, the heating power was varied between 3, 5, 8 and 10 MWm$^{-2}$. A significant difference was visible when the heat load on the material was less than 10 MWm$^{-2}$. This means that the reliability of the system detecting a delamination will reduce if the heat flux on the tile is less than 8 MWm$^{-2}$. However, this also means
that for cases below 10 MWm$^{-2}$, the consequence of the tile getting further damage will be much less severe. In the future, further enhancements are required to adapt the number of pixels detected as delaminations with respect to the heat flux on the tile. However, this requires practical experience of tile behavior during operation of water cooled divertor at W7-X which was not available during the time of thesis.

After successfully detecting delaminations in near real-time, the results were further processed to label each cluster of pixels to determine the size of the defects. An iterative method known as CCL (component connected labeling) was applied to label pixels connected to each other and to calculate the size of each label. It was necessary to cluster the defects by setting a minimal threshold for the cluster size to avoid false alarms.

For detecting surface layers, the numerical algorithm based on temperature evolution of the material was developed and implemented into the GPU. The algorithm was benchmarked with the IR data from Tore Supra observing the limiter. The detection of surface layers was successful when observing the IR data of Tore Supra before and after the cleaning of the limiter. Inertially cooled tiles from the W7-AS divertor were also used to detect the effect of surface layers. The tiles showed several areas with surface layers deposited during operation at W7-AS. The system was able to detect the areas with surface layers on the W7-AS divertor tiles.

It took on-average 10 ms to 12 ms for the GPU to detect the thermal events and to apply the clustering algorithm on the delaminations, generating a trigger alarm and to display the results on the monitor screen. The time frame can be further reduced if the results are not shown on the screen. The experiments at GLADIS were the first of its kind where the defects inside a material were successfully detected from online-analysis of the IR data.

In the recent operational campaign (2017/2018) of W7-X, inertially cooled test divertors (TDU) were installed. Ten infrared diagnostics were used in different modules of W7-X monitoring the entire divertor region, baffle and wall components. Depending on the magnetic configuration being used, different parts of the divertor were loaded. For determining the presence of surface layers on the TDU, two distinct methods were used. The first method is similar to what was applied during GLADIS experiment and Tore Supra IR data which is based on the temperature evolution of a material during the rise and decay time when a heat load is applied. The second method is based on calculating the heat transmission coefficient $\alpha_{\text{top}}$ obtained from the heat flux calculation. For this reason, THEODOR code was applied to calculate the heat flux on the TDU target elements. $\alpha_{\text{top}}$ values obtained from the iterative method can be used to identify areas where the surface layers affect the heat flux calculation. The results from the $\alpha_{\text{top}}$ values and the numerical method implemented in GPU were compared. A similar pattern of surface layers was detected using both methods. However, the iterative method for calculating $\alpha_{\text{top}}$ values is computationally expensive which restricts its usage of the method to offline applications. The results obtained from the fast numerical algorithm in GPU were considered as successful results for the detection of surface layers on W7-X divertor.
Further analysis will be required in the future when the actively cooled HHF divertor will be installed in W7-X from 2020 on.

In summary, the near real-time image diagnostic system (NRT-IDS) is successfully installed and routinely monitoring the status of the PFCs during plasma operation at W7-X. The system is capable of detecting thermal events like delaminations, and hotspots. The fast response of the system makes it possible to run the system at a maximum frame rate of 100 Hz with full image dimension of the IR camera. Continuous improvement based on the operator’s response is being conducted. The algorithms developed for the GPU are generic in a sense that they can be easily transferred to another operating system (e.g., Linux based real-time system) with little modifications.
Bibliography


Bibliography


Pre-publications (peer-reviewed)


A Appendix

A.1 Thermography Details

The theoretical concept of IR camera calibration process is broadly explained in the thesis. However, the procedure of obtaining such results was not explained in detail. In this section, the IR camera calibration is explained in detail. During the initial process of the calibration, the infrared camera (InSb or bolometric) was placed inside the immersion tube or endoscope. A black body source was placed in front of the IR diagnostic setup observing the black body temperature in the range of 25°C to 1200°C. The integration time of the IR camera was varied when keeping the black body temperature at a specific temperature.

Figure A.1: Image of black body radiator used for the calibration of IR cameras. The temperature was varied between 25°C to 1200°C.

In case of IR camera with InSb detector, the integration time used during the calibration procedure were in the range of 50µs to 800µs. As the IR camera has three different neutral density filters, a repetition of the above mentioned procedure was applied for each filter. In case of bolometric cameras, the integration time was varied between 1µs to 9µs with a similar black body temperature range of 25°C to
1200 °C. As the bolometer camera raw data contains additive noise which needs to be removed before any further process can be proceed. A non-uniformity correction (NUC) method was applied to achieve a uniform signal intensity on all the pixels of the IR image.

During the calibration process, only InfraTec IR camera with InSb detector was integrated in NRT-IDS software. The NUC process was applied using the internal software by InfraTec as the hot and cold images that are required by the in-house NUC procedure were not available. Once the NUC was applied, the measurements were taken by applying a vertical polyline on the center of the black body source and the local maxima and minima values from the curve in Figure A.2 were measured. The local maxima was considered as the raw value in digital level (DL) that the IR camera measured. The local minima was used a background level which was subtracted to calculate the effective digital level.

![Figure A.2: IR image showing a black body source (circular red color circle) and polyline on top of it to acquire the raw digital level and the background level for the calibration process.](image)

In case of bolometer camera, the company provided software (named as IRCam works) was used initially to take the measurements from the black body source by creating a polyline on the center of the source in the image. However, later it was observed that the digital levels obtained using the company software and the data obtained after applying the in-house NUC method had a difference of 1000 digital levels. The reason for this was due to the difference in the correction method used in both cases. As in the future, the in-house NUC method will be used, all the calibration files are created with respect to the later method. As the acquisition of the data for the calibration is time consuming and takes upto several weeks, a semi-automatic method to acquire the digital levels and the background level from
the thermal images was developed. The method is based on the contour detection on the region where the black body source is located as can be seen in Figure A.3. The background level was obtained by taking the maximum value (in terms of occurrence) of the histogram of the image. Once the contour was selected and assuming that the camera was not moved during the acquisition of the data, average value of all the pixels in the contour and background area were taken. Additionally, the standard deviation in the intensity level of pixels in the contour region in the image as well as in all the images in the video was used for error propagation. The semi-automatic method was later applied to InfraTec camera data for the inclusion of uncertainties in the measurement for the calibration purpose.

![Figure A.3: Region of interest created on the hot area of the blackbody visible in the image.](image)

In some cases, the automatic contour detection method was not successful in detecting the black body temperature area in the image. Such cases appeared when the black body radiation was too low when using lower integration time e.g., with 50 °C and integration time of 1 µs, the intensity level was too low that the contour detection method was not able to detect homogeneous temperature distribution. In these cases, the data was manually acquired and corrected. All the data is processed and saved in excel files. A python code was created which automatically applies the calibration procedure mentioned in Section 2.1.3 to create a list of digital levels (DL) which corresponds to effective temperature value (without the inclusion of background temperature). The list is saved in javascript object notation (json) format files which are then loaded at the start of acquisition of NRT-IDS software. A separate json file is created for each emissivity, exposure time and IR camera used in the measurements during the plasma campaign.
A.2 Possibilities of Failures during Analysis

The monitoring system designed in the framework of the thesis was successfully tested in GLADIS. However, some precautionary steps must be taken in order to avoid any false alarms during the temperature analysis inside the W7-X. During the experiments in GLADIS it was realized that it is necessary to have a temperature calibration threshold so that only the data which is above the threshold must be analyzed. The reason for such condition was due to the fact that when using the calibration settings in multi-integration mode i.e., temperature observation in the range of 300°C to 1500°C, false values appear when temperature was below 300°C. For this reason, the norm $\|t, T\|$ and $\tau$ values computed during analysis were wrong. One of the examples where wrong results were obtained when no condition was placed in case when the temperature values are outside the calibration range can be seen in Figure A.4.

![Figure A.4](image)

(a) Surface Layers result when temperature threshold is below 350°C  
(b) Delamination result when temperature threshold is below 350°C

This is one of the main reasons to include temperature threshold condition in the numerical method so that false analysis can be reduced. In future, different temperature calibrations will be used and it will be necessary to automatically update the temperature threshold condition based on the temperature calibrations being used. Another important conditions for implementing the GPU algorithms is defining the proper architecture settings (i.e. CUDA Compatibility version) during compilation of the code as different GPUs are designed with different compatibility versions of GPU architecture. In case if the GPU architecture is different than the one compiled, the GPU response will be unpredictable.

Although it is unlikely that the GPU component of the system crashes in which case the algorithm used to detect the thermal events such as delamination will not work. Therefore it is necessary for the user who is operating the system to routinely check the results obtained from the GPU. This is one of the reasons to stream the
A.2 Possibilities of Failures during Analysis

results of the GPU live for troubleshooting purposes. In case if the camera crashes, the system receives a signal that the camera is not responding and then the user operating the system has to make a fresh start of the camera or either restart the software.
A Appendix

A.3 GPU Code

```c
#include <iostream>
#include <iomanip>
#include <fstream>
#include <sstream>
#include <string>
#include <vector>
#include <map>
#include <queue>
#include <list>
#include <algorithm>
#include <utility>
#include <cmath>
#include <functional>
#include <cstring>
#include <limits>
#include "kernel.h"
#include "cuda_runtime.h"
#include "device_launch_parameters.h"
#include <cuda.h>
#include <device_functions.h>
#include <cuda_runtime_api.h>

#define NOMINMAX
typedef unsigned char uchar;
using namespace std;

/*
 * This function converts kelvin to celsius
 */
__global__ void Ke12Cel(float *img, int widthnew, int heightnew)
{
    int id = blockIdx.x * blockDim.x + blockIdx.y * blockDim.x *
             gridDim.x + threadIdx.x;
    if (id >= widthnew*heightnew) return;
    float temp = 0.0;
    /*
     * In case if the data is in deci kelvin. The data needs to be
     * first converted into kelvin and then into celsius as the
     * algorithm works only with the celsius temperature data
     */
    float temp1 = img[id] * 0.1;
    temp = temp1 - 273.15;
    img [id] = temp ;
}
```
A.3 GPU Code

```c

/**
 * Initializing the arrays used in the analysis to zero so that any garbage value is removed.
 ***/
__global__ void imageinitial ( float *im_matrix, float *im_matrix_old, int widthnew, uchar *ZL, uchar *DL, uchar *HL, uchar *Delam, uchar *Delam_old_one, uchar *Delam_old_two, uchar *Current_State, uchar *Old_State, float *State_timestamp, bool *m, bool *trig_val )
{
    int i = threadIdx.x + blockIdx.x * blockDim.x;
    int j = threadIdx.y + blockIdx.y * blockDim.y;

    im_matrix[i + (j * widthnew)] = 0.0;
    im_matrix_old[i + (j * widthnew)] = 0.0;
    ZL[i + (j * widthnew)] = 0;
    DL[i + (j * widthnew)] = 0;
    HL[i + (j * widthnew)] = 0;
    Delam[i + (j * widthnew)] = 0;
    Delam_old_one[i + (j * widthnew)] = 0;
    Delam_old_two[i + (j * widthnew)] = 0;
    Current_State[i + (j * widthnew)] = 0;
    Old_State[i + (j * widthnew)] = 0;
    State_timestamp[i + (j * widthnew)] = 0.0;
    *m = false;
    *trig_val = false;
}
```

```c

/**
 * This function analyzes the temperature data (im_matrix) and then classifies the data into surface layers, delaminations and hotspots based on the conditions mentioned.
 ***/
__global__ void imcheck(float *im_matrix, float *im_matrix_old, float timestep, float timestamp, uchar *Current_State, uchar *Old_State, float *State_timestamp, uchar *Delam, uchar *Delam_old_one, uchar *Delam_old_two, int widthnew, int heightnew, uchar *ZL, uchar *DL, uchar *HL, float layerheating, float layercooling, float mintemp, float delamlayer, float hotspoteff, float heatstate, float coolstate)
{
    float derivativ = 0.0;
    float tau = 0.0;
    int i = threadIdx.x + blockIdx.x * blockDim.x;
    int j = threadIdx.y + blockIdx.y * blockDim.y;

    // Calculation of norm[T] that is the derivate of current frame and previous frame divided by timestep * previous frame
```
if (im_matrix[i + (j * widthnew)] > mintemp && im_matrix_old[i + (j * widthnew)] > mintemp) {
    derivativ = ((im_matrix[i + (j * widthnew)] - im_matrix_old[i + (j * widthnew)]) / (timestep * im_matrix_old[i + (j * widthnew)]));
}

// Detecting the rise time derivative for surface layers
if (derivativ > heatstate) {
    // check for heating phase && im_matrix[i + (j * widthnew)] > 300 && im_matrix_old[i + (j * widthnew)] < 1500 && im_matrix_old[i + (j * widthnew)] > 350
    // set the pixel to Heating
    Current_State[i + (j * widthnew)] = 122;
    if (! (Old_State[i + (j * widthnew)] === 122 || Old_State[i + (j * widthnew)] === 255)) {
        State_timestamp[i + (j * widthnew)] = timestamp;
    }
    if (derivativ > layerheating) {
        // layer heating condition
        Current_State[i + (j * widthnew)] = 255;
        ZL[i + (j * widthnew)] = 255;
    }
}

// Detecting the fall time derivative for surface layers
else if (derivativ < coolstate) {
    // check for cooling phase
    // set the pixel to Cooling
    Current_State[i + (j * widthnew)] = 64;
    if (! (Old_State[i + (j * widthnew)] === 64 || Old_State[i + (j * widthnew)] === 32)) {
        State_timestamp[i + (j * widthnew)] = timestamp;
    }
    // layer cooling condition
    if (derivativ < layercooling && im_matrix[i + (j * widthnew)] > mintemp) {
        // Set the pixel to Delam Layer
        Current_State[i + (j * widthnew)] = 32;
        ZL[i + (j * widthnew)] = 122;
    }
    // Calculation of tau
    if (im_matrix[i + (j * widthnew)] > mintemp && im_matrix_old[i + (j * widthnew)] > mintemp) {
        tau = im_matrix_old[i + (j * widthnew)] / ((im_matrix[i + (j * widthnew)] - im_matrix_old[i + (j * widthnew)]) / (timestep));
    }
    // Defining the criteria of when it should start detecting delaminations
    if (tau < delamlayer && im_matrix[i + (j * widthnew)] > mintemp && im_matrix_old[i + (j * widthnew)] >

mintemp && timestamp >= (State_timestamp[i + (j * widthnew)] + 0.3) && timestamp <= (State_timestamp[i + (j * widthnew)] + 0.65))
{
    // sort out pixels that are below the calibrated temp
    and check if 0.5s are already over
    Delam[i + (j * widthnew)] = 8;
    // State of Pixel can be set to 1 if
    // Check with old frames if tau was greater then 2.2
    for at least 3 frames, including this one
    if (Delam_old_one[i + (j * widthnew)] == 122 &&
        Delam_old_two[i + (j * widthnew)] == 122)
    {
        Delam[i + (j * widthnew)] = 255;
        DL[i + (j * widthnew)] = 255;
    }
    else if (Delam_old_one[i + (j * widthnew)] == 255 &&
              Delam_old_two[i + (j * widthnew)] == 255)
    {
        Delam[i + (j * widthnew)] = 255;
        DL[i + (j * widthnew)] = 255;
    }
    else if (Delam_old_one[i + (j * widthnew)] == 255 &&
              Delam_old_two[i + (j * widthnew)] == 122)
    {
        Delam[i + (j * widthnew)] = 255;
        DL[i + (j * widthnew)] = 255;
    }
    else
    {
        Delam[i + (j * widthnew)] = 122;
    }
}
else
{
    Delam[i + (j * widthnew)] = 0;
}

// If it neither finds surface layers or delaminations and if
the temperature is higher than hotspottemp then mark them as hotspot
else
{
    // set the pixel to Steady state
    Current_State[i + (j * widthnew)] = 5;
    if ((ZL[i + (j * widthnew)] != 255) && (DL[i + (j * widthnew)] != 255) &&
        (im_matrix[i + (j * widthnew)] > hotspottemp))
    {
        HL[i + (j * widthnew)] = 255;
    }
    else
    {
        HL[i + (j * widthnew)] = 0;
        ZL[i + (j * widthnew)] = 0;
    }
}
A Appendix

163 164/∗∗ ∗ ∗
165 From this part the CCL codes starts, all the global functions
166 ∗ ∗ ∗/
167 const int BLOCK = 256;
168 // Initializing the values of original label matrix values and
169 // reference label matrix values to its index values
170 __global__ void init_CCL(int L[], int R[], int N)
171 {
172 int id = blockIdx.x * blockDim.x + blockIdx.y * blockDim.x *
173 gridDim.x + threadIdx.x;
174 if (id >= N) return;
175 L[id] = R[id] = id;
176 }
177
178 // Scans the whole image per pixelwise and check 4 direction
179 // connectivity
180 __global__ void scanning(uchar D[], int L[], int R[], bool* m, int
181 N, int W, int th)
182 {
183 int id = blockIdx.x * blockDim.x + blockIdx.y * blockDim.x *
184 gridDim.x + threadIdx.x;
185 if (id >= N) return;
186 int label = N;
187 if (id - W >= 0 && D[id] == 255 && D[id-W] == 255 ) label =
188 min(label, L[id-W]);
189 if (id + W < N && D[id] == 255 && D[id+W] == 255) label =
190 min(label, L[id+W]);
191 int r = id % W;
192 if (r && D[id] == 255 && D[id-1] == 255) label =
193 min(label, L[id-1]);
194 if (r + 1 != W && D[id] == 255 && D[id+1] == 255) label =
195 min(label, L[id+1]);
196 if (label < L[id]) {
197 R[L[id]] = label;
198 *m = true;
199 }
200 }
201
202 // Scans the whole image per pixelwise and check 8 direction
203 // connectivity,
204 // finds the minimum label and assigns the label to reference
205 // label matrix.
206 // Also sends information whether it found a new label or not.
207 __global__ void scanning8(uchar D[], int L[], int R[], bool* m,
208 int N, int W)
209 {
210 int id = blockIdx.x * blockDim.x + blockIdx.y * blockDim.x *
211 gridDim.x + threadIdx.x;
212 if (id >= N) return;
213 }
A.3 GPU Code

```
int label = N;
if (id - W >= 0 && D[id] == 255 && D[id-W] == 255) label = min(label, L[id-W]);
if (id + W < N && D[id] == 255 && D[id+W] == 255) label = min(label, L[id+W]);
int r = id % W;
if (r) {
    if (D[id] == 255 && D[id-1] == 255) label = min(label, L[id-1]);
    if (id - W - 1 >= 0 && D[id] == 255 && D[id-W-1] == 255) label = min(label, L[id-W-1]);
    if (id + W - 1 < N && D[id] == 255 && D[id+W-1] == 255) label = min(label, L[id+W-1]);
}
if (r + 1 != W) {
    if (D[id] == 255 && D[id+1] == 255) label = min(label, L[id+1]);
    if (id - W + 1 >= 0 && D[id] == 255 && D[id-W+1] == 255) label = min(label, L[id-W+1]);
    if (id + W + 1 < N && D[id] == 255 && D[id+W+1] == 255) label = min(label, L[id+W+1]);
}
if (label < L[id]) {
    R[L[id]] = label;
    *m = true;
}

// If the label has not changed then it checks the center of the gravity
// (the main label from which roots are connected to the current label).
// If it finds that then it labels the root version in Reference matrix.
__global__ void analysis(uchar D[], int L[], int R[], int N)
{
    int id = blockIdx.x * blockDim.x + blockIdx.y * blockDim.x * gridDim.x + threadIdx.x;
    if (id >= N) return;
    int label = L[id];
    int ref;
    if (label == id) {
        do { label = R[ref = label]; } while (ref != label);
        R[id] = label;
    }
}

// Finally the Reference values are copied to original label matrix
__global__ void labeling(uchar D[], int L[], int R[], int N)
{

```
A Appendix

240  \texttt{int id = blockIdx.x * blockDim.x + blockIdx.y * blockDim.x *} \n241  \texttt{gridDim.x + threadIdx.x;} \n242  \texttt{if (id >= N) return;} \n243  \texttt{L[id] = R[R[L[id]]];} \n244
245  return;} \n246  
247  // Labelling is done and now come the part for cluster counts and \n248  // size of the clusters. \n249  // Map the Labels only with respect to the areas which are being detected as defects \n250  \texttt{__global__ void maplabels (uchar D[], int L[], int N)} \n251  \{ \n252  \texttt{int id = blockIdx.x * blockDim.x + blockIdx.y * blockDim.x *} \n253  \texttt{gridDim.x + threadIdx.x;} \n254  \texttt{if (id >= N) return;} \n255  \texttt{int label = L[id];} \n256  \texttt{int newlabel;} \n257  \texttt{if (id > 0 && D[id] == 255)} \n258  \{ \n259  \texttt{newlabel = label;} \n260  \} \n261  \texttt{else} \n262  \{ \n263  \texttt{newlabel = 0;} \n264  \} \n265  \texttt{L[id] = newlabel;} \n266  \}
267
268  \texttt{__device__ int maxclusvalue = 0;} \n269  \texttt{__device__ int minclusvalue = 1310720;} \n270  \texttt{__device__ int totalclus = 0;} \n271  
272  // MLC = Max no of labels inside a cluster maxvalue = no of clusters \n273  \texttt{__global__ void measuring(int L[], int N, int *MLC)} \n274  \{ \n275  \texttt{int id = blockIdx.x * blockDim.x + blockIdx.y * blockDim.x *} \n276  \texttt{gridDim.x + threadIdx.x;} \n277  \texttt{if (id >= N) return;} \n278  \texttt{int label = L[id];} \n279  \texttt{if (label > 0)} \n280  \{ \n281  \texttt{if (label == id) \{} \n282  \texttt{atomicAdd(&MLC[label], 1);} \n283  \} \n284  \texttt{else if (label > 0 && label != id)} \n285  \{ \n286  \texttt{atomicAdd(&MLC[L[id]], 1);} \n287  \} \n288  \}
289
290
291
292
293
294 106
A.3 GPU Code

// make the bool value of a trig_val variable to true if any value in MLC is above safety criteria
__global__ void sendalarm(int* MLC, int N, bool* trig_val, float safecond)
{
    int id = blockIdx.x * blockDim.x + blockIdx.y * blockDim.x *
             gridDim.x + threadIdx.x;
    if (id >= N) return;
    if (MLC[id] > safecond)
    {
        *trig_val = true;
    }
}

// Sets the values of generic device members to zero (for reducing false values inside the device variables)
__global__ void deletemem(int* MLC, int N)
{
    int id = blockIdx.x * blockDim.x + blockIdx.y * blockDim.x *
             gridDim.x + threadIdx.x;
    if (id >= N) return;
    MLC[id] = 0;
    maxclusvalue = 0;
    minclusvalue = 1310720;
    totalclus = 0;
}

// Find the max and min label value to calculate the no of max and min cluster value detected. Max value corresponds to the no of clusters created.
__global__ void maxminlabelvalue(int L[], int N, int* MLC)
{
    int id = blockIdx.x * blockDim.x + blockIdx.y * blockDim.x *
             gridDim.x + threadIdx.x;
    if (id >= N) return;
    int label = L[id];
    if (label > 0 && label == id && MLC[id] > 50)
    {
        maxclusvalue = max(maxclusvalue, label);
        minclusvalue = min(minclusvalue, label);
    }
    if (minclusvalue != 1310720) { 
        totalclus = maxclusvalue - minclusvalue;
    }
}

__device__ int getboundingbox(int labelvalue, int L[], int N, int wid, int heig, int* MLC, int ym, int xm)
{
    int id = blockIdx.x * blockDim.x + blockIdx.y * blockDim.x *
             gridDim.x + threadIdx.x;
    if (id >= N) return;
    // y --> rows    x--> columns
int xmax, ymax, xtemp, ytemp;
int off = xm + ym;
if (L[id] == labelvalue)
{
    ytemp = id / wid;
    xtemp = id % wid;
    if (xtemp > xm)
    {
        xmax = xtemp;
    }
    if (ytemp > ym)
    {
        ymax = ytemp;
    }
}
return xmax, ymax;
}

/** ∗∗ ∗
From Here C functions start to call the GPU functions
mentioned above
∗∗ ∗/ 
void ImgDetec(float *d_video , float *d_video_alt , float timestep,
float timestamp, uchar *Current_StateD , uchar *Old_StateD ,
float *State_timestampD , uchar *DelamD , uchar *Delam_Old_ID ,
uchar *Delam_Old_2D, int Width, int Height, uchar *SLayerD ,
uchar *DLayerD , uchar *HSLayerD , bool *md , bool *trig_en ,
int *Ld , int *Rd , int *MLCA , int *pixels , float layerheating,
float layercooling , float mintemp , float delamlayer , float
hotspottemp , float safecond , float heatstate , float
coolstate , char *matrix , int *countclus)
{
    dim3 blocksPerGrida;
    dim3 threadsPerBlocka;
    // Grid and Block Dimensions
    if (Width > 1024) {
        blocksPerGrida =dim3(Width/32,Height/32);
        threadsPerBlocka = dim3(Height/32,Height/32);
    }
    else
    {
        blocksPerGrida = dim3(1, Height);
        threadsPerBlocka = dim3(Width, 1);
    }
    int N = Width * Height;
    int widthccl = static_cast<int>(sqrt(static_cast<double>(N) / BLOCK)) + 1;
    dim3 grid(widthccl, widthccl, 1);
    dim3 threads(BLOCK, 1, 1);
    Kel2Cel <<< grid , threads >>>(d_video , Width, Height) ;
cudaDeviceSynchronize();

imcheck <<<grid, threads>>>(d_video , d_video_alt ,
timestep , timestamp, Current_StateD , Old_StateD ,
State_timestampD , DelamD , Delam_Old_1D ,Delam_Old_2D,
Width , Height , SLayerD , DLayerD , HSLayerD, layerheating ,
layercooling , mintemp ,delamlayer , hotspottemp ,
heatstate , coolstate);
cudaDeviceSynchronize();

// // This is where CCL part starts
init_CCL <<<grid, threads>>>(Ld , Rd , N);
cudaDeviceSynchronize();
uchar *swit ;
char *arr1 = "HSL";
char *arr2 = "DL";
char *arr3 = "SL";
// To select on which result array the clustering algorithm (CCL) be applied
if (strcmp(matrix, arr1) == 0)
{
    swit = HSLayerD;
}
else if (strcmp(matrix, arr2) == 0)
{
    init_CCL <<<grid, threads>>>(Ld , Rd , N);
    swit = DLayerD;
}
else if (strcmp(matrix, arr3) == 0)
{
    init_CCL <<<grid, threads>>>(Ld , Rd , N);
    swit = SLayerD;
}
// loop until all the labels are found
for ( ; ; ) {
    bool m = false;
cudamemcpy(md, &m, sizeof(bool), cudamemcpyHostToDevice);
    scanning8 <<<grid, threads>>>(swit , Ld, Rd, md, N, Width);
    cudamemcpy(&m, md, sizeof(bool), cudamemcpyDeviceToHost);
    // cout <<" \n found new cluster " << m;
    if (m) {
        analysis <<<grid, threads>>>(swit , Ld, Rd, N);
        cudadevicesynchronize();
        labeling <<<grid, threads>>>(swit , Ld, Rd, N);
        cudadevicesynchronize();
    } else break;
}

int mmm;
maplabels <<<grid, threads>>>(swit , Ld , N);
cudaDeviceSynchronize();
measuring <<< grid, threads >>>(Ld, N, MLCA);
cudaDeviceSynchronize();

sendalarm <<< grid, threads >>> (MLCA, N, trig_en, safecond);
cudaError (cudaMemcpy(countclus, MLCA, N * sizeof(int),
cudaMemcpyDeviceToHost));

maxminlabelvalue <<< grid, threads >>>(Ld, N, MLCA);
cudaDeviceSynchronize();
cudaError (cudaMemcpyFromSymbol(&numm, totalclus, sizeof(int)));

deletmem <<< grid, threads >>>(MLCA, N);
cudaDeviceSynchronize();

/∗ ∗∗ This function calls the GPU function ∗∗ ∗/

void imagzero (float *d_video, float *d_video_alt, int Width, int Height, uchar *SLayerD, uchar *DLayerD, uchar *HSLayerD, uchar *DelamD, uchar *Delam_Old_1D, uchar *Delam_Old_2D, int *Ld, int *Rd, uchar *Current_StateD, uchar *Old_StateD, float *State_timestampD, bool* md, bool* trig_en)
{
    dim3 blocksPerGrida (40, 32);
    dim3 threadsPerBlocka (32, 32);
    imageinitial <<< blocksPerGrida, threadsPerBlocka >>>(d_video, d_video_alt, Width, SLayerD, DLayerD, HSLayerD, DelamD, Delam_Old_1D, Delam_Old_2D, Current_StateD, Old_StateD, State_timestampD, md, trig_en);
    cudaDeviceSynchronize();
}