PROBE MEASUREMENTS OF FLUCTUATIONS AND TRANSPORT IN REVERSED-FIELD PINCHES

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**Abstract**

Anomalous transport is a general problem in present day magnetic confinement fusion devices where small-scale turbulence deteriorates the plasma confinement. This thesis is aimed at better understanding of the transport processes in the edge region of one type of magnetic confinement device, the reversed-field pinch (RFP). Experimental work has primarily been carried out at the RFP experiments Extrap T1 and T2. The plasma has been studied using various types of active probes positioned in or close to the edge plasma.

The basic plasma parameters and fluctuation properties have been investigated using Langmuir probes. Fluctuations have been studied using a triple probe technique rendering simultaneous point measurements of electron temperature and density as well as plasma potential. A characteristic feature of the fluctuations in the edge plasma of Extrap T2 is the presence of fluctuations with a mode structure that is locally resonant with the magnetic field. These have been studied and their effect on particle and energy transport has been investigated. Further, the effect of non-linear coupling between low-frequency and high frequency edge fluctuations has been addressed.

Hydrogen sensitive solid state devices (Pd-MOS) have been investigated for use as detectors of neutral hydrogen escaping the plasma. Pd-MOS detectors have the potential of acting as miniature hydrogen spectrometers. The small size of a detector would enable measurements not possible with present neutral particle diagnostics. The use of Pd-MOS sensors in fusion devices has previously been demonstrated. In the present work, Pd-MOS capacitors have been used and the robustness to the plasma environment has been investigated.

**Descriptors**

magnetic confinement fusion, Langmuir probes, reversed-field pinch, electrostatic, transport, turbulence.

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Preface

This thesis is mainly based on experimental work carried out on the Extra 
trap T1 and T2 reversed-field pinch experiments at the Royal Institute 
of Technology. However, my scientific career started at the former Manne 
Siegghahn Institute of Physics working with hydrogen sensors. Soon, Lang 
muir probes entered the scene and the last years have been devoted to 
fluctuation and transport measurements with Langmuir probes. This time 
has offered both the feeling of success and despair. The transport mea 
surements on T1 mostly resulted in frustration and in questions like — 
Why am I doing this? The answer was not clear to me until the diagnostic 
was moved over to T2. Suddenly there was a structure in the signals where 
there earlier had been mostly randomness. The structure has resulted in 
this thesis which, finally, is ready.

Research work, especially in the field of fusion plasma physics, requires 
the contribution of many persons and I owe many thanks to my colleagues 
and friends. First I would like to thank Prof. James Drake for his sup 
port and advice throughout this work. I would also like to thank Hen 
rich Berghsaker who introduced me to and supervised my first years in 
the field of fusion plasma research. I am equally grateful to Guoxiang Li who 
guided me in triple probe technique and spectral analysis. Guoxiang spent 
two years at the Alfven Laboratory giving important input for my further 
research. Birger Emoth has generated a pleasant atmosphere which has 
relieved the daily work at MSL. Many thanks go to my collaborators in the 
hydrogen sensor project in Linköping and Padova. Jerzy Brzozowski is 
acknowledged for mastering T1 and his patience with our not-always-well 
working experiments. Thanks go to Gørán Hellblom for his help in the 
probe measurements on T1. The work was made easier by friends like 
Anders Welander, David Larsson, Gunnar Hedin and Lev Ilyinsky. I have 
also had first class technical assistance and I am grateful to the technical 
staffs both at the Manne Siegbahn and the Alfven laboratory for all help 
with mechanical constructions and problems.

Finally, I want to thank my family, Carina and Jacob. You are the most 
important in my life. Jacob, you have also been a great inspiration showing 
true enthusiasm in your newly begun research work. Dad’s coming home!

Stockholm, October 1998

Anders Möller
This thesis is based on the following papers

I H. Bergsäker, A. Möller, G. X. Li, G. Hellblom, J. H. Brzozowski, B. Emmoth and I. Gudowska
Edge Plasma Conditions and Plasma-Surface Interactions in Extrap T1

II A. Möller, H. Bergsäker, G. Hellblom, I. Lundström, A. Spetz, H. Sundgren, M. Bagatin, D. Desideri, N. Pomaro, G. Serianni and L. Tramontin
Hydrogen Flux Measurements with Pd-MOS Capacitors in RFX and T1
In 21st EPS Conference on Controlled Fusion and Plasma Physics, Montpellier (EPS, 1994), Vol. 18B/II, pp. 1352-1355

Characteristics of edge electrostatic fluctuations in the Extrap T1 reversed-field pinch

IV G. X. Li, J. R. Drake, H. Bergsäker, J. H. Brzozowski, G. Hellblom, S. Mazur, A. Möller and P. Nordlund
Correlation Between Internal Tearing Modes and Edge Electrostatic Fluctuations in a Reversed-Field Pinch

V A. Möller
Edge Resonant Fluctuations and Particle Transport in a Reversed-Field Pinch

VI A. Möller and E. Sallander
Electrostatic and Magnetic Measurements of Turbulence and Transport in Extrap T2
submitted to Plasma Phys. Control. Fusion
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Chapter 1

Introduction

1.1 Future Energy Sources

The major energy sources of today all rely on limited natural resources. With an unchanged consumption these will run short within the next century. Therefore new, alternative, energy resources must be exploited in order to secure our future energy supply.

The new energy sources must ideally not rely on any limited resources and must be environmentally safe. There are mainly two energy sources of global importance which meet these requirements; solar energy and nuclear energy. Solar energy, extracted in solar cells, will probably play an important role in the future global energy system. However, in densely populated areas where a more efficient energy production is needed, nuclear fusion is a potential candidate.

Nuclear fusion is the process which powers the stars, including our own sun. The outermost goal of fusion research is to control this process in a reactor for energy production. Fusion potentially promises a clean energy source with virtually inexhaustible fuel resources.

1.2 Nuclear Fusion

Nuclear fusion is the process where the nuclei of two light elements are combined to a heavier nucleus. The fusion is accompanied by the release of large amounts of energy. The most likely reaction to be used in a fusion
power plant involves two isotopes of hydrogen, deuterium and tritium. Deuterium can be found in ordinary water while tritium cannot be found in nature. Tritium may however be produced from lithium in conjunction with the fusion process. The fuel would thus be sea water and lithium with a supply that would last for millions of years. The fusion products are a helium nucleus and a neutron. The energy transferred to the helium nucleus (20%) will be used to heat the plasma while the energy of the neutron will be extracted and converted to electricity.

For the hydrogen nuclei to fuse, they must collide with high velocities. The most common approach to reach the required particle energies is thermo-nuclear fusion where a hydrogen gas is heated to a high temperature. Random collisions in the gas then lead to fusion reactions. The temperature required for this process is in the order of 100 million °C. At this temperature, the gas is fully ionized in a plasma state. The dynamics of the plasma is dominated by long-range electric and magnetic forces which gives it properties vastly differing from the gas phase.

The plasma must thus first be heated to a high enough temperature to achieve a high fusion reaction rate. The plasma temperature will then be sustained by the fusion reactions; the plasma has ignited. Ignition also requires a high plasma density to have a high enough ion collision frequency. The energy losses from the plasma, through particle losses or radiation, must also be small. These requirements are expressed in the energy confinement time which is defined as the total energy in the plasma divided by the total energy losses. It turns out that in the parameter regime where a fusion reactor most probably will operate, i.e. at a plasma temperature of 10-30 keV\(^1\), the fusion reaction rate increases about quadratically with the ion temperature. Therefore, the fusion power yield depends on the fusion triple product which is the product of the ion density, ion temperature and the energy confinement time. Detailed calculations show that the triple product must exceed about \(7 \times 10^{21} \text{ m}^{-3} \text{ keV s}\) for the plasma to ignite [1].

The hot plasma must be contained and prevented from contact with any solid surfaces. An approach to this problem is to control the plasma using a magnetic field. Different concepts exist for the realization of the magnetic container where the best developed configuration of today is the tokamak. Recent experiments at the JET\(^2\) tokamak have demonstrated

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\(^1\)In plasma physics the temperature is commonly measured in electron volts (eV). 1 eV corresponds to approximately 10,000 °C.

\(^2\)Joint European Torus, Abingdon, UK
1.3 Motivation and Outline

The processes causing transport of particles and energy across the confining magnetic field are not yet fully understood. Since the transport can not be explained by classical diffusion through particle collisions it is commonly referred to as anomalous transport. Much experimental evidence exists to the effect that this transport is caused by small scale turbulence. In the reversed field pinch as well as in the tokamak, results on several experiments have shown that the particle transport in the edge plasma is driven by electrostatic fluctuations. However, the cause of these fluctuations has not yet been clarified. The energy transport in the reversed-field pinch edge plasma is still an open question since it has not been able to explain it with magnetic or electrostatic fluctuations.

The present thesis is aimed at a better understanding of the transport processes in the edge plasma of the reversed-field pinch. The work is primarily focused on the role of electrostatic fluctuations in driving particle and energy transport. The fluctuations are studied using Langmuir probes since these supply time resolved point measurements of parameters relevant in the transport studies. Further, solid state hydrogen sensors are explored as possible detectors of neutral hydrogen from the plasma which may affect edge fluctuations and energy transport.

The rest of the thesis is organized as follows. Chapter 2 gives a background to magnetic plasma confinement specially aiming at the reversed-field pinch configuration. Chapter 3 gives a brief description of the T1 and T2 plasma experiments where the major part of the experimental work presented in this thesis has been carried out. Langmuir probe theory and its applications are discussed in Chapter 4. Methods for spectral data analysis are described aiming for measurements of electrostatic fluctuation driven transport. Chapter 5 deals with solid state hydrogen sensors applied for plasma diagnostics. The original research work presented in six papers is summarized and discussed in Chapter 6. Finally, conclusions
and some suggestions for further research work concerning transport in RFPs are given in Chapter 7.
Chapter 2

Magnetic Confinement

This chapter gives an introduction to magnetic plasma confinement. The physics that is discussed is applied in the last section to the reversed-field pinch.

2.1 Confinement

Since the particles in the plasma are electrically charged, a magnetic field can be used to compress the plasma and to isolate it from the vessel walls. Therefore the concept is called magnetic confinement. The particles in the plasma gyrate around the magnetic field lines and are thus confined perpendicular to the field. The particles can still move freely along the field lines whence the magnetic field must be closed to avoid end losses. The only geometrical shape in which a plasma can be confined by a closed magnetic field is a torus. Therefore the best developed confinement schemes of today, including the RFP and the tokamak, are toroidal devices. A schematic picture of a toroidal plasma is shown in Fig. 2.1. The figure defines the major radius \( R \) and the toroidal coordinate system \( r, \theta, \phi \) where \( r \) is the minor radius and \( \theta \) and \( \phi \) are the poloidal and toroidal coordinate directions. The ratio between the major radius and the minor radius is defined as the aspect ratio. The minor radius of the last closed flux surface (LCFS) i.e. the outermost flux surface which is not in contact with any solid surface is customarily denoted by \( a \).

In the tokamak, a toroidal current is induced which both heats and confines the plasma. However, for stability reasons, a strong toroidal field \( B_\phi \)
Figure 2.1: The toroidal coordinate system is $r, \theta, \phi$ where $r$ is the minor radius, $\theta$ is the poloidal angle and $\phi$ is the toroidal angle. Further, the major radius $R$ is defined.

is necessary. This is induced through toroidal field coils that surround the plasma. A key parameter describing the stability of the tokamak plasma is the safety factor $q$ defined by

$$q(r) = rB_{\phi}/RB_\theta.$$  (2.1)

For an individual field line, $q$ is the number of toroidal turns it makes in one poloidal turn. Plasma stability requires that $q > 1$ which puts a limit on the poloidal magnetic field and thus also on the plasma current. The toroidal field that can be applied is limited by material constraints in the toroidal magnetic field coils. The amount of Ohmic heating that can be applied in the tokamak is thus limited and auxiliary heating systems must be used to heat the plasma to ignition temperature.

Another important parameter is the $\beta$-value defined as the ratio be-
2.2. DRIFT AND TRANSPORT

tween the total energy in the plasma and the energy in the magnetic field. The \( \beta \)-value thus describes the efficiency of the magnetic field in confining the plasma.

2.2 Drift and Transport

Spatial gradients in the magnetic field will cause particle or plasma drifts perpendicular to the magnetic field. Pressure gradients \( \nabla p \) will cause a diamagnetic drift perpendicular to the gradient and to the magnetic field

\[
v_{\text{dia}} = \frac{B \times \nabla p}{qnB^2}
\]  

(2.2)

where \( q \), in this case, is the electrical charge of the particle and \( n \) is the particle number density. Since electrons and ions will drift in different directions there is also a diamagnetic current associated with the drift. The \( \mathbf{E} \times \mathbf{B} \) drift is, as suggested by its name, caused by a perpendicular electric field. The drift velocity is given by

\[
v_{\mathbf{E} \times \mathbf{B}} = \frac{\mathbf{E} \times \mathbf{B}}{B^2}.
\]  

(2.3)

Electrons and all ionic species drift with the same velocity.

In any magnetic confinement scheme, the different drift motions must be limited in the direction perpendicular to the minor radius. The particles will thus not follow a single field line but be locked to a magnetic surface\(^1\). If there were no collisions, particles would be confined on a magnetic surface in principle indefinitely. However, random collisions in the plasma will lead to cross field diffusion and a limited confinement. With a classical approach, individual particles diffuse in a random walk process with the step length of the Larmor radius \( \rho \propto B^{-1} \). With the known step length, together with the collision frequency it is possible to derive a diffusion coefficient. The perpendicular (with respect to the magnetic field) diffusion coefficient calculated in this classical way will be proportional to the inverse square of the magnetic field strength. However, the diffusion coefficient found already in early fusion experiments showed a scaling \( D_\perp \propto B^{-1} \) and moreover the experimental \( D_\perp \) exceeded the classical diffusion coefficient by orders of magnitude. This high transport was

\(^1\)The necessary condition is that the average radial drift is cancelled out.
referred to as anomalous transport. Several explanations have been proposed among them are magnetic field errors, static electric fields causing radial drifts and micro-turbulence. Indeed, minimization of magnetic field errors has led to a significant improvement of confinement in modern fusion experiments. However, the transport level is still anomalously high and today small scale turbulence is regarded as the main cause [2,3].

Electrostatic or magnetic fluctuations in the plasma give rise to particle and energy transport across the average magnetic field [4]. Electrostatic transport arises from a fluctuating perpendicular electric field $\tilde{E}_\perp$ which gives rise to a fluctuating $E \times B$ drift. If these velocity fluctuations are correlated with a density fluctuation, e.g. such that the plasma is denser when moving radially outwards than when moving inwards, a net transport of particles will arise. Similarly, correlated pressure fluctuations and velocity fluctuations will generate a net energy transport. The transport fluxes of particles $\Gamma_{es}$ and energy $Q_{es}$ due to electrostatic fluctuations will thus be [5]

$$\Gamma_{es} = \langle \tilde{P}_e \tilde{E}_\perp \rangle / B$$

$$Q_{es} = \frac{3}{2} \langle \tilde{P}_e \tilde{E}_\perp \rangle / B$$

where the tilde marks the fluctuating component of the signal. Since this transport results from $E \times B$ drift, it is intrinsically ambipolar, i.e. electron and ion fluxes are equal.

Magnetic fluctuations may lead to net cross-field transport fluxes if there is a parallel flux of the quantity. Correlated fluctuations in the parallel current $\tilde{j}_i$ will lead to a cross field particle transport while correlation of the parallel heat flux $\tilde{Q}_||$ with $\tilde{B}$ will give a cross field energy transport:

$$\Gamma_m = \langle \tilde{j}_i e \tilde{B}_\perp \rangle / (eB)$$

$$Q_m = \langle \tilde{Q}_|| \tilde{B}_\perp \rangle / B .$$

Magnetic fluctuations thus only give rise to transport if there is a parallel transport and thus parallel gradient present. The higher parallel velocity of the electrons will cause the electron flux to be larger than the ion flux, i.e. the transport is not ambipolar. Magnetic particle transport will therefore result in a positive charge build up in the plasma core. The (ambipolar) electric field thus generated acts to equalize the two fluxes. It
should be noted that the terms "electrostatic fluctuations" and "electrostatic transport" are used to label fluctuations in potential, temperature and density and transport caused by these fluctuations according to Equations 2.4 and 2.5. It does not say anything about the source of the fluctuations, which may arise from an electromagnetic mode.

Fluctuations may thus cause transport. A fluctuating component $x$ can generally be written as a sum of its Fourier components $X$. In toroidal geometry the wave number may be expressed using the poloidal and toroidal mode numbers $m$ and $n$

$$x(\theta, \phi, t) = \sum_{m,n} X_{m,n} \exp\{i \omega t - m \theta - n \phi\}.$$  

(2.8)

A mode is resonant with the magnetic field if the perturbation is constant along a magnetic field line, i.e. $k \cdot B = 0$. This may also be written

$$m/n = -q(r).$$  

(2.9)

Surfaces where $m$ and $n$ are integers, i.e. $q$ is a rational number, are particularly susceptible to instabilities. In the work contained in this thesis, mode numbers are measured by a two-point correlation technique rendering the propagation direction of the measured fluctuations. Both $m$ and $n$ numbers can therefore be positive or negative depending on the direction of propagation. The sign of the quota $m/n$ determines the helicity of the mode.

## 2.3 Plasma-Surface Interaction

The aim of magnetic plasma confinement is to isolate the plasma from the vessel walls. However, interaction between the plasma and the wall of the plasma container is unavoidable. In the D-T reaction 20% of the fusion power goes to the helium nuclei and this power must be continuously removed from the plasma either through particles or through electromagnetic radiation. Further, the helium ash must be removed from the plasma in order not to quench the fusion process.

The plasma-wall interaction is normally concentrated to a certain region [6]. This is done in the form of a limiter or a divertor. A limiter is simply a solid edge which scraps off the plasma extending beyond $r - a$. The limiter is thus in contact with the last closed flux surface so that material released from the limiter can penetrate directly in to the confined plasma.
region. This is avoided with a divertor where the edge magnetic field lines are diverted so that the plasma-surface interaction is concentrated at divertor targets in a special chamber. The region outside the LCFS is called the scrape-off layer (SOL). The parallel particle losses in the SOL is proportional to the plasma density causing the density to fall off exponentially with the minor radius. Also the temperature has an exponential decay and these gradients are characterized using the decay lengths $\lambda_n$ and $\lambda_T$ for density and electron temperature respectively. These are defined as the inverse of the normalized derivative, e.g. $\lambda_n = (d \ln n_e/dr)^{-1}$.

Particles which hit the walls will sputter, i.e. erode, materials from the walls which will enter the plasma. These impurities will dilute the hydrogen plasma and also increase the radiation power losses from the plasma.

### 2.4 The Reversed-Field Pinch

The reversed-field pinch [7,8] (RFP) is a toroidal configuration just as the tokamak. However, the toroidal magnetic field is weaker and of the same order of magnitude as the poloidal field. The plasma exists in a relaxed state close to a minimum energy state [9]. The toroidal magnetic field at the plasma edge is reversed with respect to that in the plasma core, motivating the name of the configuration. Typical radial profiles of the toroidal and poloidal magnetic fields in the RFP are shown in figure 2.2. The magnetic surface where the toroidal field vanishes is called the reversal surface. The RFP is stabilized by having a large magnetic shear, i.e. $d \ln q/dr$. However, stability also requires that the plasma is surrounded by a close-fitting conducting shell.

Interest in the RFP configuration was motivated by a high theoretical potential $\beta$ limit. Stability analysis of the reversed-field pinch implies possible $\beta$-values of more than 30% [10]. Further, since the magnetic fields in an RFP are generated by currents in the plasma there is no intrinsic limit on the plasma current, which in principle could enable ohmic plasma heating to ignition.

The toroidal magnetic field in the RFP is sustained over times longer than the magnetic diffusion time. This requires a mechanism for production of toroidal flux. The mechanism is referred to as the RFP dynamo. There are mainly two different theories explaining the dynamo; the ki-
2.4. THE REVERSED-FIELD PINCH

![Graph showing radial profiles of toroidal and poloidal magnetic fields in the RFP. The reversal surface is situated at $r/a = 0.85$.]

Magnetic dynamo theory (KDT) and the MHD$^2$ dynamo theory. In the KDT model, electrons are assumed to be accelerated in the central region by the toroidal electric field [11]. The electrons diffuse radially outwards on stochastic field lines obtaining a poloidal velocity as they follow the average magnetic field. A poloidal current is thus generated which sustains the toroidal magnetic field. On the other hand, the MHD dynamo theory explains the dynamo with correlated velocity and field fluctuations which give rise to the electric field sustaining the toroidal magnetic field.

The RFP equilibrium may be characterized by the reversal parameter $F$ and pinch parameter $\theta$ defined as

$$F = \frac{B_\phi(a)}{\langle B_\phi \rangle} \quad (2.10)$$

$$\theta = \frac{B_\theta(a)}{\langle B_\phi \rangle} \quad (2.11)$$

Here, $B_\phi(a)$ and $B_\theta(a)$ are the toroidal and poloidal magnetic fields at the edge while $\langle B_\phi \rangle$ is the toroidal field averaged over the poloidal cross-section. Figure 2.3 shows a profile of the inverse $q$ calculated with the magnetic field profiles in Fig. 2.2 and the aspect ratio of Extrap T2 (cf. chapter 3). The inverse $q$ is equal to the resonant $n$ of an $m = -1$ mode.

$^2$Magneto Hydro Dynamics. Theory where the plasma is treated as conducting fluid. The dynamics of the RFP is well described by MHD code simulations.
Figure 2.3: The inverse $q$ profile in an RFP with the magnetic field profiles shown in Fig. 2.2 and the aspect ratio of Extrap T2.

The magnetic fluctuations in the RFP are dominated by tearing modes which are internally (inside the reversal surface) resonant, i.e. $m/n < 0$. These are $|m| - 1$ modes with typical toroidal mode number in the range $|n| = 2R/a$. The value of the safety factor on the edge is typically $q(a) = 0.025$ so that externally (outside the reversal surface) resonant modes have $m/n < 1/40$.

The large magnetic fluctuations in the RFP have a major influence on the radial particle and energy transport. The core plasma may be stochastic with transport driven by electrons diffusing radially on stochastic field lines. Indeed, measurements show that both particle transport and energy transport in the core plasma are driven by the magnetic fluctuations [12-14]. In a plasma with a stochastic magnetic field, field lines connect and reconnect allowing particles to travel radially along the magnetic field [15]. As a result there is the creation of an ambipolar radial electric field which equalizes the ion and electron fluxes. It was shown by Harvey et al. [16] that the strength of this field will be

$$E_r = \frac{kT_e}{e} \left( \frac{1}{\lambda_n} + \frac{1}{2\lambda_T} \right)$$

Measurement of the electric field in the core plasma is difficult and not much data exists on this subject. However experimental data show a positive electric field for $r/a = 0.55-0.85$ supporting the assumption of a
2.4. THE REVERSED-FIELD PINCH

stochastic core plasma [17].

Outside the reversal surface the magnetic field fluctuation driven transport is less important mainly due to the decrease of the magnetic fluctuation level. On the other hand, in the region \( r/a > 0.85 \) measurements on many devices show that the particle transport is driven by electrostatic fluctuations [17-22]. In contrast, the energy transport due to electrostatic fluctuations is low which is why the energy transport in the edge plasma is still an open question. These results can be compared with tokamak results where both the edge particle and energy transport may be accounted for by electrostatic fluctuations [4,23,24].

Concerning the radial electric field, equation 2.12 is only true if there are no other non-ambipolar particle losses present. However, close to the edge there may be a region with closed magnetic field lines but where the ion Larmor radius is larger than the distance to the wall. The ion orbits will thus intersect the wall resulting in an enhanced ion loss. The electrons are still confined on closed field lines which generates a negative electric field in this region [25]. This effect has been observed both in tokamaks [26] and in RFPs [27]. A potential minimum is thus formed close to the wall, a distance of a few ion Larmor radii from the wall. The plasma inside and outside the potential minimum will thus drift in opposite directions due to the \( E \times B \) drift. The velocity shear around the potential minimum causes a decorrelation of the turbulence which may reduce the fluctuation level [28,29]. The anomalous transport may be reduced resulting in a transport barrier [22,30,31].

An asymmetry has been detected in the parallel energy flux in the edge plasma of the RFP. The energy flux is generally higher by approximately a factor 10 in the electron drift direction relative to the ion drift direction\(^3\) [32,33]. This has been attributed to the presence of superthermal electrons existing in the edge plasma. Energetic electrons have also been measured with electron energy analyzers [13,32,34] and target x-ray emission [35,36].

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\(^3\)Electron drift and ion drift directions are used to label the parallel directions. The ion drift direction is direction of the plasma current in the edge region.
CHAPTER 2. MAGNETIC CONFINEMENT
Chapter 3

The T1 and T2 Plasma Experiments

The experimental work which is reported in this thesis has mainly been carried out on the Extrap T1 and T2 reversed-field pinches. Some experiments, presented in paper II, were carried out on the RFX experiment [37] in Padova, Italy.

Extrap T1 is a small and T2 is a medium size RFP. Both have a high aspect ratio. This chapter gives a description of the experiments and the plasma diagnostics in use. The T1 device was shut-down when T2 started operation and much of the diagnostics currently in use on T2 were moved over from T1. Some parameters of the machines are given in Table 3.1.

Table 3.1: Parameters of the Extrap T1 and Extrap T2 devices.

<table>
<thead>
<tr>
<th></th>
<th>Extrap T1</th>
<th>Extrap T2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Radius (m)</td>
<td>0.50</td>
<td>1.24</td>
</tr>
<tr>
<td>Minor Radius (m)</td>
<td>0.057</td>
<td>0.183</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>8.8</td>
<td>6.8</td>
</tr>
<tr>
<td>Shell Minor Radius (m)</td>
<td>0.068</td>
<td>0.20</td>
</tr>
<tr>
<td>Vertical Field Penetration Time (ms)</td>
<td>0.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Pulse Duration (ms)</td>
<td>0.5</td>
<td>12</td>
</tr>
<tr>
<td>Plasma Current (kA)</td>
<td>90</td>
<td>180</td>
</tr>
</tbody>
</table>
Table 3.2: Typical parameters for the T1 and T2 plasmas.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Extrap T1</th>
<th>Extrap T2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global/Central Parameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electron Density (10^{10} m^{-3})</td>
<td>5–15</td>
<td>1–10</td>
</tr>
<tr>
<td>Electron Temperature (eV)</td>
<td>100–400</td>
<td>50–200</td>
</tr>
<tr>
<td>Pinch Parameter, $\theta$</td>
<td>1.6–2.8</td>
<td>1.6–2.1</td>
</tr>
<tr>
<td>Reversal Parameter, $F$</td>
<td>(0.2–1.1)</td>
<td>(0.2–1.1)</td>
</tr>
<tr>
<td>Energy Confinement Time ($\mu$s)</td>
<td>15–30</td>
<td>60</td>
</tr>
<tr>
<td>Particle Confinement Time ($\mu$s)</td>
<td>35–45</td>
<td>200</td>
</tr>
<tr>
<td>Beta Poloidal</td>
<td>10–15%</td>
<td>5–10%</td>
</tr>
<tr>
<td>Edge Parameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electron Density (10^{10} m^{-3})</td>
<td>1–3</td>
<td>0.1–1</td>
</tr>
<tr>
<td>Electron Temperature (eV)</td>
<td>5–20</td>
<td>10–30</td>
</tr>
<tr>
<td>Density Scale Length (nm)</td>
<td>8</td>
<td>14</td>
</tr>
<tr>
<td>Electron Temperature Scale Length (mm)</td>
<td>8</td>
<td>13</td>
</tr>
<tr>
<td>Proton Larmor Radius (mm)</td>
<td>2–5</td>
<td>2–3</td>
</tr>
<tr>
<td>Electron Larmor Radius ($\mu$m)</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Debye Length ($\mu$m)</td>
<td>5–6</td>
<td>10–20</td>
</tr>
<tr>
<td>Mean Free Path (m)</td>
<td>0.05–0.5</td>
<td>2–2.5</td>
</tr>
</tbody>
</table>

3.1 Extrap T1

The Extrap T1 device was in operation until 1995 and mainly operated in RFP configuration. It was a small device with a high aspect ratio $R/a = 0.5 \text{ m}/0.057 \text{ m} = 8.8$ featuring a stainless steel first wall. Figure 3.1 shows a schematic view of the experiment while Table 3.2 summarizes some plasma parameters. The vessel was made out of stainless steel bellows where the inner minor radius of the bellows was 57 mm. The six toroidal diagnostic sections had a minor radius of 59 mm with a poloidal constriction of 56 mm on each side. The diagnostic ports used for probe measurements were parallel with a minor radius and placed 20° either above or below the outer equatorial plane. The inner diameter of the ports was 18 mm. T1 was characterized by a high current density leading to a high heat flux. The maximum heat flux measured in the edge was in the order of 1 GW/m² (cf. Paper I). Among the diagnostics used on the machine was an infrared interferometer for measurements of electron density. Spec-
3.1. \textit{EXTRAP T1}

![Diagram of EXTRAP T1](image)

Figure 3.1: A schematic view of the Extrap T1 experiment.

troscopy diagnostics were used to measure ion and electron temperatures and impurity contents. Measurements of H$_\alpha$ light intensity were used to measure neutral hydrogen influx rendering a global particle confinement time. Passive surface probes were used to study hydrogen and metal fluxes in the edge plasma. A Thomson scattering system was used for measurements of the central electron temperature and density. The magnetic diagnostics included arrays of edge coils used for spatial Fourier analysis of the magnetic fluctuations.
3.2 Extrap T2

Extrap T2 began operation in 1995 and is exclusively operated in the RFP mode. Typical parameters of the plasma in T2 can be seen in Table 3.2. The machine has previously been operated as OHTE at General Atomics, San Diego [38]. It is currently the only RFP which is operated with a resistive shell, i.e. the field penetration time through the shell is shorter than the discharge time. The main objective of the experiment is to study resistive wall modes. These are modes that are unstable due to the fact that the shell which bounds the plasma has a finite resistivity so that the magnetic field can penetrate into the shell. The vessel does not have any discrete limiters but is completely covered by graphite tiles. The size of the machine is $R/a = 1.24 \text{ m} / 0.183 \text{ m}$. Figure 3.2 shows a schematic view of the experiment.

Figure 3.2: The Extrap T2 experiment.
3.2. EXTRAP T2

The vessel wall in T2 is made out of graphite tiles and large amounts of hydrogen may be trapped in the graphite. In a discharge, hydrogen is released from the walls mainly through ion induced detrapping and the plasma density is controlled through a balance between hydrogen implantation and detrapping in the graphite. As a consequence, the discharge parameters strongly depend on the history of the wall. For each discharge, hydrogen is accumulated in the wall resulting in an increasing plasma density for each discharge [39]. To control the density, glow discharges in helium are performed on a regular basis, typically every 10–20 discharges, to purge the wall from hydrogen.

The T2 discharges exhibit toroidally localized perturbations which are stationary in the laboratory frame, i.e. locked to the vessel wall [40]. The resulting localized plasma-wall interaction has a strong influence on the plasma discharges.

Much of the diagnostics in use on T2 were moved over from T1 while it in some cases were also upgraded. The Thomson scattering system was upgraded to cover three radial points at \( r = (0, 52, 103) \) mm. Spectra in the UV and VUV region are now collected several times in a discharge giving time resolved spectra. The magnetic diagnostics contains an array of 192 radial coils distributed in 32 toroidal and 6 poloidal positions. Further, a toroidal array of 16 poloidal loops measures the poloidal voltage. These are positioned outside the shell.
Chapter 4

Langmuir Probe Measurements

This chapter gives a short introduction to Langmuir probe theory with the most important results. More thorough descriptions of probe theory, aiming at fusion plasma applications, can for example be found in references 41 and 42. The probe theory is applied in single, double and triple probe diagnostics. Further, the data analysis methods used for spectral estimation and transport measurements are described. Section 4.7 addresses some experimental considerations and describes the probes that have been operated. Finally, the measurements made on T1 and T2 are discussed.

4.1 Langmuir Probes

A Langmuir probe is simply an electrode immersed in the plasma with or without a bias voltage and represents one of the earliest approaches to plasma diagnostics [43]. Langmuir probes are still one of the most commonly used diagnostics for the edge plasma in fusion devices to measure electron temperature, electron density and plasma potential. Its main advantage has been its simple construction and the relative ease of measuring a potential or a current. The main disadvantage is that the probes perturb the plasma and the interpretation of the measurements is often difficult. Nevertheless, Langmuir probes are widely adopted in studies of
local turbulence and transport [4]. Probes supply a point measurement with good spatial resolution. The low cost of a probe makes arrays with several probe tips possible in order to measure spatial dependence of the fluctuations. The possibility of simultaneous measurements of density, temperature and potential fluctuations also enable information about the relative phase between these fluctuations, which is vital in transport measurements.

4.2 Probe Theory

A characteristic feature of a plasma is its ability to screen out electrical charge. A potential disturbance in the plasma will attract particles of the opposite charge. The cloud of charge accumulation cancels out the potential disturbance which is thus screened from the rest of the plasma. The plasma is said to be quasi neutral and the screening phenomenon is referred to as Debye screening. The typical dimension of the charge cloud is the Debye length, \( \lambda_D \). The length is given by the expression

\[
\lambda_D = \frac{\varepsilon_0 k T_e}{e^2 n} .
\]

A solid surface in contact with a plasma will charge up negatively with respect to the plasma. The reason for this is the mass difference between the electrons and the ions. The main part of the potential difference between the solid and the plasma will be confined to a narrow sheath restricted to some Debye lengths in thickness. The potential distribution close to the probe surface is shown schematically in Fig. 4.1. Outside the sheath there is a volume with a weaker electric field called the pre-sheath. Ions are accelerated in the pre-sheath towards the probe. The sheath edge is defined as the position where the ions reach the ion sound speed \( c_s \) given by

\[
c_s = \sqrt{(kT_e + kT_i)/m_i} .
\]

Matching of the solutions of the Poisson equation in the sheath and the pre-sheath leads to the Bohm sheath criterion for the ion current entering the sheath. The current density will be equal to the ion saturation current density \( j_{sat} \)

\[
j_{sat} = \zeta n_e c_s e .
\]
When the plasma is accelerated towards the probe it is also diluted and \( \zeta \) is the ratio between the ion density at the sheath edge and in the background plasma. In an ideal case with no collisions, ionization or recombination in the pre-sheath and with zero ion temperature we have \( \zeta \approx \exp(-0.5) \approx 0.6 \). The ion current is insensitive to changes of the bias of the probe as long as the bias voltage does not approach the potential of the plasma \( \Phi_p \) when the sheath breaks down. When the probes are close to the floating potential the ion current can be regarded as constant equal to the ion saturation current.

The next step is the electron current to the probe. Both ions and electrons are drifting towards the probe with a velocity of the order of the ion sound speed. Since this velocity is much smaller than the electron thermal speed, the electron distribution function is still close to Maxwellian and the electrons will therefore closely follow the Boltzmann relation

\[
n_e - n_0 \exp \left( \frac{e(\Phi - \Phi_p)}{kT_e} \right)
\]

(4.4)

where \( n_0 \) is the density far away from the probe where the space potential of the plasma is \( \Phi - \Phi_p \). The total current density from the probe tip,
biased to a potential $\Phi_b$, will be

$$j - j_{sat} \left[ \exp \left( \frac{e(\Phi_b - \Phi_f)}{kT_e} \right) - 1 \right]$$

(4.5)

where the floating potential $\Phi_f$ is the potential adopted by a floating probe, i.e. when the probe current is zero. The voltage drop in the sheath is proportional to the electron temperature.

$$\Phi_p - \Phi_f + \alpha kT_e/e.$$  

(4.6)

The value of $\alpha$ will in an ideal case be $\alpha = 3.3$.

The above equations are derived under the assumption of zero ion temperature and no magnetic field. It is also assumed that all electrons that hit the probe surface are absorbed. Relaxation of these constraints of course leads to modifications of the results. However, these modifications can be limited to the parameters $\alpha$ and $\zeta$. The effect of the magnetic field is determined by the relation of the Larmor radii of ions $\rho_i$ and electrons $\rho_e$ respectively to the probe dimension $d$. In the RFP edge a good approximation is

$$\rho_e \ll d \ll \rho_i.$$  

(4.7)

The effect of the magnetic field on the ion collection will therefore be small while the electrons are strongly affected. The collection area of electrons will be the projection of the probe along the magnetic field. This will have the effect of reducing the value of $\alpha$. Secondary electron emission, or prompt reflection of electrons, from the probe surface will also have a strong reducing effect on $\alpha$. Non-zero ion temperature will also act to reduce the value of $\alpha$.

If there is a plasma flow present, the pre-sheath will be modified causing the factor $\zeta$, and thus the ion saturation current, to change. The plasma flow velocity is often given as the Mach number $M$ defined as the flow velocity normalized to the ion sound speed. Several models exist which relate changes in the ion saturation current to the Mach number. So called Mach probes have been developed which uses the up-down stream difference in ion saturation current to measure the Mach number. A Mach probe consists of two probe tips measuring the ion saturation current which are shielded in between and face opposite directions. The Guns-destrup probe is a further development of the Mach probe [44-46]. This is an array of probes arranged on the circumference of a cylinder looking in several directions.
4.3. SINGLE AND DOUBLE PROBES

The sheath also modifies the heat flux to a surface in contact with the plasma. It is customary to gather the effects of the sheath in the sheath transmission factor $\delta$. It is defined by the relation

$$Q = \delta \times j_{sat} \frac{kT_e}{e}$$  \hfill (4.8)

where $Q$ is the heat flux entering the sheath. For a floating surface, $\delta$ is given by [47]

$$\delta = \frac{2T_i}{T_e} + \frac{2}{1 - \gamma_e} + \alpha$$  \hfill (4.9)

The first term in Equation 4.9 represents the ion energy removed from the plasma while the second term is the energy transported by electrons to the probe surface. The last term accounts for the retardation of the electrons in the sheath since these had a higher energy when being removed from the plasma.

4.3 Single and Double Probes

From Equations 4.3, 4.5 and 4.6 it is clear that a Langmuir probe may be used to measure electron temperature, electron density and plasma potential.

The single probe technique uses one single probe tip with a sweeping bias, using for example the vacuum vessel as reference potential. The electron temperature and density can then be extracted from the acquired current-voltage $I(V)$ characteristic. A problem with this method is that fluctuations in plasma potential and density not can be separated.

A solution to this problem is the double probe technique where the bias is applied between two equal probe tips so that the whole system is floating [48]. From Equation 4.5 it is easily shown that the $I(V)$ characteristic of this system will be [49]

$$j = j_{sat} \tanh \left( \frac{e\Phi_b}{2kT_e} \right)$$  \hfill (4.10)

The probe current is limited to the ion saturation current which eliminates possible probe damage due to high electron currents. The slope of $j$ at the origin is $\partial j/\partial \Phi_b |_{\Phi_b=0} = j_{sat} \times e/2kT_e$. The electron temperature can thus be obtained from the ion saturation current and this slope. To measure the electron temperature using a double probe, it is thus necessary to
Figure 4.2: A double probe characteristic recorded in T2 at $r = 185$ mm. The bias sweep frequency is 1 kHz and the figure shows one cycle.

measure a full characteristic in order to have both the slope in the origin and the current saturation level. Figure 4.2 shows a double probe characteristic obtained in the extreme edge of Extrap T2. The inferred electron temperature and density is $6.5$ eV and $1.7 \times 10^{18}$ m$^{-3}$ respectively.

4.4 Triple Probe Technique

Temperature measurements using the single and double probe techniques requires a sweeping bias voltage which limits the time resolution with these methods. This motivates the triple probe technique where the temperature can be measured with a fixed bias [50, 51]. The triple probe uses a floating double probe together with a single probe tip measuring the floating potential. When the double probe is biased to saturation, i.e. $\Phi_R \gg kT_e/e$, the potential of the positive leg will be $\Phi_+ - \Phi_f + \ln 2 \cdot kT_e/e$. The electron temperature can thus be obtained from measurements of $\Phi_+$ and $\Phi_f$. A triple probe circuit is shown in Fig. 4.3.

When making the double probe characteristic of Fig. 4.2, the floating potential was recorded simultaneously. This allowed for the determination of a triple probe temperature each time the double probe was in saturation. The triple probe temperature obtained in this way was $8$ eV. For probe measurements, this magnitude of uncertainty, i.e. $\pm 20\%$, is typical
and the measured values of 6.5 eV and 8 eV are considered to be in fair agreement. This shows the problem of interpretation of probe data. Similar comparisons have also shown good agreements between double probe and triple probe measurements [52] also in the estimation of temperature fluctuations [53].

4.5 Fluctuation Studies

The triple probe can supply spatially and time resolved measurements of floating potential, electron temperature and electron density which makes it well suited for measurements of plasma fluctuations.

Fluctuations in basic plasma quantities such as density and temperature are present in all fusion experiments. The fluctuations give rise to transport of particles and energy which is why much work has been devoted to measurements of fluctuations. To determine the cause of the turbulence, measurements must be compared with turbulence models and simulations. The basic quantity describing the fluctuations is the frequency resolved (auto)-power spectrum $S(f)$. However, a better understanding may require knowledge of the dispersion relation $k(f)$ or the wave number resolved spectrum $S(k)$. The plasma fluctuations are commonly in a turbulent state where there exists no simple dispersion relation but for each frequency, the fluctuation energy may be broadly distributed in wave number space. The fluctuations are then better described by the combined frequency and wave number spectrum $S(k,f)$.

The power spectrum gives information on the fluctuation power in a
certain frequency or wave number range. It cannot give any information about the relation between different regions of the spectrum. A non-linear interaction between two spectral components may result in a third, phase coherent, component. To detect such a coupling, higher order spectral techniques must be applied. Specifically, with a quadratic coupling between two waves with wave numbers $f_1$ and $f_2$ a new third wave results with wave number $f_3$ where

$$f_3 = f_1 \pm f_2$$  \hspace{1cm} (4.11)

It should be noted that this relation intrinsically is valid for the wave numbers and that Equation 4.11 requires a linear dispersion relation. This coupling may be detected using the bicoherence, which is a third order spectrum. The bicoherence represents the fraction of power at a certain frequency $f_3$ which results from quadratic coupling of two frequencies $f_1$ and $f_2$ [54]. Bicoherence has been used in fusion experiments to detect three-wave coupling both in the wave number [55] spectrum and in the frequency spectrum [56, 57]. It has also been combined with wavelet technique [58] to study short-lived intermittent nonlinear coupling [59]. The bispectral technique is utilized in papers III, IV and VI.

**Spectral Estimation**

This section describes how to estimate $S(k, f)$ using only two fixed probes separated a distance $\chi$. A detailed description of the method may be found in reference 60. Under certain conditions [60] the spectrum $S(k, f)$ can be estimated by $S_i(K, f)$ where $K$ is the local wave number. The local wave number is defined by $K(f) = \theta(f)/\chi$ where $\theta(f)$ is the phase difference between the signals from the two probes. The data to be analyzed is divided in to several records and a wave number resolution $\Delta K$ is selected. For each data record $j$, the local wave number $K_j(f)$ and the power spectrum $S_j(f)$ is calculated. The spectral estimate can then be found as the sum

$$S_i(K, f) = \sum_j S_j(f) \times \delta(K - K_j(f))$$  \hspace{1cm} (4.12)

where

$$\delta(k) = \begin{cases} 1 & \text{if } |k| < \Delta K/2 \\ 0 & \text{otherwise} \end{cases}$$  \hspace{1cm} (4.13)

Each discharge thus contributes to one certain wave number interval for each frequency sample.
4.6. **Transport Measurements**

The average frequency and wave number spectra can now be found from the zeroth order moments

\[ S(f) = \sum_k S_i(K, f) \]  \hspace{1cm} (4.14)
\[ S(K) = \sum_f S_i(K, f) \]  \hspace{1cm} (4.15)

The first and second moments of \( S_i(K, f) \) are the average (power weighted) wave number \( \bar{k}(f) \) and the wave number width \( \sigma_k(f) \).

\[ \bar{k}(f) = \sum_k K S_i(K, f) / S(f) \]  \hspace{1cm} (4.16)
\[ \sigma_k(f) = \left[ \sum_k K^2 S_i(K, f) / S(f) - \bar{k}(f)^2 \right]^{0.5} \]  \hspace{1cm} (4.17)

The method described above is restricted to the determination of the average quantities given above. Fine structure in the wave number spectra will not be resolved [4].

### 4.6 Transport Measurements

The electrostatic fluctuation driven transport is given by Equations 2.4 and 2.5. Experimentally, the transport can be derived from the triple probe data.

To understand the mechanisms driving the flux, it is desirable to know at which frequencies the transport is driven. In a spectral representation, the particle flux may be written [61, 62]

\[ \Gamma_{es} = \frac{1}{B} \sum \hat{n} \hat{E}^*_T - \frac{1}{B} \sum i k_\perp \hat{n} \hat{\Phi}_p^* \]  \hspace{1cm} (4.18)

where the * represents complex conjugate. The flux is written using the potential rather than the electric field. This is motivated since experimentally the potential is often easier to measure than the electric field. The wave number \( k_\perp \) is the perpendicular wave number of the plasma potential. The plasma potential is measured as \( \Phi_p - \Phi_f + \alpha k T_e / e \) which is why it in principal is necessary to know the wave numbers of both the floating potential and the electron temperature. In the experiment it is normally
the wave number of the floating potential that is measured. However, it is commonly assumed that the wave numbers of the floating potential and the electron temperature are equal. Equation 4.18 is a spectral density function. It can be expanded in the form

$$\Gamma_{es}(f) \sim \frac{1}{B} k_{\perp} |\tilde{f}_e| |\tilde{\Phi}_p| |\gamma_{n\Phi}| \sin \alpha_{n\Phi} \quad (4.19)$$

where $\gamma_{n\Phi}$ and $\alpha_{n\Phi}$ are the coherence and phase difference between the density and potential respectively.

Similarly, the energy transport may be written

$$Q_{es} = \frac{3}{2B} \sum \vec{p} \cdot \vec{E}_i \quad (4.20)$$

By expanding $\vec{p}/p - \vec{F}/n + \vec{F}/T$, the energy flux can be expressed as

$$Q_{es} = \frac{3}{2} k_T \Gamma_{es} + \frac{3}{2B} n_e \sum ik_{\perp} k_T \tilde{\Phi}_p. \quad (4.21)$$

This can be put in a similar form as equation 4.19 using the coherence and phase angle between temperature and density fluctuations $\gamma_{T\Phi}$ and $\alpha_{T\Phi}$. The energy flux can also be divided in a convective part $Q_{conv}$ and a conductive part $Q_{cond}$ [63]. The conductive energy flux is the energy in the frame of reference moving with the flow velocity and the two terms may be written

$$Q_{conv,es} = -\frac{5}{2} k_T \Gamma_{es} \quad (4.22)$$

$$Q_{cond,es} = \frac{3}{2B} n_e \sum ik_{\perp} k_T \tilde{\Phi}_p - \Gamma_{es} k_T e. \quad (4.23)$$

### 4.7 Probe Operation

The triple probe measurements on T1 and T2 have been made using Langmuir probe arrays consisting of four probe tips. The individual probe tips were made of refractory metal of 0.5 mm diameter and 2 mm length. On T1 molybdenum was used while on T2 the probe tips were made of tungsten wire. The non exposed part of the wires were protected with alumina ceramic tubes with an outer diameter of 1.2 mm. These tubes were about 10 mm long and fastened in a stainless steel holder. This package was protected by an outer shield mainly against the plasma heat flux. On T1,
this armor was made of stainless steel while on T2 boron nitride was used. This construction avoids problems with conducting film coatings on the insulator areas next to the probe tip. Such films, which may consist of metal/carbon from the machine or metal sputtered from the probe tip, may otherwise act to increase the active size of the probe tip. The four probe tips were mounted in a 2 mm square on T1 and 4.9 mm square on T2. A picture of the probe used on T2 is shown in Fig. 4.4. Figure 4.5 schematically shows the operation of the probe. Two pins are used to measure the floating potential. These are aligned perpendicular to the magnetic field so that the perpendicular wave number of the floating potential may be estimated. The other two pins are connected as a double probe so that a triple probe temperature may be extracted using the averaged floating potential \(\Phi F = (\Phi F1 + \Phi F2) / 2\). This minimizes phase delay errors in the temperature. The probe type has been used on several machines to measure fluctuations and transport [17–19,21,23,64,65]. The ion saturation current density was calculated using the full area of the probe tip. Uncertainty in the length and shape of the probe tip introduces an error which is estimated to be about 10%. The finite size of the probe may in-
Figure 4.5: Schematic figure of the 4-pin probe circuit.

roduce phase errors in the temperature affecting the transport measurements [17, 66]. The wave number of the measured fluctuations is typically less than 70 m−1 leading to \( k d < 0.5 \) with \( d = 7 \) mm being the size of the T2 probe array. This corresponds to a 30° phase error in the temperature measurement. The effect on the transport measurements is less than 10%. Possible errors in the triple probe method are discussed in references 50 and 51.

Measurements on T1 were also made using a combined Langmuir and heat flux probe previously used on another RFP experiment the Eta-Beta II device [67]. The probe head carries three individual probes. Each probe is shielded in order to make directional measurements in the \( \phi-\theta \) plane. Two probes face the same direction while the third probe looks in the opposite direction. One probe in each direction is equipped with a thermo couple so that the temperature increase caused by the integrated heat flux in one discharge can be measured. The time integrated heat flux is calculated from the maximum temperature of the probe tip. It is then assumed that no heat has been conducted from the tip. The average heat flux is found by dividing by the plasma discharge length.

Since the probes are in direct contact with the plasma the probe circuit must be insulated from the data acquisition system. The probe signals were transmitted from the probe electronics to the transient recorders using opto links. The cables from the probe to the electronics were kept short, about 0.5 m. The potentials were adopted for the opto transmitter in a resistive divider while the double probe current was measured over a resistor 0.3–1 Ω.

When measuring the floating potential it is important to have a large
impedance of the probe so that the current drawn is near zero. This is achieved by having

\[ R_m \gg \frac{kT_e}{e \beta_{sat} A_p} \]  \hspace{1cm} (4.24)

where \( A_p \) is the area of a probe tip and \( R_m \) is the impedance to the vessel.

The signals were sampled at 500 kHz before digitization with a sample rate of 1 MHz. The signals on T1 were mainly recorded on 8-bit transient recorders while 12-bit recorders were used on T2. This affects the fluctuation measurements on T1 where the high mode number part of the measured spectra may be affected by bit noise.

All probes were mounted on a shaft which allowed rotation of the probes and translation along a minor radius.

### 4.8 Measurements

The probe measurements on T1 were complicated by the large heat flux in the plasma edge. This limited the region accessible with Langmuir probes to \( r > 52 \text{ mm} \) \((r/a - 0.91)\). Radial profiles were made in both machines by moving the probe from shot to shot. An example is shown figure 4.6 which shows the profile of the plasma potential in the two machines. The figure also illustrates the difference in the accessible regions in T1 and T2. In T2, a potential minimum is found at \( a - r -10-15 \text{ mm} \) while in
Figure 4.7: Electron temperature versus electron density @ r – 173 mm, \( I_p = 150 \text{ kA} \) in T2.

T1 such deep probe insertions were impossible. Figure 4.7 shows electron temperature versus the electron density in T2 measured at \( r – 173 \text{ mm} \) in 150 kA discharges. Each point represents a 2 ms time average in one discharge. The figure shows the range of the database and the low degree of correlation between edge electron temperature and density.

Triple probe measurements were made to study the edge fluctuations and fluctuation driven transport. Figure 4.8 shows typical power spectra of the floating potential. The T1 spectrum is generally broader decaying as \( 1/f^2 \) for high frequencies while the T2 spectrum decays as \( 1/f^3 \). The transport measurements on T1 also suggested that transport was driven by frequencies higher than 500 kHz [68]. The normalized fluctuation levels (ratio of root-mean-square to average value) are large with \( (\langle T_e \rangle / T_e) / (\bar{n}_e / n_e) / (eB_p / kT_e) \) being equal to 0.4/0.6/2.0 on T1 and 0.2/0.6/1.3 on T2.

The database of Langmuir probe measurements built up on T2 contains 1075 triple probe measurements out of a total of 1383 exposures. The primary goal of these measurements was to study edge fluctuations and transport and the results are presented in paper V and VI. Examples of spectral data for one T2 discharge are shown in figure 4.9. The figure shows the average toroidal mode number \( (n - k_B R) \) and mode number width, phase angle differences and cross coherences. Further, the frequency resolved particle and energy fluxes are shown and the mode num-
4.8. MEASUREMENTS

Figure 4.8: Power spectra of the floating potential measured in T1 (dash-dot) and T2 (solid). The T1 spectrum is averaged over 8 discharges while the T2 spectrum shows on discharge.

...ber power spectrum. The mode number width is large with $\sigma_n/n \approx 0.5$–1 for high frequencies indicating a turbulent state of the fluctuations. Close to anti correlation is shown between temperature and potential fluctuations, as has been reported on several RFP experiments [17–19, 21]. The implication is that the temperature fluctuation and the density fluctuation contributions to the heat transport have opposite signs. The $\hat{H}_e$ part is however dominating which is why the $I_{es}$ and $Q_{es}$ spectra are similar in shape. Two mode number spectra are shown integrated from 10–100 and 100–500 kHz respectively. This clearly shows how the fluctuation power is divided in two groups with low $n$, low $f$ and high $n$, high $f$ respectively.

The Langmuir probe data has also been used in studies of plasma-surface interactions [39, 69] and heat flux in the edge plasma [70]. Langmuir probe data have been combined with Thomson scattering data to derive average electron density and temperature profiles [71]. These comparisons show a fair agreement between the electron temperature and density measured with the Langmuir probe and the Thomson data. The edge gradients also render drift velocities which can be compared with spectroscopic measurements [72].
Figure 4.9: Spectral data for one discharge in T2 (also see Fig. 6.1 on page 54). Panel (a) shows the average mode number $n$, (b) the mode number width $\sigma_n$, (c) the phase difference $n_e - \Phi_p$ [solid] and $T_e - \Phi_p$ [dot-dash], (d) Sine of the phases, (e) coherence $n_e - \Phi_p$ [solid] and $T_e - \Phi_p$ [dot-dash], (f) $\Gamma_{es}$, (g) $Q_{es}$ [solid] ($\tilde{n}_e$ part [dash] and $\tilde{E}_e$ part [dot-dash]), (h) mode spectrum: 10-100 kHz [solid] and 100-500 kHz [dot-dash].
Chapter 5

Solid State Hydrogen Sensors

The hydrogen sensor project was performed in collaboration with the Department of Physics and Measurement Technology at Linköping Institute of Technology and Consorzio RFX in Padova. The Linköping group has long experience of molecular hydrogen sensors and all sensors were produced and mounted in Linköping. Sensors were partly exposed in RFX and the electronics used in these exposures was developed in Padova. The first section in this chapter gives an introduction to neutral particle diagnostics in fusion plasmas. Section 5.2 describes the physics of the Pd-MOS sensors for detection of molecular and energetic hydrogen. Section 5.3 describes the sensors and their mechanical interface. The last two sections discuss the ion beam and plasma exposures.

5.1 Neutral Particle Diagnostics

A neutral hydrogen atom entering the plasma has about equal probability of being ionized and undergoing a charge exchange electron transfer with a plasma ion. When a neutral and an ion exchange their charge, the energy of the new neutral is representative for the energy of the plasma ions. The energetic neutral may leave the plasma before being ionized and analysis of the neutrals thus renders information about the ion distribution function. In a machine with a high ion temperature in the edge plasma (e.g. T1, see Paper 1) the neutrals may also carry a large fraction of the total energy transport in the edge plasma affecting the power balance in smaller machines.
CHAPTER 5. SOLID STATE HYDROGEN SENSORS

The neutrals can be detected in a neutral particle analyzer [73]. Low energy neutrals are usually detected using a time-of-flight spectrometer where the neutral beam is chopped and the flight time distribution of each particle bunch is measured. High energy particles may be detected by letting them go through a new charge exchange in a stripping cell. The ions can be deflected depending on their energy and be detected. Even though these techniques are quite straightforward, the detectors are large which limits the flexibility in the measurements.

Neutrals may also be detected using passive probes where the build up rate of hydrogen on a carbon surface is used to measure the neutral particle flux. The saturation level of hydrogen on the surface gives information about the energy of the neutrals [74]. This technique requires that samples are first exposed to the plasma and then transported to a surface analysis facility. The determination of neutral particle flux also requires several samples with different exposure time. The technique does not give any in situ information and the possibility of time resolved measurements is limited.

5.2 Pd-MOS sensors

The hydrogen sensitivity of metal-oxide-silicon devices with a palladium gate (Pd-MOS) was first demonstrated by Lundström et al. in 1975 [75,76]. Today, Pd-MOS detectors sensitive to hydrogen or hydrogen containing gases have been developed. Pd-MOS devices are also used to study catalytic reactions on the palladium surface involving hydrogen since the hydrogen coverage can be continuously monitored [77]. Selective sensors for hydrogen containing molecules such as ammonia, hydrogen sulfide, ethanol and ethylene have also been developed.

Molecular Hydrogen Sensors

An MOS structure consists of a semiconductor, in our case p-doped silicon, with an oxide layer and a metal layer on top, as sketched in figure 5.1. The hydrogen response of Pd-MOS devices arises when hydrogen atoms are adsorbed in the metal-oxide interface. The palladium surface to air is reactive and hydrogen molecules which stick to the surface may be dissociated. The hydrogen can then be absorbed in the metal and rapidly diffuse to the oxide interface. The hydrogen atoms which adsorb at the interface

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Figure 5.1: Schematic figure of an MOS structure.

are polarized and a dipole layer is built up at the Pd-SiO₂ interface. The
dipole strength of this layer is proportional to the surface density of hy-
drogen atoms. The induced voltage causes a decrease of the device flat
band voltage which in turn can be detected as a shift of the electrical de-
vice characteristics, e.g. the \( I(V) \)-curve of an MOS transistor or diode or
the \( C(V) \)-curve of an MOS capacitor. The device saturates with a voltage
shift of 0.5–1 V which corresponds to surface density at the interface in
the order of \( 10^{18} \text{ m}^{-2} \) [78].

Normally, the devices are operated at an elevated temperature, typi-
cally 150°C. The reason for this is to accelerate the dissociation process
on the palladium surface and to prevent \( \text{H}_2\text{O} \) molecules sticking to it. With
a silicon substrate, the operation temperature is limited to about 250°C.
However, if instead silicon carbide is used as the semiconductor material
the operation temperature can be raised to about 700°C [79,80]. The rea-
son for this is the larger bandgap in silicon carbide compared to silicon.

A more detailed description of the basic properties of Pd-MOS sensors
can be found in references 81 and 82.

**Plasma Diagnostic**

In the present work, Pd-MOS devices are used to detect neutral hydro-
gen from a fusion plasma experiment. The sensors are exposed to the
plasma and energetic hydrogen is implanted in the metal film of the Pd-
MOS. The hydrogen is subsequently detected as in a molecular hydrogen
sensor. When using the Pd-MOS as a plasma diagnostic it is no longer desirable to have a reactive gate surface since the device would be sensitive to the neutral gas. Still, it is necessary to have a Pd-SiO$_2$ interface to have polarized adsorption sites for hydrogen. By covering the reactive gate with a layer of a non-reactive material, e.g. silver, gold or silicon, the surface may be made passive and molecular hydrogen is thus prevented from entering the structure, while the hydrogen sensitivity at the Pd-SiO$_2$ interface is preserved.

The response rate of a Pd-MOS molecular sensor operated in air is limited by the catalytic reactions on the palladium surface. This makes it relatively slow with response times in order of seconds or minutes. But, if hydrogen is implanted in the palladium, the response time of the device may be limited by the diffusion time through the palladium layer. At room temperature the diffusion coefficient of hydrogen in palladium is about $10^{-10}$ m$^2$/s [83]. The diffusion time through a 100 nm palladium gate is in the order of 200 $\mu$s while at 150$^\circ$C it has decreased to about 20 $\mu$s. This implies that a covered Pd-MOS can act as a plasma diagnostic supplying time resolved information about the impinging hydrogen flux.

The non-reactive layer can also act as a high pass energy filter much in the same way as the silicon layer on a carbon resistance probe [84]. An array of sensors with over-layers of different thickness could be integrated on the same silicon wafer and act as a miniature hydrogen spectrometer. The small size of the sensor would also make it possible to construct probes looking in different directions etc.

The sensors must also have a sensitivity which gives a detectable bias shift for a typical hydrogen dose. Assuming that 5 mV is the lowest detectable bias shift, the sensors have a sensitivity of about $10^{16}$ m$^{-2}$. The flux of neutral hydrogen from an RFP plasma in T1 is typically in the order of $10^{23}$ m$^{-2}$s$^{-1}$ at the plasma edge [85]. At about 20 mm distance from the plasma it has been reduced by an order of magnitude and a 0.5 ms discharge results in an implanted dose of $0.5 \times 10^{18}$ m$^{-2}$. A hydrogen sensor at this position which absorbs all hydrogen would then respond with a bias shift of about 0.25 V, which is easily detected. In larger experiments, the hydrogen flux is lower but the discharge times are longer giving similar hydrogen doses. The sensitivity is thus well suited for detecting neutrals from the plasma.

Rastasz et al. have demonstrated the feasibility of detection of hydrogen from an ion beam [86,87] or from a plasma [88,89] using both covered and uncovered sensors. For this purpose MOS diodes were used where the
leakage current at constant bias was measured.

5.3 Experimental Apparatus

Samples and Electronics

The experiments were performed using MOS-capacitors. The capacitors have the advantage of being relatively easy to produce and it is therefore easy to make changes and test different structure layouts for the components.

The active capacitor area had a diameter of 1-1.5 mm and an oxide thickness of 150 nm. The palladium gate thickness was 250-300 nm and on some sensors it was covered with 20-100 nm aluminum or gold films. To protect the non-metalized area of the silicon wafer, the oxide outside the active area was made 0.6-1 μm thick. This structure was achieved by first growing a 0.6-1 μm oxide on a p-doped silicon wafer. The oxide was then etched away on the areas intended to form the active capacitor areas. A new 150 nm oxide layer was grown and finally the metal electrodes were evaporated. The diameter of the metal contacts was made about 0.5 mm larger than the hole in the oxide to protect the edges from ion bombardment. This has no significant effect on the operation of the devices since the capacitance of the metal area covering the thick oxide is less than 30% of that in the active area. The maximum capacitance of these devices was in the range 1.5-2.5 nF.

The shift of the device characteristic was measured using two different techniques. The first was a C(V)-regulator which allows monitoring of bias voltage at constant capacitance. The regulator supplies the device with a bias voltage which is controlled via a feed-back system, designed to keep the capacitance of the device constant. The bias voltage is monitored and the translation of the C(V)-curve along the voltage axis can be directly measured. The regulator also has an alternative mode allowing construction of full C(V)-characteristics. The second technique measured capacitance with a saw-tooth shaped bias voltage of 50 Hz. In this way, a characteristic was made every 10 ms. A problem with this technique is hysteresis in the C(V) curve which makes it difficult to compare characteristics made with increasing or decreasing bias. The hysteresis may be caused by movable ions, commonly sodium, in the oxide which lag behind the sweeping bias. An example of this can be seen in Fig. 2 in Paper II.
The measurement of a $C(V)$ characteristic requires that the measuring frequency is higher than the characteristic frequency for minority charge carriers [90]. The excitation of minority carriers increases with temperature which is why the maximum allowable temperature at which the measurement can be done is limited by the measuring frequency. The electronics used here used a signal of 35 kHz which limited the measurements to about 150°C.

**Sample Mounting**

The sensors were mounted in ceramic 8-pin DIP capsules with up to four sensors in the same capsule. Each sensor was exposed through a hole with 1 mm diameter in the capsule lid, 0.7 mm directly over the component. Heating elements consisting of alumina plates with carbon resistance films were mounted on the back of each capsule. A heating current of up to 0.5 A could be applied over two 60 Ω heating elements connected in parallel which enabled heating of the capsule to 200°C. For temperature feedback, a diode was used which was mounted in the capsule together with the sensors. The heating was done without affecting a base pressure of $3 \times 10^{-8}$ mbar in the implantation chamber (cf. below). All connections to the capsule and the heating elements were fastened with a modified polyimide, silver system.

The capsules were mounted on a stainless steel holder. The holder was constructed to minimize heat conduction between the capsule and the stainless steel. The contact points between the capsule and the holder were made small and the supporting parts as thin as possible. The same holder could be used for ion beam implantation experiments and plasma exposures in T1 and RFX. Sensors could thus be used in all three experiments without dismounting the capsule.

**5.4 Ion Beam Calibration**

A low energy accelerator was used to expose sensors to mono-energetic, mass separated beams of hydrogen ions. To reach implantation energies below 100 eV, the retardation system of the accelerator was modified with an extra focus lens. Measurement of the beam current is complicated by the low implantation energy and much work was devoted to this matter.
5.5. **PLASMA EXPOSURES IN T1 AND RFX**

![Diagram](image)

Figure 5.2: The retardation and current measurement system of the accelerator.

When the \(C(V)\)-regulator is connected to the target it is not possible to measure the beam current on target. Therefore, to enable current monitoring during implantation, a metal mesh together with suppressor apertures was inserted in the beam path. A known fraction, about 50%, of the beam current is then measured on the mesh. The retardation, focusing and current measuring system is shown in figure 5.2.

### 5.5 Plasma Exposures in T1 and RFX

Sensors have been exposed in the T1 and RFX reversed-field pinch experiments. In T1, sensors were exposed in 60 kA RFP discharges. A linear feedthrough was used for the exposures, which made it possible to move the sensors along a minor radius 20° below the outer mid plane. The distance from the probe to the plasma edge was varied in the range 23 to 370 mm. The base pressure in the vessel was about \(10^{-8}\) mbar while the hydrogen filling pressure was \(1.5 \times 10^{-3}\) mbar. The exposures in RFX were made under similar conditions with exposures in the outer equatorial plane using a probe system described in reference 33. These measurements used the
electronics making continuous C(V) characteristics.

Figure 5.3 displays the result from a series of exposures in T1 of a room tempered sensor with a bare palladium gate. In the figure, the bias at constant capacitance C is plotted; decreasing bias corresponds to a shift of the C(V)-characteristics towards lower voltage, i.e. a hydrogen response. The linear decay is the response caused by the filling gas, and superimposed is the shift caused by the plasma discharges, indicated in the figure.

After some discharges large shifts (>1 V) were observed (for example see the discharges at about 27 min and 48 min in Fig 5.3). The sensor could recover from these shifts either by exposing it to a new plasma discharge or by removing the probe and annealing it at 200°C. This can be seen in Fig. 5.4 which shows C(V) curves recorded before and after the exposure series shown in Fig. 5.3. Curve 1 is recorded before the exposure series shown in Fig. 5.3 while curve 2 is recorded after the series. In the latter discharge, the C(V) curve changes drastically and becomes flat in the accessible bias region. Curve 3 is recorded after yet another plasma discharge. The C(V) characteristics of the device recovers in this discharge while the remaining voltage shift is still large, about 1 V from the original position. The device later recovered to its initial condition after removing
5.5. PLASMA EXPOSURES IN T1 AND RFX

Figure 5.4: $C(V)$ characteristics of a Pd-MOS capacitor exposed in T1. Curve 1 is recorded before the exposure series shown in Fig. 5.3. Curve 2 is recorded after the series and curve 3 after yet another plasma discharge.

To investigate the robustness against electric pickup and electromagnetic radiation, exposures were made where the probe was covered with a metal lid about 0.1 mm thick or with 2 μm mylar foil (3 g/m²). Figure 5.5 shows the behavior of the sensor covered with the mylar film which prevents any particles from reaching the sensor while electromagnetic radiation penetrates the film. The plasma discharges are marked with dotted lines. The discharges cause the bias to increase corresponding to a release of hydrogen. The bias shifts are small compared to the shifts observed in Fig. 5.3. This is because the sensor is nearly purged from hydrogen since it is inserted from air covered with the mylar film. It can thus not be filled with hydrogen before the experiment except from the background of hydrogen in air, normally about 1–2 ppm, known to give an initial shift of the $C(V)$ curve. The discharges causes a release of hydrogen and since the sensors are protected from particles it is interpreted as radiation induced.

The sensors were also found to react to visible light. This is caused by a photo-voltaic effect where electron-hole pairs are excited in the semiconductor. This effect was not expected since the thickness of the metal films are several times the skin depth of visible light. At room temperature the
skin depth is about 6 nm in gold and 15 nm in palladium. A possible explanation is imperfections in the metal films which leaves the oxide exposed to the light.

The large shifts acquired at plasma discharges are not caused by a usual hydrogen response, which is limited to 0.5–1 V. The large shifts may be caused by ions being implanted in the oxide. This causes a positive charge in the oxide acting to enhance the response of the device. This explanation was supported by implantation of helium ions. Implantation of 50 eV helium ions could induce bias shifts of about 4 V. The solubility of helium in gold or palladium is low which is why the helium can not diffuse to the interface as hydrogen does. The helium ions did not have enough energy to penetrate the metal layer. Also in this case imperfections in the metal film is a probable reason for the effect.
Chapter 6

Summary and Discussion of Papers

This thesis is based on the work contained in six papers. Four of these are based on experimental data from T1 while the last two papers deal with data from T2. On the T1 experiment the author worked together with a post-doctoral researcher, Dr Guoxiang Li, who was at the Alfvén Laboratory for two years. When the T2 device started operation, the author was solely responsible for the Langmuir probe diagnostics. The work includes all aspects of the diagnostic from probe design, experimental setup, software for data evaluation to planning of experiments. Concerning the specific papers, the authors contributions are as follows:

I. The author was second co-author on this paper and was responsible for part of the Langmuir and heat flux measurements as well as the experimental setup. The author also performed the data analysis of the Langmuir probe data.

II. The author constructed the probe mechanical interface and the electronics used for sensor temperature control. Further, the implantation experiments and sensor calibrations were made by the author and part of the plasma exposures and all data analysis. The author wrote the manuscript of the paper.

III. The author performed the Langmuir probe measurements in collaboration with Dr. Guoxiang Li and also part of the data analysis.
CHAPTER 6. SUMMARY AND DISCUSSION OF PAPERS

IV. Paper IV is based on the data of paper III and the author mainly contributed with spectral data analysis.

V. Paper V was done by the author alone and represents the main results derived from the experiment concerning edge transport.

VI. The author planned the experiment, was responsible for the Langmuir probe measurements and performed all data analysis, and wrote the manuscript.

6.1 Paper I — Edge plasma conditions and plasma-surface interactions in Extrap T1

The edge plasma in Extrap T1 was investigated using passive probes [85, 91, 92], Langmuir probes [92, 93] and heat flux probes. Paper I summarizes these results regarding plasma-wall interaction in the device.

The paper combines results obtained using the Langmuir/heat flux probe described in section 4.7 with measurements using passive graphite probes. The graphite probes are cylindrical with a diameter of 9 mm. Both the plasma facing end and cylinder surface were analyzed, the latter to achieve angularly resolved measurements of deuterium flux. The discharges with passive probe exposures were made in deuterium which gives a higher sensitivity of the surface analysis since a nuclear reaction may be used to detect the deuterium retained in the graphite.

The high current density in T1, with an average density up to 9 MA m$^{-2}$, leads to high parallel heat fluxes in the edge plasma with a maximum heat flux in the electron drift direction in the order of 1 GWm$^{-2}$. The ratio between the flux in the electron and ion drift directions varies in the range 3-6. This ratio is relatively low as ratios of about 10 have been measured on other experiments. The sheath power transmission factor $\delta$ is determined from comparison with the Langmuir probe measurements. The values of $\delta$ are high and at 90 kA plasma current it is about 45. To explain this high energy transmission, ion temperatures about 20 times higher than the electron temperature must be assumed.

Other observations in T1 also suggest high ion temperatures in the range of the central electron temperature. The hydrogen saturation level on passive probes implied an ion energy of about 100 eV at $I_p = 40$ kA and 200 eV at 90 kA. The metal deposition rates on the probes were also
consistent with the sputtering yields of metal from the vessel walls expected at these ion temperatures. As discussed in the paper, the results cannot be explained by electrostatic acceleration of the ions in the sheath. The edge temperature in T1 was also found to decrease with increasing plasma current [94].

The angular distributions of the ion saturation current and the ion implantation rate were also studied. The paper presents results regarding the angular distribution on the passive probes. The measured drift direction is in the direction of the plasma current which is the same direction as that of the ion diamagnetic drift or the $E \times B$ drift caused by a negative radial electric field. If the drift was caused by $E \times B$ drift, a change of drift direction would be expected with the change of the direction of the electric field at $r \approx 55$ mm. However, the drift direction is independent of the minor radius with an increasing Mach number at radii smaller than 55 mm. The toroidal drift is therefore probably dominated by diamagnetic drift. This can be compared with results from RFX where similar edge gradients and structure of the radial electric field are measured. The perpendicular drift velocity changes sign with the electric field which is why the drift likely is caused by $E \times B$ drift [95]. A possible explanation as to why the diamagnetic drift dominates on T1 is the high ion temperature.

### 6.2 Paper II — Hydrogen flux measurements with Pd-MOS capacitors in RFX and Extrap T1

In paper II results are presented from exposures of Pd-MOS hydrogen sensors in T1 and RFX. MOS capacitors covered with a 20 nm gold film were exposed in both plasma experiments.

The sensors were calibrated to enable conversion of bias shift to implanted dose. Sensors were exposed to 50 eV and 100 eV ion beams. The implanted dose was measured as depicted in section 5.4 by monitoring the current on a mesh in the beam path. Despite this, the implanted dose is the major uncertainty in these experiments. The implantation responses shown in Fig. 3 of the paper show an initial sensitivity of $0.4-0.7 \times 10^{-19}$ Vm$^2$. The fastest response is actually in the case with the lower implantation energy which is why the discrepancy between the two cases is attributed mainly to the uncertainty in the implanted dose. The sensitivity used in the experiments is the average value $0.55 \times 10^{-19}$ Vm$^2$. The im-
plication is that the 20 nm gold film is too thin to distinguish between 50 and 100 eV hydrogen atoms.

The measurements on T1 were compared with fluxes measured using passive carbon probes. The expected radial dependence was calculated accounting for the combined effect of shadowing of the aperture in the capsule lid and of the port hole. The flux to the sensor was assumed proportional to the average solid angle viewed by the active sensor area giving an inverse square dependence for large radii. Closer to the plasma, the solid angle is only restricted by the aperture which is why the predicted flux saturates. Far away from the plasma \( r/a > 2 \), the scaling of the measured hydrogen flux agreed well with the results from the graphite probes. Closer to the plasma, the hydrogen flux does not increase as predicted. It may even decrease. The results on RFX are similar with an inverse square dependence far away from the plasma while closer to the plasma the measured flux does not increase as expected. The neutral flux in RFX was only known from measurements using neutral particle analyzers and the flux measured with the Pd-MOS capacitors was an order of magnitude lower than this flux. This discrepancy may be due to low-energy neutrals. These would be promptly reflected at the gold surface or be stopped in the gold layer and diffuse back to the surface. Prompt, kinematic reflection would also affect the passive measurements which is why this discrepancy is not expected on T1.

The duration of the RFX discharges was about 100 ms and the sensors were expected to give several hydrogen dose measurements per discharge. However, measurements during discharges were prohibited by the large noise level because the probe is placed close to a discharge. To investigate the sensitivity to electromagnetic noise, sensors were exposed in T1 fully covered by a metal lid. In these discharges only small perturbations were recorded during the discharges. This implies that electromagnetic noise pick-up is not the main cause of the disturbances during the discharge. A caveat is the short discharge length which makes it difficult to evaluate the noise during a T1 discharge. The noise may be caused either by the energetic neutrals or by electromagnetic radiation. Energetic particles may affect the device by heating the metal film and a shallow layer of the semiconductor. Alternatively, hydrogen desorption from the surface may be induced.
6.3 Paper III — Characteristics of edge electrostatic fluctuations in the Extrap T1 reversed-field pinch

The spectra of the floating potential in T1, shown in Fig. 4.8, is broad decaying as 1/f at high frequencies. This is broader than the spectrum of magnetic fluctuations as measured by internal pick-up coils. Although magnetic fluctuations may contribute to the electrostatic fluctuations, they cannot fully explain the high frequency components.

The low frequency electrostatic fluctuations, below 100 kHz, were found to have toroidal mode numbers in the range $n = (0-20)$ and poloidal mode number $|m| = 0.1$ with most power in negative $m$.\footnote{The definition of the sign of the poloidal mode number used in paper III and IV differs from that used elsewhere in the thesis. $m/n > 0$ here denotes an internally resonant mode.} This mode number range is typical for the tearing mode fluctuations [96] which is why the low frequency fluctuations are referred to as internal tearing mode like. The amplitude of these fluctuations also have similar scaling with the plasma current as the tearing mode fluctuations suggesting a coupling between the two. The high frequency fluctuations have toroidal mode numbers in the range $n = -(0-45)$ and positive $m$. The higher toroidal mode number and the negative $m/n$ suggest that the high frequency fluctuations are predominantly externally resonant. The fluctuations may thus roughly be divided into low-frequency internally resonant fluctuations and into high-frequency externally resonant fluctuations.

The normalized potential fluctuation level is found to increase with the plasma current. It is proposed that this is connected with the increase of central pressure with the plasma current. The increased pressure gradients may drive resistive interchange modes (g-modes) generating the turbulence. However, the increased turbulence level may also be caused by increased internal magnetic fluctuations. It was observed that the edge temperature decreased with increasing plasma current [94]. This may affect the dynamo process and result in increased magnetic fluctuations which couple to the edge fluctuations.

Transport measurements are not presented in the paper but are reported elsewhere [68]. These showed only low particle fluxes of about 10-20% of the total particle fluxes as estimated from $H_n$ intensity or from surface probes. The particle flux was mostly driven by frequencies above 100 kHz and did not fall off at 500 kHz suggesting that transport also was driven by higher frequencies. However, the main reason for the low
flux was probably that the measurements were made too close to the wall where the transport is dominated either by scrape off parallel losses or by ion orbit losses.

6.4 Paper IV — Correlation between internal tearing modes and edge electrostatic fluctuations in a reversed-field pinch

RFPs are known to be unstable to resistive interchange modes (g-modes) [97] which have been considered as a possible drive of the edge turbulence and cross-field particle transport. However, calculations of g-mode turbulence show fluctuation levels which are too low to account for the experimentally observed transport [98]. However, if account is taken of coupling to the tearing mode fluctuations, the predicted fluctuation levels and transport may be increased. Non-linear coupling between the long wave length internal tearing mode fluctuations and the g-mode turbulence may enhance both the fluctuation levels and the particle transport [99]. If this coupling is present, a phase coherence is expected between low frequency (tearing mode) and high frequency (g-mode) turbulence.

The edge fluctuations were studied using the T1 Langmuir probe array. The data were analyzed using the triple probe technique giving time resolved measurements of electron temperature and density and floating potential. The degree of non-linear coupling in the signal is quantified using the bicoherence spectrum. Spectral data was analyzed over 64 µs records. The probe data in T1 was often saturated during the start up and normally, data can only be used from about 200 µs in to discharge so that only 150–200 µs of the data in each discharge could be used. The spectral data therefore had to be averaged over many discharges.

The bicoherence spectrum measured in T1 has indications of three-wave coupling of the turbulence. The squared bicoherency of the floating potential peaks at about 0.4 at \( f_1 = 300 \text{ kHz} \), \( f_2 = 20 \text{ kHz} \). This implies that non-linear coupling occurs between these two frequencies. As discussed in the previous section, low- and high-frequency fluctuations are predominantly internally and externally resonant respectively. The bicoherency thus implies a coupling between internally and externally resonant turbulence. Although this coupling is only implied, observation of such coupling is of great interest and should be valuable input to theoreti-
6.5 *Paper V — Edge resonant fluctuations and particle transport in a reversed-field pinch*

Paper V reports on the structure of the power spectrum of electrostatic fluctuations in T2. The spectra of the floating potential, the electron temperature and the electron density all exhibit a peak in the frequency region 100–250 kHz. An example is shown in Fig. 6.1 which shows plasma current, average and edge toroidal field, floating potential and the wavelet power of the floating potential for a specific discharge. The wavelet power is displayed as a contour plot of the fluctuation power in time-frequency space. Approximately at the reversal of the edge toroidal field at \( t \approx 0.66 \text{ ms} \), a peak appears at \( f \approx 50–100 \text{ kHz} \). This peak is seen in most discharges during the reversal. At \( t \approx 1 \text{ ms} \) the peak fluctuation power is transferred to about 200 kHz and these fluctuations dominates the spectrum until the termination of the discharge. A similar phenomenon is visible in each discharge except when local magnetic perturbations disturb the measurements. Paper V is mostly focused on the 200 kHz feature and its effect on the edge particle transport. There was a long-time trend that the power in these high frequency fluctuations increased with discharge number. This may, for example, be caused by a slow change in the edge conditions as the graphite wall was conditioned. The 146 discharges used for the present study were selected over a restricted time interval ranging from discharge \#3951 to \#5315.

The Langmuir probe array described in section 4.7 was used to study the fluctuations and the induced transport. Data was collected in 120, 150 and 180 kA discharges and with different values of \( F \) and \( \theta \). The data presented in the paper is time averaged over the period 2–4 or 3–5 ms in different discharge types. Each time interval is divided into several records over which the spectra are averaged, as described in section 4.5. This averaging process is justified by the stationary conditions displayed in the wavelet analysis of Fig. 6.1.

In the combined frequency and toroidal mode number spectrum it is seen that the fluctuations are again divided in two regions of low and high frequency (see cover). The low frequency region is below 100 kHz with

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2The transform uses the Morlet wavelet [58].
Figure 6.1: Wave form data for a 150 kA discharge in Extrap T2 with the Langmuir probe array positioned at $r = 173$ mm. The panels show plasma current, average and edge toroidal field, floating potential and wavelet power of the floating potential (darker areas correspond to high power). The vertical dotted line marks the reversal of the edge toroidal field at $t = 0.66$ ms.
6.6. PAPER VI

an average toroidal mode number $n \approx 0$. The high frequency fluctuations typically have a toroidal mode number in the range $n \approx -(40-80)$ and peak at a frequency of 100-250 kHz. It is shown that these fluctuations are externally resonant in the region $r \approx 165-175$ mm. The measurement of the poloidal mode number of the fluctuations suffers from an uncertainty due to possible misalignment of the probe. However, scaling with $q(a)$ supports the assumption that the fluctuations are $m = 1$ with a resonance at $q = -m/n$. The resonant $q$ is then transferred to a minor radius using a modeled $q$-profile. The radial position of the resonance varies and scales mainly with the plasma current. The peak in the spectrum can thus not be explained by toroidal rotation of the plasma alone since the $n$ number of the peak corresponds to the magnetic helicity on a radius differing from that of the probe.

The scaling of the resonant radius with the plasma current may be interpreted as an effect of the change of the ion Larmor radius in the edge plasma. Ion orbit losses should be the dominating transport mechanism in the extreme edge plasma preventing the build up of gradients in this region. If the fluctuations are driven by a local gradient the maximum radius where they can occur then should scale with the ion Larmor radius.

Interest in the externally resonant fluctuations is justified since they are found to dominate the electrostatic fluctuation driven particle flux. The electrostatic fluctuation driven transport was compared with $H_\alpha$ intensity measurements of hydrogen influx [100]. The flux measured as induced by electrostatic fluctuations is about $5 \times 10^{21}$ m$^{-2}$s$^{-1}$ giving a particle confinement time of about 400 $\mu$s. This is about twice the particle confinement time derived from the $H_\alpha$ measurements. The electrostatic fluctuation driven particle flux is thus a large fraction of the total transport. The electrostatic fluctuation driven energy transport is dominated by convection summing to about 200 kW. This is only about 1% of the power input which is why electrostatic fluctuations only have a minor influence on the energy transport.

6.6 Paper VI — Electrostatic and Magnetic Measurements of Turbulence and Transport in Extrap T2

In paper VI Langmuir probe measurements are combined with measurements of magnetic fluctuations. These are measured using an insertible magnetic pick-up probe simultaneously measuring three field com-
ponents. The magnetic pickup probe is inserted using a manipulator identical with that used for the Langmuir probe. The two probes are operated simultaneously and both probes are inserted vertically from the top of the machine but separated toroidally 0.73 m. A feature corresponding to the peak in the electrostatic spectra are found on the perpendicular components of the magnetic field.

To investigate the relation between the electrostatic signals and the magnetic signals it is desirable to measure the cross coherence. However, the distance between the probes is too large for any coherence to be expected and the relation must be investigated more indirectly. The peak in the floating potential spectrum roughly corresponds to an increase of the ratio of the fluctuation power in the perpendicular field components and the parallel component. For low frequencies the ratio is below 5 while for high frequencies it is about 20. The transition takes place in the frequency region 100–250 kHz which is the same region as that of the peak in the electrostatic signals. The two frequencies are shown to scale with each other which is indirect evidence that the phenomena in the two spectra are connected.

An increase of the electrostatic fluctuation driven flux with increasing electron temperature is observed which is faster than linear. This is caused by an increase of the normalized potential fluctuations which is interpreted as an effect of hot electrons escaping the core plasma. The super thermal electrons cause changes in the space potential resulting in potential fluctuations. Simultaneously, the electrons deposit part of their energy in the edge plasma. These effects combined results in the observed scaling of the potential versus the temperature.

Non-linear coupling is observed between low-frequency and high-frequency fluctuations. This may be interpreted as the effect of energetic particles from the core plasma affecting the local turbulence in the edge plasma.
Chapter 7

Conclusions

The work presented in this thesis is primarily aimed at a better understanding of the anomalous transport mechanisms in the reversed-field pinch. Anomalous transport is a general problem in magnetic fusion devices because it corresponds to a deterioration of the plasma confinement. Electrostatic fluctuations govern the particle transport in the tokamak configuration as well as in the edge of the RFP configuration. The present results are thus not only of interest in the RFP research but for a general understanding of anomalous transport in magnetic fusion plasmas. The main new results presented in this thesis are summarized below.

Electrostatic fluctuations have been studied in the T1 and T2 devices. Langmuir probes have been used to characterize the edge plasmas regarding edge parameters and their scale lengths. Both in T1 and T2 a negative radial electric field has been measured in the edge plasma. In T2, a potential minimum is reached about 10 mm from the wall where the electric field changes sign. Such deep probe insertions could not be made in T1 due to high thermal loads and the electric field is negative in the whole region accessible with probes. If the negative electric field is caused by ion orbit losses, the potential minimum is also expected at a deeper insertion in T1 since several diagnostics indicated a high ion temperature in T1.

In agreement with results from other RFP experiments, electrostatic fluctuations drive a large part of the particle transport in the edge region of T2 with a maximum approximately coinciding with the potential minimum. In T1 only a fraction less than 20% of the particle flux has been measured resulting from electrostatic fluctuations. However, this is
mainly attributed to the fact that the measurements were made close to the wall which is consistent with the negative electric field and ion orbit losses. The energy transport by electrostatic fluctuations in T2 is dominated by convection constituting only a small fraction of the total energy transport.

The electrostatic fluctuations can be divided into a low frequency part and a high frequency part. The low frequency fluctuations have frequencies and mode number in the range of the internal magnetic fluctuations. The high frequency fluctuations, above 100 kHz, also have higher toroidal mode numbers. For the first time, non-linear coupling has been demonstrated between low-frequency and high frequency electrostatic turbulence in RFP edge plasmas. The coupling, present both in T1 and T2, implies that low-frequency fluctuations originating from internal magnetic fluctuations may enhance the high frequency edge turbulence. Even if the edge particle transport is driven by frequencies above the range of the magnetic fluctuations, the turbulence and transport levels are affected by these fluctuations. The high frequency electrostatic fluctuations on T2 are dominated by externally resonant fluctuations which contribute to about 10–20% of the total fluctuation power. Despite the small fraction of the fluctuation power, the particle transport is dominated by these fluctuations. Edge resonant fluctuations have previously not been reported in RFPs which is why these have been studied on T2. Similar fluctuations may be present and generate edge fluctuations in other devices while not being as clearly distinguishable as on T2. The fluctuations are seen both in the electrostatic spectra and in the spectra of the perpendicular magnetic field components.

Solid state Pd-MOS devices have been explored as a possible detector of neutral hydrogen. The advantage of such a sensor as compared with present day neutral particle diagnostics would primarily be its small size. Pd-MOS capacitors have been calibrated using a mono-energetic ion beam and have been exposed in the T1 and RFX experiments. The measurements agree well with expected hydrogen fluxes at large distances from the plasma \((r/a > 2)\). Approaching the plasma, the hydrogen flux does not increase as predicted. This effect is attributed either to electromagnetic radiation or the energy of the impinging ions affecting the sensors. The measurements are also affected by ions being implanted in the oxide or in the semiconductor. Additional development work will be necessary before this type of detector can be used in fusion devices as a routine diagnostic.
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