Time- and space-resolved spectroscopy at the EXTRAP-T2 reversed-field pinch

Jesper Sallander

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Jesper Sallander 14 December 1998

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Abstract

Spectroscopic measurements on fusion plasmas provide a large amount of information on the properties of the plasma. Key parameters such as electron- and ion-temperature, ion densities and particle confinement time can be measured. These measurements are mostly made with single line-of-sights resulting in line averaged measurements of the light emission from the plasma. By using multiple lines-of-sight it is possible to reconstruct the spatial dependence of the emission. Thus providing spatially resolved information on the obtained quantities.

A system for time- and space-resolved visible- and UV-spectroscopy has been designed, built and installed on the EXTRAP-T2 reversed-field pinch. From the brightness measurements made with this system the radial distribution of impurity line emission has been reconstructed. The method used in the reconstruction of the emission profile has directly provided the radial ion density profiles for C_{III} to C_{VI} and O_{III} to O_{V}. The obtained results have contributed to an improved understanding of the transport properties of the plasma through comparisons with transport model calculations.

The inclusion of charge exchange recombination (CXR) in the reconstruction method has made possible direct estimations of the neutral hydrogen density profile. CXR was found to be an important process to explain the observed emission profile from both C_{V} and C_{VI}. The measured ion density and emission profiles have also been crucial in the interpretation of the ion temperature and toroidal velocity measurements. It has been possible to reconstruct both the ion-temperature and -velocity profile by combining these measurements. The obtained emission profiles have also helped to clarify the oscillations observed in both magnetic and spectroscopic measurements. Indications of very spatially localized oscillations in the line emission have been found. The observations made on the ion density of He-like carbon have been found to be very consistent with the measurements of the same quantity using VUV-spectroscopic measurements. This is clearly an indication that the spatially resolved spectroscopy produces results that are reliable and in good agreement with other observations.
Preface

My career in fusion plasma physics started with the thesis work for my master of science. This was carried out at the Alcator C-mod experiment at MIT in Cambridge, USA. To my disappointment the machine broke down a few weeks before my arrival. Hence I had never the opportunity to see it in operation during my four month stay in the US. However, the subject for my work was to design and construct a calibration unit for the Thomson scattering system, which not involved the running of the experiment. I really enjoyed my work and decided that I wanted to continue as a PhD student. The thesis work was apparently good enough to convince my supervisor, Prof. Elisabeth Rachlew, to take me on as a PhD student at Fysik II, KTH.

During my time as a PhD student I have had the possibility to design and construct my experiment from scratch. This gave me the freedom to decide how to implement the ideas we had on performing spatially resolved spectroscopic measurements on the EXTRAP-T2. It unfortunately also opened great possibilities to make mistakes. Numerous are the times when damaged fibres and noisy amplifiers made life hard in the lab. Fortunately the performance of the system and thereby the results converged towards what was desired. The satisfaction when everything works and beautiful data appears on the computer screen is beyond words to describe.

A work like this is of course not the work of one person; without help from colleagues it is very hard to obtain any results. First I would like to thank my supervisor Prof. Elisabeth Rachlew for all help and support during my five years at Fysik I (and before that). I really appreciate that you have given me much freedom in my work developing the spatially resolved spectroscopy system. I also want to thank Anders Hedqvist for all constructive discussions over the years if you have also been a great partner in the lab. I also had a very nice collaboration with Pontus Hörling and Klaus-Dieter Zastrow if former PhD students at Fysik II thank you for sharing your experience with me. I also thank Prof. Peter Erman for making Fysik I a nice place to work in. The rest of the staff also contributed to this of course.

There would have been no experiments without the team at the Alfvén lab. I wish to thank Jerzy Brzozowski for good collaboration on the spectroscopy at EXTRAP-T2. I also would like to thank David Larsson, Gunnar Hedlin, Anders Möller and Sam Holm for nice discussions. A special thank to Prof. James Drake...
for his support and kind attitude towards us spectroscopists. I also wish to thank the technical staff for all their help.

Finally I want to thank my wife Eva for all her support and understanding. Especially these last months when I have not always been present neither in person nor in my mind.

Stockholm December 14 1998
## Contents

1 Introduction  
1.1 Nuclear fusion  
1.2 Magnetic confinement  
1.2.1 The reversed-field pinch  
1.3 EXTRAP-T2  
1.4 Plasma diagnostics  

2 Plasma spectroscopy  
2.1 Excitation of ions and atoms in fusion plasmas  
2.2 Line emission  
2.3 Continuum radiation  

3 Spectroscopy at the EXTRAP-T2  
3.1 Spectroscopic measurements on EXTRAP-T2  
3.1.1 Experimental arrangements  
3.2 Intensity measurements  
3.2.1 Instrumental  
3.2.2 Line radiation  
3.2.3 Continuum radiation measurements  
3.3 Wavelength resolved measurements  
3.3.1 Line profile measurements  

4 Spatially resolved spectroscopy  
4.1 Spatial resolution  
4.1.1 Tomography  
4.1.2 Abel inversion  
4.1.3 Inversion methods  
4.2 Radially resolved spectroscopy on EXTRAP-T2  
4.2.1 Experimental setup  
4.2.2 Calibration  
4.2.3 Data analysis  

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction</td>
<td>3</td>
</tr>
<tr>
<td>Nuclear fusion</td>
<td>3</td>
</tr>
<tr>
<td>Magnetic confinement</td>
<td>4</td>
</tr>
<tr>
<td>The reversed-field pinch</td>
<td>6</td>
</tr>
<tr>
<td>EXTRAP-T2</td>
<td>7</td>
</tr>
<tr>
<td>Plasma diagnostics</td>
<td>9</td>
</tr>
<tr>
<td>Plasma spectroscopy</td>
<td>11</td>
</tr>
<tr>
<td>Excitation of ions and atoms in fusion plasmas</td>
<td>12</td>
</tr>
<tr>
<td>Line emission</td>
<td>14</td>
</tr>
<tr>
<td>Continuum radiation</td>
<td>16</td>
</tr>
<tr>
<td>Spectroscopy at the EXTRAP-T2</td>
<td>19</td>
</tr>
<tr>
<td>Spectroscopic measurements on EXTRAP-T2</td>
<td>20</td>
</tr>
<tr>
<td>Experimental arrangements</td>
<td>20</td>
</tr>
<tr>
<td>Intensity measurements</td>
<td>21</td>
</tr>
<tr>
<td>Instrumental</td>
<td>21</td>
</tr>
<tr>
<td>Line radiation</td>
<td>22</td>
</tr>
<tr>
<td>Continuum radiation measurements</td>
<td>24</td>
</tr>
<tr>
<td>Wavelength resolved measurements</td>
<td>24</td>
</tr>
<tr>
<td>Line profile measurements</td>
<td>25</td>
</tr>
<tr>
<td>Spatially resolved spectroscopy</td>
<td>29</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>29</td>
</tr>
<tr>
<td>Tomography</td>
<td>29</td>
</tr>
<tr>
<td>Abel inversion</td>
<td>32</td>
</tr>
<tr>
<td>Inversion methods</td>
<td>33</td>
</tr>
<tr>
<td>Radially resolved spectroscopy on EXTRAP-T2</td>
<td>35</td>
</tr>
<tr>
<td>Experimental setup</td>
<td>35</td>
</tr>
<tr>
<td>Calibration</td>
<td>37</td>
</tr>
<tr>
<td>Data analysis</td>
<td>38</td>
</tr>
</tbody>
</table>
5 Comments to the papers 43
  5.1 Paper I ........................................ 43
  5.2 Paper II ........................................ 43
  5.3 Paper III ....................................... 46
  5.4 Paper IV ........................................ 47
  5.5 Paper V ........................................ 48
  5.6 Paper VI ....................................... 48

6 Conclusions 49

A Signal amplifiers and filters 51

References 53
List of papers

This thesis is based on the work presented in the following papers:

I. J. Sallander
   A spectroscopic system for time- and space-resolved studies of impurities on
   the EXTRAP-T2 reversed field pinch.

II. J. Sallander, A. Hedqvist and E. Rachlew-Källne
    Measurements of neutral hydrogen profiles on the EXTRAP-T2 reversed-field
    pinch from time-resolved C$^5+$ line emission.

III. J. H. Brzozowski, J. Sallander, A. Hedqvist and A. Möller
    Studies of impurity ion rotation in Extrap-T2 reversed-field pinch plasma.
    *Proc. 25th EPS conference on Controlled Fusion and Plasma Physics, Prague*
    **22C** P4.027 (1998)

IV. J. Sallander
    Impurity profiles and radial transport in the EXTRAP-T2 reversed-field pinch.
    *submitted for publication* (1998)

V. E. Sallander, J. Sallander and A. Hedqvist
    Changes in transport and confinement in the EXTRAP-T2 reversed-field pinch.
    *submitted for publication* (1998)

VI. A. Hedqvist and J. Sallander
    On the consistency of spectroscopic ion density measurements.
    *to be submitted for publication* (1998)

The authors contribution to the papers is commented in chapter 5
Publications with contribution from the author not included in this thesis:

J. Sallander
Spatially resolved spectroscopy in the visible and near UV region from the EXTRAP-T2 reversed field pinch. *Proc. 5th EPS conference on Atomic and Molecular physics, Edinburgh* **19A** 218 (1995) *abstract*


Resistive shell operation and confinement in the Extrap-T2 RFP. *Proc. of the 16th International conf. on fusion energy organized by the IAEA, Montreal* **2** 193 (1996)


J. Sallander, A. Hedqvist and E. Rachlew-Källne
Investigation of the 5290 Å line in C\(^{5+}\) from radially resolved spectroscopy on the EXTRAP-T2 RFP. *Proc. 24th EPS conference on Controlled Fusion and Plasma Physics, Berchtesgaden* **21A** 1261 (1997)

Till Eva
Chapter 1

Introduction

In a world where the green-house effect is becoming a reality it is clear that mankind needs to find alternatives to fossil fuels for its production of energy. The prospects to replace these with renewable energy sources such as sun- and wind energy will probably remain in the dreams of the hopeful. With billions of people in the developing countries striving for a higher standard of living it is likely that the demand for energy in the form of electricity will grow dramatically in a near future. This will happen regardless if the industrialized countries manage to vastly decrease their energy consumption.

The need for large scale energy production will in this perspective be enormous. Today we have two main possibilities to produce electricity without using fossil fuels: water power and nuclear fission. The former causes large local environmental problems. Also much of the potential possibilities to build power stations have already been exploited in the developed countries. Nuclear fission i.e. conventional nuclear power is an essentially clean energy source but the waste problem remains to be solved. Also the mining for uranium has been a rather dirty business. The public opinion regarding the safety of the operation of nuclear power plants has made it politically impossible in most countries to speak for a further development in this area.

Nuclear fusion has the potential to fill this need of a clean/large scale power source. The advantages are significant. An almost infinite amount of fuel and no radioactive waste from the reaction. There are however significant practical problems that remain to be solved. Continued research is required in order to make fusion available as a power source in a not too distant future.

1.1 Nuclear fusion

Someone expressed controlled nuclear fusion as "the art of putting the sun in a box" which is a good picture of what it is all about. The sun uses fusion of light nuclei into heavier ones as its source of energy. In order to sustain this process
the sun relies on its enormous mass and the fact that it is placed in an infinite vacuum environment. To be able to reproduce these processes in a controlled fashion on earth we cannot rely on these prerequisites (uncontrolled fusion has been achieved numerous times in hydrogen bomb explosions). First we need to achieve the temperatures and densities that are required to keep the process going. We also must keep the particles involved, usually the hydrogen isotopes deuterium and tritium together during a time long enough to make the reaction self sustained. These requirements, initially derived by Lawson [1], have been put together in what is known as the Lawson fusion product or the fusion triple product:

\[ n_i T_i \tau_E > 5 \times 10^{21} \text{ [m}^{-3} \text{ keV s]} \] (1.1)

where \( n_i \) is the ion density, \( T_i \) the ion temperature and \( \tau_E \) the energy confinement time. In the sun it is the gravity that makes density very high and keeps the particles together. In an experiment in a laboratory we can instead of having the enormous density of the interior of the sun make the temperature very high. Here the second advantage of being a star comes in; we need to keep something very hot away from its surroundings both to prevent this hot substance from being cooled down and also to avoid melting of the surrounding vessel. The sun has the universe as its infinite vacuum vessel which prevents it from reacting with surrounding matter. In the lab we use a metal vacuum vessel for this purpose but still we need to avoid contact with the walls of this vessel. The research trying to face these problems and requirements follows two fundamental concepts: inertial confinement [2] and magnetic confinement. The first mentioned concept makes use of strong laser- or particle beams that are focused on small pellets of fuel. The fuel is compressed and heated by the radiation pressure to densities and temperatures high enough to meet the fusion criterion. This method will not be further treated here since the experiments in this thesis are conducted on an experiment of the second type.

### 1.2 Magnetic confinement

This concept relies on the fact that matter at the high temperatures required for fusion processes is more or less ionized. The electrons have separated from their nuclei and together they form an ionized gas that is called a plasma [3]. It is also quasi-neutral which means that given a large enough volume the positive and negative charges will cancel out. Since the plasma contains free charged particles it is electrically conducting. This makes it possible to use a magnetic field to control the motion of the particles. They will follow the magnetic field lines conducting a spiral motion around these. Thus one can construct a magnetic bottle that both prevents the plasma from coming in contact with its surroundings and also keeps the particles trapped for long enough time to make the fusion process efficient.

Over the years several magnetic configurations have been developed for this purpose. The most common today is to bend the magnetic field into a torus, like a donut. Since a torus has no end the trapped particles can in theory go round and
around forever without being lost. The magnetic field in a torus can be divided into two components; the toroidal (the long way around the torus) and poloidal (the short way around). Ideally there should be no radial magnetic field. Together these two components make a spiral-shaped magnetic field within the torus. The most developed type of experiments following this concept are the tokamaks [4]. In these the applied toroidal magnetic field is much stronger than the poloidal that is created by the toroidal current in the plasma. It is a bit of brute force type of machine that uses the very high, up to several Tesla, toroidal magnetic field to make the plasma stable. This results in a low $\beta$ value which is a measure of the ratio of the total energy in the plasma to the total magnetic energy. In a tokamak the $\beta$ value is of the order a few percent. Still the tokamak is until today the most successful magnetic confinement scheme. Large experiments such as JT60U [5] in Japan, TFTR [6] and DIII-D [7] in the USA and JET [8] in England have shown to be very successful in achieving high temperatures and long confinement times. These experiments have also performed experiments with deuterium-tritium fuel to actually achieve a significant amount of fusion processes in the plasma. In 1998 a fusion power of 6.7 MW was achieved in the JET tokamak [9].

Another concept is the stellarator [10] where a very complicated set of coils creates an intricate magnetic configuration that does not make use of a plasma current in its formation. The technical problems of constructing the advanced coil systems required have made this type of machine less common. It is a very
interesting concept though. A new experiment using super-conducting coils has recently been launched in Japan—the LHD [11]. The new German experiment Wendelstein-7X [12] which also utilizes super-conducting coils is about to be built.

1.2.1 The reversed-field pinch

The experiments described in this work are conducted on a third type of machine called a reversed-field pinch (RFP) [13]. Like the tokamak it relies initially on an externally applied toroidal- and a plasma generated poloidal magnetic field. These are of the same order of magnitude unlike in the tokamak. The plasma is allowed to relax into a minimum energy state [14] in which the toroidal magnetic field changes direction close to the plasma edge and is more or less generated by the plasma itself. The resulting radial profiles of the toroidal and poloidal magnetic fields (calculated from the polynomial function model (PFM-model) [15]) are shown in figure 1.2. The process that sustains this configuration relies on a transformation of poloidal flux into toroidal through magnetic fluctuations in the plasma. It is usually referred to as the RFP dynamo. The magnetic stability in an RFP is also dependent on a conducting shell close to the plasma boundary. Since the magnetic field lines cannot penetrate a conducting shell it will suppress instabilities in the plasma.

In theory the RFP is a very appealing concept with its dynamo that provides
Unfortunately the world is not always as ideal as one could wish. The conducting shell is one thing that can cause problems. The demand for port holes in the vessel for diagnostics and pumps etc. perforates the shell and introduces magnetic field errors. This in combination with the finite resistivity of the shell can lead to so-called wall-locked modes. The magnetic field lines grow through the shell causing the charged particles following them to crash into the wall resulting in major releases of impurities from the wall.

Even without wall-locked modes there are inherent problems related to the dynamo mechanism. The generation of toroidal flux by the dynamo relies on magnetic fluctuations in the plasma. These also drive transport of energy and particles in the plasma. The increase in transport causes a degradation of the confinement properties of the plasma.

To address these problems there is a need of a better understanding of the processes going on in the plasma. The application of different diagnostics can provide this. In this sense spectroscopy is an important tool to provide information from the whole plasma volume from the center to the very edge. For example the transport in the interior of the plasma is difficult to measure using probes but the results in paper IV show that we can estimate this quantity from spectroscopic measurements. There are ideas how to attack the problems with the resistivity in the shell as well as the dynamo induced transport. Without measurements we will never know if they succeed.

Today there are only a few RFP-experiments in the world. TPE and REPUTE in Japan, MST in the USA, RFX in Italy and the extrap-T2 here in Stockholm are the major ones. Since the RFP community is rather small there is a tight collaboration among the different groups to match the competition from the large tokamak experiments.

### 1.3 extrap-T2

The extrap-T2 is a medium sized RFP featuring a resistive shell. The purpose of a resistive shell is to study the effects of field-lines penetrating the shell. In a future steady state reactor all shells will be more or less resistive depending on the time scale considered. In a short pulse experiment it is possible to construct a shell that appear fully conducting to the plasma during the short pulse duration. Thus it is of interest to investigate the effects of resistivity in the shell.

The inside of the vacuum vessel is completely covered with graphite tiles. This makes carbon and oxygen the dominant impurities in the plasma. Only very slight traces of metals are detected. The vacuum vessel has a circular poloidal cross-section. The main parameters for the extrap-T2 are given in table 1.3. The machine was acquired from General Atomics in San Diego where it was previously operated under the name OHTE.

As mentioned in the previous section there are a lot of unsolved problems with the RFP also present in the extrap-T2. The resistive shell causes a wall-locked...
mode to emerge in almost every discharge. This made the time evolution of the discharges very unpredictable. The behaviour of this wall locked mode was investigated by G. Hedin and described in his PhD thesis [24].

The other main feature of the T2TR the carbon first wall also made the predictability of the discharges very difficult. The carbon could contain a significant amount of hydrogen that was released during the discharges contributing to the density in an uncontrollable way. The high degree of plasma wall interaction further enhanced this behaviour. In extreme cases the local heating of the wall lead to a very rapid release of hydrogen which caused plasma disruptions [25]. The role of plasma-wall interaction in the EXTRAP-T2 was investigated by D. Larsson [26]. The plasma edge properties has been investigated by A. Möller [27].

Spectroscopic measurements have complemented the work mentioned here and contributed to the interpretation of the results from these other diagnostics. It
1.4 Plasma diagnostics

In order to improve our experiments we are dependent on information on the processes that take place in the experiment. To provide this a large amount of different diagnostics have been developed. The magnetic diagnostics measures the different components of the magnetic field using coils of different shapes and constructions. The plasma current and loop voltage are key parameters that are derived from these measurements. Probe diagnostics, where probes are inserted into the plasma, can measure especially edge properties of the plasma. Interferometry measures the plasma density. From scattering of electro-magnetic waves by the charged particles one can measure both temperature and density. Especially Thomson scattering is an important method to measure these quantities. Spectroscopic diagnostics which are the ones treated here are used to measure various quantities through studies of the light emitted by the plasma. The electron- and ion-temperature, ion density and particle confinement time are examples of important quantities that can be measured this way.

In order to gain understanding of the plasma behaviour a combination of all these diagnostics is needed. Then it is possible to build a consistent picture of what is going on in the plasma. When performing a spectroscopic measurement it is often necessary to build some kind of model to interpret the measured data. This usually requires input from other diagnostics for temperature, density etc. The obtained results can then be compared with knowledge of the plasma behaviour.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
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<tr>
<td>Major radius</td>
<td>1.24 m</td>
</tr>
<tr>
<td>Minor radius</td>
<td>0.183 m</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>6.8</td>
</tr>
<tr>
<td>Plasma current</td>
<td>70–250 kA</td>
</tr>
<tr>
<td>Central electron density</td>
<td>$10^{19}$ m$^{-3}$</td>
</tr>
<tr>
<td>Edge electron density</td>
<td>$10^{19}$ m$^{-3}$</td>
</tr>
<tr>
<td>Central electron temperature</td>
<td>50–200 eV</td>
</tr>
<tr>
<td>Edge electron temperature</td>
<td>10–30 eV</td>
</tr>
<tr>
<td>Central ion temperature</td>
<td>100–250 eV</td>
</tr>
<tr>
<td>Edge ion temperature</td>
<td>10–30 eV</td>
</tr>
<tr>
<td>Particle confinement time</td>
<td>$\sim 200$ µs</td>
</tr>
<tr>
<td>Energy confinement time</td>
<td>$\sim 50$ µs</td>
</tr>
<tr>
<td>Pinch parameter</td>
<td>1.6–2.1</td>
</tr>
<tr>
<td>Reversal parameter</td>
<td>$-(0.2–1.1)$</td>
</tr>
<tr>
<td>Plasma discharge duration</td>
<td>5–15 ms</td>
</tr>
</tbody>
</table>

Table 1.1. Main plasma parameters for the extrap-t2

has also produced results independently of these investigations of which parts are included in this thesis.
obtained from other diagnostics and models. If necessary one must then go back to
the model again and improve the input parameters to obtain a consistent picture
of the plasma behaviour. With these results in hand it is possible to go on and
improve the ideas and concepts for the overall plasma control and performance.
When we heat a gas enough it will start to be ionized fully or in part depending on temperature and density. Long before the temperatures needed for ionization are reached the atoms in the gas will be excited by collisions and electro-magnetic radiation. Also the not fully ionized ions can be excited. If the atom has not entered a metastable\(^1\) state it will almost instantaneously be spontaneously deexcited and release its excess energy by emitting a photon. This process is known as spontaneous emission. The result is a spectrum of electro-magnetic radiation with discrete energies emitted by the plasma. In addition to this a continuous distribution of radiation is emitted. This light emitted by the plasma carries an enormous amount of information on the conditions in the plasma. With the right methods we can analyze it and extract at least some of the information therein. This is what plasma spectroscopy is all about.

One great advantage of spectroscopic diagnostics is that it is usually non-perturbative. Because of the high temperatures in fusion plasmas it is only possible to use diagnostics that involves putting probes into the plasma for plasma edge measurements. Attempts to put anything solid into the central regions of a fusion plasma usually end up with destroyed diagnostic probe and a degraded plasma. The risk of only measuring the influence of the probe to the plasma is evident. It should be said though that probe measurements from the plasma edge region often produce valuable results.

The spectroscopist can sit comfortably outside the plasma and wait for the photons to come. This is a pleasant situation both from the scientists and the plasmas

\(^1\)A metastable state is a state in an atom or ion which can not relax to the ground state through an allowed transition. Since the transition rate for forbidden transitions is usually many orders of magnitude lower than that for an allowed transition this will make the lifetime of a metastable state very long. In a fusion plasma discharge this lifetime might be comparable to the particle confinement time and the metastable state will thus not be depopulated before the particle is lost from the plasma. This will make the metastable state act almost like a ground state for practical purposes.
point of view. The measuring equipment is on a safe distance from the hot plasma and the plasma is unaffected by the measurements. The negative part of making observations from outside the plasma is the difficulty to obtain information on the spatial dependence of the light emission. Also the possibility of light absorption in the plasma can be cumbersome.

### 2.1 Excitation of ions and atoms in fusion plasmas

Before an ion or atom can emit light through spontaneous emission it has to be transferred into an excited state. The type of process that is responsible for the excitation highly affects which excited states are populated. The probability for a certain process to occur is very much dependent on the ion or atom species involved. Temperature and density. Since the interpretation of the measurements is often dependent on the degree of population of a certain energy level it is important to consider all the excitation and deexcitation processes involved.

In fusion plasmas it is usually collisional processes that dominate the excitation of the ions but not always. Under some circumstances the photons emitted by the ions in the plasma can be reabsorbed within the plasma. This will of course change the intensity of the light when observed from outside the plasma. It will also cause the absorbing ions to be excited which makes it important to consider this process when calculating an excited level population. If we can neglect the absorption of emitted photons by the plasma it is said to be optically thin. In the opposite case we refer to it as optically thick. The optical depth of a Doppler broadened line can be estimated from [29G30]:

\[
\tau = 5.4 \times 10^{-13} n \lambda \sqrt{\frac{m_i}{m_p T_i}}
\]

where \( \lambda \) is the wavelength, \( n \) the physical path length, \( T \) the temperature in eV and \( n \) the number density. If \( \tau < 1 \) then the plasma is optically thin.

If we are sure that the plasma is optically thin we only have to consider collisions as responsible for the excitation. Actually there is a contribution to the excited level population from cascades from higher lying levels too. The ions are then assumed only to be deexcited through spontaneous emission. The time dependence of the number density of an ion with charge \( z \) in an excited state \( i \) is then given by:

\[
\frac{dn_{z,i}}{dt} = \sum_j n_{z,j}(A_{ji} + n_e q_{ji}(T_e, n_e)) - \sum_j n_{z,i}(A_{ij} + n_e q_{ji}(T_e, n_e)) \\
+ \sum_k n_{z+1,k} \alpha_{z+1,ki}(T_e, n_e) - \sum_k n_{z,i} \alpha_{zi,k}(T_e, n_e) \\
+ \sum_k n_{z+1,k} m_H C_{z+1,ki}(T_e, n_e) - \sum_k n_{z,i} m_H C_{zi,k}(T_e, n_e)
\]

\(^2\)Since atoms in fact are ions with zero charge 1 will from now on only refer to ions, meaning both ions and atoms unless otherwise stated.
where $A$ is the radiative transition probability $q\Gamma aC$ and $S$ are the rate coefficients for electron collisional excitation, dielectronic recombination, charge exchange recombination, and ionization. The sums over $j$ are for different levels in the same ionization stage and sums over $k$ denotes a summation over adjacent ionization stages.

If the density of the plasma is low the time between collisions will be long compared to the time for excitation and deexcitation which is of the order $10^{-8} - 10^{-12}$ s. The result of this is that the excited ion will have time to relax to the ground state or to a metastable state before the next collision. Hence it is common to assume that all excitations start from the ground state or a metastable state. This reduces the amount of transitions in equation (2.2) that needs to be taken into account considerably. The steady state equilibrium under these conditions is called a corona equilibrium since this is the situation in the solar corona. If we have no metastable levels the rate equation in equilibrium now takes the form of:

$$n_{z,i} \sum_j A_{ij} = n_{z,1} n_e q_{1i} + n_{z+1,1} n_e a_{z+1,1i} + n_{z+1,1} n_H C_{z+1,1i}$$

$$+ n_{z-1,1} n_e S_{z-1,1i} + \sum_j n_{z,j} A_{ji}$$

The temperature and density dependence of the rate coefficients is implicit. The level indices $1$ refer to ground states. The contribution from metastable states can be included by summing (2.3) for all the metastable states. Another way to include this is to use effective rate coefficients which include the contributions from metastable states for the equilibrium situation. Also the sum of the cascades from higher lying levels might be included this way.

Often it is found that electron impact excitation is the dominant process. Then (2.3) reduces to:

$$n_{z,i} = n_{z,1} n_e q_{1i}(T_e, n_e) \frac{1}{\sum_j A_{ij}}$$

This expression is usually a good first assumption when estimating the population of a level in an ion. In the equilibrium situation one often uses effective rate coefficients which include the contribution from other processes which makes this an even better approximation. To get a detailed picture including the time dependence it is necessary to solve equation (2.2) in full using numerical methods.
2.2 Line emission

The number of photons emitted per unit volume through spontaneous emission from a certain transition between levels $i \rightarrow j$ is directly proportional to the excited level population through the transition rate $A_{ij}$.

$$\epsilon_{z,ij} = n_{z,i}A_{ij} \quad (2.5)$$

From this expression it is in principle possible to determine the number density of an excited state by observing the intensity of the emitted light. This is however not as easy to do in practice as we will see in chapter 3.

The photons from a certain transition will have a certain energy since the energy levels are discrete to the first approximation. This light with a certain wavelength is called an emission line\(^3\). In reality it is not true that the observed light has a discrete wavelength. There are several processes that act together to spread the wavelength of the emitted light. The most important processes to consider in plasma spectroscopy are the natural line width, the Doppler broadening and the instrumental function of the spectrometer.

The natural line width is a result of the finite mean lifetime of the excited state $\tau_i$ which is the inverse of the total deexcitation rate:

$$\tau_i = \frac{1}{\sum_j A_{ij}} \quad [\text{s}] \quad (2.6)$$

The uncertainty in the energy $\Delta E_i$ for a level $E_i$ is coupled to the mean lifetime through Heisenberg’s uncertainty principle so that:

$$\Delta E_i \propto \frac{\hbar}{\tau_i} \quad (2.7)$$

Since the wavelength of the emitted light is dependent on both the upper $E_i$ and lower $E_j$ energy level this will make the emission line broader. The line-shape will not be a delta function any more. The intensity as a function of wavelength will have the shape of a Lorentzian:

$$I_N(\lambda) = I_0 \frac{\delta \lambda_N}{(2\pi)} \frac{1}{(\lambda - \lambda_0)^2 + (\delta \lambda/2)^2} \quad (2.8)$$

where $\delta \lambda$ is the full width at half maximum (FWHM)

$$\delta \lambda_N = \frac{\lambda_0^2}{\pi c \tau_i} \quad (2.9)$$

and $\lambda_0$ is the unperturbed wavelength. The normalization is such that:

$$\frac{1}{I_0} \int_{-\infty}^{\infty} I_N(\lambda)d\lambda = 1 \quad (2.10)$$

\(^3\)The word “line” has historical reasons. In the time when photographic plates were used in the spectrometers each wavelength appeared as a line on the plate.
Figure 2.1. Left: A comparison of the Doppler width (dashed) and natural line width (solid) of the resonance line at 40 Å in C\textsubscript{v} \(\{1s^2-1s2p, 1S-1P\}\) at a temperature of 100 eV. Even though the lifetime of the upper state is very short, \(1.1 \times 10^{-12}\) s, it is evident that the Doppler width dominates the line width at this temperature. Right: A comparison of a Lorentz (solid) and a Gaussian (dashed) with the same FWHM.

The natural line width is usually very small compared to the broadening by other mechanisms but the Lorentzian function has very long wings. The intensity decreases very rapidly in the vicinity of the central wavelength but further away from it the decrease is slow. Thus even though the natural width is small it can contribute quite significantly to the line-shape at some distance from \(\lambda_0\). A comparison of the widths and shapes of these line-profiles can be seen in figure 2.1.

Since a fusion plasma is a hot environment the velocities of the particles are high. This will make the Doppler broadening of the line large. Assuming a Maxwellian velocity distribution this broadening will cause the line to have a Gaussian intensity distribution:

\[
I_D(\lambda) = I_0 \sqrt{\frac{\ln 16}{\pi}} \exp \left[ - \left( \frac{\lambda - \lambda_0}{\delta \lambda_D} \right)^2 \right]
\]

(2.11)

This expression is normalized in the same way as the one for the Lorentzian. The FWHM is given by:

\[
\delta \lambda_D = \lambda_0 \frac{7.716 \times 10^{-5}}{\sqrt{T_i/m_i}}
\]

(2.12)

where the ion temperature \(T_i\) is in eV and the mass in atomic mass units. \(\lambda_0\) can
then be given in arbitrary length units. The comparison in figure 2.1 clearly shows that the Doppler width dominates the line profile even for resonance transitions which have a large natural width compared to non resonant transitions.

The observed line width is the convolution of these two line-shapes if no other broadening mechanisms are present. The resulting profile is called a Voigt-profile. There is unfortunately no analytical expression for the Voigt function but there are approximative solutions that are useful in the analysis of line spectra [31]. It is common to use Gaussians when fitting measured line profiles to analytical functions. This usually produces an acceptable fit to the width of the line but can fail when calculating the intensity. The long wings of the Lorentzian part of the profile figure 2.1 can have a significant contribution to the integral over the whole line shape which defines the total intensity of the line.

The instrumental function of the spectrometer used is of course not a real broadening mechanism but the effect on the measured spectra is similar. It is convoluted with the real line width (natural and Doppler) and produces a new line-shape. If we know the instrumental function it is possible to deconvolute it. This will be discussed in chapter 3.

There are also other broadening processes [32] that in some cases can be important to consider. Pressure broadening is usually not an issue in fusion experiments since the density is too low. Zeeman and Stark\(^4\) effect are no real line broadening processes. The magnetic (Zeeman) or electric (Stark) field lifts the energy degeneracy of different \(m_j\) states of the level and split the emission line into several close lying components. If the resolution of the spectrometer is too low to resolve these they will instead introduce an apparent broadening of the line. If the magnetic field is high as in tokamaks it is necessary to include the Zeeman effect in the analysis.

### 2.3 Continuum radiation

All light emitted by a fusion plasma is not line emission. There is also an emission of continuum radiation over the whole spectral region. This originates from two totally different processes than the line emission.

Charged particles emit light when experiencing an acceleration. This occurs when the fast moving particles undergoes inelastic collisions with each others. Since the particles have a continuous velocity distribution this will produce a continuous spectrum of radiation called bremsstrahlung. The charged particles also follows the magnetic field lines conducting a spiral motion around these. The resulting particle trajectories are bent and hence there are particles feeling an acceleration resulting in an emission of radiation called cyclotron- or synchrotron-radiation\(^5\). In fusion plasmas this process does not contribute much to the continuum radiation in the visible and UV-region.

\(^4\)To makes things really confusing one often refer to pressure broadening as Stark broadening.

\(^5\)This process is utilized in synchrotrons where an electron beam is bent into a circular path to produce continuum radiation with a very broad spectral range.
When a free electron recombines with an ion the difference in energy between the free state and the bound state is emitted as a photon, so called recombination radiation. Since the free electrons have a continuous distribution of velocities this will produce a continuous spectrum of light. The contribution of the visible recombination radiation is at low energies (\(\sim 10\,\text{eV}\)) about 10\% of that of the bremsstrahlung and decreases rapidly at higher energies [33].
Chapter 3

Spectroscopy at the EXTRAP-T2

All spectroscopic observations are external. The emitted light is collected by a viewing system located outside the plasma. Usually this is made through a window in the vacuum vessel for visible and UV light. Shorter wavelengths in the vacuum UV and x-ray region require a vacuum connection to the plasma without a window. The result from any such measurements is the line integral of all the emitted light along the line of sight often called the brightness.

\[ I = \frac{1}{4\pi} \int_L \epsilon_{z,ij}(l)dl \]  \hspace{1cm} \text{[Photons/m}^2\text{ sr s]} \hspace{1cm} (3.1)

where \( L \) is the integration path along the line of sight and \( \epsilon_{z,ij} \) is the emission from equation 2.5. A single measurement will thus only provide information of the line average emission which can be overcome by using several lines-of-sight. This will be discussed in chapter 4. However, it is often possible to estimate the volume of origin for light from a certain species and thus be able to determine the actual emission.

The analysis of spectroscopic measurements performed on the EXTRAP-T2 can be divided into two main areas: time resolved intensity measurements and wavelength resolved measurements. In the former case one selects a small wavelength region and studies the time evolution of the emitted light. The selected wavelength region needs to be narrow enough in order to select light from only one emission line (or continuum radiation from a line free region). To achieve this one can use either a filter or a monochromator\(^1\). Interference filters provide a simple way of

\(^1\)A monochromator and a spectrometer is essentially the same thing. The difference is that the monochromator lacks wavelength resolution in the detection system while the spectrometer uses a detector that adds this to the measurements. Thus, a monochromator acts in practice as a tunable filter.
selecting the wavelength to study. The advantage is the high efficiency compared to monochromators. The resolution on the other hand is quite low \( \text{5-10 Å} \). Hence the use is limited to spectral regions with few emission lines or to very strong lines that completely drown all other nearby lines. Typical use is for studying emission from neutral hydrogen and for measurements of the continuum radiation. It is necessary to use monochromators to gain a higher resolution. These use gratings or crystals for the wavelength selection and have the possibility to change the selected wavelength by turning the grating or crystal, which makes the use more flexible.

Using filters and monochromators for studies of single emission lines (or continuum radiation) usually provides a very good time resolution since photo-multiplier (PM) tubes can be used for the light detection. These also have the advantage of a very high sensitivity.

The addition of spectral resolution makes it possible to study apart from the intensity also the shape and position of an emission line. This is usually achieved by adding a spatially resolved detector in the image plane of a spectrometer. The signal along the dispersive direction will then be intensity as a function of wavelength. The time resolution will decrease compared to pure intensity measurements since this kind of detectors usually CCD’s or diode arrays have fairly long readout times. Typically it is possible to obtain up to 10 spectra per ms, compared to the MHz detection rates possible with PM-tubes. In larger machines with long plasma pulse duration this is not a problem but in smaller ones such as the EXTRAP-T2, it severely limits the possibility to have good time resolution. However, the gain in information on the spectra makes these measurements invaluable for the spectroscopist.

### 3.1 Spectroscopic measurements on EXTRAP-T2

Spectroscopic measurements have been used to study both the majority ions, usually hydrogen but also deuterium, and the impurity ions. Due to the use of carbon as a plasma facing wall material the only impurities of importance are carbon and oxygen. Metal ions usually observed in machines with limiters are absent in the spectra. Also the presence of nitrogen is so low that the line emission is not measurable. Several spectroscopic techniques have been used to investigate the EXTRAP-T2 plasma. I will here review the measurements made with emphasis on the ones that are the focus of this thesis.

#### 3.1.1 Experimental arrangements

The vicinity of a fusion experiment is a very unhealthy environment for electronics since it is difficult to shield out the high magnetic fields from the coils around the plasma. Hence it was necessary to put most of the spectrometers and detection systems in a diagnostics laboratory adjacent to the experiment hall. The light was gathered with single lenses that made it possible to limit the viewed volume to a thin tube through the plasma. These also focused the light on the ends of the
optical fibers that were used to transmit it to the diagnostics laboratory. Different types of fibres were used for different types of measurements. Thin 200 µm diameter glass fibres were used for intensive lines in the visible region of the spectrum. In the UV region it is not possible to use optical glass. Instead we used UV-grade fused silica fibres with 600 µm core diameter. The diameter used was larger for these fibres since the attenuation is large at short wavelengths even with UV grade fibres. The transmission is acceptable down to 2000 Å. Also the lenses are UV-grade fused silica or sapphire in these setups.

In the diagnostics laboratory the fibre ends are equipped with similar lens systems as on the experiment side. These either focus the light on the entrance slit of a spectrometer or collimate it to pass through an interference filter.

Some equipment such as the vacuum-UV (VUV) spectrometer and soft x-ray diagnostics that require direct connection to the vacuum vessel are of course situated in the experiment hall.

### 3.2 Intensity measurements

#### 3.2.1 Instrumental

Intensity measurements have been made both with and without absolute intensity calibration. Uncalibrated measurements of course only provide information on the

![Figure 3.1. An overview of the positions of the spectroscopic diagnostics on the extrap-τ2. Some other diagnostics are included too.](image-url)
temporal behaviour of the line emission which actually can provide a great deal of information. The time resolution has in both cases been good since PM-tubes [34] were used for the light detection. The limiting factor has been the sampling rate (100 kHz in this case) of the digitizers used for recording the signals from the PM-tubes.

A PM-tube is actually close to an ideal current generator where the output current is proportional to the number of incoming photons2. Since the digitizers sample the voltage rather than current it is necessary to convert the output current to a voltage. Since the signal from a PM-tube is weak it is usually also necessary to have an amplifier between the PM-tube and the digitizer. A system comprising of a current to voltage converter and an amplifier and a low pass filter was designed for this purpose. A description of this system can be found in appendix A.

The digitizers used are so-called transient recorders which have a memory so that they can record the rather short plasma pulses for later readout by the data acquisition system. For the visible and UV measurements a sampling frequency of 100 kHz was used. After each plasma discharge the information in the memory of the transient recorders are read out through a camac highway into a VAX computer. The MDS [35] data acquisition system is used to store and organize the recorded data for later use.

3.2.2 Line radiation

Hydrogen

The intensity measurements on hydrogen were made using the Balmer-α and -β lines at 6562.8 Å and 4861.3 Å. Both are very strong in intensity and relatively well separated from other lines. Hence it is well suited to use interference filters for the wavelength selection.

The calibrated Hα measurements are used to measure the particle hydrogen flux. The simplest way to estimate this for a steady state situation with balance between influx and ionization is by using the following relation [36]:

\[ I \propto \xi \Gamma_H \]  \hspace{1cm} (3.2)

where \( \xi \) is the number of Hα photons per ionization calculated by Johnson and Hinnoy [37]. Usually one also needs to consider the effects of the radial profiles to get a good estimation of this quantity [31]. The time evolution of the Hα and Hβ is also a good indicator on the occurrence of local plasma instability with increased plasma wall interaction. In a stable plasma discharge the hydrogen emission will go down to a low stable level when the plasma current reaches a flat-top. If there is a local plasma wall interaction the hydrogen emission will increase significantly if the line-of-sight is situated close to the perturbation. Measurements at other positions

2It is also possible to use PM-tubes for photon counting. Each photon actually produces a small current pulse on the anode output from the tube. If the pulse rate is low enough it is possible to count these pulses. The count rate is then proportional to the light intensity.
are often not influenced and continue to show a low emission. Hence it is valuable to have a large amount of measurements from different positions around the torus.

Another application of H_α and H_β was tested on a former machine the EXTRAP-T1 [38]. The ratio between H_α and H_β is dependent on the electron temperature and density. With calibrated measurements of both these lines from the same plasma volume it is then possible to calculate the electron temperature given that the density is measured or assumed to be constant. The density dependence is also weaker than the temperature dependence. Since neutral hydrogen is only present at the very edge of the plasma the obtained temperature is representative for this region. In EXTRAP-T1 these measurements gave a temperature around 1 eV [39] which was in agreement with that found from probe measurements. The idea was not implemented on the EXTRAP-T2 since the edge temperatures of 10-20 eV [40] are too high for this method to be reliable.

**Carbon and oxygen**

The measurements on the intrinsic impurities carbon and oxygen are made in a similar fashion as the hydrogen measurements. Monochromators are used since the number of lines available for these measurements is very large. These also have the benefit of a better wavelength resolution compared to filters which makes it possible to select a certain line even when there are other lines present nearby. A better resolution also requires careful wavelength calibration of the monochromator. If the setting of the grating is only deviating very slightly from the expected one might end up with no signal at all or even worse with signal from another nearby line. The wavelength calibration has been made using lines from spectral lamps with known spectra. The remaining uncertainty in the wavelength setting of the monochromator often requires that a lower spectral resolution than what is actually possible is used. This can be achieved by using entrance and exit slits on the monochromator with larger slit widths which also has the benefit of increasing the light throughput of the monochromator.

Compared to the hydrogen lines most impurity lines are much weaker in intensity. Hence a good efficiency of the measuring system is required. Not only the efficiency of the monochromator has to be considered. Also the light gathering system and the alignment and matching of the aperture on the monochromator side is very important. On the machine side one must assure that the view of the fiber and lens system is not limited by the edges of the port holes. This requires careful aligning of the mounting device. Also the window is of great importance. Quartz or sapphire windows must be used for UV-measurements. One great problem is fogging of the windows by the plasma. This problem increases at shorter wavelengths. Apart from regular cleaning which is not always possible since it usually requires a vacuum break one can try to put in protective masks between the plasma and the window. Also keeping a large distance from the plasma to the window improves the situation.

On the spectrometer side it is of course important to align the optical system
so that the optical axis is perpendicular to the entrance slit of the spectrometer. The lens system used must also be matched to the numerical aperture of the fiber and to the f-number of the spectrometer. The optimal focal length and f-number of the lens system used is determined by these factors. Also the lens system on the plasma side must be matched to the numerical aperture of the fiber.

The inaccuracies in the absolute wavelength setting of the monochromator makes it difficult to keep a reliable intensity calibration when switching between wavelengths. Hence most of these measurements are made uncalibrated. The temporal evolution of the emission from impurities still provides valuable information especially when comparing simultaneous measurements on different ions and ionization stages.

### 3.2.3 Continuum radiation measurements

By measuring the absolute level of continuum radiation it is possible to calculate the effective charge of the plasma \( Z_{eff} \). This requires that the recombination radiation can be neglected compared to the bremsstrahlung which is the quantity of interest. The relationship looks like [41]:

\[
Z_{eff}(r) = \frac{\epsilon_{\lambda}(r) \lambda^2 \sqrt{T_e(r)}}{1.89 \times 10^{-28} n_e(r)^2 \tilde{g}_{ff} \exp \left(-12400/T_e(r)\lambda\right)} \text{ [W cm}^{-3} \text{ Å}^{-1}] \tag{3.3}
\]

where \( \epsilon_{\lambda} \) is the emission and \( \tilde{g}_{ff} \) is the free-free Gaunt factor. Temperatures are in eV and wavelengths in Å. Since the continuum radiation is very weak compared to most emission lines it is important to find a wavelength region that is line free. The ones used were the 5232± 5 Å and 4767± 5 Å.

At low to normal electron densities (\( \sim 2 \times 10^{10} \text{ m}^{-3} \)) these measurements gave unreasonably high values with a \( Z_{eff} \) of about 10-20. The reason for this is probably that emission from the region very close to the wall disturbs the measurements. It is also possible that there are weak lines not resolved in the spectra present which will destroy the measurements. At high electron densities (\( \sim 6 - 10 \times 10^{19} \text{ m}^{-3} \)) the \( Z_{eff} \) values becomes more realistic at about 2.

### 3.3 Wavelength resolved measurements

The addition of the dispersive dimension greatly enhances the possibilities of the spectroscopic measurements. Not only the intensity and temporal dependence of the emission can be studied. Also the shape and position of each line can be investigated. The shape, i.e., the width of the line will give the ion temperature of the studied ion species. The position, or rather the shift in position will provide us with information on the velocity of the ions. The light emitted from an ion in motion will be Doppler shifted and hence the wavelength of the observed light will change as a function of the velocity.
3.3. Wavelength resolved measurements

The intensity of the emission lines is of course also of interest. Both to estimate ion densities and for calculating line ratios. These can be used for electron temperature measurements. The population of different levels in an ion can have very different temperature dependencies. Hence the line ratio will change with temperature. This method has been utilized for temperature measurements using line in the VUV spectra [42]. Also ion densities have been calculated from line intensities using these spectra.

The VUV spectrometer is a SPRED [43] equipped with a fast optical multi-channel analyzer (FOMA). It has three gratings with 2901450 and 2105 rules/mm. Most spectra have been taken with the 450 rules/mm grating which gives a spectrum from 100 Å to 1100 Å. The FOMA has 1024 channels and makes it possible to read out one full spectrum each 256 µs resulting in about 40 spectra per plasma discharge.

For measurements in the visible and UV region three different spectrometers have been utilized, one 0.5 m focal length Ebert [44][45] mount, a 1 m and a 1.5 m Czerny-Turner mount. Each of these is equipped with an optical multi-channel analyzer (OMA). The readout time of these is such that only one full spectrum per discharge can be obtained. By reducing the number of pixels being read out it is possible to get some time resolution also using these detectors.

The 0.5 m spectrometer has mainly been used for survey spectra and some special studies of various lines. The resolution of this instrument is too low to make ion temperature and velocity measurements. Instead the 1 m and 1.5 m spectrometers have been utilized for these measurements.

3.3.1 Line profile measurements

As was mentioned earlier it is possible to extract the ion temperature from the line width and the ion velocity from the shift in the wavelength of the line due to the Doppler shift. Since these effects are rather small it is necessary to use spectrometers with high dispersive resolution. Especially for ion temperature measurements it is necessary to have the number of detector pixels that cover the line profile as large as possible to be able to deconvolute the spectrometer instrumental function in a good manner.

Ion temperature

To be able to extract the ion temperature from a line profile it is necessary to extract the part of the line width that comes from Doppler broadening. The natural line width is usually no problem since it is negligible compared to the Doppler width (figure 2.1). Assuming that other broadening mechanisms such as Zeeman effect and pressure broadening can be neglected it is only the instrumental function that is necessary to eliminate.

A convenient way to deconvolute the instrumental function is to make a transform into Fourier space. Since a convolution transforms into a simple multiplication
in Fourier space it is then easy to just divide the transformed signal with the transform of the instrument function. To achieve the real line profile one just transforms back to wavelength space. This method is however not used here due to its sensitivity to noise in the signal. Instead a function made up of one Voigt- and one Gaussian function is fitted to the line. The width of the instrumental function is added to the real line width in this procedure and it is the real width that is the fit parameter.

The instrumental width must also be measured. This is done by using a mercury lamp which has several strong lines in the UV- and visible-spectral region. Since the discharge in the lamp is much colder than the plasma and mercury is a heavy metal the line from the lamp will be a good approximation of an ideal line profile i.e. a delta function in wavelength space. A fit to the measured mercury line will hence only include the instrumental width for our practical purposes.

**Ion velocity**

The measurements of the ion velocity made refer to the toroidal velocity also called toroidal ion rotation. To measure this rotation it is necessary to arrange so that the line-of-sight of the observations is in the toroidal direction. In practice this means that one looks tangentially in the toroidal direction. All other observations described here are made by observing radially in one poloidal plane of the torus.

The best way to perform this kind of measurements is to have two co-parallel lines-of-sight observing the same emission line. Then the line will be shifted in the opposite direction by the same amount in the both spectra. Thus there is no need to determine the absolute position for the unshifted line. In our case we wanted to be able to observe as many ion species as possible at the same time and hence we had to find another approach. Instead of observing the same emission lines with the two co-parallel lines-of-sight they were set to different lines. Then it was necessary to fix the absolute position of the spectra on the detectors. This was made by moving the viewing optics to a radial view at regular intervals assuming that the radial velocity of the ions is almost zero. If the spectrometers were perfect this should only have to be done once. In reality the position of the detectors and gratings shift slightly over time even over a day. This is caused by temperature changes and mechanical imperfections in the mounting of the detectors. By checking the line positions at regular intervals it was possible to achieve a very good accuracy in the absolute line position.

The shift of the line is coupled to the velocity along the line-of-sight as:

$$\Delta \lambda = \frac{v \lambda}{c}$$

(3.4)

It should be noted that if the observed light emerges from the plasma edge an error will be introduced since the observation in this region is no longer purely toroidal. This error is rather small though up to 15%.

By only reading out 28 pixels for each line it was possible to use each detector
for two different lines and also have a time resolution. One spectra/ms was achieved maintaining enough integration time to produce a useable signal level. The four species mostly used for these measurements were \( \text{O}^{3+} \), \( \text{O}^{5+} \), \( \text{C}^{3+} \) and \( \text{C}^{5+} \). At the same time the ion temperature was calculated for these lines. Since these species occur at different radial positions in the plasma it was then possible to extract the radial dependence of the ion rotation and temperature.

Calculating temperatures from tangential measurements is somewhat dangerous. If the ions change velocity or if there are populations of ions with different velocities the resulting line profile will be broadened. The result is an overestimate of the temperature. Taking averages over a large number of discharges might reduce the influence of this effect.
Chapter 4

Spatially resolved spectroscopy

4.1 Spatial resolution

All the spectroscopic measurements discussed previously produced results that were line averaged along the line-of-sight. In many cases this is sufficient. Especially if the emission can be expected to originate from a certain position in the plasma. For the hydrogen measurements it is almost always correct to assume that the emission is localized to a thin shell close to the plasma edge.

The opposite is to detect emission from higher ionization stages since these are assumed only to exist in the plasma center. Transport simulations have indicated that the only ionization stages present in the central plasma of the EXTRAP-T2R with its moderate electron temperatures and particle confinement time are oxygen from O V I I and carbon from C V and higher ionization stages (a not altogether correct assumption as we shall see later).

To gain further information on the spatial dependence of the emission while still making the observations from outside the plasma one has to use a set of lines-of-sight. These can be combined to calculate the spatial dependence in two or even three dimensions [46].

4.1.1 Tomography

Most of us have heard of CAT-scans, magnet cameras and PET-scans from the field of medicine. The pictures produced show cuts through brains and other internal organs. The technique to obtain these detailed pictures is called tomography (CAT stands for Computer Aided Tomography and PET for Positron Emission Tomography). It concerns the problem of acquiring information of the internal structure of an object by using external observations. This is actually exactly the problem we
have in plasma spectroscopy. The technique has mainly been applied to soft x-ray emission [47] but also to visible and UV radiation [48].

By having a very large number of lines-of-sight in one plane one can reconstruct the structure of the emission or absorption\(^1\). The main problem is to obtain a large enough number of lines-of-sight. In the medical applications it is usually only one line-of-sight that is rotated around the object to produce hundreds of thousands of lines-of-sight. This is possible since one can keep the patient in one position for quite a long time. In plasma spectroscopy we do not have this possibility. The plasma changes very rapidly and the whole discharge might durate from microseconds in small experiments to minutes in large machines. Also the freedom to place ports and windows is very limited. Hence one can only observe the plasma from a few discrete positions usually in one poloidal cross-section. This limits the practically obtainable number of lines-of-sight to a few hundred in the best cases. The brightness from each line-of-sight is the one given in equation 3.1. These are labeled by their impact parameter \(p\) and the angle \(\xi\). The definition of these parameters can be seen in figure 4.1. This transformation from spatial coordinates to the

\(^1\)Of course it is also possible to measure absorption this way by putting a radiation source behind the object and monitor the absorption instead of passively observe emission from the object.
\( (p, \xi) \) space is called the Radon transform. In a poloidal plane \((x, y)\) (or in polar coordinates \((r, \theta)\)) this becomes:

\[
I(p, \xi) = R\epsilon = \int_L \epsilon(x, y) dl
\]  

(4.1)

The brightness measurements we perform is in fact the Radon transform of the spatial distribution of the emission. Thus an inverse transformation will return the spatial distribution of the emission. With the relations

\[
x = p \cos \xi + l \sin \xi \\
y = p \sin \xi - l \cos \xi
\]

the inverse transformation (from reference [49]) is

\[
\epsilon(x, y) = [R^{-1} I](x, y) = -\frac{1}{2\pi^2} \int_0^\pi d\xi \int_{-\infty}^{\infty} \frac{1}{p-x \cos \xi - y \sin \xi} \frac{\partial}{\partial p} I(p, \xi) dp
\]  

(4.2)

given that the function \(\epsilon(x, y)\) is continuous and equal to zero outside a radius \(a\). Also \(\partial f / \partial p\) should be continuous. A special case of this transform is obtained when assuming a radial symmetry of the emission. The inverse transform is then called Abel inversion (equation 4.11) which will be further discussed in section 4.1.2.

The inverse transform (equation 4.2) might appear to be straightforward which is not actually the case. In reality \(p\) and \(\xi\) are not continuous functions. The measurements made with a discrete number of lines-of-sight which imposes a discrete rather than a continuous solution. Several methods have been developed to solve this problem. Series expansion like the one described below and finite element methods [50] are the most common. The art of performing good tomographic measurements is to apply the most suitable method for the given geometry.

One method that has been applied when performing tomography on fusion plasmas is the one developed by Granetz for soft x-ray tomography on Alcator [51] and JET [47]. The method is based on the work by Cormack [52, 53]. It is basically an analytical method. It has also been combined with ideas from finite element methods. I will here give a brief description of the analytical part of this method as taken from reference [47].

The measurements made are assumed to be of the same kind as described before providing line integrated data of the emission.

\[
I(p, \xi) = \int_{L(p, \xi)} \epsilon(r, \theta) dl
\]  

(4.3)

The functions \(I\) and \(\epsilon\) are decomposed into their harmonic constituents

\[
I(r, \theta) = \sum_{m=0}^{\infty} [I_m^r(r) \cos(m\theta) + I_m^s(r) \sin(m\theta)]
\]  

(4.4)

\[
\epsilon(p, \xi) = \sum_{m=0}^{\infty} [\epsilon_m^r \cos(m\xi) + \epsilon_m^s \sin(m\xi)]
\]  

(4.5)
By inserting these into equation 4.3 one will obtain (the radius of the region is here set to 1 as in figure 4.1)

\[
I_m^{c,s} = 2 \int_r T_m(r/r) dr
\]

and

\[
\epsilon_m^{c,s} = -\frac{1}{\pi} \int_r \frac{I_m^{c,s} T_m(r/r) dr}{p/\sqrt{p^2 - r^2}}
\]

where \(T_m(x) = \cos(m \cos^{-1}(x))\) is the Chebyshev polynomial of the first kind. This system is however not that easy to solve numerically. Cormack therefore introduced a new basis set representation. The \(\epsilon_m(r)\) functions are expanded in so called Zernike polynomials [54] and one gets:

\[
\epsilon_m(r) = \sum_{l=0}^{\infty} a_{ml} R_{ml}(r)
\]

where

\[
R_{ml} = \sum_{s=0}^{l} \frac{(-1)^s (m + 2l - s)!}{s!(m + l - s)! (l - s)!} r^{m+2l-2s}
\]

The Zernike polynomials provide a very simple form of the \(I_m\) functions

\[
I_m(p) = \sum_{l=0}^{\infty} a_{ml} \frac{2}{m + 2l + 1} \sin \left[ (m + 2l + 1) \cos^{-1} p \right]
\]

By expanding the Fourier components of the measured data in series of equation 4.10 through a least square fit to the data one can obtain the coefficients \(a_{ml}\). These can then be put into equation 4.8 to obtain \(\epsilon_m(r)\) without having to evaluate equation 4.7 numerically. The result is then put into equation 4.3 to obtain the reconstructed emissivity.

### 4.1.2 Abel inversion

In an RFP the number of port holes is very limited since any imperfection in the conducting shell will cause perturbations in the magnetic field. Thus it was only possible to have one viewing position on the EXTRAP-T2 making it impossible to have intersecting lines-of-sight. To compensate for this limitation it is then necessary to make assumptions on the symmetry of the emission from the ions. In the EXTRAP-T2 the most natural assumption is that of a poloidal circular symmetry. Both the circular poloidal cross-section and the magnetic configuration suggest this approach. In an RFP the magnetic field is more or less poloidal unlike in a tokamak where the toroidal field is at least an order of magnitude larger than the poloidal field. The field is almost toroidal in the center but the strong magnetic shear makes the poloidal component significant even at small radii. At the reversal surface there
is a purely poloidal field. Since the particles essentially follow the field lines it can be assumed that any differences in temperature or density are rapidly equilibrated along the field lines. Hence the assumption of poloidal symmetry of the emission from the ions is justified.

Making this assumption it is then possible to reconstruct this circularly symmetric emission from line integrated measurements. It was shown by the mathematician Abel that this problem has an analytical solution now called Abel inversion. This is a special case of the Radon transform where \(\epsilon(r, \theta) \rightarrow \epsilon(r)\):

\[
\epsilon(r) = -\frac{1}{\pi} \int_r^\infty \frac{dI(p)}{dp} \frac{1}{\sqrt{p^2 - r^2}} \, dp
\] (4.11)

Where \(I\) is the line integrated brightness from a line-of-sight with the impact parameter \(p\) and \(a\) is the radius of the observed volume, i.e. the minor radius in this case. There are also methods which allow for a predetermined amount of asymmetry, such as a Shafranov shift of the plasma [55].

In an ideal situation with an infinite number of lines-of-sight and no noise on the signal this would provide the solution needed. In reality the number of lines-of-sight is limited and the signals are affected by noise and other errors which makes this solution less usable. Since the inversion formula contains the derivative of the measured brightness with respect to the impact parameter it is very sensitive to errors in the measured brightness. Direct Abel inversion might be useful if an analytical function is fitted to the measured brightnesses to average out noise and inaccuracies in the measurements. A great problem is also that the inverse does not have a unique solution for a discrete set of lines-of-sight.

### 4.1.3 Inversion methods

The analytical Abel inversion is in reality rarely used for the reasons mentioned above. Instead various approximative methods have been developed. These use basically the same ideas as the methods to solve the inverse Radon transform for a discrete number of lines-of-sight. Many of these methods make use of series expansion methods or polynomials.

The series expansion methods involves the assumption that the emission can be expressed in the form of a series expansion

\[
\epsilon(r) \approx \sum_k c_k f_k(r)
\] (4.12)

Normally we assume that the emission has a smooth behaviour and then the above approximation will be correct. The brightness can now be expressed in matrix form:

\[
\bar{I} = \mathbf{A} \bar{\epsilon}
\] (4.13)
or written out

\[
\begin{pmatrix}
I_1 \\
\vdots \\
I_n
\end{pmatrix} =
\begin{pmatrix}
a_{11} & \ldots & a_{1n} \\
\vdots & \ddots & \vdots \\
a_{n1} & \ldots & a_{nn}
\end{pmatrix}
\begin{pmatrix}
c_1 \\
\vdots \\
c_n
\end{pmatrix}
\]

(4.14)

where

\[I_i = I(p_i)\]

(4.15)

the matrix elements are the line-integrated basis functions

\[a_{ik} = 2 \int_0^{\sqrt{\alpha^2 - r_i^2}} f_k(\sqrt{r_i^2 + l^2}) dl\]

(4.16)

The solution can now be obtained from a simple matrix inversion

\[\tilde{c} = A^{-1} \tilde{I}\]

(4.17)

The emission is then obtained as

\[\epsilon(r) = \tilde{c}^T \tilde{f}\]

(4.18)

Since the transformation matrix is only dependent on the basis set chosen and the geometry of the viewing system it is constant. Thus it is only necessary to perform the matrix inversion once. For a large basis set this will of course improve the performance. The matrix \(A\) must be square in order to be inverted as usual. The consequence of this is that the number of lines-of-sight determines the size of the basis set.

If the number of lines-of-sight is larger than the size of the basis set we talk about an overdetermined system and in the opposite case of an underdetermined system. In these cases it is not possible to directly apply the method described above but there are methods to deal with this kind of problems. However, an underdetermined system will lack information and the inversion will usually fail. In the over determined case there is an excess of information which can be used to produce a best fit when the measured brightness includes noise and other errors; for example from the calibration. Since this is usually the case an overdetermined system can help to deal with these errors. The sacrifice is a lower resolution which might be accepted if the number of lines-of-sight is fairly large. In our case with only five lines-of-sight it is necessary to use all the information available in order to have a reasonable resolution.

This method was tested using various functions for the basis set. The initial tests using synthetic emission profiles were very promising. In reality when noise and other errors are added it did not perform very well.

Another method is the “onion peeling method”. The emission is then assumed to have a shell structure with constant emission within the shell. The emission is then line-integrated starting from the outermost line-of-sight. If the boundaries of each shell are placed so that only one new shell comes into the line-of-sight for each
step there will be only one solution per line-of-sight. Also this method was tried but without any greater success.

There are more methods that I will not go into here. The ones usually applied are of the series expansion type. Also the one finally applied on our experiment is of this kind which will be described in section 4.2.3.

4.2 Radially resolved spectroscopy on EXTRAP-T2

As already mentioned it is usually the access to and number of viewing ports that set the limit for the resolution of spatially resolved spectroscopy. This is especially true for the RFP. It is dependent on a (more or less) conducting shell around the plasma column to obtain plasma stability. Each port represents a deviation from the ideal shell and will thus decrease the performance of the machine. On the EXTRAP-T2 we have had only one 50 mm diameter window available for the spatially resolved spectroscopy. In addition to the small size of the window the access has been limited by the coils for the magnetic field. These circumstances should be kept in mind when judging the performance of the system.

4.2.1 Experimental setup

The window used was from the beginning mounted directly on the vacuum vessel with an o-ring gasket arrangement that had historical reasons\(^2\). The advantage of having the window close to the plasma is of course that the possibilities to

---

\(^2\)The EXTRAP-T2 was actually a reincarnation of the OHTE machine [23] that was operated in San Diego in the 1980's. Since the machine from the beginning had very small port holes it was at some stage found to be necessary to add some larger windows with a good view of the plasma. These were then mounted with o-ring gaskets directly on the vacuum vessel. It is for me unknown why they chose this less than optimal arrangement.
view the plasma at a large angle increase. On the other hand the window is in a
dangerous vicinity of the plasma. Dangerous because of the risk of either damaging
the window or to get deposits from the plasma on the window. This is actually what
happened, the plasma deposited a film on the window which effectively absorbed
almost all UV-light. This was overcome by adding a tube with a mask between
the window and the vacuum vessel. The mask had a slit that was big enough not
to interfere with the view of the optical system. The tube did not decrease the
maximum angle at which the plasma could be viewed. This arrangement vastly
improved the situation even though there were deposits found on the window after
a period of use. The absorption caused by this deposit could in the worst cases be
up to 50% but usually it was much less.

Above the window an aluminium holder was placed to fix the viewing telescopes.
The mounting was fixed with a close fit of the telescopes to obtain the desired lines-
of-sight. The telescopes actually consisted of single lenses to provide a collimated
view of the plasma. The lenses were plano convex 5 mm diameter 10 mm focal
length UV-grade fused silica lenses. The ends of the optical fibres used to transmit
the light to the diagnostics laboratory were placed in the focal plane of these lenses.
The fibres were 18 m long of UV-grade fused silica with a 600 μm core diameter.

The other ends of the five fibres were imaged on the entrance slit of the spectrometer. The imaging system consisted of two f=50 mm 25 mm diameter plano
convex lenses mounted with their curved sides facing each other. The large apert-
ure was necessary since the fibres were mounted with a 3 mm separation so that
the outermost fibres were 6 mm off axis. A smaller lens would have caused uneven
illumination of the grating in the spectrometer and loss of light.

The idea of this setup was to use one spectrometer for all the five channels each
representing one line-of-sight. By using the imaging properties of the spectrometer
it is possible to use different parts of the entrance slit for different channels. By
doing so it is possible to change the wavelength setting simultaneously for all the
channels. The disadvantage is that only one of the channels is in the ideal position
on the optical axis of the spectrometer. The other channels will suffer from slightly
poorer imaging on the exit slit and the dispersion in the spectrometer will differ from
the on axis position. The latter error could actually be seen in the measurements
of the instrumental function as a small but not insignificant wavelength shift of
these channels (figure 2 in paper I). This could cause about 10-15% difference in
the transmission of light through the spectrometer system. The use of curved slits
would cure this problem.

The images of the fibres on the entrance slit are further imaged on the exit slit of
the spectrometer. These images are then imaged on five PM-tubes using a similar
lens system as on the entrance side. The magnification of this is set to 10:1 to allow
for enough separation between the light spots to fit in the PM-tubes. These have
integrated high voltage converters and need only 15V power supply. The gain is set
via a 0-1 V bias voltage applied using a 10 turn precision potentiometer for each
channel. The signals are then amplified and digitized as described in section 3.2.1
and appendix A.
4.2.2 Calibration

An important issue is the intensity calibration of the system, both the relative between channels but also of the absolute sensitivity. It is in principle quite straightforward to use absolutely calibrated tungsten lamps sources for this purpose. These are equipped with a diffuser system in order to behave like ideal Lambert radiators. In our case there were two major problems though. Firstly, the intensity of the light from the plasma is very high compared to a tungsten lamp. Secondly, tungsten lamps are almost useless below 3500 Å since the intensity drops very rapidly at shorter wavelengths (a quick look at Planck's radiation law confirms this behaviour).

The first problem was addressed mainly by acquiring a new lamp with higher intensity. This has an integrating sphere to make a Lambert radiator. Since the lamp with sphere is directly calibrated in W cm\(^{-2}\) sr\(^{-1}\) s\(^{-1}\), it is very convenient to use. In principle one only has to see to that the lamp fills the view of the system to be calibrated. The measured quantity from the plasma has the same units as the one from the lamp so that the signal from the detection system when using the lamp can be directly compared to the signal when using the plasma as the light source. The resultant quantity from the lamp is W cm\(^{-2}\) sr\(^{-1}\) s\(^{-1}\) V\(^{-1}\) which then can be multiplied with the signal in volts read out by the data acquisition system. The light was chopped to produce light pulses of the same duration as a plasma discharge.

The signal from the lamp as measured by the digitizers is still very weak though. Since the sampling time could not be changed it was necessary to average the signal from several pulses from the chopper. Better measurements were obtained when the output from the amplifiers were measured with a digital oscilloscope instead of the transient recorders. The oscilloscope had the possibility to make averages over a large number of chopper pulses which vastly improved the signal to noise ratio. These results deviated less than 10\% from those using the transient recorders and the analysis was much easier as was the overall ease of use.

The problem with the low intensity in the UV-range requires a different approach. Instead of using the tungsten lamp for the calibration in this wavelength range we used a calibrated deuterium lamp. The problem is that this lamp is calibrated with regard to irradiance (W sr\(^{-1}\) s\(^{-1}\)) instead of radiance as the tungsten lamp. Hence it would be necessary to scan the lamp very carefully in the field of view of the viewing system in order to be able to use its calibration directly, not a very easy task.

The method we decided to use exploits the fact that the calibration curve with regard to irradiance as a function of wavelength will not change with position of the lamp in the field of view. Both lamps have an overlapping wavelength region where they have measurable intensity. By measuring the signal obtained by viewing the deuterium lamp when placing it in the field of view to obtain maximum signal a calibration curve was obtained with regard to the wavelength dependence of the signal. By matching this curve to the absolutely calibrated curve in the visible
region measured from the tungsten lamp it was possible to extend the absolute calibration down to 2250 Å.

The procedure was applied to all five channels. It was then possible to have absolutely calibrated measurements in the whole range from 2250 Å to 6750 Å. Also the wavelength scale of the spectrometer was calibrated using spectral lamps.

4.2.3 Data analysis

The data analysis proved to be more difficult than first expected. Of course it is possible to use the calibrated raw signals directly but to really exploit all the possibilities it is necessary to make an inversion of the measured signals as described in section 4.1.2.

The first attempts were made using the analytical series expansion method. It had been tested on synthetically produced emission profiles with good results. However, when applied to real measurements which always include errors to some degree it failed. The choice of basis set functions did not matter in a significant way. The reason for this failure may also partly be in the limited number of lines-of-sight. This made it impossible to resolve fine structures in the emission pattern. Also it was desirable to exclude the zeroth order function i.e. a constant background since this would further reduce the possible number of higher order components.

Another approach was needed. By including some assumptions on the physics behind the emission there should be better possibilities to arrive at a physically relevant emission profile. As a first approximation it is fair to assume that the excited level responsible for the observed emission is mainly populated through electron impact and then use equation 2.4 to calculate the emission. Since the shape and value of the electron temperature can be estimated from measurements it is then only the ion density that is unknown. This ansatz has several benefits. The ion density profile is calculated directly in the inversion procedure. Since it is the ion density rather than the emission profile that is usually of main interest this is convenient. The rate coefficient will automatically impose a temperature dependence on the emission i.e. the emission will go to zero at the edge. The same goes for the electron density. A drawback is that it is no longer as easy to perform the inversion i.e. the nice matrix inversion is difficult to apply.

The inversion was made numerically. The emission was calculated and line integrated in the same way as the measured signals. The line-integrated calculated emission was then fitted to the measurements using the IDL routine curvefit. Figure 4.3 gives an example of results from a single plasma discharge (2468). The ion density can be any function that has up to four parameters to fit one parameter less than the number of measured values. The use of the curvefit routine makes this very easy since it only requires a function and a set of parameters to fit to the measured data. The fit-function can then contain both the calculation of the emission from the ion density i.e. the electron density and the rate-coefficient.

\footnote{IDL, Interactive Data Language, from Research Systems Inc. is used for all the data analysis made in my work.}
The inversion procedure must be somewhat modified when charge exchange reactions [56] are expected to contribute to the emission. It is then necessary to estimate the ion density of the $z+1$ ions and the neutral hydrogen profile. The $n_{z+1}$ density can to a first approximation be set to a fraction of the $n_z$ density at least for centered profiles. The relation between the $n_z$ and $n_{z+1}$ density was
determined from a calculated ionization balance. The hydrogen profile is estimated from simulations [57]. With these assumptions one can then apply the method described above.

The function that describes the ion density with this method can be of any kind. One should be careful though in the implementation to assure that it is nonnegative everywhere. For centrally dominated species like C\textsubscript{v} it is possible to use a Gaussian shape of the profile. For more complicated (read edge dominated) profiles one can use polynomials/\textit{functions} of the type \((1 - (r/a)^\alpha)^\gamma\). A kind of polynomials that is found to be useful are the Zernicke polynomials mentioned earlier (equation 4.9).

These are the ones used in the Granetz method for tomographic inversions. These are two-dimensional and have the interesting property of having a nice analytical form in both \((r, \theta)\) and \((p, \xi)\) space. The radial shape is also very suitable for this kind of applications as can be seen in figure 4.4. In the poloidally symmetric case we can set \(m = 0\) and get:

\[
R_l = \sum_{s=0}^{l} \frac{(-1)^s(2l - s)!}{s!(l - s)!(l - s)!} p^{2l-2s} \tag{4.19}
\]

The Zernicke polynomials represent a complete set of orthogonal functions. In reality we cannot sum \(l\) to infinity but have to limit it to fit the number of lines of sight. In my implementation I have used \(1 - R_l\) summed from 1 to 4. The
orthogonal properties of these functions make the curve fitting procedure converge rapidly. With this method it has been possible to fit a large variety of profiles as shown in paper III and IV.
Chapter 5

Comments to the papers

This thesis is based on six published papers and manuscripts. I will here give some comments and additional information on the results presented in these.

5.1 Paper I

A not insignificant part of my work on the EXTRAP-T2 experiment was to design, construct and install the system for radially resolved spectroscopy. Apart from the Thomson scattering (TS) system this is the only spatially resolved diagnostic on the EXTRAP-T2. The TS has only three spatial points and no time resolution though. The absence of other spatially resolved diagnostics is mainly due to the difficult access on the EXTRAP-T2.

In chapter 4 I have also described the setup, calibration and data analysis. No changes to the setup was done after the article was written. The calibration was remade several times though. This resulted in an extension of the calibrated region to 2250 Å. Earlier the calibration was extrapolated from 2500 Å. This vastly improved the measurements on CV and CIII.

Most of the work presented in this paper was done by myself. This also counts for the writing of the paper. It is of course inevitable that the work was done “with a little help from my friends” [58].

5.2 Paper II

This paper was the result of an unexpected exploration. From the simulations that were made when developing the analysis software for the inversion of the data from the radially resolved measurements we knew that the easiest emission pattern to invert was a central one. Thus we wanted to tune the monochromator to a line from an ion that we could be certain only to be present in the plasma center. The
choice fell on Cvi at 5290 Å. It is a fairly strong line which lies in a wavelength region with few other lines.

To our surprise we found that the emission was not central at all in many discharges. Instead it seemed that the emission was largely coming from a region close to the plasma edge. It was immediately assumed that the observed line was mixed with a line from some lower ionized ion. This was checked by taking full spectra with the 1-m spectrometer. Since Cvi is a hydrogen-like ion all the \( l \)-states of the same \( n \)-state are almost degenerate. The observed line (which is an \( n = 8 \rightarrow 7 \) transition) will thus appear as a single line at the resolution used. Most other lines will appear as multiplets sharing the same upper state. The relative intensity of the components of these multiplets is mainly determined by the deexcitation rate \( A_{ij} \). Thus if we could find a nearby line with a multiplet component coinciding with the 5290 Å line that might explain the observed emission. It does exist such lines from Ci for example but these were very weak compared to the Cvi line.

The 5290 Å line is often used when observing charge exchange reactions with hydrogen mainly when using neutral beams. The approach of adding charge exchange recombination with neutral hydrogen for the interpretation of our data was successful. It manages to explain the shape of the emission profile. It also opened a possibility to estimate the change in neutral hydrogen concentration and profile. The emission is expected to be due mainly to charge exchange recombination.
with hydrogen in $n = 2$ since the rate coefficient of this reaction is many orders of magnitude larger than the rate coefficient for reactions with the ground state $[^5\text{Li}]$. 

The still remaining problem is the absolute emission. It is a factor of 10-20 higher than what could be expected from calculations of the ion densities. For the charge exchange part of the emission it might be the estimation of the $n = 2$ population that is uncertain. Using the Johnson-Hinov [37] estimation might not be correct in the edge region since the hydrogen released from the wall to a large extent is in the form of H$_2$ [62]. The very recent data from reference [61] gives a rate coefficient that is a factor of two larger than the one used in the paper. The rates used for the electron impact excitation are also a bit uncertain since they are calculated from an approximate formula [36F63] with corrections according to the Aggarwal and Kingston calculations [64].

There is also the possibility of mixing with the $n = 8 - 7$ line in OvI. The wavelength of this line is close enough for not being resolved from the Cvi line. The difference lies in that OvI is not hydrogen-like it is lithium-like. Hence the different $l$-states are not fully degenerate and one should be able to see the lines from the lower $l$-states well separated from the main line. The contribution from
OV\textsuperscript{i} was too small to be able to explain the discrepancy in the absolute level of the emission. The spectra are shown in figure 5.1.

Performing a fit (figure 5.2) to the measured line using complete \(l\)-mixing (from reference [65]) shows that it is possible to obtain a very good fit with fixed relative intensities of the different \(l\)-components. The small deviation on the short-wavelength side of the line might indicate a deviation from the assumption of full statistical \(l\)-mixing. The good fit makes it difficult to believe that the line should be mixed with other lines. The fit also gives the ion temperature in the example in figure 5.2 this is 70 eV which is rather typical for this ion when the emission is observed mainly from the plasma edge region.

Still the approach of using CXR as the source of the somewhat unexpected edge emission does explain the overall behaviour of this line. The examples shown in this paper clearly demonstrate this.

Apart from the VUV-measurements which were performed by A. Hedqvist I did most of the work in this paper myself including writing the paper. The co-authors took part mainly on a basis of discussion of the results and their presentation.

5.3 Paper III

The studies of the ion rotation started along with the measurements of ion temperature anisotropy [66]. It was then arranged so that the plasma could be viewed tangentially in the toroidal direction. This made it possible to also measure the ion velocity from the Doppler shift of the observed emission line. These measurements are line-of-sight averaged and without further information it is not possible to make any statements on the radial velocity distribution. By combining the ion velocity measurements with the results from the radially resolved spectroscopy this became possible. We could then estimate the radial profiles both for the ion temperature and toroidal velocity (figure 1 in the paper). It is also interesting to see how the change in velocity is coupled to an apparent change in position of the maximum ion density (figure 3 in the paper).

The measurements presented have a great importance for the understanding of the driving mechanism of the rotation. Rotation shear, i.e. change of velocity over the radius, is believed to have a stabilizing effect on the plasma [67]. There are two main processes that are responsible for this effect:

\begin{equation}
 v_{\text{dia}} = -\frac{\nabla p \times B}{nqB^2}
\end{equation}

and E\times B drift

\begin{equation}
 v_{E\times B} = \frac{E \times B}{B^2}
\end{equation}

Combining the presented measurements with simulations will make it possible to investigate which of these processes is mainly responsible for the rotation. The
initial results indicate that the diamagnetic drift has a large contribution to the rotation for central ions. For ions closer to the edge it seems that the diamagnetic drift more or less cancels out since the pressure gradient is negative on the inboard side and positive on the outboard side of the density profile. This makes the $E \times B$ drift to be mainly responsible for the rotation in these cases. This would also explain the observed change in rotation direction for very edge localized species such as C$^+$ and C$^+$ since the electric field is measured to have a change in direction close to the edge [40]. A very recent paper has also high-lighted these issues [68].

In this paper I am responsible for the radially resolved measurements. I also took part in the analysis of the ion temperature and rotation measurements and wrote most of the computer code needed for this purpose.

5.4 Paper IV

This paper concludes the measurements I have made using radially resolved spectroscopy. It presents a clear picture of the ion density profiles for C$^+$-CVI and O$^+$-OV. These profiles provide means to improve the transport simulations that previously were made using somewhat ad hoc assumptions on several parameters. It is nice to see that the initial simulations were not that far from predicting the actual density profiles. For many of the ions the difference was within the errors of the measurements. The exception from this is CV which clearly deviates from the measurements in the initial simulations. By adjusting the edge transport parameters it was possible to get much closer in result to the measurements. It was also necessary to consider the contribution to the emission from CXR [69]. Since there is much to be understood concerning the transport mechanisms in RFP's it is of great importance to have this kind of measurements to rely on in order to improve the understanding of these. It can also be said that the strength of this work is that we have studied the radial profiles for many different ionisation stages. Without this extensive study it would not have been possible to draw conclusions on the transport in the RFP.

There is an inherent strength in having measured ion density profiles instead of only simulations. Hence it is somewhat strange that this kind of measurements of several ion species is rather scarce. The measured profiles have proven to be very useful for the interpretation of other diagnostics as shown in paper III. The radially resolved line emission has also provided further understanding of other spectroscopic measurements which is shown in paper V.

For this paper I did the measurements and the analysis of the data and also the transport simulations. I also wrote the paper myself.
5.5 Paper V

From time to time we have observed what looked like oscillations in the spectroscopy signals. When the surface-barrier diodes were installed to study soft x-ray emission the oscillations also appeared in the signals from these. Since the soft x-ray emission is coming from the center of the plasma at the temperatures obtained in the EXTRAP-T2 it was surprising to see correlated oscillations in spectroscopic signals from edge ions. These studies show for the first time identified correlations with oscillations in spectroscopic and magnetic signals from the EXTRAP-T2 plasma.

There is evidently a coupling between the center and the edge of the plasma that transfers energy to excite the ions at the edge. We could also see that the emission can be very localized. The mechanisms behind these observations are not yet fully understood.

In this paper I am responsible for the radially resolved measurements and the analysis of these. I contributed in the discussion of the results and wrote the part of the text concerning my measurements.

5.6 Paper VI

After submitting paper IV we found that the results from the measurements of Cv ion density using VUV-spectra and radially resolved spectroscopy produced strikingly similar results. Well, of course they should if we had made everything right but the level of agreement was far better than expected when looking at the line average density. The two methods include several assumptions of different kind and the VUV-method does not even use direct measurements of Cv. This paper is an acknowledgement of the ideas presented in a paper by K-D Zastrow et al. [70].

In this paper I made the density calculations from the radially resolved visible spectroscopy measurements. I also took part in the writing of the paper.
Chapter 6

Conclusions

The installation of a fairly simple, though well designed, system for multiple line-of-sight, time-resolved spectroscopy on the EXTRAP-T2 has provided a possibility to make spatially resolved measurements. This kind of measurements has not previously been available on this experiment except for the three spatial-point Thomson scattering. The Thomson scattering measurements lack time-resolution though, providing information only from a very short time interval (∼ns). The results from the spatially resolved spectroscopy are thus the only information available on the internal structure of the light emitted from the EXTRAP-T2 plasma. This knowledge makes it possible to extract spatial information for quantities derived from these measurements.

The investigation of hydrogen-like carbon, C_\text{vi}, made it possible to measure the neutral hydrogen density in the plasma edge region. It was previously thought that the concentration of fully stripped carbon was too low to contribute significantly to the C_\text{vi} through charge exchange reactions with the neutral hydrogen. These measurements proved the opposite and provided a new possibility for measuring neutral hydrogen concentrations. With the good time resolution available it was also possible to study sudden events of hydrogen influx from the carbon wall. Since the influence of plasma-wall interaction on the plasma performance has been one of the major issues during the EXTRAP-T2 operation these measurements are of great interest.

The knowledge provided on the radial distribution of the brightness of line emission from different ion species made it possible to reconstruct the radial emission profiles. By using the ion density as the fitted quantity and relate it to the emission through a one dimensional ionization balance it was possible to obtain the density directly from the fit. The obtained results for C_{\text{III}}-C_{\text{VII}} and O_{\text{III}}-O_{\text{V}} made it possible to make comparisons with transport simulations and improve the knowledge on the radial transport properties of the plasma. This opens new possibilities to compare the radial transport properties in RFP’s and tokamaks.

For the first time temporal correlation with fast oscillations from spectroscopic
and magnetic diagnostics have been identified on the EXTRAP-T2. These oscillations might indicate a channel for energy loss in the RFP which connects the core region with the plasma edge. The oscillations have also been observed in the signals from the radially resolved spectroscopy. These observations indicate that the oscillations in the signals from emission in the visible region come from the edge region and are highly localized. The spectroscopic signals from soft x-ray measurements show that the oscillations in the core region are toroidally symmetric.

The presented results clearly show that time- and space-resolved spectroscopic measurements provide valuable information to the fusion plasma research community. The very clear goal of the fusion research to provide the basis for a new source of energy makes every step closer to this goal important.
Appendix A

Signal amplifiers and filters

The signal from a PM-tube can be very weak which makes it necessary to be careful in the signal processing. This becomes even more true in the vicinity of a fusion experiment since this environment is full of potential sources of noise and other signal degrading effects. This was fully experienced when installing the spectroscopic diagnostics on the EXTRAP-T2.

Electrically the output from a PM-tube is close to an ideal current source with an almost infinite output resistance. Since most signal detection systems such as oscilloscopes or transient recorders actually measure voltage rather than current it is necessary to convert the current to a voltage. Usually the output current is very low which makes it necessary also to have some sort of signal amplifier.

The easiest way to both convert current to voltage and produce a voltage high enough to be recorded is to simply drive the current through a large resistor. On a high impedance digitizer or oscilloscope it is possible to use the usually very high (~ 1MΩ) input resistance. The main problem with this is that the time constant coming from the capacitance of the PM-tube will make the arrangement act like a low-pass filter. This will destroy the otherwise very fast response of the PM-tube and make measurements with a high time resolution impossible. There will also be a bad match to the cables which are usually 50 Ω or 75 Ω making the method only to work satisfactory if the load resistor is connected very close to the PM-tube. Instead of this a system comprising a pre-amplifier, an amplifier and a low-pass filter was constructed.

The pre-amplifier acts as a current to voltage converter and is designed to be placed directly on the output from the PM-tube. It uses an LF-356 operational amplifier to convert 100 μA to 1 V. To be able to drive a 50 Ω load there is also a LH-0002 driver stage on the output side (in later designs changed to a BUF-634P). Both the input and output are 50 Ω to match the cable impedance.

The main amplifier has a low pass filter on the input side. This is necessary to avoid aliasing in the digitizing of the signal. This will occur if frequencies above half the sampling frequency is allowed to enter the digitizer. The result would
be that these too high frequencies would be aliased into lower frequencies and misinterpreted as real signal in the region below half the sampling frequency. The applied filters have their cut-off frequency (-3 dB) at 49 kHz and at the sampling frequency (100 kHz in this case) the damping is 14 dB compared to DC response. An even steeper filter would have been preferred but the phase shifts introduced would then have been unacceptable. The filter is designed to have a 50 Ω input impedance.

The amplifier has selectable amplification by means of different resistors selectable with a switch. It also uses the LF-356 OP-amplifier and an LH-0002 output driver (later changed to BUF-634P). Also this stage has 50 Ω output impedance. The signals are then fed into the transient recorders which have 100 kΩ input impedance.
References

References


References


