Edge plasma temperature and density profiles in TJ II stellarator

Master Thesis
presented by

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Density limit of stellarators exceeds the one of tokamaks. It has been reported that when the radiated power from the plasma reaches a certain fraction of the input power, plasma collapses. Radiative collapse is mainly due to the formation of the radiative layer forming in the plasma boundary. Atomic processes between plasma particles and plasma surrounding (walls, limiters) induce strongest impurity radiation at the plasma edge and the formation of a strong radiative layer as a mechanism of energy loss causing the strong decay of the electron temperature below 20 eV in the plasma edge. At such low temperatures reaction rates for the ionization processes that sustain the plasma, decay exponentially so that the electron/ion sources cannot compensate for the losses and the plasma begins to collapse.

This work is devoted to the observation of this phenomena in TJ-II stellarator through the behavior of its most relevant edge parameters, $T_e$ and $n_e$ in the NBI phase of the discharge. Electron density and temperature profiles are deduced by means of spectroscopic method from the ratio of the He emission lines on the basis of the Collisional Radiative Model developed in TEXTOR tokamak and extrapolated to the TJ-II conditions.

To study the edge $T_e$ and $n_e$ profiles in TJ-II stellarator we use a fast CMOS camera coupled with an intensifier. With bifurcated fibre bundles, as a part of detection system, it was possible to record two different He emission lines simultaneously, so to apply He-line ratio technique. Data are collected continuously during the discharge which enabled us to focus on the dynamics of obtained profiles therefore we were able to reconstruct the edge parameters for increasing average electron densities up to the plasma edge collapse.

In the present work we performed 1D and 2D analysis of the edge plasma parameters. Radial profiles compared with other diagnostics were in a good agreement. We observed tendency of the localized plasma cooling in the plasma boundary and complementary 2D imaging had shown the formation of the layer in the plasma edge with much lower temperature than the rest of the surrounding.
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Chapter 1

Introduction

World energy demand is increasing and next this generation will have to provide a long-term solution for the future energy sources. Fossil fuels (coal, natural gas and oil) are still leading suppliers of energy, although they are directly responsible for the greenhouse effect by the emission of $\text{CO}_2$. Fossil fuels cannot be considered as a long term energy source mainly because of the environmental impact and also because their sources are limited.

Controlled thermonuclear fusion is a promising solution for the energy problem. Thermonuclear fusion fuses two light elements: hydrogen isotopes deuterium (D) and/or tritium (T), with $\alpha$ particle and fast neutron as products, the same processes happening in the stars. There are several possible nuclear reactions but the most favorable reaction for energy production and consumption is:

$$D + T \rightarrow \alpha(3.5\text{MeV}) + n(14.5\text{MeV}) \quad (1.1)$$

Reaction (1.1) has the highest reaction rate (number of fusion collisions per unit volume per unit time), among other reactions, and produces significant amount of nuclear energy. Deuterium is present in the ocean water and can be easily extracted whilst the most favorable concept for tritium breeding is from the reaction:

$$\text{Li} + n \rightarrow \alpha + T + 4.8\text{MeV} \quad (1.2)$$

Reaction (1.2) is the envisaged solution: that is to breed tritium in the blanket, the surrounding environment where D-T reaction would take place.

D-T reaction has the highest reaction rate in the temperature range of 10-30 keV. As a consequence of such high temperatures the working gas is fully ionized. This state of matter is known as plasma. In order to fuse D and T one needs to overcome the electrostatic Coulomb repulsion between protons, to place the nucleons in high proximity (order of nucleon radius) in order for nuclear forces to take place.

In the Sun, plasma is confined by its own gravitational force. It enables enormous pressure and temperature conditions so every second millions of tons
of hydrogen are fused. Having Sun on the Earth is a big challenge for scientists and engineers.

Nowadays the most promising confinement method is by means of a magnetic field in toroidal devices. A torus can have magnetic field lines closed everywhere, so charged particles will gyrate around magnetic field line restricted by Lorentz force. This geometry enables to have charged particles confined for sufficiently long time, named confinement time $\tau_{\text{conf}}$. The efficiency of the magnetic confinement is expressed in terms of ratio between kinetic pressure of the particles inside the chamber and the pressure due to magnetic forces confining the plasma, known as $\beta$ limit. Therefore in fusion machines there is always a competition between those parameters; low $\beta$ is easier to achieve but with lower confinement efficiency, whilst high $\beta$, meaning the higher plasma pressure, induces various instabilities inside the plasma.

Within magnetically confined plasmas in toroidal devices, two major concepts are developed: tokamak and stellarator concepts.

The tokamak is an axysymmetric configuration and its magnetic fields are generated by the means of transformer effect. A DC current through primary winding of the transformer induces a toroidal plasma current that generates the poloidal component of magnetic field, therefore part of the responsibility for confinement is on the plasma itself. This fact is one of the major drawbacks of tokamaks: duration of the discharge is limited by the maximum current that can be driven through the transformer and heating of coils due to ohmic dissipation. Therefore, tokamak operates in a pulsed regime (ramp up, flat top, ramp down). However future fusion reactor will require steady-state operation, that is, externally driven currents in the plasma. Fortunately, neo-classical theory predicted occurrence of the bootstrap current, driven by the pressure gradients. In order to achieve input/output power balance economically acceptable, pressure inside a tokamak has to exceed MHD $\beta$ limit [1]. This problem is addressed to the advanced tokamak regime where by means of pressure and current profile control, a large fraction of bootstrap current can be induced [2]. Due to high $\beta$ this requires an additional rotational stabilization.

Stellarators are more complex machines with 3D geometry. They can be described as helically symmetric system bend into a torus [3]. Magnetic field in stellarators is generated completely by means of complex external coils, and can operate continuously. The crucial advantage of stellarators is that the plasma does not need to have ohmically or externally driven currents present so there are no disruptions. Moreover the plasma exceeds the density (Greenwald) limit for tokamaks. Disadvantage is that the construction of the complex coils is more of an engineering challenge and yet very expensive, so stellarators are still in early stage of development compared with the tokamaks.

The next step for the stellarator concept is Wendelstein 7-X. Stellarator with superconducting coils, being built in Greifswald and should start the operation next year. For tokamaks, next step, and the biggest one so far in fusion community, is the prototype of fusion reactor being built in the south of France. It is International Thermonuclear Experimental Reactor (ITER).
Reason for this is that tokamaks as simple machines are one generation ahead the stellarators.

In order to get fusion energy both, stellarators and tokamaks, have to confine plasma at temperatures of at least 10 keV (about 100 million °C), at densities of the order of \( n \approx 10^{20} \text{ m}^{-3} \) and for a long period of time \( (\tau > 5 \text{ s}) \). Quality of confined plasma is determined by the product of those three parameters (Lawson criterion) and in most advanced stellarators is order of magnitude lower than for tokamaks. It is mainly because stellarators are smaller machines and with lower input power (energy confinement time is proportional to the size of the machine and input power). For D-T reaction minimum value of triple product is for temperatures of \( T=14 \text{ keV} \):

\[
n \cdot T \cdot \tau_E > 3 \cdot 10^{21} \text{ m}^{-3} \text{ keV s}
\]  

with the energy confinement time \( \tau_E = W/P_{\text{loss}} \) defined as the ratio of the energy content of the plasma \( W \), and the power losses \( P_{\text{loss}} \). On the other side, particle confinement time \( \tau_P \) can be defined as the time in which certain species are confined inside the machine (i.e. electrons, ion, impurities).

Control of the plasma is another major problem for fusion community. That is, how to prevent plasma damaging the wall, therefore the problem is addressed to the plasma-wall interaction. Two concepts have been developed in order to separate hot plasma core from the walls and are known as limiter and divertor concepts. Detailed explanation is given in chapter 2.

While plasma core conditions for ignition are defined by Lawson criterion, plasma edge conditions are strongly influenced by plasma-wall interaction, heat loads on the wall and its erosion. One of the critical issues is degradation of confinement time through the production of impurities and neutrals coming from the wall in the process of recycling (ions from the plasma are recombining on the walls entering the plasma as neutrals) and sputtering. The measured particle confinement times are independent of the operating conditions and moreover ratio of confinement time of impurities \( \tau_I \) and fuel particles (hydrogen) \( \tau_H \) \((\tau_I/\tau_H)\) is almost constant since the same transport mechanism applies to hydrogen and impurities [4]. Therefore, the major improvements in plasma cleanliness have only been achieved by proper choice of limiter and wall material (reduction of impurity sources), and their proper treatment (wall conditioning, carbonization or boronisation, glow discharge).

It is clear that achieving high energy confinement time is of prime importance. It is a demanding task because magnetic field changes the energy transport properties and induces anisotropic plasmas. In order to completely determine \( \tau_E \) it is necessary to characterize all the micro processes happening in the plasma. Transport theory developments were based on the binary collisions and are the basis of classical and neo-classical theories that have been developed. However these theories predicted rather small transport coefficients for fusion plasma; classical transport coefficients being of the order of \( \approx 0.01 \text{ m}^2/\text{s} \) while the neo-classical values were slightly higher \( \approx 0.5 \text{ m}^2/\text{s} \). Indeed, transport theory predicted optimistic confinement time with respect
to the experimentally observed one. The key role in this failure appeared to be due to anomalous, turbulent transport. Anomalous transport has not been understood to date, so experimentally obtained scaling laws are revealing physical processes behind, and of more practical importance foreseeing drastic changes in confinement, this way directly helping more effective design of future reactor.

In general there are two distinct modes of confinement: L mode that stands for 'lower' confinement and H mode for 'higher' and is about of factor 2 higher then the L mode. They depend on the amount of external heating power delivered to the plasma and plasma-wall interaction point. Nowadays both modes are achieved routinely in fusion machines. H mode was first achieved in ASDEX tokamak [5]. It is characterized by development of a transport barrier at the edge and simultaneous drop in the density of the neutrals in the boundary region, leading to a sudden drop of $H_\alpha$ emission. This transport barrier at the edge prevents accumulated impurities to come out from the plasma core, resulting in quasi-periodic collapse of the barrier. These instabilities are known as Edge Localised Modes (ELMs) and are fast coherent structures propagating radially outwards and delivering high power loads of heat and particles to the wall causing the severe damage.

Although the core conditions can be fixed, still in certain regimes of the operation are completely controlled by the edge processes. Edge parameters sets the constrains on the heat loads, the erosion of the wall, particle exhaust and those constrains appear to be quite limiting for the operation. Moreover the impurity radiation at the edge determines the achievable density limit of the plasma, therefore the main task is to optimize the edge conditions in order to achieve desired conditions in the plasma core. To make a link between edge and core parameters, more deep understanding of the plasma boundary is necessary.

Since both stellarators and tokamaks have to satisfy the ignition criterion to provide sustainable operation required for the reactor, they have to operate near the operational limit [6]. Most of tokamak discharges terminates by a dramatic quench of the plasma current while in a stellarator current free scenario, the duration of the discharge is limited by attainable density limit. Therefore in stellarator the density limit is of special importance. Many physical processes limits the feasible densities but the most important ones are strong radiation of the low-Z impurities accumulated in the plasma edge or high-Z impurities accumulated in the core. Generally, when radiation becomes comparable to the input power, plasma looses its energy and begins to collapse. This scenario is the main disruptive effect for the stellarators. Indeed data from the NBI discharges in W7-AS shows that threshold density at the edge scales with $P^{0.5}B^{0.8}$ where $P$ is the net power crossing the Last Closed Flux Surface [7] addressing the problem to the plasma boundary.

Requirements for high confinement, that assures longer confinement time of plasma, and its control by edge processes, triggered emphasis on edge studies and installation of different diagnostics for edge plasma in all fusion devices.
Knowledge about $T_e$ and $n_e$ profiles, ion temperature ($T_i$), density of impurities ($n_I$), radiation power ($P_R$), particle and heat outflux rates to the surface is possible to deduce nowadays with the help of different edge diagnostics such as Langmuir probes or spectroscopic methods. Of special importance are the spectroscopic methods that are non perturbative and stationary methods. For instance, Langmuir probes are in direct contact with plasma, therefore the life-time is quite limited due to the extreme conditions in the fusion plasmas (high temperatures) contrary to the spectroscopic methods where the system is quite simple, can be placed far away from the plasma (outside the machine) so the longer life-time of the system is assured.

This work is based on stationary and non-perturbative spectroscopic studies. Here we present the most basic information about plasma edge in TJ-II stellarator: its $T_e$ and $n_e$ radial profiles, using a intensified high speed camera system for detection. With the help of double bundles, mounted on the intensified camera, we were able to record two emission lines simultaneously and reconstruct 1D profiles and 2D images of edge $T_e$ and $n_e$ for different $\langle n_e \rangle$ in TJ-II by means of He-line ratio technique with the 2D implementation as explained in the Ref. [8]. This detection system together with He-line ratio technique appeared to be very elegant and simple solution for plasma edge studies requiring only inserted limiter inside the plasma and the He beam. Moreover this stationary method can deliver information about the plasma edge continuously providing the valuable information about temporal evolution of the plasma edge. Taking advantage of such system the main objective of this work is the systematic study and characterization of edge $T_e$ and $n_e$ profiles during the NBI phase of the discharge in TJ-II stellarator for different average electron densities. We focus on the dynamics of the edge profiles during the density ramps up to the collapse of the plasma for the case of He puffing and recycling.

Thesis is organized as follows:

Chapter 2 outlines plasma edge physics and plasma-wall interaction concepts developed up to date; limiter and divertor concepts. We will introduce plasma boundary with a Scrap-Off-Layer (SOL) and its characteristics. We will present main atomic processes as the sources of the visible emission in the plasma edge and also the main characteristics of TJ II stellarator will be presented here.

Chapter 3 gives an overview of visible spectroscopy for plasma edge characterization. We focus on the atomic beam diagnostics and He-line ratio technique used in this work presenting the idea of Collisional Radiative Model (C-R) developed in TEXTOR.

Chapter 4 describes our experimental setup. Complex detection system requires detail and careful manipulation, therefore we will discuss on each component of the optical system separately.

Chapter 5 presents data acquisition process we adopted in order to select appropriate shots for the analysis and moreover we will present in details the image analysis followed in order to obtain $n_e$ and $T_e$ profiles.
Chapter 6 presents the observations and interpretation of obtained $T_e$ and $n_e$ profiles for the case of recycling and puffing.

Chapter 7 comprises the conclusions and summary of the present work.
Chapter 2

Plasma edge processes and TJ-II stellarator

As discussed in the introductory part of this work, optimized control and the better confinement of the plasma is the priority task to solve for the fusion community. Confinement time is degraded and particles are lost due to the existence of the radial diffusion, neoclassical and anomalous transport and the theory gives rather optimistic predictions with respect to the experimentally obtained one. On the other side, full plasma control is not achieved to date, due to lack of knowledge about the edge plasma processes that are governing the plasma wall interaction. Moreover because of the presence of fast transport of particles and energy along the field lines in the machine, its walls are continuously subject to the heat loads where particles deposit their energy. Radiated power from the plasma can be absorbed on the walls leading to the additional heating.

Experiments revealed that in certain operational regimes in tokamaks plasma core processes are completely determined by the plasma boundary behavior. Plasma boundary, where steep gradients of $T_e$ and $n_e$ exists, sets the boundary condition for the confinement of the particles thus understanding cross-field transport and processes in the plasma edge is of major importance for the operation of the fusion reactor.

In this chapter will be discussed some fundamentals of the plasma edge and the concepts developed for better control of the plasma. Therefore we will present the concept of plasma boundary and its most relevant characteristics. Atomic processes leading to the visible emission in the plasma edge will be discussed briefly with emphasis on those relevant for TJ-II stellarator.

2.1 Plasma edge

The plasma edge can be understood as a transition region between the hot plasma core where magnetic field lines are closed into themselves so the main loss of particles and energy is their diffusion across the field lines in the radial
direction, and the Scrape-off Layer (SOL) region, where magnetic field lines are not closed into themselves and the transport of heat and particles along them is very fast (order of magnitude higher than the radial transport). Since field lines are not closed into themselves they are directed towards the walls of the machine therefore the heat and particles are also directed towards the walls, following the magnetic field lines. This fast transport puts constrain on the materials to be used as the first wall of the vessel because they have to withstand extreme loads of heat and particles and to control the production of the impurities released from the walls. These impurities can be later released back causing pollution of the plasma and increase of the power radiated from the plasma. This is the main mechanism of sudden plasma termination in the stellarators. In this sense plasma edge has to confine the core plasma in order to prevent heat and particles escaping from the plasma and to maintain ignition conditions in the plasma core.

2.1.1 Plasma wall control - Limiter and Divertor concept

Plasma in fusion machines is confined by the means of magnetic fields forming nested magnetic flux surfaces. Last Closed magnetic Flux Surface (LCFS) is defined by the contact point between plasma and plasma facing component (PFC). In order to localize plasma-surface interaction and prevent erosion and damage of the vessel walls, due to the fast parallel transport, two concepts in fusion devices are developed: limiter and divertor concept.

The limiter is an object inserted into plasma chamber and intersects closed magnetic surfaces, therefore the position of the LCFS is defined by the limiter position, see Figure 2.1. Limiter separates hot plasma core, where ignition condition takes place, from the Scrap-Off Layer where magnetic field lines are not closed into themselves and the power is redirected toward the walls of the device. Transport of heat and particles is fundamentally different in these two regions: in the plasma core the particles are drifting across the magnetic field lines, while in SOL region parallel transport, along $\vec{B}$, is dominant. Outside LCFS transport of particles is very fast and directed toward limiter area where plasma-limiter interaction takes place. This causes erosion, sputtering and recycling of the particles which some of them are brought back to the plasma in form of neutrals causing dilution of the plasma fuel and its pollution. Choices for limiter materials are mainly light elements that can stand high heat loads. The major problem in the limiter configuration is that limiter is placed in close proximity to the plasma and it increases diffusion of the impurities inside, towards the plasma.

TJII operates in the limiter configuration. It has a toroidal limiter, and two poloidal limiters that can be additionally inserted.

Divertor configuration is achieved by means of external extra coils with the currents alternating magnetic field of the machine and generating magnetic null (X-point). Magnetic field line crossing X-point creates last closed flux
2.1 Plasma edge

surface known as separatrix. Outside the separatrix radial diffusion of the plasma meets the fast parallel transport along the field lines, so that particles and energy are deposited on the divertor target plates. The divertor concept is preferential with respect to the limiter configuration. It better protects plasma from the impurity accumulation because the divertor plates are placed far away from the plasma but requires larger space in the fusion machine and tends to focus heat loads on the small area of the divertor.

Figure 2.1: Poloidal cut of magnetic flux surfaces in limiter (left) and divertor (right) configuration. SOL region is marked in yellow
2.2 The Srape-Off Layer (SOL)

SOL is the region outside the LCFS. In order to describe processes in this part of plasma boundary, different approaches can be used: ‘simple’ and ‘complex’ SOL model [9]. In any case, both SOL models are based on the features of the following scenario:

When plasma is in contact with any solid surface (limiter, divertor plates, probes), voltage difference spontaneously develops between plasma and the surface, called floating potential. The surface will become potentially negative and potential drop will develop in a thin sheath developed between plasma and the surface. The length scale of the sheath is of the order of Debye length. The sheath has accumulated positive net charge since plasma electrons are repelled by the negative surface. This positive net charge shields the plasma from the potential of the solid surface. Because of the imperfections of the sheath small residual field penetrates into plasma forming pre-sheath. Potential drop of the pre-sheath is small $\approx kT_e/2e$ and accelerates ions from the plasma towards the sheath. At the sheath/plasma interface ion drift velocity is equal to the ion acoustic speed ($Bohm$ criterion):

$$v_\parallel = c_s = \sqrt{k(T_e + T_i)/m_i}$$

Consequence of the sheath formation is that ions are accelerated towards the solid surface (i.e. limiter) with higher energy than the one associated with ion temperature $T_i$. Sheath also controls the rates at which particles and energy are removed from the plasma and estimated ion flux density out of the plasma is: $\Gamma_s \approx 0.5 n_0 c_s$, with $n_0$ as the plasma density in the core.

Due to the presence of the sheath and higher ion impact energy, the ion sputtering is increased. There is also tendency for inequality $T_i > T_e$ in the SOL since high energetic electrons from the distribution tail are escaping from that region and opposite, high energy ions are accelerated towards the sheath. Another reason is that the backscattered ions tend to bring a certain fraction of their impact energy back to the plasma. Depending on the ratio of $T_e/T_i$ this process can result in a net cooling of heating of the plasma ions. Since LCFS is defined by the position of the limiter processes in the SOL are strongly influenced by the presence of the limiter and formation of the sheath.

Scheme of the simple SOL is presented in the Figure 2.2. The main sink of the particles and heat is their fast flow along the field lines towards the limiter. The main source, if we neglect local ionization of neutrals (this is not valid for the complex SOL model), is the cross-field diffusion governed by the Fick’s law $\Gamma_m = -D_\perp dn/dx$, where $D_\perp$ is cross-field diffusion coefficient. An important parameter of the SOL is the connection length, $L_c$, a length that plasma must travel along the SOL, following the field line, to reach the limiter. The strength of the limiter sink is inversely proportional to the $L_c$. For a device with single poloidal limiter $L_c \approx \pi R$ and for toroidal limiter $L_c \approx \pi R q$, where $q$ is the safety factor of toroidal machine, defined as $q \equiv r B_T/R B_p$. Values
2.2 The Srape-Off Layer (SOL)

Figure 2.2: Schematic of cross-field diffusion from the core plasma across the field lines ($B_{\text{perp}}$) in the simple SOL and the fast transport along the field lines ($B_{\text{par}}$) towards the limiter.

of connection lengths for fusion devices are in order of tens of meters, i.e. for JET $L_c = 40$ m.

Equating cross-field and parallel particle flux, radial SOL length is:

$$\lambda_{\text{SOL}} = \sqrt{\frac{2D_{\perp}L_c}{c_s}} \quad (2.2)$$

For a typical tokamak edge parameters with $D_{\perp} \approx 1 \text{ m}^2/\text{s}$, connection length $L_C = 10$ m and the strength of the magnetic field $T_e = T_i = 50 \text{ eV}$, estimated SOL length is $\lambda_S = 30 \text{ mm}$. And the SOL confinement time:

$$\tau_{\text{SOL}} = \frac{L_c}{c_S} \quad (2.3)$$

This simple SOL model is good to understand some basic properties of SOL. The complex SOL model takes into account formation of the radiative layer (RL) in the plasma boundary that can extend to a SOL region, and in this case atomic processes strongly influence local energy and particle balance. In the complex SOL model the source of the plasma particles is mainly ionization of the neutrals inside the SOL. The incoming flux density of neutrals can be expressed as [10]:

$$\Gamma_n = n_n v_n = D_{\perp} n_e(a)/\lambda_n \quad (2.4)$$

where $\lambda_n$ is the density scrap-off length, characteristic gradient length, and when ionization becomes an important particle source it tends to increase $\lambda_n$ [9]. This broadening of the SOL would decrease heat loads on the limiter and screen the limiter from the impurities.

The formation of the radiation layer at the plasma edge determines the maximum plasma density at which the machine can operate. The total fraction...
of radiated power from the plasma increase with the average electron density \(<n_e>\) and can reach levels close to the total input power. Once this scenario occurs the plasma starts to shrink, therefore plasma radiation from the edge becomes dominant and plasma may ‘detach’ from the limiter. There is always the competition between core and edge radiation and when the edge radiation dominates, plasma experience radiation collapse. This effect starts locally at the plasma edge, where local cooling of plasma takes place and plasma shrinks and moves radially inward. This termination of plasma due to the radiative collapse is observed on the raw plasma videos recorded during our experiment in TJ-II stellarator and is happening because once the \(T_e\) drops, the reaction rates of the reactions responsible for maintaining the plasma falls down exponentially, so plasma collapses, see Figure 2.3.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2.5</td>
<td>(e + H_2 \rightarrow e + 2H(n = 1)) dissociation</td>
</tr>
<tr>
<td>2.2.6</td>
<td>(e + H_2 \rightarrow e + H + H^*) excitation from (H_2)</td>
</tr>
<tr>
<td>2.2.9</td>
<td>(e + H_2 \rightarrow 2e + H_2^+) molecular ionization</td>
</tr>
<tr>
<td>2.2.12</td>
<td>(e + H_2^+ \rightarrow e + H^+ + H(n = 1)) ionization from (H_2^+)</td>
</tr>
<tr>
<td>2.2.14</td>
<td>(e + H_2^+ \rightarrow H(n = 1) + H^*) excitation from (H_2^+)</td>
</tr>
</tbody>
</table>

Table 2.1: Most relevant atomic and molecular reactions for ionizing plasma conditions; low density, high temperature TJ II plasmas.

![Figure 2.3](image_url)

Figure 2.3: Reaction rates of most relevant TJ II plasma reactions listed in the Table 2.1.

### 2.3 Atomic and molecular processes in the edge plasma

Formation of atomic and molecular neutrals is important for the SOL including recycling of the fuel ion species at the solid surface, chemical and physical
sputtering of the plasma facing surfaces, gas puffing of the plasma fuel species or intentionally puffed impurity species.

When an incident ion, coming from the plasma and accelerating in the plasma sheath, strikes the solid surface it recombines forming a neutral atom or molecule, later released back or it recombines on the surface and can be deposited there. Release mechanisms may be different, depending on the nature and energy of incident particle, the temperature of the wall, type of the target atoms and angle of incidence of impinging particle onto the surface. This released particles undergoes different atomic processes, some of them being sources of visible emission in the plasma boundary.

Incident ions can be backscattered as an atom or molecule after recombination with electrons on the wall in the process of recycling. This is also the simplest refueling case, and when recycling coefficient reaches the unity (all ions reaching the wall are brought back into the plasma as neutrals) external fueling sources can be switched off. Recycling can maintain a constant plasma density and its flat profiles. Since peak profiles are preferential for reactor operation, core fueling can be maintained by pellet or neutral beam injection.

Atom from the plasma facing components can be released by physical sputtering due to momentum transfer between the incident ion and the wall. These mechanisms are generally the major source of impurities inside the plasma. Plasma impurities are mainly medium/high-Z elements that emit line and bremsstrahlung radiation. This mechanism reduces the core temperature and induces the formation of hollow temperature profiles. Low-Z impurities generate the formation of a radiative layer mainly in the boundary region of the plasma (until they reach the core they are completely ionized, therefore cannot be excited) with strong line radiation, leading to the radiative collapse of the plasma. This effect starts locally at the plasma edge, where local cooling of plasma takes place and plasma shrinks and moves radially inward. Since radiation power is proportional to the product \( n_e \times n_{imp} \) this mechanism sets up the upper density limit, and since stellarators can exceed Greenwald limit for tokamaks, this would be the upper limit of density valid for stellarator machines. Reported scaling low for W7-AS shows that the threshold densities at the edge scale as \( n_{es} \propto P_s^{0.5} D^{0.8} \) where \( P_s \) is the net power crossing the LCSF \[7\] therefore are determined only by the power crossing the LCFS and not the total radiated power. Impurity influxes can be measured by means of visible emission spectroscopy, and the impurity influx is estimated as \[9\]:

\[
\Phi_{imp} = 4\pi \frac{\bar{\sigma}v_i(T_e)}{\bar{\sigma}v_{lm}(T_e)} \times \frac{I_{ph}}{b_r} \tag{2.5}
\]

where \( \bar{\sigma}v_i(T_e) \) and \( \bar{\sigma}v_{lm}(T_e) \) are the average ionization and excitation rate coefficients, and \( b_r \) is the branching ratio. This requires knowledge about edge electron temperature since the rate coefficients are dependent on it and for the experimental setup absolute calibration would be required. He line ratio technique in our studies was applied for the case of He recycling and also with active gas He puffing. Gas was puffed through the hole in the limiter, with the
observation system looking tangentially on it. This is an active spectroscopic method and the level of local plasma perturbation depends on the puffing rate. For the low puffing rates we concluded that the perturbation level is very local and very low.

Sputtered and recycled atoms are released back into the plasma and can undergo different atomic processes. Released particles have different energies, depending on their release mechanism, therefore they can experience different reactions and be a source of the visible light emission in the plasma edge described in the following section.

2.4 Sources of visible emission

Line radiation due to de-excitation: Atoms and molecules can be excited by i.e. collision with the electrons or ions to a higher energy state than the fundamental state. After a certain time, the atom/molecule decays into a lower energy state emitting a photon of energy equal to the energy difference between two levels \( \hbar \nu = E_2 - E_1 \), where \( E_2 > E_1 \) are the energy of the respective levels and \( \hbar \) is the Plank constant). The frequency of this emission can be in visible range. This radiation has a narrow width and can be broadened due to the different mechanisms (i.e. Doppler broadening) and is the characteristic frequency for a given species. Can be used for identification of the species present in plasma. This is the reason why by means of optical emission spectroscopy one can know exactly which elements are present in the machine simply by looking into their characteristic emission lines with spectrometers. Intensified fast cameras with narrow band filters are also capable of such studies and are especially important since filtering the light leads to reduced intensity. Therefore light amplification is needed and can be easily achieved by an image intensifier.

Another source of visible emission in the plasma is Blackbody radiation. Everything that has a temperature above absolute zero emits electromagnetic radiation. At room temperature most of the radiation is in infrared spectral region and shifts towards visible and UV as temperature increases. It is very common to see visible Blackbody radiation coming from the wall of fusion devices due to the overheating. Langmuir probes that are mounted on the poloidal limiter of TJ-II gets overheated and emit Blackbody radiation in a visible range. Generally speaking, visible Blackbody radiation can be detected when the surface temperature is above 1000 Celsius.

Visible Bremsstrahlung radiation is an electromagnetic radiation that is emitted when charged particle is deflected by another charged particle (an electron decelerated by an ion for the case of plasmas). Bremsstrahlung has a continuous spectrum, and usually radiation is in x-ray regime. In a visible range it has been reported in the high density machines, but TJ II is a low density/high temperature device therefore this type of visible radiation in practically not present in our experiment.
Dominant visible emission in TJ-II plasmas comes from the de-excitation of hydrogen, He and radiation of the low-Z impurities. In our experiment we collected light coming from the He using interference filters, therefore line radiation due to the de-excitation of helium is the most important light source for our experiment.

2.5 TJII

TJ-II stellarator is a medium size flexible heliac machine, see Figure 2.4 installed at Spain’s National Fusion Laboratory, CIEMAT. Some of important parameters are listed in the Table 2.2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major radii</td>
<td>1.5 m</td>
</tr>
<tr>
<td>Minor radii</td>
<td>0.22 m</td>
</tr>
<tr>
<td>B</td>
<td>1 T</td>
</tr>
<tr>
<td>( \frac{\iota}{\pi} )</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Table 2.2: Some parameters of TJ II

The flexible Heliac TJ-II is the project done by CIEMAT, with partial financial support from EURATOM. Construction of TJ II started in 1990 and the first plasma was produced in 1997 [11].

TJ II is a four period machine and the magnetic topology is generated by means of various sets of coils that completely determine the magnetic surfaces before plasma initiation. The toroidal field is created by 32 coils. The three-dimensional twist of the central axis of the configuration is generated by means of two central coils: one circular and one helical, see Figure 2.4. The horizontal position of the plasma is controlled by the vertical field coils. TJ-II discharges are about 0.3 s long and can be repeated approximately every seven minutes.

Figure 2.4: Schematics of TJ II field coils and shape of the plasma (Image from the Ref. [12] )
In the TJ-II stellarator, the plasmas are created and heated by two ECRH gyrotrons, each of them delivering up to 300 kW in of nominal power, and with two neutral beam injectors (NBI), each of them can produce $\leq 300 \text{ ms}$ pulses of neutral hydrogen accelerated to 40 keV, to provide up to 1.2 MW of absorbed additional heating for central electron densities up to $1.6 \times 10^{20} \text{ m}^{-3}$.

The TJII vacuum vessel is made out of stainless steel and plasma wall control is mainly localized at the helical limiter, but additionally two poloidal limiters can be inserted such as for the case of our study. Wall conditioning is made with boron, carbon and lithium coatings and helium glow-discharge.
Chapter 3

Visible spectroscopy to characterize the plasma edge

As mentioned in the previous chapter atomic emission lines are footprints of the species present in plasmas. Human eye is sensitive to the visible range of the electromagnetic spectrum therefore the detection systems for the visible range are very developed and accessible. Collecting the visible light coming from the plasma gives a valuable information about plasma species and characteristic parameters such as $T_e$ and $n_e$ can be deduced from the atomic emission lines.

In this work we deduce plasma edge $T_e$ and $n_e$ by means of emission spectroscopy in the visible range. This method can be categorized in active and passive spectroscopy. Active spectroscopy would mean that we probe plasma locally-by radiation or injected particles (Laser beam or Atomic beam, respectively). If we just observe light coming from the plasma as a result of the atomic processes, without any external atomic or light sources, then we talk of passive spectroscopy. In order to correctly interpret visible emission coming from the plasma, all atomic processes have to be taken into account. If we keep in mind that plasma consists of neutrals (atom, molecules), ions and electrons, in order to interpret emission light we have to take into account all the possible combinations of collisions between the particles but also some other processes specific for specific plasma conditions (i.e. very high density plasmas). The processes involved in population/depopulation of excited level are characterized by their reaction rates and can be listed as (but are not limited to):

- Electron impact excitation/de-excitation: $(q^e_{j\rightarrow i}/q^e_{i\rightarrow j})$;
- Ion impact excitation/se-excitation : $(q^i_{j\rightarrow i}/q^i_{i\rightarrow j})$;
- Electron impact ionization: $(S^e_i)$;
- Ion impact ionization: $(S^i_f)$;
- Spontaneous decay: $((Aj \rightarrow i/Ai \rightarrow j)$;
3.1 Atomic beam emission spectroscopy

- Radiative recombination \([\alpha_i^{(r)}]\);
- Dielectronic recombination \([\alpha_i^{(d)}]\);
- Three-body recombination \([\alpha_i^{(3)}]\);
- Charge-exchange \((q_i^{C,X})\)

In its most general form Colissional Radiative Model (C-R) includes all the processes to simulate the population density of the species which emits the light. In most general words by the C-R model one can obtain population density of excited state (i.e \(i\)) taking into account all the possible population and depopulation processes (some of them listed above) of this state, characterized by their rate coefficients.

Rate coefficients are strongly dependent upon plasma parameters. In low density \((n_e < 10^{19} m^{-3})\) high temperature \((T_e > 10\ eV)\) plasmas, condition relevant for TJ II plasmas, electron collisions with atoms and molecules dominate. These reactions are sources of visible plasma emission in the plasma edge. When an electron density is low (which is often seen in astrophysical situations, such as in the corona region in the Sun), the plasma state can be described by a coronal model. In a coronal model, low electron density and radiation field makes collisional deexcitations and three body recombination insignificant. Collisional ionization or excitation is balanced by radiative recombination or spontaneous decay, respectively. Taking into account simplifications in low density regime plasmas, C-R model can be quite simplified.

This thesis is devoted to extraction of \(T_e\) and \(n_e\) in the plasma edge from the ratio of visible emission lines of He. In order to do so plasma had to be supplied by helium which is done in a simple way taking advantage of the poloidal limiter inserted into plasma with a possibility of He puffing through the hole made in the limiter or He recycling on the limiter. This falls in the domain of well developed technique known as atomic beam spectroscopy.

In the following we will present the basis of atomic beam spectroscopy together with the He-line ratio technique as the basics of our work.

3.1 Atomic beam emission spectroscopy

In fusion devices plasmas are magnetized and only neutral particles are allowed to penetrate into it. After injection they interact mainly with plasma electrons and ions through the processes listed in the previous section. It is important to note that this approximation is valid also for the case of the recycling, since recycled neutrals are entering plasma like a beam from the limiter [13]. Once injected, the density of neutral atoms drops until all atoms are ionized. So the penetration of the atomic beam is dependent on its ionization energy. In order to extract relevant plasma parameters it is very important to assure that atomic beam does not perturb the plasma locally and, whether the perturbation will happen or not, depends on the energy of the injected particles. When
using thermal He beam (low energy beam) only electron-atom interactions can be taken into account so the C-R model is quite simplified. These thermal beams have energies below 0.1 eV and can be delivered to plasma continuously. In our experiment puffing rates are kept low in order to avoid local perturbation for the case of puffing. For the recycling case it has been checked that 50% of the He energetic neutrals do not contribute to the emission above the limiter while the rest 50% are desorbed He atoms building up the density cloud in front of the limiter and their energy falls below 0.1 eV [14]. Validation of atomic beam diagnostics relies strongly on atomic database and for the operational range of fusion plasmas C-R model has been developed and improved.

When the beam atoms enter the plasma, they are excited and ionized by inelastic collisions mainly with electrons (ionizing plasma conditions). These processes are dependent on electron density and temperature.

In optically thin plasma intensity of spectral line (number of emitted photons per unit solid angle) of a transition between two states $i > j$ is:

$$\varepsilon_{i,j}(r) = \frac{h \nu_{ij}}{4\pi} n_i(r) A_{i\rightarrow j}$$

where $n_i$ is particle density in the excited state $i$ and $A_{i\rightarrow j}$ is rate coefficient of spontaneous emission, Einstein coefficient. Integrating over the line of sight $dl$ gives measured line intensity:

$$I = \int \frac{h \nu_{ij}}{4\pi} n_i(r) A_{i\rightarrow j} dl$$

Taking into account that population density of the atom beam is mostly in the ground state $n_1$, CRM relates population density of excited state to population density of the beam, depending on the plasma parameters. In the simple approximation, coronal equilibrium model can be applied, where balance of population/depopulation of excited state is achieved by electron impact excitation ($q_{e_{i\rightarrow j}}$)/spontaneous emission ($A_{i\rightarrow j}$), respectively. Balancing those two processes can give us information about the population density of the excited state $i$. Hence, in this model equality holds:

$$n_e n_1 q_{e_{i\rightarrow j}} = n_i \sum_{j} A_{i\rightarrow j}$$

where $n_e$ is the electron density and rate coefficient for electron impact excitation is a function of $T_e$.

Now with this simple approximation and integration of line intensity over the volume and observation time will give us dependence of $I$ on the electron population density and the beam density:

$$I(r) = \frac{1}{4\pi} n_e(r) n_1(r) q_{e_{1\rightarrow i}}$$
3.2 He-line ratio technique

Equation (3.4) expresses the line intensity in terms of electron density $n_e$, population density of the neutrals $n_1$, and the reaction rate for electron impact excitation $q_{f\rightarrow i}$ that brings the neutral from the fundamental to the excited state, $i$. Excitation rate coefficients have different dependencies on $T_e$ or $n_e$ for different species.

The idea behind He-line ratio technique is that from the intensities of two different emission lines it could be possible to deduce electron temperature providing that ratio of the excitation rate coefficients does not depend on the density or this dependence is known.

Some of the first calculations for excitation rate coefficient have been done by Brenning [15] but other rate coefficients necessary for determination of the population of exited level for He were rather poor at that time for the result to be reliable. C-R model for a thermal He-beam entering the plasma boundary was first developed in TEXTOR tokamak [16] for the low density, high temperature edge plasmas. Other C-R models were developed and applied to other fusion devices like in reversed field pinch [17]. Model from TEXTOR has been already applied for the TJ-II stellarator [8]. It has also been reported that He ratio technique can be implemented for the case of He recycling on a limiter [14]. Fast beam He emission spectroscopy has been developed in MST [18].

Edge plasma parameters (low density, high temperature) in TJ-II stellarator are similar to those of TEXTOR, therefore C-R model of TEXTOR is used to extrapolate applicability of He-line ratio technique to TJ-II stellarator. In the following we will present the basic idea behind development of the CRM for TEXTOR [16].

Thermal He-beam population has been calculated up to the main quantum
number \( n=4 \). Providing that velocity of the atomic beam is constant, stationary, simple coronal equilibrium is applied (with the assumption that ionized He atoms are lost due to magnetic forces) and with the initial conditions on \( T_e \) and \( n_e \) are assumed to be known (the range of TEXTOR edge parameters). Then the calculated equilibrium population density is fitted to an exponential function:

\[
n_i(t) = n_i [1 - \exp(-t/\tau_r)]
\]  

(3.5)

For the range of \( 10^{17} < n_e < 10^{20} \) m\(^{-3} \) and from \( 10^3T_e \) to 1000 eV the longest relaxation times \( (\tau_r) \) are presented in the Figure 3.2. Taking into account that the longest relaxation times (time to establish equilibrium) needs to be longer than decay time of the plasma parameters the lower density limit is set to \( 10^{12} \) m\(^{-3} \). The upper limit is set by the ionization of the He. After obtaining the population densities line ratios for all allowed transitions were calculated and had shown a good agreement with the experiments. Moreover three emission lines were selected since their ratios had shown either strong dependence on electron temperature or the density and they are, (see Figure 3.1): \( \lambda_1 = 728.13 \) nm with \( 3s^1S \rightarrow 2p^1P^0 \), \( \lambda_2 = 706.52 \) nm with transition \( 3s^3S \rightarrow 3p^3P^0 \) and \( \lambda_3 = 667.82 \) with transition \( 3d^1D \rightarrow 1p^1P \). Those lines are also very accessible: they are very strong in the visible range which makes them easy to detect, and also they are lying in the relatively narrow region of the visible spectrum. The intensity ratio of \( \lambda_1 \) and \( \lambda_2 \) is used for \( T_e \) measurements since it is weakly dependent on \( n_e \), and ratio of \( \lambda_3 \) and \( \lambda_1 \) is only weakly dependent on \( n_e \).

\[
R_{T_e} = \frac{I(728nm)}{I(706nm)}
\]

(3.6)

\[
R_{n_e} = \frac{I(667nm)}{I(728nm)}
\]

(3.7)
3.2 He-line ratio technique

Later on systematic calculation of all possible ratios is done for different
temperature and density conditions. This data set is valuable and is used for
simultaneous measurements of \( n_e \) and \( T_e \), see the Figure 3.3. Dashed lines
present \( R_{n_e} \) and are sensitive on \( n_e \) and only weakly on \( T_e \). Solid line \( (R_{T_e}) \)
shows only weak dependence on \( n_e \) and strong on \( T_e \). Line intensity ratio
cannot be applied for \( T_e < 10 \text{ eV} \). It can be seen that lower limit for the mea-
surement of the electron density is about \( 2 \times 10^{18} \text{ m}^{-3} \) where the relaxation time
is too long and the typical decay lengths of the plasma parameters are shorter
than the relaxation length. Recently hybrid time dependent/independent line
ratio solutions has been developed [20] that improves the range of application
of TEXTOR model.

Intensified fast cameras looking at the polidal limiter tangentially filter he-
lium lines. With two bundles it is possible to record two emission He lines
simultaneously, therefore apply He-line ratio technique. This technique is very
desirable because it does not require an absolute calibration of the system.
In the [14] it was reported that 1D profiles and 2D images were successfully
obtained within the TJ II limits using the data set of TEXTOR and are in a
good agreement with other edge diagnostics (Thomson scattering, reflectrom-
etry). Those studies were done with a passive He emission (recycling) in front
of poloidal limiter and extraction of \( T_e \) and \( n - e \) for TJ-II conditions can be
found there. Work of this thesis is mainly continuation of reported results for
TJ-II is extended to determination of \( n_e \) and \( T_e \) profiles for both scenarios, He
puffing through the hole made in a limiter and He recycling on the limiter.
The main accent is on the neutral beam injection (NBI) phase of the discharge
where certain density and temperature thresholds have put the limits on a
plasma duration. Before reporting the results of our study we will devote a
big part of this work in order to explain experimental technique used in this
experiment.
Chapter 4

Experimental setup

As we already mentioned, the valuable information about plasma edge can be deduced by means of non perturbative spectroscopic method and the information can be delivered continuously allowing to study the dynamics of the processes inside the plasma. Detection system of our experiment is the intensified fast camera equipped with the double bundle so the He-line ratio technique can be applied. This means that we are able to record two emission He lines simultaneously and continuously. Ratio of the two recorded emission lines provide the information on electron density or temperature as explained in the previous chapter. Schematic view on our detection system with all the components is presented in the Figure 4.1 and double image acquired with an intensified camera in the Figure 4.2.

In order to interpret results correctly an important requirement for experimental physicist is to understand each component of the diagnostic system. In order to do so we will present each component of the system separately with special care about the limits of the implementation of this diagnostics.
4.1 High speed cameras

High frame rate imaging began more than a hundred years ago with Eadweard Muybridge and his sequence of cameras that recorded galloping of the horse. Purpose of this photographic experiment was to determine whether the galloping horse ever lifts all four feet of the ground, because the human eye cannot resolve it for this speed of moving object [21]. In early 1930s Kodak developed the high speed cameras that ran the film on 1,000 frames per second [22] (fps) and was used by Bell Laboratories to study relay bounce. Ten years later, the rotating mirror high speed camera has been patented by Cearcy D. Miller and it was able to operate theoretically up to million frames per second. Based on the ideas of Miller, Harold Edgerton invented rapatronic camera, built by EG&G, for the purposes of Manhattan project in order to capture rapidly changing of matter during nuclear explosion, see Figure 4.3.

Nowadays high speed cameras have found its application in variety fields of science and industry. In the fusion plasma experiments the visible light is collected and analyzed with a spectroscopy approach, taking advantage of atomic processes, in order to understand and characterize the plasma and its interaction with the walls (erosion, recycling, etc) and tracking the dust particles accumulated in plasmas. An early reference of fast imaging dates from 1892 with an images from ASDEX and DITE [24]. These were high speed film cameras running at 5,000 fps for the plasma wall interaction studies and dust observation. A few years later visible imaging of edge fluctuation has been done in Tokamak Fusion Test Reactor (TFTR) [25]. Today, imaging diagnostics is ongoing on almost all fusion operating machines, some of them are: ASDEX-

\[\text{Figure 4.2: Double image obtained by an intensified fast camera. Region of interest is enclosed in the white rectangles. Limiter is placed below the white rectangles.}\]

1Eadweard James Muybridge (1830-1904), was an English photographer important for his pioneering work in photographic studies of motion
2Harold Eugene Edgerton (1903-1990) was a professor of electrical engineering at the MIT
Figure 4.3: Trinity nuclear test explosion photographed by fast camera less than 16 millisecond after detonation. Image from the Ref. [23]

Upgrade [26], COMPASS [27], Alcator C-Mod [28][29], DIII-D [30, 31], TJ-II [8].

With improvement of an image sensors and technology, the fast cameras acquired enormous recording speed, up to $10^6$ fps and they became especially important for studying fast events such as ELMs and turbulence. They are also important for tracking pellets as fueling system of the plasma core and, indeed, it is one of the next campaign experiments planned in TJ II stellarator.

During our work, we use a fast camera system to collect the visible light emission from He present in the plasma edge region in order to obtain electron density and temperature profiles. Using bifurcated fibre bundles we were able to record simultaneously a pair of emission He lines per discharge. In order to reduce error due to cross dependence of $T_e$ and $n_e$, it would be convenient to introduce third bundle so all three emission lines could be recorded simultaneously.

In this chapter we will explain the basics of the two main types of the visible sensor architectures. Then we will focus on the properties of each component of the optical system. At the end, we will discuss viewing geometry of TJ II stellarator with respect to the optical system.

4.2 Fundamentals of sensor architectures - CCD and CMOS

The main component of the optical system is the digital camera. Depending on the type of the image sensor, sensitive to visible light emission and the operation itself, they can be classified into CCD (Charge-coupled device) and CMOS (Complementary Metal Oxide Silicon) cameras. Both, CCD and CMOS image sensors operate by means of the photoelectric effect to convert light into electrical signals and both have to perform the same functions:

- To generate and collect charge
- To measure generated charge and convert it into voltage or current signal
4.2 Fundamentals of sensor architectures - CCD and CMOS

- To perform analog to digital conversion

What makes CCD and CMOS image sensors different is the way they are performing some of those operations.

![Figure 4.4: Photosensitive elements; photo-diode and photo-gate.](image)

Generation and collection of the charge is the first task of the image sensors. Incident photons are generating charge in photosensitive element during the exposure time. This element box can be photo-diode or photo-gate and is called a pixel, see Figure 4.4. Photo-diode has implanted ions in the silicon \(^3\) to create pn junctions that can store generated electron-hole pairs in the depletion region around the junction. On the other side, photo-gates use MOS capacitors to create potential wells to store generated charge. In both cases the generated charge will fill the well proportional to the number of photons hitting the pixel. After the exposure finishes, the relative quantity of photons in each pixel is sorted into various intensity levels and its precision is determined by bit depth. For an 8 bit image intensity level gray scale is 0-255. The pixel saturates when the amount of light absorbed by the pixel generate more electrons than needed to fill the well. Above this threshold charge will spill around in the neighboring pixels causing blooming and smearing of the output image. Sensitivity of the image sensor depends on the size of the photosensitive area (the bigger the pixel, the more photons are collected) and the efficiency of photoelectric conversion (known as quantum efficiency, QE). Quantum efficiency represents how many electrons are generated by an incident photon. It is also affected by the wavelength of incident light. Photo-gates can have up to 100% of the photosensitive pixel area because of the higher full-well capacity.

Major difference in two image sensor technologies is the charge transfer to the output node. CCD cameras use the serial shift register and only few amplifiers for a signal transfer, while CMOS systems use a parallel connection of amplifiers to transfer the voltage signal coming from each pixel on the silicon diode plate, see Figure 4.5. In other words, CCD moves signal from pixel to pixel, while CMOS converts the signal to voltage in each pixel. Later, analog signal can be processed by additional camera electronics but it is also possible

---

\(^3\)Energy gap between the valence and conductive zone of Si is about 1 eV. The energy of the incident visible light is higher than 1 eV.
4.2 Fundamentals of sensor architectures - CCD and CMOS

Figure 4.5: CCD sensors move generated charge from pixel to pixel and convert it to a voltage in an output node; CMOS sensor converts charge into voltage signal inside each pixel.

to place digitization on the sensor. High output uniformity of CCD sensor guarantees higher quality images than CMOS, but CMOS sensor technology converts visual information to digital data more quickly than CCD sensors. Also, the major advantage of CMOS cameras is that they are low power devices, requiring lower voltage, having longer battery lifetime, therefore they are of major use in commercial purposes.

TJ II camera group has, at the moment, two high speed cameras. One CCD camera with built-in intensifier (ICCD), and one CMOS camera coupled with an image intensifier, Figure 4.6. Example of CMOS camera shot, made at a frame rate near the operational limit, with view on poloidal limiter is presented in Figure 4.7.

In our experiments we used intensified CMOS camera coupled with an image intensifier. It is a Photron FASTCAM SA1 intensified camera. This camera operates in full frame of 1 Mpx (1024 x 1024 px) resolution at 5,000 fps recording speed but it can go up to 675 kfps at resolution of 64x16 pixel and 12 pixel bit depth, Table 4.1 It has 8 Gb of internal memory. During the experiment, the usual practice is to store recorded video on the PC before the next discharge. The camera is remotely controlled by the PC in the control room.

Camera parameters

Technical details of the camera will be presented here:

Frame rate stands for the recording speed of the camera. It is a number of frames recorded in one second (fps). Usual practice during our experiment was to record videos at $2 \times 10^5$ fps. This parameter determines time resolution of the diagnostics.

Exposure time is also called camera integration time and is the time for
which camera shutter remains open. It sets the spatial resolution of an image. For a good image the exposure time must be set such that \( 1/\tau_{\text{exp}} \) is always greater than or equal to the speed of the moving object else the image will be blurred. This is very important when studying fluctuations.

**Intensifier exposure time** \( \tau_{\text{exp}}^I \) is parameter relevant for cameras coupled with an intensifier, such as our case. The collecting of the light by an intensifier is controlled by this parameter and intensifier is triggered by applying a voltage on it. It behaves as another shutter and effective exposure time is indeed, intensifier exposure time.

**Dead time** is the time between the frames where no image is acquired.

**Trigger time** is the time when the camera starts operating and is remotely set from the control room few ms before the discharge, see Figure 4.8. This is also a good time reference for relating our optical system with other diagnostics.

**Resolution** of digital sensor is expressed as a number of pixels in the sensor. Precision at which pixel determines the intensity (number of generated free electrons) is called bit depth. The maximum pixel resolution in CMOS camera is \( 1024 \times 1024 \) up to a camera speed of \( 5400 \) fps and decreases to a resolution of \( 64 \times 16 \) at the maximum speed of \( 6.5 \) kfps. The variation of the pixel resolution with the speed is shown in Table 4.1.
<table>
<thead>
<tr>
<th>Frame Rate [fps]</th>
<th>Maximum resolution [pix]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Horizontal</td>
</tr>
<tr>
<td>1000</td>
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<tr>
<td>2000</td>
<td>1024</td>
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</tr>
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</tr>
<tr>
<td>300 000</td>
<td>64</td>
</tr>
<tr>
<td>675 000</td>
<td>64</td>
</tr>
</tbody>
</table>

Table 4.1: Frame rate specifications for Photron SA1 camera
4.3 Image intensifier

Low visible signal in the plasma edge is a consequence of more reasons. It could be due to filtering of atomic lines, requirements for very short integration times, less than 1\(\mu\)s, or low concentration of the species which emission lines needs to be recorded. These events require image intensifier that can amplify the signal coming from the plasma. Therefore they are designed to be very sensitive to light flux, and indeed are very vulnerable for long exposure times and high fluxes, hence operation and coupling to the camera has to be done carefully. Camera group of TJ-II has done coupling as recommended by a Hamamatsu manufacturer and operation itself is done remotely from the control room. In our experiment we used two intensifiers C9548-03BL and the C10880-03S. Both intensifiers include two step intensification of GENI and GEN II components, schematically presented in the Figure 4.9.

Typical image intensifier consists of photo-cathode that converts incident light into electrons, a micro-channel plate (MCP) that multiplies the electrons and a phosphor screen that reconvert the electrons into light. Those components are set in a close proximity design and therefore the photo cathode delivers the image to the phosphor screen with very low distortion. Types of image intensifiers are classified in generations-GEN. Our image intensifier consists of two GEN types: GEN I and GEN II. GEN I does not use MCP and its amplification is fixed (amplification factor of 50) while GEN II multiplication is regulated by the MCP voltage. Applied MCP voltage can vary from 600 V to 800 V for different exposure times although in the expense of spatial
4.3 Image intensifier

resolution. This effect has been studied in [32] using a reference pattern and images acquired in this experiment are presented in the Figure 4.10.

![Image of the operating principle of the two-stage C9548-03 image intensifier. Image from the Ref. [33].](image)

**Figure 4.9:** The operating principle of the two-stage C9548-03 image intensifier. Image from the Ref. [33].

The test target was kept away 1.3 m, which is the same distance as the focal plane at the TJ II limiter from the viewing chord and was done with a 50 mm objective. The first image on the left was obtained without intensifier and the other two are with 700 V and 800 V applied voltage, respectively. Images are recorded with different exposure times so as to get a similar signal level: 1 ms, 12.5μs and 4μs, respectively. For lower exposure times (12.5μs) and no intensification, an image was not resolved. With intensification of 700 V 1 mm line was resolvable, and for 800 V intensification 2 mm line could be

![Test target images and their intensity profiles](image)

**Figure 4.10:** The test target images and their intensity profiles along the vertical arrow without image intensifier (left), with intensifier at 700 V (center) and 800 V (right), respectively. (Image from the Ref. [32])
resolved although smearing and blooming of an image increases with applied voltage. Fluctuations of the intensity profile along the arrow, for image with no intensification, are the real intensity profile produced by the matrices of the fibres. It has been concluded that spatial resolution is satisfactory for plasma emission in the edge especially because sharp profiles are rarely present.

In the same publication it has been reported that intensifier does not saturate for this range of applied MCP voltage (600 V-800 V). GEN II intensifier has a photo-cathode of 25 mm and by MCP is connected with a phosphor screen of P-46 type. Image intensifier has two built-in protection systems for over-light protection and auto shutdown protection for high integrated line intensity operation. During our experiment intensifier was operating in this voltage range.

4.4 Bifurcated coherent fibre bundle

Because of the presence of a magnetic field and space restrictions, electronics and optical system of fusion devices should be kept away from the viewing port. In the TJ II case in front of the viewing port only objectives are mounted to the end of the optical fibre bundles. Coherent fibre bundles are transmitting the light from the plasma to the relay optics coupled with intensifier. Bundles are very flexible. Manufacturing of the bundles introduces light losses in the system. Light that is transmitted along the fibre bundle can be scattered from the true geometric path for different reasons: imperfections in the bulk of the fibre, irregularities in the core/cladding interface of the bulk and surface scattering upon entry. Transmitting losses increase with the length of the bundles. The fibre bundles of the optical system in TJ II are custom made by company Schott. Each bundle of our system is 4.5 m long, with a square cross section of 36 mm$^2$ (6x6 mm) with 50 fibres/mm. This corresponds to 300 x 300 fibres per each branch. The bundle bend radius is 10 cm and the maximum operating temperature 120 $^\circ$C. Transitivity of the bundle of this length is about 20% -30% for wavelengths higher then 500 nm and drops for shorter wavelengths, while 1 m long bundles have significantly higher transmittance, of about 40%

4.5 Relay-lens optics

The relay-lens optics is designed to transport the image between fibre bundles and intensifier on one side, and intensifier and photo-sensor of the camera on the other (see the scheme on the Figure 4.1). Relay-lens system design requires proper magnification so to place the whole image onto the photo-sensor of the intensifier and also onto the sensor of the camera. Depending on the application, different relay optic systems can be used. For low light emission processes it is better to have smaller magnification therefore place the whole image onto the photo sensor and obtain more luminous image. This
way active area of the photo-sensor is smaller but image quality is improved. Moreover, when operating at high speeds, only a small part of the sensor is active, therefore it is necessary to re-size an image so to place it onto the active sensor area using relay optics. This also can be done by changing the focal length of the objective thus varying field of view. Camera group of TJ-II has four systems with different magnification in the range of -1 to -2.5. In our experimental setup first relay optics system lens has magnification M=-1.7 and is constructed out of two 50 mm diameter achromatic lenses of 150 mm and 100 mm focal length, mounted with C mount and F-mount adapter at its ends. The system was optimized with and optical design software ZEMAX. In Figure 4.11 typical relay lens design is presented together with a simulation of the object and an obtained image on the image plane.

![Figure 4.11: Typical lens layout design and ray tracing of one relay lens system (up). Corresponding simulation of the object and image (down). Image from the Ref. [32]](image)

Relay-lens optics that transports the image from an image intensifier to the photo-cathode of the camera is commercial with magnification of M=-1, constructed by Hamamatsu.

### 4.6 Objective Lenses and support structure

Objective lens collects the light coming from the plasma and focuses the light rays into onto the bundles. TJ-II camera group has three objectives of 50 mm diameter but of different focal lengths, 35, 50 and 75 mm. Different experiments require different focal lengths depending on the desired field of view and magnification. Aperture of the objective can be controlled manually so to have more or less light intensity coming into an optical system, by adjusting the iris of objective. The aperture stop of the lens is specified by F-number (F/#) and determines the amount of light reaching to the sensor. It is defined as the ratio of focal length (f) and effective aperture diameter (D). Incident flux is proportional to the area of the aperture and the inverse square of F/#.
4.6 Objective Lenses and support structure

A simple way of manipulating the light flux is to change the F/#. However, there is a difference between collected light and useful light. Low F/# lenses are collecting more light but lens aberration determines the quality of light beam. Lens aberration increases rapidly with lesser F/# and optical system cannot focus poor quality beam into an output image.

For density measurements we used ratio of 667 and 728 nm He lines. Relative intensity of 667 nm He line is much higher then of 728 nm line and with completely opened iris, videos of recorded 667 nm line could be saturated. Therefore objective with 667 nm filter line was adjusted to F/4 and iris of the 728 nm objective was completely opened, F/1.8. For this we obtained correction factor as follows:

![Histogram of an averaged image sequence of the white pattern with F/1.8 (left) and F/4 (right), respectively. Note the mean value of gray scale counts that is used for the calculation of the correction factor.](image)

White pattern was irradiated from light source placed far away so to obtain a sequence of images for different F numbers, F/1.8 and F/4 respectively. Averaging over few frames we obtained final 16 bit grayscale images in both cases. Mean value of counts is obtained from histograms of each average image, see Figure 4.12. From ratio of the mean values of the two we obtained correction factor of light influx for F/4, $C = 2.6$. That is, for the same light intensity light flux is 2.6 times lower for F/4 than for F/1.8 due to the smaller aperture area. He 667 emission line is corrected for this factor while processing the data.

The lenses are mounted on a supporting structure presented in the Figure 4.13 with a small tilting angle so to have the same field of view. Tilting angle depends on the object distance and in our case is about 1° for the object distance of 1.3 m. In bifurcated fibre bundle case this angle can introduce some non similarity between the same view chord and during image processing this is corrected by commercial software for image analysis.
4.7 Interference filters

Interference filters are optical filters that reflect one or more spectral bands and transmit others. They can be divided into high-pass (transmits high frequency light above the cutoff frequency), low-pass (transmits the light lower than a cutoff frequency), and band-pass filters (passes the frequencies within a certain range).

![Support structure for objectives.](image)

**Figure 4.13**: Support structure for objectives.

![Specifications of a 667 nm band pass filter of Andover corporation.](image)

**Figure 4.14**: Specifications of $\lambda = 667\,\text{nm}$ band pass filter of Andover corporation. Image from the Ref. [34]

In our experiment, we used band-pass interference filters mounted at the ends of objective lenses. Their transmitting properties are defined by FWHM value for the central wavelengths. For atomic line ratio 1 nm FWHM band-pass filter is sufficient because the atomic lines width in plasma are lower than 1 nm. For this, we also checked with a spectrometer if some of parasite lines were
Interference filters are present. Transmission losses of narrow band interference filters are about 50%. Interference filters are also sensitive to an incident angle of incoming light flux. At 650 nm, incidence angle should be less than 5° for our geometry. In our case where the object distance is 130 cm, only light influx coming from a field of view of 22 cm x 22 cm satisfies this condition. For larger angles of incidence the filter transmittance is reduced and even cut and therefore emissions from these regions cannot be transmitted through the filter.
4.8 Viewing geometry

In general TJ II plasma interacts with helical (toroidal) limiter and two additionally inserted poloidal limiters. Poloidal limiter of our interest is located in sector C, Figure 4.15, and the camera looks tangentially on it. Poloidal limiter is fitted with Langmuir probe installation and gas injection system, so that gas can be puffed into plasma through the hole made in the limiter. Also, the biasing voltage can be applied.

![Figure 4.15: Location of the fast camera port and its field of view.](image)

![Figure 4.16: Camera viewing geometry and magnetic field lines in TJ II. Spatial scale is in meters. Image from the Ref. [8]](image)

Visible emission we observe is localized in the region above the limiter. It is coming from neutrals entering the plasma due to recycling in case of hydrogen/helium or due to sputtering in the case of impurities. In the case of puffing, gas is puffed directly into plasma-edge through the hole in the limiter.
Hence, limiter acts as poloidaly extensive (40 cm) and toroidally short (8 cm) neutral source. As can be seen from the Figure 4.16, view chords are nearly parallel to the magnetic field lines, so all the plasma parameters belonging to each chord can be considered as constant and line integrated light belongs to the poloidal cut in front of the limiter with constant parameters.
Chapter 5

Data acquisition process and image analysis

5.1 Data acquisition

Emission light in the plasma edge region, during the TJ-II discharge, is monitored by Photron SA1 fast camera. Specifications of the camera are given in Chapter 3. Raw plasma movies are acquired by a software PFV (Fotron Fastcam Viewer) for different frame rates and exposure times, depending on the plasma parameters. This can be regulated by changing the voltage of the intensifier taking into account that the intensity of the signal of the acquired images is above 30.

Typically we recorded videos at camera speed of $2.5 \times 10^5$ fps which for the typical TJ-II discharge of 250 ms gives us up to 5,000 fps and the raw data are stored in TIFF format videos between the discharge on the PC. Later on, these raw data are processed.

The interface of the PFV software can be seen on the Figure 5.1 where some of the video characteristics are displayed (i.e. model of the camera, frame rate, resolution, total number of frames, etc.).

In between the discharges raw videos are checked for possible reposition of the bundle and saturation. Raw plasma movies are saved as 8 bit TIFF images, therefore grayscale varies from 0-255. The upper limit of light intensity on an image, that further can be processed, is determined by grayscale limit. Images with intensity of 255 were not taken into account because of their saturation.

The next step in the data processing was to select the ’good shots’ which means that desired field of view overlapped with region of interest, to check if the videos were saturated or if there was sufficient light. This selection has to be done manually.

The next step in the shot selection is to choose a ’similar shots’. In order to apply He ratio technique we selected a group of two similar discharges relevant for our studies. Similar discharges refer to a plasmas with similar plasma parameters (i.e. average density, temperature, energy content). This condition is required because the data set used for $n_e$ or $T_e$ introduces a cross
5.1 Data acquisition

For our purpose characterization of the shots is done through the plasma energy content and soft X-rays signal. Diamagnetic energy ($W_{\text{dia}}$) and soft X-rays signals ($RX$) depend on $T_e$ and $n_e$, see Equations: (A.5), (A.6). Assumption of $Z_{\text{eff}} = \text{const}$ is made. Dependencies on $T_e$ and $n_e$ are:

\[
RX \sim T_e n_e^2 Z_{\text{eff}}
\]

\[
W_{\text{dia}} \sim (T_e n_e + T_i n_i)
\]

TJ II discharges start with the ECRH heating system providing the lower average density profiles ($0.3 \times 10^{19} \text{ m}^{-3} < \langle n_e \rangle < 1 \times 10^{19} \text{ m}^{-3}$) followed by NBI (Neutral Beam Injection). TJ II group has two NBI injectors each of them with a power of about 500 kW that can accelerate neutral Hydrogen up to 40 keV during the 300 ms long pulse discharge. Average densities can go up to $8 \times 10^{19} \text{ m}^{-3}$.

After selection of the similar shots, with both density and temperature filters for case of He puffing and recycling, we proceeded with image processing using Image J and MATLAB processing software.
5.2 Image analysis

After the videos are acquired as explained previously, good videos are selected for chosen similar shots. In any case, analysis process has to be applied in order to obtain edge plasma parameters, therefore in this section we will explain the process following exactly the steps that are done during this work.

The scan for different average electron densities is done, and we extracted an image sequence of 20 frames for each average density. Averaging over 20 frames which correspond to 1 ms time. We are taking the average of 20 images (about 1 ms) to have good a signal to noise ratio and we therefore need stationary conditions during such time periods. For density and temperature profiles this is sufficient taking into account that typical relaxation times for low density, high temperature plasmas are of the $\mu$s order.

![Image of averaged image sequence of two emission lines 667 nm and 728 nm, respectively. ROI is enclosed in the white rectangles. Color is introduced to enhance the contrast.](image)

**Figure 5.2:** Example of averaged image of and image sequence of two emission lines 667 nm and 728 nm, respectively. ROI is enclosed in the white rectangles. Color is introduced to enhance the contrast.

The averaged image sequence is shown in the Figure ???. This is an example of discharge with density filters for the case of He puffing.

As mentioned in the previous chapter fast cameras are capable to record images under high speeds (frame rate) and with low exposure times. Atomic processes require low exposure times and very high speed so the light reaching the camera needs to be amplified. This is done with the help of the intensifier coupled with a camera. Photocathode of an intensifier has a circular cross-section and light influx is regulated by the size of the circular surface of the intensifier so in order to get a better quality image, at low light flux detection surface of the intensifier is very small. In the ideal case circular cross-section of the effective detection area should deliver perfectly uniform picture (light distribution should be the same over the image). However we observed that it is not true and that image is more bright in the center than in the edges, up to 25%. Correction for the non-uniformity is explained in the appendix. After averaging process is done, we subtracted background radiation (estimated value far away from the plasma) and then correct it for the non-uniformity by
5.2 Image analysis

multiplication with a uniformity response matrix obtained in the appendix.

![Image](image_url)

**Figure 5.3:** Raw emission images, their ratio and obtained 2D of $T_e$, respectively. This is the case of the He recycling and one of the shots analyzed in this work.

The obtained average picture, corrected for the non-uniformity is a 32-bit gray scale matrix with a resolution of i.e. $640 \text{ pix} \times 352 \text{ pix}$ which corresponds to a region of $8 \text{ cm} \times 9 \text{ cm}$ that determines our field of view. However region of interest (ROI) is smaller that that therefore image has to be cut and rotated needed. Then the ROI (see Figure 5.2) is chosen and two identical sub-matrices are created as shown in the Figure 5.3. The relative calibration coefficients either for the density or temperature are applied on the ratio. Calibration coefficients are given in the appendix.

**Coordinate transformation**

In order to compare the results with other diagnostics image to real space coordinate transformation needs to be done. Results from the He-line ratio technique are compared with Thomson scattering and Integrated data analysis [35].

From standard magnetic field calculations in a vacuum, the radius of the plasma at the position of the limiter is $r=13 \text{ cm}$ and corresponds to a $\rho = 1$. On the figure 5.4 it is clarified that tangential field of view of the camera captures the radial distance up to $\rho = 0.6$. Radial profile of the emission line is measured from the position of the limiter that can be placed outside or inside
5.2 Image analysis

Figure 5.4: Pixel to space coordinate transformation and normalized radius for comparison with data from other diagnostics

the LCFS, depending on the experiment. This re-positioning of the limiter demands normalization of camera coordinates to the standard ones in order to compare the data with other diagnostics. On the Figure 5.4 poloidal limiter (PL) is placed 1 cm outside the last closed flux surface which corresponds to a 32 pix in image coordinates. This value is deduced from the distance between visible Langmuir probes. In order to normalize camera line view to standard normalized radius in TJ II we proceed as follows:

$$\rho = \frac{r}{a} = \frac{r - a + a}{a} = \frac{a - (a - r)}{a} = 1 - \frac{a - r}{a}$$  (5.3)

$$\rho = 1 - \frac{(a - r) \times 0.031 (cm)}{a}$$  (5.4)

where \((a-r)\) is the radial coordinate in pixels. Equation (5.4) is valid when the limiter is at the LCFS, and more general expression is of the form:

$$\rho = 1 - \frac{\mp d (cm) - (a - r) \times 0.031(cm)}{a(cm)}$$  (5.5)

where \(d\) is the radial distance of the limiter from the LCFS and \(\mp\) stands for limiter outside or inside the LCFS, respectively.
Chapter 6

Experimental results

As explained in the previous chapter, the camera was looking tangentially on the inserted mobile poloidal limiter, so the light recorded is coming from the cloud of neutrals in front of it. We analyzed shots in two different scenarios: the case of puffing where the visible light is due to the interactions between puffed neutral gas and plasma, and the case of recycling where the emission comes mainly from the neutrals recycled at the limiter [8]. For the case of the gas puffing through the nozzle limiter was outside LCFS, as defined by magnetic field calculations, and for the case of recycling it was placed inside the LCFS to increase local recycling. Puffing rate was kept low in order not to perturb the plasma globally and to have approximately the same intensity level of the emission lines as for the case of recycling.

Region above the limiter was observed with the intensified fast camera capturing simultaneously two emission He lines with double bundle, each pair depending on either the electron density or the electron temperature. Each double image was corrected for the non-uniformity as explained in the appendix and the background light (the intensity level far away from the plasma region) has been subtracted. In our experimental campaign only one NBI1 injector was operating and average density profiles were in the range of: \(1 \times 10^{19} \text{m}^{-3} < \langle n_e \rangle < 4 \times 10^{19} \text{m}^{-3}\).

Figure 6.1 shows an example of one of the analyzed discharges. Density scan is done through NBI phase of the discharge and is presented with solid gray lines. For these points of average density we later obtained edge profiles of either density or the temperature for the similar shot. It can be seen that during this discharge Edge like modes are detected on the \(H_\alpha\) signal. Closer look on the time evolution of Edge like modes is presented in the Figure 6.2. This region was not taken into account while extracting the image sequences because of its strong influence on edge plasma parameters. Results are compared with Thomson scattering data if not for the same discharge, then for the similar one (same magnetic configuration and average density).
6.1 Edge $T_e$ and $n_e$ profiles for the case of He puffing

6.1.1 Double image

First we selected a pair of similar discharges with sufficient intensity level with density and temperature filters for the discharge with active gas puffing at the limiter. Discharge in the TJ II machine begins with the ECH plasmas,
providing the low density plasmas, up to \( \langle n_e \rangle = 1 \times 10^{19} \text{ m}^{-3} \) followed by the neutral beam injection, where the average electron density raise up to \( \langle n_e \rangle = 4 \times 10^{19} \text{ m}^{-3} \). During the experiment only one NBI injector was operating with nominal power of 1 MW. Videos are recorded with speed of 25 kfps and exposure time of 20 \( \mu \text{s} \). Voltage of the intensifier was set to 700 V. He gas was injected through the hole in the limiter perpendicular to the camera line of sight.

![Image](image_url)

**Figure 6.3:** Two images in one frame obtained with double bundle. Image is averaged over 20 frames and color is introduced to enhance the contrast. Black arrows marks the radial direction over which the radial profiles are obtained.

The Figure 6.3 shows a double image of two emission lines 667 nm and 728 nm, recorded simultaneously. The original image obtained by the camera was an 8-bit gray scale image. An image is averaged over 20 frames and the color is introduced to enhance the contrast. Radial emission profiles are obtained along the black arrows marked on the figure. Beginning of an arrow corresponds to the position of the injection point on the limiter. In the Figure 6.4 radial profiles of those emission lines are presented. Left image is the smooth profile of 667 nm emission line and right one is the radial profile of 728 nm emission line. Ratio of those two emission lines is weakly dependent on \( T_e \) and strongly dependent on the \( n_e \). This way, electron density can be obtained from \( R_{n_e} \).

### 6.1.2 Smoothing

For the data analysis signals were smoothed, when noisy, and in the Figure 6.5 smooth and original data are shown for comparison. Smoothing can be performed with no loosing the information about general trend in the profile.
6.1 Edge $T_e$ and $n_e$ profiles for the case of He puffing

Figure 6.4: Smooth radial profiles of the 667 nm and 728 nm emission lines obtained along the arrows marked on the Figure 6.3 during the ECH phase of the discharge. Limiter was 1 cm outside the LCFS. Shot # 32382 with density filters.

Figure 6.5: Original and smooth profile for the density ratio $R_{n_e}$

6.1.3 Local perturbation

Gas flow injected into the plasma edge spreads in the cone shape above the limiter. The density of injected particles is expected to be highest just above the injection point, and decreases as going deeper due to the ionization and spreading of the neutrals with the width of the cone. Therefore the highest influence on edge parameters is expected to be just above the nozzle. Perturbation level if exists, depends also on the puffing rate. In the Figure 6.6 we present effect of the local perturbation simply by the comparison of the radial profile of the ratio $R_{n_e}$ of the two emission lines during the ECH and during the NBI phase. During the ECH phase (blue solid line) we observe peaking of the profile within the first centimeter. For this discharge (shot # 32382)
6.1 Edge $T_e$ and $n_e$ profiles for the case of He puffing

limiter was 1 cm outside the LCFS. Green dashed line represents the same profile during the NBI phase for the same discharge. It can be seen that for this case the same peak just above the limiter is not observed.

Figure 6.6: Radial profile of the $R_{n_e}$ from the Figure 6.4. Local peak of the $R_{n_e}$ profile is observed to be just above the nozzle, outside the LCFS.

The influence on the edge electron density is shown in 2D imaging presented in the Figure 6.7. The radial $\langle n_e \rangle$ profiles obtained along two arrows marked in the 2D image are shown in the Figure 6.8.

Figure 6.7: 2D imaging of $n_e$ for $\langle n_e \rangle = 1 \times 10^{19}$ m$^{-3}$
It is shown that the density along the central arrow is higher at the injection point but then the profile completely coincides with the one obtained along the left arrow. We can say that for our puffing rates neutrals puffed from the limiter does not perturb the plasma parameters.

Figure 6.8: Radial profiles obtained along the marked arrows in the Figure 6.7
6.1 Edge $T_e$ and $n_e$ profiles for the case of He puffing

6.1.4 Radial profiles of $T_e$ and $n_e$ in the ECH phase

Figure 6.9 shows the density profile for the same discharge as treated above. Limiter for this case was 1 cm outside the LCFS. In the SOL region between the limiter and the LCFS (1 cm outside), we observe the peak of the density profile as a consequence of the active gas puffing. As explained in the previous section, it does not influence the general trend of the profile. At the LCFS and inwards, electron density increases monotonically from $n_e = 2 \times 10^{18} \text{m}^{-3}$ at the 1 cm ($\rho = 1$) to $n_e = 7 \times 10^{18} \text{m}^{-3}$ at the 5 cm ($\rho = 0.7$). ECH plasma had average electron density of $\langle n_e \rangle = 0.7 \times 10^{19} \text{m}^{-3}$ and central electron temperature $T_e$=1 keV.

Figure 6.9: Radial density profile obtained during the ECH phase for the average density of $\langle n_e \rangle = 0.7 \times 10^{19} \text{m}^{-3}$. Shot #32382

Radial $T_e$ profile is shown in the Figure 6.10 for the similar discharge. Limiter was 2 cm outside the LCFS. Local peak of the $T_e$ profile is observed within the SOL region and is probably a consequence of the backscattered radiation from the limiter, but the more global trend of plasma cooling is observed.

Fall in the plasma temperature continues crossing the LCFS and continues inwards, up to 4 cm which corresponds to $\rho = 0.85$ for this case. Inside the $\rho = 0.85$ $T_e$ is increasing very rapidly from 20 eV to 100 eV within the 2 cm which confirms existence of steep gradients in the plasma edge.

Comparison with data from Thomson scattering is given in the Figure 6.11. It is seen that the density profile is in a better agreement then the temperature. TS data are taken for the similar shot providing the same average electron density. Temperature profile obtained for the similar discharge had shown less good agreement then the density data. Indeed, systematic underestimation of
6.1 Edge $T_e$ and $n_e$ profiles for the case of He puffing

Figure 6.10: Radial temperature profile obtained during the ECH phase for the average density of $\langle n_e \rangle = 0.7 \times 10^{19}$ m$^{-3}$. Shot #32398

Figure 6.11: Comparison of TS data (○) and 1D analysis of He line-ratio technique (−∗−), for the ECH phase

the $T_e$ has been reported in [19, 14] with respect to other diagnostics (Thomson scattering, Li beam). We also have to note that small error is introduced due to the fact that cross-dependence of $n_e$ and $T_e$ however exists, and we are...
not able to record data for all three emission lines simultaneously. This error would be negligible by introducing a third bundle into our detection system. Presented error bars are due to the uncertainties in the calculations of the rate coefficients in the C-R model from TEXTOR, as suggested by [19] and are up to 30% for $T_e$ and 15% for $n_e$.

### 6.1.5 Radial profiles of $T_e$ and $n_e$ in the NBI phase

Now we focus on the dynamics of the $T_e$ and $n_e$ radial profiles for the same discharges during the NBI injection.

Figure 6.12 shows the intensity lines of the same discharges as treated in the ECH case, together with the ratios $R_{ne}$ of the lines, from which we deduce relevant edge parameters.

![Figure 6.12](image_url)

**Figure 6.12:** Emission lines and their ratios for electron density and temperature calculations during the NBI.

The time evolution of the signals from different diagnostics of TJ II is shown in the Figure 6.13. Here we focus only on those signals that are relevant for correlation with the plasma edge $T_e$ and $n_e$ profiles during the density ramp up. In the Figure 6.13 (up) we present the average electron density $\langle n_e \rangle$ that is nearly constant during the ECH heating and with NBI injection increases until certain threshold, where suddenly falls. Soft X rays signal (RX) give the quantitative idea of the plasma temperature. RX105 signal represents the temperature in the edge, where the poloidal limiters is placed, and RX102 signal is the core temperature. Those signals are given in arbitrary units. In the Figure 6.13 (down) we show separately energy content of the plasma during the discharge $W_{dia}$, $H_\alpha$ signal as a reference for the L-H transition and appearance of the H-modes and bolometer signal that quantifies the radiated power from the plasma in the plasma boundary.
6.1 Edge $T_e$ and $n_e$ profiles for the case of He puffing

Figure 6.13: Time evolution of the signals of some of the TJ II diagnostics relevant for our studies. Black arrows are presenting points in time and the average density for which we obtained edge radial profiles presented in the Figure 6.14. If not labeled, units of the signals are arbitrary.

Figure 6.14 shows obtained radial profiles of $n_e$ and $T_e$ for different average electron densities. Discharges are the same as the one analyzed for the ECH phase and limiter position was 1 cm outside the LVFS for density case and 2 cm outside for the temperature case. Labels are representing values of average density in units of $(10^{19} \text{ m}^{-3})$.

LCFS is at 1cm for the case of density and 2cm for the case of the temperature. Decrease, of about 10 eV, in the $T_e$ is observed for all $\langle n_e \rangle$ within the region of 2 cm inside the LCFS. On contrary the electron density increases monotonically and continues increasing through the hole profile. The onset of $T_e$ that induced the sudden collapse is seen to be below 20 eV.

In order to follow the dynamics of the edge profiles we will refer to the time evolution of global plasma parameters from the Figure 6.13.

Before the ECH gyro-trons are switched off NBI power is injected with a single injector NBI1 of nominal power of 1MW. Qualitative idea on the plasma temperature during the NBI phase is given by the X-ray signal (RX). At the
beginning of the NBI injection RX signal increase, plasma is heating and the electron temperature increases. With the density increase H\(\alpha\) signal decays as the indication of the L-H transition and the emission light of the H\(\alpha\) is reduced because of the increase in hydrogen confinement. With an increase of the electron density more energy is absorbed in the plasma and the energy content of the plasma is rising. The same is observed in the edge electron density, shown in the Figure 6.14. With an increase of the electron density radiation losses becomes dominant due to the impurity accumulation mostly in the edge, therefore plasma looses its energy, see the Wdia signal. When the average electron density reaches the value of 2.5 × 10^{19} m^{-3} temperature in the edge falls down to about 20 eV. Reaction rates for the ionization to sustain the plasma decays exponentially at these temperatures, so the sources of the electrons and ions cannot compensate for the losses and plasma begins to collapse.

Figure 6.14: Dynamics of the edge \(n_e\) and \(T_e\) during the NBI injection for increasing \(\langle n_e \rangle\), respectively.
6.1.6 2D imaging

Radial profiles are very valuable to describe the general character but 2D images as a complementary diagnostics can be very suitable for covering the extended region of view and give the information about complexity and anisotropy of the plasma edge (i.e. in the region above the limiter). Here we present 2D imaging of edge $n_e$ and $T_e$ for the same discharges as discussed above so to have a better look onto the plasma boundary.

In the Figure 6.15 we present 2D imaging of the electron density during the ECH phase. The channel of the neutrals entering the plasma from the injection nozzle can be clearly seen in the figure.

![Figure 6.15: 2D imaging of ratio $R_{ne}$ (left) and calculated electron density (right) during the ECH phase. Units of $n_e$ are given in $10^{18}$ m$^{-3}$. The average electron density is $\langle n_e \rangle = 0.7 \times 10^{19}$ m$^{-3}$](image)

2D image of electron temperature during the ECH phase is shown in the Figure 6.16. The limiter position is marked as the injection point and it was 2 cm outside the LCFS. The local $T_e$ increase can be seen just above the injection point like a cloud (enclosed in dashed circle). This is in agreement with the obtained radial profile where we observed the local peak of $T_e$ outside LCFS.

The evolution of the $T_e$ with different $\langle n_e \rangle$ is shown in the Figure 6.17. Plasma cooling is observed in the region above the LCFS and in the last figure it completely shrinks. This scenario corresponds to the radiation collapse observed in the radial profiles.
6.1 Edge $T_e$ and $n_e$ profiles for the case of He puffing

Figure 6.16: 2D imaging of electron temperature during the ECH phase.

Figure 6.17: Edge $T_e$ for different $\langle n_e \rangle$ during the NBI. Units of $n_e$ are given in $10^{19}\text{ m}^{-3}$ and average density is labeled as 1.5, 2.1, 2.7, 3, respectively. Electron temperature is given in (eV), labeled only in the first calibration bar. Position of the LCFS is schematically presented by dashed line.
6.2 **Edge $T_e$ and $n_e$ profiles for the case of He recycling**

6.2.1 **Recycling conditions**

As discussed in the Chapter 2, when ion strikes the limiter it can be brought back as a neutral in the case of recycling, after which undergo to the different atomic processes. Even the most dominant visible emission in the plasma edge for the case of recycling is due to hydrogen recycling, for us the most important is the emission coming from the He. Therefore we were working with H/He plasmas. With the help of He-line ratio technique we filtered two emission lines, as in the case of puffing, and deduced main plasma parameters in the plasma boundary using the same method as explained in the previous chapters.

When poloidal limiter is inserted inside LCFS, as defined by the magnetic field calculations, plasma flux to surface increases and number of released He neutrals increases so the same happens with the light emission above the limiter. Change in the limiter position therefore can influence the intensity of light coming from the cloud in front of the limiter. For our case poloidal limiter for the Shot #36123 with temperature filters was inserted 2 cm inside the LCFS and the one with density filters, shot #25608, was inserted 1.5 cm inside the LCFS. In order to check if the intensity light was similar in both cases, we compared mutual emission line at $\lambda = 728$ nm for both discharges.

![Figure 6.18: Emission line $\lambda = 728$ nm common for both discharges. Poloidal limiter is marked with white dashed line](image)

From the emission profiles shown in the Figure 6.19 we show that the intensity of the same line for the two different positions are approximately the same and the intensity of the lines of more than 50% of its maximum within the 3 cm above the limiter indicating strong recycling in this region. This is the main argument to say that the emission light just above the limiter is indeed the light coming from the recycled He.
6.2 Edge $T_e$ and $n_e$ profiles for the case of He recycling

6.2.2 Radial profiles of $T_e$ and $n_e$ for the NBI phase

1D analysis of the electron temperature profiles for different $\langle n_e \rangle$ is shown in the Figure 6.20. Limiter was 2 cm inside the LCFS and profiles could be obtained for the region up to 3.5 cm inside the limiter which corresponds to $\rho = 0.6$. Electron temperature at the limiter position is calculated to be about 60 eV for higher $\langle n_e \rangle$ and 70 eV for the lower $\langle n_e \rangle$. It has shown the oscillatory behavior in the range of about 10 eV for different $\langle n_e \rangle$ at the limiter position, the same has been observed for the case of He puffing.
another diagnostics is shown in the Figure 6.21. All three shots are different but with the similar energy content and for the same values of $\langle n_e \rangle$. He-line ratio technique shows very good agreement with the Integrated data method.

![Figure 6.21](image)

**Figure 6.21:** Comparison of $n_e$ with Bayesian method analysis and Thomson Scattering data.
6.2.3 2D imaging

From the emission frames of the 728 and 706 line we obtained the 2D image as shown in the Figure 6.22. The limiter corner is schematically shown (white dashed line). The temperature values outside the limiter corner are not real and are probably result of the reflected blackbody radiation coming from the limiter causing higher temperatures in that region. Overheated langmuir probe is visible in the 667 emission frame. We also note the asymmetry in the electron temperature above the limiter. Left part is more heated than the right one, but this also can be the effect of the reflected blackbody radiation observed in the emission frame of the 667 nm line.

![Figure 6.22: 2D imaging of the $T_e$. Poloidal limiter is marked with white dashed line. Shot #36123, limiter was 2 cm inside the LCFS.](image)

In the Figure 6.23 we show 2D image of edge electron density at the beginning of the NBI injection. We note that intensity of the 728 nm line is very low. For the average density of $\langle n_e \rangle = 1 \times 10^{19} \text{ m}^{-3}$ it was sufficient to deduce the edge electron density values.
6.2 Edge $T_e$ and $n_e$ profiles for the case of He recycling

Figure 6.23: Edge electron density before the ECH cut-off.

The dynamics of the edge electron temperature is presented in the Figure 6.24. Again, limiter corner is schematically marked with a white dashed line and $T_e$ frames are corresponding to a different average electron densities. The time evolution is obtained during the NBI phase of the discharge. Frames are averaged over 1ms which is the equilibration time of the neutrals. Frame 1 corresponds to an average electron density of $1 \times 10^{19} \text{ m}^{-3}$. Here we note very high temperatures around the limiter corner probably due to the backscattered radiation from the limiter. While average density increases to $1.5 \times 10^{19} \text{ m}^{-3}$ (frame 2) the plasma edge starts to cool down forming a low temperature bell above the limiter. With an increase of the average electron density it can be noted that plasma shrinks and the low temperature belt becomes wider (frame 3). In the frame 4 we can note that although the plasma was about to collapse (it could be seen on the frame 3) the temperature increased. This could be due to the effect of Edge like modes that tends to bring certain amount of heat from the core plasma to the edge. (I have to check the signal of this shot)
Figure 6.24: 2D dynamics of $T_e$ during the NBI phase for different average densities.
Chapter 7

Conclusions and summary

A quantitative study of edge $T_e$ and $n_e$ is done by 1D and 2D analysis of the recorded emission images. The extraction of the profiles is done by means of a spectroscopic method the so-called He-line ratio technique developed in TEXTOR tokamak and extrapolated to TJ-II edge conditions [8]. The experimental setup comprises a fast CMOS camera coupled with an image intensifier, a bifurcated fibre bundle, objective lenses and interference filters. Besides understanding and operating the different hardware tails, we have operated the system in TJ-II during the 2013-2014 campaign. Some calibrations in laboratory were made necessary for the quantitative analysis. An exhaustive work was dedicated to the analysis of the data and comparison with other TJ-II diagnostics.

We performed the experiments for both scenarios: active and passive spectroscopy. For the active spectroscopy gas was injected into the plasma through hole in the limiter. A part of the work is devoted to study the effect of the gas puffing on the general behavior of the plasma edge parameters. Particularly we studied the behavior of the edge electron density above the injection point and concluded that it had no perturbative effect on the profiles.

We have compared our profiles with that of Thomson Scattering and Integrated data analysis and generally speaking, a good agreement was found. As all the diagnostics, He-line ratio technique introduces errors, the main is thought to be introduced during the extraction of $n_e$ and $T_e$ from the emission lines based on the C-R model and the inaccuracy of calculated reaction rate coefficients. Inaccuracy is estimated to be up to 30% for $T_e$ and 10% for $n_e$ [19]. The other important error comes from the cross-dependence of $n_e$ and $T_e$. Since we work with a double bundle we can record only two emission lines per discharge, extract the information on i.e. electron density by making assumptions on the electron temperature. We try to minimize the error due to the cross-dependence by choosing the most similar discharges. Introducing the third bundle would completely eliminate this error. Another source is due to the emission collected from the regions far away from the limiter. The radial extension of profiles is limited to the local region up to 5 cm ($\rho \approx 0.6$) inside the LCFS where the local emission is always stronger than the background emission.
emission.

Continuous measurements of $T_e$ and $n_e$ enabled us to study the dynamics of the profiles for increasing average electron densities up to the point when plasma starts to collapse. We performed quantitative analysis of the edge radial profiles and 2D analysis of the emission frames during the density ramp. The electron temperature had shown the tendency of plasma cooling in the plasma boundary as an onset of the radiative collapse. On the complementary 2D imaging of the electron temperature, the radially extensive layer of low electron density, formed during the density ramp is observed. This is, indeed the main indication of sudden plasma termination in stellarators.
Appendix A

Calibration constants and non-uniformity of the intensifier

Experimental set-up in our experiment is a quite complex structure consisting of fibers, narrow-band interference filters, photosensors. All these components are limited by their transmission properties, so the light coming into the system can be partially lost during the transmission. It happens that what we actually measure is not the actual light intensity entering into the bundles so recorded intensity must be corrected for this effect. Here we will describe how we obtained the calibration constants for the spectral response of our system and correction matrix for non-uniformity of the intensifier.

A.1 Calibration constants

Intensity of the detected light is proportional to the product of the photon flux and the absolute spectral response of the system for the specific wavelength.

\[ I_{\lambda} = r_{\lambda} \times N_{\lambda} \]  \hspace{1cm} (A.1)

The advantage when making the ratio of the two emission lines is that the spectral response has to be known only for the parts of the system that are changed during the detection of the emission. During our experiment we recorded simultaneously two emission lines with the same camera and the same bundles, but with a different interference filters, each filter transmitting the different wavelength. All the components of the optical setup have their specific transmission properties, therefore when taking the ratio, transmission properties of the mutual components will be neglected. So happen in our case, where transmission properties of filters only has to be taken into account when talking about emission line ratio. This is one of the mayor advantages of He-line ratio technique. The expression from the Eq. A.1 can be rewritten for each pair of the wavelengths in terms of their photometric values.

\[ R(T_e) = \frac{N_{728}}{N_{706}} = \frac{I_{728}}{r_{728}} \times \frac{r_{706}}{I_{706}} = c(T_e) \frac{I_{728}}{I_{706}} \]  \hspace{1cm} (A.2)
A.1 Calibration constants

\[
R(n_e) = \frac{N_{667}}{N_{728}} = \frac{I_{667}}{I_{728}} \times \frac{r_{728}}{r_{667}} = c(n_e) \frac{I_{667}}{I_{728}} \tag{A.3}
\]

This way, calibration constants \(c(T_e)\) and \(c(n_e)\) can be obtained for each line ratio. The idea behind is that we can record the emission \(I_\lambda\) from the known source that will give us the number of photons entering the detector. From the recorded emission we can obtain number of detected photons. By knowing the transmission properties of interference filters used in the experiment (from Andover manufacturer) we can easily obtain those calibration constants.

In order to obtain those calibration constants we illuminated a white pattern with a halogen lamp and recorded an image sequence of this white pattern. Videos are obtained in a full frame (1Mpx) for each interference filter (for this studies we use 1nm FWHM interference filters at 667.8, 706.5 and 728.1 nm filters, respectively). Videos are made for two cases: first when increasing the wavelength, then when decreasing the wavelength. This way we obtained two sets of videos for each wavelength. Averaging process of the two gives us intensity \(I_{av}\) of detected light. An example of the image of the white pattern and histogram is presented in the Figure A.1:

![Image of the white pattern and histogram](image.png)

**Figure A.1:** Image of the white pattern and the obtained histogram. Note that colors are introduced to an image to enhance the contrast and important number on the histogram is the mean value of the counts.

The average values of the intensity recorded from the white pattern are listed in the Table A.1 such as other specifications of the interference filters. Up to this point we obtained intensity of the emission lines from the known light source (halogen lamp). Relative spectral irradiance of the halogen lamp in the VIS \(^1\) is given in the Figure A.2

From this information we obtained number of photons entering the detector by passing from radiometric to photon quantities using the expression of the

\(^1\)Visible region (380-750)nm
A.1 Calibration constants

<table>
<thead>
<tr>
<th>$\lambda$[nm]</th>
<th>$I_{av}$</th>
<th>$N_f 10^{15}$[m$^{-2}$s$^{-1}$]</th>
<th>$S_{eff}$[m$^2$]</th>
<th>T %</th>
</tr>
</thead>
<tbody>
<tr>
<td>667.8</td>
<td>2517</td>
<td>1.901</td>
<td>1.12</td>
<td>0.5</td>
</tr>
<tr>
<td>706.5</td>
<td>2606</td>
<td>2.121</td>
<td>1.39</td>
<td>0.5</td>
</tr>
<tr>
<td>728.1</td>
<td>2249</td>
<td>2.267</td>
<td>1.14</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table A.1: Estimated average intensity $I_{av}$, number of photons $N_f$, effective surface of the filters and transmittance (T) of the filters for different wavelengths indicated. Those are effective values used for calculation of the relative calibration constants.

![Figure A.2: Relative spectral irradiance of the halogen lamp](image)

Dividing total irradiated power by energy of a single photon we can easily obtain number of photons for desired wavelength coming from the halogen lamp. From the curve fit we extract number of photons at specific wavelengths relevant for our experiment, see Figure A.3

![Figure A.3: Number of photons calculated from the irradiated power of the halogen lamp](image)
A.2 Response uniformity of the system

Now taking into account the transmission properties of the interference filters we can rewrite the Equations (A.5) and (A.6) in a way:

$$
c(T_e) \frac{I_{728}}{I_{706}} = \frac{N_{728} \times S_{eff(728)} \times T(728)}{N_{706} \times S_{eff(706)} \times T(706)} \quad (A.5)
$$

$$
c(n_e) \frac{I_{667}}{I_{728}} = \frac{N_{667} \times S_{eff(667)} \times T(667)}{N_{728} \times S_{eff(728)} \times T(728)} \quad (A.6)
$$

Then, corrected relative calibration constants for different ratios are estimated to be:

$$
c_{T_e} \approx 1 \quad (A.7)
$$

$$
c_{n_e} \approx 0.75 \quad (A.8)
$$

NB: In the analysis of the experimental results, all line intensities are corrected by these calibration constants.

A.2 Response uniformity of the system

It was discussed in the previous chapters that the fast events requires low exposure times so within these time scales not much light can be collected. Moreover some of the light emitted in the visible range has no sufficient intensity level to be detected by the camera sensor therefore the light has to be amplified. This is the reason why intensified fast cameras are of the special importance as a spectroscopic diagnostics and they meet all the requirements of the fast plasma events at the low light emission.

Due to the low light fluxes image intensification has to be set properly and the light is collected inside the circular cross-section of the photosensor. Amplification over the circular cross-section should be uniform in ideal case but it has been observed that is is not true. the acquired images are found to be more sensitive (bright) in the center than on the edges. This also can be due to the non uniform lightening from the source and also the distance from the light source can affect uniformity as well. In order to correct all images for non-uniformity effect we obtained a uniformity matrix, which is an image of the white pattern obtained as follows:

White pattern (the same one used for the calibration constants) has been illuminated by the lamp placed far away from in order to get as much uniform light distribution as possible. We recorded the video of this illuminated white pattern and obtained an average normalized image. The normalized response matrix is presented in the Figure A.4 together with the intensity profile obtained along ab arrow. It can be seen that the response is maximum in the center and falls smoothly as moving towards the edges. This effect is not visible on a gray image, therefore we present colored image in order to enhance the contrast. Non uniformity has been estimated up to 20 %.
**A.2 Response uniformity of the system**

**Figure A.4**: White pattern-left (in colors) and the non-uniform profile obtained along an arrow, respectively.
Bibliography


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Finally my parents and family deserves the greatest thanks for their moral support even from far away...
Declaration in lieu of oath

Herewith I declare in lieu of oath that I have prepared this thesis exclusively with the help of my scientific teachers and the means quoted by them.

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