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HiPIMS, HPPMS, plasma, electron transport, Rogowski coil

Nyckelord

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Keywords
Abstract

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In this study, the current densities in three different directions \( (r, \varphi \text{ and } z) \) have been measured above the target during a HiPIMS discharge by the use of a Rogowski coil. This was done to examine the key transport parameter \( J_\varphi/J_D = \omega_e \tau_{\text{EFF}} \) throughout the whole measured area, which is a key parameter describing how electrons are transported across magnetic field lines. The coil was adapted to the certain plasma environment that is present during a HiPIMS discharge in consideration due to the extreme environment that is present during the experiment. The thin film deposition system, where the measurements were performed, had a background pressure of \( \sim 10^{-6}\text{Torr} \) and during the discharges the chamber were filled with an Ar to the partial pressure of 3 mTorr. The previously reported anomalous fast transport of charged particles was verified and the faster-than-Bohm cross-B transport was found to be present in the chamber during the whole discharge but occupying a diminishing area closer to pulse turn off.
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Chapter 1

Introduction

1.1 Thin films

By coating a thin film on to a substrate a new product is made that has a combination of the properties of the substrate with the properties of the thin film e.g. high conductivity, high hardness or low friction to name a few. These thin films are within the range nanometres to micrometres and can consist of a wide amount of different materials. New materials with new properties are e.g. necessary in order to produce improved integrated circuitry or to make a metal wear resistant. To be able to develop and deploy new films the deposition techniques also need to be improved and refined which means that the physics that is driving the deposition and transport of the material to the bulk material also needs to be properly described and ultimately optimised.

The two most used ways of depositing thin films are defined by on whether the process utilises a chemical reaction or a physical process to deposit the vapourised material on to the desired substrate. In this thesis only a specific physical vapour deposition technique were used which will be described further in the following section.

1.2 Physical Vapour Deposition (PVD)

Physical Vapour Deposition or PVD is the term for a thin film deposition technique in which the deposition material is evaporated from a solid material (called target)
by some sort of physical process which could be by thermal means or by sputtering, which is a process in which particles from the target is pushed out into the chamber by the collision from an incoming ion. The resulting vapour from the target is then transported to and condensed or embedded on the desired substrate to create a thin film on the surface. The different ways of vapourising the target material all have their advantages and disadvantages but the method used in this thesis is a plasma enhanced PVD or sometimes referred to as a ionised PVD (IPVD) technique called high power impulse magnetron sputtering (HiPIMS).

1.2.1 Magnetron sputtering

The basic principle behind magnetron sputtering is the same as in an electric glow discharge meaning that the system consists of a cathode-anode setup in a vacuum chamber, where the initial pressure is low to decrease the amount of undesired particles that might cause undesired chemical reactions or contaminations in the film. The chamber is usually filled with an inert gas at a low pressure that is in the range of a few mTorr ($1\text{Torr} = 133.322\text{Pa} = 1.3332 \times 10^{-3}\text{bar}$), in general Ar. By the use of a magnetron as a magnetic trap close to the target in the vacuum chamber a current, i.e. electrons, will start to flow close to the target when the target is charged to a negative potential. In the present study, the magnetron used was an unbalanced, meaning that the magnetic field lines are not completely closed hence giving the electrons a chance to escape the trap so that the plasma occupies a larger area.

The plasma is created due to random free electrons that are present inside the chamber all the time will start to flow throughout the gas when an electric field is introduced to the chamber by applying a negative voltage to the target (usually several hundreds of volts). The electrons will then interact with the inert gas atoms. This interaction will create another free electron and an ion which in turn is accelerated in the opposite way, towards the target due to its charge and the electric field, while the free electrons can interact with other inert gas atoms. The collision between an ion and the target (cathode) will release both electrons and target atoms where the electrons are called secondary electrons, which can collide with gas atoms and hence create more ions. A breakdown then follows due to the large number ions created inside the chamber which in turn contributes to release even more electrons into the gas. All the secondary electrons and electrons from
ionisation will eventually be enough to create a self sustaining glowing plasma \[3\], meaning that enough secondary electrons are released into the chamber to create enough new ions to regenerate the electrons that are lost to the anode and chamber walls.

The process where the target particles are pushed out into the chamber due to ion bombardment and then travel to the substrate where they are deposited as a film, is called cathode sputtering and is the driving physics in thin film deposition using magnetron sputtering. The sputtered particles travel through the plasma and a fraction of the particles will eventually arrive at the surface of the substrate and be deposited. Due to the low pressure very few particle interactions will occur on the path between the target and substrate hence the direction and kinetic energy of the particles are preserved so that the impact energy at the substrate is large enough to deposit a thin film \[4\].

There are different types of magnetron sputtering where direct current magnetron sputtering (DCMS) is a popular technique commonly used by the industry \[4\]. DCMS utilises a setup as previously described and where the target is given a constant applied voltage to drive the sputtering process throughout the desired deposition time. In the case of DCMS most of the sputtered material will never become ionised and thus traverses the plasma and arrives at the substrate as neutrals \[5\]. This implies that the material flux is very difficult to control and hence the substrate needs to be within line of sight of the target. If instead more of the neutral flux could be ionised then the flux would be controllable due to the charge of the ions. For example, a negative potential on the substrate would then accelerate the ions towards it and give them directionality as well as a larger kinetic energy before impacting on the surface, hence the possibility to create denser films and more control over the incoming particles \[4\].

To increase the degree of ionisation of the incoming target particles is an ongoing research subject and there are different techniques that addresses the issue where one of the more promising is High Power Impulse Magnetron Sputtering (HiPIMS) introduced by Kouznetsov et al. \[6\].
1.2.2 HiPIMS

The same setup as in a DCMS system is used in a HiPIMS system with one exception, the target power supply. Ionising a large part of the sputtered particles with the same setup as in a DCMS is done by using high power levels under pulsed conditions. The high energy in each pulse leads to a denser plasma which improves the probability of ionising collisions between the plasma and the sputtered target particles and hence increases the amount of ionised sputtered particles. Target melting would occur if the same power levels were used during DCMS since it is the thermal load in combination with cooling capabilities on the target that limits the maximum power applied. This means that the duty cycle is an important parameter, i.e on-time divided by period length, were a typical pulse length is between $5\mu s - 500\mu s$ and the frequency can be varied somewhere between $10Hz$ to $10kHz$ [7].

![Typical voltage pulse, 200µs long](image1.png) ![Typical current pulse, 200µs long](image2.png)

Figure 1.1: Example of a typical discharge from the signal generator used in this experiment

Since there are some different manufacturers of HiPIMS power supplies and that they still are being improved and examined there are some different pulse behaviours. One of the main difference is the size of the capacitance in which the charge is stored and then released from. The voltage on the target might in some cases fluctuate during the pulse because of the power supply’s inability to hold the voltage at a certain level for a longer time(see Lundin et al. [8] for an example on a discharge with a changing voltage level). In figure 1.1 typical
discharge characteristics for the HiPIMS pulses used in this work are given. This shows that there are some changes in the voltage during a pulse but since the level only changes from $-650\,\text{V}$ to $-600\,\text{V}$ the change is relatively small. One of the consequences of having a stable voltage is a more stable discharge condition which can be seen in figure 1.1, the current plot, since the current is rising throughout all of the on-time for the pulse. This type of plot is important since the current is a measurement of both the amount of secondary electrons that is knocked out from the target and the incoming ions from the plasma.

1.3 Project objectives

This project is a continuation of a work done by Lundin et al. [8] where they measured and described the internal currents during a HiPIMS pulse. In that study the current density was measured at a distance that spanned from $4\,\text{cm}$ out to $8\,\text{cm}$ from the target and with a radial distance that varied between the centre of the target out to $8\,\text{cm}$ from the centre. Since they did not measure the current flowing in the radial direction a complete study of charged particle transport could not be concluded. Hence the type of electron transport across magnetic field lines was only correctly determined at the area above the racetrack were the field lines are parallel to the target surface. Another difference was the measuring grid that was decided upon which, in this work, was much denser and it covered a larger discharge volume.

In this study the internal currents have been measured in three dimensions which means that we were able to compare the current that is flowing parallel to the magnetic field lines with the one which is flowing across the field lines which means that we were able to look for the previously reported faster-than-Bohm transport [8] in a larger area. The aim of the project is to study the effect of charged particle transport during the HiPIMS process in order to be able to characterise the flow of ions and electrons in this type of discharge. Furthermore, the mechanism determining how fast electrons are transported across magnetic field lines has never been determined in time as well as space in this type of discharge. It is thus for the first time possible to resolve this issue during a complete HiPIMS pulse.
Chapter 2

Plasma dynamics

A plasma consists of both electrons and ions of almost equal positive and negative charge densities, which is a part of the plasma condition called quasi neutrality, which means that it is on average almost neutral but not entirely [9]. Another behaviour that is characteristic for a plasma is that if a charge concentration is introduced the charge carriers inside the plasma will shield out the external potential, this is called Debye shielding. The definition of quasi neutrality also states that the dimensions of the system must be larger than the Debye length, that is a measurement of the shielding thickness with the additional condition that there needs to be enough particles in the plasma cloud to effectively shield out an external electrical field. Since the Debye length is an important parameter for sheaths in a plasma environment (which is the case of the measurements) a closer look at both sheaths and the Debye length is needed. Later on an investigation of the behaviour of the individual charged particles in an environment with magnetic field and their interaction with other charged particles will be given.

2.1 Debye length and sheaths

An equation for calculating the length of the shielding sheath is both given and derived by Chen [9] p. 10] and is presented below as equation 2.1 where $\varepsilon_0$ is the permittivity of free space, $n$ the number of particles, $k_B$ is Boltzmann’s constant, $T_e$ is the electron temperature and $e$ is the elementary charge. The reason for only using the electrons in the equation is the superior mobility (compared to ions) that they have, which gives them the ability to either create a surplus or deficit
in any plasma region and hence shield out any voltage \[9, p. 10\].

\[
\lambda_D \equiv \left( \frac{\epsilon_0 k_B T_e}{nc^2} \right)^{1/2} \tag{2.1}
\]

In equation 2.1 the term $k_B T_e$ or $k_B T$ is the thermal energy of particles in a plasma and where $\frac{1}{2} k_B T$ is the average kinetic energy per degree of freedom \[9, p. 6\]. The average energy is a measurement of the collective behaviour that a species of particles have inside a plasma while the individual particles meaning ions and electrons both have their motions described mainly by Maxwell’s equations \[9\]. These equations account for the electromagnetism behaviour and by combing them with fluid equations will include the collective behaviour inside the plasma, in this report it is mostly the electromagnetic forces that will be taken into account.

Close to e.g. the chamber wall during a thin film deposition, a plasma sheath will appear close to the wall and shield out the potential of the wall which is negative compared to the plasma potential. The difference between the potentials is due to the higher mobility that electrons possesses compared to the ions, which are heavier, and hence the plasma electron loss rate to the chamber walls is initially greater. This effect raises the plasma potential to a value that usually is positive compared to the chamber walls \[9, p. 290\]. A sheath that shields out this potential difference will have a thickness that is dependant on the Debye length (equation 2.1), where approximately five times the theoretical value for the Debye length is reported for this thickness \[10\]. In a typical HiPIMS discharge the length is between $10^{-6} - 10^{-5} m$ \[3\] hence the sheaths only have a limited influence on the main plasma behaviour e.g. a sheath that could occur around a grounded probe inside the plasma.

Close to the target another kind of sheath is created due to the high negative voltage applied to the target. Assuming that all electrons are repelled by the voltage there will only be an ion current towards the target. By using these assumptions the sheath thickness can be derived, which has been done by Lieberman and Lichtenberg \[11\], called Child Law sheath:

\[
s = \frac{\lambda_D}{3} \left( \frac{2V_0}{T_e} \right)^{3/4} \tag{2.2}
\]
A typical cathode (or target) sheath is of the length $100\lambda_D$ which in the case of a HiPIMS discharge results in a sheath that is in the millimetre range. Hence any measurements that are carried out a few centimetres from the target will not be affected by this sheath.

### 2.2 Particle movement

For both the electrons and ions that are moving through a space that contains both a magnetic field (measured in Tesla and denoted $\mathbf{B}$, vector notation) and an electric field (denoted $\mathbf{E}$) the Larmor radius is an important parameter. This motion is a gyration around a guiding centre which will occur even in the absence of an electric field and the equations which are derived by Chen [9, p.20]:

\begin{align}
\omega_c &= \frac{|q|B}{m} \\
r_L &= \frac{v_\perp}{\omega_c} = \frac{mv_\perp}{|q|B}
\end{align}

Where $\omega_c$ is the cyclotron frequency, $r_L$ the Larmor radius, $q$ the charge of the particle which decides the direction of the gyration, $m$ the particle mass and $v_\perp$ the perpendicular velocity. By using equation (2.3) with the lowest value for magnetic data from Bohlmark et. al. [12], to get the upper limit for the Larmor radius, the following values are obtained for an electron:

$$\omega_c = 0.1 \times 10^{-3} T \times 1.602... \times 10^{-19} C / 9.109... \times 10^{-31} kg = 17.588... \times 10^6 \text{ rad/s}$$

Due to the fact that an electron travelling through a low magnetic field strength part will need a velocity that exceeds that of light to even be in the centimetre range for the Larmor radius, calculated value for $\omega_c$ in equation (2.4) they are more or less bound to the magnetic field lines. For ions which have a mass that is $\approx 1800$ times larger means that the Larmor radius is larger by an equal amount. Lundin [3, p.50] reports that the Larmor radius for the ions are $\sim 0.1m$ and $\sim 0.0001m$ for electrons in the HiPIMS discharge. Hence the ionic Larmor radius is on the same scale as the vacuum chamber giving the ion a movement that travels unhindered through the chamber [3] while the electrons gyrate on a much lower scale.
The investigation above implies that the electrons are following (or magnetised) to the magnetic field lines while the ions travels more freely throughout the chamber. These differences in the motions between the particles will later be an important part in the discussion of charge particle movement across magnetic fields.

2.3 Cross-B resistivity and Faster than Bohm diffusion

Diffusion or movement of plasma particles that exists in a space with a magnetic field inside it have two main directions, cross-magnetic field diffusion and movement along the magnetic field lines. Electrons and ions, which are magnetised, will follow the field lines unless they encounter some obstacle and collide (depicted in figure 2.1). Without a collision there would not be any diffusion across the magnetic field lines and the particles would continue on the same path. In classical theory it is only collisions between particles that drive the plasma perpendicular to the magnetic field lines, where the collision rate is dependent on the size of the Larmor radius and hence the magnetic field strength, meaning that a stronger magnetic field gives a smaller Larmor radius and hence fewer collisions (also implying that electrons are less likely to diffuse across field lines due to a smaller gyro radius) [9, p.169-171].

Experiments conducted to investigate the diffusion dependence of the magnetic field strength showed that the predictions only were true up to a certain value for the magnetic field strength where the diffusion rate started to rise again, by Lehnert and Hoh [13]. The differences between theory and experiments were found to be caused by a plasma instability which develops in the plasma at high magnetic fields, discovered by Kadomtsev and Nedospasov in 1960.

Collisions between charged particles, whether it is between an electron and an ion or two electrons, it involve Coulomb forces giving it the name Coulomb collision. The classical way of calculating the exchange of momentum forces in these collisions is given by the resistivity of the particles in the plasma. By using the resistivity in combination with the so called MHD equations, a classical diffusion coefficient can be derived. This has been done by Chen [9, p. 187]:
2.3 Cross-B resistivity and Faster than Bohm diffusion

Figure 2.1: An illustration of a collision between two particles that causes diffusion across a magnetic field

\[ D_\perp = \frac{\eta_\perp n \sum KT}{B^2} \]  \hspace{1cm} (2.5)

In equation (2.5) the diffusion coefficient is proportional to \(1/B^2\) which most experiments showed were not the case, instead it seemed to be proportional to \(1/B\). A semiempirical formula of the poorer magnetic confinement were given by D.Bohm, E.H.S Burhop and H.S.W Massey \[15\] and is presented by Chen \[9, p. 190\] and called Bohm diffusion:

\[ D_\perp = \frac{1}{16} \frac{KT_e}{eB} \equiv D_B \]  \hspace{1cm} (2.6)

Bohm diffusion states that the diffusion will occur faster than is stated in the classical theory due to a less effective magnetic confinement. During a HiPIMS discharge there is an occurrence of another anomalous transport reported by Lundin \[et al. \[16\]. This anomaly is likely the result of another plasma instability called the modified two-stream instability, which is due to a difference in the relative motion of between electrons and ions which causes oscillations in the local electric field and electron density that will enhance the oscillations which eventually will
start to grow exponentially, see Hurtig et al. [17]. Ultimately this phenomena leads to a faster transport of electrons across the magnetic field lines (cross B). An expression for the cross B resistivity can be rewritten to include the effective electron collision time. The modified plasma resistivity given by Lundin [3, p. 22]:

\[ \eta_\perp = \frac{B}{\omega_{ge} \tau_{EFF} e n_e} \]  

(2.7)

In equation 2.7 the term \( \omega_{ge} \tau_{EFF} \) is a particularly interesting one. Rossnagel and Kaufman [18] has shown that by taking the quotient between the Hall and Pedersen currents this exact term is reached which means that a measurement of the resistivity in the plasma examined could be determined by simply dividing two measured currents, in a cylindrical coordinate system \( J_\phi \) is flowing in the \( \phi \)-direction while \( J_{D\perp} \) is directed perpendicular to the magnetic field lines.

\[ \frac{J_\phi}{J_{D\perp}} = \omega_{ge} \tau_{EFF} \]  

(2.8)

As previously described the term \( \omega_{ge} \tau_{EFF} \) in equation 2.7 is a relatively easy way to correlate the currents to the transverse resistivity and hence the cross magnetic field diffusion. A typical value for this quotient for HiPIMS according to Böhlmark [12] is \( J_\phi / J_{D\perp} \approx 2 \) where the value for Bohm diffusion is somewhere between \( 8 < \omega_{ge} \tau_{EFF} < 30 \), with a theoretical value of \( \omega_{ge} \tau_{EFF} = 16 \). To be able to examine the behaviour of charged particles during a HiPIMS discharge both the currents flowing parallel and perpendicular to the magnetic field lines need to be measured so that \( \omega_{ge} \tau_{EFF} \) can be determined correctly, in accordance with equation 2.8. This implies that the current needs to be measured in all directions (e.g. for a Cartesian coordinate system: \( x, y, z \)) to determine the quotient correctly.
Chapter 3

Experimental setup

3.1 Magnetic measurements in a plasma

To measure local current flow patterns inside a plasma a probe can be inserted. A probe which is commonly used when measuring a change in the magnetic field strength, which is directly proportional to the change in time of current flowing through the probe, is the Rogowski coil. One of the main advantages of using this probe is that it is relatively easy to manufacture and of low cost. The main concerns regarding inserting a Rogowski coil inside the plasma chamber is that it might affect the plasma or that the probe is damaged by e.g. the heat flux \[19\] p. 37. Regarding the probes influence on the particle motions inside the chamber it should be limited due to that the very source of the currents are located relatively far away and hence the probe only has an influence on the current fields in the close vicinity of it and not on the general behaviour of the plasma \[19\] p. 39. Precautions were also taken to minimise the probes influence on the HiPIMS discharge so that the process was not disturbed.

3.2 The Rogowski coil

The voltage induced in a coil with \( n \) turns where each turn has the area \( A \) is described by:

\[
V = \frac{\mu_0 n A dI}{2\pi R} \frac{dt}{dt}
\]

(3.1)
Where \( R \) is the effective radius of the probe and \( \mu_0 \) is the vacuum permeability. The design of the probe is made in the same way as described in [8] which means that a wire was wound around a rigid non-magnetic core, in this case a PVC ring. The probe has a toroidal shape where the "end" wire is returned through all the wire loops which results in a back winding. The reason for doing a back winding is to eliminate the electromagnetic fields coming from outside the loop [20] and thus eliminate any components of the current that are not perpendicular to the probe surface \( A \). When deciding the actual size of the probe a number of key parameters are crucial for the design where the inductance is one of the most important and decides the signal strength from the probe (which comes from equation (3.1) and here with a circular cross-section).

\[
M = \frac{\mu_0 \pi r^2 n}{2\pi R} \tag{3.2}
\]

To transform the measured voltage into current density measurements equation (3.1) was used but solved for \( \frac{dI}{dt} \):

\[
V = \frac{\mu_0 An}{2\pi R} \frac{dI}{dt} \Rightarrow \int \frac{dI}{dt} = I = \frac{2\pi R}{\mu_0 An} \int V \tag{3.3}
\]

### 3.2.1 Designing the size of the Rogowski coil

The probe described by Lundin [8] and its mutual inductance was used as a reference when designing the new probe. The calculation that resulted in the value later used is presented below:

\[
M = \frac{4\pi \times 10^{-7} \times \pi \times (5.9 \times 10^{-3})^2 \times 470}{2\pi \times 15.6 \times 10^{-3}} \approx 0.658957 \mu H \tag{3.4}
\]

To make sure that the probe will give a signal that is strong enough to be detected, additional parameters needs to be considered. One design goal was to make a smaller probe compared to the reference probe which meant that either the mutual inductance had to be decreased (and hence the signal strength) or that the wire could be one with a smaller diameter, to ensure that a larger amount of turns could be wound. A drawback that could arise from doing this is that since the wire has a smaller cross-section the resistance will become larger which changes
3.2 The Rogowski coil

Figure 3.1: A figure of the final version of the coil with both the inner radius (r) and the outer radius (R) drawn into the figure

the behaviour of the probe and if it becomes too big the transfer function (the frequency response) could be affected.

In the present work the approach using a thinner wire was chosen. That choice meant that a smaller probe is achievable, but by looking at equation 3.2 one can see that it is more efficient to have a larger cross-section radius compared to increasing the number of turns. This was also investigated more thoroughly by Tumanski [21] who shows that the sensitivity of the probe grows roughly as $D^3$, were D is the diameter of the probe and that it increases the SNR (signal to noise ratio) proportional to $D^2$. Tumanski [21] states that lowering the wire diameter will increase the sensitivity but it will not affect the SNR since it will also increase the thermal noise in the probe due to an increase in resistance. The equation for calculating the thermal noise is given below were $k_b$ is Boltzmann factor ($1.38 \times 10^{-23} W s K^{-1}$), $\Delta f$ is the bandwidth, $T$ is the temperature and $R$ is the resistance, from Tumanski [21]:

$$V_T = 2\sqrt{k_b * T * \Delta f * R}$$ (3.5)

Hence the thermal noise $V_T$ (equation 3.5) will increase as the wire thickness
Experimental setup

shrinks (since the resistance will increase). This made it a bit hard to make the probe smaller compared with the reference probe and still being able to detect a good signal further away from the magnetron than was investigated by Lundin et al. [8]. The solution that was chosen was that the wire used to wind the coils was substituted to one with a smaller diameter while the probes cross-section radius were lowered to achieve a mutual inductance that was on the same order as the reference probe. To be able to calculate and hence compare the different probe designs I used a rewriting of the variable \( n \) in equation 3.2 since it is hard to estimate the number of turns, \( n = 2\pi R_{mean} \eta_{eff} / t_{wire} \). This is a rewriting that describes the number of turns that one should be able to fit on a ring with mean radius \( R_{mean} \) (halfway in between the inner and outer radius), where \( \eta_{eff} \) is an efficiency factor that I determined by studying the reference probe and determined to be around 0.95 and \( t_{wire} \) is the diameter of the wire. One should note that this is an approximation used and a very simple model which does not explain the whole picture but is useful when deciding a cross-section radius.

\[
M = \frac{\mu_0 \pi r^2}{2\pi R_{mean} t_{wire}} \cdot \frac{2\pi R_{mean} \eta_{eff}}{t_{wire}} = \frac{\mu_0 \pi r^2 \eta_{eff}}{t_{wire}} \quad (3.6)
\]

This approximation gives a simple relationship between the cross-section radius, wire diameter and the mutual inductance which is the main parameters that could be changed. A wire diameter of 0.15 mm was decided on to be able to increase the sensitivity and reducing the size which then by using equation 3.6 and solving for \( r \) resulted in a cross-section radius of \( \approx 5.13 mm \) which was later chosen to be 5 mm to get an easier number to work with and it still gives a mutual inductance that is close enough compared to the reference probe.

To determine the inner and outer radius of the probe there was a wish to make it smaller than 21.7 mm but not to make it unusable in the experiment. By setting the outer radius to 19 mm then the inner radius (which is 10 mm smaller since the probe has a toroidal design) becomes 9 mm, see figure 3.2 for diameters. The resulting area was \( 1.134 \times 10^{-3} m^2 \) which is approximately 22% smaller than the area of the Rogowski coil that Lundin et al. used \( \approx 1.452 \times 10^{-3} m^2 \). In the review written by Tumanski [21] he describes how the size of the outer radius is an important parameter in the signal to noise ratio (SNR) since the SNR increases and hence decreases proportional to the outer radius squared. Since the outer radius
3.2 The Rogowski coil

on the probe used in the experiment was $21.7\,mm - 19\,mm = 2.7\,mm$ or 87.56% of the reference probe. This squared gives an expected SNR to approximately 76.7% of the reference probe due to a smaller outer radius which mostly will be because of increased noise since the mutual inductance should be around the same value.

In conclusion the measurements in the final version of the coil were: the inner radius $r = 9\,mm$ and the outer radius $R = 19\,mm$ giving a cross-section radius of $5\,mm$, see figure 3.1 and 3.2.

![Figure 3.2: A simple view of the coils dimensions were the inner diameter were 19\,mm and the outer diameter 19\,mm, which made the diameter of the coil cross section 10\,mm](image)

3.2.2 Experimentally determining the mutual inductance

![Figure 3.3: A schematic of the test bench](image)

To determine the probes mutual inductance a test bench that consisted of a signal generator, an amplifier and a reference current transformer were used. To
analyse and save the signal a Tektronix 405 oscilloscope was used to be able save the data and later process the data in the software Origin Pro 8. Two parallel coupled 10Ω resistances were used to limit the current and then the wire from the amplifier was drawn through both the Rogowski coil centre and the reference current transformer (see figure 3.3).

Figure 3.4: The mutual inductance for the coil (quotient between the coil current and reference transformer) that were later used in the measurements over a frequency range from 250hz to 500kHz.

One of the most interesting purposes of the test bench were to investigate the frequency behaviour of the probe which where done with a sine wave where the frequency was varied, ranging from 250hz up to 500kHz. The resulting signal was integrated in Origin Pro 8 to get the measured current and then analysed, calculating the peak to peak value for the current signal. The mutual inductance for the Rogowski coil was calculated by taking the quotient between the peak to peak currents measured by the reference transformer (which had a known current to voltage signal) and the Rogowski coil. The result are presented in figure 3.4 which shows the quotient for different frequencies where the maximum variation compared to the low frequency response is around 25%. The peak that appears at the end of the frequency range investigation in figures 3.4 and 3.7 seems to follow the same behaviour as the one presented by Djokic [22], where a small peak
appears close to the maximum frequency hence the Rogowski coil frequency was expected to follow the same behaviour. Unfortunately the test bench used in this work could not generate stable signals at frequencies above 500kHz and hence this behaviour could not be seen in our investigation.

Figure 3.5: The Rogowski probes step response integrated data at 20kHz compared with the reference transformer and the raw signal from the probe

A square wave test were later performed to look how the probes step response would look like and to make sure that the coil were able to measure one at a high frequency. The measurements were done by using the same test bench as previously to make sure that the Rogowski coil gave a response that was similar to the reference transformer. The gain constant that was used to get a true (or similar to the one from the reference coil) signal were \(1/(6.45 \times 10^{-7})\). A comparison between the two signals in figure 3.5 shows that they are similar to each other which means that the step response is valid if the pulses don’t occur too close to each other i.e. the signal is on a higher frequency than is appropriate or that the duty cycle is small compared to the frequency which also may cause the signal not to settle from the initial step response. For the purpose of monitoring the internal currents in the HiPIMS pulse the described Rogowski coil fulfilled the requirements. The calibration shows that the coil is able to measure a signal with good accuracy to a frequency of 1MHz and that it is possible to measure a square wave with the coil.

The mutual inductance determined by the test bench experiment was later
on used when equation 3.3 were implemented in a Matlab script. To calculate the measured current a preconstructed function that uses cumulative trapezoidal numerical integration to perform the discrete integration of the voltage signal was used. The current together with both the inductance and the known area of the Rogowski coil then gave the resulting current density and a typical result is presented in figure 3.6.

3.2.3 Inserting the coil close to a HiPIMS discharge

A Rogowski coil in close proximity to a voltage source with a large $dV/dt$ may pick up voltage signal instead of the change in current $23$. Intrator et al. states that the probe should have ”a shield” that consists of a non magnetic metal layer to minimise the influence on the measured signal. This layer should be connected to ground to ensure that fast changing voltage signals hopefully sees this layer as a ground connection and is cancelled out. Due to the fact that the layer introduces capacitance connection between the coil and ground, which makes the fast changing signal to see this capacitance more or less like a wire while other signals, like the currents magnetic field, sees a short circuit and instead creates an induced voltage in the probes wire. By placing the coil inside the chamber in line of sight of the target while sputtering is performed, a thin metal film will be deposited on the Rogowski coil. This shield could then be connected to ground hence creating a shield for the coil.
3.3 Measurements in the magnetron sputtering chamber

One concern was that the metal shield created on the probe during the measurements would change the gain (mutual inductance) of the coil and hence a new investigation of it was performed. In figure 3.7 shows that the gain of the coil is more or less in the same area and that eventual difference could be related to noise in the measurements.

In conclusion the probe was modified and investigated to make sure that the Rogowski coil would be able to pick up a good signal during a discharge. Precautions to make sure that the influence on the discharge where taken and it was made sure that the performance of the coil would not deteriorate considerably in time, meaning reliable measurements. The probe was also calibrated several times after it had been used to make sure that the previous statements were valid during the measurements.

3.3 Measurements in the magnetron sputtering chamber

All the measurements were performed inside a vacuum chamber at IFM, Linköping University, Sweden, named Kain, see figure 3.8. The chamber is a cylindrical chamber with a diameter of 450mm and a height of 705mm. Inside the chamber a 0.15m diameter copper target was mounted constituting the cathode. No substrate
Experimental setup

Figure 3.8: The vacuum chamber named Kain that was used during the experiment holder was inserted during the experiment making sure that the only obstacle in the chamber was the Rogowski coil and a rod which it was mounted to. To maintain sputtering the chamber was filled with an argon gas consisting of 99.9999% purity and maintained at a pressure of 3 mTorr during the entire experiment. Before filling the chamber with argon the chamber was pumped down to around 3 \( 10^{-6} \) Torr.

Pulses were delivered to the target by a power supply supplied by Ionautics AB, Sweden, named HiP3. The voltage and current profiles of the discharges can be seen in figure 1.1 which give the power distribution presented in figure 3.9. In a typical pulse the peak power was around 63 kW and a distributed power over the target area of \( \approx 4.2 \) kW/cm\(^2\). The power supply used an average power limit of 500 W to determine the pulse shape and it was equipped with an arc suppressor to limit the influence of an arc if one should occur during the 200\( \mu \)s that the pulse is turned on. In figures 3.9 and 1.1 0\( \mu \)s denoted when the pulse switches on, \( t_{on} \) and the point \( t = 200\mu s \) is denoted \( t_{off} \), since this was the time when switching off the HiPIMS pulse.
3.3 Measurements in the magnetron sputtering chamber

Figure 3.9: A typical power signal from the signal generator used in the experiment

Figure 3.10: Each 'x' in the graph represent a measurement in the chamber. The target is located at the x-axis between [0,0] and [7.5, 0] which is the r-direction while the y-axis is directed in the z-direction.

Figure 3.10 shows the measuring points that were decided upon which was measured in each direction in a cylindrical coordinate system (r-, ϕ- and z-direction) (see figure 3.12). The area close to the target was expected to contain more details and changes in the current densities and thus being of great interest. The distance between measuring points close to the target (4 – 8cm from the target and between the center of the target out to a radial distance out to 8cm) are 0.5cm, which
changes to 1 cm in the area further from the target. The center of the Rogowski coil was used when calculating the position of the probe for each point of measurement. A fear of electrostatic discharges between the grounded probe and the low potential of the target was the reason for not conducting measurements closer distances to the target surface. Since the probe torus extended about 2 cm from the probe center it means that the edge of the probe was never moved closer than 2 cm to the target surface. The plasma discharge inside the chamber is assumed to be cylindrical symmetric which is why a cylindrical coordinate system were used and for each direction a total of 320 measurement points were investigated, resulting in a total of 960 points of measurements.

Figure 3.11: The robotic arm used to turn the coil inside the chamber

A robotic arm was mounted on the chamber feed through and it had electrical motors and cogs that made it possible to turn the probe, located in the middle of figure 3.11. This improved the coil handling when measuring the z-part of the current where the radial distance could be varied without the need to open the chamber (which is time consuming).

Another feature of the arm were the ability to move the feed through rod up
3.3 Measurements in the magnetron sputtering chamber

and down which meant that the distance from the target could be varied in an easy way. Since the control also is equipped with two digital counters that shows both the relative z-distance and the degrees turned by the arm this made sure that the probe could be moved inside the chamber within 1mm precision. The ability to turn the Rogowski coil a certain amount of degrees were used to be able to go through all the measuring points in the z-direction. Since the plasma currents were assumed to exhibit axial symmetry in the radial direction only one measurement was conducted at a certain length from the target at each radial distance, in order to verify the accuracy of the measurements some re-measurements were conducted for several points. By using a trigonometrical relationship where the fact that the distance to the centre of the target is a fixed one and that turning the probe creates an isosceles triangle, which means that the triangle has two sides of equal length, the radial distance could be varied without the need to break the vacuum.

\[
\sin \left( \frac{\theta}{2} \right) = \frac{d}{2} \cdot \frac{1}{r} \Rightarrow d = 2r \sin \left( \frac{\theta}{2} \right) \\
\theta = 2 \arcsin \left( \frac{d}{2r} \right)
\]  

(3.7)

By using the bottom relationship in equation 3.7 (derived from figure 3.13) with \( r = 15cm, d = 0.5cm \) (where \( d \) is the distance to target center) the amount of degrees needed to turn the probe to change the radial distance from the center of the target was determined to be almost 1.91° between each measurement point in
Figure 3.13: A top down view of the chamber (not to scale) which shows the situation for the Rogowski coil while measuring the current in the z-direction.

The radial direction. Since the robotic arm controller only measured the amount of degrees turned in whole units and the possibility of measuring errors an evaluation of the impact an $0.1^\circ$ turn error would have. By using the upper equation 3.7 with $\theta = 0.1^\circ, r = 15cm$ gives a radial distance of $\approx 0.5mm$. This distance was well within the error margins that would occur if one would do the repositioning of the probe in the r-direction by hand. Which were used when measuring the $\varphi$- and r-component of the current density, the robotic arm was used to change the distance from the target (z-coordinate) for the Rogowski coil. Hence the measurements were preformed by first measuring all the points in the z-direction before changing the r-position. The probe setup for these measurements were the same as in figure 3.12 but faced in the appropriate direction and where the main difference between $\varphi$- and r-direction is the angle between the coil and the target center, in which the center of the coil were pointed at the target center for r-measurements and at a $90^\circ$ angle when conducting $\varphi$-measurements.
Chapter 4

Measurements and results

All the data was saved into data files from the oscilloscope which saves 2500 data points and depending on the resolution set by the user these points determine the amount of details used. In this experiment a resolution of 5 points/$\mu$s were used which means that the pulse will occupy $200 \times 5 = 2000$ of these points. This leaves 250 points on either side of the pulse to record the behaviour of the Rogowski coil before and after the pulse. By using Matlab to process the data all of it could be analysed and properly integrated in an autonomous way. In this section the measured current densities will be presented after a small introduction of some concerns about the measurements are discussed.

4.1 Raw data

At pulse initiation the voltage on the target changes from 0 V down to almost $-700$ V in a short amount of time ($\sim$ nano seconds). This behaviour is almost like a Heavy side function which means that the coil will react to the steep step function by oscillating, presented in figure 4.1. This behaviour was not to our advantage since it could influence the integrated data if the resolution of the pulse isn’t enough, a loss of data. This would in the end lead to an offset in the integrated data or if the data lost track of the oscillation at the end step-response, which can result in a non-return to zero for the integrated data. Since this could present a problem no data after pulse turn-off were considered being trustworthy due to the fact that the oscillations after this time were often so large that the end-point ended at a value $\neq 0$ despite the original coil voltage ending with 0 V as an
output. Furthermore, when measuring the current density in the r-direction a lot of interference was recorded which gave the data an offset at the first step response, meaning that when integrating the first oscillation the current value would rise by almost 1kA/m$^2$ at some measuring points. This data did not seem to follow the rest of the points surrounding them and that the shape of the current density had a shape that implies that instead of a sharp rise/lowering in the beginning it should remain close to zero. Hence in these cases the integrated current densities were lowered (i.e. compensated) so that the current densities were 0A/m$^2$ after the oscillations.

### 4.2 Integrated data, current density data

A script to remove any initial gradient in the data was also constructed. The gradient appears because of any interference in the first measurement will affect the whole integration by creating a non zero voltage as the starting point and hence the integrated data will be curved. This script used the fact that the position of the pulse turn on was known so that the slope of the line between the first point and $t_{on}$ could be calculated and later on subtracted from all the individual unprocessed data to get the correct pulse despite any noise in the beginning of the
4.3 Current densities map

Figure 4.2: A typical integrated signal from the Rogowski coil, this were taken 4cm from the target at a radial distance of 2.5cm

pulse. In figure 4.2 the effect of the starting and end step-response can be seen after integration. In the beginning the oscillations more or less cancels out and doesn’t influence the total value while after the pulse is turned off the current ends on a value above zero, almost 800 A/m² which is the reason for not using any data after 200 µs.

4.3 Current densities map

All the different measurement positions (see grid in figure 3.10) give one individual measurement in each of the cylindrical directions (r, φ, z, figure 3.12). By selecting a specific time after pulse initiation for the different positions snapshots of the current density throughout the chamber can be presented for each of the directions.

Figure 4.3 shows the discharge current with five markers that represents the different times during HiPIMS pulse-on in which the current flow patterns are presented below as current density maps. The different times are measured in µs after the target bias is turned on, so the following times will be presented in the three different directions: 40 µs, 100 µs, 140 µs, 170 µs, 195 µs. A model of the magnetic field from the magnetron was added to the maps in order to be able to
Figure 4.3: A typical target discharge current generated by the power supply (i.e. not a recorded internal current) with the times for the chosen current maps marked, the signs next to the points contain both the time (x-coordinate) and the discharge current value (y-coordinate)

see the influence of the field lines throughout the chamber.
4.3 Current densities map

4.3.1 Azimuthal-direction

The probe data constituting the current densities in the azimuthal direction show a strong and clear signal. As can be seen there is an intense circulating Hall-current directed approximately perpendicular to both the \( E \) and \( B \) field\[9, p. 23\] at \( r \sim 6 \text{cm} \), i.e. in the vicinity of the target race track (a ring that .
Figure 4.4: The current density measured in the $\varphi$-direction for different times. The black lines represent the magnetic field lines of the magnetron. The magnetron is located at $z = 0cm$, $r = [0, 7.5]cm$
4.3 Current densities map

Between $t_{on}$ and $t_{off}$ the general behaviour was that a strong current is created between 4.5 and 8cm which grows as the time moves on and reaches the maximum value at $t_{off}$, which coincides with the peak of the discharge current (see figure 4.4). In the surface plots it can be seen that the center of the current ring was measured to be located somewhere in the vicinity of 6cm from the target at a radial distance of 7cm, at the line where the magnetic field should be at its strongest. At the end of the pulse length the center seems to shift to a position that lies closer to 4cm. These results are in line with previous measurements on circulating currents in the HiPIMS setup presented by Lundin et al. [8].

4.3.2 z-direction

The measured z-currents plotted into current density maps at the different times are seen in figure 4.3. The current density in the z-direction consists of two different areas with two different directions and where the sign of the current density shows the direction of the measured current. There are two different directions for the current either towards the target or a current that is moving away from it. The signs of the current density is defined so that a negative current density implies that the current is directed towards the target in that area, hence the electrons moves away from the target as proposed by Lundin et al. [8].
Figure 4.5: The current density measured in the z-direction for different times. The black lines represent the magnetic field lines of the magnetron. The magnetron is located at $z = 0 \text{cm}$, $r = [0, 7.5] \text{cm}$.
4.3 Current densities map

A general behaviour could be found by looking at the plotted current density, see figure 4.5 and is presented in figure 4.6. Close to the target, between the center of the target and out to a distance around \( r = 7.5\, \text{cm} \) there is an area with upwards moving current. This area ends at the strong magnetic field which enters the measured area at a radial distance from the center of \( r \sim 7.5\, \text{cm} \). On the other side of the magnetic "barrier" the current flowed in the opposite direction, away from the target with the highest current density located above the area where that magnetic field lines enters the area and starts to bend off towards the center. At the point where the field lines are parallel to the target (coordinates \( z \approx 4\, \text{cm}, \, r = 5 - 6.5\, \text{cm} \)), see figure 4.5f, the strongest downwards directed currents were measured in the beginning of the pulse. A transient behaviour was also detected by looking at the current density. Starting close to \( t_{on} \) and beyond the different areas grew in strength and widths. Most notable is that the area where the current was flowing downwards expanded upwards and occupied a larger area above the magnetic confinement at the end of the pulse hence moving the border between the current areas, see figure 4.5e and figure 4.5f (presented in figure 4.7).

At the same time the areas with the strongest currents moved closer to each other. The center of the upwards current widened and moved downwards and
Figure 4.7: A simplified view of the transient behaviour of the electron movement in the z-direction during a pulse with an approximation of where the barrier between the two current zones are located. In the figure the shaded (grey dotted lines) electrons represent early movement and the black lines the electrons during a late stage of the pulse.

right at $t_{off}$, located at $\sim 8 - 9\text{cm}$ in radial distance from the center of the target while the downwards current center shrinks in size and moves closer to the border between the two current zones, figure 4.5e.

4.3.3 $r$-direction

To measure $J_r$ the coil was positioned in a similar way as for $J_\phi$ but turned 90° so that the coil was directed towards the center of the target. As previously discussed, when going through the measured data for the $r$-current some problems were detected.

Figure 4.8 contains measured data 5cm from the target ($|z|$) and at a radial distance of 5.5cm from the center ($|r|$) of the chamber, after integration. The data exhibits an unrealistic behaviour when it increased by a large amount ($\sim 1500\text{A/m}^2$) in the first $\mu$s and with an oscillating behaviour. This could be because a loss of data in the strong oscillating area that occurs due to the step like pulse that is used to drive the HiPIMS discharge. Since the oscilloscope limited the amount of data depending on the zoom, hence if all of the step response should be taken into account it limits the resolution of the interesting part between $t_{on}$ and $t_{off}$.
4.3 Current densities map

Figure 4.8: The integrated measured data at a radial distance of 5.5cm and 5cm from the target. This shows that problems were evident when measuring the r-current, mainly the large increase in current density at $t_{on}$ and $t_{off}$ where the step responses occurs in the beginning and the end. Due to this fast rise a word of caution regarding the behaviour of the radial data has to be issued but the data was analysed and this possible offset was removed so e.g. in figure 4.8 when picking out the values for the current density surface plot all the values were subtracted by 1500 A/m$^2$ to get an “imaginary” starting point with the values $\sim 0$ A/m$^2$ close to $t_{on}$.

Another possible factor influencing the results of measuring $J_r$ is due to the difficulties that arise when measuring the current in the r-direction. Here the strong azimuthal current is flowing around the coil and might influence the measurements, maybe by instead of flowing around the coil a part of the strong current might be diverted and flow into the coil. This was suspected due to the fact that all the measurements with problems, like figure 4.8 occurred at a radial distance between 4–8cm which was the area where the strongest azimuthal currents were measured.

When defining the directions of the currents a positive current was defined as the direction out into the chamber from the target center, where it should follow the magnetic field lines out into the chamber. Hence this implies that a negative value on the current meant that current was flowing inwards into the chamber and where the electrons are moving in the opposite direction. The minimum value
presented in figure 4.9 was limited to $-8000\text{A/m}^2$ to obtain a higher resolution while in reality the minimum value measured was $\approx -12000\text{A/m}^2$.

Figure 4.9: The current density measured in the r-direction for different times
By an examination of the figures 4.9 a) - e) in the first figures the area closest to the center of the target showed an increase in current density where the electrons flowed out into the chamber and where the peak value occurred at a radial distance between $2 - 2.5\text{cm}$. At a radial distance beyond $7.5\text{cm}$ an area where electrons were flowing out towards the chamber walls starts to grow forth. Between the radial distances $4 - 7.5\text{cm}$ it becomes harder to see some kind of general behaviour but it seems as if a "collision" between the two directions occurred in the inner areas (close to the target) were the magnetic field lines are parallel, in agreement of figure 4.6 and Lundin et al. [8].
4.3.4 Azimuthal-current divided by z-current

In this section equation 2.8 is used in a similar way as Lundin et al. [8] to investigate the particle movement:

Figure 4.10: The quotient between $J_\phi/J_z$ for different times
4.3 Current densities map

Figure 4.10 shows the quotient between $J_\phi/J_z$ and for the same timestamps as in previous figures (4.4, 4.5 and 4.9). These surface plots made it clear where the border between the different current zones was located by identifying where the quotient becomes large. This is possible due to the very low current in the $z$-direction at the border, which makes the quotient ($J_\phi/J_z$) very large. At the beginning of the pulse there was no clear line which could be due to low currents at the start of the pulse, figure 4.10a. At 100 $\mu$s, figure 4.10b, a line which consisted of a high value quotient measurements (that seemed to follow the magnetic field lines) stretch out into the chamber. This border line then moved to higher $z$-coordinates as the current flowing downwards in the $z$-direction grew and started to occupy a larger area and hence followed the border between the two different $z$-current area. In this border the current consisted of more or less only a current in the $r$-direction due to the lack of $J_z$. A first and preliminary investigation of $\omega_{ge}\tau_{EFF}$ can be done by looking at figures 4.10a)-e). The quotient gave values $\sim 2 < \omega_{ge}\tau_{EFF} < 4$ at the beginning of the pulse but as the pulse time came close to $t_{off}$ the value of $\omega_{ge}\tau_{EFF}$ rises close to the target and settles for values $\sim 3 < \omega_{ge}\tau_{EFF} < 8$ at the parallel magnetic field lines towards the end of the pulse.

In figure 4.10 the colour bars in the surface plot needed a fix maximum value to get a good resolution in the whole surface plot. This was due to the fact that at the border between the upwards and downwards current areas where the measured $z$-current was very low at some places and hence the quotient gave a high value. This made the automatic scaling for the colours in surface plots inappropriate to use when trying to show low values for $\omega_{ge}\tau_{EFF}$. So in conclusion by looking at the quotient between $J_\phi$ and $J_z$ the border between the different current zones in the $z$-direction is visible at the same time as the correct values for $\omega_{ge}\tau_{EFF}$ is present where the magnetic field lines are parallel to the target surface but not for all of the measured area. To use equation 2.8 successfully throughout the whole area the current flowing in the $r$-direction needs to be included to correctly describe $J_{D\perp}$ in the whole discharge region.

4.3.5 Inclusion of r-current

To give a better picture of the transverse resistivity throughout the chamber, which is dependant of the value for $\omega_{ge}\tau_{EFF}$, the current in the $r$-direction needs to be
Measurements and results

taken into account since the current flowing across the magnetic field lines is a mixture of both r-current and z-current for most of the chamber due to the fact that the B-lines are bent as can be seen in figure 4.11. By looking at the numerical simulated magnetic field lines present in e.g figure 4.7 the ratio between \( J_r \) and \( J_z \) could be calculated.

A cosine approximation was used to determine the percentage of \( J_z \) \((R_z)\) inside the specific areas presented in figure 4.11. At the areas where the magnetic field lines are almost parallel, a smaller structure was decided upon to make sure that the areas with parallel field lines (hence a pure \( J_z \) flows across the magnetic field line) are located at a position that is accordingly to the simulated magnetic field lines. Above 10\( \text{cm} \) from the target has a magnetic field topography that differs from the area below 10\( \text{cm} \) which is the reason to divide it into separate areas. By selecting two points and use them to calculate the relative change in the coordinates inside the chosen areas the ratio \( R_z \) could be calculated for each area using equation (4.1):

\[
R_z = \frac{\Delta x}{\sqrt{(\Delta x)^2 + (\Delta y)^2}}
\] (4.1)
The ratio of current in the r-direction ($R_r$) used when determining the quotient (or $\omega_{ge} \tau_{EFF}$) was simply: $R_r = 1 - R_z$. In figure 4.12 the maximum values which are shown in the figures 4.12a - 4.12e are limited in the same way as described in the previous section.

![Graphs showing current densities map](image)

Figure 4.12: The calculated values for $\omega_{ge} \tau_{EFF}$ presented for different times
Chapter 5

Discussion

In this chapter a discussion of the results as well as the reliability of the Rogowski coil measurements are presented. The chapter starts with a comparison between the results that were obtained during this work and the paper by Lundin et al.\cite{8} due to the fact that the measurements presented in this thesis work was performed in a similar way. A closer look on the currents measured by the Rogowski coil were done by using Kirchhoff’s current law which gave a better picture of the reliability of the coil before ending with an analysis of the cross-B resistivity.

5.1 Comparison with earlier results

Due to the fact that the experiment conducted in this thesis work is a continuation of the work by Lundin et al.\cite{8} some resemblance was expected, although it has to be noted that the shapes of the HiPIMS discharge current and voltage were not the same in the two experiments (but the deposition system and magnetron were identical). The differences in the discharge currents stems from the different power supplies used, where the one used in this experiment exhibited a more stable discharge both in the voltage and the current behaviour, where the current is rising throughout the whole pulse duration, see figure 1.1, compared with a quick rise followed by a slope. In the previous work the current peak occurred after $\sim 50\mu s$ which was 25% of the pulse duration time. The discharge current in the present work instead showed a steady increase in time between $t_{on}$ and $t_{off}$ for the current densities, while in the results presented by Lundin et al.\cite{8} the plasma seemed to go through some different discharge regions due to the changes in the
target voltage (starting at $\sim -830$ and ending at $\sim -400$). Hence the generator current discharge used in this experiment seemed to exhibit the same behaviour throughout the entire pulse discharge.

Lundin et al. \[8\] proposes an evolution of the internal currents based on the $z$-currents where the measured current densities in the $z$-direction presented in this work (figure 4.5) does in fact seem to follow the proposed behaviour, as will be described in the following section. The low current densities in the first $\mu s$ after $t_{on}$ (figure 4.5a) indicates that most of the ionisation takes place close to the target and that the electrons mainly move towards the ground shield close to the target, this is due to the low plasma density further away from the target which makes the easiest path for the electron transport to be towards the anode ring \[8\]. Figures 4.5b to 4.5e indicate that when the plasma density grows in the chamber the electron transport increases in the bulk plasma region at larger $z$ values and hence starts to cross the magnetic field lines further and further away from the target, which implies that the area where the current returns to the anode ring (closes the current loop) moves further from the target in respect with time.

By looking at the top values for the current density we find that in the $\varphi$-direction $J_{\varphi, \text{max}} \approx 31 kA/m^2$ in the measurements preformed by Lundin et al. \[8\] while the maximum measured current density in the same direction obtained in this work was $J_{\varphi, \text{max}} \approx 20 kA/m^2$. The previous work both reaches higher values and quicker which could be explained by the fact that the discharge current peaks much earlier in the HiPIMS pulse and hence the chamber should be filled with electrons faster and in a greater extent due to a larger peak current, $\approx 150 A$ compared to $\approx 120 A$ in this thesis. A comparison of the top values measured for the current density in the $z$-direction gives a similar result where $J_{z, \text{max}} \approx 8.8 kA/m^2$ for Lundin et al. \[8\] and $J_{z, \text{max}} \approx 3kA/m^2$ in this work. The calculated values for the $J_{\varphi}/J_z$ quotient shows some resemblances with each other where Lundin et al. \[8\] shows a figure of the quotient early in the pulse time that exhibits a high quotient line located at a radial distance approximately between $4 cm$ and $7 cm$ which is located around the same area as the previously described border between the current zones, presented in figure 4.10.
5.2 Kirchhoff’s law investigation

A first approach to determine whether the data gathered with the Rogowski coil is reliable was to perform an investigation of the current densities measured and analysed. The total current measured flowing upwards from the target ($I_{target}$) can be estimated due to the fact that a cylindrical symmetry is assumed inside the chamber i.e. the measured current density ($J_z$) should be applied to the whole circular area to get the total current.

$$I_{target} = 0.075^2 \pi \frac{1}{n} \sum_n J_z$$  \hspace{1cm} (5.1)

By using equation [5.1] where the summation of the measured current density is done at a distance of 4cm (z-coordinate) from the target and between the radial distances 0 - 7.5cm (since the target radius were 7.5cm (or 0.075m)) with 0.5cm between each measuring point resulting in an $n = 16$. Equation [5.1] used throughout the discharge should result in a curve that resembles the discharge curve from the power supply and the result is presented in figure [5.2].

The total estimated current (figure [5.2]) compared with the discharge current from the power supply (seen in [1.1b]) shows a difference both in the total amount of current and the shape of the curve (looks more like a plateau than the constant
increase which the power supply exhibits) that seems to reach the peak value for the current earlier. The discharge currents total value is a factor of around 6.5 times larger compared to the current estimated to flow in the z-direction at the investigated area, where this factor was reached by using the maximum values of the current plots which could be a somewhat wrongful comparison due to the different times that they occur. Due to the behaviour of the discharge current where it increases constantly during $t_{on}$ (and with a larger value for the derivative at the end of the pulse) the factor of which the discharge current is larger increases towards the end of the pulse, while it is only 2 times as large in the beginning of the pulse ($40\mu s$ after pulse initiation).

A more accurate way of describing the current flowing across the boundary at $z = 4\text{ cm}$ is to leave the average current approach across that boundary and instead divide it in segments, which will form rings due to rotational symmetry along the z-axis, where each measurement in the radial direction defines the radius (e.g. $r = 0.5, 1, 1.5 \ldots$). This was implemented in Matlab by using the following equation:

$$I_{target} = \pi \sum_m J(m)(r_m^2 - r_{m-1}^2)$$  \hspace{1cm} (5.2)

In equation 5.2 each ring has its own measured current density values and hence the ring areas further away from the target center becomes larger which results in
5.2 Kirchhoff’s law investigation

a more realistic approximation. The result is presented in figure 5.3 and shows a slightly higher estimated current compared to the one presented in figure 5.2.

![Graph](image)

Figure 5.3: An estimation of the total amount of current flowing downwards at a distance of 4 cm from the target and from the center of the target to a radial distance of 7.5 cm between 30 µs − 200 µs by using equation 5.2

One possible reason for the discharge current being larger than the estimated current could be due to the uncertainty of the size in the effective collection radius for the Rogowski coil i.e. at which distance from the coil center that the current is directed inwards and into the coils measuring zone. Another factor that likely contributes to the found difference is that the internal z current was measured at z = 4 cm and we are thereby not able to capture the full picture of the current transport, since part of the electrons will likely travel radially outwards to the ground shield below z = 4 cm.

5.2.1 The r-current compared with the z-current

Another way of determine both the accuracy of the Rogowski coil and if there was any data corruption from the strong ϕ-current during the measurements, is to compare the current densities measured in the z-direction with the current density in the r-direction.
Figure 5.4: The following square will be used when analysing the measured current densities by comparing the currents flowing into and out of a the analysis square.

Figure 5.5: A current density map with the measurements in the r-direction present. Also printed in the figure is the two white squares (due to the different scales in the axes they appear to be rectangles) in which the edges of the squares are the borders where the relative current densities are calculated.
5.2 Kirchhoff’s law investigation

The individual currents at each of the borders for the square (presented in figure 5.4) was calculated by averaging the measured current densities at the specific border area and then multiplying by the appropriate area (see equation (5.3)).

\[
I_z = J_{z,\text{average}} \int_0^{2\pi} \int_{r_1}^{r_2} r \, d\varphi \, dr = J_{z,\text{average}} \pi (r_2^2 - r_1^2)
\]

\[
I_r = J_{r,\text{average}} \int_0^{2\pi} \int_{z_1}^{z_2} r \, d\varphi \, dz = J_{r,\text{average}} 2\pi r (z_2 - z_1)
\] (5.3)

The analysis was performed for two squares with different side lengths presented (1cm and 2cm) in figure 5.5. The calculated currents were also varied through time to visualise the transient behaviour of the currents.

Figure 5.6: The average measured currents in flowing in the z-direction in accordance with figure 5.4 varied through time and where the length of the sides are 2cm. The left figure has the current plotted for the lower border while in it is the upper border that is plotted in the right figure.

The figures shows that the current measured by the Rogowski coil in the r-direction is bigger than the z-current in this location and especially at the border located 6cm from the target center (r = 6cm) where the largest measured current was flowing out towards the end of the pulse. At the same time the current flowing in the z-direction is lower at a distance of 4cm from the target (z = 4cm) compared to the current flowing down into the upper border of the square. This behaviour can be due to the fact that the electrons flow in the opposite direction compared to the current meaning that the electrons for the z-direction moves in the same di-
Figure 5.7: The average measured currents in flowing in the z-direction in accordance with figure 5.4 varied through time and where the length of the sides are 2 cm. The left figure has the current plotted for the left border while in it is the right border that is plotted in the right figure.

The amount of current at each border for different times can be used to perform an estimation of Kirchhoff’s current law for the analysis area, i.e. a current continuation analysis of the amount of current flowing into and out of the square presented figure 5.4. From figures 5.7 and 5.6 the current values at 130 µs after pulse initiation gives the following values:

\[
\text{Current in} = 1.46 + 2.818 + 10.91 = 15.188[A] \\
\text{Current out} = 4.706[A]
\]
Hence about 3 times more current is measured to flow into the analysis area than is flowing out and a similar analysis at 180µs results in approximately 4 times more current is flowing out across the borders than is flowing in. This could indicate that there is some sort of buildup inside the area which is released towards the end of the pulse but this seems very unlikely. A more probable explanation is that the probe is affected by the strong current flowing in the \( \varphi \)-direction which is located in the vicinity of the analysis area and hence the current measured points at 6cm from the target center \((r = 6cm)\) could be overestimated due to a part of that strong current is redirected into the probe and hence measured.

Figure 5.8: The average measured currents in flowing in the z-direction in accordance with figure 5.4 varied through time and where the length of the sides are 1cm. The left figure has the current plotted for the lower border while in it is the upper border that is plotted in the right figure.

The same analysis for the smaller square in figure 5.5 reveals that the same situation (figure 5.8 and 5.9) is more or less apparent though the current crossing the \( r \)-border 5cm from the target center \((r = 5)\) has the same direction throughout the pulse. An examination of the combined currents directed out from and into the analysis square at 130µs and 180µs after pulse initiation results, in both cases, in a larger amount of current flowing into the square than out. Where it was \( \approx 6 \) times more at the first investigated time and \( \approx 2.25 \) times for the second time. This indicates that more current was measured at the borders of the analysis square than should have been if the continuation of the current where valid for the measurements. Since this was the result for both of the cases presented here and for a few more not presented there could be an overestimation of the measured
Figure 5.9: The average measured currents in flowing in the z-direction in accordance with figure 5.4 varied through time and where the length of the sides are 1 cm. The left figure has the current plotted for the left border while in it is the right border that is plotted in the right figure.

currents in either one of the directions or both. It could be due to, as previously stated, influence from the strong $\varphi$-current where a part of the current could have been redirected into the probe and hence a large error would be present in the measurement.

As a last remark there was a visible trend in both analysis is that when the electrons/current start to flow out in a greater number out of the squares right side (in the r-direction) the current that is flowing in the z-direction drops to lower values hence instead changing its direction the current continues in the same direction which means that less collisions occurs inside the analysis area.
5.3 The cross-B resistivity

In figures 4.12 (a) – (c) the area located between a radial distance of 4 – 8 cm from the target center, the values of $\omega_{ge} \tau_{EFF}$ could be uncertain due to the problems regarding the data. The data shows that the area which previously was described as a magnetic shield for the current in the $z$-direction has a high value for $\omega_{ge} \tau_{EFF}$, hence the resistivity is high between $r = 6$ and 8 cm. Some sort of resistive line seems to be present at $z = 7 cm$ with an opening where the magnetic fields are parallel to the target. This seems like it could be due to some sort of measuring error at that distance from the target. Since the measurements were done by starting with the probe 15 cm from the target ($z = 15 cm$) and when moving it towards the next measurement position it was the $z$-position that was changed down to a distance of 4 cm from the target, then changing the radial distance from the center. Hence it seems unlikely that an error in the measurements to be present for so many of the different radial distances and only at that distance from the target. In figure 5.10 a closer investigation of the high cross-B resistivity line is conducted and it shows that despite that the whole line has a large value there are regions within where the values are much larger closer to the center of the target, almost twice as large as the values further out from the target center.

![Figure 5.10: The calculated values for $\omega_{ge} \tau_{EFF}$ presented for 140$\mu$s and with two different maximum levels for $\omega_{ge} \tau_{EFF}$](image)

(a) 500 as the maximum value presented  
(b) 1200 as the maximum value presented

The faster-than-Bohm diffusion seems to be present during the whole pulse especially close to the target center and below a $z$-coordinate of 7 cm with $2 <$
$\omega_{ge} \tau_{EFF} < 7$. Hence it is not present for the whole discharge area, especially above the magnetic shield where the area seems to change character and enter the Bohm regime ($8 < \omega_{ge} \tau_{EFF} < 30$) and above.
Chapter 6

Conclusions

A Rogowski coil has been successfully designed and constructed. With it we were able to measure the plasma current density in three directions ($r$, $\varphi$, $z$) for a HiPIMS pulse inside a vacuum chamber with a large measurement area and was able to investigate the transient behaviour of the current density. The electron behaviour was investigated and it was confirmed that the proposed behaviour by Lundin et al. \cite{Lundin2005} does occur during the HiPIMS pulse. In the $z$-direction it was found that the current flows downwards close to the target center and that at distances further out from the target center (or at a greater $r$-distance) the current flows in the opposite direction (upwards) with a clear border between the areas with a transient behaviour, where the border moves from a curved line into a line that is located at a fixed $r$-coordinate throughout the chamber.

For the first time (since all the current directions have been measured during a HiPIMS pulse) $\omega_{ge}\tau_{EFF}$ (a measurement of the transverse resistivity) was determined in a large area inside the vacuum chamber and hence the anomalous current transport could be detected during the pulse on time. It was found to be present throughout the pulse in certain areas of the chamber, and that $2 < \omega_{ge}\tau_{EFF} < 8$ in a large area close to the target ($[r = 0\,cm - 4.5\,cm, z = 4\,cm - 6.5\,cm]$).
Bibliography


