Edge Plasma Studies using Fast visible Cameras on stellarator TJ-II

Master Thesis
presented by

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Abstract

The development of diagnostics for plasma parameter measurement in fusion devices is a challenge, due to hostile environment, the complex and compact fusion reactor geometry, the strong magnetic fields, the radiation, etc. Additionally the measurements should if possible have a good temporal (time scales down to a few microseconds) and spatial (typical dimensions of few millimeters) resolution. Moreover in the last few years it has been demonstrated that the plasma edge in fusion devices is strongly inhomogeneous when studying important phenomena such as Turbulence, ELMs, disruptions, pellet or dust tracking etc. This gives rise to the need for 2D measurements or imaging techniques. In the present work on plasma emission structures (blobs), diagnosis with fast intensified cameras are employed. The use of intensifiers along with the fast camera allows us to achieve high speed range in the order of $10^5$ frames per second and above at short exposure time. In the present work we study the fast camera parameters such as exposure time and intensifier voltage with two different apparatus, single and double bundle system. With such a system we have shown that the small structures that evolve around the edge or edge to SOL region are indeed blobs and not noise.
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Chapter 1

Introduction

In a fusion power plant the transport at the plasma edge must be carefully controlled so that power is deposited onto material surfaces designed to handle it. There has been growing interest in the role played in this transport by field-aligned filamentary structures, particularly with the advent of fast high-resolution cameras able to resolve their fast dynamics. In magnetized plasmas, it has long been observed that the radial transport in the scrape-off layer (SOL) is characterized by turbulent intermittency [24,16,19], appearing as B field-aligned filaments or perpendicular-plane blobs, which unfavorably increase recycling at walls, reduce the divertor efficiency and thus may lead to a high level erosion of the first wall in fusion devices. Several theories have been existing on transport processes in the edge of fusion plasmas right from classical, neo-classical theory, one replacing the other, the diffusive processes being dominant in understanding the cross field transport. This however failed to meet the experimental results observed. With the discovery of H-mode cross field anamalous transport was reduced considerably and the notion of diffusive processes playing a key role in the edge transport is no longer considered as the main reason for radial transport mechanisms. Strongly pulsed events known as Edge Localized Modes (ELMs) is regarded as the reason for a very important fraction of heat deposited at walls rather than continuous diffusion. Moreover in the recent past macroscopic structures have been detected in most of the machines using measurements from image diagnostics and probe arrays [2,14,15]. Edge transport studies is better understood when considered as a convective process, and does have a better agreement with experimental results.

The use of visible fast cameras have become a routine practice in major fusion experiments across the world. The importance and the vital reason for use of fast cameras as a key diagnostic is it’s capability to study these plasma phenomena having time scales down to micro second range and typical dimensions down to a few millimeters. However in most of the devices, the fast camera compliments other diagnostics such as probe arrays.

The main objective of this master thesis was investigation of very small
structures and try to understand whether these structures are blobs or mere noise. In order to achieve this, systematic study of the fast camera parameters were performed. The coupling of image intensifiers to fast cameras is not trivial, however for TJ-II plasmas in order to achieve high speeds of the range of 100,000 frames per second with short exposure times in the microsecond range (1-10\(\mu\)s), which makes it possible to observe these small structures bigger, image intensifiers are used. All plasmas studied in this master thesis work are predominantly with ECRH plasmas. The blobs are detected using the Blob detection code and characterized with respect to their geometrical parameters.

In this master thesis work, the second chapter is a basic introduction to Nuclear fusion and magnetic confinement, describing thermonuclear fusion, ignition condition and a brief summary of various magnetic confinement fusion reactors and their operating principles in a pedagogical way. The third chapter deals with the plasma edge physics pertaining to plasma facing components like Limiters and divertors and more related to the Plasma edge in stellarartor TJ-II, H-recycling over the poloidal limiter in TJ-II and the results of the spatially resolved \(H_\alpha\) emission simulations with EIRENE and studies on hydrogen atomic and molecular physics at ionizing plasma conditions. The fourth chapter explains the experimental set up employed for the fast camera measurements in TJ-II and various apparatus used for this master thesis work. The Experimental results are given in the fifth chapter followed by the conclusions of this thesis work.
Chapter 2

Physics of Nuclear Fusion

2.1 Introduction

Any energy production from nuclear reactions is based on differences in the nuclear binding energy. Fig. 2.1 shows the nuclear binding energy per nucleon (proton or neutron). It has been derived from measurements of the masses of the nuclei, when it was observed that the masses of nuclei are always smaller than the sum of the proton and neutron masses which constitute the nucleus. This mass difference corresponds to the nuclear binding energy according to Einstein’s energy-mass relation $E = \Delta m \cdot c^2$. An explanation of the structure of Fig. 2.1 was given by C. F. von Weizsäcker in 1935. Starting from the very limited range of the strong nuclear force he assumed that each nucleon just influences its nearest neighbours. The binding energy per nucleon would thus be constant. The smaller binding energies for smaller nuclei are due to the relatively large surface to volume ratio. The nucleons at the surface have missing partners and thus their contribution to the total binding energy of the nucleus is reduced. The decrease of binding energy per nucleon for nuclei beyond $A \approx 60$ is due to the repulsive coulomb force of the large amount of positive protons.

The finer structures in Fig. 2.1 are due to quantum mechanical effects, i.e. at certain so called ‘magic’ proton and neutron numbers the nucleus formed is a very stable configuration. This is roughly comparable to the stable electron configurations of the noble gases, where electron shells are completed. The first magic number is 2, which is manifested as a most remarkable example of a local maximum in Fig. 2.1, i.e. the helium nucleus with 2 protons and 2 neutrons.

From Fig. 2.1 it is clear that there are two ways of gaining nuclear energy:
1. By transforming heavy nuclei into medium-size nuclei: This is done by fission of uranium.
2. By fusion of light nuclei into heavier ones: In particular the fusion of hydrogen isotopes into stable helium offers the highest energy release per mass.
unit. Doing this in a controlled manner has been the goal of fusion research for about 40 years.
The energy release per nucleon is of the order of $1\text{MeV} (= 10^6\text{eV})$ for fission reactions and in the order of a few MeV for fusion reactions. This is 6-7 orders of magnitude above typical energy releases in chemical reactions, which explains the effectiveness and potential hazard of nuclear power.

All the nuclear reactions are mostly governed by the strong nuclear force acting over very small distances in the order of the radius of the nuclei, but for distances above a few fermi (i.e. 1015 m) the repulsive Coulomb force between the positively charged nuclei becomes dominant. The potential energy of two nuclei as a function of the distance between the nuclei is shown in Fig. 2.2. The depth of the deep well at small radii is determined by the binding energy, discussed before, while the barrier at a few fermi is given by the Coulomb potential of $Z_1Z_2 e^2/4\pi\epsilon_0 r_m$ which is much smaller, but still poses a principal problem. For $\alpha$ – particle decay (where a $^4\text{He}$ nucleus separates itself out of a positive nucleus) as well as for fusion of lighter nuclei, this diagram demands a particle energy of the order of 500keV, and this would make fusion processes almost impossible.
However, it was known since the end of the last century, that $\alpha$ – particle
decay occurs at room temperature, and in 1928 Gamov explained this by the tunneling effect, which in turn also allows fusion reactions to occur at temperatures far below the Coulomb barrier: Due to quantum mechanical effects the minimum distance between the two nuclei is not fixed (as it is indicated by the repulsion in Fig. 2.2), but there is a finite probability for the nuclei to get closer, and eventually "tunnel" through the Coulomb barrier, as indicated by the dotted line in Fig. 2.2. In terms of wave functions, the amplitude is not zero for $r \leq r_{min}$, but it is finite and decays slowly for smaller radii. Therefore it can still be finite for $r \leq r_n$, i.e. the particles have a possibility to approach close enough for a fusion reaction to occur. This tunneling probability is a strong function of the relative velocity $v$ of the reacting particles with charge $Z_1, Z_2$.

$$P_{\text{tunneling}} \sim \exp \left( -\frac{2\pi Z_1 Z_2 e^2}{\hbar \nu} \right)$$  \hspace{1cm} (2.1)
This equation shows that reaction partners with small mass (and charge \(Z\)) are preferred, and that the reaction probability increases strongly with the temperature (\(\sim\) relative velocity \(v\)). In the light of the above discussion it becomes clear why fission energy has been much more readily obtained than fusion energy: fission is triggered by thermal neutron capture, i.e. no force prevents the neutron from entering the uranium nucleus at room temperature and causing a fission reaction.

### 2.2 Thermonuclear Fusion

As discussed before, for a fusion reaction to occur, the two nuclei have to 'touch' each other since the range of the nuclear force is of the order of the dimensions of the nuclei. The repulsive Coulomb force counteracts all attempts to bring them close together.

The simplest approach to realize the fusion reactions would be to accelerate the reactants to about 100 keV and bring them to collision. This does not lead to a positive energy balance, since the elastic Coulomb scattering as another reaction type has a much larger cross-section, as shown in Fig. 2.3. Thus the two particle beams would just scatter and diverge after one interaction.

A way of overcoming this problem is to confine a thermalized state of deuterium and tritium particles at energies of about 10 keV. Since the average energy of particles at a certain temperature is about \(kT\), where \(k\) is the Boltzmann constant, temperatures are often given in electron volt units (1 eV ≈ 11600 C). At energies of 10 keV the hydrogen atoms are completely ionized and form a plasma of charged ions and electrons. For now it should suffice to observe that in a plasma, the particles thermalize as a result of many Coulomb scattering processes and thus entail a Maxwellian velocity distribution:

\[
f(v) = n \left( \frac{m}{2\pi kT} \right)^{3/2} \exp\left( -\frac{mv^2}{2kT} \right)
\]

where \(f\) is the number of particles in the velocity interval between \(v\) and \(v + dv\), \(n\) is the density of particles, \(m\) is their mass, and \(kT\) is their temperature.

The reaction rate per unit volume, \(R\), can be written as:

\[
R = n_D n_T \langle \sigma v \rangle
\]  

(\(2.3\))

with \(v\) now being the relative particle velocity and \(\langle \sigma v \rangle\) being the reaction parameter, i.e. the average of the product of cross-section times velocity.

Calculation of the reaction parameter requires integration over the distribution function of deuterium and tritium. After some numerical transformations one obtains:

\[
\langle \sigma v \rangle = \frac{4}{(2\pi m_r)^{1/2}(kT)^{3/2}} \int \sigma(\epsilon_r) \epsilon_r \exp\left( -\frac{\epsilon_r}{kT} \right) d\epsilon_r
\]

(\(2.4\))
where \( m_r \) is the reduced mass, and \( \epsilon_r \) the relative kinetic energy.

Fig. 2.4 shows the reaction parameter for some important fusion reactions. At temperatures of interest the nuclear reactions come predominantly from the tail of the distribution. This is illustrated in Fig. 2.5, where the integrand of the last equation is plotted versus \( \epsilon_r/T \) together with the two factors \( \sigma(\epsilon) \) and \( \epsilon \cdot \exp(-\epsilon/kT) \) for a D-T plasma at a temperature of 10keV.

Thermalization is thus not just a way of handling the large cross-sections for elastic Coulomb scattering, it also considerably increases the reaction rate considerably in relation to beam experiments with single particle energies.

## 2.2.1 Ignition

In the following the condition which a thermalized D-T plasma has to satisfy to serve as an energy producing system is investigated. Historically, in 1957 John D. Lawson deduced a criterion for a positive energy balance using quantities such as the thermal cycle efficiency \( \eta \) of power reactors. Today the approach has changed slightly to a more physics oriented condition: the aim is an ignited plasma where all energy losses are compensated by the \( \alpha \) particles from the fusion reactions, which transfer their energy of 3.5 MeV to the plasma while slowing down. The neutrons cannot be confined and leave the plasma without interaction.

Transport processes such as diffusion, convection, charge exchange and others are empirically described by an energy confinement time \( \tau_E \) leading to the power loss term \( 3n k T/\tau_E \) with \( 3n k T \) as the inner thermal plasma energy (\( n \) is the electron density). Note that this is twice the ideal gas value since every
2.2 Thermonuclear Fusion

Figure 2.4: Reaction parameter $<\sigma v>$ as a function of ion temperature $T_i$ for different fusion reactions.

The hydrogen atom is split into two particles (electron and nucleus). Another loss mechanism is the bremsstrahlung, which becomes particularly important at high temperatures and impurity concentrations. The power loss due to bremsstrahlung can be written as:

$$P_{\text{bremsstrahlung}} = c_1 n^2 Z_{\text{eff}} (kT)^{1/2}$$  \hspace{1cm} (2.5)

with $c_1$ being the bremsstrahlungs constant ($c_1 = 5.410^{-37}$ Wm$^3$keV$^{1/2}$), and $Z_{\text{eff}}$ the effective charge of the plasma, including all (impurity) species: $Z_{\text{eff}} = \Sigma_z n_z Z^2 / n$. The energy balance now reads:

$$(n/2)^2, <\sigma v > \epsilon_\alpha = 3nkT/\tau_E + c_1 n^2 Z_{\text{eff}} (kT)^{1/2}$$  \hspace{1cm} (2.6)

and this can be rewritten to the ignition condition

$$n\tau_E = \frac{12kT}{<\sigma v > \epsilon_\alpha - 4c_1 Z_{\text{eff}} (kT)^{1/2}}$$  \hspace{1cm} (2.7)

where $\epsilon_\alpha$ is the energy of the $\alpha$-particle, 3.54 MeV. This equation shows that the product of the particle density and energy confinement time is only a function of the plasma temperature, with a minimum at about 13 keV. In the range of 10 keV the reaction parameter $<\sigma v>$ is roughly proportional to $T^2$, which motivated the definition of the so-called fusion product

$$n\tau T = \frac{12kT^2}{<\sigma v > \epsilon_\alpha - 4c_1 Z_{\text{eff}} (kT)^{1/2}}$$  \hspace{1cm} (2.8)

which has a flat minimum of about $35.10^{20}s/m^3keV$ around 10 keV. The fusion product dictates the strategy for developing fusion power as an energy
producing system: One has to attain temperatures of around 10 keV (about 100 million degree $C$) and achieve the required density and energy confinement time simultaneously. There are two distinct approaches:

1. The hot plasma is confined by strong magnetic fields leading to maximum densities of about $1.5 \times 10^{20} m^{-3}$, which is $2 \times 10^5$ times smaller than the atom density of a gas under normal conditions. With these densities, the energy confinement time required is in the range of 2 to 4 seconds.

2. The other extreme is to maximize the density. This can be done by strong, symmetric heating of a small D-T pellet. The heating can be done with lasers or particle beams and leads to ablation of some material causing implosion due to momentum conservation. It is clear that the energy confinement time is extremely short in this concept: it is the time required for the particles to leave the hot implosion center. Since it is the mass inertia which causes the finiteness of this time, this approach to fusion is often called inertial fusion. The density required is about 1000 times the density of liquid D-T; the pressure in the implosion center reaches (at temperatures of 10keV) that in the center of the sun.

Fig. 2.6 (left) illustrates the progress of nuclear fusion research in approaching the required $n \tau T$ condition. Today a factor 7 is missing for ignition, where as in the mid-sixties the best experiments fell short of the required conditions.
by more than 5 orders of magnitude. However, it has to be kept in mind that achieving ignited plasmas is not sufficient for building fusion reactors. In addition, this plasma state has to be maintained for very long times to allow continuous energy production. One of the most difficult problems will be the interaction of the edge plasma with the surrounding structures and the removal of helium ash. Consequently, edge plasmas constitute an increasingly important research topic. Impurities from the walls worsen the ignition condition in two ways. They dilute the fuel concentration and even in small amounts they can significantly enhance the radiation losses. Fig. 2.6 (right) shows the maximum tolerable impurity concentration to reach ignition. Depending on the charge it ranges from a few percentage for light atoms to the few $10^{-4}$ level for high Z materials.

2.3 Magnetic confinement

As discussed earlier, plasmas can be confined by magnetic fields but in linear configurations the end losses are by far too large to reach the necessary energy confinement time $\tau_E$ of the order of some seconds. These end losses can be completely avoided in a toroidal system, but in a simple toroidal system with purely toroidal magnetic field, the magnetic field curvature and gradient (approximately as in Fig. 2.7) result in a vertical drift which is in opposite
directions for ions and electrons.

The resulting electric field causes an outward $E \times B$ drift of the whole plasma, and therefore such a simple magnetic field configuration will be unstable. To avoid this charge separation, it is necessary to twist the magnetic field lines by additional magnetic field components. Then, single field lines map out so-called flux surfaces. On these flux surfaces, plasma transport is fast, as it is always parallel to $B$, and therefore plasma parameters usually are constant on a given flux surface. Perpendicular to the flux surfaces, transport is hindered because particle motion perpendicular to $B$ is restricted by the Lorentz force, and therefore plasma parameters can vary strongly in this direction.

![Figure 2.7: Vertical drifts and associated $E \times B$ in a toroidal field.](image)

2.3.1 The Stellarator

The stellarator was invented in 1951 by Lyman Spitzer, Jr. in Princeton. In a stellarator the twist of the field lines is created by external coils wound around the plasma torus, as shown in Fig. 2.8. Due to these external currents the plasma shape is not circular, but shows some indentation. In this case, with four coils (neighbouring coils carry opposite current), the plasma has an oval shape.

These external coils have the advantage that the current can be controlled from outside, and can flow continuously, but the configuration shown in Fig. 2.8, is very difficult from the engineering point of view. Therefore such “classical” stellarators nowadays have been replaced by “modular” stellarators, where the planar toroidal coils and the helical coils have been replaced by one complex, but modular system of non-planar coils.

2.3.2 The Tokomak

The second approach is the tokamak proposed by two Russian physicist, Tamm and Sakharov, in the year 1952 and realized by Artsimovich. The word
tokamak itself is derived from the Russian words for toroidal chamber with magnetic field. The tokamak concept is outlined in Fig. 2.8. The toroidal magnetic field is provided by simple magnets and the necessary twist is produced by the plasma itself, by means of an electric current in the plasma which gives rise to the poloidal component of the twisted magnetic field. The current also serves for plasma build-up and heating. This current is produced by induction, the plasma acting as the secondary winding of a transformer. Tokamaks have proved to be very successful in improving the desired fusion plasma conditions and the today’s best experiments are based on the tokamak principle. Of course, a transformer can induce the (dc-) plasma current only during a finite time, while, as mentioned before, a stellarator may principally run steady-state. For truly continuous tokamak operation, alternative current drive methods are being developed. Another disadvantage of the required large plasma current is the potential danger of so-called disruptions: uncontrolled very fast (10 ms) plasma current decays which can give rise to large forces on the machine.
Chapter 3

Some Edge Physics and TJ-II Stellarator

Physical processes taking place in the edge of a plasma in general plays a crucial role right from achieving a steady state burning plasma till confinement of the plasma itself. The first wall has to withstand and exhaust the $\alpha$-particle heating power and the helium ash must be removed(pumped) from the plasma. Wall erosion affects the lifetime of the wall elements and releases impurities into the plasma, which then causes fuel dilution and energy loss due to radiation from the plasma centre. Moreover global confinement properties can be affected by edge plasma processes. Therefore, understanding these processes and controlling the edge plasma by appropriate means is an important field of research.

No unique definition exists for the term “plasma edge” or “plasma boundary”. An important part of the edge plasma is the scrape of layer(SOL) which is that region of the plasma where the magnetic field lines intersect wall elements. However, significant processes occur also inside the confined plasma, like neutral particle penetration, ionization, charge exchange or impurity line radiation. These atomic processes do have an impact on the properties of both, the edge plasma and the core plasma.

In this regard, in the following chapter, I will briefly discuss these process at the edge of the plasma with significant relevance to the master thesis work. I will discuss the relevant processes following the transport cycle of the particles beginning with the boundary conditions which are given by the magnetic topology. After a basic illustration of the SOL the penetration of the neutrals into the plasma is discussed. Finally the results of the $H_\alpha$ emission spectroscopy at Edge of TJ-II tested and proved by using the EIRENE code[4,6,18] is discussed followed by a section which introduces the stellarator TJ-II.
3.1 Magnetic Topology

Wall elements which intersect the magnetic field serve as a perfect plasma sink and impose a flow directed along the field lines. The flux tubes generated at each wall element are filled with plasma by perpendicular transport (diffusion, drifts). This property helps to build up a particle density sufficient for helium exhaust. On the other hand the concentration of plasma flow on small areas is less beneficial for power exhaust, since a uniform plasma flow to the whole wall would avoid peak heat loads. The very details of particle and heat load on the wall are determined by the magnetic topology and the geometry of the plasma facing components. There are two concepts distinguished, namely “Limiter” and “Divertor”.

![Diagram showing Magnetic Topology]

**Figure 3.1**: Standard Limiter(left) and Divertor(right) configurations employed in magnetic confinement devices.

Fig. 3.1 depicts a limiter(left) and a poloidal divertor(right). Tokamaks such as JET, ASDEX-upgrade, DIII-D and a few others have the poloidal divertor configuration. Tore Supra, TEXTOR(toroidal belt limiter) have the limiter configuration. In TJ-II stellarator we have two poloidal limiters placed at geometrically opposite ends. For this thesis work, the fast camera system was focussed on one of these poloidal limiters(fig. 3.2).

3.2 The Edge Plasma and the Scrape-Off-Layer(SOL)

Energetic plasma particles strike the solid surface, dislodging atoms from the lattice in a process called sputtering. In time, sputtering can result in sub-
Figure 3.2: Photograph of TJ-II limiter(Z2) on the left and a simulation of the limiter with the bean shaped plasma projection on the right.

Substantial erosion of the surface. The sputtered atoms enter the plasma where they may be ionized by the impact of plasma electrons. Usually the intended plasma species-hydrogen isotopes in the case of fusion devices—is different from the solid species and sputtering thus results in plasma contamination. Of yet greater importance, the basic properties of the plasma, such as its density and temperature, are often strongly dependent on the way solid and plasma interact. At the interface between the solid and the plasma, a thin net-charge layer called the Debye sheath develops spontaneously. The most important practical consequence of the formation of a sheath is that it mediates the flow of particles and energy out of the plasma to the solid surface. It therefore plays a central role in establishing the temperature, density and other properties of the plasma.

Several other major phenomena that are very crucial in the magnetic confinement of plasma take place in the edge, like the impurities arising from PSI(Plasma Surface Interaction) and the resulting transport motion of the impurity ions through the plasma. The plasma fluctuations, which are believed to be the cause of the unexplained(anomalous), rapid transport of particles and energy.

The region radially outboard of the LCFS is called the scrape-off layer, SOL. Cross-field velocities are of order:

\[ v_\perp = D_\perp/l_\perp \]  

where \( D_\perp \) is the cross-field diffusion coefficient \([m^2s^{-1}]\) and \( l_\perp \) [m] is the characteristic radial scale length of density. According to fick’s law of diffusive motion:

\[ \Gamma = -D.dn/dx \]

where \( \Gamma \) is the particle flux density \([\text{particles } m^2s^{-1}]\), \( D \) is the particle diffusion coefficient and \( dn/dx \approx n/l_\perp \), and with \( \tau \) related to an effective cross-field ve-
3.3 Hydrogen Recycling and $H_\alpha$ emission spectroscopy at Edge of TJ-II

To date, attempts to calculate $D_\perp$ from first principles have been of limited success. $D_\perp$ is generally anomalous compared with classical rates and is obtained from experiment. Values of order $1m^2s^{-1}$ are found empirically. The radial density length may be as large as the minor radius, ‘a’, which would be the case if the neutrals were all ionized at the very centre, e.g. for deep injection of fuel pellets. More typically $l_\perp$ is of the order of the ionization mean free path, mfp, of the recycling neutrals at the edge, $\lambda_{iz}^{\text{neutral}}$. Thus $v_\perp$ may be as slow as $\approx 1ms^{-1}$, while $v_\parallel \approx$ plasma sound speed, $c_s$, which is typically many orders of magnitude larger. $c_s$ is calculated as shown:

$$c_s^2 = k(T_e + T_i)/(m_e + m_i)$$  \hspace{2cm} (3.3)$$

$$c_s \approx [k(T_e + T_i)/m_i]^{0.5}$$ \hspace{2cm} (3.4)$$

for example for $T_e = T_i = 25eV$, and $D^+$ ions, $c_s \approx 5 \times 10^4ms^{-1}$. It is this enormous difference between $v_\parallel$ and $v_\perp$ that makes the SOL so thin relative to its length. The fig. 3.3 shows a picture of a simple limiter SOL where the ionization of Hydrogen neutrals take place in the main plasma itself. More details of this with respect to TJ-II stellarator is provided in the following section.

![Figure 3.3: Image depicts a simple SOL with neutrals recycled.](image)

### 3.3 Hydrogen Recycling and $H_\alpha$ emission spectroscopy at Edge of TJ-II

Exploring the idea that for fusion devices operating at different plasma edge conditions, the transport physics and hydrogen recycling can be very different.
E.de la Cal et al (CIEMAT) performed and studied in detail both experimentally as well by running simulation code EIRENE to understand the recycling of Hydrogen, puffing through the valve in the Limiter and also more periodic studies on different plasma conditions such as low density high temperature cases at the plasma edge (the case in TJ-II which is of high relevance to the current work) by spatially resolved $H_{\alpha}$ emission spectroscopy with a CCD camera. The detailed study were continued by the same author in order to understand the underlying mechanism of hydrogen atomic and molecular physics in low density high temperature plasmas using the EIRENE code. In this section, I would like to highlight the methods involved in this detailed study and the results which play a crucial part in this master thesis work. In this series of work performed the first one was related to neutral hydrogen atoms or molecules recycled at the limiter surface and that are easily re-ionised at the plasma edge due to the high electron temperature in this region ($T_e > 30$eV).

Experiments were performed in this regard with a fast CCD camera operated at very high speed (100000 frames/sec) with the use of $H_{\alpha}$ interference filters focussed on the limiter in a tangential view plane as shown in (fig. 3.4). With this orientation of the CCD camera for this experiment, most of the $H_{\alpha}$ emission is from clouds localized in front of the Limiter.

![Figure 3.4: Experimental set up for the H-recycling over limiter experiment performed using CCD camera in TJ-II.](image)

The $H_{\alpha}$ emission integrated over tangential viewing chord is this region is given by:

$$I(r) = c n_e(r) \Sigma_j n_j(r) k_j$$  \hspace{1cm} (3.5)

or

$$I(r)/n_e(r) = c \Sigma_j n_j(r) k_j$$  \hspace{1cm} (3.6)

where $c$ is a constant, $k_j$ is the electron collisional rate coefficient and and the sum is taken over all possible $H_{\alpha}$ emission precursors with density $n_j$. The excitation rate coefficients can be taken as constants here since they do not vary very much in the temperature range of $40eV < T_e < 100eV$ (true within 20% and $r/a > 0.4$) which are the conditions prevailing. This approximation we make here and the equations above play an important part which shall be discussed later in the following chapters.
This work was followed by more detailed studies to achieve a better understanding of the hydrogen atomic and molecular reaction physics (including ionization, excitation, dissociation, charge exchange, etc.) in the ionizing plasma conditions, where the edge is of high temperature and low density (like the one in TJ-II). The region of interest in TJ-II plasmas for this particular study (the $10^{18} m^{-3} < n_e < 1.10^{19} m^{-3}$ and $40eV < T_e < 100eV$) fall very much into this ionizing plasma condition.

<table>
<thead>
<tr>
<th>Number</th>
<th>Most Relevant Reactions</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$H_2(n = 1) + e \rightarrow 2H + e$</td>
<td>dissociation</td>
</tr>
<tr>
<td>2</td>
<td>$H_2 + e \rightarrow H(1s) + H^+(n = 2) + e$</td>
<td>excitation from $H_2$</td>
</tr>
<tr>
<td>3</td>
<td>$H_2 + e \rightarrow H_2^+ + 2e$</td>
<td>molecular ionization</td>
</tr>
<tr>
<td>4</td>
<td>$H_2^+ + e \rightarrow H^+ + H(n = 1) + e$</td>
<td>ionization from $H_2^+$</td>
</tr>
<tr>
<td>5</td>
<td>$H_2^+ + e \rightarrow H(1s) + H^+(n &gt; 1)$</td>
<td>excitation from $H_2^+$</td>
</tr>
</tbody>
</table>

Table 3.1: Atomic and molecular reactions most relevant at the plasma edge for low density high temperature plasmas.

Tab. 3.1 shows the most relevant atomic and molecular reactions in this context to study the dominant precursor for $H_\alpha$ emission. Finally it is concluded experimentally and by calculations obtained by running the EIRENE code on TJ-II plasmas that the dominant precursors for $H_\alpha$ emission is $H_2^+$ near the separatrix and not $H_2$ as generally assumed. This result is illustrated in fig. 3.6.

The main conclusions made were that the ionization of $H_2$ (reaction number 3 in Tab. 3.1) is nearly five times more important than dissociation, one producing 2H atoms in ground level (reaction number 1) and the other producing also excited atoms to n=2 state (reaction 2). It is also very clear that the
main $H^+$ production rate is through ionization from $H_2^+$ (reaction 4). Finally the radial profiles of different sources of $H_\alpha$ emission rates is represented in Fig. 3.6 d as a function of plasma radius. The molecular contribution is only important in the first few centimetres inside the separatrix and in the SOL, where as the emission from atomic hydrogen extends well inside the plasma. At the separatrix the contributions from both atomic and molecular hydrogen is the same. An important finding is that contribution of $H_\alpha$ emission from $H_2^+$ is stronger than $H_2$ by about a factor of 3. This is illustrated in fig. 3.7.

The above phenomena shown in fig. 3.7 is in contrast with the a lot of studies where the main molecular $H_\alpha$ precursor was $H_2$. In order to understand this we can examine the relative concentrations of $H_2^+$ and $H_2$ ($n_{H_2^+}/n_{H_2}$) in low density high temperature fusion plasmas with the help of the steady state balance equation of $H_2^+$. To do so the maximum contributors of $H_2^+$ source and sink
3.4 The Stellarator TJ-II

reactions are considered (reaction 3 and 4 in Tab. 3.1)

\[ \frac{dn_{H^+_2}}{dt} = 0 = k_3 n_{H_2} n_e - k_4 n_{H^+_2} n_e \]  \hspace{1cm} (3.7)

\[ \frac{n_{H^+_2}}{n_{H_2}} = \frac{k_3}{k_4} \]  \hspace{1cm} (3.8)

where \( k_j \) are the reaction coefficients. For different electron temperatures we obtain the Fig. 3.7. TJ-II at the first centimeters inside the separatrix we have \( T_e \approx 40 \text{eV} \) and we get a quotient \( n_{H^+_2}/n_{H_2} \approx 0.3 \). The calculations such as above equations were performed for TJ-II and the result obtained was \( I_{H^+_2}/I_{H_2} \approx 3 \), where \( I_{H^+_2} \) and \( I_{H_2} \) are the relative contribution to the \( H_\alpha \) emission from \( H^+_2 \) and \( H_2 \) respectively. One of the results which is crucial for this thesis work from the above work is that at ionizing plasma conditions, of low density and high temperature at the edges, and for the conditions prevailing at the TJ-II edge the rate coefficient does not vary significantly and can be assumed as a constant.

\[ I(\bar{x}) \propto n_e(\bar{x}) \sum_j n_j(\bar{x}) k(n_e, T_e)_j \]  \hspace{1cm} (3.9)

can be simplified as:

\[ I = n_e n_0 k(T_e, n_e) = c n_e n_0 \]  \hspace{1cm} (3.10)

where \( c \) is a constant.

3.4 The Stellarator TJ-II

The TJ-II is a low magnetic shear (global shear) stellarator of the heliac type (Fig. 3.8) with an average major radius of 1.5m and an average minor radius, \( a \leq 0.22m \), situated in CIEMAT, Madrid[1,11]. The magnetic field \( (B_0 \leq 1.2T) \) is mainly generated by 32 Toroidal field coils-TF (28 + 4), 1 circular coil-CC and 1 helical coil-HX. The central conductors, which provide the flexibility of the TJ-II device, consists the circular and the two helical coils. In addition to these two vertical field coils-VF allow positioning the magnetic axis. The ohmic coils-OH(2+2) can generate a loop voltage of 0.1V, intended to cancel the spurious toroidal currents. A model of TJ-II is shown in Fig. 3.9. The radial coils-R(2+2) produce a trimming electric field of up to 100G, intended to compensate stray fields.

The main characteristics of the TJ-II are:

- the strong helical variation of its magnetic axis.

- very favorable MHD characteristics with potential for high-beta operation.

- bean shaped plasmas with a wide range of operational flexibility.
3.4.1 Confinement Studies in TJ-II Plasmas.

Two gyrotrons (53.2 GHz, each of 300kW) in the second harmonic, with X-mode polarization (ECRH). The power is transmitted to the plasma by two quasi-optical transmission lines (QTL1 and QTL2). The gyrotrons can be modulated for perturbative transport experiments, and can be used to drive current. TJ-II also disposes of two neutral beam injectors (NBI), each of which can produce $\leq 300\,\text{ms}$ pulses of neutral hydrogen accelerated to 40keV, to provide upto 1.2 MW of absorbed additional heating for central densities upto $1.6\times10^{20}\,\text{m}^{-3}$. Additionally, a state of the art set of plasma diagnostics has been installed. Furthermore, a powerful data acquisition system is in operation to handle enormous amounts of data.
3.4 The Stellarator TJ-II

(a) Thomson scattering profiles of helium plasmas with injected power of 300 kW, rotational transform \( \iota(0)=1.51 \) and different electron density. ECE temperature profile is displayed for the low density case in which the ITB appears.

(b) Evolution of diamagnetic energy content as a function of rotational transform for helium and hydrogen plasmas and several values of heating power.

**Figure 3.10:** Some plasma profiles of TJ-II, Image Courtesy: From latest results of TJ-II stellarator, CIEMAT.

### 3.4.2 Plasma profiles for ECRH Plasmas.

In this section, a brief overview of the plasma profiles in TJ-II for ECH plasmas are illustrated. Several diagnostics are employed in stellarator TJ-II. Interferometry and Reflectometry are used for calculation of plasma density. Thompson scattering, Electron cyclotron Emission (ECE) is used to measure the electron plasma temperature. Neutral particle analyzer is used to measure the ion temperature. The plots above are some the profiles calculated using these diagnostic methods Fig. 3.10.
Chapter 4
Experimental Technique

4.1 Diagnostics: Cameras, Image Intensifiers, & Set Up

The use of visible cameras for two dimensional plasma imaging has gained in the last years more and more interest, since the plasma emission in the edge is strongly inhomogeneous and one dimensional profiles as obtained with linear array detectors can give a too simplified or incomplete view of the underlying physics. This is especially important for fast phenomena such as turbulence, ELMs, disruptions, filamentary structures, pellet or dust tracking, etc, presently of high relevance in the fusion physics community.

The TJ-II fast camera group employs in addition to the fast cameras, image intensifiers[17] coupled to increase their sensitivity so as to study low light phenomena at high speed, going down to the $10\mu s$ range for filtered impurity line emission and below the $1\mu s$ range for unfiltered plasma light emission. By low light we mean emission intensities which cannot be visualised at high speed without an image intensifier, such as filtered atomic impurity emission or emission at dark regions of the far SOL. The system comprises CMOS fast cameras with up to $6.5\times 10^5$ frames per second recording speed, to which a special image intensifier has been coupled, the effective sensitivity thereby being increased by up to a factor of 100 without significant image distortion, at least for the here shown studies. With such a system it is possible e.g. to capture high-speed videos of filtered atomic impurity lines and ultra-fast unfiltered plasma movies.

4.1.1 Physics of CMOS Camera

The Fast CMOS camera used to make the measurements of this master thesis work is a Photron SA1 model. There are two other models of APX-RS in CIEMAT. The SA1 model is faster: 5000 full frames per second (fps) at one Megapixel ($1024 \times 1024$) spatial resolution with 12 bits pixel depth. Its maxi-
mum speed is 650 kfps at 64 x 16 pixels, but we usually operate at a maximum speed of 200 kfps to have a resolution of 182x80 pixels. This camera has a 8 Gigabytes digital internal memory.

<table>
<thead>
<tr>
<th>Frame Rate (fps)</th>
<th>Maximum Resolution Horizontal (px)</th>
<th>Maximum Resolution Vertical (px)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>1024</td>
<td>1024</td>
</tr>
<tr>
<td>2000</td>
<td>1024</td>
<td>1024</td>
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<td>3000</td>
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<td>5000</td>
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</tr>
<tr>
<td>5400</td>
<td>1024</td>
<td>1024</td>
</tr>
<tr>
<td>10,000</td>
<td>768</td>
<td>768</td>
</tr>
<tr>
<td>15,000</td>
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<td>64</td>
<td>32</td>
</tr>
<tr>
<td>650,000</td>
<td>64</td>
<td>16</td>
</tr>
</tbody>
</table>

Table 4.1: Specifications of the Fast CMOS camera, Photron SA-1 used in this master thesis work.

The fast CMOS camera sensor is a 12-bit ADC (Bayer system color, single sensor) with 20µm pixel whose size is 17x17 mm. Tab. 4.1 shows the the maximum resolution (horizontal and vertical) for all possible frame rates. The maximum speeds which we operated this campaign (Jan-Jun 2010) is predominantly 100kfps, with a few measurements for different experimental investigations like Impurity blow-off at 200kfps. Fig. 4.1 depicts the torus without operation and with illumination from a halogen lamp. It gives a clear understanding of the specifications in Tab. 4.1. For example at speeds of 10kfps (768x768 px) and 100kfps (320x128 px), the sensor area which we view is illustrated along with the bundle area. The objectives which were used for this master thesis work were 50 mm and 75 mm ones. Both the objectives have a f-number (N) equal to 1.8. The f-number of an optical system expresses the diameter of the entrance pupil in terms of the focal length of the lens and \( N = \frac{f}{D} \), where \( f \) is the focal length of the objective and \( D \) is the effective aperture diameter.
In order to understand this better Fig. 4.2 shows the calibration performed before the experimental days. The calibration were performed at a similar distance to that from the port to the limiter region which is $\approx 135$ cm over a plain surface with markings made on them (small dashes correspond to 2.5 cm and big ones 5 cm). We clearly see that when 50 mm objective is used we see a larger region where as with a 75 mm one we see lesser region of interest but with a better resolution. It is hence always a trade off between the region of interest (bigger or smaller) and the image resolution(lower or higher) relatively.

**Figure 4.1:** Reference image depicting the sensor areas for different camera speeds along with the bundle captured with a short focal length objective.

**Figure 4.2:** Images from camera calibration depicting the region of interest for different objectives 50 mm(left) and 75 mm(right) objectives.
4.1.2 Image Intensifiers, Relay optics & Fiber Bundles

The coupling of an image intensifier to a fast camera is not trivial, since relatively high light intensity fluxes, sufficient for short exposure times down the $\mu$s range, are captured continuously for a long time period, typically of up to some seconds. As is well known, image intensifiers (as photomultipliers) are vulnerable to this combination and if not operated correctly, they can be damaged. Moreover, not only the amplification factor is important, but also the image quality and the response linearity. There are different possible approaches for this critical coupling, and we followed what the company Hamamatsu recommended, which includes a two-step intensification: a GEN II and a GEN I intensifier, also called booster.

![Operating Principle of the Image Intensifier](image.png)

**Figure 4.3:** Operating principle of the image intensifier in TJ-II camera system.

The operation principle is shown in Fig. 4.3. With this configuration both, linearity and sensitivity are optimised, since the GEN I has a lower saturation level at higher brightness as compared to Micro Channel Plates (MCP). Additionally, the longevity is increased, since the GEN II photocathode operates at lower currents. The two purchased image intensifiers are built by Hamamatsu, the models are the C9548-03BL and the C10880-03S. Both comprise two-step amplification (see Fig. 4.3). A first GEN II intensifier with a 25 mm diameter Multi-alkali photocathode is coupled to the MCP and at its exit to a P-46 phosphor screen. The second GEN I intensifier is coupled by Fibre Optic Plate (FOP) to the first one, and also has a Multi-alkali photocathode, an electron accelerating tube and a P-24 Phosphor. The gain of the GEN I tube is fixed (amplification factor of about 50) and that of the GEN II can be adjusted through the MCP voltage. The intensifiers can be operated manually or remotely with a computer. Continuous or by the fast camera gated operations are possible. The intensifiers include two protections: an over-light protection to limit the input light intensity and an auto-shutdown function to prevent too high time integrated light intensity (light fluency) operation. They are coupled to the Fast Cameras with a relay lens built by the same company with 1:1 magnification.

The light from the plasma is guided to the intensifier via a bundle and a relay optics as shown in Fig. 4.4. The image received by the objective (focal length
of 35mm, 50mm or 75mm) is approximately 1.3m away from the limiter. The image is then formed in the entrance plate of the OF bundle, of 6x6 mm. The image then travels along the bundle until the first relay lens is reached at the other side. This relay has a magnification \( M = -1.72 \), and projects the image on the 25 mm diameter photocathode at the entrance of the II, therefore using only a fraction of it. After intensification, the image is emitted again at the phosphor plate, which has a diameter of 15 mm. Last, the second relay lens (\( M = -1 \)) transmit it into the camera sensor (17x17 mm). Hence, this set up uses only a small fraction of the total sensor, but it allows to cover most of the limiter interaction area at high speed, when the number of available pixels is greatly reduced.

![Diagram](image.png)

**Figure 4.4:** The optical setup of the whole camera system(Camera+Image intensifier+Optical fibers) mounted in the window(BST). Red line indicates the image from the plasma cross section via the bundle through the relay to the camera system. Image courtesy: D. Carralero, CIEMAT.

Fig. 4.5 shows three images taken with one of the fast cameras of a test target 1.3 m away (as the TJ-II focal plane at the poloidal limiter), with the bundle and a 50 mm focal length objective. The left one is without intensifier, the other two with it at 700 V (centre) and 800 V (right). For the same intensity light level, the exposure time of the one without intensifier was a factor of 80 longer than for the one with intensifier at 700 V and 250 longer than at 800 V. The smearing and blooming of the images with intensifier increases with the applied voltage, but at 700 V the 1 mm wide line triplets (white strips) can be resolved and with 800 V those of 2 mm. In figure 6b we have represented in the same order the intensity profiles of the images along the arrows crossing the 3 horizontal white strips that are 4 mm wide. The apparent noise in the profile of the camera without intensifier (left figure) is the real intensity profile produced by the matrix of the bundle fibres. We consider that the resolution of the intensified images is for most applications in fusion plasma physics good, especially for those studying the plasma emission itself, where sharp profiles (edges) are rarely present.

Two different bundles were employed in this campaign, namely single and double bundle. Measurements were taken using both the bundles and the results
obtained by using different bundles is the most significant part of my thesis work.

The bifurcated coherent fibre bundle was custom made by Schott. Each branch is 4 m long and has a square section of 6 mm x 6 mm, with 50 lines/mm, which corresponds to 300 x 300 fibres. The bundle bend radius is of 10 cm, its recommended maximum operating temperature is of 120°C and the end claddings comprise a C-mounting, which can be rotated +/- 180°. The transmission of the bundle is of 20 - 30% for wavelengths higher than 500 nm and drops strongly for shorter ones. This high cost in transmission is the price to pay for the relatively simple and flexible image transmission system. Bundles of 1 m have a significantly higher transmission of about 40% after specifications of the manufacturer. The relay-lens optics is designed such as to transport the image of the dimensions of the common end of the branches (12 mm x 6 mm) onto the photocathode of the camera. Therefore, a lens system with a magnification of 1.6 is constructed with commercially available components: two 50 mm diameter achromatic lenses of 150 mm and 100 mm focal lengths mounted into optical barrels with a C-Mount and an F-mount adapter at the ends.

In order to capture the optics system with both the bundles, is the need for a support structure. The support structure, as shown in Fig. 4.6 is build so as to place both objectives nearly parallel with a small angle tilting capability of both optical axes in order to obtain the same field of view at both ends. This tilting angle depends on the object distance and it is about 1° for our object distance of 130 cm. We have three pairs of objective lenses all with 50 mm diameter but different focal lengths (35 mm, 50 mm and 75 mm). Depending on the experiment the appropriate focal length is chosen so as to have the desired field of view and magnification.
This support structure was specially designed in CIEMAT by Eduardo de La Cal/D.Carralero, in principal to capture images simultaneously using different interference filters in the two different objectives and study the different He lines for analysis of edge density and temperature by the well known Helium line ratio method. In this campaign we used this setup to study the structures at the edge with a main motive as to confirm that what we see as structures are structures with physical meaning and not just mere noise.

### 4.1.3 Fast Cameras TJ-II Experimental set up

The TJ-II plasma is viewed from the tangential port B8T, which covers the region over the limiter, as depicted in Fig. 4.7. In this campaign in order to couple the camera system and the objective we used a coherent bundle of 4 m long for both single and double bundle experimental setups. The data acquisition is done through remote accessing the computer in the Torus hall by a computer in the control room. The time between two shots is approximately 10 minutes which is more than sufficient to save the videos. Even a 100kfps video takes only from 2-3 minutes for downloading. The data is later stored in an external hard disk for further analysis. The calibration for the camera system was performed consistently before the experimental days.

The view plane with respect to the magnetic field structure for TJ-II plasmas is illustrated in Fig. 4.8. In Fig. 4.8, the magnetic structure is for the regular standard configuration of vacuum fields for 100-44-64. The figure also illustrates the field of view on the limiter cross section including the view plane and the magnetic flux surface distribution along with the limiter cross section.
As mentioned earlier, TJ-II is a four period machine in which bean shaped magnetic flux surfaces rotate poloidaly around the central solenoid, one complete turn in each of them (see figure 4.8a). Vacuum vessel is constructed around the plasma it is intended to confine, and is therefore shaped helically, with 32 modular stainless steel toroidal elements which are designed accordingly with the poloidal position of the bean in their interior. The central solenoid is encased in the outer structure of these moduli, creating a protrusion in the chamber which acts as a helical limiter, and setting the maximum radial position of the LCFS. To reduce the confined volume, two poloidal movable carbon limiters separated 180° toroidally can be used to set it in lesser radial values. In this campaign two other magnetic structure configuration were employed, namely 100-40-63 and an island configuration of 96-35-59 with the vacuum fields.
Figure 4.8: TJ-II Magnetic structure (vacuum fields for 100 44 64 configuration).
(a) General view of the magnetic geometry: LCFS is represented featuring the local modulus of magnetic field (T). Poloidal C limiter and camera view optical axis included. (b) Detail of the limiter region, including view plane. (c) Magnetic flux surface distribution on the limiter toroidal section. Image courtesy: D. Carralero, CIEMAT.

4.2 Image Analysis

The raw plasma movies are measured using the software PFV (Photron Fast-cam Viewer), in the real time scale from 1000-1200 ms (usually triggered at 1020 ms). These movies are recorded at different speeds (frame rates) for different intensifier voltages and exposure times. The raw data is recorded in such a way that the S/N ratio is always above a minimum value of 2, never less than that. Very good plasma movies at optimum intensifier voltage and exposure times have S/N approximately 5 and above.

4.2.1 Deaveraging Process

In order to study the structures and analyze them we further make sure that the images are not only smoothed but the average of these images (background)
over a certain number of frames (in our case 3 frames above and below each frame) is subtracted from each frame. By this way we have minimized the noise and what we get as the resulting image is the fluctuating structures. This process is called “Deaveraging”.

As discussed earlier in Section 3.3, from the work of E.de.la.Cal on EIRENE simulations and experimental verification of the same, detailed analysis on the $H_\alpha$ emission reaction rates, it clearly shows that at `ionizing plasma conditions’ (low density and high temperature, as in the edge of TJ-II plasmas) the fluctuations in $n_e$ leaves the $H_\alpha$ reaction rates unaffected ($10^{18}m^{-3} < n_e < 1.10^{19}m^{-3}$ and $40eV < T_e < 100eV$). It is also very clear that in such plasmas the $H_\alpha$ emission predominates. Hence the intensity of the signal in these images as given in eq. 3.5 and eq. 3.6 can be approximated as follows:

$$I(x) \propto n_e(x)n_0(x)$$

where $I(x)$ is the camera signal, $n_e$ is the electron density and $n_0$ is the neutral hydrogen density. These Fast CMOS cameras can not only be used to measure density levels but also the density fluctuations. Assuming that $n_0 \ll n_e$, the right hand side of the equation 4.1 can be further decomposed as:

$$n_e.n_0 = <n_0><n_e> + <n_0>n_e \sim n_e$$

The analysis of structures using images can be attributed to the above equation, in particular the second term, $<n_0>n_e \sim n_e$, since $n_0 \ll n_e$. By Deaveraging we deduce $n_e$, the fluctuation in electron density.

To get a clear picture of this process, the deaveraging process is depicted in Fig. 4.9, where we take a number of frames in succession, calculate the average of these frames and then subtract it from each frame to get the deaveraged frame which depicts the structure in each frame. Once we have the frames deaveraged, we made deaveraged movies with those frames in order to perceive and understand the evolutions of the structures. All the raw plasma movies measured this campaign (Jan-Jun 2010) were decomposed into deaveraged frames and made into movies where structures propagate as a part of this master thesis work.

### 4.2.2 Blob Detection & Characterization

A common assumption in modelling the edge plasma has historically been that loss of particles and energy from the edge was an essentially diffusive process. Deaveraged images show direct evidence that dynamics at the plasma edge are more complicated than this, producing intermittent convective “blobs” or “filaments”. These may result in large transient transport of particles and energy far from the plasma edge, dominating the expected flux due to diffusive processes. During their evolution, filaments gradually dissipate as they travel
4. Experimental Technique

![Figure 4.9: Deaveraging Process](image)

The analysis of blob detection and characterization carried out as a part of my thesis is based on the principle, Event detection using thresholding. The code for blob detection was written by B.Ph. van Milligen (CIEMAT) and was used for this thesis work with a few alterations made. The algorithm, Fig. 4.10 is as follows:

- The raw plasma images are decomposed from the fast movies recorded and are deaveraged in order to remove the background in the images and these deaveraged images are converted back to gray scale. These images of structures in gray scale are the input data for the blob detection code.

- A threshold value is assigned to the deaveraged images on a scale of 0-1. This value is relative to the maximum intensity in that particular image. For example throughout this master thesis work a threshold of 0.7 was assigned after thorough study at different thresholds and visualization with the images. So all structures or more precisely all pixel values having an intensity level of 70% and above with respect to the maximum intensity in that image is detected. Now these pixels check with their neighboring pixel intensity (top, bottom, right and left neighbors, not the diagonals). If they are comparable then these pixels all together are detected as a structure(blob).
4.2 Image Analysis

![Image Analysis Diagram]

**Figure 4.10:** Algorithm of the Image Analysis performed, consisting of 3 major steps; Image processing and making fast plasma movies of structures evolving, Blob Detection using event detection by thresholding and blob characterization where the blobs are characterized with respect to aspect ratio, surface area and inclination angle.

<table>
<thead>
<tr>
<th>Number of blobs</th>
<th>Area</th>
<th>Integral (Sum)</th>
<th>$X_{position}$</th>
<th>$Y_{position}$</th>
<th>Epsilon(px)</th>
<th>Theta(rad)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>47.00</td>
<td>11348.0</td>
<td>310.426</td>
<td>269.702</td>
<td>0.578503</td>
<td>0.191675</td>
</tr>
<tr>
<td>2</td>
<td>35.00</td>
<td>9017.0</td>
<td>261.000</td>
<td>160.000</td>
<td>0.427028</td>
<td>0.000000</td>
</tr>
<tr>
<td>3</td>
<td>33.00</td>
<td>7974.0</td>
<td>263.000</td>
<td>147.000</td>
<td>1.000000</td>
<td>1.57000</td>
</tr>
<tr>
<td>4</td>
<td>43.00</td>
<td>10279.0</td>
<td>249.628</td>
<td>201.512</td>
<td>0.604314</td>
<td>0.471480</td>
</tr>
<tr>
<td>5</td>
<td>37.00</td>
<td>8945.0</td>
<td>270.378</td>
<td>119.378</td>
<td>0.665613</td>
<td>-0.315719</td>
</tr>
</tbody>
</table>

**Table 4.2:** Sample output of the blob detection code with the blob characteristics listed for an example of 5 blobs.

Once these structures, blobs in our case are detected, the area is defined as the number of pixels encompassing this non linear structure. These struc-
tures are considered as elliptical structures. This is a valid approximation one can make in order to study irregular structures with respect to the principle axes, vertical and horizontal, in our case with an ellipse (approximation) it is the major and the minor radii. A summation is done over all these pixels over the area (determined from counting the pixels satisfying the threshold condition) with the intensity levels of each pixel taken into account (weighted sum) and the integral emission of the elliptical structure (blob) is calculated. Regions where the filamentary structures overlap with the neutrals are illuminated and this is taken into account in the summation which is the integral value obtained in the code. It has been noted that these blobs that we see in our deaveraged images (in 2D) are the projection of the toroidal filament structure on the view plane on which the camera system is focussed. Moreover it has been proved in earlier studies by J.A. Alonso et al [5], that the local magnetic field lines in this region are almost parallel to the line of view (Fig. 4.11) and differ by a maximum of 10°. Hence these blob like structures captured (deaveraged images) are 2D projections along the local magnetic field lines are of a toroidal slice of the plasma, which eventually are distributed in the poloidal and radial directions.

Figure 4.11: Image shows the view plane and the field lines in the limiter region, dotted lines show the optical axis. Image Courtesy: J.A. Alonso.

-Eigen Analysis is performed in order to define the major and minor radii of the elliptical structure. In this case a inertia tensor (mass moment of inertia) is defined for the structures detected, which automatically outputs the X and Y position of these structures with respect to the deaveraged frame. The center of mass of these structures also allows us to define the principle axes. Once
the principle axes, in our case both the major and the minor axis is defined, the Aspect Ratio is determined. Aspect ratio of an ellipse is the ratio of the semi minor axis to the semi major axis \( \frac{b}{a} \), in our case it gives an estimate of the elongation (on a scale of 0-1) of the blob. The inclination angle is derived once the principle axis is defined. The inclination angle is the angle between the semi major axis and the X-axis (east). It is the measure of how inclined the structure is with respect to the X axis of the image in our case. The range of the inclination angle is \([−\pi, +\pi]\).

Once the blobs are detected the code throws an output file which contains all the blob characteristics such as depicted in Tab. 4.2. Various statistics are performed from these blob parameters and are shown in the following chapter.
Chapter 5
Experimental Results

All experimental work performed as a part of this master thesis work in this campaign (Jan-Jun 2010) were predominantly with ECRH plasmas. There were a couple of days with NBI heating when measurements with fast cameras were recorded, however not very significant with respect to the present work on structures. TJ-II plasmas are heated by a combination of ECRH power (2x300 kW lines) and NBI systems (2x400 kW aprox.). A third gyrotron is being installed and tested in order to provide additional Bernstein heating. High density plasmas in TJ-II achieve a central electron density $n_e(0) = 8 \times 10^{19} m^{-3}$ with temperatures of about $T_e(0) = 150$ eV, while conventional NBI discharges remain in $4 \times 10^{19} m^{-3}$ and $T_e \approx 1$ keV. TJ-II discharges last around 0.25 s, with a repetition frequency of about 10 minutes$^{-1}$. For the measurements with fast cameras pertaining to this work, He gas puffing was performed through the valve in the poloidal limiter Z2 on which the fast cameras are focussed tangentially upon. Measurements were made with both single and double bundles as described in the previous chapter.

5.1 Deaveraging Process

As mentioned in the previous chapter the deaveraging process was done systematically and movies of the structures evolving were made from the raw data to perceive and understand the motion of these structures convincingly. For example the figure below shows a raw image recorded during one of the shots and its average and deaveraged frames. In the raw image we observe the structures along with the background and this is removed by subtracting the average of a certain number of frames from each of the raw image. This process defined as deaveraging and was performed using MATLAB and movies with these deaveraged frames do give us a clear picture of the evolution of the structures. Another interesting observation in these images is the Langmuir probes on the limiter, which even though were not used for measurements acts as very good reference points in order to determine the spatial scales. The probes saturated, as they appear in the image due to black body radiation due to over heating.
5.1 Deaveraging Process

(a) Example of raw image when the limiter is pushed up to LCFS.

(b) Average of 100 frames (background of the 100 raw images).

(c) Deaveraged frame (background subtracted from the raw image).

Figure 5.1: Raw (a), Averaged (b) and Deaveraged (c) images of frame #7300; shot #24084.
The main investigation performed as a part of this thesis work is the systematic study of the camera parameters using single and double bundles and detect small structures and investigate whether these are blobs or noise. All measurements made using single bundle discussed in this chapter are using an objective of 50mm and that of double bundle are using 75 mm objective. The f-number(N) is 1.8 for both the objectives used(f = 1.8D). The image analysis is usually done on pixel scale, however knowing the objectives used we can fix the pixel to normal length scale. For 50 mm objective, 1 pixel corresponds to 0.3571 mm(approx.) and for 75 mm objective 1 pixel corresponds to 0.3125 mm(approx.). The pixel to real length scale here also takes into account the total magnification of the camera system. The use of two different Relay optics system is the reason for such a close value on the length scales for 50 mm and 75 mm objectives. The net magnification for the single bundle system was \( M = 1.72 \) and for the double bundle system \( M = 2 \). The distance between two consecutive langmuir probes on the limiter is 50 mm and between the langmuir probe and the valve on the limiter through which He gas is puffed is 25 mm.

### 5.2 Systematic Study of the Fast camera Parameters

In order to detect the structures by running the Blob detection code, one important necessity was to get the best possible image of the structures before the blob detection. To do this we did a systematic study of the Fast camera system which includes variation of the exposure time(integrating time) and the Image intensifier voltage( MCP voltage). The use of image intensifiers with the fast camera is not a usual practice, however in TJ-II plasmas in order to make movies with very high speeds(in the order of 100,000 frames per sec) at short exposure time(less than 10\( \mu \)s), this practice is very much a necessity. The advantage of using Image intensifiers is that we can go to high speeds with high integration times, and the setback is the quality of the images to a certain extent. It is trivial that when the image intensifier’s voltage is raised beyond a certain level or in general for high values of the Intensifier voltage, there is considerable amount of noise(salt and pepper) in the image. The need for optimum level of these parameters, intensifier voltage and the exposure time plays an important role in the S/N ratio of these movies recorded.

#### 5.2.1 Variation of the Intensifier voltage

For this study three different shots, namely 24176, 24184 and 24195 were studied at 700V, 800V and 750V respectively for the same exposure time of 1\( \mu \)s. The movie was recorded at 54000 frames/sec. The limiter was placed for all the three discharges studied above at the LCFS, which was 362 mm for this mag-
5.2 Systematic Study of the Fast camera Parameters

Figure 5.2: Raw, Average and Deaveraged image of shot 24176. The intensifier voltage is 700V and the exposure time is 1µs. Dotted line shows the Limiter position (at LCFS).

Fig. 5.2 shows the raw, average and deaveraged images. The signal is not as strong as the ones in Fig. 5.2 which were measured at higher intensity voltages. However when comparing the images of Fig. 5.4 and Fig. 5.4, the raw image shows that the signal is relatively weaker when compared to the other two at higher voltages but still is a good for analysis, since in the corresponding deaveraged frame we do see the structures propagating distinctly. Moreover this deaveraged frame when compared with the other two in Fig. 5.4 does pave way for us to reach higher exposure times by which we would at present expect better S/N as we have seen earlier in our calibration that as we increase the intensifier voltage (MCP), there is an inevitable increase in the noise level.

Fig. 5.4 depicts raw, average and deaveraged frames of two shots (24195 and 24184) with same exposure times but different Intensifier voltages and there is a clear indication of of increase in the level of signal when we look at the raw images. The figures on the right were measured at an intensifier voltage of 800V and the ones in the left at 750V. The average images of both the shots does confirm that both the images are not saturated, even though when we look at the raw image, it gives us a slight indication that a small region on the top right (in the raw image of shot 24184) looks saturated. The structures (deaveraged images) of both the cases are in the bottom. Looking at the deaveraged frame in the bottom right where we see one big structure, poses two possibilities. First one is what we observe, it might be one big structure evolving or it might be several structures, but appears as one due to the fact that we are making the measurement at high Intensifier voltage. Considering that all these three shots were measured all at similar conditions including these frames which were chosen for this study similar speed and similar range of density for the frames chosen for this analysis. The time evolution of density
for these discharges are plotted in Fig. 5.3.
This study indicates that for the discharges, the movies recorded in the fast camera with use of image intensifiers at high voltages might indicate that what we observe is just noise from the raw images at first sight, however it does let us explore and question more about the structures which are viewed at high signal levels at high voltages along with some noise (raw images).

5.2.2 Variation of the Exposure time

For this study three consecutive plasma shots were studied namely 24195, 24196 and 24197 with almost similar density evolution as seen in the Fig. 5.5. The movies were recorded at 54000 frames per second and in order to analyze these movies, frames around 1080 ms - 1090 ms and deaveraged movies were made. The exposure times were varied as 1µs, 500 ns and 250 ns. Since we reduced the exposure time by a factor of 2 every time we were able to cross check in the raw scale (RGB) that the signal level also fell by a factor of 2 confirming that \( I \propto \text{exposure time} \).

In Fig. 5.6 we see the raw, average and deaveraged frames for the exposure time of 250 ns. The intensity on the raw scale for this image is very low when compared to those with higher exposure times as shown in Fig. 5.7 where we can see the data of raw, average and deaveraged frames for shots 24195(left) and 24196(right). Very close to the LCFS we can see the scale levels correspond to close to 150 (in average image of 24195) to around 70-80 for the case of 24196(right). Following the same trend is also observed in In Fig. 5.6 where the signal is around 30-40 for both the average and raw images. This dependence
of the Intensity of the signal proportional to the exposure time is consistently observed even in the raw images of 24195 and 24196 in Fig. 5.7. From the deaveraged frames of all three shots we can see the same trend with respect to the intensity of the structures and this is only a consequence of the signal intensity obtained for different exposure times. Hence in order to achieve maximum possible signal for the movies, the videos have to be recorded with maximum exposure time (integrating time), however keeping in mind we cannot exceed...
or get close to the limit which would result in saturated signals. In our study since for these three shots we were close to the limit, we wanted to check how the signal is when we exceed this 1µs exposure time, for which we chose another plasma shot (24174) which was recorded at 700V intensifier voltage and with exposure time of 5µs. The results of the raw, average and deaveraged
frames shown in Fig. 5.8 Initial observation of the raw image does indicate to us that the image is saturated at a few regions, however the average picture shows that it is close to saturation however not saturated. This a an example where the intensifier voltage is less and exposure time is high and we see very high S/N. The corresponding deaveraged frame is very good showing the structures (positive and negative structures or blobs and holes) very clearly evolving around the LCFS.

5.3 Blob Detection of Single bundle Data.

Once the images are deaveraged they were fed into the blob detection code which is based on the principle of event detection by thresholding. The motive behind this study is to detect the blobs or filament structures and characterize these elliptical structures based on their area (size), aspect ratio and their inclination angle. The blobs are detected by assigning a threshold value on the scale of 0 to 1. All blob analysis carried out in this master thesis work was performed with a threshold value of 0.7 as mentioned in the previous chapter.

5.3.1 Blob detection and characterization.

Applying the blob detection code to plasma shots where the limiter was not interacting with the plasma, several interesting phenomena taking place in the SOL can be visualized. For example, in Fig. 5.9, we can clearly visualize the results of the blob detection over a deaveraged frame. From the various parameters the code outputs like the Aspect ratio-AR (ratio of semi-minor axis to the semi-major axis) and the number of pixels detected as the area of the blob; we can determine the the major axis of these elliptical structures, approximated as the blob size (2a).

$$a = \frac{(\text{Area})}{\pi b}; AR = b/a; \implies a = \left(\frac{(\text{Area})}{\pi(AR)}\right)^{1/2}$$

(5.1)

where ‘2a’ is the size of the blob (‘a’ is semi major axis of the elliptical structure); ‘b’ is the semi-minor axis and Area is obtained from the code. Fig. 5.9 is from shot #24080 (100 kfps). In this shot the Limiter was placed 3.3 cm below the LCFS, whose position is 362 mm from the magnetic axis for the magnetic field configuration employed for this shot (100-44-64). There was a density ramp up in this shot as shown in Fig. 5.10. The image shows the blobs detected and the blob parameters for two blobs.

The threshold density is around $0.6 \times 10^{19} \text{m}^{-3}$ for TJ-II plasmas[21]. Previous works in CIEMAT by J.A.Alonso[13,14], D.Carraler[12] have shown by deaveraged images, the inversion that takes place once this threshold density
is reached. The structures rotate counter-clockwise till the threshold density, till the radial electric field is positive(outwards). Beyond the threshold density, the radial electric field is negative(inwards) and these structures change the direction of poloidal velocity and starts evolving clockwise, thereafter. This was
5.3 Blob Detection of Single bundle Data.

Figure 5.8: Raw, Average and Deaveraged image of shot 24174. The intensifier voltage is 700V and the exposure time is 5µs. Dotted line shows the Limiter position (at LCFS).

Figure 5.9: Figure depicts the blobs detected in a frame and the various blob parameters like blob area (calculated in \( cm^2 \)), Aspect ratio (AR) and the inclination angle (theta) for two of the largest blobs detected for shot #24080 (100 kfps), frame #6525. Dotted lines in the bottom show the limiter position, which was 3.3 cm outside the LCFS.

observed in the structures from the present data, however it is not a part of this master thesis work since it has been explored and studied various times for
TJ-II plasmas. In order to study this all plasma frames from region A and B as shown in Fig. 5.10 were processed and the blobs were detected. The regions A and B are before and after the threshold density respectively.

5.3.2 Blob Statistics

The blob detection and characterization were performed for several plasma discharges and the blob rate (blobs/frame and blobs per millisecond) and other statistics for different plasma conditions and fast camera parameters like variation of exposure time and intensifier voltage, different limiter positions (outside LCFS, at LCFS and inside the plasma), density (before and after threshold density for different limiter positions) were calculated. These preliminary results are illustrated in the following sections. First we studied the variation in the blob rates for variation of Fast camera system parameters, namely exposure time and intensifier voltages. Fig. 5.11 shows the evolution of number of blobs or structures (blobs/frame; number of frames scaled to time in ms). The three shots 24195, 24196 and 24197 were recorded at 54,000 frames per second and intensifier voltage of 750 V at an exposure time of 1μs (red), 0.5μs (blue) and 0.25μs (black).
5.3 Blob Detection of Single bundle Data.

Variation in Blob rates Vs Exposure Time

**Figure 5.11:** Variation in blob rates for 3 different exposure times $1\mu s$ (red), $0.5\mu s$ (blue) and $0.25\mu s$ (black)

**Figure 5.12:** Poisson PDF's for the blob rates described above.
There is an indication from the figure that the number of structures detected per frame decreases as the exposure time is reduced. This is clear in the Fig. 5.12 where the mean of the Poisson PDF’s gradually increase with the increase in exposure time. The non-gaussian behavior, the skewness in the profile and the long tail of the PDF’s can be predicted as a consequence of increase in the blob count when there is an increase in the density, more precisely due to the intermittency in the density fluctuations in SOL [7] and all the three plasma discharges had a density ramp up. Variation of the blob rates with respect to density is studied and shown in Fig. 5.18 and Fig. 5.17. The mean of the Poisson PDF’s are 645, 475 and 200 structures/frame for $1\mu s$ (red), $0.5\mu s$ (blue) and $0.25\mu s$ (black). At a speed of 54000 frames per second, the blob rates decreases as $3.48 \times 10^7$ blobs/second ($1\mu s$), $2.56 \times 10^7$ blobs/second ($0.5\mu s$) and $1.08 \times 10^7$ blobs/second ($0.25\mu s$).

Similar behavior is observed in the blob rates for increase in the intensifier voltage (Fig. 5.13). Three plasma discharges namely 24176 (green), 24184 (blue) and 24195 (red) were investigated, all three discharges recorded at 54000 frames per second, exposure time of $1\mu s$ for intensifier voltages of 700 V, 800 V and 750 V respectively. The respective Poisson PDF’s are shown in Fig. 5.14 and we can see there is not much increase in the blob count from 750V to 800V, however the PDF does show that the blue curve (800V) has a long tail to the left and the red curve (750V) has a similar long tail in the right. The mean blob rates are $3.48 \times 10^7$ blobs/sec and $3.52 \times 10^7$ blobs per second for intensifier voltages of 750 V and 800 V. The reason for such a close value is probably due to the fact that these frames were recorded close to the threshold density of $0.6 \times 10^{19} m^{-3}$ and from previous works of D.Carraler et al., it has been showed that the blob rates fall in this regime where the shear layer develops and the inversion takes place. The mean blob rate for the shot 24176 at 700 V is $2.12 \times 10^7$ blobs/second.
Variation in Blob rates Vs Intensifier Voltage

Figure 5.13: Variation in blob rates for 3 different intensifier voltages, 750V (red), 800V (blue) and 700V (green).

Figure 5.14: Poisson PDF's for the blob rates described above.
Variation in Blob rates Vs Limiter position

Figure 5.15: Variation in blob rates for different limiter positions.

Figure 5.16: Poisson PDF's for the blob rates for different limiter positions.
5.3 Blob Detection of Single bundle Data.

The blob rates were studied also for different plasma conditions like for different densities (during a ramp up) and for different limiter positions. In Fig. 5.15, we see the variation in blob rate for three different limiter positions (away from LCFS(24080), at LCFS(25217) and limiter inside the plasma(24085), all three discharges were recorded at 100,000 frames per second and shot 25217 with a 75 mm objective. We observe that as the limiter is moved into the plasma the number of structures detected are lesser. This is also seen in the mean values of the Poisson PDF’s in Fig. 5.16 where the blob rates are 2.3x10^7 blobs/second (limiter 3.3 cm outside LCFS), 1.55x10^7 blobs/second (at LCFS) and 1.36x10^7 blobs/second (limiter inside plasma by 0.5 cm). He gas was puffed through the valve in the limiter for all these discharges. One possibility for the reduction in the number of blobs as the limiter is pushed maybe due to the fact that we don’t observe the interactions of the neutrals in the SOL and it has been predicted that the blob evolution is maximum in the edge to SOL region. The regions of high intensity that we detect as blobs from the 2D images (deaveraged) are those which are above the threshold of 0.7. We can argue that the interaction of the plasma with the neutrals in the SOL gives rise to these illuminated structures observed by the fast camera and once this edge to SOL distance is reduced we observe less blob activity. Another possibility for the decrease in the number of structures detected is the threshold value assigned. The threshold value of 0.7 was assigned in order to detect small structures and for this value the bigger blobs gets detected as more than one structure which accounts for the drastic increase in the blob count. The above statement is a prediction by the author and more studies with respect to this phenomena will lead to conclusive results.

Fig. 5.17 and Fig. 5.18 show the PDF’s for two plasma discharges 24080 (limiter outside by 3.3 cm) and 24085 (limiter inside plasma by 0.5 cm) ad each plasma discharge was analyzed at two different density ranges; \( n_1 = 0.6 \times 10^{19} m^{-3} \) (approx) and \( n_2 = 0.85-0.95 \times 10^{19} m^{-3} \) during a density ramp up as shown in Fig. 5.10 and Fig. 5.19 respectively. The PDF’s in both the figures indicate an increase in the blob rates with density irrespective of the limiter position. It however depicts a strong increase in Fig. 5.18. The blob rates increases from 2.14x10^7 s^{-1} to 2.34x10^7 s^{-1} when the limiter is placed outside LCFS during the ramp up and an increase from 1.35x10^7 s^{-1} to 1.92x10^7 s^{-1} when the limiter is pushed into the plasma by 5 mm. There has been theoretical models and experimental investigations in the past that have shown that density blobs formed in the edge or edge to SOL regions have strong dependence on the poloidal velocity shear [228, 27, 22]. However this has not been investigated in detail in this thesis work.
Variation in Blob rates Vs Density

**Figure 5.17**: Poisson PDF’s of blob rates for different densities for limiter position 3.3cm outside LCFS.

**Figure 5.18**: Poisson PDF’s of blob rates for different densities for limiter position 0.5 cm inside LCFS.
5.4 Fast movie Measurements using Double bundle.

As mentioned in the experimental set up in the previous chapter, one of the main questions to be addressed as a part of this thesis work is, how convincingly can we prove that these small structures are very much blobs and not mere noise. In order to answer this, a double bundle was used with 75 mm objectives, unlike the single bundle measurements which were measured using 50 mm objective. Here in the double bundle we make movies simultaneously in two objectives and the objectives are calibrated in a fine way by tilting the objectives up and down which are held together by the solid support structure. Additionally the use of double bundles also were very advantageous in order to study the impurity transport by using different interference filters for different objectives and was very handy for making movies for edge density and temperature measurements using passive spectroscopic imaging.

5.4.1 Deaveraging process with double bundles.

When the double bundle was used for measurements, we avoided high speed videos, since it is always a trade off between the sensor area (horizontal and vertical resolution) and eventually the region of view which decreases with increasing speeds and the more over we wanted the maximum resolution possible
(a) Example of raw image with limiter positioned at 18 mm away from LCFS.

(b) Average of 100 frames (background of the 100 raw images).

(c) Deaveraged frame (background subtracted from the raw image).

**Figure 5.20:** Raw (a), Averaged (b) and Deaveraged (c) images of frame #2146; shot #25202. The image is split into two, image of top objective (right) and bottom objective (left).
with the fiber bundles. This was one of the reasons we changed to a 75 mm objective for double bundle measurements from a 50 mm one used for single bundle measurements, so that we can have a closer look of the desired region of interest instead of a larger region interest as observed with 50 mm objective. Moreover we never recorded movies at very high speeds using the double bundle, since doing so we would not be able to capture the maximum sensor area which is very important in double bundle measurements considering the sensor area is divided between the two objectives.

Systematic parameters of the camera system were studied by varying the exposure times and the intensifier voltage similar to what we did for the single bundle. Fig. 5.20 shows the raw, average and the deaveraged data. At first observation of the deaveraged frames it is motivating since we see almost the same thing in both the frames. If it were noise we shouldn’t be seeing the same structures. However no conclusions were made initially and the analysis was performed by varying the exposure times and the intensifier voltage to verify and address several questions.

### 5.4.2 Variation of Intensifier voltage and Exposure times

From the studies of the camera parameters for the single bundle, it is clear we should not go to very high Intensifier voltages and very low exposure times, failing which the signal is either tends to get saturated or the S/N ratio is going to be very low, neither of which is an unfavorable condition for image analysis. However in order to get to a conclusion of the same, intensifier voltage was raised to maximum of 800V (in the intensifier voltage variation study), which in a way helps to get an intuitive picture of these structures which people most times misinterpret as noise. By increasing the intensifier voltage to 800V, one adds a lot of salt and pepper noise to the image in addition to the to a few dead fibres of the bundle which are already prevailing in the images. For the systematic study of the camera parameters for the double bundle which are the exposure time and intensifier voltage measurements which were analyzed were discharges for which the limiter was away from the plasma, at 18 mm outside the LCFS (for exposure time studies) and at LCFS for the intensifier voltage variation studies.

These studies were carried out this way, since we know the signal levels are related not only to the exposure times and intensifier voltages but also to the speed at which we record, the objectives used, the limiter position and the $H_e$ gas puffing through the valve in the limiter.

For the variation in exposure time studies 3 shots were analyzed, namely 25197, 25198 and 25200. The first two shots were at 650V and exposure time of 2$\mu$s and 1$\mu$s, where as the other shot was measured in 700 V at 0.5$\mu$s. All 3 videos were recorded at 16000 frames per second and the limiter was placed at 380 mm from the magnetic axis.
Fig. 5.21 shows the shot 25200 which was recorded at 0.5$\mu$s exposure time. The signal level is low as we can see in both the raw and the averaged frames. However we do see that the structures on both right and left, meaning top and bottom objectives look alike, which is something we were expecting to be. In Fig. 5.21 we see the other two observations from shots 25197 and 25198 where the exposure time was increased by a factor of two and hence the intensity of the signals as we see in the averaged frames are more by a factor of two which is also verified on the RGB color scale.

The interesting aspect from all three sets of images is that in the deaveraged frames of all the three shots we see similar structures in both these objectives, in most of the cases with almost the same signal level. The limiter for these 3 sets of measurements was places 18 mm outside the LCFS and there was gas puffing through the valve in the limiter. From these images one thing that is very clear before blob detection analysis is these are structures since we see it being the same recorded by both the objectives on several cases with different parameters.

The Intensifier voltage was systematically varied and plasma movies were recorded for similar exposure times. Plasma discharges 25211(700 V), 25212(750 V) and 25214(800V). All the movies were recorded at 16000 frames per second. The exposure time for the discharges were 250 ns for 25211 and 25212 and was 120 ns for the 25214 shot. In all the three discharges we can clearly observe two saturated regions and they are the valve through which the He gas is puffed(left) and the other(right) is the Langmuir probe on the limiter. For this study the limiter was at LCFS. From the raw images of 25214 (Fig. 5.23) and the raw images of the other two discrges(Fig. 5.24), we can see that at
5.4 Fast movie Measurements using Double bundle.

Figure 5.22: Images measured at 16fps at similar intensifier voltage of 650V and at different exposure times. Raw, average and deaveraged frames of shot 25197(2μs) on the left and shot 25198(1μs) on the right respectively. Dotted line shows the Limiter position (at LCFS).

higher Intensifier voltage there is considerable amount of noise in the signal. The deaveraged images show similar trend as shown before, depicting clearly the
same structures, recorded through the top and bottom objectives in the double bundle set up. The signal levels are maximum for shot 25214 for which the measurement were recorded at the highest I.I voltage (800 V w.r.t this study), however there is considerable amount of noise in the signal and for this to be reduced at the same conditions such as the limiter at LCFS with He gas puffing through the valve in the limiter.
5.4 Fast movie Measurements using Double bundle.

Figure 5.24: Images measured at 16kfps at similar exposure time of 250 ns and at different intensifier voltages. Raw, average and deaveraged frames of shot 25211(700V) on the left and shot 25212(750V) on the right respectively. Dotted line shows the Limiter position.(at LCFS).

5.4.3 Blob Detection of Double bundle Data

The structures or blobs for these deaveraged frames were detected using the blob detection code and were characterized with respect to size, AR and inclination.

Fig. 5.25 depicts the blobs detected in a deaveraged frame for shot 25213. This
Figure 5.25: Blob detection performed for shot 25213, recorded at a speed of 16000 frames per second, 750V and an exposure time of 120 ns.

Image clearly shows both the images recorded by two similar objectives placed one above each other in the support structure, in one frame. These are images recorded simultaneously and focused to get almost the view of similar region of interest. The structures appear similar in both the images. More importantly these structures are marked using different shapes and different colors to show that they are the same structures visualized in both the objectives. This clearly shows that these are very much structures or blobs and not noise. All these blobs have similar area (blobs detected in the top of the green rectangle by both top and bottom objectives are with (major axis) size = 0.44 cm and 0.53 cm), however with different aspect ratio and inclination angle. The difference in aspect ratio and inclination is due to the fact that these images are viewed and recorded by two different objectives, tilted (top objective tilted down and bottom objective tilted up, in order to view similar region of interest in both the objectives) and clamped to the support structure and their orientation is bound to be different. This is also a clear indicative suggesting this method of analysis of blobs detected by the principle of event detection using a threshold value is a fine way to estimate the structures and characterize them.
Chapter 6
Conclusions

The results obtained in the experimental campaign from January-June, 2010 using intensified fast visible cameras with both single and double bundle system along with a different objectives and relay lenses are illustrated and discussed in this master thesis work. The use of image intensifiers even though not trivial, has been very useful for the above work in particular for plasma movies recorded at very high speed with short exposure time. Several fast plasma movies of the structures evolving for various plasma conditions and camera parameters were made. Based on the results obtained while performing these experiments in ECRH plasmas in stellarator TJ-II over the past 6 months, the following conclusions are outlined:

- The deaveraged images and the movies of the structures give us a clear understanding of the evolution of these structures across the edge or edge to SOL region. Furthermore, these images are scanned using a threshold value and the blobs are eventually detected using the blob detection code. These blobs are characterized according to geometrical parameters such as surface area and size, Aspect ratio and inclination angle. The question regarding whether these plasma emission structures that we observe are blobs or mere noise has been answered with the use of the state of the art double bundle system where these structures are vividly distinguished as filament structures or blobs and not noise. The use of double bundle for the structure studies is a novel idea and has been accomplished for the first time by the fast camera team here in CIEMAT.

- Systematic studies of the fast camera parameters, the exposure time (integrating time) and intensifier voltage (MCP voltage) were studied at different plasma conditions and limiter positions. It is clearly evident that the intensity of the signal (plasma emission) increases with increase in exposure time and intensifier voltages with both single and double bundles, however has a saturation limit with respect to each of the camera parameters. The intensity of the signal also depends on the limiter position, the more the limiter is pushed in (more interaction with the plasma), the higher the signal received by the
fast camera. The signal also depends on the Helium gas puffing through the valve on the poloidal limiter. The effective use of the image intensifiers are thoroughly examined and accomplished by going to very high speeds of the range of 100,000-150,000 frames per second at relatively short integrating time from a few micro seconds down to 125 ns depending on the limiter position for the discharges with Helium gas puffing.

-Blobs were detected and characterized for both single and double bundles and the blob rates were studied systematically for different camera parameters, limiter position and density ranges. There is an increase in the blob rate with increase in density, exposure time and intensifier voltage and decrease in the blob rate when the limiter is pushed into the plasma. Considering these are density blobs, a preliminary argument for this behavior can be attributed to the fact that the blobs decrease as the region between the edge and the SOL decreases. The blob statistics gives us a preliminary insight of the evolution of these blobs or structures in the edge of TJ-II plasmas (ECH). The intermittent behavior of the blob evolution and the corresponding Poisson PDF’s are intriguing and paves the way for more unanswered questions relating the dynamics of these density blobs in the edge to SOL region.

- Structures of similar size less than 1 centimeter are detected, which usually are misinterpreted as noise or ignored using the double bundle as shown in the results. These blobs have similar blob area however different aspect ratio and inclination angle which is explained as an effect of tilting the objectives on the support structure on which they are fixed in order to optimize the objectives (top and bottom) to observe almost the same region of interest with maximum possible sensor and bundle areas.

In the above master thesis work, by using a threshold value we only detect the blobs and not the holes. Improvements can be done with respect to that in the code by assigning two different threshold values, one above certain value to detect the blobs and one below certain value to detect the holes simultaneously. The blob detection by threshold scanning takes a considerable amount of time when we analyze for a large number of frames and if we can impose two thresholds one for positive and other for negative, one could save a lot of computing time. With respect to the fast camera system, we were able to observe some discrepancies, i.e. the images appeared more brighter on one of the objectives than the other when the double bundle was used. Normalization of the sensitivity of the sensor with a white screen must be carried during the next calibration session to fix this problem.

Several interesting phenomena were observed during this campaign which includes the impurity transport studies across the SOL, which we attempted
to visualize using the double bundle by fixing Carbon filter in one of the objectives. Helium filters were also fixed in order to study the singlet and triplet states and hence obtain the edge plasma density and temperature using Helium line ratio method.

These results are only preliminary results, and future work with respect to the structure propagation are to be analyzed for NBI plasmas and at even higher camera speeds. The use of other image analysis methods besides event detection by thresholding such as Discrete wavelet transform are being employed presently in order to have a better estimate of these blobs or filament structures.
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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 him.

City, the

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Thangabalan S Aruneshwar
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