A high power pulsed plasma system for material testing under simultaneous continuous and transient loads

Citation for published version (APA):

DOI:
10.6100/IR748465

Document status and date:
Published: 01/01/2013

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher’s website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.

Download date: 06. Aug. 2024
A high power pulsed plasma system for material testing under simultaneous continuous and transient loads

Jakub J. Zielinski
2013
A high power pulsed plasma system for material testing under simultaneous continuous and transient loads

PROEFSCHRIFT

ter verkrijging van de graad van doctor aan de Technische Universiteit Eindhoven, op gezag van de rector magnificus, prof.dr.ir. C.J. van Duijn, voor een commissie aangewezen door het College voor Promoties in het openbaar te verdedigen op maandag 14 januari 2013 om 16.00 uur

door

Jakub Jedrzej Zieliński

geboren te Łódź, Polen
Dit proefschrift is goedgekeurd door de promotoren:

prof.dr. N.J. Lopes Cardozo
en
prof.dr.ir M.C.M van de Sanden

Copromotor:
dr.ir. G. De Temmerman

The work described in this dissertation is part of a research program of the ‘Stichting voor Fundamenteel Onderzoek der Materie’ (FOM) with financial support of the ‘Nederlandse Organisatie voor Wetenschappelijk Onderzoek’ (NWO) and EURATOM. The views and opinions expressed herein do not necessarily reflect those of the European Commission. The research was carried out at ‘FOM DIFFER - Dutch Institute for Fundamental Energy Research’ in Nieuwegein, the Netherlands.

@Copyright 2013 Jakub J. Zieliński
Cover by Jakub J. Zieliński
# Contents

1 Introduction ............................. 1
   1.1 Nuclear fusion: progress, status and an outstanding issue ....... 1
   1.2 The research field of this thesis: PSI in fusion reactors during ELMs 2
   1.3 Magnum-PSI and Pilot-PSI; a need for a pulsed plasma source ... 3
   1.4 A pulsed plasma source: plan of approach .......................... 4
   1.5 List of publications ............................................. 6

2 Characterization of a high power-current pulsed magnetized arc 8
   2.1 Introduction ...................................................... 9
   2.2 Experimental setup: the PPS in Pilot-PSI
      and the electrical circuit ........................................ 10
      2.2.1 Pilot-PSI .................................................. 10
      2.2.2 Pulsed plasma source ...................................... 10
      2.2.3 Electrical circuit ......................................... 11
      2.2.4 Diagnostics .................................................. 12
   2.3 Results and discussion .......................................... 12
      2.3.1 DC arc-physical background .................................. 12
      2.3.2 Steady state arc without magnetic field .................... 15
      2.3.3 Pulse mode without magnetic field .......................... 16
      2.3.4 Influence of magnetic field .................................. 18
      2.3.5 Electron temperature and density by TS ................... 23
      2.3.6 Plasma velocity ............................................. 26
   2.4 Conclusions ...................................................... 27

3 Power and particle transport in a pulsed magnetized beam 28
   3.1 Introduction ...................................................... 29
   3.2 Experimental set-up .............................................. 30
   3.3 Results ............................................................ 31
      3.3.1 Influence of the discharge current on the plasma ........... 31
      3.3.2 Plasma at the target (downstream) .......................... 33
      3.3.3 Influence of the vessel pressure ............................ 33
   3.4 Discussion ........................................................ 33
3.4.1 MAR in DC and during the pulse ...................... 33
3.4.2 Evolution of plasma parameters with current .......... 37
3.4.3 Role of impurities - experimental evidence .......... 39
3.4.4 An overview of electron temperature and density .... 39

3.5 Conclusions ................................................. 44

4 The self-shielding of tungsten target exposed to high power pulsed hydrogen plasma 45
4.1 Introduction ................................................. 46
4.2 Set-up and measurements methods ......................... 46
4.2.1 Pilot-PSI .............................................. 46
4.2.2 Surface temperature measurements and heat flux calculations .............................................. 47
4.2.3 Calculation of heat flux ................................ 47
4.3 Results and discussion .................................... 48
4.4 Conclusions ................................................. 55

5 ELM simulation experiments on Pilot-PSI using simultaneous high flux plasma and transient heat-particle source 57
5.1 Introduction ................................................. 58
5.2 Experimental .............................................. 59
5.3 Behavior of tungsten under steady and pulsed plasma exposure .. 62
5.3.1 Tungsten release ...................................... 62
5.3.2 Evolution of tungsten morphology .................... 68
5.4 Discussion ................................................. 71
5.5 Conclusions ................................................. 72
5.6 Acknowledgments ......................................... 73

6 Evaluation and conclusions 74
6.1 Goals and approach ....................................... 74
6.2 Development of the pulsed plasma technology ............ 75
6.3 The plasma beam during pulsed operation .................. 76
6.4 PSI during the pulse: the strongly coupled regime and self-shielding 77
6.4.1 Relevance of self-shielding to ITER divertor ........ 78
6.5 Discovery of the synergistic effects of pulse and CW .... 78
6.6 Valorization .............................................. 79
6.6.1 Deposition of metal nanoparticles ...................... 79
6.6.2 Surface hardening with pulsed plasma exposure ...... 80

Summary 82

Acknowledgments 85

Curriculum Vitae 87
Chapter 1

Introduction

1.1 Nuclear fusion: progress, status and an outstanding issue: power exhaust

Nuclear reactions, either the fission of large nuclei or the fusion of light ones can release large amounts of energy per reaction; typically a million times more than a chemical reaction. Therefore, nuclear reactions are of great interest as a source of energy. The advantages of nuclear energy are that there are no or little emissions of CO$_2$ or polluting waste gases, while the events of March 2011 at Fukushima showed that even in technologically highly-developed societies the risk of accidents cannot be fully excluded. The fusion reaction, on the other hand, holds the long-time promise of clean and safe nuclear energy without long-lived radioactive waste, but to date, has not been realized as a viable energy source. Fifty years of research have demonstrated spectacular progress - the first power-producing reactor is presently under construction - but also show that it remains a huge technological and scientific challenge to produce electricity from nuclear fusion in a controlled manner [1].

The first fusion reactor that will produce more power than is needed to run it, is currently under construction. This project; ITER, is one of the largest international scientific collaborations with participation of China, India, South-Korea, Japan, Russia and the USA, while Europe is the host and leading party. ITER, which will generate 500 MW of fusion power during pulses of 10 minutes or more, is intended to demonstrate the scientific and technological feasibility of fusion power. After ITER, the first demonstration reactor DEMO, can be built which will deliver electricity to the grid. In ITER, the fuel - a mixture of hydrogen isotopes - is heated to about 250 million degrees. At that temperature all atoms are ionized. This hot plasma is kept together by means of strong magnetic fields, in a reactor chamber which has a toroidal geometry. A reactor of this generic design is called a tokamak. In ITER, a number of the original challenges of fusion...
research are expected to have been overcome: the fuel plasma will be confined stably in the magnetic field and heated to the required temperature. As a result, the expected 500 MW of fusion power can be generated. However, this leads to a new challenge: a large heat load on the wall of the reactor \cite{2, 3}. Due to the magnetic fields that are used to confine the plasma, this heat load is concentrated on a relatively small area: a strike zone with a width of only 2 cm. This strip is located in the so-called divertor of the reactor. In the strike zone, a time averaged heat flux density of $\approx 10 \text{ MW} \cdot \text{m}^{-2}$ is expected, as well as a hydrogen ion flux density of $10^{24} \text{m}^{-2} \text{s}^{-1}$. These numbers pose serious challenges to the strike zone materials in terms of heat conductivity, melting point, sputtering threshold, evaporation and sensitivity to thermo-mechanical stress. The problem is further complicated by the fact that the exhaust fluxes are not continuous but transient, due to the occurrence of so-called Edge Localized Modes (ELMs) which are introduced below.

1.2 The research field of this thesis: plasma wall interaction in fusion reactors during ELMs

This thesis concentrates on the plasma wall interaction at these strike zones, under conditions such as they are expected to occur in ITER. In particular, this thesis deals with the urgent issue of the heat and particle loads to the strike zones during ELMs.

During those ELMs, up to 6% of the energy stored in the plasma, $\approx 20 \text{ MJ}$ in the case of ITER, is dumped on the strike zone in a time span of about 1 ms. The ELMs occur regularly, with a repetition frequency of 10 - 300 Hz. During an ELM, the power flux density on the strike zone is enhanced by two orders of magnitude, with energy densities in the MJ$\cdot$m$^{-2}$ range \cite{4}. Such a pulse induces an excursion of the surface temperature of the plasma-facing components. Since many processes, the evaporation of material to start with, are highly nonlinear functions of the surface temperature, the fact that the power load is pulsed causes serious lifetime issues. Melting, cracking and evaporation are among the detrimental effects that occur and could limit the operational period of ITER between shutdowns to days instead of the planned years. Therefore, the effects of ELMs must be mitigated in order to allow ITER - and hence future fusion plants - to operate for a prolonged period of time.

For this reason, ELMs and their effect on the plasma-facing components are a very active area with fusion research. However, the size-scaling works out in such a way that the wall loads during ELMs are about a factor thousand larger in ITER than in present devices such as the Joint European Torus (JET, about half the size of ITER) or smaller tokamaks. Therefore it has not been possible to study this problem in conditions that are relevant to ITER. Also, since the effects of ELMs on plasma-facing components are strongly non-linear, predictions are unreliable and difficult to validate, especially in the divertor region of fusion
Hence, there is a clear need for an accessible laboratory experiment with well-controlled experimental conditions, in which the conditions typical of the plasma-wall interaction in ITER, during and in between ELMs, can be reproduced. The Magnum-PSI experiment and its smaller forerunner Pilot-PSI at DIFFER were designed for exactly that purpose [5].

1.3 Magnum-PSI and Pilot-PSI; a need for a pulsed plasma source

Magnum-PSI (fig. 1.1) is a linear plasma generator that has been designed to simulate ITER-divertor conditions: a heat flux density of $10 \text{ MW} \cdot \text{m}^{-2}$ and particle flux density of $10^{24} \text{m}^{-2} \text{s}^{-1}$ at the (low) electron temperature of 1-7 eV (1 eV corresponds to approximately 10000 K). Magnum-PSI is designed to operate with a steady state longitudinal magnetic field of up to 3 T and a plasma beam diameter of 10 cm. The smaller Pilot-PSI has the same basic lay-out, but a lower magnetic field ($<1.6 \text{ T}$) that is pulsed (up to 10 s at 1.6 T, longer at lower values with steady state capability at 0.2 T), while the beam diameter is also smaller at typically 2 cm. The work described in this thesis was mostly carried out at the development machine Pilot-PSI device as Magnum-PSI only became operational towards the end of the research period.

Earlier work at Pilot-PSI has established its capability of achieving the conditions required to study the plasma wall interaction in the ITER divertor in the
period in between, but not during ELMs, in quasi-steady state. The electron density \( n_e \) and temperature \( T_e \) at the end of the beam, i.e. in front of the target, are \( 10^{10} - 10^{21} \text{m}^{-3} \) and \( 0.2 - 10 \text{ eV} \), respectively. \( T_e \) and \( n_e \) are measured at the target and source position with a Thomson Scattering (TS) system. To study the impact of the power load on a surface, the machine is equipped with fast cameras. The surface temperature is monitored by infrared camera (\( \approx 10 \text{ kHz}, 3 - 5 \mu\text{m} \)) to elucidate the heat flux and energy density. Fast visible spectroscopy (75 kHz) based on a Phantom 12.1 camera is employed to investigate material ejection from the sample due to the evaporation and erosion processes. A quadrupole mass spectrometer is installed in the vicinity of target holder to track plasma chemistry during exposure to perform laser induced breakdown spectroscopy (LIBS) and measure the recycling of hydrogen isotopes between material and plasma. In a fusion reactor, all those processes occur under steady state plasma conditions but they are extremely aggravated during an ELM.

The fusion community did not have any device at its disposal that was capable of superimposing transient heat and particle fluxes on the steady state plasma in the relevant power flux regime, whereas clearly there was a need for such a device. Therefore, this research project aims at developing a pulsed plasma system that would enable Pilot-PSI and later Magnum-PSI to create ELM-like conditions superimposed on a continuous wall load representative of the inter-ELM period in ITER.

1.4 A pulsed plasma source: plan of approach

As starting point for the development of the pulsed plasma system (PPS) the cascaded arc plasma source used in Pilot-PSI [6] was chosen. This is a channel in which a plasma is generated by running a current through a gas flow, so that the gas is ionized and heated. The discharge is stabilized by the cooled walls. The normal mode of operation is in steady state. However, it was already shown in 1984 by Timmermans [7] that the temperature and density of the outflowing plasma jet can be transiently increased for few milliseconds by inducing a short current pulse on top of the steady state operation. This is achieved by discharging a capacitor bank. This technique was pioneered by Timmermans at power levels of 29 kW in steady state whereas during the pulse up to 1.5 MW. For the present application, this had to be scaled up to 6.5 MW.

It was not obvious that such a scale-up would even be possible. At 36 kW, the steady state operation of the Pilot-PSI source is already at higher power level than in the case of Timmermans, who worked at 29 kW, and in particular the ionization degree in the channel is higher. Therefore, it is not clear that simply dissipating more power in the narrow channel will result in the desired increase of the plasma density and temperature. Indeed, in steady state operation, increasing the discharge current from 180 to 900 A was found to broaden the beam rather than increase the density and temperature. A transient increase of the heat
flux density by a factor of 100, the goal of our study, clearly requires that the plasma temperature and density do increase. Moreover, the current pulse that can achieve this increase will be violent and potentially damaging to the source with evaporation of the source material and a strongly contaminated plasma as a result - if the source survives at all. Non-linear effects associated with the local heating in the source channel, the spatial distribution of the current and the dissipated power make it difficult to predict the performance of a cascaded arc source that is subjected to such strong pulses. Therefore, the technology of the source, its geometry, choice of materials and selection of safe boundaries in operation space was the first step in this research program, which is reported in Chapter 2.

Another interesting aspect concerns the transport between an arc and the target. In case of a DC plasma, the electron-ion recombination is very efficient for plasma below $<3$ eV. Neutral particles that enter the beam efficiently enhance plasma recombination, resulting in energy loss on the way to the target. However, if we succeed in the goal of achieving a denser and hotter plasma during the pulse, the loss mechanisms may be fundamentally changed, and possibly reduced, leading to a more efficient transport of energy from the source to the target. On the other hand, if the pulse does result in release of material from the wall of the source, the contamination of the plasma and the ensuing radiation may change the picture in an adverse way. Chapter 3 considers the plasma beam and investigates the limiting factors of pulsed operation. The energy losses between source and target are investigated, as well as plasma contamination due to the material ejection from overheated source components.

Finally, the principal objective of the development of the PPS is to reach the required flux density at the target and study the interaction of the plasma with the target in those conditions. The rapid increase of $T_e$ and $n_e$ during the pulse results in a peak of the heat flux, which may lead to melting or evaporation, or to outgassing of the target. The particles that come off the target, e.g. hydrogen released during the pulse or target material, can be ionized and trapped in the plasma in front of the target, which would lead to the so-called strongly coupled regime of plasma-wall interaction. In short, if the plasma pulse does reach the characteristics of an ITER ELM, we enter uncharted water the exploration of which is the true aim of this study. This exploration is the subject of Chapter 4 and Chapter 5.

In Chapter 4, the effect of a single pulse on the plasma surface interaction is investigated. First the relation between the amplitude of the current pulse and the energy deposition on the target is mapped out and the transition to the strongly coupled regime is investigated, followed by an exploration of this essentially new domain of plasma surface interaction.

In Chapter 5, finally, the full potential of the set up is used in a study in which the steady state plasma exposure is combined with ELM-like pulses, where the latter result in excursions of the surface temperature and all the non-linear effects associated with that. The open question here is: will the surface damage inflicted
by this combined exposure be the linear sum of the two types of exposure, or will there be synergistic effects that make the combined exposure more - or less - damaging. The answer to that question is of immediate relevance to the design and choice of materials for the ITER divertor, and for the establishment of limits for acceptable ELMs.

1.5 List of publications

The following publications are related to this thesis:

- **Characterization of a high power/current pulsed magnetized arc discharge**  

- **Production and characterization of transient heat and particle pulses in Pilot-PSI**  

- **ELM simulation experiments on Pilot-PSI using simultaneous high flux plasma and transient heat/particle source**  

The author of this thesis is a co-author of following publications:

- **Nanostructuring of molybdenum and tungsten surfaces by low-energy helium ions**  

- **New linear plasma devices in the trilateral euregio cluster for an integrated approach to plasma surface interactions in fusion reactors**  
• Production of high transient heat and particle fluxes in a linear plasma device

• Thermographic determination of the sheath heat transmission coefficient in a high density plasma

• Radiative type-III ELMy H-mode in all tungsten ASDEX Upgrade
Abstract
A high power pulsed magnetized arc discharge has been developed to allow the superimposition of a high power plasma impulse onto a DC plasma within a single plasma source. A capacitor bank (8400 μF) is parallel-coupled to the current regulated power supply. The current is transiently increased from its stationary value (200 A) up to 14.5 kA in 650 μs. The discharge power is thus raised from 18 kW to 6.5 MW, corresponding to a power density of up to 1.7·10^{12} W·m^{-3} - 100 × higher than in the DC mode. The plasma parameters are measured by TS \approx 4 \text{ cm downstream the nozzle}. The \( T_e \) and \( n_e \) vary from \approx 2.6 \text{ eV} and 7·10^{20} \text{ m}^{-3}, in DC up to 15 eV and 80·10^{20} \text{ m}^{-3} during the pulse. A saturation of \( n_e \) with increasing current is observed while the \( T_e \) increases monotonically. Time resolved voltage and current measurements of the arc are used to explain the role of the magnetic field and the evolution of the temperature.

2.1 Introduction

There is a growing interest in the application of high power pulsed plasmas for material processing and thin film deposition [8, 9] because of both its high power density compared to continuous discharges and the high potential of the transient sheath which causes a high kinetic energy of ions striking the surface [10, 11]. Due to the plasma sheath dynamics the ion acceleration to the surface is enhanced so that the heat flux received by the processed material is increased considerably over the pulse. This enables the efficient production of nanostructures/nanotubes [12, 13]. Pulsed plasmas have been widely investigated in terms of technological applications such as: metal hardening, pulsed immersion ion implementation, nitrification, re-solidification of surface layers and metal deposition [14, 15, 16]. At the same time, low temperature plasma-assisted processing is a widely used technique for a variety of applications. Being able to combine both methods would open new prospects for plasma processing. In addition, plasma-surface interaction studies in the field of nuclear fusion require the ability to combine high transient heat loads (for ms duration) with high-flux continuous plasma, in order to consistently reproduce what is expected in a fusion reactor during so-called ELMs [17]. In this paper, we present a pulsed magnetized arc system satisfying those requirements.

DC arc discharge sources have been used as very efficient sources of dense plasma with moderate temperatures for more than 50 years [18, 19, 20]. A high pressure pulsed argon arc discharge was previously described by Timmermans [7]. The discharge current was transiently increased from its DC value by discharging a parallel-coupled capacitor bank. In addition, the gas pressure was increased during the plasma pulse. Increases of both the plasma density and temperatures were observed. A similar plasma source, coupled to a strong magnetic field, is used in Pilot-PSI [6, 21] to generate plasma conditions relevant for the study of plasma-surface conditions under ITER-relevant plasma conditions.

In the present paper, we combine those two concepts to develop a high-power pulsed magnetized arc discharge allowing the combination of a high-flux DC plasma and a high-power plasma impulse. The discharge current is pulsed from its DC value (200 A) to a maximum of about 14.5 kA in a millisecond pulse. A detailed characterization of the pulsed plasma will be presented with the aim to clarify the effect of the magnetic field and the transient current increase on the plasma properties.
2.2 Experimental setup: the PPS in Pilot-PSI and the electrical circuit

2.2.1 Pilot-PSI

The PPS described in this article was installed on the Pilot-PSI linear plasma device, which is designed for the study of plasma-surface interactions under fusion-relevant plasma conditions [21]. The machine consists of a 1.2 m long, 0.4 m diameter vacuum vessel placed inside five magnetic coils. An axial magnetic field (up to 1.6 T) is used to confine the plasma in a ≈1 cm FWHM plasma beam which interacts with a water-cooled target situated 0.5 m downstream. Two roots pumps (with a $2 \times 4000 \, \text{m}^3\text{h}^{-1}$ pumping speed) are used to create the vacuum and exhaust the process gas.

2.2.2 Pulsed plasma source

A cascaded arc plasma source (fig. 2.1) is used to generate the high density plasma, as has been extensively described in [6]. Coupled with the strong axial magnetic field, the source creates high fluxes of hydrogen plasma. The source is typically powered by a DC current-regulated power supply. In this work we present an upgraded construction of the source designed to produce transient increases of the discharge current from 200 - 220 A up to 14.5 kA on a millisecond timescale. High power pulses are thus superimposed on the DC plasma, with the
aim of transiently increasing the power flux to the surface.

The pulsed plasma source (PPS) consists of six copper plates, a nozzle and one cathode (fig. 2.1). The thickness of the plates is 6 mm, and they are cooled by a water flow at 20 bars. The plates are electrically insulated from each other by 1 mm-thick boron nitride (BN) spacers with an inner diameter (φ18 mm) larger than that of the plasma channel (φ10 mm). The insulation ensures a gradual potential drop along the channel to avoid high gradients of electric field on the edge of plates. The total length of arc channel is \( L = 4 \) cm. The interior of the channel is made of molybdenum inserts with an inner diameter of φ10 mm and outer φ12 mm, to accommodate the high power density during a pulse and minimize the impurity content in the plasma. A tungsten cathode (φ6.4 mm) with a tapered tip is located at the end of the channel close to the gas inlet. Electrons are emitted thermionically from the cathode tip. New electrons are heated ohmically in the high density plasma. The current is carried mostly by electrons from the cathode to the grounded nozzle. The plasma flow is driven by the increasing gas velocity due to the pressure gradient between the arc channel and the vessel. The nozzle’s geometry (φ10.5 mm) has been chosen to optimize the source output [22].

Volumetric gas flow rate can be varied from 4 to 18 slm (standard liter per minute: 1 slm=4.42·10^{20}s^{-1}) corresponding to pressures of 0.044 - 0.210 mbar in the vacuum vessels and 30 - 80 mbar in the cathode chamber, respectively.

### 2.2.3 Electrical circuit

The core of the pulsed-power supply consists of 56 capacitors; the total capacitance of which is 8400 µF. They are joined in seven stacks of eight capacitors (7×1200 µF). Every stack is connected through a 70 µH coil to the cathode of the plasma source. The coil parameters determine the peak current (eq. 2.1) and the discharge duration which is \( \approx 1.3 \) ms. The energy stored in the capacitor bank is discharged in a fixed time determined by the inductance of the coil so that the peak current is tuned only by the charging voltage of the system, i.e.

\[
\tau \propto \sqrt{LC}
\]  

(2.1)

The charging time of the capacitor bank depends on the charging voltage (up to 5 kV) and is of the order of \( \approx 10 \) s. Once charged the power supply to the capacitors, is isolated from the circuit and the capacitor bank is connected to the plasma source. The capacitor bank is then coupled in parallel with the DC-power supply, so that the plasma source continues to operate before and after the capacitors are discharged into the source (fig. 2.2). An optical-fiber based system is used to control the discharge of the capacitor bank and synchronize the different diagnostics.
2.2.4 Diagnostics

The arc voltage is measured between cathode and nozzle (anode) and a Rogowski coil measured the arc current. The data is recorded by an oscilloscope with a time resolution of 0.4 $\mu$s. Plasma pulse velocity measurements are performed by a high resolution 2 m spectrometer combined with fast camera (Phantom V12.1) with frame rate of 4000 - 6000 fps to resolve the Doppler shift of hydrogen Balmer-$\beta$ line.

Radial profiles of electron temperature and density are obtained using single pulse of TS. Scattered light is collected by a detection system consisting of a fiber-optic bundle and a spectrometer that is equipped with an ICCD camera. The spectral broadening is measured to obtain $T_e$ while the integrated spectrum gives $n_e$ [23]. Owing to the high plasma density during a pulse and the high sensitivity of the TS detection system, measurements are possible with a single laser pulse (10 ns) nevertheless 4 - 5 laser pulses were averaged to improve statistics. This enables measurements of the temporal evolution of the plasma parameters during a generated pulse [24].

2.3 Results and discussion

2.3.1 DC arc-physical background

External power sources are needed to sustain the non-equilibrium plasma. The input power is dissipated in the arc and consumed by the production of new electrons and ions, by heating, radiation and conductive and convective energy losses.
Ion production in the source depends on power dissipation in the arc channel. This process can be described by the mass and energy balance of ions and electrons and neutrals such that temperature and densities are appropriate to sustain a stable discharge. Firstly, electrons are generated and then ohmically heated by the current driven through the channel. According to Ohm’s law (eq. 2.2) the input power is defined as

$$P_{in} = \sigma E_z^2 = j E_z$$  \hspace{1cm} (2.2)$$

where \( j \) is the current density, \( \sigma \) the electron conductivity, \( P_{in} \) the input power and \( E_z \) the axial electric field that is considered constant along the axial direction in the plasma channel. This energy is then transferred to the heavy particles via elastic and inelastic collisions. To maintain the plasma, the input power must be sufficient to compensate for the different losses. In the case of a hydrogen discharge, input power covers the demands for dissociation, ionization and heating in the absence of other losses(eq. 2.3).

$$P_{in} = \frac{n_e}{\tau_{loss}} \left( E_{ion} + E_{dis} + \frac{5}{2} kT_i + \frac{5}{2} kT_e \right)$$ \hspace{1cm} (2.3)$$

Depending on the conditions in the channel, different loss mechanisms are expected to dominate. If perpendicular transport to the wall is reduced by magnetic confinement then the majority of produced electrons and ion flow leave the source channel. The gas pressure drops rapidly at the exit. It is thus predominantly an axial flow and particle losses occur due to convection. In the absence of magnetic confinement, strong radial transport exists and then diffusive loss mechanisms dominate. If two main transport mechanisms are considered; convection and diffusion, then a characteristic loss time can be defined as eq. 2.4

$$\frac{1}{\tau_{loss}} = \frac{1}{\tau_{diff}} + \frac{1}{\tau_{conv}}$$ \hspace{1cm} (2.4)$$

A general simplified mass balance (eq. 2.5) can be proposed as a balance between ionization and losses as

$$n_e n_o k_{ion} \exp \left( \frac{-E_{ion}}{T_e} \right) = \frac{n_e}{\tau_{loss}} = \frac{n_e c_s}{L}$$ \hspace{1cm} (2.5)$$

The electron temperature needs to be sufficiently high for the ionization rate to equilibrate with convective and conductive losses. Combining the ion production rate \( (n_e n_o k_{ion}) \), convective ion loss \( (c_s n_e / L) \), channel geometry and equation of gas state \( (p = n_o kT) \), one can estimate the critical electron temperature (eq. 2.6) necessary for a DC discharge as [25]

$$T_e = \frac{E_{ion}}{ln(n_o \tau_{loss} k_{ion})}$$ \hspace{1cm} (2.6)$$
which yields $T_e$ values of 1 - 2 eV. At higher ionization rates, the plasma properties are determined by Coulomb interactions of charged particles. In non-equilibrium plasma, the electron temperature is higher than the heavy particle temperature. This implies that electrons determine transport due to the mass ratio between electrons and heavy ions. The electron conductivity is defined for a highly ionized gas by the Spitzer equation (eq. 2.7). For hydrogen the formula is given by [26].

$$\sigma_e = 2 \cdot 10^4 \frac{T_e^{3/2}}{\ln \Lambda} \left( \frac{1}{\Omega m} \right)$$  \hspace{1cm} (2.7)

If the plasma is not magnetized radial heat transport (eq. 2.8) is also dominated by electrons due to their high mobility.

$$\kappa_e = 1.6 \cdot 10^4 \frac{T_e^{3/2}}{\ln \Lambda} \left( \frac{W}{eV} \right)$$  \hspace{1cm} (2.8)

The cascaded arc source has previously been characterized both in hydrogen and argon, which have significantly different properties linked to their molecular structure and molar mass. A hydrogen ion is 40 times lighter than argon and thus has a higher mobility. In wall-stabilized arcs, one can distinguish two regions: an active ionization volume and a recombining boundary layer close to the source wall. For this reason, strong radial gradients of electron temperature and density exist and are determined by gas properties and conditions in the source (i.e. input power and pressure). A simplified approximation of this situation considers the filling fraction [27], which is defined as the ratio between the cross-sectional areas of the well ionized conductive core and the total arc channel. The transition between those two regions is actually not sharp, however the effective radius can be defined [28] as the position where the Coulomb collision rate is equal to the electron-neutral collision rate. The conductive core of arc is surrounded by recombining plasma, where the electron-neutral collisions become dominant. The conductivity drops significantly. In this case Ohm’s law (eq. 2.9) can be written as

$$I = 2\pi E_z \int_0^{r_{eff}} \sigma(r)rdr.$$  \hspace{1cm} (2.9)

The active core of a hydrogen plasma is limited by recombination at the wall surface (which acts as a sink) and in the volume by Molecular Assisted Recombination (MAR) [29]. The hydrogen ions experience a charge exchange reaction with excited molecules coming from the wall. This implies the existence of a hollow profile of neutral atomic particles that reaches a maximum at the wall and peaked profile of electron conductivity which is proportional to $T_e^{3/2}$ with a maximum at the axis of the arc.
2.3.2 Steady state arc without magnetic field

It was previously observed [6] that in the discharge current range of 150-900 A the axial electric field produced by the potential between the cathode and anode is constant \( E_z \approx 2500 \text{ V/m} \) and the radial \( T_e \) profile is flat in the central (ionizing) part for a source diameter of \( \varnothing 8 \text{ mm} \) and \( \varnothing 10 \text{ slm} \) of hydrogen. To satisfy Ohm’s law, \( r_{eff} \) increases with increasing power - the filling fraction becomes larger, and for current >1 kA approaches 100%. The volume of the active central plasma, which is responsible for ion production and therefore enlarges. Additionally it was shown that ion production efficiency increases from 3% to 10% with increasing input power in the range 10 to 45 kW [6]. This demonstrates that the gas efficiency (the ratio of ions produced to the injected gas atoms/molecules) is directly correlated with the active plasma volume which is a function of the discharge current - the higher the current, the more effective the ion production.

For steady state plasma, DC current of 200 A and 10 slm of hydrogen, the potential drop from cathode to anode is \( \approx 90 \text{ V} \) \( (E_z=2250 \text{ V/m}) \) and resistance is \( \approx 0.45 \Omega \). This flow rate ensures a pressure of 50 mBar around the cathode which is necessary for a stable discharge. The input power is 18 kW. Calorimetric measurements showed that under those conditions 11.1 kW is deposited in the cooling water of the plasma source. That means that 60% of the input power is transported through the boundary layer to the wall by heat conduction as a leading loss mechanism (eq. 2.10).

\[
Q_{in} = 0.6 \cdot P_{in} \tag{2.10}
\]

The plasma temperature in the active plasma is so high that one can neglect finite \( T_e \) at the wall, which varies between 0.5 - 1 eV [31]. Hence electron heat conduction (eq. 2.11) for this case is given by [6]

\[
Q_{cond}^e = 4.1 \cdot 10^4 \frac{T_e(r=0)}{r^2 \ln \Lambda} \tag{2.11}
\]

Substituting \( ln \approx 6 - 7 \) in eq. 2.11, the estimated electron temperature is \( \approx 2.2 \text{ eV} \) which is in good agreement with measured data by TS system \( (T_e=2.6 \text{ eV} \pm 0.3 \text{ eV}, n_e=7 \cdot 10^{20} \text{ m}^{-3} \pm 1 \cdot 10^{20} \text{ m}^{-3}) \).

We note that the criterion for an ideal plasma (eq. 2.12) is fulfilled, such that the number of particles \( (N_\lambda) \) in each particle’s Debye’s sphere

\[
N_\lambda = \frac{4}{3} \pi \lambda_D^3 n_e = 1.7 \cdot 10^{12} \frac{T_e^{3/2}}{\sqrt{n_e}} > 1 \tag{2.12}
\]

is much greater than unity \( (\approx 300 \text{ for DC, 900 - 1700 for pulse mode}) \), while simultaneously the Debye length is much smaller in comparison with the macroscopic dimension of the plasma \( (\lambda_D=0.53/0.35 \mu \text{m respectively}) \). This implies that the plasma can be considered as ideal and the basic Spitzer equation (eq. 2.7) can be applied [32]. Knowing \( T_e \) and having measured the arc resistance, one can
estimate the diameter of the active plasma by assuming a flat temperature profile \[27\]. Considering the geometry of the source, the ratio between the cross section of the active arc to channel is \(\approx 30\%\) giving \(r_{eff} \approx 2.7\) mm. If the current is increased, the active plasma volume broadens. The low filling fraction at low power densities is caused by MAR process in the edge of the plasma. \(H_2(r, v)\) molecules created at the wall cause charge transfer to \(H_2^+\) which can dissociatively recombine \[29\].

### 2.3.3 Pulse mode without magnetic field

Historically one of the first pulsed plasma experiments based on a wall stabilized source has been presented in \[7, 20\], albeit with slightly different conditions than those described here: both the pressure and current were pulsed and varied in a range 1.6 - 14 bar, 60 - 2200 A, respectively. The duration of the pulse was 2 - 5 ms. This yielded \(T_e = 2 - 3\) eV, \(n_e = 10^{24}m^{-3}\). In order to explore a higher current mode and heat the plasma to higher \(T_e\), the pressure in our setup is fixed and only the current is varied. Figure 2.3 illustrates the temporal evolution of the discharge current and voltage during a pulse. Both current and voltage increase during the pulse. Peak values of 14.5 kA and 450 V, respectively have been measured for the highest input power of 6.3 MW (charging voltage 1000 V). The pulse duration is seen to be about 1.3 ms. A reduction in the discharge voltage is observed after the pulse. Recovery to the pre-pulse values occurs after 2 - 3 ms. One can attribute this to a transient residual decrease of the plasma resistance due to active arc channel broadening and an increase of \(T_e\) and ionization degree during the pulse.

![Figure 2.3: An example of the temporal evolution of current and voltage during the pulse. Dashed line: voltage; solid line: current](image-url)
Figure 2.4: Peak values of voltage as a function of current for steady and pulse modes (dashed lines are placed to guide an eye). Filled circles: pulse mode; open: steady state measurements by Vijvers et al. [6] for an 8 mm channel; star: steady state for a 10 mm channel.

Figure 2.4 and fig. 2.5 show the relationship between the peak current during a pulse and the discharge voltage and resistance, respectively. For currents lower than 1 kA the discharge voltage stays constant, due to the increasing filling fraction \( r_{eff} \) (an increase of conductive plasma volume). It yields a drop of resistance \( R \propto I^{-1} \) from 0.6 to 0.1 \( \Omega \) for currents \(<1 \) kA. For currents above 1 kA the discharge voltage increases with increasing currents, but still the resistance drops with current to values as low as 0.03 \( \Omega \) in the current range 5 - 14.5 kA, the variation is roughly according to \( R \propto I^{-0.5} \). It was shown in [6] that for a power density of about \( 3.6 \times 10^{10} \text{W} \cdot \text{m}^{-3} \) (8 mm source, input power 65 kW, 900 A in fig. 2.4 represented by empty circles) the active plasma spreads out over almost the whole channel i.e. \( r_{eff} \approx 1 \). The diameter of the PPS is 10 mm, so the cross section of the arc channel is 36% larger but the power deposited in the plasma is 100 times larger with a power density of up to \( 1.7 \times 10^{12} \text{W} \cdot \text{m}^{-3} \). Considering that a power density of \( 3.6 \times 10^{10} \text{W} \cdot \text{m}^{-3} \) is needed to reach a filling fraction of 1 for a source with a 8 mm diameter channel, one can calculate the critical power density for a 10 mm source. This yields a current of 1.12 kA for the present source, in agreement with the measured data (fig. 2.4).

Knowing both the arc channel geometry (\( \varnothing 10 \) mm, length 40 mm) and that almost the whole channel is conductive an estimate of \( T_e \) inside the arc (for a given resistance) is then possible by means of the Spitzer equation (eq. 2.7). The average electron temperature is found to be in the range 3.5 - 4 eV (for a current range of 5 - 14.5 kA). This indicates that the input power is not fully used for
plasma heating and the energy from the core of the discharge diffuses quickly to the wall. On the other hand, the input power is expected to be fully dissipated in the plasma channel. Therefore using eq. 2.10 and eq. 2.11 electron temperature can be estimated as 5 - 11 eV respectively for a current range of 1.7 - 14.5 kA. As will be shown in next section, even higher temperatures are experimentally measured for the magnetically confined plasma due to plasma confinement and post heating effects.

### 2.3.4 Influence of magnetic field

In the absence of a magnetic field, the plasma is transported from the source to the target by expansion in the vacuum vessel driven by the pressure gradient along the beam. An axial magnetic field confines the plasma expansion. Radial electron-ion and heat transport is much reduced and thus losses to the wall decreases. This results in an increased particle flux to the target. The radial transport is disturbed due to the Hall effect, which is a limitation of the particle diffusion due to gyro motions. The Hall parameter (eq. 2.13) is defined as the ratio of the cyclotron frequency to the frequency of particle and is given by [33].

\[
H_{ei} = 6.2 \cdot 10^{22} \frac{T_e^{3/2} B}{n_e ln \Lambda} \tag{2.13}
\]

The Hall parameter for electrons varies from 130 - 140 in DC to 83 - 125 during a pulse and (assuming \(T_e=T_i\)) for ions is in the range \(T_e=2.6 - 15\) eV and
$n_e = 5 \cdot 80 \cdot 10^{20} \text{m}^{-3}$. An additional aspect of the magnetic field is that the electron current cannot go directly from the cathode to the anode anymore, but is forced by the magnetic field to travel along an external path via the plasma column and return via the outer layer of the plasma column to the anode \cite{34}. If $H_{ei} \gg 1$, as is the case here, the plasma is magnetized and radial transport (eq. 2.14, 2.15) is reduced. Electron thermal conductivity and electrical conductivity along magnetic field are then given respectively as

$$\kappa_{e||} = 1.6 \cdot 10^4 \frac{T_e^{5/2}}{(1 + H_{ei}^2) \ln \Lambda} \quad (2.14)$$

$$\sigma_{e||} = 2 \cdot 10^4 \frac{T_e^{3/2}}{(1 + H_{ei}^2) \ln \Lambda} \quad (2.15)$$

Convection starts to dominate because radial electron heat conduction and diffusion become very slow compared to axial transport. This leads to an increased density in the core of the arc or plasma beam \cite{35} due to strong confinement, preserving more energy inside the plasma core. The electron flux to the target increases and therefore the ion flux increases.

Figure 2.6: The relative temperature change of cooling water in the source plates. The magnetic field is on at $t=0$ but the drop in the water temperature appears $\approx 10$ s later due to the distance between the source and sensors ($\approx 15$ m). The dashed box shows the moment when the reduction of the cooling water temperature takes place due to the switching of the magnetic field.

Figure 2.6 shows the variations of the water cooling temperature of each plate in the source when the field is switched on. The heat load on plates 2, 3 and
Figure 2.7: Overall voltage-current characteristic for hydrogen, helium and argon. Every data point represents a peak voltage and current.

4 decreases when the magnetic field is switched on. This clearly shows that radial transport is reduced and energy is not transported directly to the wall anymore. The temperature of plate 6 increases slightly due to the heat transfer from the adjacent nozzle that receives the returning current and the majority of the output power. In the case of plate 5, the cooling and heating effect appear to compensate each other, thus temperature remains almost constant. The first plate (not presented on the plot) is always very hot due to the adjacent cathode tip. Due to its different geometry the surface facing the hot plasma is larger and therefore the amount of received heat is higher as well. The temperature of the cathode easily reaches more than 2500°C, oscillating around melting point, and radiates strongly to the surface of the first plate that is a few millimeters away from the hot tip.

The peak values of the discharge current and voltage during a plasma pulse are plotted in fig. 2.7 for different gases: H₂, He and Ar. The most striking fact is the observed linear behavior of all measurements independent of the gas species. Moreover data point obtained for an 8 mm arc channel diameter at 1.6 T (open circles) fit to the general trend of the 10 mm channel at the same field. This indicates that the observed trend is associated with electrons that dominate electrical and heat transport in the source.

At constant gas flow (10 slm) and charging voltage (600 V) the magnetic field is as varied in the range 0.4 - 1.6 T (by steps of 0.4 T). The arrow in fig. 2.7 indicates the direction of the field increase. For all gases, an increase of the discharge voltage with the magnetic field is observed. As stated above, the field hinders the current transport between cathode and anode by increasing the
current path and thus the resistance, which is consistent with these observations. However, it should be noted that since the magnetic field causes the current to propagate outside the source, the measured potential drop in fig. 2.7 consists of two components; inside the arc and outside the source (within the magnetized beam).

The arc resistance of the non-magnetized plasma is calculated according to Ohm’s law using the data from fig. 2.7. Figure 2.8 shows the evolution of the arc resistance as a function of current. It decreases from 0.3 to 0.03 Ω as the current increases from 0.7 to 14.5 kA. From eq. 2.7 this implies an increasing temperature with the current. Additionally, the resistance of the nonmagnetized plasma (fig. 2.8, empty stars) is lower than for the magnetized beam (all other data points), which is consistent with the expectations of Section 2.3.4. This is further illustrated in fig. 2.9.

Another important aspect of the magnetic field is associated with power dissipation in the plasma. The field hinders radial electron transport and extends the current path, which results in an increase of the voltage across the arc. These observations concern both steady and pulse mode. A comparison between the two cases is depicted in fig. 2.10. For a DC current of 200 A the cathode potential is ≈90 V (for 10 slm of H₂) which gives a steady-state power of 18 kW without field. In the case with magnetic field the cathode potential increases up to ≈180 V so that the power dissipated in arc and the beam is doubled to 36 kW. The enhancement of power dissipation by the magnetic field in pulsed mode is up to 600 kW.

Figure 2.8: Resistance of the arc as a function of peak cathode current during a pulse.
Figure 2.9: Comparison of the peak resistance of the pulse as a function of peak current with and without magnetic field.

Figure 2.10: Input power calculated from Ohm’s law as a function of current for a magnetized and non-magnetized plasma.
2.3.5 Electron temperature and density by TS

The influence of the peak discharge current on the peak density and temperature is described in fig. 2.11 and fig. 2.12. The measurements are done 4 cm downstream from the nozzle. The electron temperature increases with the discharge current in the range 6 - 15 eV. In contrast, the electron density is almost constant in the range 1.5 - 5 kA at $6 \times 10^{20} \text{m}^{-3} - 80 \times 10^{20} \text{m}^{-3}$. A strong increase in the density is measured between 200 A (DC) and 1.7 kA but the density increase saturates beyond this point. $T_e$ and $n_e$ were increased by a factor of $\approx 6$ and $\approx 15$, respectively relative to the steady state beam parameters ($T_e \approx 2.6$ eV, $n_e \approx 7 \times 10^{20} \text{m}^{-3}$ at 0.2 kA).

![Figure 2.11: Evolution of the electron temperature as a function of the discharge current (the dashed line is an exponential fit to the data points). The insert presents the same data on a double logarithmic scale.](image)

The evolution of temperature (fig. 2.11) with the current is a projection of the relation between electron heat conduction and Joule term. The power dissipation becomes less efficient due to the increasing $T_e$ which decreases the resistivity and increases the conductivity ($\sigma$) making the Joule term ($j^2/\sigma$) smaller thus the dissipated power is lower as well. Therefore, it is not possible to proportionally increase $T_e$ with current. Equating eq. 2.11 where the Joule term is expressed by current density ($j$) and Spitzer conductivity ($\sigma \propto T_e^{3/2}$) shows the expected $T_e$ scaling with current:

$$T_e^{7/2} = \frac{j^2}{\sigma(T_e^{3/2})} \Rightarrow T_e^5 \propto j^2 \Rightarrow T_e \propto j^{0.40} \quad (2.16)$$

23
The dashed line in fig. 2.11 represents an exponential fit: $T_e \propto I^{0.39\pm0.1}$ in very good agreement with exponent in eq. 2.16.

The density saturation is in agreement with full ionization of the plasma beam. Plasma is expected to be fully ionized in the arc center (source channel) whilst at the edge recombination processes take place and $n_e$ values rapidly fall-off close to the wall. On the other hand, the neutral density profile is hollow and reaches its maximum at the wall where the temperature of the gas is low. With increasing current, $n_e$ and $T_e$ profiles slightly develop from peaked at lower currents to broad and flat at the higher currents. There are still neutrals at the edge but at high currents the full flow becomes ionized. The excess of energy injected into the arc is therefore invested in plasma heating up to 15 eV. Such an efficient $T_e$ rise is possible due to the structure of the hydrogen atom: its single electron is stripped immediately and the plasma becomes a mixture of protons and electrons. Therefore, it is easy to further heat the gas because the energy cannot be consumed into further (multiple) ionizations or other excitations, such as in the cases of helium or argon, but results in an increase of the kinetic energy of the particles. For instance in [7] an Ar plasma reaches temperature 2-3 eV at current pulse of 2.2 kA, whilst in pure hydrogen $T_e$ is 12 eV in this current range (fig. 2.11) in our experiment. The only losses that can occur in the fully ionized hydrogen plasma far away from the walls are associated with electron (heat) conduction. For the same reason the density cannot increase any further for a given gas flow. At currents higher than 5 kA, an impurity release from the source affects this picture. Details of this will be described in Chapter 3.

One can demonstrate that for the magnetized arc discharge, most of the power
is actually dissipated in the beam i.e. outside the source. As mentioned previously, the I-V characteristic measured in the presence of a strong magnetic field consists of two components (arc and beam) and it is not straightforward to distinguish directly the relative contributions of the source and beam. Assuming that the temperature variation between the source and the TS measurement location (located 4 cm downstream) is small, the voltage/resistance drop can be estimated according to Spitzer formula using the temperature measured by TS. Considering the critical case, where plasma parameters in the source channel (with the field on), are at least equal to those measured by TS (fig. 2.11): 10-15 eV, one can calculate the resistance across the arc length and compare it to the total resistance measured by the scope. Results are presented in fig. 2.13. At 4.3 kA the ratio between total and arc resistance is about \(\approx 20\). This ratio correlates with the one of total current path to arc length. The electrons are fully magnetized (at 1.6 T, \(H_e=130\)) therefore, the total current path can be considered as two times the distance between source and target (2\(\times\)0.5 m). Hence the ratio between the total current path to the arc length is \(\approx 25\). This might explain the reason of higher resistance in the magnetized beam. The conclusion is that the majority of the power is dissipated in the beam and the source contribution decreases with current due to the increasing \(T_e\). This means that the power dissipated in the discharge is efficiently transferred to the beam increasing its \(T_e\) and \(n_e\) and hence heat flux to the target.

Figure 2.13: Triangles: the contribution of resistance associated with the arc (calculated according to the Spitzer equation and TS data). Squares: measured resistance of the arc and beam combined together. The insert represents the ratio between total and arc resistance.
2.3.6 Plasma velocity

Optical emission spectroscopy (OES) was performed to elucidate the evolution of the axial velocity of plasma both in DC and pulsed mode. The light is collected by an array of 40 optics fibers (0.4 mm in diameter) focused about 4 cm (i.e. at the location of TS measurements) downstream from the nozzle, with an angle of 10° relative to the beam’s axis. The light is transmitted to the spectrometer in Littrow configuration to measure the Doppler shift of hydrogen Balmer-β line (486.13nm) with respect to the un-shifted model line of a hydrogen lamp. The light is resolved by a grating with a groove density of 1200/mm, and size 11×11 cm. The focal length of the optical system is 2.25 m. A double Voigt profile [34] is fitted to the measured spectra to measure the shift of the Balmer-β line with respect to the position of line obtained from a calibration lamp. The velocity is calculated according to eq. 2.17.

\[ \lambda = \lambda_{\text{lamp}} \left(1 \pm \frac{v}{c}\right) \]  (2.17)

The information about ions is available by OES of excited (n=4) neutral atoms due to the strong coupling of neutrals and ions [35]. This stems from the much longer characteristic radiation time of Balmer-β line (3 - 6×10^{-8} s) [35] comparing to the time constant of the charge exchange reaction (1.3×10^{-9} - 7.1×10^{-11} s) estimated for presented experimental conditions according to Janev [36]. Therefore the line emission gives a prompt record of the conditions of the fully ionized hydrogen.

![Figure 2.14: The axial velocity of the plasma measured 4 cm downstream from the nozzle in DC and pulse regimes. The dashed line represents an exponential fit to the data.](image-url)
Figure 2.14 presents the axial velocity of the plasma in DC and pulse. The velocity increases from \( \approx 3 \text{ km/s} \) (DC) up to 20 - 25 km/s during the pulse. The curve shows the velocity dependence on current \( (v \propto j^{0.2}) \). This indicates that the speed correlates with plasma temperature: \( v_{th} \propto T_e^{0.5} \) and \( T_e \propto j^{0.4} \). Hence the dependence between speed and \( T_e \) scales as \( v_{th} \propto j^{0.2} \). This means that the ion flow increases by a factor of 70 considering the ten-fold increase of electron density which demonstrates a significant improvement of ion production during the pulse.

### 2.4 Conclusions

The effect of a transient increase of the discharge current and magnetic confinement on the plasma production of a cascaded arc discharge was studied. For currents higher than 1 kA, the filling fraction of the arc reaches 100%. The IV characteristic goes from a flat gradient for currents of up to 1 kA (constant voltage across the arc) to a positive gradient above this, while at the same time the electron temperature of the plasma is found to increase with input power. In case of a strong magnetic field (1.6 T) the radial losses to the wall by electron heat conduction are attenuated, because charged particles are insulated from the cold wall preventing heat diffusion. This was demonstrated by a drop of cooling water temperature in some source components: the heat flux is reduced while field is on. This implies that the main loss mechanism is switched from radial electron heat conduction to axial convection. Since electrons and ions are separated from the colder region, the energy dissipation becomes more efficient and full ionization is reached. No more neutrals can be ionized, so the excess of energy is consumed for plasma heating thus electron temperatures reaches 15 eV. With the magnetic field on, the majority of energy is dissipated in the external beam outside of the plasma source. Plasma velocity is measured to be in the range of 22 - 25 km/s i.e. seven times higher than in DC indicating an increased ion flow leaving the source.
Chapter 3

Power and particle transport in a pulsed magnetized plasma beam

Abstract
The first issue described in this work is the transport efficiency of plasma from the source to the target which is discussed in terms of losses due to recombination along the beam. Pulsed plasma is characterized by high $T_e$ up to 15 eV and $n_e$ up to $10^{22} \text{m}^{-3}$. $T_e$ and $n_e$ do not decrease significantly along the beam during the pulse until peak current reaches 4.3 kA. This indicates the small influence of MAR, in contrast to the case of low current (0.2 kA) steady state plasma, where recombination is the dominating process and $T_e$ is determined by classical plasma equilibrium. Above this 4.3 kA threshold the plasma heating is limited and $n_e$ steeply increases suggesting the appearance of a source of neutrals. The second aspect tackled in this work considers the impact of source wall material (i.e. impurity in the plasma) on the quality of plasma performance. Analysis of data collected by plasma sources made out of copper and molybdenum were found to produce plasma of different $T_e$. The proposed reason is impurity ejection from the wall of the copper source to the plasma. This process is more pronounced in case of Cu-source due to the much lower melting point and sputtering threshold in respect to Mo. Injection of model impurity (argon) into the hydrogen flow reinforces this observation. The calculation of $T_e$ both in pure and contaminated plasma stays in a good accordance with measured values by TS which validates our assumptions and model. This implies that impurity appearance induces the change of power dissipation mechanisms from electron heat conduction (in pure H$_2$) to radiation in a H$_2$ - Ar mixture.
3.1 Introduction

The interaction between plasmas and surfaces has a dual nature being both extremely beneficial for plasma-assisted synthesis and processing of materials [37], and potentially very detrimental when it comes to the interaction of the magnetically confined plasma with surrounding plasma-facing materials in the next step fusion energy tokamak - ITER [38]. In the latter case, surfaces are exposed to heat and particle fluxes of up to $10 \text{ MW} \cdot \text{m}^{-2}$ and $10^{24} \text{m}^{-2} \text{s}^{-1}$. In addition, plasma instabilities such as ELMs can induce extreme transient heat fluxes (several GW·m$^{-2}$) for 0.5-1 ms [39] which could lead to erosion, melting and vaporization of the plasma-facing materials [40].

Plasma generators with high intensity plasma flows provide a practical way to test the behavior of materials under excessive particle and energy fluxes. Those devices have been used in particular in relation to atmosphere re-entry problems [41]. For fusion-related issues, the necessity of operating the plasma source in hydrogen (or deuterium) with high ion fluxes and low pressure sets extra requirements on the plasma generator as it requires a high injected flow and a low pressure. Two related approaches have been followed in the past having in common the use of a magnetic field to limit diffusion and heat losses and thus provide high electron temperature/density on the plasma-exposed target. The first approach is to use axial electrostatic confinement to build-up electron density, the applied potential between anode and cathode, accelerates the ion flow to the surface. The PISCES facilities at UC San Diego work on that concept [42, 43]. The second approach is to use a hot hollow cathode source and guide the plasma to the target [44]. The present approach is along the second line, however with a thermal plasma (cascaded arc) source and very intense pumping to keep the pressure sufficiently low [35]. In order to provide the possibility to study the effect of simultaneous continuous and transient plasma effects, the plasma source is additionally pulsed to high currents to reach densities close to $10^{22} \text{m}^{-3}$ and electron temperatures up to 15 eV [46].

Previous work [46] has focused on the effect of the magnetic field and the transient current increase on the plasma properties in the source. Here the transport of plasma from the source to the target area is examined which has to be large enough to allow for differential pumping and diagnostic access [5]. We will show that in the plasma column, as in the source, the plasma conditions are determined by local plasma and particle balances. The presence of impurities, induced by the high heat loads in the plasma source, and molecular gas around the plasma column also influence the plasma properties and source efficiency. Finally, the effect of plasma recycling at the target will be shown to strongly affect the near-surface plasma.
3.2 Experimental set-up

The pulsed cascaded arc source described in details elsewhere [46] was installed on the Pilot-PSI linear plasma device, which is designed for the study of plasma-surface interactions under fusion relevant plasma conditions. The machine consists of a 1.2 m long, 0.4 m diameter vacuum vessel placed inside 5 magnetic coils. An axial magnetic field (up to 1.6 T) is used to confine the plasma in a ≈1 cm wide plasma beam which interacts with a water-cooled target situated 0.5 m downstream. Two roots pumps (with a $2 \times 4000 \text{ m}^3\text{hr}^{-1}$ pumping speed) are used to create the vacuum and exhaust the process gas.

The cascaded arc plasma source has been modified to allow for transient increases of the discharge current from the DC values (200 A) up to 14 kA on a millisecond timescale. High power pulses are thus superimposed on the DC plasma, with the aim of transiently increasing the power flux to the plasma-exposed surface.

The core of the pulsed-power supply consists of 56 capacitors; the total capacitance of which is 8400 µF. They are joined in 7 stacks of 8 capacitors ($7 \times 1200 \mu\text{F}$). Every stack is connected through a 70 µH coil to the cathode of the plasma source. The coil parameters determine the peak current and the discharge duration which is ≈1.3 ms. The energy stored in the capacitor bank is discharged in a fixed time determined by the inductance of the coil so that the peak current is tuned only by the charging voltage of the system. The charging time of the capacitor bank depends on the charging voltage (up to 5 kV) and is of the order of ≈10 s. Once the capacitor bank is charged, the power supply is isolated from the circuit and the capacitor bank is connected to the plasma source. The capacitor bank is then
coupled in parallel with the DC-power supply so that the plasma source continues to operate before and after the capacitors are discharged into the source. An optical-fiber based system is used to control the discharge of the capacitor bank and synchronize the different diagnostics.

Radial profiles of electron temperature and density are obtained using single pulse TS [23]. Scattered light is collected by a detection system consisting of a fiber-optic bundle and a spectrometer that is equipped with an ICCD camera. The spectral broadening is measured to obtain $T_e$ while the integrated spectrum gives $n_e$. Owing to the high plasma density during a pulse and the high sensitivity of the TS detection system, measurements are possible with a single laser pulse (10 ns) nevertheless 4 - 5 laser pulses were averaged to improve statistics. This enables measurements of the temporal evolution of the plasma parameters during a generated pulse at the source and the target (fig 3.1) [22].

3.3 Results

3.3.1 Influence of the discharge current on the plasma at the source (upstream)

Figure 3.2 presents the evolution of the electron temperature and density with the peak discharge current during a pulse, measured about 4 cm from the plasma source exit. Plasma parameters measured with a 200 A DC current while the other data points have been obtained when pulsing the input power. A strong increase in plasma production is observed when increasing the discharge current from $T_e=2.5$ eV and $n_e=6\cdot10^{20}$ m$^{-3}$ at 200 A up to $T_e\approx15$ eV and $n_e\approx10^{22}$ m$^{-3}$, respectively, at 4.3 kA. It was shown [46] that in the range 0.2 - 4.3 kA, the electron temperature depends on the discharge current as $\propto I^{0.4}$ (Chapter 2) which was derived from equating the electron heat conduction term ($\propto T_e^{7/2}$) of fully ionized hydrogen with the ohmic term which represents the power dissipation in the plasma ($\propto T_e^{-3/2}$). The evolution of the electron temperature is then understood until 4.3 kA as indicated by the good agreement between the dotted line and the experimental data points. Above 4.3 kA, a strong deviation is observed. The measured data points lie below the modeled curve i.e. the measured temperature does not increases with discharge current as anticipated. Simultaneously, the electron density remains almost constant up to 4.3 kA and starts increasing above this value (fig. 3.2).

It is also interesting to note that the evolution of $T_e$ with current shows a deterioration effect. The circle points in fig. 3.2 were obtained during a monotonic increase of the current. Subsequently, measurements were repeated at lower currents at 3.04 and 5.64 kA (triangles in fig. 3.2). The measured temperatures were then systematically lower than those obtained during the initial scan.

Figure 3.3 demonstrates the radial profiles of electron temperature and density of high (4.3 kA) and low (0.2 kA) current. One can see a great improvement of
Figure 3.2: The electron temperature and density (upstream) measured 4 cm from the plasma source as a function of current with fixed flow of 10 slm H₂ at 1.6 T. The rapid increase in $T_e$ stops above 4.3 kA whilst $n_e$ starts increasing beyond this current. Triangles represent temperature deterioration due to possible source damage.
The diameter of beam is about 1 cm independently of current. Both electron and temperature profile are Gaussian apart from the density profile at low current which is hollow.

### 3.3.2 Plasma at the target (downstream)

A similar characterization of the plasma density and temperature has been carried out at a distance of 2 cm from the plasma exposed target, and about 0.5 m from the source exit (fig. 3.4). Plasma parameters are typically found to be lower at this position than close to the source while the general evolution, i.e. almost constant plasma density and increasing electron temperature up to 4.3 kA, is qualitatively similar at both locations. At 200 A, \( T_e \leq 1 \text{ eV} \) and \( n_e = 2.5 \times 10^{20} \text{ m}^{-3} \) are measured, while \( T_e \approx 12 \text{ eV} \) and \( n_e \approx 50 \times 10^{20} \text{ m}^{-3} \) are observed at 4.3 kA (fig. 3.4).

Above 4.3 kA, however, the evolution of the downstream plasma parameters differ significantly from that of the upstream plasma. A monotonic decrease of the electron temperature is observed in the range 4.3-12 kA (down to \( \approx 3 \text{ eV} \) at 12 kA) despite the increasing input power. In parallel, a doubling of the electron density is observed in the same current range.

### 3.3.3 Influence of the vessel pressure

Figure 3.5 shows the evolution of the peak \( T_e \) and \( n_e \) in pure hydrogen plasma as a function of arc channel pressure, for a peak current of 4.3 kA and a magnetic field of 1.6 T. Since the pumping speed is fixed, the pressure in the vessel is fixed by the flow of the process gas into the source. Several trends can be observed from fig. 3.5. First, an increase of the electron density and a corresponding decrease of the electron temperature is observed with increasing pressure. Second, despite a higher magnetic field, the density of mixed argon/hydrogen plasmas is significantly higher than that of pure hydrogen plasmas. At the same time, the electron temperature of argon-containing plasmas is lower than that of pure hydrogen plasmas. In pure hydrogen plasma \( T_e \) drops slightly from 5 to 4 eV whilst density rises from \( 20 \times 10^{20} \text{ m}^{-3} \) to \( 40 \times 10^{20} \text{ m}^{-3} \). In case of hydrogen-argon mixture at the same conditions the electron temperature is lower at 3.5 eV and the density is higher \( (25 \times 10^{20} \text{ m}^{-3} - 100 \times 10^{20} \text{ m}^{-3}) \), compared to the pure hydrogen.

### 3.4 Discussion

#### 3.4.1 MAR in DC and during the pulse

Electron temperatures and densities affect the kinetics of ionization-recombination reactions and establish the mean free paths for diffusive processes. The maximum reaction rate for MAR observed in a linear plasma generator is in a \( T_e \) range 1 - 2 eV [29]. Therefore losses of power flux along the beam are significantly different
Figure 3.3: Demonstration of electron temperature and density enhancement due to the pulse shown in radial profiles for low (0.2 kA) and high (4.3 kA) current cases in the upstream plasma. Hydrogen flow was 10 slm, magnetic field 1.6 T.
Figure 3.4: The peak electron temperature and density downstream, measured $\approx 2$ cm from the target (10 slm of $\text{H}_2$, 1.6 T). $T_e$ increases with current then drops after the current threshold, whilst simultaneously $n_e$ rises beyond this point indicating the appearance of new electrons in the system coming from the outgassing target.
in DC and pulse mode. At low currents (as in DC) losses due to MAR are significant because of the low electron temperature. In these circumstances the plasma is recombining. The pulsed mode is much more efficient in terms of power transport due to the high electron temperatures and densities - the pulsed plasma is ionizing.

For instance an electron heat conduction \( \kappa \propto T_e^{7/2} \) and an electron conductivity \( \sigma \propto T_e^{3/2} \) calculated both for DC and pulse demonstrate a difference of transport efficiency between these two modes. These are strong functions of \( T_e \) thus pulsed plasma due to its high temperature has more efficient transport than DC mode as the following values indicate: \( \kappa_{\text{pulse}}/\kappa_{\text{DC}} \approx 10 - 15 \) while \( \sigma_{\text{pulse}}/\sigma_{\text{DC}} \approx 50 - 80 \).

MAR is the main process responsible for the loss of power flux in Pilot-PSI [29]. This process consists of two main steps; firstly a charge exchange (CX) reaction (eq. 3.1) occurs between a hydrogen ion (coming from the core of the beam) and ro-vibrationally excited neutral hydrogen molecule coming from the volume surrounding the beam.

\[
H^+ + H_2 (r, \nu) \rightarrow H(1s) + H_2^+ (r, \nu)
\]  

(3.1)

This reaction is followed by dissociative recombination of the \( H_2^+ \) with an electron (eq. 3.2).

\[
H_2^+ (r, \nu) + e^- \rightarrow H^*(n = 3) + H(1s)
\]

(3.2)

The efficiency of MAR will depending on the local plasma conditions and will thus
change when varying the source current. Considering the DC regime MAR is a dominating process in the majority of the beam volume, especially downstream where the plasma is cooler and less dense. Upstream, the recombination occurs only at the beam periphery due to the low $T_e$ at the edge ($\approx 1$ eV) compared to the center where it is $\approx 2.5$ eV. At this location in the core, $n_e$ is of order of $10^{21}$ m$^{-3}$. At these high electron densities the mean free path of hydrogen neutral molecules (diffusing into column) is small ($\approx 1$ mm). This distance is relatively short compared to the beam diameter ($\approx 10$ mm) and thus in the core plasma MAR is not present and recombination is weak or absent. This means that further penetration of H$_2$ is attenuated by charge exchange (eq. 3.1). This process is followed by ionization if the density exceeds $10^{20}$ m$^{-3}$ and $T_e$ is sufficiently high ($\approx 3$ eV). This is the case for the DC regime close to the source. Therefore the DC plasma is ionizing upstream in the vicinity of the axis and recombining on the edge whilst the downstream plasma is recombining in the full volume of the beam due to the low $T_e \approx 1$ eV and $n_e < 3 \cdot 10^{20}$ m$^{-3}$.

In the case of the pulse, the situation is drastically different. MAR can only occur far from the beam center because of the large increase of the electron temperature and density in the center of up to 10 - 15 eV and 40-10$^{20}$ m$^{-3}$ - 60-10$^{20}$ m$^{-3}$, respectively. The hydrogen gas is fully ionized and the high electron density prevents any neutrals from diffusing into the plasma. MAR is therefore disabled in the core of the plasma and occurs only residually at the edge. The losses of power flux are therefore significantly reduced.

### 3.4.2 Evolution of plasma parameters with current

#### DC and pulse

The electron temperature in a recombining plasma is determined by existence demand. It follows directly from the mass balance that the $T_e$ in the source has to be such that the net ion production counterbalances the convective ion flow [25] leaving the channel of the source. Both up- and down-stream electron temperature are established by the competition between ionization and recombination. One can estimate $T_e$ according to formula (eq. 3.3) derived in section 2.3.1.

$$T_e = \frac{E^\text{ion}}{ln(n_o k^\text{ion} \tau)}$$ (3.3)

At low currents (DC) the plasma is not fully ionized thus $T_e$ is determined by equation 3.3, where $n_o$ is a neutral density, $k^\text{ion}$ - ionization rate, $\tau$ - a convective time loss. The temperature thus depends on source gas flow [6]. The increase of $T_e$ with current results in the gradual disappearance of neutrals in the beam. The possibility of collisions between ions and neutrals decreases and recombination is attenuated. Once the power density ensures full ionization (in our system this occurs above 1.7 kA [46]) the loss mechanism is switched from radiation to electron heat conduction thus an efficient plasma heating is possible.
Upstream plasma

It was previously shown [46] that plasma parameters upstream (close to the nozzle) are significantly increased by superimposition of a current pulse to the DC discharge. Within the current range, 0.2 kA to 4.3 kA the power density rises from $10^{10}$ W·m$^{-3}$ to $10^{12}$ W·m$^{-3}$ over the pulse. It was demonstrated that the majority of this additional power is dissipated in the external plasma column, i.e. outside the plasma source, increasing $T_e$ and $n_e$ from 2.5 eV and $6 \cdot 10^{20}$ m$^{-3}$ (DC) up to 15 eV and $80 \cdot 10^{20}$ m$^{-3}$, respectively. The electron temperature was found to vary with the current ($T_e \propto I^{0.39\pm0.1}$) in good accordance with expectations ($T_e \propto I^{0.4}$) based on theory accounting electron heat conduction as a main loss mechanism in the pure fully ionized hydrogen plasma. Conversely $n_e$ remains at relatively constant level due to the full ionization of the input gas.

The trends changes for currents above 4.3 kA. Figure 3.2 shows upstream $n_e$ as a function of current. The increase of density from 50 - $70 \cdot 10^{20}$ m$^{-3}$ up to $10^{22}$ m$^{-3}$ above 4.3 kA implies that more and more electrons appear whilst in a pure plasma this would not be expected - since full ionization has already occurred. For this reason, an external electron source has to be present in the system. Since the power density inside the source is significant at high currents, the possibility of impurity generation from the source wall has to be investigated. Historically, the source was made of copper but significant damages occured (plate melting) during pulsed operations, and molybdenum was later used as a source material.

Figure 3.7 summarizes all the measurements done with those 2 different sources in terms of peak temperature and density. Data points were collected both at the target (downstream) and at the source (upstream).

The data can be organized within two regimes. One group of data points (called the high temperature regime) shows increasing $T_e$ up to 15 eV (circles) with increasing plasma densities. The other group (the low temperature regime) is characterized by saturating $T_e$ at 4 - 5 eV and increasing electron density up to $150 \cdot 10^{20}$ m$^{-3}$ (squares). The high $T_e$ regime could only be reached with a plasma source with molybdenum walls. The other regime was consistently observed for a copper-based source, or in the case of a molybdenum source, close to the target and at currents above 5 kA. Since the melting point of molybdenum (2623°C) is considerably higher than that of copper (1084°C), and considering that significant melting of the copper source wall was observed post mortem, one can infer that impurities being released from the source could significantly affect the plasma production during a high current pulse. Since it is difficult to quantify the amount of copper being released during a pulse, experiments were carried out with addition of argon to the hydrogen gas in order to quantitatively assess the role of impurities on the plasma parameters.
3.4.3 Role of impurities - experimental evidence

As a model impurity argon was used because of its well documented energy structure [18] and relatively low requirements for first ionization/excitation. The temporal evolution of the plasma density and temperature were measured close to the source for similar magnetic fields (1.6 T) and injected gas flows. In one case, a pure hydrogen plasma was used, while in the other case, the injected flow was a mixture of 5:1 ratio hydrogen and argon. Results are summarized in figure 3.6. For the Ar - H$_2$ mixture, the electron density follows the current trace, while the electron temperature reaches its maximum value very early during the pulse and then remains almost constant. This demonstrates clearly that incoming power is constantly used for the production of new electrons through ionization.

On the other hand one can observe in fig. 3.6 (up) that in the case of a pure hydrogen plasma $T_e$ rises up to 15 eV at 3.7 kA while the density remains almost constant during the pulse. In this case, full ionization is reached early during the pulse and additional input power is solely used for electron heating.

3.4.4 An overview of electron temperature and density

Quantification of the effect of argon addition

The effect of argon on the evolution of the plasma parameters during a pulse can be quantified by an estimate of electron temperature obtained from a simple power balance. Power conservation can be expressed by the Elenbaas-Heller equation that represents the local power balance of a plasma column/arc. The ohmically dissipated power is balanced by electron heat conduction (EHC) to colder regions/walls and radiation losses (eq. 3.4). In the case of a hydrogen/argon plasma, radiation becomes the dominant energy loss and in the following only two terms will be considered: Joule heating and radiation.

$$P_{\text{Joule}} = P_{EHC} + P_{\text{radiation}}$$

The radiation power needs to be defined. Only radiation of Ar$^+$ will be taken into account because at high currents Ar$^+$ is the pre-dominant argon particle. Furthermore, the gaps between energy levels in the argon II and III systems are wider compared to hydrogen neutral atoms (which are occasionally present in fully ionized gas) and so more energy escapes via argon emission at those conditions as de-excitation rates $\propto \Delta E$. Saturation of excited levels of Ar$^o$ occurs easily [45] at our experimental conditions $0.5 \cdot 10^{21}$m$^{-3}$ and any further excitation leads directly to ionization. At this high enough electron density (above $10^{21}$m$^{-3}$) excitation rate upward from level 2 to 3 ($k_{23}$) becomes faster than de-excitation to the ground state ($A_{21}/n_e = k_{21}$). This implies that fast ionization of Ar$^o$ occurs almost immediately whilst ionization of Ar$^+$ is energetically very demanding. Having singly ionized argon, the energy will be used now for excitation of Ar$^+$. The energy gaps between these states are in a range of 20 - 27 eV.
Figure 3.6: The temporal evolution of peak electron density (squares) on the left axis and temperature (circles) on the inner right axis, and the peak current temporal evolution during the pulse (outer right axis). Top: upstream in a pure hydrogen plasma (10 slm, 1.6 T). $T_e$ follows the current trace due to the ohmic power dissipation whilst $n_e$ is constant over the pulse due to the full ionization. Bottom: downstream in a mixed hydrogen and argon plasma (10 slm H$_2$ + 2 slm Ar, 1.6 T). $T_e$ saturates whilst $n_e$ follows the current. The situation is inverted: $n_e$ follows the current and $T_e$ is constant due to impurity radiation.
Figure 3.7: The influence of impurities on plasma performance (10 slm H$_2$, 1.6 T). The plasma source made out of copper (squares) produces plasma of low $T_e$ (<5 eV) and higher densities whereas the molybdenum source generates $T_e$ of up to 15 eV and lower density (circles). This indicates radiation losses are generated by copper atoms in the plasma which are not present in a molybdenum source. The addition of argon to a hydrogen plasma when using the molybdenum source reproduces results characteristic of copper source (triangles) illustrates this further.

For this reason the power loss of the system narrows to Ar$^+$ radiation which means that the power balance can be simplified to a balance between Joule heating and radiation losses of Ar$^+$. One can derive a power law for $T_e$ estimation by combining dissipated power (eq. 3.5) with radiation losses (eq. 3.6).

The Joule term is expressed by current density ($j$) and Spitzer conductivity ($\sigma$), which is proportional to $T_e^{3/2}$. This gives

$$P_{Joule} = \frac{j^2}{\sigma} = \frac{\ln \Lambda}{2 \cdot 10^4 T_e^{3/2}} \left( \frac{I}{\pi r^2 P_{shape}(j)} \right)^2$$

(3.5)

where $\ln \Lambda$ - is the Coulomb logarithm (7 - 9 under our experimental conditions), $I$ - the current, $j$ - current density, and $r$ - the radius of the active plasma beam ($\approx 0.5$ cm). $P_{shape}(j)$ is a shape factor that expresses the current profile in the plasma beam. The higher the current the broader the current profile.

The radiation term (eq. 3.6) is the product of the total excitation and ionization rate ($k_{Ar^+}$) of the Ar$^+$ system. The electron and Ar$^+$ ions densities ($n_e \approx n_{Ar^+}$) and the average excitation energy $\Delta E$. $f_{Ar^+}$ is the argon fraction in the gas mixture (0.1). Argon is expected in this model to be singly ionized. $k_{Ar^+}$
Figure 3.8: The upstream electron temperature of an argon-hydrogen mixture (10 slm of H$_2$, 2 slm of Ar, 1.6 T). The dashed line shows a fit using the solution of eq. 3.7, it represents the expected $T_e$ due to the impurity (argon) presence in the hydrogen plasma. The good agreement between modeled and measured $T_e$ indicates that the main power loss mechanism is associated with the radiation of multielectron atoms present in the hydrogen plasma.

strongly depends on electron temperature, and varies with temperature roughly as $k_{Ar^+} \propto 5 \cdot 10^{-17} T_e^{3.3}$ according data in the temperature range 3.5 - 10 eV [18].

$$P_{rad} = k_{Ar^+} n_e n_{Ar^+} f_{Ar^+} \Delta E$$

(3.6)

By combining eq. 3.6 and 3.5 the dependence of $T_e$ on discharge current $I$ is derived (eq. 3.7).

$$P_{Joule} = P_{rad} \rightarrow T_e = 1.31 \cdot \left( \frac{I}{P_{shape}(j)} \right)^{0.2}$$

(3.7)

Figure 3.8 shows the comparison between experimental data and predictions according to presented model. The calculated electron temperature follows the data points quite closely. The governing process that causes $T_e$ saturation faster ($I^{0.2}$) than it would be expected for electron heat conduction ($I^{0.4}$) only can thus be attributed to argon radiation. Impurities in the plasma would thus lead to a lowering of the electron temperature.

One can now understand the two different regimes shown in fig. 3.7. The high temperature regime corresponds to a pure hydrogen plasma for which full ionization is reached and further power increase leads to electron heating. The low temperature regime is a consequence of impurity injection in the plasma caused
by excessive heat loads in the source and evaporation/melting of its copper components. In this case, as was described above, the electron temperature increase is limited by impurity ionization and radiation losses. A confirmation of this assumption, besides the measurements made with a hydrogen/argon mixture, is the observation of copper deposition on the plasma exposed target at high currents, the details of which will be published elsewhere.

As mentioned above, however, even in the case of a molybdenum source, the temperature increase is found to saturate for currents above 6 kA. Following our previous reasoning, this might indicate a damage threshold for the molybdenum wall of the plasma source.

**Downstream plasma**

The evolution of the downstream electron temperature reveals a dramatic collapse specifically for currents above 4.3 kA. $T_e$ decreases starting from 12 eV (4.3 kA) to 3 eV (12 kA) and simultaneously $n_e$ rise is observed (fig. 3.4). The mechanism invoked to explain the evolution of the upstream parameters cannot account for such an effect and another mechanism seems to be important. Since the plasma parameters are measured very close to the target, and since the wall is an ideal sink for the plasma particles striking the solid, the effect of the plasma-exposed target on the near-surface plasma needs to be examined in details. First of all, since the electron temperature is at most 12 eV close to the target, the ion energy will remain lower than 60 eV during the pulse. The particle reflection coefficient for such low-energy hydrogen ions on a tungsten surface is higher than 65% while the energy reflection coefficient is higher than 43%. Under those conditions, the flux of particles reflected from the surface is of the same order of magnitude as the incoming ion flux ($\approx 10^{26} \text{m}^{-2}\text{s}^{-1}$) and those particles will have an energy similar to the incoming particles of a few tens of eV. In addition, hydrogen is known to be retained in tungsten upon exposure to high fluxes of low-energy ions. The high transient heat flux (up to $10^9 \text{W}\cdot\text{m}^{-2}$) will induce a strong temperature rise of the target of up to 2000°C on a sub-millisecond timescale. This will release some of the gas retained in the material.

If we consider the amount of retained particles determined by Thermal Desorption Spectroscopy in a sample exposed under a sequence of 20 s of DC plasma and 5 plasma pulses, about $3 \cdot 10^{15}$ are trapped in the tungsten sample. One can assume that most of the retained hydrogen is retained within the first micron below the surface and that particles are released with a thermal velocity. In that case, the flux of particles released during the temperature excursion could be as high as $10^{28} \text{m}^{-2}\text{s}^{-1}$ i.e. significantly higher than the incoming flux. Even if this back of the envelope calculation is an over-estimate, it indicates that the flux of particles released from the surface is significant compared to the incoming flux. Ionization of such a high flow will require a significant part of the input power and can thus be expected to affect the near-surface plasma. In [24], a strong increase of the electron density, of the order of the peak density, was observed.
200-300 $\mu$s after the peak current which was attributed to particles released from the plasma exposed target. In addition, the interaction of the incoming plasma with the dense cloud of neutrals in front of the target will cause a strong deceleration of the incoming plasma resulting in an increase of the plasma density and a decrease of the electron temperature. A side-effect of the influence of the back-flow of particles is a lowering of the incoming heat flux. A more complete treatment of the influence of particles released from the target during a plasma pulse on the near-surface plasma will be published elsewhere.

### 3.5 Conclusions

The plasma during the pulse is efficiently transported from the source to the target (fig. 3.2, 3.4). It is demonstrated that higher $T_e$ during the pulse enhances energy transport and attenuates MAR which is the main process with respect to losses of power flux along the beam. Electron temperatures close to the source and target increase with current until 4.3 kA. Above this threshold other loss mechanisms play a role. Therefore upstream $T_e$ saturates. $T_e$ downstream reaches its maximum at $\approx$5 kA of 12 eV then a monotonic decrease is observed down to $\approx$2.5 eV. The measurements indicate plasma deceleration and cooling in the end of the beam or impurities release from target could play an important role. Therefore this matter was discussed in term of electron temperature. Experimental simulation of contaminants (by argon admixture) reveals a saturation of $T_e$ similar to what is seen above 5 kA. This effect is not visible in pure hydrogen. Simultaneously $n_e$ of a hydrogen-argon mixture increases over the pulse, but stays constant in pure hydrogen. This implies that the loss mechanism is switched from electron heat conduction (in pure hydrogen) to radiation (in hydrogen with argon admixture). Finally, the effect of temperature saturation is explained by a simple model. The modeled $T_e$ evolution fits the measurements which confirms our statement that radiation is the dominating loss process in a contaminated plasma.
Chapter 4

The self-shielding of tungsten target exposed to high power pulsed hydrogen plasma

Abstract
In this paper we focus on the characterization of the power deposition on a tungsten surface, otherwise exposed to a continuous high flux plasma, during a transient plasma pulse. The situation mimics what is expected in a fusion device during plasma instabilities. The emphasis is put on the correlation between the the near-surface plasma parameters and the power deposition on the target with an emphasis on the role of particle recycling at the target on the power deposition. Upon increasing the input power to the plasma source, the energy density to the target (determined by thermography) first increases and then rolls over and subsequently decreases. The electron temperature close to the target is found to follow the same trend and decreases down to almost 2 eV while the upstream temperature is close to 15 eV. We suggest that this is caused by the sudden release of particles from the target surface from backscattering and desorption and their subsequent ionization. In the strongly-coupled regime, where the ionization mean-free path is smaller than the plasma size, this back-flow of neutrals will significantly affect the power transfer to the target, providing a shielding of the metal surface from the intense plasma flux.
4.1 Introduction

ELMs are a major concern for the lifetime of the divertor materials in ITER due to the very high and localized heat and energy deposition occurring on surfaces otherwise exposed to an intense steady-state plasma flux. Numerous studies involving plasma guns [47], electron beams [48] and plasma combined with lasers [50, 49] have been carried out to characterize the damage mechanisms of a surface exposed to ELM-like transient loads. Those studies, however, are usually performed on as-manufactured materials i.e. on materials which have not been exposed to any prior plasma exposure and thus possess the designed structure and properties. The question however remains to know how the material response to those transient events will be affected by exposure to the intense inter-ELM plasma, the magnitude of which is several orders of magnitude higher than what is typically encountered in plasma processing technologies.

A novel plasma source system has been developed to allow combined steady-state and transient plasma loads to be generated in Pilot-PSI for ELM simulation studies. The plasma source allows for the first time to superimpose millisecond plasma pulses to the divertor-relevant high flux steady plasma with an independent control over the two phases. This has been possible by a systematic analysis of the physics of the pulsed plasmas [46] allowing the performances of the source to be optimized without sacrificing on the plasma cleanliness. Initial experiments [17] hint to the importance of synergistic effects on the surface behavior.

In this chapter, we focus on the characterization of the power deposition on a tungsten surface, otherwise exposed to a continuous high flux plasma, during a transient plasma pulse. A correlation is made between the evolution of the near-surface plasma parameters and the power deposition on the target with an emphasis on the role of particle recycling at the target on the power deposition.

4.2 Set-up and measurements methods

4.2.1 Pilot-PSI

Experiments were performed on the Pilot-PSI linear plasma device, which is designed for the study of plasma-surface interactions under fusion relevant plasma conditions. The machine consists of a 1.2 m long, 0.4 m diameter vacuum vessel placed inside 5 magnetic coils. An axial magnetic field (up to 1.6 T) is used to confine the plasma in a 1 cm wide plasma beam which interacts with a water-cooled target situated 0.5 m downstream.

The source is typically powered by a 0.2 kA DC current regulated power supply. The ELM-like plasma pulse is superimposed to the DC plasma using the PPS described in more details in [46]. In this work the pulsed current was varied up to 12 kA, with a pulse duration of about a millisecond. All experiments were performed using hydrogen plasmas, with a gas flow rate of 10 slm. The magnetic
field was kept constant throughout this work at 1.6 T.

An optical-fiber based system is used to control the discharge of the capacitor bank and synchronize the different diagnostics. Radial profiles of electron temperature and density, at a distance of 17 mm from the plasma-exposed surface, are obtained using single pulse TS [23]. Scattered light is collected by a detection system consisting of a fiber-optic bundle and a spectrometer that is equipped with an ICCD camera. The spectral broadening is measured to obtain $T_e$ while the integrated spectrum gives $n_e$. Owing to the high plasma density during the pulse and the high sensitivity of the TS detection system, measurements are possible with a single laser pulse (10 ns). However, to improve the quality of the data, they are averaged over 4 - 5 plasma pulses to improve statistics. The TS system is set to measure at the peak of the discharge current.

4.2.2 Surface temperature measurements and heat flux calculations

The time evolution of the surface temperature during the pulse was monitored by a fast infrared camera (FLIR SC7500MB) which collects IR radiation in the wave-length range 1.5-5.1 $\mu$m. The frame rate was set to 7800 fps. The spatial resolution was 0.33 mm/pixel. The radiation was collected through a CaF$_2$ window - transparent in range of 1 - 10 $\mu$m. The camera is calibrated up to 3000$^\circ$C using a blackbody source. The temperature-dependence of the surface emissivity is taken into account in the case of tungsten following the work by [53]. A background substraction is performed for every measurement to eliminate the influence of the infrared light emitted by the plasma source and/or the surrounding elements within the vacuum vessel. Details about the infrared camera calibration can be found in [52].

Figure 4.1 depicts an example of the temporal evolution of the surface temperature during a plasma pulse. Steady state temperature is about 600 - 700$^\circ$C. In few hundreds $\mu$s the surface temperature increases with 1200 - 1300$^\circ$C in respect to steady conditions reaching the maximum at $\approx$2000$^\circ$C and then falls down with longer time scale.

4.2.3 Calculation of heat flux

The temporal surface temperature measured by IR camera is an input for numerical routine (THEODOR) for heat flux calculation [54]. This is a 2-D inverse heat transfer code which considers the presence of a layer on top of the substrate. The layer is characterized with a given $\alpha$ parameter, the ratio of the heat conductivity to the thickness of the layer [55], this parameter is defined by the equation 4.1

$$q = \alpha(T_{IR} - T_{bulk}), \alpha = \frac{\lambda}{\delta} \tag{4.1}$$
where \( q \) is the heat flux, \( T_{IR} \) - the surface temperature, \( T_{bulk} \) - temperature of bulk material, \( \lambda \) - the thermal conductivity which is temperature dependent (W·m\(^{-1}\)s\(^{-1}\)), \( \delta \) - the layer thickness. \( \alpha \) is a heat transmission coefficient (W·m\(^{-2}\)s\(^{-1}\)), without this parameter, negative heat fluxes can be calculated by the code because of the overestimation of the surface temperature induced by the bad thermal contact of the disturbed layer with the bulk. In order to determine the values of \( \alpha \) to be used, the method described in [56] and [57] is used, i.e. the value of \( \alpha \) is varied until negative heat fluxes are removed. The initial values of \( \alpha \) used in code are 25·10\(^4\) and 5·10\(^{10}\)W·m\(^{-2}\)s\(^{-1}\) for the water cooled side and top surface (exposed to the plasma), respectively.

### 4.3 Results and discussion

An example of the typical temporal and spatial evolution of the surface heat flux during a plasma pulse (10 slm, 1.6 T) is presented in fig. 4.2. The plasma pulse results in a strong increase of the heat flux from its pre-pulse value (around 5 MW·m\(^{-2}\) in the present case) up to about 1 GW·m\(^{-2}\) during the pulse (the shot performed at the peak current of 1.7 kA). The heat flux profile has a Gaussian shape with a full width at half maximum (FWHM) in the range of 3.7 - 4.7 mm as expected from the shape of the plasma density and temperature profiles.

In [46], it was shown that for currents higher than about 1.5 kA, the plasma was fully ionized and further increase in the discharge current did not affect
Figure 4.2: Temporal evolution of the radial heat flux profile. Hydrogen flow 10 slm, magnetic field 1.6 T, peak current 1.7 kA.

Figure 4.3: Peak heat flux as a function of current (10 slm of H₂, 1.6 T, I=0.2 - 4.3 kA). The heat flux at 0.2 kA is much lower than other values due to the recombination losses occurring in the plasma volume at this current.
Figure 4.4: Energy density as a function of current measured in the middle of the sample. Energy density increases from 0.3 to 0.8 MJ·m$^{-2}$ in current range of 0.7 - 1.7 kA, reaching its maximum of 0.9 MJ·m$^{-2}$ at 1.7 kA. It then monotonically drops to 0.3 MJ·m$^{-2}$ at 9.2 kA. This trend is the result of a disrupted heat flux to the surface.

the plasma density during a pulse. In addition, the peak electron temperature was found to increase with the discharge current as $T_e \propto I^{0.4}$ (Chapter 2). It is known from sheath theory [51] that heat flux scales with temperature as $q \propto T_e^{3/2}$. Therefore one could expect the relationship between the heat flux and discharge current to be $q \propto (I^{0.4})^{3/2} \Rightarrow q \propto I^{0.6}$. However, fig. 4.3 shows the evolution of the peak power load as a function of peak current with the simple exponential fit which is characterized by much lower exponent ($q \propto I^{0.41}$). The peak heat flux increases only from 1 to 1.2 GW·m$^{-2}$ in the current range of 1.7 - 4.3 kA. This means that the heat flux is increased by only 20% whilst the input current increases by a factor of 2.5. This suggests an attenuation in power transport from the plasma to the surface. The large scatter between the data points measured under similar conditions is caused by the intrinsic reproducibility of the pulsed power supply.

The energy density deposited on the target is calculated by a temporal integration of the heat flux (fig. 4.4). As shown in fig. 4.4, the peak energy density (corresponding to the peak heat flux in the middle of the plasma beam) varies from 0.3 to 0.9 MJ·m$^{-2}$ in the current range of 0.7 - 9.2 kA. Surprisingly, the peak energy density drastically increases from 0.3 MJ·m$^{-2}$ at 0.7 kA up to (its maximum) 0.9 MJ·m$^{-2}$ at 1.7 kA and then monotonically decreases with increasing input power down from 0.9 MJ·m$^{-2}$ at 1.7 kA to 0.3 MJ·m$^{-2}$ at 9.2 kA.

To understand the apparent contradiction between fig. 4.4 and fig. 4.3, the
temporal evolution of the peak heat flux at different input powers is analyzed in more details in fig. 4.5 in comparison with the temporal evolution of the discharge current. The three examples of heat flux traces are shown for discharge currents of 1.7, 3.0 and 4.3 kA. For a current of 1.7 kA, the peak heat flux and the discharge current follow the same temporal evolution with the maximum heat flux occurring at the peak current. The rise and fall times of the heat flux are equal and about 500-600 µs.

Figure 4.5: Three examples of heat flux traces are shown for 1.7, 3.0 and 4.3 kA. To demonstrate the evolving character of the heat flux with input power the current evolution is plotted as a reference. For a current of 1.7 kA, the peak heat flux and the discharge current follow the same temporal evolution. The rise and fall times are equal at about 500-600 µs. At 3 and 4.3 kA the shape of the heat flux is different from the current - this suggests distortion of the heat transfer from the plasma to the surface.

The situation is drastically different for pulses performed at 3 and 4.3 kA (fig. 4.5). The lines representing heat fluxes do not follow the current trace anymore. In these cases the heat flux risetime decreases with the peak current: from 500 µs at 1.7 kA to 200-300 µs at 3 and 4.3 kA. Simultaneously, the e-fall time becomes shorter. It is reduced from 600 µs at 1.74 to 350 µs at 4.34 kA. While the peak heat fluxes is indeed increased from 1.74 to 3 kA, the actual heat pulse is shortened at high input powers. The apparent shortening of the heat flux pulse accounts for the decrease of the energy density to the surface as a function of the input power. The power transported to the target is thus impeded for high input powers and does not follow the temporal evolution expected from the upstream plasma parameters evolution or that of the input power.

Interestingly, the evolution of the plasma parameters measured 17 mm away
from the target surface by TS at the time of the peak current shed some light on the mechanisms at stake. The electron temperature increases with input power up to about 12 eV for 4.3 kA and then steadily decreases for higher currents down to about 2 eV at about 12 kA (fig. 4.6 upper-plot). At the same time, the electron density is almost constant up to 5 kA, as expected form the previously mentioned full ionization (fig. 4.6 lower-plot) and then increases for higher currents. Upstream TS measurements, a few cm from the source, don’t reveal similar effect [46] and show a slow increase of the electron temperature with the discharge current. Therefore, while the plasma production at the source increases with input power, a strong cooling of the plasma beam occurs close to the target at high currents.

Clearly, the evolution of the upstream plasma cannot account for the effect observed close to the target. Since the plasma parameters are measured very close to the target, and since the wall is an ideal sink for the plasma particles striking the solid, the effect of the plasma-exposed target on the near-surface plasma needs to be examined in further details. First of all, since the electron temperature is at most 12 eV close to the target, the ion impact energy at the target will remain lower than 60 eV during the pulse. The particle reflection coefficient for such low-energy hydrogen ions on a tungsten surface is higher than 65% while the energy reflection coefficient is higher than 43% [58]. Under those conditions, the flux of particles reflected from the surface is of the same order of magnitude as the incoming ion flux ($\approx 10^{26} m^{-2}s^{-1}$) and those recycled particles, being reflected as neutrals from the target, will have an energy of a few tens of eV. Since the mean free path for ionization of those recycled particles is smaller than the plasma beam diameter ($4 \cdot 10^{-3} - 2 \cdot 10^{-4} m$) [36], most of these particles will be ionized close to the target and will increase the local plasma density and decrease the plasma temperature. Since the plasma density is highest in the middle of the plasma beam, the largest flux of reflected neutrals will also come from the centre of the plasma beam, which should be the most affected region. The spatial evolution of the heat flux profile seems to confirm this hypothesis (fig. 4.7).

The maximum of electron temperature fig. 4.6 and energy density (fig. 4.4) are at 4.3 and 1.7 kA, respectively. This discrepancy can be explain by the distance between target and laser of TS. $T_e$ measurement is affected by back-flux only if it reaches the TS-laser. This means that the propagation of back-flux becomes intensive enough to influence $T_e$ at about 4.3 kA.

The upper-plot in this figure presents 4 examples of the heat flux profiles taken at four instants during the pulse (peak current of 1.7 kA). A broadening of the heat flux profile is observed during the pulse as a result of the increased input power but in all cases, the profiles remained peaked i.e. that the maximum heat flux is obtained in the middle of the plasma beam as expected from the TS measurements. At higher currents however, the heat flux profiles become hollow. This suggests the appearance of a cooling/dissipating mechanism impeding the heat transfer from the plasma to the target.

In addition, hydrogen is known to be retained in tungsten upon exposure to
Figure 4.6: Plasma parameters as a function of current presented in the full experimental range up to 12 kA. The decline in $T_e$ for currents higher than 4.3 kA correlates with an $n_e$ increase beyond the same threshold, suggesting the appearance of neutrals in the plasma coming from the target.
Figure 4.7: Radial profiles of heat flux during the pulse performed at 1.7 kA (upper plot) and 4.3 kA (lower plot) demonstrate the appearance of a self-shielding effect at higher current. The hollow profiles at 4.3 kA suggest the attenuation of power transfer from the plasma to the target.
high fluxes of low-energy ions. The high transient heat flux (up to $10^9 \text{W} \cdot \text{m}^{-2}$) will induce a strong temperature rise of the target of up to 2000$^\circ\text{C}$ on a sub-millisecond timescale. This will lead to a sudden release of the gas inventory in the near surface. This is particularly true for the mobile hydrogen particles present in the near-surface. Indeed, since the solubility of hydrogen in tungsten is very low, most of the implanted particles will not be able to find a trap and a large concentration of mobile hydrogen will be present in the near-surface. If we assume, as a very conservative approach that the amount of mobile hydrogen is equal to that of the trapped hydrogen and a concentration of 1% of the lattice density, one can calculate that the flux of mobile hydrogen released from the surface during the plasma pulse is about $5 \cdot 10^{24} \text{m}^{-2} \text{s}^{-1}$ for a peak temperature of 2000$^\circ$. The concentration of mobile hydrogen is unknown under our conditions and to our knowledge, has been measured during plasma exposure only for the case of molybdenum and tungsten under low flux plasma exposure. For molybdenum, it was found that the concentration of mobile hydrogen was equal to that of the trapped hydrogen. One can however suppose that the amount of mobile hydrogen will scale with the incoming plasma flux density, as has been observed [59] so that much larger concentrations can be expected in the present case. This will naturally increase the outgoing flux of mobile hydrogen.

While, it is not possible at the present time to distinguish between the reflected and desorbed neutrals as the main responsible for the observed plasma cooling, it is clear that these have a significant and beneficial effect on the heat deposition on a plasma-exposed target. In the so-called strongly-couple regime where the mean free path of particles released from the surface, the backflow of particles from the surface can induce a detachment of the plasma and hence reduce the energy density to the surface. Since the latter is the value determining the damage to the exposed surface, this induced a self-protection of the plasma exposed surface. To our best knowledge, this is the first report of such an effect and its prospects in terms of material lifetime should be studied in more details.

### 4.4 Conclusions

A characterization of the power deposition on a tungsten surface, otherwise exposed to a continuous high flux plasma, during a transient plasma pulse, has been investigated in details. A non-linear relationship between the upstream plasma parameters and the measured energy density to the target has been observed to occur at high discharge currents. Both the magnitude of the energy density to the target and the temporal evolution of the heat pulse are modified. This results in a decreased energy transfer to the surface despite the increased power flux from the plasma source. This self-shielding effect is attributed to the release of neutrals from the plasma-exposed target due to particle back-scattering and outgassing. The plasma conditions in the present study is such that the mean free path for ionization is shorter than the plasma size, so that neutrals released from the target

55
are ionized in the very vicinity of the target and this protects the plasma-exposed surface from the intense plasma flow. To our knowledge, this is the first time that such an effect is reported and its potential implications for material lifetime in a nuclear fusion reactor warrants further studies.
Chapter 5

ELM simulation experiments on Pilot-PSI using simultaneous high flux plasma and transient heat-particle source

Abstract
A new experimental setup has been developed for ELM simulation experiments with relevant steady-state plasma conditions and transient heat/particle source. The setup is based on the Pilot-PSI linear plasma device and allows the superim- position of a transient heat/particle pulse to the steady-state heat flux plasma. Energy densities as high as 1 MJ·m\(^{-2}\) have been reached for a pulse duration of about 1.5 ms, and for a variety of gases (H\(_2\), He, Ar). In this contribution, we report on the first experiments, investigating the effect of the combined steady-state/pulsed plasma on polycrystalline tungsten targets. Under such conditions, the threshold for tungsten release and surface roughening is found to be much lower than in previously reported experiments. This suggests that the combination of the high flux plasma and transient heat/particle source lead to role of synergistic effects.

ELMs are a major concern for the lifetime of the divertor plasma-facing materials (PFMs) in ITER. The very high localized heat fluxes will lead to material erosion, melting and vaporization [40]. In addition, the repetition of such thermal shocks can lead to a degradation of the thermo-mechanical material properties. In ITER, the PFMs will be subjected to both the steady state detached divertor plasma and the intense heat and particle fluxes during ELMs. A steady-state heat flux of about 10 MW·m\(^{-2}\) is expected at the divertor targets [60] while energy densities of up to 10 MJ·m\(^{-2}\) are predicted for unmitigated Type-I ELMs [39]. In parallel, strong modifications of the surface morphology can occur during bombardment by low energy plasma ions (D\(_2\), T\(_2\), He) such as blistering [61] or formation of helium-induced nano-structure [62]. In such a situation, the transient heat/particle pulse associated with an ELM will interact with a surface with modified properties and this might strongly affect the material damage threshold, some evidence of which have been described previously [49, 50].

Several techniques are currently being used to investigate the behaviour of materials under ITER relevant transient heat loads. Electron guns such as the JUDITH facility [63] can produce relevant energy densities and durations but at the absence of the plasma environment. On the other hand plasma guns [64] produce heat loads and ion energies relevant for the studies of ELM/material interactions but cannot combine it to the relevant steady-state plasma. Finally, the use of powerful lasers associated with linear plasma generators [49, 50] combines a plasma environment and transient heat fluxes. Still, the plasma conditions in those devices are quite different from those expected in ITER and the use of a laser does not allow reproducing the transient particle flux associated with an ELM.

In order to overcome those limitations and allow ELM simulation experiments with relevant steady-state plasma conditions and transient heat/particle source, a new experimental setup is being developed. The initial setup is based on the Pilot-PSI linear device, whose plasma source has been modified to be compatible with pulsed operations. This allows, for the first time, the superimposition of a transient heat/particle pulse to the steady-state heat flux plasma [24]. Energy densities as high as 1 MJ·m\(^{-2}\) have been reached for a pulse duration of about 1-1.5 ms [22]. In this contribution, we report on the properties of the pulsed plasmas and on the first experiments made to investigate the effect of the combined steady-state/pulsed plasma on polycrystalline tungsten targets. Post-mortem analysis of the targets was done by Scanning Electron Microscopy (SEM). Fast visible imaging was used to determine in-situ the threshold for tungsten release from the surface.
5.2 Experimental

The Pilot-PSI linear device produces plasma parameters \( n_e \sim 0.1-10\cdot10^{20}\text{m}^{-3}, \ T_e \sim 1-5 \text{ eV} \) relevant to the study of steady-state plasma-surface interactions in the ITER divertor [35]. The high flux plasma is generated by a cascaded arc plasma source which is powered by a current regulated power supply. In parallel, a capacitor bank (8400 \( \mu \text{F}, 4.2 \text{ kJ} \)) is connected to the plasma source and discharged in the plasma source to transiently increase the input power (fig. 5.1). This results in a transient increase of the electron density and temperature. The plasma source was modified to accommodate the high heat fluxes generated during such pulses. Peak discharge currents of about 14 kA have been generated, corresponding to a peak input power in the plasma source of about 5.5 MW. The evolution of the discharge current and input power during a hydrogen plasma pulse is shown in fig. 5.2. The steady-state current and voltage were 180 V and 200 A, respectively for a magnetic field of 1.6 T and a gas flow of 10 slm. Both the current and voltage in the source increase during the plasma pulse. The peak input power in that case was about 3.8 MW. The current trace reveals a smooth bell-shaped curve, while a short spike in the source voltage can be noticed at the beginning of the pulse, which lasts for about 100 \( \mu \text{s} \). A detailed study of the electrical properties of the arc during pulsed operations will be published elsewhere. The pulse duration was about 1.3 ms, although the pulse duration and shape can be adapted to the needs. The plasma source can be operated with a variety of gases (e.g. Ar, H\(_2\), D\(_2\), He, N\(_2\)) as well as with gas mixtures.

The plasma parameters are measured by means of a TS system [23] located 17 mm in front of the plasma exposed target (fig. 5.1). The magnetic field, the trigger to the capacitor bank and the TS system are synchronized in time with accuracy better than 1 \( \mu \text{s} \) to ensure a reproducible time delay between every step of the sequence. The time evolution of the density and temperature during such a pulse have been described in [24, 22]. The time evolution of the surface temperature
Figure 5.2: Temporal evolution of (a) the discharge current and (b) input power during a hydrogen plasma pulse. The peak input power was about 3.8 MW. The magnetic field was 1.6 T and the vessel pressure about 10 Pa.
Figure 5.3: Temporal evolution of the surface temperature and peak heat flux of a tungsten target, illustrating the superimposition of the steady-state and pulsed plasmas.

during the pulse is monitored by a fast infrared camera (FLIR SC7500MB) which measures infrared radiation in the wavelength range 2-5 µm. The frame rate of the camera was set to 10 kHz. The infrared camera was calibrated up to 3000°C using a blackbody source. The target heat fluxes are calculated using THEODOR [54], a 2D inverse heat transfer code which considers the presence of a layer on top of the substrate. The layer is characterized with a given α parameter, the ratio of the heat conductivity to the thickness of the layer [55]. Without this parameter, negative heat fluxes can be calculated by the code because of the overestimation of the surface temperature induced by the bad thermal contact of the disturbed layer with the bulk. In order to determine the values of α to be used, the method described in [56, 57] is used, i.e. the value of α is varied until negative heat fluxes are removed. The heat fluxes derived from IR measurements have been compared to those calculated from the plasma density and temperature using sheath heat transmission factors and a relatively good agreement was found [24]. Fast visible imaging was done using a Photron APX-RS camera equipped with interference filters (Hα at 656.2 nm, and WI at 400.9 nm) and operating at a frame rate of up to 75 kHz.

The plasma exposed target was a 30 mm diameter polycrystalline tungsten disc, 1 mm thick, which was kept at floating potential during the exposure. After polishing, the targets are ultrasonically cleaned in ethanol and acetone. They are then outgassed at 1000°C for 15 minutes following a temperature ramp of 60°C·min⁻¹.

Figure 5.3 shows the temperature and heat flux evolution during a typical
discharge. The magnetic field was triggered for a duration of 2 s, the surface temperature reached an equilibrium value (about 650°C in the present case) after about 0.5 s. The pulsed plasma was triggered at t=1 s resulting in a strong increase of the surface temperature (up to 2700°C) during the pulse. The surface temperature then returns to its pre-pulse value.

Figure 5.4: Temporal evolution of the Hα signal recorded by a fast filtered visible camera and the peak heat flux to the surface determined from the infrared camera.

Figure 5.4 shows the time evolution of the Hα signal measured by the fast visible camera during a pulsed plasma compared to the time evolution of the power flux density to the target determined from infrared thermography. The temperature rise time during a pulse is in the range 0.5-1 ms which is in good agreement with typical risetimes for Type-I ELMs in tokamaks [39]. Evidently, the time evolution of the peak heat flux is well correlated with the time evolution of the Hα signal, which in turn is well correlated with the time evolution of the discharge current.

5.3 Behavior of tungsten under simultaneous steady state and pulsed plasma exposure

5.3.1 Tungsten release

To study the influence of the combined steady-state/pulsed plasma on the surface damage of tungsten, tungsten targets were exposed to identical steady-state plasma conditions while the energy density deposited during the pulsed plasma was varied. The steady-state plasma duration was 2 s and the pulsed plasma was
Figure 5.5: Series of snapshots taken by the fast visible camera (operating at 12 kHz) of the WI emission from the target during a hydrogen plasma pulse. The energy density to the target was $0.3 \text{ MJ} \cdot \text{m}^{-2}$.
triggered at \(t=1\) s. Both hydrogen and helium plasmas were used. In that case the source settings were identical, which resulted in different surface temperatures; 400\(^\circ\)C and 750\(^\circ\)C for hydrogen and helium plasmas, respectively. WI line emission at 400.9 nm was recorded by a fast visible camera, to characterize the threshold for tungsten release. The optical filter used in this study was centred around 400.5 nm and had a bandwidth of 2 nm. In order to eliminate the possible contribution of continuum emission from the plasma, the signal measured 5 cm away from the target was subtracted from the measurements. However, it was observed that the emission from the plasma was negligible compared to the WI line intensity from the target. According to the NIST database [65], emission from iron lines occur in a similar wavelength range. Although the vacuum vessel is made of stainless steel, no trace of iron has ever been found by surface analysis of the exposed samples so that the possibility of iron emission from the target is not considered.

Figure 5.5 shows a series of 2D snapshots from the fast filtered camera taken during a plasma pulse in hydrogen. Two main effects can be observed. First, an emission cloud is formed in front of the target (indicated by the black dashed line in fig. 5.5). Second, extended tracks (indicated by the white dotted line in fig. 5.5) can also be observed moving away from the target. These tracks appear quite random in nature but all appear to originate from the target. It should be mentioned that the camera was focused on the centre of the target and had a relatively narrow field of view because of the aperture used and the high magnification, this makes it difficult to assess the precise shape of these trajectories. The estimated velocity of motion of this second type of emission is in the range 50-500 m·s\(^{-1}\) which is larger than the velocity of tungsten particle released from a tungsten surface during QSPA experiments [40], but in agreement with the velocity of carbon particles released during disruptions in tokamaks [66]. The precise assignment of this effect to dust particles release from the target will be investigated in future experiments.

Figure 5.6 shows the time evolution of the WI line brightness profile (1D lineout) taken at the centre of the plasma exposed target during a hydrogen plasma pulse similar to that of fig. 5.5, but acquired with a framerate of 75 kHz. A significant broadening of the emission profile is observed during the pulse and emission can be observed up to 12 mm away from the target.

A comparison of the temporal evolutions of the surface temperature (from IR imaging) and of the WI brightness is shown in fig. 5.7 for a hydrogen plasma pulse with an energy density of 0.5 MJ·m\(^{-2}\). The temperature risetime is about 0.7 ms in the present case. It should be mentioned here that Pilot-PSI is not equipped with a central clock system and the different fast cameras are running on their internal clock, which makes it difficult to synchronize the signals. In some cases, tungsten release from the plasma source is observed during the first 100 \(\mu\)s of the plasma pulse (fig. 5.7b), although the effect is erratic in nature and not reproducible. For that reason, and since the emission from the source can clearly be distinguished from the emission from the target (different timescales), only the
Figure 5.6: Time evolution of the WI line brightness profile (1D lineout) taken at the centre of the plasma exposed target during a hydrogen plasma pulse with energy density of 0.3 MJ·m\(^{-2}\).

Figure 5.8 shows the influence of the energy density to the target on the WI emission intensity, the latter was integrated over the pulse duration to account for the total release of tungsten during the pulsed plasma. For both hydrogen and helium plasma, a clear threshold behaviour is observed with no release observed below a certain energy density and increasing tungsten emission with increasing energy density after the threshold value. In the case of a hydrogen plasma, the threshold for release is around 0.20 MJ·m\(^{-2}\), while no release is observed below 0.25 MJ·m\(^{-2}\) for helium. The WI intensity measured during helium plasma remains systematically lower than that measured for hydrogen plasmas. Since the electron temperature (and thus S/XB) might be different in both cases, this might contribute to the different emission intensities. It should be mentioned that no firm conclusion can be drawn on the different thresholds for helium and hydrogen plasmas because of the different surface temperatures during the steady-state phase. The evolution of the WI signal as a function of the energy density appears to be linear, whereas an exponential increase would be expected. Although no explanation can be given yet, it is important to keep in mind that the plasma conditions during the pulse vary strongly with increasing input power and this makes the direct interpretation of the WI line intensity rather difficult. The threshold for release measured in the present experiments corresponds to a heat flux parameter of about 7 MW·m\(^{-2}\)s\(^{1/2}\) which is much lower than the energy densities at which cracking is observed in QSPA \[64\] (15 MW·m\(^{-2}\)s\(^{1/2}\)) and considerably lower than the threshold for melting (50 MW·m\(^{-2}\)s\(^{1/2}\)).
Figure 5.7: Time evolution of the surface temperature (a) and WI brightness (b) measured by fast infrared and visible imaging respectively, during a hydrogen plasma pulse with energy density of 0.5 MJ·m$^{-2}$. 
Figure 5.8: Evolution of the WI line intensity (integrated over the plasma pulse duration) as a function of deposited energy density for hydrogen and helium plasmas.

Given that the electron temperature remains low during the plasma pulse (below 6 eV), physical sputtering of tungsten can be neglected because the ion impact energy will remain lower than the threshold for sputtering. The observed release of neutrals from the surface is probably caused by several simultaneous effects. First, during the plasma pulse, a sudden increase of the surface temperature occurs with maximum values close to the melting point for the highest energy densities, so that thermal evaporation will represent an increasing particle source with increasing temperatures. Figure 5.8 shows the evolution of the WI brightness against the surface temperature. As mentioned above, the infrared and visible cameras are both running on their internal clocks so that the synchronization of both diagnostics is not perfect. In addition, temperature measurements on tungsten at high temperatures are complicated by the temperature-dependent emissivity. In any case, it is clear from fig. 5.8 that the WI brightness evolves with surface temperature with a factor 10 increase in the light intensity between 1200°C and 2700°C. The tungsten release from evaporation is expected to be negligible at temperatures below 2500°C and increases very rapidly with increasing surface temperature, which would explain the strong increase in WI intensity between 2500°C and 2700°C. However, significant emission is observed below 2200°C. The visible camera could not be calibrated at the time of the experiments so that the tungsten release rate can not be inferred from the measured intensity. In the future, such measurements will be repeated with synchronized cameras and calibrated visible emission diagnostics.

Dust release from the surface represents another possible source of tungsten
Figure 5.9: Evolution of the WI brightness measured by fast visible imaging as a function of the surface temperature measured by infrared thermography.

and is regularly observed during experiments in the QSPA plasma gun [40] for example. Supporting this hypothesis, it has been observed that cracking of the exposed surface due to the transient heat loads could result in the formation of large particles with almost no attachment to the edges of the cracks. This effect will be described in the following section. Finally, as mentioned in [50], the blisters formed on a tungsten surface during the steady-state phase could burst during the transient heat load as a result of the sudden pressure rise. In some cases, burst blister caps were observed during the present experiments (not shown here). More experiments are ongoing to assess the influence of this effect on the global surface erosion.

5.3.2 Evolution of tungsten morphology

The influence of the surface morphology of tungsten surfaces exposed to combined steady-state/pulsed plasma has been investigated for hydrogen plasmas using SEM. Samples were exposed according to the procedure described in Section 5.2, although in this case the steady-state plasma duration was 4 s and the plasma pulse was triggered at t=2 s. The peak energy density during the pulse was 0.15 MJ·m⁻². Since the plasma density and temperature have a Gaussian profile during the pulse [24], a gradient of energy deposition exists on the surface. Figure 5.10 shows the target temperature profile during the steady-state phase, with a peak temperature of about 560°C, and during the peak of the plasma pulse when the peak surface temperature is about 1000°C. The SEM observations were performed at the target centre corresponding to the area of maximum energy
Figure 5.10: Surface temperature profiles measured by a fast infrared camera during the steady phase of the discharge and during the plasma pulse.

deposition and at radial positions corresponding to half the peak energy density (according to the 2D IR measurements). Samples were exposed to 10 and 17 pulses corresponding to a steady-state plasma duration of 40 s and 68 s, respectively. Reference samples were exposed to similar steady-state plasma conditions in the absence of plasma pulses to isolate the effect of the combined exposure with that of possible morphology changes induced by the hydrogen plasma alone. The plasma conditions during the steady-state phase were $n_e \sim 5 \cdot 10^{20} \text{m}^{-3}$ and $T_e \sim 1 \text{ eV}$.

Figure 5.11a shows the morphology of the reference tungsten sample exposed for 40 s in the absence of any plasma pulse. No morphology changes can be noticed compared to that of a polished non-exposed sample. The morphology of the reference sample exposed for 68 s (not shown here) is similar to that shown in fig. 5.11a. On the other hand, significant morphology changes are observed when the surface is simultaneously subjected to plasma pulses. Surface roughening is already noticeable after 10 pulses at 0.07 MJ m$^{-2}$ (fig. 5.11b), and increases with the pulse number (fig. 5.11c). For higher energy densities, the effect is much more pronounced as illustrated by fig. 5.11d and also evolves rapidly with the number of pulses (fig. 5.11e).

In addition to the above mentioned surface roughening, cracking of the tungsten surface is also observed. More importantly, the formation of dust-like particles is regularly observed at the surface of the cracks. Examples of such an effect are shown in fig. 5.12. The size of those particles can be between a few microns (fig. 5.12a) and up to 50 µm (fig. 5.12a). This clearly indicates that cracking is not only a concern for the integrity of the solid surface but also a source of dust.
Figure 5.11: (a) SEM pictures of tungsten samples after exposure to 40s of steady-state hydrogen plasma without plasma pulses. The following pictures show the surface morphology of tungsten targets exposed to similar steady-state plasma conditions with additional plasma pulses. (b) and (c) SEM pictures of tungsten surface after 10 and 17 plasma pulses with energy density 0.07 MJ·m$^{-2}$ respectively. (d) and (e) Surface morphology after 10 and 17 pulses with energy density 0.15 MJ·m$^{-2}$ respectively.
Figure 5.12: (a) and (b) Evidence of the formation of loosely bound particles as a result of cracking of the tungsten surface exposed to 6 pulses with energy density $0.15 \text{ MJ}\cdot\text{m}^{-2}$ with helium as a working gas. The formation of these particles represents a possible source of dust release from the surface.

Particles which can be released from the surface.

5.4 Discussion

The development of the PPS on Pilot-PSI aims at studying the possibility of synergistic effects caused by the simultaneous exposure of a metallic surface to a divertor-relevant high flux plasma and a transient heat/particle source. Under such conditions, strong release of tungsten is observed at energy densities lower than the energy density for which mass loss is observed in plasma gun experiments, and lower than the energy density at which tungsten emission is observed in the absence of plasma-induced surface modifications [68]. In addition, surface roughening of a tungsten surface is already observed after exposure to 68 s of steady-state plasma and 17 plasma pulses with energy densities as low as $0.07 \text{ MJ}\cdot\text{m}^{-2}$.

It was observed in [49] that the laser ablation threshold of tungsten was strongly reduced by the formation of helium-induced nanostructure on the surface. In the case of a tungsten surface exposed for 5400 s to low energy helium ions, the threshold for tungsten release is lowered to a value of about $12 \text{ MW}\cdot\text{m}^{-2}\cdot\text{s}^{1/2}$. In that case, the laser pulse duration was about 5-7 ns. Similar observations were made with sub-ms laser pulse duration [67, 68], which is closer to the plasma pulse duration in the present study. The tungsten emission from a tungsten surface pre-irradiated by a helium plasma was found to occur at lower energy densities and also found much higher than for unexposed tungsten surface. A lowering of the damage threshold of tungsten was also observed for simultaneous hydrogen plasma and laser exposure in PISCES-A [50]. This effect did not occur when the surface temperature was about 630°C, underlining the role of the near-surface gas content and voids/bubbles. In both cases, the bursting of holes and blisters containing gas is proposed as a possible explanation for the observed reduced damage threshold.
In the experiments described here, the surface temperature for both the helium and hydrogen plasma cases is in a range where such an effect might be expected. The threshold for tungsten release is observed to be as low as $7 \text{ MW} \cdot \text{m}^{-2} \cdot \text{s}^{1/2}$ for a steady-state plasma exposure time which is two orders of magnitude lower than the duration of the plasma pre-irradiation period in [49]. It is not possible to precisely assess at present where this dramatic difference comes from. However, those results strongly suggest that in the case of a combined exposure to a high flux plasma and a transient heat/particle source, the role of synergistic effects on the surface damage is strongly enhanced.

In addition to a reduced threshold for tungsten release, strong modifications of tungsten surfaces have been observed for energy densities as low as $0.07 \text{ MJ} \cdot \text{m}^{-2}$ and only 17 pulses. Similar surface roughening of tungsten has been observed in [69] for tungsten exposed to the JUDITH electron gun where a tungsten surface is bombarded by high energy electrons. This is attributed to the plastic deformation of the heated grains due to compressive stresses during the transient heating which leads to irreversible swelling after the cool-down [69]. Such an effect is observed when the base temperature of the material is already above the ductile to brittle transition temperature (DBTT) [70] which is clearly the case in the present experiments. In [69], the energy density at which surface roughening is observed depends on the material grade and preparation but even in the worst case is around $0.2 \text{ MJ} \cdot \text{m}^{-2}$ which is much higher than the energy density at which surface roughening is observed in the present experiments where the sample is exposed to the transient heat/particle pulse while being exposed to a hydrogen plasma. This again suggests that the damage of tungsten is enhanced under the specific experimental conditions of the PPS in Pilot-PSI, which simulate the conditions expected during ELMs in ITER.

### 5.5 Conclusions

Pulsed operations of the Pilot-PSI plasma source enable ELM simulation experiments with relevant steady-state plasma conditions and transient heat/particle source, allowing plasma-surface interactions under those conditions to be studied in a self-consistent manner. Energy densities as high as $1 \text{ MJ} \cdot \text{m}^{-2}$ have been reached for a pulse duration of 1 ms, in a variety of gases (H$_2$, He, Ar). First experiments were made to investigate the effect of the combined steady-state/pulsed plasma on the morphology of polycrystalline tungsten targets. Tungsten release during the plasma pulse was monitored with a fast visible camera filtered around the WI line at 400.9 nm. A clear threshold behaviour is observed. In the case of a hydrogen plasma, the threshold for release is around $0.2 \text{ MJ} \cdot \text{m}^{-2}$, while no release is observed below $0.25 \text{ MJ} \cdot \text{m}^{-2}$ for helium. Significant morphology changes are observed when the surface is exposed to combined steady-state/pulsed plasmas. Surface roughening is already noticeable after 10 pulses at $0.07 \text{ MJ} \cdot \text{m}^{-2}$, and increases with the number of pulses. Our results strongly suggest that in the case of
a combined exposure to a high flux plasma and a transient heat/particle source, the role of synergistic effects on the surface damage is strongly enhanced.

5.6 Acknowledgments

The authors gratefully acknowledge the help and support from the Pilot-PSI staff. This work is part of the research programme of the Stichting voor Fundamenteel Onderzoek der Materie (FOM), which is financially supported by the Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO). It is supported by the European Communities under the contract of Association between EURATOM and FOM and carried out within the framework of the European Fusion Programme.
Chapter 6

Evaluation and conclusions

6.1 Goals and approach

The principal goals of this research project were

- to create an experimental facility in which a target could be subjected to a plasma load similar to that expected to occur in the divertor of ITER, including the pulsed load that results from ELMs, and

- to explore the interaction of the plasma with the surface under those conditions.

Key figures to be realized were: a hydrogen plasma pulse that exceeds $1 \text{ GW} \cdot \text{m}^{-2}$ and $0.5 \text{ MJ} \cdot \text{m}^{-2}$ with a typical duration of $\approx 1 \text{ ms}$, on top of a steady state plasma load with a heat flux density of more than $5 \text{ MW} \cdot \text{m}^{-2}$, at plasma temperature in the eV range during steady state and well above 10 eV during the ELM-like pulse. The principal facilities to be used were the linear plasma generators Pilot-PSI and Magnum-PSI at DIFFER, and the main hardware addition to developed was a source capable of providing both the steady state and pulsed plasma generation, in superposition.

The project was developed in four stages: i) the development of the source and electrical set up, ii) investigation of the energy transport from source to target, iii) investigation of the plasma surface interaction regime during a pulse, and finally iv) investigation of the combined effect of the steady state and pulsed plasma exposure on the target. In this section, we evaluate whether these goals were achieved, non-trivial steps were needed to get there; we reflect on the new physics results that came out of these studies and we consider possible spin-off applications that might evolve from this work.
6.2 Development of the pulsed plasma technology

The two-line summary is that a source was developed and an operational regime was established that results in a peak heat flux of up to $\approx 1.5 \text{ GW} \cdot \text{m}^{-2}$ delivered to the target, superimposed on the steady mode that delivers a few $\text{MW} \cdot \text{m}^{-2}$. This is achieved at values of plasma density and temperature that are fully relevant to the ITER divertor. With those specifications, the first realistic ELM-emulator in the world has been created and the principal goal of the project was reached. Here we shall first look back on this development in an effort to distinguish, in retrospect, where non-trivial steps had to be made in the development of the source.

The basic approach followed was to superimpose a current pulse - induced by discharging a capacitor bank - on top of the DC current in a cascaded arc source. This technique had been pioneered by Timmermans in the 1980s, but in our case we i) aimed for a much stronger current pulse, ii) used hydrogen as the working gas rather than argon, and iii) applied a strong longitudinal magnetic field. The higher power could be expected to cause damage to the source. The same was true for the use of hydrogen, which due to its high mobility conducts heat to the channel wall much better than argon and is highly corrosive on top of that. On the positive side, the magnetic field not only confines the plasma beam but results in highly efficient plasma heating by ohmic dissipation outside the source. Hence, it was not clear beforehand that the same technique applied by Timmermans would yield the required results in our conditions. Nonetheless, the experiment was initiated by building a set-up similar to Timmermans’s as starting point and expanding the parameter space from there by introducing hydrogen operation, gradually increasing the current pulse (to 14 kA on top of a 200 A plateau) and exploring operation in high B-field (up to 1.6 T).

In this exploration it became clear that the original source design was unable to withstand the power loads in the discharge channel during the pulses, leading to serious damage of the source on the one hand and strongly contaminated plasma on the other. Two measures were found to be necessary and sufficient to allow operation in the targeted parameter regime with the pulsed source:

- the channel diameter was increased from 8 to 10 mm in order to decrease the heat load on the wall
- the plasma-facing surfaces of the channel were changed from copper to molybdenum in view of its higher melting point and sputtering threshold

With those technical changes to the source, it became possible to run it for prolonged periods in hydrogen with the combination of pulsed and DC mode while producing a clean plasma.

It can be argued that tungsten would be an even better material for the inside of the source, but molybdenum was chosen in our experiments because of the
difficult machining properties of tungsten. Experiments with a tungsten source are foreseen for later experiments.

As an unexpected spin-off result, it was found that the copper source, i.e. without molybdenum coating, when operated above the power threshold for damage to the source, proved to be a very efficient source of copper nanoparticles. These form from material that is ablated inside the source and are transported with the plasma beam to the target. Whereas copper was observed spectroscopically in the plasma beam, the nanoparticles were evident as deposits on the target surface. Analysis showed the nanoparticles to have a narrow size distribution with a mean diameter of 10 nm. It is presently under discussion with external parties whether this production method of nanoparticles can be used for commercial applications.

With the knowledge acquired during this development, some suggestions for further improvements of the source design can be formulated. In particular, the shape of the plates that make up the source could be modified in such a way that they shield the boron-nitride separation disks from the plasma. Further, a more effective cooling system has been devised. These ideas are presently under consideration by the team.

6.3 The plasma beam during pulsed operation

In terms of the physics of the plasma beam, it was found that the combination of magnetic confinement and high power density during the pulse resulted in efficient heating and full ionization of plasma in the middle of the beam. This enabled the increase of the electron temperature to up to 15 eV as measured by TS. The high temperatures were only achieved after the source material had been changed from copper to molybdenum. In the copper source, the plasma was strongly contaminated by eroded material (Cu), as was established by spectroscopy. As a result, radiation was an important loss channel and the temperature stayed below 5 eV, a similar value as was achieved in the - also radiating - argon plasma. The experiments with different source materials and different gases clearly showed the importance of radiation as the dominant loss channel in all cases except the highly ionized hydrogen plasma.

The fact that it was possible, with the current pulse, to burn through the radiation barrier and produce a highly ionized hydrogen beam with a temperature of 15 eV was a novel finding that came out of this source development program.

These parameters bring the plasma pulse in Magnum-PSI in the realm of the loads expected for ITER-ELMs. The electron temperature determines the potential across the plasma sheath, which is is a critical parameter for the occurrence of physical sputtering. The value during continuous wave (CW) operation - a few eV - is low enough to exclude physical sputtering for any wall material, including carbon. But at 15 eV, the threshold for physical sputtering is exceeded for carbon. The threshold for tungsten, the other material planned for the ITER divertor, lies much higher at a plasma temperature of about 100 eV.
Experiments with the pulsed source led to the discovery two phenomena in PSI that are highly relevant to the power exhaust in ITER and more generically, i.e. the self-shielding effect in the strongly coupled regime and the synergistic effect of pulsed and CW plasma exposure, and one discovery which might have application in material science.

6.4 Plasma surface interaction during the pulse: access to the strongly coupled regime, observation of self-shielding

The high intensity of the plasma pulses allowed the study of plasma surface interaction in an essentially new regime, in which the plasma is as much determined by the material that is released from the target i.e. embedded hydrogen or target material - as by the incoming plasma. In this regime, the interaction between target and incoming plasma is highly non-linear and no reliable predictions exist. The experiments with the pulsed source demonstrated the occurrence of a self-shielding effect shown by measurements of the temporal and radial profiles of the heat flux show from the plasma to the wall. At low pulse power (peak current up to 1.7 kA, 1 GW·m$^{-2}$), it was shown that the heat flux is proportional to the dissipated power in the plasma: the temporal evolution of heat flux follows the current. For higher pulse power this relation is broken. Here, the signature behavior is an initial sharp increase of the heat flux, which suddenly stops at $\approx 1$ GW·m$^{-2}$ and then drops while the current pulse is still rising. This interesting discovery correlates with radial profiles. This means that at low pulse energy the radial profile of the heat flux is a projection of the upstream radial profiles of temperature and density. The heat flux profile has an approximately Gaussian shape, i.e. is peaked in the center of the beam. However, at high pulse energy the radial heat flux profiles are peaked only at the beginning of the rise phase of the pulse. It then becomes flat and even hollow in the middle of the target. The electron temperature measured at 17 mm from the target decreases significantly from 12 eV at low pulse current (4.3 kA) to 2 eV (at 12 kA). At the same time, the density increases. It is therefore hypothesized that the cooling is due to a strong source of hydrogen. Measurements made in the upstream plasma do not show this temperature drop and density increase. Therefore, the hydrogen source has to be located in the target region, gas release and/or back-scattered particles from the target being the most obvious possibilities.

To explain this release of hydrogen the DC plasma load on the target is considered. The pressure of the beam on the target will lead to a large number of hydrogen atoms that are loosely bonded to the material. These can be released during the pulsed load when surface temperature rises. The particles that come off the surface will be trapped in the interaction zone due to the high electron density. In the prevailing conditions, the mean free path for ionization (calculated
using to Janev’s tables [36] is <1 mm. This means that all released particles become ionized and magnetized close to the surface, and even before they reach the location of the TS measurements of temperature and density.

6.4.1 Relevance of self-shielding to ITER divertor

The discovery of the self-shielding effect raises the question whether fewer large pulses - that exceed the threshold for self-shielding - may in fact be less damaging to the surface than many small ones. This is of great importance for the operational regime of ITER, where the present thinking is that the large Type-I ELMs cannot be tolerated, and scenarios with the more frequent but smaller Type-III ELMs are favored. It is too early to answer that question on the basis of the work in this thesis. But Magnum-PSI is now fully set up to address this question in a systematic way including a variation of the target tilt.

6.5 Discovery of the synergistic effects of pulse and CW - and placing this result in the frame of literature

Until our experiments, transients heat loads had been simulated by laser pulses or electron beam pulses, which were used to induce a surface temperature excursion on top of a steady state plasma exposure. Our experiments showed that the threshold for surface damage is considerable lower if plasma pulses are combined with a steady state plasma exposure. Whereas the PISCES-team reported a threshold for surface damage of 0.4 MJ·m\(^{-2}\) in experiments with laser pulses, we found the threshold to be 0.15 MJ·m\(^{-2}\) with the combined CW-plasma exposure and plasma pulses. It is therefore essential that such realistic, combined pulse-CW plasma experiments are used to investigate and predict the effect of ELMs on the target materials.

We must stress that both the CW plasma load and the pulsed plasma load are important for the surface damage, independently - and as said synergistically when combined. One might have expected that the surface damage is primarily due to the pulses, whereas the CW load stays below the damage threshold. However, it was already demonstrated by Kajita in experiments a CW helium plasma exposure combined with laser pulses, that there are important synergistic effects [49].

Our experiments show that the threshold for damage is reduced by the combined application of CW and pulsed plasma exposure. Moreover, they show that the threshold decreases with increasing exposure time to the CW load.

As an explanation of these observations, it is proposed that sufficiently high fluxes cause the implantation of helium into the metal, eventually leading to the formation of bubbles. These bubbles then burst under influence of the pulsed loads, with the release of target material as a result.
The essential difference between our system, with plasma pulses superimposed on a CW plasma load, and the experiments described in the literature which apply pulsed loads with non-plasma techniques, lies in the contribution of the ions. Not only the enhancement of plasma temperature (during the pulse) leads to a higher sheath potential and ensuing high physical ion impact, but the ions are also important because of their chemical activity. In the case of hydrogen, the power transport from the plasma to the target is effectuated by the hydrogen ions. Thus, it appears that there is a true synergy between the CW plasma load and the plasma pulse, each having their distinct effects but reinforcing each other. For this reason, the PPS described in this thesis is the most relevant tool for the study of the effect of ELMs on the target material in ITER.

Finally, the question may arise why surface damage due to plasma pulses is observed in our experiments, when we have demonstrated that effective self-shielding can occur. The solution to this paradox lies in the high threshold ($\approx 1$ GW·m$^{-2}$) for the occurrence of the self-shielding. The experiments on the synergistic surface damage of pulsed and CW loads were done below that threshold. Since ELMs can occur in different regimes - the high-amplitude low-frequency type I or the fast, small type III - it will be of great importance to understand the mechanisms which cause the surface damage, including the synergistic effects mentioned.

6.6 Valorization

6.6.1 Deposition of metal nanoparticles

![SEM image of copper nano-particles deposited during the pulsed discharge.](image)

Figure 6.1: SEM image of copper nano-particles deposited during the pulsed discharge.

As said above, it turned out during the development stage that the PPS is capable of depositing nano-particles on the surface (fig. 6.1). These deposits
were analysed using Scanning Electron Microscopy (SEM), which revealed nanoparticles that were agglomerated on the target. The process is very efficient: a few plasma pulses suffice to cover the entire surface homogeneously with a densely packed layer of spherical copper nano-clusters. Analysis by X-Ray Photoelectron Spectroscopy (XPS) showed that the particles are indeed formed out of copper. After this finding, an aluminum cathode was installed in plasma source, this resulted in the deposition of aluminum particles. These results suggest many materials with a sufficiently low melting point can be deposited with this method. This deposition method stands out by the narrow size-distribution of the deposited particles (fig. 6.2). It is hypothesized that the strong magnetic field acts as a size filter, but this hypothesis has not yet been checked experimentally. Large particle travels in magnetic field around larger Larmor orbits therefore it goes out of the beam in contrast to smaller one which stays inside the beam and is deposited onto target area. At 50 nm/pulse, the deposition rate is high. Effectively, this means that a 1 micrometer coating can be deposited in \( \approx 3 \) minutes with a pulse frequency of 100 Hz.

![Figure 6.2: The diameter distribution of copper nano-particles.](image)

### 6.6.2 Surface hardening with pulsed plasma exposure

Another beneficial effect of the plasma pulses is an observed hardening of the metal surface. This is attributed to the very fast heating of 1500°C in 200-500 \( \mu s \) (3 - 7.5 \( \times \) \( 10^6 \) K s\(^{-1} \)). These temperature excursions can change the crystallographic structure and composition of the metal, and thereby change the physical properties of some allotropic forms of metals. These affect the mechanical features of surface. The fast heating and subsequent rapid cooling allow a crystallographic
reorganization which results in hardening of the surface. Owing to the fact that this type of plasma source can operate on different gases: hydrogen, deuterium, helium, neon, argon, nitrogen, silane, etc. apart from physical treatment the chemistry can be involved. One of the examples is nitrification, widely used in industry [71, 72]. Surface processing was beyond the scope of the thesis, but nevertheless the system provides unique and promising conditions for surface treatment which could be developed in a follow-up project, possibly with industrial parties.
Summary

The research described in this thesis is done in the frame of the development of nuclear fusion as a source of clean, safe and virtually inexhaustible power. Fusion energy is being developed in an international program, which is presently culminating in the construction of the test reactor ITER. ITER is designed to produce ten times more power than is needed to run it, at a level of 500 MW (comparable to a small power plant). In ITER a plasma of hydrogen isotopes is confined by strong magnetic fields and heated to 250·10^6 °C. The basics of the magnetic confinement and heating are well understood, but there are other areas where ITER enters uncharted waters. One of these is the interaction that takes place where the plasma meets the wall of the reactor: plasma surface interaction (PSI), the topic of this thesis.

The high power density in the reactor leads to potential problems with melting, evaporation and erosion of the wall material, as well as the retention of hydrogen either in the wall itself or in redeposits of eroded material. In ITER, the fluences of particles and energy to the wall are two orders of magnitude larger than those in earlier experiments, and if the PSI and materials issues are not dealt with properly, the life time of the strike zones i.e. the strips of material that take most of the power, could be days rather than years.

The problem of the power exhaust is twofold. To start, the time averaged heat flux density to the strike zone is already extreme, at 10 MW·m^{-2}. Yet, materials and cooling techniques have been developed that can handle that power load if it comes as a steady flux. However, the situation is aggravated by the occurrence in ITER of a quasi-periodic instability (the so-called ELM), which results in a bursty character of the heat release with peak loads exceeding 1 GW·m^{-2} during 1 ms, with typically 10 - 300 Hz repetition rate.

The first step in this research project was the development of a PPS for use in the linear plasma generators at DIFFER (Pilot-PSI and Magnum-PSI) which would allow a realistic simulation of the plasma load on the strike zone in ITER, and in particular to superimpose the transient heat/particle load on the steady state plasma load. A device with that capability did not exist in the world. After that, using this device, the effect of the pulsed load and the combination of pulsed and steady state exposure on the material was investigated.

The first goal was achieved by applying current pulses to a running cascaded
arc plasma source. This technique, pioneered by Timmermans in 1984, was taken to a new power level which required a number of design changes to the source: a wider plasma channel (to reduce heat load in the source), the cladding of all plasma facing components in the source with molybdenum, the redesign of the cathode and anode and application of a strong longitudinal magnetic field. With those modifications, current pulses of up to 4.3 kA could be superimposed on a steady operation at 200 A, resulting in heat pulses in excess of 1 GW·m$^{-2}$ and an energy density of 0.5 MJ·m$^{-2}$ with millisecond duration, superimposed on steady load of up to 5 MW·m$^{-2}$. At the target, the plasma density reached up to 60·10$^{20}$ m$^{-3}$ at a plasma temperature of up to 12 eV (about 140 thousand K). With those parameters, the PSI conditions that will occur in ITER during ELMs can be realistically simulated.

During the source development process, it was discovered that the source plasma purity plays an essential role, leading to an operational bifurcation between two plasma temperature regimes. Without the molybdenum cladding in the source, the plasma was contaminated with copper. Compared to the clean plasma obtained with molybdenum cladding, this resulted in plasmas with much lower temperature ($\approx 5$ eV instead of $\approx 15$ eV) but higher electron density (up to 150·10$^{20}$ m$^{-3}$ rather than 60·10$^{20}$ m$^{-3}$). In contrast, the clean hydrogen plasma obtained in the molybdenum-coated source becomes highly ionized, has low radiation losses and goes into the high temperature mode.

In order to guide the plasma (pulse) from the source to the target a strong magnetic field was applied ($\leq 1.6$ T). In the steady state discharge at 200 A, there is a significant (typically 90%) loss of power flux, mostly due to MAR. In the pulsed mode (kA-regime) this loss process is confined to the cool edge of the beam. As a result the efficiency of the power transport is found to be 2.5 times higher during the pulse than in steady state.

With the pulsed source operating in the ITER-ELM relevant regime two studies of the interaction of the plasma pulse with a tungsten (the material foreseen for the ITER strike zone) target were undertaken. First, the impact of a single pulse on the target was studied. Then, the combined effect of the pulsed ELM-like plasma and the steady state plasma load was investigated.

The interaction of the pulsed plasma with the tungsten target was found to show an interesting and unexpected relation between the pulse energy and the energy deposited on the target. Upon increasing the energy in the plasma pulse, the energy delivered to the target first increases proportionally, but then rolls over and decreases. This is ascribed to a sudden release of particles from the target which leads to a drop of the plasma temperature. Two mechanisms were considered: desorption of mobile hydrogen from the surface due to the rapid temperature rise, or the back-scattering of a cloud of ions impinging the wall during the pulse. It is not possible at this stage to distinguish which mechanism dominates. The experiments were carried out in the strongly coupled regime, characterized by the fact that the mean free path - before ionization and trapping in the magnetic field - of the particles released from the surface is smaller than
the plasma size. In this regime - which is typical of fusion reactors, but until now had not been reproduced in a laboratory experiment - the backflow of particles from the surface can induce detachment of the plasma and hence reduce the energy density to the surface. To our knowledge, this is the first report of such a beneficial self-protection effect and its implications in terms of prolongation of material lifetime should be studied in more detail.

The superposition of the pulsed and steady state plasma exposure also showed an unexpected result. The release of tungsten during the plasma pulse was monitored with a fast camera, tuned to the WI line at 400.9 nm. A clear threshold behaviour was observed as a function of the pulse energy. In the case of a hydrogen plasma, the threshold for tungsten release from the target was found to be around 0.2 MJ·m⁻², while no release was observed below 0.25 MJ·m⁻² for helium plasma exposure. Significant morphology changes were observed when the surface was exposed to superimposed steady state and pulsed plasmas. Surface roughening was already noticeable after 10 pulses at 0.07 MJ·m⁻², and increased with the number of pulses. Our results strongly suggest that in the case of a combined steady state and pulsed exposure, synergistic effects occur which lower the damage threshold for tungsten by a factor of two compared to the values currently found in the literature.

The implications of these results for the fusion reactor are mixed. The self-shielding might be good news, if it can be shown to be equally effective in the reactor geometry. This finding suggests - unexpectedly - that low-frequency, high-amplitude ELMs might be less damaging to the wall than frequent small ELMs. On the other hand, the synergistic effect of steady state and pulsed plasma loads appear to cause damage to the tungsten surface at much lower threshold energy than was previously expected. In any case, with the Magnum-PSI device equipped with the PPS, a research environment has been developed that is ready for deeper studies into the physics of these new phenomena.
Acknowledgments

I am happy that I had the possibility to work with so many experienced and helpful people during my time at FOM DIFFER. I know that without their support my thesis would not be in its current shape.

First of all I want to thank my supervisor Greg De Temmerman for his guidance. He invested great effort and patience into my project and in me. He has supported me in every aspect of my work, was always available for discussion and answered my questions, even when I posed the same one a few times!

I am indebted to my promoter Niek Lopes Cardozo for his general guidance and substantial assistance in the final stage of my PhD. I’d like to thank also my co-promoter Richard van de Sanden for his valuable remarks considering my thesis.

I owe my deepest gratitude to Daan Schram for enormous support during my PhD. He has taught me plasma physics, helped with interpretation of difficult results, motivated me and raised my self-confidence.

I’d like to thank my mentor Michael Gleeson for help in difficult times. I thank Jürgen Rapp for supervision in the first few months of my PhD, Gerard van Rooij and Wim Goedheer for discussions of plasma physics with them.

I thank for their technical support Marc van der Pol and Richard Al for keeping the machine running during my experiments, Andries Lof for testing my plasma sources and Wim Melissen, Bob Krijger, Ton van der Grift for handling the electrical set-up. Thanks to people from the workshop; Peter Wortman, Jan Lagerweij (Jan The Little), Ronald Wolbeer and the rest of the crew for Friday’s beer and for fixing my plasma sources immediately during my experimental time.

I am grateful to Tomasz Sokolowski, Alexey Kuznetsov, Ryszard Sobierański, Diego de Lazzari, Nicola Bertelli for being my first friends in Nd’s and for ’getting messy’. I’d like to thank Kirill Bystrov for being a friend and good 2nd person during my experiments, İrem Tanyeli for friendship and teaching me whistling on my fingers, Tom Morgan for assistance with experiments and writing, Hennie van der Meiden, Wouter Vijvers and Miranda van den Berg - for being my office mates, Bram Lamers for nice drawings, Rianne ’t Hoen and Thijs Versloot for everything, and Gijs van Swaaij, Wolf Weymiens and Vincent van Beveren for their help with latex and programming issues. Moreover, I would like to thank Hector Alvaro Galue, Josipa Grzetic, Jeroen Westerhout, Amy Shumack, Rob
Wieggers, Alex Poelman, Paul Smeets, Hans van Eck, Vivike Lapoutre, John Scholten, Dagmar de Rooij, Martijn Graswinkel, Serge Brons, Oge Kruijt, Niek den Harder, Jonathan Citrin, Gieljan de Vries, Haiyan Xu, Thomas Olivier, Bas Hansen, Sjaak van Diepen and rest of the Magnum and Pilot-team.

I appreciate the time I have spent with my friends under one roof. Special thanks goes to Lydia Mellaart, Michael Roch and Romek Mokhovykov.

I thank my friends in Poland: Marcin Jażdż, Sylwek Wawrzyniak, Maciek Slowikowski and Lukaz Kałuża.

Above all, I would like to thank my parents, grandmother and Milenka for motivation, understanding and general support during these years.
Curriculum Vitae

Jakub J. Zieliński was born on the 1st of May, 1983 in Łódź, Poland. Between 2002 and 2007 he obtained a Master’s degree in Chemical and Process Engineering at the Technical University of Łódź. In the second half of 2006 he participated in the Socrates-Erasmus exchange program at the University of Southern Denmark in Odense. His masters project was devoted to the construction and characterization of a plasma needle for surface treatment sensitive to thermal damage. Subsequently, he worked in the Division of Molecular Engineering the Technical University of Łódź on the development of his own idea of a microplasma electrode reactor for surface treatment under atmospheric pressure which yielded a patent at the end of 2008. Since January 2009 he studied for his PhD in the Plasma Surface Interactions Experimental group at the Dutch Institute For Fundamental Energy Research (DIFFER) in Nieuwegein, The Netherlands. This resulted in this thesis entitled A high power PPS for material testing under simultaneous and transient loads.
Bibliography


Herrmann A. and ASDEX-Upgrade team (2001) Contribution to the 27th Conf. on Plasma Physics and Controlled Fusion (Budapest, Hungary)


