Importance of radial profiles in spectroscopic diagnostics applied to the EXTRAP-T2R reversed-field pinch

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**Abstract**

The determination of the plasma confinement properties demand data as the electron temperature, the ionic and electron density profiles and the radiative emissivity profiles. The focus of this thesis is the importance of radial profiles in spectroscopic diagnostics applied to the EXTRAP-T2R reversed-field pinch.

EXTRAP-T2R is a resistive shell reversed-field pinch with a magnetic field shell penetration time much longer than the relaxation cycle time scale. Significant improvements in confinement properties derived by quantitative plasma spectroscopy in the vacuum ultraviolet are observed compared to the previous device EXTRAP-T2. The low level of magnetic turbulence and the good magnetic surfaces in the edge region explain this observed improvement. A current profile control experiment reduces the stochastic transport, which is connected to the dynamo, and improves the confinement in EXTRAP-T2R even more.

A comparison of the electron temperature estimated by using a ratio of line intensities from the same ionization stage of oxygen and the Thomson scattering system shows that the difference is explained by the different spatial dependence of the excited state populations and the corresponding emissivity of these spectral lines.

A collisional radiative model gives estimates for radial profiles of impurities which are not measured in EXTRAP-T2R. The estimated profiles can in turn be used to determine the radial profile of the effective ion charge, the emissivity and finally the radiative power. As input, the model uses radial profiles.

Neutral hydrogen is predominantly present in the boundary region of the plasma. Spectroscopic investigations in this area show very asymmetric spectral lines of hydrogen due to the movement of atoms. The velocity of the hydrogen atoms depends on the type of plasma-wall interaction and their measurement helps to identify the different interaction processes. The existence of hydrogen molecules in the edge complicates the interpretation of the line shapes and on the determination of the particle confinement time.

**Keywords**

Reversed-field pinch, EXTRAP-T2R, quantitative plasma spectroscopy, VUV spectroscopy, line-integrated electron temperature, oxygen, profiles, confinement properties, power balance, hydrogen, particle confinement time.

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Preface

My first introduction to fusion research, and plasma spectroscopy in particular, was in 1997. As a student I attended a seminar given by Frans Meijer at the Department of Physics at the ‘Universiteit van Amsterdam (UvA)’. I cannot say that the seminar changed my life completely but it surely made me fascinated by the subject. This fascination to that end forced me to do research at the FOM Institute for Plasma Physics ”Rijnhuizen” for my Master of Science examination.

One thing led to another and in the spring of 1999 I started as a PhD student under supervision of Elisabeth Rachlew at the Department of Physics at the Royal Institute of Technology. EXTRAP-T2 was shut down at that time and it would take until September, 2000 for the resumed operation of the device under the name EXTRAP-T2R. Finally, I was able to do experimental work again! It was also my first introduction to the reversed-field pinch: a magnetic configuration which turned out to be much more perplexing than a tokamak.

The enthusiasm and ‘power’ of my colleagues surrounded me for a while before it really struck me, took hold of me ... and finally inspired me. The analysis of the EXTRAP-T2R data resulted in questions and puzzlement ... discussions and ideas led to many more. Many times I fought against the darkness and sometimes the light came ... I guess this is the essence of research and I want to thank Elisabeth Rachlew for giving me the opportunity and all my colleagues for their helping hand in times of darkness.

This thesis describes the experimental work of the last years on the reversed-field pinch EXTRAP-T2R. In chapter 1 the reader will be introduced to thermonuclear fusion, the reversed-field pinch and plasma spectroscopy. Chapter 2 presents the EXTRAP-T2R device and the quantitative data analysis using spectroscopy on EXTRAP-T2R plasmas. The influence of radial distributions on the analysis of spectroscopy and relevant plasma parameters is illustrated in chapter 3, while the behavior of hydrogen in fusion plasmas, and especially in the boundary, is referred to in chapter 4. Chapter 5 summarizes some results of my work followed by concluding remarks in chapter 6 with an outlook of the role of quantitative plasma spectroscopy on the reversed-field pinch EXTRAP-T2R and fusion research in general.

Stockholm, October, 2003

Bob Gravestijn
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List of papers

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

I. P R Brunsell, H Bergsäker, M Cecconello, J R Drake, R M Gravestijn, A Hedqvist and J-A Malmberg
   Initial results from the rebuilt EXTRAP T2R RFP device

II. R M Gravestijn, M P Kuldkepp, M Cecconello and E Rachlew
    A spectroscopic method to determine changes in the electron temperature profile

III. M Cecconello, J-A Malmberg, G Spizzo, B E Chapman, R M Gravestijn, P Franz, P Piovesan, P Martin and J R Drake
    Current profile modification experiments in EXTRAP T2R

IV. R M Gravestijn, J R Drake, A Hedqvist and E Rachlew
    Comparison of confinement in resistive-shell reversed-field pinch devices with two different magnetic shell penetration times

V. Y Corre, E Rachlew, M Cecconello, R M Gravestijn, A Hedqvist, B Pégourié, B Schunke, V Stancalie
   Radiated power and impurity concentrations in the Extrap-T2R RFP

VI. R M Gravestijn, F G Meijer and the RTP team
    Toroidal rotation of hydrogen in the RTP tokamak
Papers related to this work but not included in this thesis:

F G Meijer, M de Baar, D Hogewij, D Badoux and R M Gravestijn
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31st EGAS conf. on Atomic Spectroscopy (Marseille, France, 1999)
Frans Meijer, Jos de Kloee, Bob Gravestijn, Dave Badoux and the RTP-team
The effect of off-axis pellet injection on plasma rotation
Frans Meijer, Bob Gravestijn, Elisabeth Rachlew
High resolution spectroscopy for plasma rotation measurements on the T2R reversed field pinch
32nd EGAS conf. on Atomic Spectroscopy (Vilnius, Lithuania, 2000)
Frans Meijer, Bob Gravestijn, Dick Hogewej, Marco de Baar and the RTP-team
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First Results From the EXTRAP-T2R RFP Experiment
M Cecconello, J H Brzozowski, R M Gravestijn, A Murari
Total radiation losses studies in EXTRAP T2R
Frans Meijer, Bob Gravestijn, Elisabeth Rachlew
Plasma Rotation and H-Alpha Emission at the T2R Reversed Field Pinch
F G Meijer, R M Gravestijn, E Rachlew
Plasma rotation measured by H-alpha emission from the T2R reversed field pinch
De weg om te slagen is: moed houden en geduld en stevig doorwerken
– Vincent aan Theo van Gogh, 1886

Sometimes I freeze - until the light comes
Sometimes I fly - into the night
Sometimes I fight - against the darkness
Sometimes I’m wrong - sometimes I’m right

"Freeze" (part iv of "fear")
Vapor trails
Rush
Chapter 1

Introduction

1.1 Thermonuclear fusion

The understanding of physics has led scientists to realize that release of energy can be obtained from certain nuclei. The heaviest elements, like uranium (U), release energy when broken into smaller, radioactive atoms (nuclear fission). The lightest atoms, like hydrogen (H) or its isotopes (deuterium (D) and tritium (T)), release energy when they combine, or fuse, to form heavier elements, which are not radioactive. Both these processes can be the solution for solving the growing global energy demand.

To obtain fusion of the light positively charged nuclei, the electrostatic repulsion has to be overcome. This is achieved at very high temperatures, in the order of millions of degrees, such as in the interior of the sun. At these high temperatures atoms are partly or completely ionized and form a plasma. The least difficult fusion reaction is between the hydrogen isotopes D and T:

\[ {}^2_1 D + {}^3_1 T \rightarrow {}^4_2 He \ (3.5 \text{ MeV}) + {}^0_1 n \ (14.1 \text{ MeV}) \]  

(1.1)

For this fusion reaction a temperature of \( T = 10^8 \text{ K} \) is needed, corresponding to an energy \( E \approx 10 \text{ keV} \) (\( E = kT \), where \( k \) is the Boltzmann constant and the conversion factor is 1 eV = 11600 K). The thermal velocities of the nuclei are then high enough to produce reaction 1.1 although the energy is not as high as the energy of maximum cross-section of 100 keV. That fusion is obtained at \( T = 10^8 \text{ K} \) is a result of the thermal particles in the high energy tail of the Maxwellian distribution of the D and T nuclei.

A solution to confine this high temperature, ionized gas is magnetic fusion. It is based on the fact that charged ions and electrons gyrate around magnetic field lines as a result of the Lorentz force. At present, magnetic fusion research is undertaken in three different magnetic configurations: the tokamak [1], the stellarator [2] and the reversed-field pinch [3, 4].
Chapter 1. Introduction

1.2 The tokamak versus the reversed-field pinch

The tokamak\(^1\) is the most studied and most advanced fusion machine to date and is the most likely magnetic configuration to be converted into a reactor. In a tokamak, the toroidal field is created by coils that surround the torus shaped vacuum vessel. By using the plasma as the secondary coil of a transformer a toroidal plasma current is induced, which itself induces a poloidal magnetic field. These two magnetic fields combine to closed nested magnetic surfaces, which are being formed by helical field lines and result in the confinement of the plasma.

A reversed-field pinch (RFP) is related to the tokamak. The main difference is that in the RFP the poloidal magnetic field \(B_\theta\) is of the same order as the toroidal magnetic field \(B_\phi\) rather than \(B_\theta \ll B_\phi\) as in a tokamak. A toroidal current induces the poloidal magnetic field, while the toroidal magnetic field is by large produced by the plasma itself through a relaxation process called the RFP dynamo. Taylor [5] has shown that the magnetic configuration of the RFP plasma relaxes to a state, the so-called Taylor state, in which magnetic field energy is minimized subject to the constraint of conservation of magnetic helicity

\[
K = \int A \cdot B dV
\]

where \(A\) is the vector potential related to the magnetic field \(B\) by \(B = \nabla \times A\) and \(V\) is the plasma volume. Magnetic helicity is, alternatively put, the knottedness of the poloidal and toroidal magnetic field.

The equilibrium magnetic field profiles of the RFP corresponding to this minimization are described by the condition:

\[
\nabla \times B = \mu B
\]

where the normalized parallel current density \(\mu\) is spatially constant (i.e. \(j \cdot B/B^2 = \text{constant}\)). This means that the radial profile of the current density parallel to the magnetic field should be flat, as shown in figure 1.1. However, the Taylor state is only possible in an ideal plasma. In experiments, the temperature in the edge of the plasma is lower than in or close to the core resulting in a higher resistivity in the edge which leads to a peaking in the current density profile. This is inconsistent with a spatially constant value of \(\mu\). Resistive diffusion leads finally to a further decay of the Taylor state. The resulting current density gradient creates then a state with free energy available for the growth of destabilizing resistive magnetohydrodynamic instabilities and the appearance of fluctuations. These in turn redistribute the total magnetic helicity and create a dynamo electric field which suppresses current in the core and drives a current in the edge. This leads to a modification (a flattening) of the current profile which drives the system back toward the Taylor state. When the resistive diffusion re-appears, departure from the Taylor state will trigger the relaxation cycle until the plasma reaches the near-minimum energy state through self-organization by conserving the magnetic helicity.

\(^1\)Tokamak is an acronym from the Russian 'toroidalnaya kamera i magnitnaya katushka', meaning: toroidal chamber and magnetic coils.
1.2. The tokamak versus the reversed-field pinch

Figure 1.1. The equilibrium magnetic field and current density profiles of the RFP calculated with the polynomial function model (PFM) [8]. The current density $j$ is the sum of the current density parallel to the magnetic field $j_\parallel$ and the current density perpendicular to the magnetic field $j_\perp$. Note the field reversal of the toroidal magnetic field and, hence, the origin of the name of the RFP configuration. Furthermore, experiments are only partially relaxed in that $j_\parallel$ tends to be constant over the inner half of the plasma, but then decreases to zero at the wall indicated by the vertical dashed line at $r = 0.183$ m and gray area.

Experiments show that the RFP can achieve much higher values for the poloidal beta (efficiency of confinement of plasma pressure by the poloidal magnetic field) than those in tokamaks. The energy confinement time in RFP’s is unfortunately still much lower than in tokamaks with the same plasma current. A disadvantage of the essential dynamo is that it destroys magnetic surfaces in the plasma interior. The resulting stochastic magnetic field structure (due to the growth and overlapping of magnetic islands) is a strong source of particle and energy transport parallel to the magnetic field lines and thereby diminishes the confinement properties [6, 7].
Chapter 1. Introduction

1.3 Plasma spectroscopy

The main plasma parameters (like the density, the temperature, the plasma current) are of key importance for the study of plasmas. Many of the macroscopic properties of a plasma may be inferred from electrical measurements made externally to the plasma boundary. Other macroscopic properties can be obtained by the use of plasma diagnostics. Predominantly, these diagnostics observe either radiation or neutral particles which are spontaneously emitted by the plasma and, therefore, yield information on plasma characteristics.

During a plasma discharge elements other than the filling gas (normally hydrogen) can be released into the plasma: impurities. These impurities can have a negative effect on plasma operation but they can also be used to obtain plasma parameters. The most suitable diagnostic tool to measure the behavior of plasma atoms and impurity ions is spectroscopy. In a fusion plasma the hydrogen is completely ionized apart from a region close to the edge. Together with the partly ionized impurity ions, the hydrogen atom can be collisionally excited to a higher energy level and subsequently emit electromagnetic radiation by spontaneous emission to a lower energy level. The wavelength associated herewith is characteristic for each specific transition due to the fixed energy levels in atoms or ions according to quantum physics. An experimentally obtained wavelength spectrum therefore only contains lines at specific wavelengths and is a "fingerprint" for a given atom or ion.

The measurement of a wavelength spectrum provides a tool to obtain information about the species present in the plasma. The intensity of a spectral line with respect to the wavelength furthermore provides information about the densities of the different ions, their velocities, temperatures and the effect of electric and magnetic fields on spectral line emission. Nevertheless, the spectroscopic analysis of the observed radiation can be complicated by the spatial dependence of plasma properties as the electron density and electron temperature. The importance of radial profiles in spectroscopic diagnostics applied to the EXTRAP-T2R reversed-field pinch is the focus of this thesis.
Chapter 2

EXTRAP-T2R

EXTRAP-T2R [9, paper I] started operation in 2000 as the rebuild of EXTRAP-T2 (and formerly OHTE) device which was a medium-sized RFP \( R/a = 1.24 \text{ m}/0.183 \text{ m} = 6.8 \) [10]. The vacuum vessel was made of stainless steel and the inside wall was fully covered with graphite tiles. The pulse lengths were many times the magnetic field shell penetration time: the time for the magnetic field to penetrate the shell. However, the shell penetration time was such that phase-aligned, stationary magnetic field perturbations, so-called wall-locked modes, appeared. At the position where the modes were locked, the wall was locally heated and a strong influx of hydrogen and impurities (mainly carbon from the graphite wall) were observed. This in turn resulted in a degradation of confinement by the plasma performance; i.e. a higher loop voltage (an increase of plasma resistance) and a drop of the central temperature. EXTRAP-T2 and other resistive shell experiments demonstrated that the shell penetration time was too short compared to the time scale that characterizes the relaxation cycle dynamics.

In EXTRAP-T2R the shell penetration time of 6.3 ms is intermediate: this characteristic time is much longer than the time scale characterizing the cyclical relaxation dynamics but still sufficiently short so that the global radial equilibrium could be effectively controlled with externally applied vertical fields that penetrate the shell on the shell time scale. What else did change during the rebuild? The graphite wall is replaced by an all metal first wall with molybdenum limiters, the field errors are reduced, and the replacement of the helical coil with a conventional solenoid-type coil provides improved access for diagnostics to diagnose the plasma.

Did the changes and especially the change in the shell penetration time work? The operation parameters of EXTRAP-T2R are similar to parameters in the best performing conducting shell devices although the pulse lengths are sustained for up to four shell times. However, it is still short enough to allow plasma positioning control with applied vertical field. At present, EXTRAP-T2R operates with relatively low plasma currents of up to 120 kA and toroidal loop voltage as low as 20 to 30 V. The electron density is shot to shot reproducible, which was impossible on EXTRAP-T2 where the recycling at the graphite wall was difficult to control. Without gas puff, the electron density decays throughout the discharge and drops below \( 5 \times 10^{19} \text{ m}^{-3} \). Gas puffing helps to sustain the density constant in the range of \( 1 - 2 \times 10^{19} \text{ m}^{-3} \). The electron temperatures are comparable with those in EXTRAP-T2: e.g. between 50 and 250 eV.
Chapter 2. EXTRAP-T2R

### Table 2.1. Typical parameters of EXTRAP-T2 and EXTRAP-T2R.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>EXTRAP-T2</th>
<th>EXTRAP-T2R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major radius</td>
<td>$R_0$</td>
<td>1.24</td>
</tr>
<tr>
<td>Minor radius</td>
<td>$a$</td>
<td>0.183</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>$R/a$</td>
<td>6.8</td>
</tr>
<tr>
<td>Plasma current</td>
<td>$I_p$</td>
<td>70 − 250</td>
</tr>
<tr>
<td>Loop voltage</td>
<td>$V_{loop}$</td>
<td>70 − 160</td>
</tr>
<tr>
<td>Electron density</td>
<td>$n_e$</td>
<td>$1 \times 10^{19}$</td>
</tr>
<tr>
<td>Electron temperature</td>
<td>$T_e$</td>
<td>50 − 250</td>
</tr>
<tr>
<td>Ion temperature</td>
<td>$T_i$</td>
<td>100 − 300</td>
</tr>
<tr>
<td>Effective charge</td>
<td>$Z_{eff}$</td>
<td>1.5 − 6.0</td>
</tr>
<tr>
<td>Confinement time</td>
<td>$\tau_E$</td>
<td>20 − 60</td>
</tr>
<tr>
<td>Poloidal beta</td>
<td>$\beta_p$</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>Pinch parameter</td>
<td>$\Theta$</td>
<td>1.6 − 2.1</td>
</tr>
<tr>
<td>Reversal parameter</td>
<td>$F$</td>
<td>−0.40 − −0.20</td>
</tr>
<tr>
<td>Discharge duration</td>
<td>$\tau_{pulse}$</td>
<td>$\leq$ 16</td>
</tr>
<tr>
<td>Penetration time</td>
<td>$\tau_s$</td>
<td>1.5</td>
</tr>
</tbody>
</table>

#### 2.1 Spectroscopy on EXTRAP-T2R

To investigate the properties of the EXTRAP-T2R plasma several spectroscopic diagnostics are available. A vacuum ultraviolet (VUV) spectrometer [11], at grazing incidence in a radial view equipped with a fast detection system, measures the temporal evolution of impurity spectral emission. The spectrometer is absolutely calibrated using the branching ratio technique [12] and allows the deduction of the line averaged electron temperature, impurity concentrations and the effective charge $Z_{eff}$ [13]. The instrument covers a spectral range of 100 to 1100 Å using the 450 l/mm grating, alternatively 155 to 1700 Å with the 290 l/mm grating. Ion temperature and rotation velocity are measured with the 1 m Czerny-Turner spectrometer (grating 2400 l/mm) equipped with an optical multichannel analyzer allowing 2 ms time-resolution. The 1.5 m Czerny-Turner spectrometer with the 1180 l/mm grating studies the H$_\alpha$ line profile from EXTRAP-T2R. The detector system consists of an image intensifier optically coupled to a linear charge-coupled camera detector operating at a time resolution of 0.4 ms. Identification of the impurities present in the (edge) plasma is done with the 0.5 m Ebert spectrometer (with the 1180 l/mm grating), while small monochromators monitor the time evolution of line emission of selected spectral lines in the visible range. Several photomultipliers with interference filters with a narrow bandwidth, typically 10 Å, record H$_\alpha$ emission at different poloidal and toroidal positions around the torus.
2.2 Quantitative plasma spectroscopy at EXTRAP-T2R

The aim of quantitative plasma spectroscopy is to use spectral line emission from the plasma to determine quantities like temperature and density. The intensity of a spectral line depends on the population of an excited state \( n^* \)

\[
I = n^* A
\]  

where \( A \) is the radiative transition probability. Measurement of the line intensity for a line in which \( A \) is known gives a rather direct tool to measure the excited state population. However, the population of the excited state and its distribution strongly depend on the electron temperature in the plasma. In EXTRAP-T2R, the main impurity is oxygen (O) and its ionization states can be used as a rough indication on the electron temperature, see figure 2.1. The temperature of the plasma is non-uniform and leads to that different ionization stages dominate in different parts of the plasma. For example, \( O^{2+} \) tends to occur in the outer cooler part of the plasma.

In order to have estimates of the population of all the ionization stages of oxygen it is important to know more about the individual ionization stage populations. The density of the ground states of every ionization stage as well as the excited state populations can be calculated with a model based on ionization and recombination: the collisional-radiative model.

![Figure 2.1](image.png)

Figure 2.1. The fractional abundances of oxygen as a function of temperature as calculated in coronal balance. Data are taken from [14].
### 2.2.1 Ion densities and effective ion charge

The density of the ground state of an ionization stage $z$ for oxygen, can be described by an ionization balance:

$$
\frac{dn_z}{dt} = n_{z+1}n_e\alpha_{z+1}(T_e, n_e) - n_{z}n_e\alpha_z(T_e, n_e) + n_{z-1}n_eS_{z-1}(T_e, n_e) - n_{z}n_eS_z(T_e, n_e) + \sigma - \frac{n_z}{\tau_p}
$$

where $S(T_e, n_e)$ and $\alpha(T_e, n_e)$ are the ionization and recombination coefficients which are function of the electron temperature $T_e$ and electron density $n_e$. At steady-state, e.g. $\frac{dn}{dt} = 0$, the density of an ionization stage $z$ is a balance between recombination and ionization between the surrounding ionization stages $z - 1$ and $z + 1$. However, two more terms are apparent in equation 2.2. The first is a source term, $\sigma$, which is the influx of neutral particles as a result of the interaction between the plasma and the surrounding wall. The second term is the loss of particles with a characteristic time, the particle confinement time $\tau_p$, as a result of transport and plasma-wall interaction.

The density of the excited state $i$, for a certain ionization stage $z$, is described by an excitation balance:

$$
\frac{dn_{z,i}}{dt} = \sum_j n_{z,j}(A_{ji} + n_eq_{ji}(T_e, n_e)) - \sum_j n_{z,i}(A_{ij} + n_eq_{ij}(T_e, n_e)) + \sum_k n_{z+1,k}n_HC_{z+1,ik}(T_e, n_e) - \sum_k n_{z,i}n_HC_{z,ik}(T_e, n_e)
$$

where $A_{ij}$ is the transition probability from state $i$ to state $j$, $q_{ij}(T_e, n_e)$ is the electron collision coefficient, $n_H$ is the neutral hydrogen density and $C(T_e, n_e)$ is the charge-exchange coefficient. Furthermore, only charge-exchange with neutral hydrogen is taken into account. At steady-state the densities of the excited states are in balance between different excitation and de-excitation processes; absorption and emission of radiation as well as collision processes. Normally, the ions are excited by collisions with electrons and de-excited by emitting a photon. The decay time of an excited state is usually much shorter than the collision time. As a result, the density of excited states is low in comparison with that of the ground state and virtually all collisions involve ions in the lowest energy state. The excitation balance takes the form,

$$
\frac{dn_{z,i}}{dt} = n_{z,1}n_eq_{i1}(T_e, n_e) - \sum_j n_{z,i}A_{ij} = 0
$$

which gives the solution

$$
n_{z,i} = \frac{n_{z,1}n_eq_{i1}(T_e, n_e)}{\sum_j A_{ij}}
$$

where $n_{z,1}$ is the ground state density of an ion with a certain ionization stage $z$ which can be estimated by the ionization balance (equation 2.2). The intensity of a transition (equation 2.1), between states $i$ and $j$, induced by electron collision excitation can then be given by

$$
I = n_{z,1}n_eq_{ij}(T_e, n_e)\frac{A_{ij}}{\sum A_{ij}}
$$
2.2. Quantitative plasma spectroscopy at EXTRAP-T2R

In the VUV wavelength region the resonance lines of oxygen all the way to lithium-like (O$^{5+}$) are found in the spectra. These lithium-like ion densities are calculated from line intensities using the excitation balance. However, at temperatures around 150 eV, a large fraction of the emission from oxygen appears in the soft x-ray region. In this wavelength region no direct measurements of these lines are available on EXTRAP-T2R and another approach to calculate their densities is needed. The helium-like ion density ($n_{O^{6+}}$) is calculated using the ionization balance,

$$\frac{dn_{O^{6+}}}{dt} = \frac{n_{O^{5+}}n_eS_{O^{5+}ightarrow O^{6+}}}{\tau_p} + n_e\alpha_{O^{6+}ightarrow O^{5+}}$$  \hspace{1cm} (2.7)

where the helium-like ion is regarded as the final stage for oxygen in EXTRAP-T2R plasmas.

The final step is to calculate the effective charge of the plasma $Z_{eff}$, by summing up the contributions from different ionization stages of oxygen,

$$Z_{eff} = \sum_{i=1}^{n} \frac{Z_i^2n_i}{Z_in} = 1 + \sum_{i=1}^{k} \frac{n_iZ_i(Z_i-1)}{n_e}$$  \hspace{1cm} (2.8)

At EXTRAP-T2R, the impurity ion densities of ionization stages lower than lithium-like and helium-like carbon and oxygen are neglected since they have a lower density and have no or little effect on the final result of $Z_{eff}$. The impurity ion densities up to O$^{5+}$ are present in a small region, i.e. the edge plasma, and are regarded to be small. Moreover, their influence is negligible small since they contribute to $Z_{eff}$ with a factor of $Z(Z-1)$. One can discuss the neglect of heavier impurities like molybdenum or other metals, but spectral lines of these ions have not been found in the recorded spectra. The hydrogen-like densities of oxygen and the densities of fully stripped ions are left out of the analysis due to the moderate temperatures present in EXTRAP-T2R plasmas.

The ionization and recombination rate coefficients are a function of both electron temperature $T_e$ and electron density $n_e$. For the calculations of the helium-like ion densities the line-averaged electron density $n_e$ is measured by interferometry\(^1\), as well as the electron temperature $T_e$ are necessary.

2.2.2 The electron temperature

A technique for estimating the electron temperature inside a plasma is to use the ratios of intensities of lines \(^1\) from the same ionization stage of an impurity \(^1\). Taking the ratio cancels the direct dependence on the ground state density of oxygen of a certain ionization stage and leaves a parameter that depends on the rates of excitation, see equation 2.6. These rates depend on the electron temperature, while they are weakly dependent on the electron density.

For this technique to work well one wants to use sufficiently strong and well isolated spectral lines. In principle, a lot of spectral lines may be used, but the number that fulfills the above mentioned conditions is limited. In typical EXTRAP-T2R plasmas, the lithium-like oxygen, O$^{5+}$, is one of the dominating ionization stages of oxygen (see figure 2.2) and is present over most of the plasma radius. Comparison of figure 2.1 with figure 2.2 shows that a finite particle confinement time $\tau_p$ (as included in figure 2.2) strongly reduces the average ionization degree at a chosen temperature.

\(^1\)The line-integrated electron density $n_e$ is measured with a CO$_2$ interferometer. The interferometer has four possible viewing chords which allows the reconstruction of the density profile \(^1\).
Chapter 2. EXTRAP-T2R

Figure 2.2. The fractional abundances of oxygen as a function of temperature calculated for an electron density $n_e$ of $1 \times 10^{13}$ cm$^{-13}$ and a particle confinement time $\tau_p$ of 250 $\mu$s.

Figure 2.3. Grotrian diagram for all levels of O$^{5+}$. Indicated are the 150.1 Å and 1032.0-1037.6 Å transitions which are used to obtain the electron temperature.
The strongest lines in the spectrum of this ionization stage are usually the ones which end in the ground state, the so-called resonance transitions. In this case, the $2s^2S-3p^2P^0$ and $2s^2S-2p^2P^0$ transitions at 150.1 Å and 1032.0-1037.6 Å, respectively, are suitable. See figure 2.3.

![Figure 2.4](image.png)

**Figure 2.4.** The transition rates for the spectral emission at 150.1 Å and 1032.0-1037.6 Å for two electron densities.

The $2s^2S-3p^2P^0$ transition at 150.1 Å has a pronounced dependence on the electron temperature $T_e$ below 300 eV as shown in figure 2.4. The $2s^2S-2p^2P^0$ multiplet at 1032.0-1037.6 Å is on the other hand more or less independent on the electron temperature and serves as a reference. Figure 2.5 on page 14 illustrates the line ratio of the 150.1 Å to 1032.0-1037.6 Å transition which is a function of the electron temperature. Hence, the ratio can be used to estimate the electron temperature in the plasma.
Figure 2.5. The line ratio of 150.1 Å to 1032.0-1037.6 Å as a function of the electron temperature.
Chapter 3
The role of radial distributions

Gradients in the profiles, i.e. the radial distributions, of plasma density and temperature lead to transport of particles and energy. For example, keeping the heat towards the center of a fusion plasma creates a gradient in the temperature. If this gradient becomes too steep, the heat will move towards the cooler, outer edge. This process of heat transport has long prevented the demonstration that fusion on the large scale would make a capable energy source. The occurrence of gradients in the radial distributions can, however, also be beneficial. Very steep temperature gradients lead to advanced confinement regimes. Examples are the H-mode [18] and internal transport barriers [19] in tokamaks. Pulsed poloidal current drive (PPCD) [20, 21] in an RFP leads to improvement in confinement accompanied by a steepening in the electron temperature profile [22].

Plasmas show similarities to sandpiles with density and temperature gradients corresponding to the steep sides of the sandpile [23, 24]. When sand grains are dropped onto the pile, some of them will cause avalanches of sand to fall away from the pile. The case is the same with plasmas. As heat begins to move outward, it too may create avalanches. The sandpile provides thus an illustrative model for the studies of gradients in advanced confinement regimes.

3.1 The electron temperature

The electron temperature $T_e$ in EXTRAP-T2R is measured by two different and independent diagnostics. A single shot, single point Thomson scattering system [17, 25, 26] measures the on-axis electron temperature $T_e(0)$ using a ruby laser. The laser beam is shot horizontally (from the outboard) through the center of the plasma. The electrons scatter this light in all directions. Due to the velocity distribution of the electrons this light will be Doppler shifted. The light that is scattered perpendicular to the direction of the laser path is collected with a fiber. The collected light is guided into a spectrometer which produces a spectral image of this scattered light. The Doppler shift of the scattered light is then finally used to determine the temperature along the laser beam. Values of the central electron temperature $T_e(0)$ can be measured from 10 eV up to 500 eV with an expected average accuracy of 10-15%. The other estimation of the electron temperature is the time-resolved line-averaged electron temperature using the 150.1 Å to 1032.0-1037.6 Å line ratio of the VUV emission from O$^{5+}$. 
In EXTRAP-T2R plasmas the different ionization stages of oxygen dominate in different parts of the plasma (see figure 3.1) where they distribute themselves as concentric shells: the lowest ionization stage at the edge and the highest ionization stage is reached in the center. The radial profile of the electron temperature, the transport coefficients and the particle confinement times determine the thickness of these shells. The effective volume from which the radiation, from for example $O^{5+}$, is detected is therefore normally much smaller than the total plasma volume along the line of sight viewed by the VUV spectrometer. Without some kind of radial resolution of the emission profile, for example by tomography, the estimations of the line-averaged electron temperature or oxygen densities (by their electron temperature dependence) are sensitive to the assumptions made.

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{fig3_1}
\caption{The radial distributions of the different ionization stages of oxygen computed by an one-dimensional onion skin collisional-radiative (OSCR) model [27, paper V]. The vacuum vessel wall is indicated by the vertical dashed line at $r = 0.183$ m and gray area.}
\end{figure}

Comparison of the electron temperature measured by the VUV spectrometer and the Thomson scattering shows that the two diagnostics agree for some plasma scenarios, but disagree for others [28, paper II]. The estimation of the electron temperature by the VUV seems to be asymptotic towards a value of 100 eV, as shown in figure 3.2. One basic assumption in order to do quantitative spectroscopy on emitted light is that every photon emitted along the line of sight in the direction of the observer, is recorded and not absorbed by the plasma. The lines from the plasma are said to be optically thin in such a case. However, the problem of re-absorption may arise under certain plasma conditions. Under the normal operational conditions of EXTRAP-T2R the emission lines from the plasma are optically thin [29] and, hence, do not explain the discrepancy between the electron temperature measured by the VUV spectrometer and the Thomson scattering. This could be an indication that $O^{5+}$ is moving outwards
3.1. The electron temperature

to another radial position and reflects where O$^{5+}$ is excited. Hence, the lack of information on the position and thickness of the radiating shell limits the determination of the central electron temperature $T_e(0)$ by using the ratio of line intensities.

The intensities of the 150.1 Å and 1032.0-1037.6 Å spectral lines in O$^{5+}$ depend on the radial profiles of the ground state density $n_{z,1}$ of O$^{5+}$, the electron density $n_e$ and the electron temperature $T_e$,

$$I = n_{z,1} n_e q_{ij}(T_e, n_e) A_{ij} \sum A_{ij}$$  \hspace{1cm} (2.6)

The ratio of the intensities of these lines cancels the direct dependence on the ground state density of O$^{5+}$ and the electron density. The 150.1 Å to 1032.0-1037.6 Å ratio only depends on the rate coefficients for electron impact excitation $q_{ij}$ which predominantly depends on the electron temperature (see figure 2.5). The different electron temperature dependence of both transitions allows the determination of the (line-averaged) electron temperature, but also affects the effective volume from which the radiation originates.

When the electron temperature profile is flat, the emissivity profiles for the 150.1 Å and 1032.0-1037.6 Å transitions extend over the same or similar plasma radius. The line-averaged electron temperature, by using a ratio of line intensities, is then virtually in agreement with the on-axis electron temperature $T_e(0)$. A more peaked electron temperature profile with the same on-axis electron temperature $T_e(0)$ reduces the region in the plasma where the electron energies are sufficient to excite the 150.1 Å transition, which requires approximately 80 eV. However, the energy to excite the 1032.0-1037.6 Å multiplet is just about 12 eV. The line integrated intensity with a
more peaked electron temperature profile will consequently show a stronger decrease in the 150.1 Å spectral line than in the transition at 1032.0-1037.6 Å and, hence, a lower intensity ratio. This in turn will be interpreted as a lower electron temperature than the actual on-axis temperature. This is illustrated in figure 3.3.

At first, the lack of spatial information looks to be a disadvantage, but it can also be used to provide important information. The difference in the line-averaged and central electron temperatures measured by the VUV spectrometer and the Thomson scattering, respectively, makes changes in the electron temperature profile transparent, even though the actual profile is not measured on EXTRAP-T2R. The model is described in paper II. However, not only the intensity of a spectral line depends on the spatial distribution of certain quantities as we will see in the following section.

### 3.2 Confinement properties

A quality parameter for a fusion plasma is the so-called beta-value, \( \beta \), and measures the efficiency of the magnetic field to confine a plasma of a certain pressure. This dimensionless ratio between the plasma pressure \( p \) and the magnetic pressure \( B^2/(2\mu_0) \) characterizes any kind of magnetic confinement configuration and is limited by stability conditions. The poloidal \( \beta \) is defined as

\[
\beta_0 = \frac{\langle p \rangle}{B_0^2/(2\mu_0)} = \frac{16\pi^2}{\mu_0 T^2} \int_0^a r(n_e T_e + n_i T_i)dr
\]

and depends on the radial distributions of the densities and temperatures of the electrons and ions, respectively. In many experiments the spatial information of ions, and sometimes even of the electrons, is not present and certain assumptions have to be made.

Another important aspect of the efficiency of the RFP configuration is given by the power balance. For typical RFP experiments, the loop voltage derived from classical resistivity is lower than the applied resistive loop voltage \( V_{res} \). The origin of this missing portion of the loop voltage, referred to as non-Spitzer or anomalous loop voltage, has been unclear and there exist many explanations for this variation [30, 31]. Furthermore, a loop voltage \( V_k \) is required to sustain the RFP equilibrium. This voltage is a function of the current density, magnetic field and, similar to the so-called Spitzer loop voltage, classical or Spitzer resistivity \( \eta_S \) given by

\[
\eta_S = 3.04 \times 10^{-5} \frac{\ln \Lambda Z_{eff}}{\gamma T_e^{3/2}}
\]

with \( \gamma \) a shape factor obtained from the plasma pressure and \( \ln \Lambda \) is the so-called Coulomb logarithm and has a value of approximately 15 for fusion relevant plasmas.

The Spitzer resistivity \( \eta_S \) has a radial dependence from the electron temperature \( T_e \) and \( Z_{eff} \). In (large) experiments, the electron temperature as a function of the radius can be measured by multi-points Thomson scattering system. At EXTRAP-T2R, a single shot, single point Thomson scattering system unfortunately only allows the measurement of the on-axis electron temperature \( T_e(0) \).

The profile of the average ion charge is difficult to measure in RFP’s and one way to circumvent this problem is to sum up all the radial profiles of impurity ions estimated from simulations (see figure 3.4) or transport calculations. The results from transport calculations show that the spatial dependence of \( \eta_S \) is mainly dominated
Figure 3.3. (Left) A flat electron temperature profile leads to similar emissivity profiles for the 150.1 Å and 1032.0-1037.6 Å transitions and the line-averaged electron temperature $T_e$(VUV) is then virtually in agreement with the on-axis electron temperature $T_e(0)$. (Right) A more peaked electron temperature profile affects the spatial dependence of the excited state population and the corresponding emissivity. The line-integrated electron temperature $T_e$(VUV) will consequently be lower than the actual on-axis temperature $T_e(0)$.
by the electron temperature profile and therefore an average, spatially uniform \( Z_{\text{eff}} \), based on the VUV data, can be used [32].

![Figure 3.4. The simulated profile of the average ionic charge \( Z_{\text{eff}} \) computed by the one-dimensional onion skin collisional-radiative (OSCR) [27, paper V] code with 5% of oxygen in the plasma.](image)

### 3.3 Pulsed poloidal current drive

Recent RFP experiments show that major improvements in confinement are possible in conditions with non standard operation which can be related to changes in magnetic profiles. A current profile technique which is known as pulsed poloidal current drive (PPCD) is an example of such non standard operation. The technique originated and is improved on MST [20, 21, 33] and has been successfully applied in RFX [34], TPE-RX [35] and EXTRAP-T2R [36, paper III].

How does PPCD work? Inducing a poloidal electric field, leads to an auxiliary parallel current in the outer region of the plasma and flattens the radial profile of the current density parallel to the magnetic field, see figure 3.5 on page 21. This brings the plasma closer to the Taylor state and reduces the fluctuation-induced transport in the RFP. In other words, with PPCD we affect the dynamo mechanism and reduce the level of fluctuations. This in turn leads to a decrease in the magnetic stochasticity and improves the formation of magnetic flux surfaces. During PPCD on EXTRAP-T2R the plasma poloidal beta increases to 14%, and the energy confinement time doubles to 380 \( \mu s \) [36, paper III].
3.3. Pulsed poloidal current drive

Figure 3.5. The parallel current density profile versus radius in the outer region with and without the current profile technique which is known as pulsed poloidal current drive (PPCD).
Chapter 4

Hydrogen

In the boundary region of the plasma, the confinement of plasma particles and energy by the magnetic field is degraded. This is due to localized processes which give rise to enhanced losses of charged particles and energy. Losses of thermal energy occur when the magnetic field lines intersect with the wall of the vessel and particle bombardment on the wall releases impurity elements due to processes as physical and chemical sputtering. When the pulse length of a plasma is normally many times the particle confinement time $\tau_p$, the hydrogen atoms (as well as impurity atoms and ions) recycle several times on the plasma facing materials, such as the wall or limiter, during a plasma discharge. Recycling includes de-absorption of absorbed hydrogen, reflection processes and molecule release by recombination and thermalization. Consequently, hydrogen is present as atoms or molecules near the edge and their density and velocity distributions influence the boundary plasma and, indirectly, the plasma and its confinement properties as a whole.

4.1 Line shapes

The line shape of hydrogen emission originating in the plasma boundary is mainly determined by the Doppler and the Zeeman (Pashen-Back) effect. The Doppler shift $\Delta \lambda$ of a spectral line emitted by a hydrogen atom moving with a velocity $v$ in the direction of the observer

$$\Delta \lambda = \lambda - \lambda_0 = \frac{v}{c} \lambda_0$$

leads to a Doppler broadened profile. Spectroscopic investigations often show very asymmetric spectral lines of hydrogen around the unshifted position of the line $\lambda_0$ due to the movement of atoms away from the limiter (or divertor) and the walls. The velocity of these atoms depends on the type of plasma-wall interaction, which produces the neutral atoms, and their measurement consequently helps to identify the different interaction processes. The existence of hydrogen molecules in the edge may give rise to atomic line radiation which complicates the interpretation of the line shapes.

Measurements of the $\text{H}_\alpha$ and $\text{D}_\alpha$ profiles tokamaks [37, 38, 39, paper VI] revealed that at least three populations of hydrogen with different velocities determine the overall line profile. To clarify the nature of the hydrogen release these experimental

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1The time-scale on which particles are lost from the plasma.
results are compared with code simulations as DEGAS [40] or EIRENE [41]. The unshifted and most dominating emission originates from dissociative excitation, while the emission from atoms produced by reflection and charge-exchange leads to broad shifted components. The release mechanisms for hydrogen depend on the device due to the local plasma conditions and require great effort to comprehend the physical processes. But all the release mechanisms considered have one common property: they produce hydrogen atoms with low energies, roughly below 1 eV. These low energy atoms originate from dissociation of highly, vibrationally excited hydrogen molecules which origin is probably at the surface and not in the plasma [42].

4.2 Particle confinement time

The particle confinement time $\tau_p$ may be estimated from the hydrogen influx, which in turn is calculated from $H_\alpha$ measurements. The influx of the hydrogen atoms, $\Gamma_H$, can be determined by using an 0-dimension model [43], which relies on line-average data of the electron density and temperature. However, the balance between the influx of neutral hydrogen and the ionization occurs at the edge of the plasma. To take this into account, the influx of hydrogen can be obtained from a simple model which is based on the radial profiles of temperature and density [32, 43, 44]. In this model, the neutral hydrogen density as a function of the radius is modelled for unit influx. This allows the calculation of the intensity of the $H_\alpha$ line at unit influx and the comparison between the measured and calculated intensity determines the influx of neutral hydrogen.

![Figure 4.1.](image)

**Figure 4.1.** The neutral hydrogen density as a function of the radius is modelled for unit influx, which allows the calculation of the intensity of the $H_\alpha$ line at unit influx. The comparison between the measured and calculated intensity determines finally the influx of neutral hydrogen.

Having found the hydrogen influx, the confinement time in steady-state can be estimated by

$$
\tau_p = \frac{n_p}{\gamma V \Gamma_H - \frac{dn_p}{dt}}
$$

(4.1)

where $\gamma$ is a shape factor obtained from the electron density profile and the proton density $n_p$ is calculated from the electron and ion densities under the constraint of quasi-neutrality; i.e. $n_p = n_e - \sum_{i\neq p} n_i Z_i$. The radial profile of the electron density as well as the electron temperature in this model, are assumed to be of the form
\section*{4.2. Particle confinement time}

\[ \sim (1 - (r/a)^4) \]

Furthermore, it is assumed that the density is varying on a timescale comparable with \( \tau_p \).

A solid model to determine the particle confinement time is a must, but one has to be critical about observations as well. Influxes of hydrogen can be very local and therefore depends on the toroidal and/or poloidal position around the torus. The measurement of H\(_{\alpha}\) radiation is therefore more a local rather than a global measurement. To solve this problem one has to have several lines of sight into the plasma to be able to determine a global value for the particle confinement time.

At EXTRAP-T2, \( \tau_p \) was calculated to be approximately 175 \( \mu s \) from a series of discharges where there were no influx events and the electron density and H\(_{\alpha}\) emission were constant [13]. Similar measurements in EXTRAP-T2R estimate the particle confinement time \( \tau_p \) in the range of 200-400 \( \mu s \) and this result is confirmed by probe measurements [45, 46]. Figure 4.2 shows the translation of the absolutely calibrated intensity for H\(_{\alpha}\) to particle flux using the line-averaged electron density and temperature. The particle flux in turn leads to an estimation of the particle confinement time \( \tau_p \).

The above described method for the measurement of the particle confinement time relies on the influx of neutral hydrogen and hydrogen atoms. However, hydrogen atoms can also find their origin in the dissociation of hydrogen molecules released from the wall [47]. Therefore, corrections are required to estimate the hydrogen influx. Instead of using the conversion factor from photons to atomic fluxes \( \left( \frac{S}{XB} \right)_H \), an effective \( \left( \frac{S}{XB} \right)_{\text{eff}} \) coefficient for atomic hydrogen should be used. This coefficient denotes the ratio of collisional ionization \( S \) to electron impact excitation \( X \) rate coefficients, divided by the branching ratio \( B \). The commonly accepted value of about 15 for electron temperatures between the wide range of 20 to 200 eV is only valid for atomic flux and has to be corrected for the presence of molecules. If a molecular flux is present, the effective \( \left( \frac{S}{XB} \right)_{\text{eff}} \) is given by

\[
\left( \frac{S}{XB} \right)_{\text{eff}} = \frac{S}{XB} \left( 1 + \frac{2\eta \Gamma_{H_2}}{\Gamma_H + 2\Gamma_{H_2}} \right)
\]  

where \( \frac{S}{XB} = 15 \), as accepted in the 20-200 eV range, \( \eta \) describes the number of emitted H\(_{\alpha}\) photons per molecule, which depends on the type of dissociation process and \( \Gamma_{H_2} \) is the calibrated molecular hydrogen flux. The latter can be obtained by summation of all Fulcher-band photons of the Q-branch in the intense Fulcher transition \( (3p^3\Sigma_u^+ \rightarrow 2s^3\Sigma_g^+) \) in H\(_2\) molecules present in the visible range. However, the ratio of molecules to atoms is difficult to determine due to the influence of factors such as surface temperature of the vessel [42] and plasma density [38].
Figure 4.2. The particle confinement time $\tau_p$ calculated by using the model based on the measured absolute intensity of the H$\alpha$ emission, the line-averaged electron density $n_e$ and electron temperature $T_e$ and the derived hydrogen flux $\Gamma_H$. 
Chapter 5

Summary of papers

5.1 Paper I

Initial results from the rebuilt EXTRAP-T2R RFP device

Many thin shell experiments have not shown rotating modes, but instead wall-locked modes. EXTRAP-T2 suffered from these wall-locked modes due to the resistive shell which had a shell penetration time of 1.5 ms. This is comparable with the rise time of the wall-locked modes. A possible key to successfully sustain discharges in a thin shell RFP is to provide favorable conditions for tearing mode rotation to occur. It is possible for this to happen when the shell time is long compared to the current rise time and prevents the occurrence of wall locking during the RFP start-up phase. The idea with the rebuild of the EXTRAP-T2 device was to extend the shell time so the rotating modes would see the shell as a perfectly conducting wall. This makes it possible for the RFP configuration to establish itself before the wall-locked modes have time to grow strong.

The initial results of EXTRAP-T2R show that the goal of the rebuild has been achieved. In this paper, the improved running conditions are described. Mode rotation is observed and the toroidal loop voltage is reduced by a factor of two or three compared to that in EXTRAP-T2.

Spectroscopic measurements in the VUV and visible wavelength region indicate that oxygen is the main impurity in the device while carbon is only present in small amounts. The time traces for these impurities are much more stable and reproducible than previously observed in EXTRAP-T2. The line-averaged electron temperature is in the range of $T_e = 100 - 200$ eV and the effective ion charge is around $Z_{\text{eff}} = 2$; mainly due to the observed reduction of carbon impurity. Photo-multipliers equipped with H$_\alpha$ interference filters show complete ionization of hydrogen after an intensive signal in the beginning of the discharge. The intensity of the signal is higher at the outboard than at the inboard side indicating that the plasma is lying a bit outwards of its symmetry position. This is in agreement with magnetic measurements. The H$_\alpha$ radiation at different toroidal locations indicate that the plasma wall interaction is more toroidally symmetric in EXTRAP-T2R. Moreover, no transient influxes of gas from the wall are observed, as before in connection with the locked mode.

Estimates of the classical Spitzer loop voltage, using the line-averaged electron temperature, the effective ion charge and assuming a flat resistivity profile, gives re-
sistive loop voltages of around \( V_{\text{res}} = 10^{-30} \) V. The reduction in loop voltage observed in EXTRAP-T2R compared to EXTRAP-T2 may be explained by a reduction in the classical resistivity due to a lower value for \( Z_{\text{eff}} \) or a reduction of the non-axisymmetric perturbation of the last closed flux surface (indicated by the improved uniformity of the \( H_\alpha \) emission).

**Modifications afterwards**

All discharges have been characterized by so-called pump-out, i.e. a continuous decrease of density. To overcome this problem gas puff valves utilizing the piezoelectric effect are installed on three toroidal positions. This provides a symmetry as well as a variable spatial dependence of gas feeding. Density control by gas feeding in EXTRAP-T2R enables many studies as shown in references [17, 48].

The five turn primary coil has been reconfigured to a ten turn one which enables long pulse operation, i.e. longer than previously with the five turn ohmic primary. The long pulse operation asks in turn for an active radial equilibrium control. A vertical field system provides this possibility. An active feedback system to stabilize the resistive wall modes\(^1\) is recently installed and the first results are optimistic.

5.2 **Paper II**

**A spectroscopic method to determine changes in the electron temperature profile**

The electron temperature \( T_e \) on EXTRAP-T2R is measured by two different and independent diagnostics. A single shot, single point Thomson scattering system measures the on-axis electron temperature \( T_e(0) \) from 10 up to 500 eV with an expected average accuracy of 10-15%. The VUV spectrometer estimates time-resolved line-averaged electron temperatures by using a ratio of line intensities from the same ionization stage of oxygen, \( O^{5+} \), with an accuracy of circa 10%. This is one of the dominating ionisation stages of oxygen and is present over most of the plasma radius. The \( 2s\,2S-3p\,2P^0 \) transition at 150.1 Å has a pronounced dependence on the electron temperature \( T_e \) below 300 eV. The \( 2s\,2S-2p\,2P^0 \) transition at 1032.0-1037.6 Å on the other hand is more or less independent on the electron temperature and serves as a reference.

Comparison of the electron temperature measured by the VUV spectrometer and the Thomson scattering shows that the two diagnostics agree when the \( T_e \) profile is assumed to be flat, but disagrees with more peaked profiles. Although the electron temperature profile is not actually measured, information about the changes in the profile can be made transparent.

The electron temperature deduced from the line intensity ratio is spatially averaged and depends on the radial profiles of the ion density \( n_i \) of \( O^{5+} \), the electron density \( n_e \) and the electron temperature \( T_e \). A simple model that includes the radial profiles as well as the estimated errors of the actual measurements of these parameters is used to study these effects. The result is unambiguous, only the shape of the electron temperature can fully explain the difference between the two measurements.

\(^1\)Resistive wall mode are magnetohydrodynamic modes that are stable when the surrounding wall is conductive, but are unstable when the wall is resistive.
The sensitivity of the estimates of the changes in the electron temperature profile depends on the measurement of the electron temperature by the VUV spectrometer and the Thomson scattering system. Modelling shows that the shape of the electron temperature profile changes due to the error in the measured electron temperatures (figure 5.1), but it cannot explain the broad range of values of the only free parameter of the modelled electron temperature profile: fitting parameter $\alpha$. Modification of the ion density profile dependence on the central electron temperature (figure 5.2 on page 30) leads to the same conclusion. The discrepancy between the electron temperature measured by the VUV spectrometer and the Thomson scattering is caused by the changes in the electron temperature profile and is the direct result of the spatial dependence of the excited state populations and the corresponding emissivity of the spectral lines.

**Figure 5.1.** The combined uncertainty of the electron temperature by the VUV spectrometer and Thomson scattering system is estimated to 15%. This error slightly adjusts the electron temperature profile, but cannot explain the broad range of values of $\alpha$. 
Chapter 5. Summary of papers

Figure 5.2. The ion density profile \( n_i \) of \( O^{5+} \) is determined with transport calculations for a central electron temperature \( T_e(0) = 100 \text{ eV} \). Other values of \( T_e(0) \) adjust \( n_i(r) \) but have no or little effect on the actual shape of \( T_e(r) \).

5.3 Paper III

Current profile modification experiments in EXTRAP T2R

Pulsed poloidal current drive (PPCD) is a technique where a poloidal current is induced in the edge plasma to sustain the toroidal field reversal against resistive diffusion. This current is otherwise produced by the plasma itself through the dynamo, which requires magnetic fluctuations, leading to a stochastic magnetic field in the plasma. By driving an auxiliary current less is required from the dynamo, and thus a lower level of magnetic turbulence, leading to an improvement in the formation of magnetic flux surfaces and to an increment in the energy confinement of up to 10 times. This is accompanied with a peaking in the electron temperature profile during the PPCD period.

This paper presents the first results of PPCD experiments in EXTRAP-T2R performed at weak and strong reversal of the edge toroidal magnetic field\(^2\). The results show that the PPCD technique improves the plasma confinement properties in a resistive shell RFP. All the previous PPCD experiments were done in conductive shell RFP’s.

During the current profile modification phase, the fluctuation level of the internally resonant tearing \( m = 1 \) modes decreases, while an acceleration in their rotation is observed. The \( m = 0 \) modes are not affected during PPCD, although termination occurs

\(^2\)The plasma equilibrium in the weak reversal is characterized by a reversal parameter \( F = B_y(a)/(B_z) \approx 0.15 \) and pinch parameter \( \Theta = B_y(a)/(B_z) \approx 1.6 \). The strong reversal equilibrium is characterized by \( F \approx 0.65 \) and \( \Theta \approx 2.1 \).
with a burst in the $m = 0$ amplitude. The PPCD phase is furthermore characterized by an increase in the central electron temperature (up to 380 eV) and in the soft X-ray signal. During PPCD, the plasma poloidal beta increases to 14%, and the estimated energy confinement time doubles up to 380 $\mu$s. The reduction in the fluctuation level and the corresponding increase in the energy confinement time are qualitatively consistent with the Rechester-Rosenbluth theory of a reduction of parallel transport along stochastic magnetic field lines [6].

The characteristics of the (impurity) radiation in EXTRAP-T2R during PPCD shows a number of features. It is found that the line intensities of different ionization stages of oxygen and iron change due to the improvement of electron temperature in the center of the plasma during the PPCD phase. In particular, spectral emission from $O^{5+}$ at 150.1 Å disappears almost completely while the 1032.0-1037.6 Å multiplet decreases more moderately. This is consistent with an increase in the central electron temperature and a more peaked radial profile. The radiative power of the emission present in the spectrum between 100 and 1100 Å shows a decrease during PPCD (figure 5.3), similar to observations in RFX. $H_\alpha$ emission at different toroidal positions, decreases as well. The reduction in the $H_\alpha$ radiation indicates reduced plasma wall interaction.

![Figure 5.3](image_url)

**Figure 5.3.** The radiated power between 100 and 1100 Å measured by the VUV spectrometer for a strong reversal PPCD discharge. The vertical dashed line indicates the start of the PPCD.
5.4 Paper IV

Comparison of confinement in resistive-shell reversed-field pinch devices with two different magnetic shell penetration times

The RFP is characterized by the conservation of magnetic helicity resulting in a dynamic configuration. In order to sustain the RFP equilibrium a loop voltage is required. The magnetic field shell penetration time $\tau_s$ has, furthermore, a critical role on the stability and performance of the configuration. Plasma operation in EXTRAP-T2, an RFP with a resistive shell on the dynamo cycle time scale, was characterized by phase-locked internally-resonant tearing modes resulting in destroyed flux surfaces and degraded confinement. Its rebuilt, EXTRAP-T2R has a $\tau_s$ much longer than the relaxation cycle time scale, but still much shorter than the pulse length: i.e. the machine is conductive on the dynamic time scale and resistive on the pulse duration time. Its plasma parameters show significant improvements in confinement compared to the previous device.

- The electron density in EXTRAP-T2 showed a large scatter due to the difficulty to control the plasma-wall interaction and recycling, while the electron density in EXTRAP-T2R is much more reproducible due to the possibility of gas injection.
- The loop voltage level in EXTRAP-T2R is comparable to the best performing RFP experiments and is partly due to the lower $Z_{\text{eff}}$ than in the previous device at comparable $I/N$. It is also expected to be lower with a conductive shell compared to a resistive.

A quality parameter for a fusion plasma is the so-called beta-value, $\beta$, and measures the efficiency of the magnetic field to confine a plasma of a certain pressure. In EXTRAP-T2, the electron poloidal beta $\beta_{\theta,e}$ decreased strongly with $I/N$, or decreased collisionality, consistent with the picture of destroyed flux surfaces. Comparable values, but with a slower degradation of $\beta_{\theta,e}$, are observed in EXTRAP-T2R, which indicates partial restoration of flux surfaces.

The comparison between the resistive loop voltage $V_{\text{res}}$, the Spitzer loop voltage $V_S$ and the loop voltage $V_k$ required to sustain helicity, or the helicity loop voltage, in the plasma volume shows that EXTRAP-T2 had a large loop voltage contribution due to a large scrape-off layer volume as a consequence of the almost complete destruction of flux surfaces by the wall-locked modes. EXTRAP-T2R has a loop voltage comparable to an optimized conducting-shell RFP and suggests that the transport and loss at the surface of helicity is not dominated by a transport parallel to the magnetic field implying good magnetic surfaces in the edge region.

The main explanation for the observations on EXTRAP-T2R is that as long as the dynamic time scale of the relaxation cycle is short compared to the magnetic field shell penetration time and the tearing mode rotation is sufficiently fast so that the radial perturbation is suppressed, the transport of helicity at the surface is not increased for a resistive shell RFP.

An interesting feature is the effect the electron temperature profile on the Spitzer resistivity $\eta_S$ and, indirectly, on the Spitzer loop voltage $V_S$ and the helicity loop voltage $V_k$. In EXTRAP-T2R, an electron temperature profile of the form $\sim (1 - (r/a)^4)^4$ results in a Spitzer loop voltage which is slightly below the applied voltage and a helicity loop voltage that is more or less equal to the applied voltage. A more steep profile would lead to an increment in both $V_S$ and $V_k$, where the latter would
Figure 5.4. A comparison of the Spitzer loop voltage $V_S$ (●), the helicity loop voltage $V_h$ (○) and the resistive loop voltage $V_{res}$ in EXTRAP-T2R.

overcome the applied loop voltage $V_{res}$: a nonphysical observation. The choice for the electron temperature profile seems therefore justified.

5.5 Paper V

Radiated power and impurity concentrations in the Extrap-T2R RFP

For the understanding of the confinement properties of an RFP one has to measure and identify all the contributions to the energy balance. The radiative power loss of EXTRAP-T2R plasmas is measured by an 8-chord bolometric array based on a thin gold film detector [49]. Apart from measuring the radiated power, it is also possible to model the radiated power by using a collisional radiative model. These calculations are done considering an onion skin model, i.e. assuming poloidal symmetry, at steady state and includes charge exchange with neutral hydrogen. The model uses as input; the radial profiles of the electron temperature, the electron density, neutral hydrogen and the main impurities. The profiles for the total concentration of carbon and oxygen are assumed to be flat and are 3% and 5% of the electron density$^3$, respectively. The model shows that the densities of C$^{4+}$ and O$^{6+}$ dominate in the center, but that the radiation is expected to come from C$^{3+}$ and especially O$^{4+}$. From the estimated radial profiles of these impurities the radiative power, the emissivity and finally the radial profile of the effective ion charge, $Z_{eff}$, can be determined.

$^3$Values for the impurity concentrations, $n_{O^{5+}} \approx 3 \times 10^{11}$ cm$^{-3}$ and $n_{C^{3+}} \approx 1 \times 10^{11}$ cm$^{-3}$, are estimated by the analysis of the VUV spectra.
Comparison of the simulation with experiment shows a 30% lower simulated total radiative power than the experimental value, but confirms the peaked radiation profile. The lower magnitude of simulated radiation may be due to the neglect of bremsstrahlung, the impact of energetic neutrals onto the detector which do not follow the field lines and the finite particle confinement time of particles, i.e. transport.

5.6 Paper VI

**Toroidal rotation of hydrogen in the RTP tokamak**

The Rijnhuizen Tokamak Project (RTP)\(^4\) [50] studied the transport properties of the plasma under various conditions. The research was mainly concentrated on the transport of energy and particles in the plasma. This was done by disturbing the plasma by gas puffing, electron cyclotron heating and injection of solid hydrogen pellets. The research at Rijnhuizen has resulted in the discovery of transport barriers inside the tokamak plasma [51]. The energy confinement time is determined by layers in the plasma with widely different transport coefficients. These layers seem to be related to gradients in the plasma rotation [52].

At RTP two very high resolution spectrometers, one for the visible light (VIS) [53] and a normal incidence spectrometer (NIS) [54] in the vacuum ultraviolet region were used to study the emission spectra of ionized plasma particles. One of the goals of the research with the two spectrometers was to study the effect of the plasma parameters as current, density and the toroidal magnetic field on the plasma rotation. These plasma parameters have all different effects on the toroidal plasma rotation.

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\text{Figure 5.5. Schematic drawing of the setup of the visible light (VIS) spectrometer at RTP.}
\]

A session especially dedicated to the study of the behavior of neutral hydrogen revealed an unexpected complicated H\(_\alpha\) line profile while monitored in the toroidal direction into the plasma by the VIS. The intriguing line shape can not be explained by simple line broadening mechanisms like natural line broadening, pressure broadening, Doppler broadening, Stark and Zeeman splitting or for high magnetic fields

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\(^4\)RTP ended operation in September 1999.
the Paschen-Back effect. Calculations with the operational parameters of the RTP tokamak show, however, that Doppler broadening must be the most dominant broadening mechanism for hydrogen [55]. Only the Paschen-Back effect could, under the observation conditions, give rise to a detectable broadening of the H$_\alpha$ line.

Fitting of the H$_\alpha$ line profile with Gaussians showed that at least three groups of hydrogen atoms with different velocities must exist. These different groups of hydrogen are due to different collisional processes of hydrogen which can contribute to the H$_\alpha$ emission.

Collisions of hydrogen ions with the wall results in the neutralization of hydrogen ions and producing H$_2$. These molecules detach from the wall and penetrate into the plasma edge where they dissociate and get collisionally excited. This excited hydrogen can consequently contribute to the observed H$_\alpha$ line emission.

By charge-exchange where the momentum of a hot bulk H$^+$ ion is transferred to an excited hydrogen atom it is possible to explain the group of hydrogen atoms which move towards the spectrometer. The radiation of this group of hydrogen atoms can therefore be the observed component with the positive velocity.

The third group of hydrogen atoms we ascribe to collisional processes with H$_2^+$ molecules. By dissociative recombination or dissociative excitation an H$_2^+$ molecule can produce an excited neutral hydrogen atom that has the same toroidal velocity as the H$_2^+$ molecule. This component is the one observed with the negative velocity. This negative velocity can be explained by the origin of the H$_2^+$ ions. We assume the origin of H$_2^+$ ions is at the top of the limiter. In the local electric field close to the limiter complex conditions can appear and even flow of H$_2^+$ in the opposite direction of the rotation of the bulk plasma is very well possible and, hence, the observed velocity is negative.

**Hydrogen studies on EXTRAP-T2R**

The H$_\alpha$ emission on EXTRAP-T2R is studied with the 1.5 m Czerny-Turner spectrometer equipped with an 1180 l/mm grating. The line profile measured in the poloidal
plane can usually be fitted with 3 Gaussians, while observations in the tangential view show a wide splitting of the H$_\alpha$ line into many components. These represent different groups of hydrogen, each with different temperatures and different velocities. Density, plasma current and gas puff show a pronounced influence on the behavior of hydrogen [48].
Chapter 6

Conclusions and outlook

This thesis focuses on the role of radial profiles in plasma spectroscopy and the diagnosis of EXTRAP-T2R plasmas in general. EXTRAP-T2R is a resistive shell reversed-field pinch with a magnetic field shell penetration time much longer than the relaxation cycle time scale, but still much shorter than the pulse length. Its operation is characterized by global plasma parameters that are comparable to those expected for an optimized conducting shell reversed-field pinch of the same size, although the pulse lengths are longer than the shell time. The low level of magnetic turbulence and the good magnetic surfaces in the edge region explain the observed significant improvements in confinement in EXTRAP-T2R compared to the previous device EXTRAP-T2.

Studies on the determination of the central electron temperature by using the ratio of line intensities show the limitations of this technique when the spectroscopic measurements are made with only one line of sight. Without some kind of radial resolution of the emission profile, for example by tomography, the estimation of the line-averaged electron temperature or oxygen densities (by their electron temperature dependence) are too sensitive to the assumptions made. Models may offer a helping hand but to overcome this problem the measurement of the position and thickness of the radiating shells by radially resolved spectroscopy is required. The (re)installation of a five viewing-chord tomographic system to observe the O^{4+} or O^{5+} emission would solve many problems. The observed radial profile of one of the ionization stages of oxygen might serve as input in the one-dimensional onion skin collisional-radiative model and improve the analysis of the radiative power loss of EXTRAP-T2R plasmas as measured by the 8-chord bolometric array.

On the other hand, the use of only one line of sight can also be used to provide important information. The difference in the line-averaged and central electron temperatures makes changes in the electron temperature profile transparent, even though the actual profile is not measured on EXTRAP-T2R. Using the electron density profile, the ion density profile together with rate coefficients for collisional excitation allows the calculation of the line intensity ratio. The electron temperature estimated from the vacuum ultraviolet spectra and Thomson scattering, respectively, give then a tool to determine the effect of the electron temperature profile on the spatial dependence of the excited state populations and the corresponding emissivity of the involved spectral lines. In this model the electron temperature profile is modelled according to $\sim (1 - (r/a)^{\alpha})^{4-\alpha}$ and thus with one free parameter: fitting parameter $\alpha$. As a result of this choice nonphysical profiles for the electron temperature are possible. A
modification of the model to obtain reasonable profiles is a must to take fully advantage of the provided information in the future. Nevertheless, a multi-point Thomson scattering system with a single or double pulse should offer the best solution; it can measure the electron temperature and density profiles and in theory even the current profile \((j\)-profile\).

The replacement of the graphite wall (EXTRAP-T2) by an all metal first wall with molybdenum limiters significantly reduced the amount of carbon in EXTRAP-T2R plasmas and, consequently, oxygen is the dominating impurity. The absence of wall-locked modes together with an all-metal wall explain therefore the relatively low value of the average ion charge \(Z_{\text{eff}}\) and a toroidal loop voltage comparable to the best performing reversed-field pinch experiments. For spectroscopy, on the other hand, these improvements are not so beneficial. The reduction in the amount of impurities limits the emission from the plasma and in turn the diagnostic possibilities of the plasma. Impurity seeding would enhance the radiation from the plasma and substantially improve the quality of the spectroscopic analysis of the plasma. It will also allow new studies. Impurity seeding enables to maintain or even improve the energy confinement at much higher densities and in spite of the increase of radiative power loss. This type of discharge regime in the presence of a radiating mantle is called the radiated improved confinement mode and is obtained on many tokamaks. It will be interesting to check if this enhanced confinement regime can also occur in a reversed-field pinch.

The measurement of the particle confinement time depends on the influx of neutral hydrogen and hydrogen atoms. Hydrogen molecules in the edge complicates the estimation of the hydrogen influx. Hydrogen atoms can namely also find their origin in the dissociation of hydrogen molecules so that the conversion factor from photons to atomic fluxes has to be corrected for the presence of molecules. An estimation for the molecular hydrogen flux is worthwhile trying by using the intense Fulcher transition in \(H_2\) molecules. In addition, this measurement will clarify more about the nature of the hydrogen release and will be fruitful for the analysis of the radiative power loss.
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