

UNIVERSIDADE DE LISBOA INSTITUTO SUPERIOR TÉCNICO



UNIVERSITÁ DEGLI STUDI DI PADOVA

Development of high efficiency negative ion source: from conceptual studies to experimental test

Michele Fadone

Supervisors: Doctor Artur Jorge Louzeiro Malaquias Doctor Piero Martin

Thesis approved in public session to obtain the PhD Degree in Techonological Physics Engineering Jury final classification: Pass with distinction



UNIVERSIDADE DE LISBOA INSTITUTO SUPERIOR TÉCNICO



UNIVERSITÁ DEGLI STUDI DI PADOVA

Development of high efficiency negative ion source: from conceptual studies to experimental test

Michele Fadone

Supervisors: Doctor Artur Jorge Louzeiro Malaquias Doctor Piero Martin

Thesis approved in public session to obtain the PhD Degree in Techonological Physics Engineering Jury final classification: Pass with distinction

Jury

Doctor Luis Raúl Sánchez Fernández, Escuela Politécnica Superior, Universidad Carlos III de Madrid, Espanha

Doctor Alfredo Pironti, Scuola Politecnica e delle Scienze di Base, Università degli studi di Napoli "Federico II", Itàlia

Doctor Horácio João Matos Fernandes, Instituto Superior Técnico, Universidade de Lisboa

Doctor Kristel Crombé, Faculty of Engineering and Architecture, Ghent University, Bélgica

Doctor Giuseppe Zollino, Scuola di Ingegneria, Università Degli Studi di Padova, Itàlia

Acknowledgements

Firstly, I would like to express my sincere gratitude to my supervisor Dr. Vanni Antoni for the continuous support of my Ph.D study and related research, for his patience, motivation, and immense knowledge. He put his trust in me without hesitation leaving me speechless. His guidance helped me in all the time of research and writing of this thesis. I could not have imagined having a better advisor and mentor for my Ph.D study.

Besides my supervisor, I would like to thank Dr./Ing. Emanuele Sartori. Working together with a brilliant mind it is always an honor and I hope that following your advice and methodology during these 3 years will help me to become a better researcher. I must mention also Dr. Alessandro Fassina who always supported me despite his several activities: his comments and experimental experience were fundamental to complete all the measurement campaigns.

My sincere thanks also goes to Dr. Pierluigi Veltri, Prof. Gianluigi Serianni, Dr. Matteo Zuin and Dr. Francesco Taccogna who always had time for me when I had doubts during all the period of the thesis, from the design to the operational tests of the experiments. Moreover, I thank Vannino Cervaro from the workshop because he helped me to improve and optimize my projects from a mechanical point of view, saving me a lot of time and giving me precious experience for future works.

I cannot forget also Ivo Furno, who gave me the possibility to join RAID team at SPC in Lausanne, allowing me to introduce a huge contribution to my thesis project. I thank my fellow labmates in for the stimulating discussions and for all the fun we have had in the last three years.

Last but not the least, I would like to thank my family: my parents and my brother for supporting me spiritually throughout writing this thesis and my my life in general.

Abstract

Nuclear fusion constitutes a promising energy source to meet the future increasing world energy demand. To obtain an energy gain through the fusion reaction of light nuclei in a reactor based on magnetic confinement, the temperature of a confined plasma up to 15keV has to be obtained. To test the scientific and technological feasibility, the international scientific community is committed to build the first reactor prototype, called ITER. This machine is based on the tokamak configuration but requires some additional heating. Among the external auxiliary heating systems, there is the Neutral Beam Injector (NBI). The subject of this PhD thesis is related to NBI R&D for ITER and future fusion reactors. Schematically, a NBI will operate with Hydrogen/Deuterium negative ions and consists of a plasma source, an extraction and acceleration system, a neutralization stage. Since the parameters required have unprecedented values, all these components need an extensive R&D before the actual realization of the NBI for ITER. This is the reason why a Neutral Beam Test Facility (NBTF) for ITER has been built at Consorzio RFX. In this site, the operation in Hydrogen of the source SPIDER for ITER NBI has been already started, while the full size NBI prototype MITICA is still under construction. The work of this PhD thesis dealt with this issue focusing on optimization of present sources and alternative ways to generate negative ions from a plasma source. To optimize the generation in SPIDER, a study on cesium distribution inside a vacuum chamber has been performed: indeed the alkali metal deposition on a surface is fundamental to enhance the generation of negative ions. For DEMO and future reactors, the next step in the fusion reactors roadmap after ITER, it is necessary to improve the efficiency of the whole NBI and in particular of the mechanisms to produce negative ions. Specifically, the optimization of two main negative ion generation mechanisms, surface and volume, have been studied separately in two different experiments. The first one has been built taking advantage of aerospace technology and it has operated for the surface production. The knowledge acquired in the SPIDER cesium study has been used to enhance the extraction of the negative ions from this source. As for the volume production, the activity has taken place at SPC-EPFL in Lausanne where there is a Radio-Frequency (RF) resonant helicon antenna plasma source. The device has been proved very effective in generating negative ions by volume mechanism. However, the extraction in this device is still an open issue due to the perturbation of the magnetic field confining the plasma. To overcome this problem, extractor system prototypes have been designed in order to take full-advantage of the high H^- density found in the generated plasma. The result of a thorough analysis performed by electromagnetic and particle tracing simulations has confirmed the potential of optimum negative ion generation at a level of proof of principle, so that the design of two different extraction systems have been carried out. Both concepts have been considered worth an experiment test so that

at present one is under construction and the second one is planned to be tested later. If successful, the experimental test will open the possibility of future development for the DEMO ion source.

5 Key-words: Negative ions, Neutral Beam Injectors, Caesium, Hall Effect Thruster, RF Antenna, Proof of Principle

Sommario

La fusione nucleare costituisce una promettente fonte di energia per soddisfare il futuro aumento della richiesta di energia a livello mondiale. Per ottenere un guadagno energetico per mezzo della fusione di elementi a basso numero atomico in un reattore a fusione basata sul concetto di confinamento magnetico del plasma, è necessario raggiungere una temperatura di plasma di almeno 15keV. Per testare questo tipo di tecnologia, la comunità scientifica internazionale si è impegnata nella realizzazione del primo prototipo di reattore, denominato ITER. Il design scelto per questo dispositivo è la configurazione tokamak; nonostante ciò, è necessario avere dei mezzi di riscaldamento ausiliari esterni per il plasma. Il Neutral Beam Injector (NBI) è uno di questi. L'argomento di questa tesi di dottorato rientra proprio nella ricerca e sviluppo dell'NBI per ITER e futuri reattori a fusione. Lo schema generale di un NBI che opera in Idrogeno/Deuterio è costituito da una fonte di plasma, un sistema di estrazione e accelerazione e una fase di neutralizzazione. Dal momento che i requisiti richiesti per questa tecnologia hanno valori senza precedenti, tutti questi componenti necessitano di una approfondita analisi prima della realizzazione effettiva dell'NBI per ITER. Questo è il motivo per cui la Neutral Beam Test Facility (NBTF) per ITER è stato realizzata presso il Consorzio RFX. In questo sito, campagne sperimentali in idrogeno della sorgente SPIDER per ITER NBI sono già iniziate, mentre il prototipo NBI in scala 1:1, denominato MITICA, è ancora in costruzione. Per ottimizzare la generazione di ioni negativi in SPIDER, uno studio sulla distribuzione del cesio all'interno di una camera da vuoto è stata eseguita: la deposizione di metalli alcalini sulla superficie di estrazione è fondamentale per migliorare la generazione di ioni negativi. Per DEMO e futuri reattori, il prossimo passo nella roadmap per i reattori a fusione dopo ITER, è il miglioramento dell'efficienza dell'intero NBI e in particolare dei meccanismi per produrre ioni negativi. Il lavoro di questa tesi di dottorato si è concentrato sull'ottimizzazione delle sorgenti odierne e su modi alternativi per generare ioni negativi da una sorgente di plasma. In particolare, l'ottimizzazione dei due principali meccanismi di generazione di ioni negativi, processi di superficie e di volume, sono stati studiati separatamente in due diversi esperimenti. Il primo è stato costruito sfruttando una teconologia proveniente dal settore aerospaziale ed è stato testato nel contesto della produzione di superficie. L'esperienza acquisita nello studio del cesio in SPIDER è stata fondamentale per il miglioramento dell'estrazione degli ioni negativi da questo nuovo dispositivo. Per quanto riguarda la produzione in volume, l'attività si è svolta all' SPC-EPFL di Losanna dove è presente una sorgente helicon alimentata in radiofrequenza. Nel plasma generato da questa antenna è stata trovata una elevata densità di ioni negativi prodotti per mezzo del processo di volume. Tuttavia, l'estrazione di queste particelle in questo dispositivo è ancora un problema aperto a causa della perturbazione dell'intrinseco campo magnetico assiale che confina il plasma. Per superare questo problema, due prototipi di estrazione sono

9

stati progettati per sfruttare l'elevata densità di ioni negativi presente nel plasma. Da un'analisi approfondita eseguita tramite simulazioni elettromagnetiche e di particle tracing, è stato confermato che è possibile estrarre ioni negativi in termini di proof of principle. Entrambi i prototipi sono stati considerati meritevoli di un test sperimentale e al momento uno dei due è in fasse di costruzione mentre il secondo dovrebbe essere testato in seguito. In caso di esito positivo, il test sperimentale aprirà la possibilità di sviluppi futuri per una eventuale sorgente alternativa di ioni negativi per DEMO.

5 Parole chiave: ioni negativi, iniettori di neutri, cesio, propulsore a effetto Hall, antenna RF, proof of principle

Resumo

A fusão nuclear constitui uma fonte de energia promissora para atender ao futuro aumento demanda mundial de energia. Para obter um ganho de energia através da reação de fusão da luz núcleos de um reator baseado em congestionamento magnético, a temperatura de um plasma de até 15keV deve ser obtido. Para testar o conhecimento científico e tecnológico viabilidade, a comunidade científica internacional está comprometida em construir a primeira protótipo de ator, chamado ITER. Esta máquina é baseada na configuração do tokamak mas requer algum aquecimento adicional. Entre o sistema de aquecimento auxiliar externo sistemas, existe o injetor de feixe neutro (NBI). O assunto desta tese de doutorado é relacionados à pesquisa e desenvolvimento da NBI para ITER e futuros reatores de fusão. Esquematicamente, um NBI irá operar com íons negativos de hidrogênio / deutério e consiste em uma fonte de plasma, um sistema de extração e aceleração, um estágio de neutralização. Como os parâmetros exigidos, com valores sem precedentes, todos esses componentes precisam de uma extensa pesquisa e desenvolvimento antes da realização real do NBI para o ITER. Esta é a razão pela qual um neutro O recurso de teste de feixe (NBTF) para ITER foi construído no Consorzio RFX. Neste site, a operação em hidrogênio da fonte SPIDER para o ITER NBI já foi iniciado, enquanto o protótipo de tamanho grande da NBI MITICA ainda está em construção. Para otimizar a geração no SPIDER, um estudo sobre distribuição de césio dentro de uma câmara de uum foi realizada: de fato, a deposição de metais alcalinos em uma superfície é fundamental para melhorar a geração de íons negativos. Para DEMO e futuro reatores de fusão, o próximo passo no roteiro dos reatores de fusão após o ITER, é necessário melhorar a eficiência de todo o NBI e, em particular, dos mecanismos para produzir íons negativos. O trabalho desta tese de doutorado tratou desta questão focando otimização das fontes atuais e formas alternativas de gerar resultados negativos íons de uma fonte de plasma. Especificamente, a otimização de dois principais íons negativos mecanismos de geração, superfície e volume, foram estudados separadamente em dois diferentes experiências. O primeiro foi construído aproveitando o espaço aeroespacial tecnologia e tem operado para a produção de superfície. O conhecimento adquirido no estudo SPIDER césio tem sido usado para melhorar a extração do negativo íons dessa fonte. Quanto ao volume de produção, a atividade ocorreu no SPC-EPFL em Lausanne, onde existe um helicóptero ressonante de radiofrequência fonte de plasma da antena. O dispositivo provou ser muito eficaz na geração de íons negativos por mecanismo de volume. No entanto, a extração neste dispositivo ainda é uma questão em aberto devido à perturbação do campo magnético no plasma. Para superar esse problema, protótipos de sistemas extratores foram projetados para tirar o máximo proveito da alta densidade de H plasma encontrada no plasma gerado. O resultado de uma análise minuciosa realizada por simulações eletromagnéticas e de rastreamento de partículas confirmam

o potencial de geração ótima de íons negativos em um nível de prova de princípio, de modo que o projeto de dois sistemas de extração diferentes realizado. Ambos os conceitos foram considerados dignos de um teste experimental, para que atualmente, um está em construção e o segundo está planejado para ser testado mais tarde.Se for bem-sucedido, o teste experimental abrirá a possibilidade de desenvolvimento futuro para a fonte de íons DEMO.

Palavras-chave: Íons negativos, injetores de feixe neutro, césio, propulsor de efeito Hall, antena de RF, prova de princípio

Contents

1	Intr	roduction	14
	1.1	Energy problem	14
	1.2	Nuclear Fusion	14
		1.2.1 Nuclear fusion reaction	15
		1.2.2 ITER	16
		1.2.3 DEMO	16
	1.3	Auxiliary Heating Systems	17
	1.4	NBI	18
	1.5	Motivation of the work and summary	20
2	Neg	ative ions	22
	2.1	Negative Ion Generation	22
		2.1.1 Volume production	22
		2.1.2 Surface production	23
	2.2	Negative Ion Extraction	24
		2.2.1 Langmuir Introduction	24
		2.2.2 Ion beam sources design	26
		2.2.3 Why negative and not positive ion sources	26
		2.2.4 Negative Ion Sources challenges	26
	2.3	Role of Caesium	27
		2.3.1 Negative Hydrogen ions enhancement	27
	2.4	Efficiency of generation	27
3	SPI	DER Caesium	29
	3.1	SPIDER description	29
	3.2	CAesium Test Stand	30
	3.3	Fixed Langmuir-Taylor detector	31
		3.3.1 Circuit	31
		3.3.2 Measurements	31
	3.4	LAS	34
	3.5	Movable Langmuir-Taylor detector	35
	3.6	Quartz Crystal Micro-balance	35
	3.7	Avocado	37
		3.7.1 Interpretation of the results	38
	3.8	SPIDER simulation	41
		3.8.1 First model	42
		3.8.2 Auxiliary grid model	42
		3.8.3 Final model	45

	3.9	Conclusions	45				
4	ATI	ATHENIS 4					
	4.1	Hall Effect Thruster	47				
	4.2	Design	48				
	4.3	Diagnostics	51				
		4.3.1 Magnetic measurements	51				
		4.3.2 Langmuir probe	51				
		4.3.3 Retard Field Energy Analyzer	52				
		4.3.4 Spectroscopy	53				
	4.4	Plasma Characterization Data	54				
		4.4.1 Estimate of the H^- current	55				
	4.5	Extraction	57				
		4.5.1 Electromagnetic simulations and trajectories analysis	57				
		4.5.2 Cesium evaporation system	59				
		4.5.3 Extraction campaign results	61				
	4.6	Conclusions	63				
5	B A1	П	64				
5	\mathbf{RA}	ID Introduction	64				
5	RA 5.1	ID Introduction	64 64				
5	RA] 5.1	ID Introduction 5.1.1 Helicon Plasma Sources 5.1.2 RAID	64 64 64				
5	RA 5.1	ID Introduction 5.1.1 Helicon Plasma Sources 5.1.2 RAID Fytraction Problem Analysis	64 64 65 67				
5	RA 5.1 5.2 5.3	ID Introduction 5.1.1 Helicon Plasma Sources 5.1.2 RAID Extraction Problem Analysis Badial Extraction	64 64 65 67				
5	 RA 5.1 5.2 5.3 	ID Introduction 5.1.1 Helicon Plasma Sources 5.1.2 RAID Extraction Problem Analysis Radial Extraction 5.3.1 First Conceptual Design	64 64 65 67 69 60				
5	RA5.15.25.3	ID Introduction 5.1.1 Helicon Plasma Sources 5.1.2 RAID Extraction Problem Analysis Radial Extraction 5.3.1 First Conceptual Design 5.3.2 Electromagnetic Simulations	64 64 65 67 69 69 71				
5	RA5.15.25.3	ID Introduction 5.1.1 Helicon Plasma Sources 5.1.2 RAID Extraction Problem Analysis Radial Extraction 5.3.1 First Conceptual Design 5.3.2 Electromagnetic Simulations 5.3.3 Final configuration	64 64 65 67 69 69 71 73				
5	RA 5.1 5.2 5.3	ID Introduction 5.1.1 Helicon Plasma Sources 5.1.2 RAID Extraction Problem Analysis Radial Extraction S.3.1 First Conceptual Design 5.3.2 Electromagnetic Simulations S.3.3 Final configuration	64 64 65 67 69 69 71 73 74				
5	 RA 5.1 5.2 5.3 5.4 	ID Introduction 5.1.1 Helicon Plasma Sources 5.1.2 RAID Extraction Problem Analysis Radial Extraction 5.3.1 First Conceptual Design 5.3.2 Electromagnetic Simulations 5.3.3 Final configuration Axial Extraction	64 64 65 67 69 69 71 73 74 74				
5	 RA 5.1 5.2 5.3 5.4 	IDIntroduction5.1.1Helicon Plasma Sources5.1.2RAIDExtraction Problem AnalysisRadial ExtractionS.3.1First Conceptual Design5.3.2Electromagnetic Simulations5.3.3Final configuration5.4.1First conceptual design5.4.2Final configuration	64 64 65 67 69 71 73 74 74 74				
5	 RA 5.1 5.2 5.3 5.4 5.5 	IDIntroduction5.1.1Helicon Plasma Sources5.1.2RAIDExtraction Problem AnalysisRadial ExtractionS.3.1First Conceptual Design5.3.2Electromagnetic Simulations5.3.3Final configuration5.4.1First conceptual design5.4.2Final configurationConclusions	64 64 65 67 69 71 73 74 74 75 78				
5	 RA 5.1 5.2 5.3 5.4 5.5 C 	ID Introduction 5.1.1 Helicon Plasma Sources 5.1.2 RAID Extraction Problem Analysis Radial Extraction 5.3.1 First Conceptual Design 5.3.2 Electromagnetic Simulations 5.3.3 Final configuration 5.4.1 First conceptual design 5.4.2 Final configuration Conclusions	64 64 65 67 69 69 71 73 74 74 75 78				
5	 RA 5.1 5.2 5.3 5.4 5.5 Con 	ID Introduction 5.1.1 Helicon Plasma Sources 5.1.2 RAID Extraction Problem Analysis Radial Extraction 5.3.1 First Conceptual Design 5.3.2 Electromagnetic Simulations 5.3.3 Final configuration 5.4.1 First conceptual design 5.4.2 Final configuration Substructions Substructions	64 64 65 67 69 69 71 73 74 74 75 78 82				

Chapter 1 Introduction

This brief chapter will give a general idea on the Neutral Beam Injector (NBI) concept. It is necessary, though, to start from the role of nuclear fusion reactors in the energy production topic, where the future devices ITER and DEMO are quoted. Then, there is a section dedicated to the auxiliary heating systems necessary to sustain the fusion plasma in the needed temperature ranges that guarantee the expected energetic gain. Successively, different negative ion sources will be listed, focusing on the experiments that will be cited in the other chapters. In closing, there is a reminder of the motivations for this PhD project.

1.1 Energy problem

During the last decades, an increasing of the consumption rate of the natural resources has been recorded. This trend is caused by the world technological progress and by the economic growth, especially of the developing countries. All of this contributed also to the increasing of the world population [1]. Nowadays, the world energy demand is meet for 86% by fossil fuels and its consumption is steadily increasing. At this rate though, there is the serious risk that the oil and gas resources are going to be exhausted by 2070 if no new reserves are discovered [2]. Furthermore, there is a tangible threat from a climatic and pollution point off view: every year there is a neat CO_2 emission around 22Gtons [3]. It is therefore necessary to find alternative ways to produce electricity.

1.2 Nuclear Fusion

Renewable energy resources alone are still not sufficient enough to meet the future energy demand [4][5][6][7][8][9]. Among other artificial resources, nuclear fusion reactors has been chosen as possible solution for the next humankind generation [10]. From an environmental impact point of view, nuclear fusion reactors are a really attractive option since the main product of the reaction is Helium. Moreover, it is a CO_2 free source and it does not emit greenhouse gases or other harmful chemicals in the atmosphere. The only concern could derive from the generation of high energy neutrons, which are collected by the fusion blanket. The material of this structure can be therefore activated and become radioactive. Its short life though is really short, about 100 years, so its storage is not a serious threat for multiple future



Figure 1.1: a)Binding energy of atoms. b) Reaction rates of fusion reactions according to the plasma temperature.

generations. Fusion reactors are an actual option even for their safety. To sustain the plasma, it is necessary to provide continuously the fuel. Therefore, there is no risk of having a melt-down because of chain reactions as happened in fission reactor accidents.

1.2.1 Nuclear fusion reaction

Generally speaking, in the nuclear fusion process there is an energy release due to the mass difference between reactants and products, energy that follows Einstein relationship $E = m \cdot c^2$.

From figure 1.1a it is possible to see the huge relative gain when the nuclear fusion involves light elements. Specifically, for Hydrogen and its isotopes Deuterium and Tritium, the reaction with the highest reaction rate, and therefore more likely to happen, is the following (see the blue dashed line of figure 1.1b):

$$D + T \longrightarrow He(3.5MeV) + n(14.1eV)$$
 (1.1)

where D stands for Deuterium, T for Tritium, He for Helium and n for the remaining neutron. To use this main reaction for energy production purposes, it is necessary to satisfy and overcome the Lawson's criteria [11]. This means to go beyond the break-even configuration, that is when the fusion power produced is greater than the sum of all the powers used to sustain the plasma. This condition can be written down in mathematical terms by means of the triple product:

$$n \cdot \tau_E \cdot T > 3 \cdot 10^{21} keV s/m^3 \tag{1.2}$$

where n is the plasma density, τ_E is the energy confinement time and T is the plasma temperature. From this product, it has been possible to find the minimum operative plasma temperature, which is $150 \cdot 10^6 K \approx 15 keV$. To be able to work at this temperatures, it is mandatory to generate a plasma in a vacuum chamber and to confine it by means of high intensity magnetic fields in order to avoid direct contact between the vacuum chamber walls and the plasma itself. It is therefore clear how the attempt to build a fusion reactor is a hard technological challenge.

1.2.2 ITER

ITER (International Thermonuclear Experimental Reactor) is the first step in the fusion reactor roadmap. ITER is an international project [12] for which it has been decided to use a tokamak configuration for the plasma confinement. The final aim is to produce a total fusion power ten times the one necessary to sustain the all facility. Another goal is also to increase as much as possible the duty cycle. In table 1.1 the

	ITER	DEMO
Plasma Major Radius	6.2m	8.6m
Plasma Minor Radius	2.0m	2.9m
Plasma Volume	$840m^{3}$	
Plasma Current	15.0MA	28.0MA
Maximum Toroidal Field	5.3T	6.9T
Fusion Power	500 MW	3600 MW
Pulse Duration	> 400s	steady state
Energy Gain Factor	> 10	13.5
Costs in 10 years	$10 \cdot 10^{9} \in$?

Table 1.1: ITER and DEMO nominal paramters

main ITER geometrical and energetic parameters are reported. Figure 1.2 shows



Figure 1.2: ITER design scheme.

the final ITER design where it is possible to note the classical D shape of the coils that impose the toroidal magnetic field and act as support for the first wall materials that are facing the plasma. ITER is under construction in St Paul-lez-Durance in France and in [13] a brief description of the ITER construction status can be found.

1.2.3 DEMO

DEMO (Demonstration Fusion Power Plant) is the ITER successor device. Precisely, it will be the first fusion reactor prototype potentially able to produce electricity.

Currently there are no final conceptual designs, but in table 1.1 preliminary parameters can be found. The main differences with ITER can be summarized as follows [14]:

- Long pulse operation;
- Diagnostics only for operation and not to study the plasma physics behavior;
- Optimization of all the systems, from cooling to auxiliary heating, thanks to ITER experience;
- It will have all the components necessary to transform the thermal power generated by the plasma to electricity.

Theoretically, DEMO should be operative by the end of 2050 to show the possibility to produce electricity by means of a fusion reactor. However, there are currently a lot of R&D activities going on, such as (i)the breeding blanket technology and coolant, (ii) divertor design and technology, (iii)first-wall protection and integration to the blanket, (iv) Heating&CurrentDrive (H&CD) systems capability and (v) remote maintenance.

1.3 Auxiliary Heating Systems

As written previously, the confined plasma must have a really high temperature. It can be considered as a conductor, therefore the plasma current causes a temperature increase due to the ohmic resistance of the plasma itself. Since the plasma ohmic



Figure 1.3: Auxiliary heating systems in tokamak configuration plasma.

resistivity is proportional to $T^{-3/2}$ it is perceivable how this effect is not enough to reach the 15keV of plasma temperature. Even with the self-heating caused by the Helium particles before the break-even point configuration is not possible to meet the Lawson criteria. It is then necessary to use auxiliary heating systems. Two methods are used: Radio-Frequency (RF) systems and NBI. The benefits of the former technology are (i) raising the temperature, (ii) steady state non-inductive current drive by direct input or by asymmetric deformation of the electron distribution function, asymmetric heating, scattering of trapped particles into circulating orbits. The RF coupling can be used for localized H&CD since it is based on the concept of resonance layers inside the confined plasma. So it is possible to act on a specific part of



Figure 1.4: a)Conceptual scheme of a NBI, with a general illustration of the interaction between the beam and the background gas. b) Plant of a full-scale NBI.

the plasma volume for a specific particle, density and/or magnetic field value, flexibility which is really useful for plasma control. On the other hand, the advantages of the NBI are (i) broad profile heating, (ii) current drive, (iii) momentum input for plasma rotation, (iv) fueling, (v) access to advanced plasma scenarios, (vi) boost fusion power by beam-target reactions, (vii) diagnostic purposes, (viii) stabilization for sawteeth plasma instability and (ix) avoidance of impurity accumulation. A more detailed description of the two typologies of H&D systems can be found at [15] and references therein.

1.4 NBI

The topic of this thesis is related to the NBI field. Figure 1.4 shows a conceptual and a plant of what a NBI is. NBI consists of a RF plasma source from which negative ions are generated, extracted and accelerated. Then there is the necessity to neutralize them and to remove the residual ion before the beam injection into ITER plasma. The following paragraphs briefly describe the current experiments strictly related to the ITER NBI and to the thesis.

NIO NIO1 (Negative Ion Optimization 1) is a versatile H- ion source aimed to study the physics of production and acceleration of hydrogen beams up to 60 keV for an expected current of 135 mA. The beam is composed of 9 beamlets disposed in a 3×3 matrix. Figure 1.5 shows NIO1 facility located at Consorzio RFX in Padua.



Figure 1.5: NIO1 facility [16].

Its operation has the aim to identify the figures of merit that affect the negative ion beam efficiency, that is to reduce the losses due to background gas and to optimize the optics. For this reason its design is modular to guarantee a certain level of flexibility in case additional diagnostics or components are needed. References [17] and [18] describe in detail the experiment and operation.



Figure 1.6: ELISE source.

ELISE ELISE (Extraction from a Large Ion Source Experiment) is the half-size ITER source developed at IPP in Garching. It is the first step to test and study the negative ion sources for ITER NBI. The whole structure is inside a $9m \times 6m \times 6m$ concrete housing to avoid radiation since the potential radiation caused by the 60kV of acceleration [19]. With 4 RF drivers for a maximum power of 360kW, it represents the first large-scale ion source in which it is possible to understand the mechanisms to optimize the NBI efficiency for ITER and DEMO. In [20][21], first results on H^- current densities extracted in pulsed operation have been recorded: during cesium evaporation they achieved ITER requirements ($\approx 300 \frac{A}{m^2}$).



Figure 1.7: SPIDER vessel.

SPIDER SPIDER (Source for Production of Ion of Deuterium Extracted from Radio Frequency plasma) is the ion source prototype for ITER and started first operations in June 2018. SPIDER purpose is to fulfill Mission 1 and 6 of the fusion

roadmap, that is to anticipate potential issues for the ITER full-scale NBI. Therefore, it is necessary to optimize its performances by maximizing the extracted negative ion current density and its spatial uniformity and by minimizing the ratio of coextracted electrons, in order to match ITER requirements. SPIDER consists of a RF plasma source with 8 drivers which can supply up to 100kW each. Then the negative ions can be accelerated up to 100kV and a calorimetric diagnostic and a beam dump are finally used to characterize the beam. The most important thing is that for the first time a beam source completely vacuum insulated is operating: in the ion source the pressure is 0.3 Pa, while the background pressure in the vessel should be less than 40 mPa. In [22] and references therein, there is a full description of the facility.



Figure 1.8: MITICA prototype for ITER. All main components highlighted.

MITICA Figure 1.8 shows MITICA design. MITICA (Megavolt ITER Injector & Concept Advancement) is the full scale injector prototype for ITER and is related, as SPIDER, to Mission 1 and 6 of the fusion roadmap. The beam source is the same of SPIDER, while the acceleration system can supply up to 1MV thorugh 5 grid stages. Beyond the beam source, MITICA consists of the gas neutralizer, residual ion dump and calorimeter as a proper NBI should be. MITICA is still under construction and by the end of 2022 the characterization of the cryogenic pump should occur. As for SPIDER, in [22] there is a full description of the experiment.

1.5 Motivation of the work and summary

The subject of this thesis has focused on the study, development and optimization of current and alternative negative ion sources in fusion research field. SPIDER ITER source has just started to operate and its operation with cesium are yet unexplored. Cesium is an alkali metal that can enhance the generation of negative ions by means of the surface mechanism, but at the same time can create issues inside a vacuum chamber. For this reason, a cesium distribution analysis in a ITER facility at Consorzio RFX has been performed. Among DEMO relevant topics, there is the optimization of the Neutral Beam Injectors performances. The efficiency of these devices depends also on the negative ion sources parameters. For this reason, alternative plasma sources have been explored in this work. In chapter 4, a negative ion source based on a Hall Effect thruster has been designed, built and operated in Hydrogen with the aim to optimize the surface mechanism, even with cesium deposition. In chapter 5, a helicon plasma source in another international laboratory has been analyzed. The optimization consisted on the design of extraction system prototypes to take advantage of the negative ion densities found in the confined plasma. In chapter 6, there is a final discussion on the results obtained and promising proposal for future optimization works on the system analyzed.

Chapter 2

Negative ions

2.1 Negative Ion Generation

As cited previously, to achieve a beam with 1 MeV of energy it is necessary to neutralize accelerated Hydrogen negative ions, otherwise the neutralization process with positive ions would suffer too many losses. In the following subsections, the two main process to generate Hydrogen negative ions are briefly described.

2.1.1 Volume production

The volume production of negative Hydrogen ions can be explained by two mechanism [23][24]:

- i Dissociative attachment of electrons to vibration excited hydrogen molecules [25];
- ii Dissociative attachment to electronically excited long-lived states of hydrogen molecules $H_2(C^3\Pi_u)[26]$.

Dissociative attachment (DA) is the following process:

$$e^- + H_2 \longrightarrow H_2^- \longrightarrow H^- + H$$
 (2.1)

The first step shows how it is possible to have a new compound, H_2^- . The second step, which is a decay, happens only when the initial excitation of the H_2 molecule is high enough to be the dominant process in the plasma, that is, the process with the greatest cross section [27]. When the H_2 molecule is not sufficiently excited, the DA becomes a simple excitation of H_2 :

$$e^- + H_2(v, J) \longrightarrow H_2^- \longrightarrow e^- + H_2(v + \delta v, J + \delta J)$$
 (2.2)

where v and J are the vibrational and rotational excitation terms.

Now it is possible to understand the real mechanism of the volume production in the plasma sources. To enhance this mechanism, we should have a 2 region plasma source [28] one very energetic or hot and a cold one. In the first region, it is possible to observe the excitation of H_2 molecules through multiple collisions with hot electrons. Then, using a proper magnetic field, the electrons are filtered and only the ones with lower energy can access that particular plasma region. We need cold electrons since we have to consider also the destructive process of the negative Hydrogen ions. For high electron temperatures, the reaction rate of DA is much lower than the destructive process. On the other hand, with low electron temperature the DA is the dominant process.

2.1.2 Surface production

First emission of H^- ions from a solid surface was observed in 1931 and described in [29]. The details of the general process is described in [30]. It simply consists of an electron transfer from a solid material to a Hydrogen atom that leaves the surface. However, we need to better understand this mechanism if we want to find out how to enhance it. First of all, we need to consider both H atoms and H^+ ions, which collide with a metal surface, as the main responsible for the surface generation. Specifically, H^+ ions behave like neutral projectiles as H atoms since they undergo a rapid neutralization while they reach the surface because of the memory loss effect. The electron transfer depends on two parameters: i) the energy



Figure 2.1: Electron transfer by tunneling during surface negative ion generation [30]

difference between the affinity level of H atom and the valence band of the metal from which the electrons are captured (for the last one we look at the work function of the metal); *ii*) the coupling between these two energies which is defined by the electron wave function overlap. Moreover, these two factors are affected by the distance of the particle from the surface and by the atom parallel velocity. While the particle comes closer to the surface, the affinity level is smoothly down-shifted by the image potential (see 2.1a), making possible the electron transfer by tunnelling in both directions. Here, over a certain distance, the electron tunnelling rate is so high that the memory of the initial charge state is lost as previously mentioned. Now the final step happens, that is, when the atom leaves the surface. In 2.1b, it is possible to see that the affinity level of the new negative ion overlaps with the empty states in the conduction band of the surface. In this way, the electron can return to the surface. At this point, we can introduce the freezing distance [31] [32] as the distance where the equilibrium charge state is frozen. With a technique described in the next section, it is possible to reduce this distance and therefore maximize the generation of negative ions not allowing the returning of electrons in the conduction band.

2.2 Negative Ion Extraction

According to Langmuir, knowing the density of the charged particles available it is possible to determine the maximum current density achievable applying a voltage difference between the area considered and an electrode. This value depends not only on the voltage but also on the geometry of the extraction system.

2.2.1 Langmuir Introduction

Langmuir introduced the current density limit analytical equation which flows between different electrodes geometries. It is important to recall his study because it can be associated to the extraction systems for the negative ion sources. In all geometry cases, the current density limit assumes this form:

$$j = \frac{P_c}{A} \cdot V^{3/2} \tag{2.3}$$

where P_c is called Perveance, with $\frac{A}{V^{3/2}}$ as unit of measure, and V is the voltage applied between the 2 electrodes [33]. Here, only the sphere and cylindrical cases will be reported because they can be associated to 2 present types of extractors.

Sphere electrodes Figure 2.2a shows 2 concentric spheres where the emitter corresponds to r_0 radius while the collector to r, so in this case the current density has an outward direction. According to Langmuir calculations [34], the total current limited by space charge and collected by the external surface is:

$$i = \frac{4\sqrt{2}}{9}\sqrt{\frac{e}{m}}\frac{V^{3/2}}{\alpha} \tag{2.4}$$

where m is the electron mass and α is a function that depends on $\frac{r}{r_0}$ and whose values have been tabulated by Langmuir. It is possible to change the form of eq. 2.4 in this way:

$$j = \frac{D}{r_0^2 \cdot \alpha} \left(\frac{A}{cm^2}\right) \tag{2.5}$$

where $D = \frac{5.455 \cdot 10^{-8} V^{3/2}}{\sqrt{M}}$ with M the ion mass and with the radius values expressed in cm^2 . Eq. 2.5 is the fundamental reference if the plates facing the plasma source have been designed with holes and the meniscus has a concave shape like the one shown in Fig. 2.2b.



Figure 2.2: a)Concentric Spheres Langmuir-Blodget scheme. b) Simple scheme of particle extraction. c) Coaxial Cylinders Langmuir-Blodget scheme

Cylindrical electrodes Figure 2.2c shows 2 coaxial cylinders where the emitter corresponds to r_0 radius while the collector to r, so in this case the current density has an outward direction. According to Langmuir calculations [35], the total current per unit length limited by space charge and collected by the external surface is:

$$i = \frac{2\sqrt{2}}{9} \sqrt{\frac{e}{m}} \frac{V^{3/2}}{r\beta^2}$$
(2.6)

where *m* is the electron mass and β is a function that depends on $\frac{r}{r_0}$ and whose values have been tabulated by Langmuir. It is possible to change the form of eq. 2.6 in this way:

$$j = \frac{D}{r \cdot r_0 \cdot \beta^2} \left(\frac{A}{cm^2}\right) \tag{2.7}$$

where D has the same expression of the previous paragraph. Eq. 2.7 is the fundamental reference if the plates facing the plasma source have been designed with slits and with the same assumption of the sphere case about the meniscus shape.

2.2.2 Ion beam sources design

The scheme of a ion beam source consists of a plasma source and of an extraction system. The focus in this subsection is on the latter one. When a metal plate faces a plasma without being polarized, the system plasma-plate can be studied as a simple bounded plasma [36]. The system reaches an equilibrium: an interface region will generate between the two parts and no current is collected by the plate since it receives the same flux of negative (e^- and H^-) and positive (H^+) charged particles. When the plate is actively polarized, it will collect a positive or negative current according to the sign of voltage polarization. However, the aim is to generate an ion beam and not to collect a current. Therefore, instead of a plate, a pair of grids with holes or slits can be used: one to face the plasma source and the second one to impose an electric field which extracts the particles present in the volume region near the first grid. This electric field penetrated in the plasma source through the apertures of the first grid and defines the so called meniscus, a 0V potential surface through which the charged particles can pass and go towards the second grid.

2.2.3 Why negative and not positive ion sources

First ion beam sources were designed to generate positive particle beams. For ITER purposes, though, the charged beam must accelerated to an energy of 1 MeV before being neutralized [37]. As it is possible to see in Fig.2.3, the neutralization efficiency



Figure 2.3: Maximum neutralization efficiency in D_2 vs beam energy, for each of the four beams, D^+ , D_2^+ , D_3^+ , and D^- . [38]

is negligible for positive ions compared to negative ones (60%). This is why negative Hydrogen/Deuterium ions are the only option available for Neutral Beam Injectors for fusion applications.

2.2.4 Negative Ion Sources challenges

As written before, the design of a ion beam system is nearly the same for both negative and positive ion sources. Negative ion sources present several problems. One of them is the co-extraction of electrons, since they have the same charge sign. Electrons can cause 2 types of problems: they can enhance the destruction mechanism of H^- and deposit a significant thermal load on the extraction and acceleration grids. To reduce this population before it gains too much energy, a magnetic filter is used: imposing a magnetic field perpendicular to the electric field, the electrons will be subjected to the Lorentz force. Even the negative ions behave like the electrons, but the huge difference in mass determines a much higher trajectory curvature for

the electrons than the ions. The other main problem for negative ion sources is the "fragility" of the negative ions. The binding energy of the negative ion is only 0.7eV [20], therefore the probability of losing the additional electron before being fully accelerated because of a collision with the background gas is quite high [39]: this kind of loss is called stripping losses.

2.3 Role of Caesium

Caesium is an alkali metal with 133 as atomic weight and 55 as atomic number [40]. Its melting point is 28.44°C while its boiling one is 671°C. Cesium is involved in the NBI field because of its work function, which is 2.14eV [41]. The current density of negative Deuterium ions (D^- , an isotope of Hydrogen) is among ITER requirements, specifically it is $200\frac{A}{m^2}$ [37]. If we attempt to extract negative ions with the two methods mentioned previously, it is impossible to meet ITER requirements. Moreover, with the plasma densities achieved in the RF plasma sources of current NBIs, the maximum current density extractable is around $20\frac{A}{m^2}$ [20], where the contribution of the volume mechanism is dominant. Through the use of Cesium it is possible to increase this value taking advantage of the surface process.

2.3.1 Negative Hydrogen ions enhancement

As mentioned previously, the main parameters for the surface generation of negative ions are the affinity level of Hydrogen (and Deuterium) and the work function of the metal surface of the plasma grid. We know that the affinity level of Hydrogen is 0.754eV, while the usual work function for metals is around 5eV, specifically 4.36 -4.95eV for Molybdenum which is the material used in NBIs. The energy difference is too high to allow an electron transfer rate sufficient for ITER requirements. We need to reduce the work function and, to do that, it is possible to coat the surface with a metallic film [42]. It is straight to think that the best solution is to cover completely the metal surface with Caesium to decrease the work function to 2.14eV. However, the structural disposition of Cs on a surface has been studied and it was found that the minimum work function obtainable is $\approx 1.6eV$ when the coverage is ≈ 0.64 mono-layers of Cs[43].

2.4 Efficiency of generation

Knowing the plasma source characteristics and the plasma grid surface condition, it is possible to have a quick estimation of the maximum Hydrogen negative ion current that can be extracted. Taking advantage of a 1-D model by McAdams [44], the behavior of electrons, H^+ and H^- in the plasma sheath is defined. The contribution of H^- is considered both from the plasma itself and from the plasma grid. It is possible to combine this work with the studies conducted in [45] and [46]. According to the energy of H and H^+ hitting a surface with a particular work function, it is possible to associate an efficiency of H^- generation. Figure 2.4 shows that the Matlab script developed has replicated all the relations described in [44]. The aim of this part of the section has been to



Figure 2.4: Verification of Matlab script with model described in [44]. a) Matlab script plot. b) Original plot from [44].

find out if there is a virtual cathode condition for the values of density comparable to the ones measured in the sources analyzed in chapter 4 and 5. For a plasma density of $n = 10^{16}m^{-3}$ and estimating a current density generating at the plasma grid of $j_{extr} = 20\frac{A}{m^2}$, a virtual cathode is forming. The maximum current density achievable then is not the one estimated but the one limited by the virtual cathode, that is $j_{max} \approx 10\frac{A}{m^2}$. Therefore, for future estimations, a factor of 0.5 will be used to consider the effect of the high space charge accumulation caused by the generation of negative ions nearside the plasma grid region during extraction.

Chapter 3

SPIDER Caesium

The aim of this chapter is to study the caesium behaviour in vacuum because this alkali metal is the fundamental ingredient to enhance the surface generation mechanism of the negative Hydrogen ions. Before the plasma source ignition at low pressures, the caesium evaporation occurs to guarantee its deposition on the surfaces where negative ions are generated. The evaporation goes on even during plasma operations, but the interaction plasma-caesium is a far complex problem to analyze. However, it is necessary to know the caesium distribution during the vacuum phase because the presence of this metal in undesired regions can induce unwanted voltage breakdowns and vacuum insulation damaging. Thanks to a facility in Padova, it is possible to study the caesium evaporation and to use numerical models to validate empirical coefficients used to foresee the caesium distribution in SPIDER. This kind of analysis is relevant even for minor experiments where caesium is involved.

3.1 SPIDER description

SPIDER is the negative ion source prototype for ITER. The aim of this experiment is to understand the challenges that the fusion community is going to face during MITICA operations. MITICA is the full scale prototype of the whole NBI for ITER. Both MITICA and SPIDER are hosted at ITER NBTF in Padua. SPIDER is not only a negative ion source. Indeed, besides the RF plasma source, there is an extraction and acceleration system up to 100kV, with a calorimeter at the end of the accelerated particles path. The problems that SPIDER could face may have a different type of nature but always linked by a common factor: for the first time the beam source is completely vacuum insulated. In the context of negative ion generation, the contribution of SPIDER in my thesis regards the role of Caesium. Thanks to this experience, it was possible to study the Caesium behaviour in a vacuum chamber to understand potential issues and to maximize the surface process of H^- . Moreover, it is important to keep in mind that the deposition of Caesium can be critical and can facilitate the formation of voltage breakdown discharges or vacuum insulation damaging.

3.2 CAesium Test Stand

Experimental part of the thesis regards the CAesium Test Stand (CATS), the facility at the ITER NBTF whose main purpose is to test the reliability of the three Caesium oven prototypes that are going to be installed on SPIDER (see figure 3.1).



Figure 3.1: a) Cs oven position on SPIDER source. b) Cs oven scheme. c) CATS facility scheme. d) CATS actual facility.

The facility consists of a cylindrical vacuum vessel with a diameter of 400mm and length of 927mm (figures 3.1c-3.1d). Inside there is a diaphragm that separates the chamber in two regions leaving only an external ring gap of 20mm along the radius. In the back region the following devices are hosted:

- main Caesium oven structure;
- 100l/s turbo-molecular pump;
- thermal infrared IR camera;
- access port with electrical feedthroughs;
- capacitive gauge.

In the front region, called evaporation zone, there is the nozzle of the oven from which the Caesium evaporates. In addition, there are three type of diagnostics.

3.3 Fixed Langmuir-Taylor detector

LT detectors are simple tungsten filaments with 0.3mm of diameter. When they are in vacuum, a current power supply guarantees enough current to make them incandescent, i.e. 3.2A for a filament length around 5cm means the temperature filament is greater than 1000K [47]. When Cs evaporates, it can hit the filaments and can be ionized [48]. The ionization probability depends on the coverage state of the filament: at the temperature indicated previously, the filament can be considered clean, therefore the ionization probability is 100% [48]. It is possible then to collect a current of Cs+ ions polarizing positively the filaments. From the current it is possible to find the Cs flux and/or the Cs density:

$$\Gamma = \frac{I}{A \cdot q} \tag{3.1}$$

$$n = 4 \cdot \frac{\Gamma}{\hat{v}} \tag{3.2}$$

$$\dot{m} = \frac{I}{q \cdot m_{Cs}} \tag{3.3}$$

Eq. 3.1 gives the specific flux Γ expressed in $\frac{1}{s}$ from the current I detected, with A the collecting lateral surface of the filament. Through eq. 3.2, the local Cs density n can be found, assuming T=300K for the particle thermal velocity \hat{v} . In closing, Eq. 3.3 shows the relation of the mass flow rate \dot{m} with the current I, knowing the mass of a Cs atom m_{Cs} . For the fixed LT, the current detected must be corrected by a view factor since not all the Cs atoms flowing from the nozzle holes hit the filament: according to [49], this correction factor is 5.4%.

3.3.1 Circuit

Figure 3.2a shows the fixed LT around the nozzle and the mobile LT installed on the longitudinal z-shifter manipulator. It is necessary to positive polarize the ionizer filament so the positive Cs ions are repulsed towards the ground or to the second filament. During experimental campaigns, we detected a failure in both collector filaments. We opted then to short-circuit the collector filaments to the ground.

3.3.2 Measurements

Figure 3.3 shows an example of the I-V characteristic plot obtained by the diagnostic. The black line shows the limit to Child-Langmuir law considering the space charge effect. Overcoming a certain level of polarization of the ionizer filament, we see that the signal tends to keep a constant value because the Cs density available around the filament cannot supply more positive ions. The I-V characteristic plots have been obtained varying two key parameters of the facility: the temperature of the oven reservoir T_{res} and the temperature of the duct T_{duct} connecting the nozzle to the oven reservoir. Figure 3.4a shows that the plot nearly overlap for different days of operation during the year and with the same temperatures imposed. Only the one taken in April 2018 differs from the others, but the vacuum vessel was just ventilated so it is possible that the system can be affected for a couple of days after operations in air. Figure 3.4b shows a summary of all the I-V characteristics taken during



Figure 3.2: a)Fixed and movable LT detectors. b) Electrical diagram of the LT detectors, valid for both fixed and movable ones.



Figure 3.3: Fixed LT experimental measurement example. The black line represents the limit due space charge while the other lines represent experimental data.



Figure 3.4: a)Direct comparison example of I-V plots with same operative parameters but in different days. b) Summary of all the I-V characteristics before operational prototype tests.



Figure 3.5: LAS line of sight in CATS



Figure 3.6: Movable SID component.

2018 before the full test of the oven prototypes. It show that as T_{res} increases also the saturation level increases. Keeping T_{res} constant, T_{duct} increases the saturation level, much more at higher values of T_{res} .

3.4 LAS

A tunable diode LAS system is installed to measure the line of sight integrated Cs density. The applied system is described in detail in [50]. The line of sight crosses the volume in vicinity of the nozzle, at 9cm from the oven axis as shown in Figure 1. The Cs density is calculated considering an absorption length of 48cm.



Figure 3.7: Movable SID component. L_p length of the tungsten wires. r_p position of the wires along the vessel radius. ϕ_p twist angle of the wires. θ_p angle subtended by the wires projection.

3.5 Movable Langmuir-Taylor detector

Figure 3.6 shows the movable SID on its support which has been installed on a z-shifter manipulator as shown in figure 3.2a. The geometrical design has been developed and explained in [51]. As a result, the length of tungsten wires is $L_p =$ 5cm, located at a radius $r_p = 14$ cm and twisted by an angle $\phi_p = 11^{\circ}$. Data has been collected moving axially the LT detector and also around the nozzle. Figure 3.8 shows a summary an example of the data collected for the experimental approach. Figure 3.8a shows that there is no dependence between the Cs density and the angle of view of the nozzle. The Cs flux therefore was too high to see the effect of the 6 holes of the evaporation nozzle. Figure 3.8b shows that Cs density changes along the axial direction of the vessel and moving away from the nozzle. This kind of behavior has not been always recorded so it is not possible to extend this trend for all the cases. The aim was to find the weight of 2 signal components on the data collected by the LT detector: i the Cs evaporation coming from the vessel walls as a result of flux equilibrium determined by the Cs vapour pressure; *ii* the Cs evaporation coming directly from the nozzle/Cs oven. A correction factor has been applied in order to consider the view factor between the nozzle apertures and the filaments along the axial direction. Despite this, the two effects seems to have the same weight and any kind of interpretation is too strongly affected by initial assumptions. Considering then that this effect is not always seen, it is not possible to affirm that the Cs evaporation from the vessel is dominant compared to the Cs coming from the nozzle in a certain position of the vessel.

3.6 Quartz Crystal Micro-balance

The diagnostic has been installed in the part of the vacuum chamber where the evaporation occurs, specifically at the lateral wall of the chamber and near the diaphragm. The diagnostic consists of two quartz crystal electrodes, one exposed to the Cs evaporation while the other not since it has to be used as reference. The



Figure 3.8: a)Current collected moving the movable LT detector around the nozzle. b) Current collected moving the LT detector axially.


Figure 3.9: QCM diagnostic



Figure 3.10: QCM example of acquisition

deposition of mass over the first crystal changes its resonance frequency. Thus, measuring the frequency difference in time, it is possible to find the deposited mass Δm and, consequently, an index of sticking:

$$\Delta m = -\Delta \nu \frac{A(\rho_q \mu_q)^{1/2}}{2\nu_0^2}$$
(3.4)

Figure 3.10 shows an example of acquisition through the QCM diagnostic for three different Cs evaporation rates Γ_{Cs0} . From the slope of the plots it is possible to determine another kind of evaporation rate which is strictly related to a sticking factor if associated to Γ_{Cs0} .

3.7 Avocado

Avocado is a code with which it is possible to study the pressure distribution of a gas [52]. It takes into account only the gas particles-wall collisions with a cosine angle diffusion approach. The code receives a post processed mesh geometry generated by ANSYS in which the surfaces are assigned to a specific label: in this way it is possible to specify the pressure, the specific pumping speed or the specific gas pumping power on that area. The results of the code are valid only if the Knudsen number is greater than one: $K_n = \lambda/L$ where λ is the mean free path of the particle and L is the characteristic length of the system. Since L = 300mm (depth of the evaporation region) and $\lambda \approx 30$ m for Cs case with a vacuum experimental pressure of 10-4 Pa, we have $K_n >> 1$. Once the whole solution is complete, it is possible



Figure 3.11: a) Avocado pressure output for CATS model with s=2%. b) Avocado pressure output for CATS model with s=50%

to determine the pressure profiles even along custom lines inside the volume. The sticking coefficient study is possible if we apply, over a surface, a negative pumping speed which correspond to an adsorption rate flux [53]. To determine this negative pumping speed, we have to consider the following relations:

$$\phi = \Gamma \cdot A = \frac{p \cdot A}{\sqrt{2\pi k_B \cdot T \cdot m_{Cs}}} \tag{3.5}$$

$$Q = \phi \cdot k_B \cdot T \tag{3.6}$$

$$Q = p \cdot S \tag{3.7}$$

Eq.3.5 is the evaporation flux contribution ϕ from a wall with temperature T, surface A, chamber equilibrium pressure p and Boltzmann constant k_B . Eq.3.6 and Eq. 3.7 show two different definitions of the pumping power Q, where S is the pumping speed expressed in m^3/s . Combining 3.5, 3.6 and 3.7, we obtain the relation for the negative specific pumping speed \hat{S} [53]:

$$\hat{S} = \frac{S}{A} = \frac{1}{4}\sqrt{\frac{8 \cdot k_B \cdot T}{\pi \cdot m_{Cs}}} \cdot s = \frac{1}{4}\hat{v}s \tag{3.8}$$

The sticking coefficient s is assumed constant and the temperature dependence is not considered since the surfaces where the sticking is applied have a constant temperature of 300K. In closing, the code inputs are the specific flow rate of Cs from a surface of the nozzle, the specific pumping speed caused by the real pumping system, the temperatures of the gas and of the various surfaces as well as their sticking coefficients, the last ones always in terms of negative specific pumping speed.

3.7.1 Interpretation of the results

Fig. 3.11 shows the output of the model dedicated to CATS for two sticking specific case. In the case of s = 2% (Fig. 3.11a) the pressure on the external surfaces of the vessel is nearly the same. It is visible the effect of the equivalent vacuum pump in



Figure 3.12: Cs density along LAS line of sight for several sticking coefficient cases.

the external light blue ring. Finally, there is also the realistic fading effect due to the tubes of the LAS line of sight. Comparing this case with the one with s = 50% (Fig. 3.11b), the first thing to note is the lower value of pressure. As written previously, increasing the sticking means that the particles stay attached on the surface with less collisions. It is also expected to see the six nozzle holes projection on the lateral surface of the cylindrical vessel: this shows how increasing the sticking corresponds to a spatial dependence of the cesium distribution. Another information from the model is the density along the LAS line of sight. In Fig.3.12 cesium density profiles are shown for several sticking coefficient cases. The straight line for s = 0% is expected with that trend since cesium equally distributes on every surface of the model. When the sticking increases, the plot changes form with a wide peak at the center. This maximum value decreases raising s since the Cs particles tend to stay attached to the walls after few collisions. On the other hand, the width of the peak is not changing. Indeed, this length corresponds to the effect of the volume of the main vacuum chamber, specifically it is equal to the diameter of the chamber (400mm). Moreover, the value of the maximum density is nearly two times the one recorded in the pipes of the LAS line of sight. As last comment on Fig.3.12 is that the value read by an ideal LAS diagnostic inside the model would be the integral of the density along the line:

$$n = \frac{\int n(x)dL}{L} \approx \frac{\sum_{i} n_{i} \cdot \Delta x}{L} = \frac{\Delta x \cdot \sum_{i} n_{i}}{L} = \frac{\sum_{i} n_{i}}{N}$$
(3.9)

where n is the cesium density recorded by the ideal LAS, n(x) is the density value as a function of the line of sight location, L is the total length of the line of sight (80cm), Δx is the step of 2mm used to build the plots and N is the equivalent number of steps. As shown in eq.3.9, the value to compare with the experimental LAS measurements is the simple average of the plots in Fig.3.12. Fig.3.13 shows the first step to compare experimental and numerical results. Fig.3.13a represents



Figure 3.13: a) Cs \dot{m} apparent dependency on s. b) LAS experimental data (orange dots) comparison with numerical results (dashed black lines)



Figure 3.14: Cs final experimental-numerical data comparison. Numerical results as solid lines. Rectangles and black dots as experimental data.

the mass flow rate \dot{m} dependence over s. To obtain this plot, it is necessary to remind that the numerical simulations have been run with only one Cs emission rate, $\dot{m} = 20mg/h$. The density profile along a ring-shape line has been detected in the model in the actual position of the fixed LT, always for all the sticking coefficient cases considered. The values have been normalized by the density corresponding to s = 100%. The plot in figure 3.13a is nonetheless the normalized density values applied to $\dot{m} = 20mg/h$: as expected, the emission rate increases as the sticking decreases it takes a high number of collisions to stop Cs atoms. This plot has been necessary to build figure 3.13b. The black dashed lines separates the plot in several sticking regions thanks to the \dot{m} post-processing. On the y-axis the target thickness is reported, that is, the caesium density multiplied by the LAS line of sight length: in this way it is possible to compare numerical and experimental LAS results without being affected by the use of different line of sight length. The orange dots are the experimental LAS data collected for different emission rates. From that plot, a first guess is that the model matches the experimental data when the sticking coefficient applied is $\approx 2\%$. The final interpretation is deducible from figure 3.14. The red solid line corresponds to the numerical density where the movable LT detector is located in CATS. The blue solid line is LAS density found through eq.3.9. The rectangles, blue for the LAS and red for the movable LT detector, represent the range of values found through the diagnostics. As indicated by the arrows, the final guess for the sticking coefficient applied for CATS is 2%. The black dots are the results derived from the QCM and corresponds to the figure OCCHIO: the points seems to follow the trend of the numerical solid lines, partially proving the good quality of the simulations.

3.8 SPIDER simulation

SPIDER has not operated with caesium evaporation yet. It is useful to run some simulations then taking advantage of the information just gained thanks to CATS facility, that is, applying a sticking coefficient of 2%.



Figure 3.15: a) SPIDER plasma source region model. (b) Detailed view of the Cs oven nozzles location.

3.8.1 First model

Figure 3.15 shows the model defined for SPIDER. In figure 3.15a it is possible to see the eight RF drivers encumbrance while in figure 3.15b the location of the three Cs oven nozzles is shown. The first visual result is shown in figure 3.16 with the hypothesis that 1280 plasma grids holes capture all the particles at the first collision: the cesium specific flux ϕ expressed in 1/s is negative because Cs particles tend to stay attached to the plasma grid. Keeping attention to the fact that the blue color corresponds to a higher value of ϕ , the figure shows how the Cs particles are focused more in the center of the plasma grid, but in general the distribution is nearly equal over all the surface. From Avocado it is possible to read the specific fluxes and the particle collisions over all the surfaces of the model. In figure 3.17 this information is summarized. The blue curve represents the percentage of cesium that remains in SPIDER plasma source region. The red one is the number of particle collisions necessary to arrest them. As expected, the two curves have an opposite behavior considering the sticking coefficient used. The number collisions has been shown as a check-flag of the result obtained by the model. On the other hand, the amount of cesium not overcoming the plasma grid is an issue: for s = 2%, chosen as input from CATS experiment, only 30% of evaporated cesium is going to stay inside SPIDER plasma source volume.

3.8.2 Auxiliary grid model

Considering the plasma grid holes as "black holes" is a strong assumption. After the plasma grid, there are other two grids, the extraction and the grounded ones, always with 1280 holes but with a different shape (double truncated cone with varied angles and depths). To take into account the vacuum conductance of the whole package, a



Figure 3.16: Cs specific flux distribution on SPIDER plasma grid.



Figure 3.17: % of Cs passing through SPIDER grid and n° of particle collisions before arrest dependency over sticking coefficient



Figure 3.18: a) Section view of the model used to simulate the grid system impact on cesium distribution in SPIDER (b) Cs specif flux distribution for s = 0%

simple model has been built.

Figure 3.18a shows a section view where 5x5 holes matrix has been used to check the effect of a Cs particle passing through the plasma grid. The red surface is the inlet from which the atoms are emitted while the plasma source side and beam transport side surfaces do not allow the particles to bounce. The analysis consists of varying the sticking coefficient only over the grid surfaces in order to use the results for further simulations on the previous model: in figure 3.18b there is an example with no sticking. In the model, several fluxes must be identified to conclude this study:

- ϕ_{inlet} as the Cs specific flux imposed as Avocado input. The actual input is the pressure but it is possible to determine a flux through the relation $\phi = \frac{p \cdot A}{\sqrt{2\pi m_{Cs} k_B T}}$, where A is the inlet surface, m_{Cs} is the Cs atom mass, k_B is the Boltzmann constant and T is the particle temperature, here assumed 473K;
- $\phi_{inAvocado}$ as the neat flux given by Avocado as output for the inlet surface (Cs particles can be bounced back);
- ϕ_{source} as the specific flux collected by the walls of the plasma source side;
- ϕ_{over} as the specific flux collected by the walls of the beam transport side;



Figure 3.19: Cs specific flux ratio wasted for the plasma, extraction and grounded grids numerical model. Cs loss considering the plasma grid as positive effect(red+triangles) and without considering it (green+rhombus)

• ϕ_{PG} as the specific flux collected by the plasma grid surface facing the plasma source side, included the first-half truncated cone surface

Knowing the value of the total flux emitted in the model, ϕ_{inlet} , it is possible to determine the total flux staying in the plasma source side as:

$$\phi_{source,total} = \phi_{source} + \phi_{PG} + (\phi_{inlet} - \phi_{inAvocado}) \tag{3.10}$$

Figure 3.19 is the result of this analysis, that is the plot of the percentage of cesium wasted beyond the plasma grid:

$$\%Cs_{wasted} = 1 - \frac{\phi_{source,total}}{\phi_{inlet}} \tag{3.11}$$

This percentage can be thought as a sticking coefficient to apply on the plasma grid holes of the previous SPIDER model. The actual study is done with the values represented by the red curve. The green one corresponds to the case in which we do not consider the cesium deposited on the plasma grid holes as a positive effect for SPIDER: for low sticking coefficient the two plots do not differ much.

3.8.3 Final model

Repeating the study of the first model, the new result obtained is shown in figure 3.20. As expected, both flux ratio and n° of collisions increased compared to the plots of figure 3.16. For s = 2%, the % of cesium staying in the plasma source side is increased from 30% to 80%. It is a more reasonable value but still the remaining 20% of Cs going beyond the plasma grid can cause unwanted phenomena, like breakdown discharges among the grids or towards the experiment chassis.

3.9 Conclusions

Experimental campaigns on cesium ovens have been done in order to test the reliability of those devices. All the mechanical parts of the oven prototypes, after some initial issues, worked properly. The electrical parts, regarding the thermocouples and acquisition system, worked as well. Moreover, thanks to the three types of



Figure 3.20: % of Cs passing through SPIDER grid and n° of particle collisions before arrest dependency over sticking coefficient

diagnostics installed in the vacuum chamber, it has been possible to monitor the cesium distribution behavior. From an engineering point of view, it is important to see how the signals collected are repeatable in time for the same temperatures of the oven. From the physics point of view, it is interesting to note how there is a transient trend in the cesium behavior, probably due to the composition state of the vacuum vessel surfaces. This is important for SPIDER operations because it can affect the initial part of the experimental campaigns when cesium will be evaporated in the plasma source region. Meanwhile, a model of the cesium oven facility has been developed to match the results obtained by means of the diagnostic system. In this context, an empirical coefficient of the model, named sticking, has been introduced. From the post-processing of experimental and numerical data, the best match found is 2%. This value has been taken into account for further models related to SPIDER plasma source region. The main purpose of this analysis has been to confirm that no cesium at all goes beyond the plasma grid. From an initial study, the percentage of evaporated metal kept inside the plasma source region was really low, raising doubts about the negative ion beam generation efficiency. After this initial consideration, another model has been developed to understand the effect of the other grids (i.e extraction and grounded) beyond the plasma grid. By means of this correction, the results showed that, for an empirical sticking coefficient of 2%, the evaporated cesium during the vacuum phase should be a process that interests only the plasma source region. Finally, this experience confirmed that the evaporation of this metal at low pressures affects nearly all the surfaces of the vacuum vessel considered, except the ones separated by small conductance regions.

Chapter 4 ATHENIS

Neutral Beam Injectors (NBI) are one of the auxiliary heating systems foreseen for ITER and are under thorough investigation for their application to future fusion reactors. In particular, for the reactor prototype DEMO, an improvement of the efficiency of all the processes involving the NBI performance is required, including the negative ion generation in the ion source, a key component of a NBI. Current R&D on negative ion sources for NBI is aimed to guarantee constant and reproducible negative ion current with spatially homogeneous current density and minimum fraction of co-extracted electrons [54] as well as a minimum power required to sustain the ion source plasma [55]. In an ion source, plasma inhomogeneity is caused by the magnetic filter field, through the ExB and the diamagnetic drifts of particles [54]-[55]-[56]. The filter field is anyway necessary to reduce the population of fast electrons, which is the main cause of destruction of negative ions [57]. Recent progresses in the understanding of negative ion generation, both in theory and in experiments [45]-[27], have provided key indications on the surface conversion by ions and neutral atoms when the surface is covered with an optimum layer of cesium [58]-[59]. Moreover, recent works have highlighted the role of surface desorption of pre-adsorbed ions [45] and sputtering [60] in negative ion generation, processes affecting the duration of the optimum coverage. Therefore, a negative ion source based on an alternative scheme, which allows the kinetic energy of the ions directly impinging on the cesiated surface to be tuned, could contribute to better understand the role of ions in the complex interplay of the different processes mentioned above. In this chapter, the design, realization and optimization of this alternative source that I have carried out is described.

4.1 Hall Effect Thruster

The new concept is an adaptation of a Hall effect thruster (HET), a propulsion device used in the aerospace field and whose scheme is shown in figure 4.1. The working principle consists of the following points[61]: i) the external cathode emits electrons which go towards the internal anode; ii) thanks to the configuration created by the axial symmetric and quasi-radial magnetic field and the electrical discharge between the anode and the cathode, the electrons are trapped by the magnetic field in a cyclotron motion in the azimuthal direction; iii) the trapped electrons form a volumetric zone of gas ionization and a virtual cathode to accelerate the generated ions; iv) the exhaust plume composed mainly of accelerated ions is the



Figure 4.1: Schematic view of HT with crossed electric and magnetic fields, and ion and electron paths.

source of the thrust. The choice of a HET device takes advantage also from other interesting features: (i) high reliability of the thruster, demonstrated during longterm space missions; (ii) good uniformity of particles density at the exit plane, due to the axisymmetric magnetic field and the absence of unwanted particle drifts; (iii)intrinsic modularity, which allows large extraction surfaces to be obtained by combining several small HET's in suitable matrices, increasing again reliability and global uniformity. Previous studies on the use of HET devices with Hydrogen as fuel and its potential role in DEMO NBI sources have been carried out and described in [62] and references therein. A EuroFusion enabling research has been granted in order to investigate the potential of such an alternative ion source: a Hall Effect Thruster named ATHENIS (Alternative Thruster Hall Effect Negative Ion Source) has been developed, built and operated at Consorzio RFX in Padova.

4.2 Design

The description of the system will begin with the final configuration already defined in order to understand better all the electromagnetic simulation that are following. Figure 4.2 shows a scheme of ATHENIS: the inner diameter is 6mm, the outer



Figure 4.2: Scheme of ATHENIS, a Hall Effect thruster operating at Consorzio RFX.

diameter is 25.2mm and the length is 58.5mm. The magnetic field is generated by permanent magnet disks inserted in rings of aluminum (15 magnets for each ring).In order to get the classical magnetic radial profile of a HET [61], the magnetic circuit is closed through the axial cylinder (purple one in figure 4.2), which is insulated from the rest of the device except for the central screw, which determines its potential. Moreover, the inner green rings and the yellow and orange plates complete the magnetic circuit since they are made of 430 ferromagnetic stainless steel. Finally, the bottom aluminum ring is without magnets, to avoid an excessive negative value



of the magnetic field, not beneficial for HET operation. The channel walls are

Figure 4.3: a) HT during assembling procedure. b) HT covered with Kapton and Mylar for electric isolation purpose.

quartz tubes protecting the ferromagnetic rings from the plasma. The exit of the channel consists of a Boron Nitride squared panel, a dielectric material with low sputtering yield and low secondary electron emission coefficients [61]-[63]. Finally, figure 4.3 shows the thruster during the assembling operation and in its final form with isolation made by Kapton and Mylar. To ignite the plasma, a ring-shaped tungsten filament has been placed at 2.5 cm from the exit plane so that it works as an emissive cathode. The best position of the filament to let the emitted electrons enter the HET channel before the ignition has been obtained as the outcome of a numerical simulation of the trajectories of electrons leaving the cathode in every direction. They are subjected to the electric and magnetic field found by means of FEMM 4.2 simulations and that are shown in figure 4.4. Figure 4.5 shows the projection on a 2D plane of the 3D trajectories found with a simple code that implements the Lorentz force through a Runge-Kutta integration: for each time step, the 3D position of the electrons is known and it is recorded in the mesh grid, giving the possibility to see where the electrons are confined most of the time. As a general result it has been found that it is better to locate the cathode away from the exit plane in order to let the electrons reach the channel before the ignition. The electrical scheme of HET is shown in figure 4.6. According to the same figure, the following definition in the text is adopted:

- by plasma discharge voltage, the voltage recorded by the power supply connected to the anode and therefore the voltage between the anode and the ground;
- by plasma discharge current, the current recorded by the same power supply;
- by cathode potential, the negative bias at which the cathode operates;
- by cathode current, the current supplied by the cathode power supply through the tungsten filament.



Figure 4.4: a) Magnetic field contour plot in vacuum. b) Axial profile of the radial component of the magnetic field (plot along red line in (a). c) Potential density plot in vacuum.



Figure 4.5: Projection of electrons trajectories on a 2D axis-symmetric plane. Exit plane at z=81.5mm. Position of the cathode (red cross): (a) r=17mm, z=85mm; (b) r=17mm, z=95mm; (c) r=17mm, z=105mm.

Figure 4.7a shows the experimental set-up hosting ATHENIS. The device is installed inside the small cubic chamber, while the larger vacuum chamber is necessary to keep the Hydrogen concentration within the safety requirements. Vacuum of the order of $10^{-6}mbar$ without gas injection, and, as illustrated in figure 4.7d, of $10^{-2}mbar$ with gas injection up to 0.15mg/s (regulated by a mass flow controller) is regularly



Figure 4.6: Electrical scheme of HET with Langmuir probe location.

achieved by a 1000 l/s turbopump and a rotative pump of 60 m^3/s . The cathode is negatively biased with a maximum voltage of -90V, while the anode is positively biased to a maximum of 250V. The anode consists of all the metallic parts that delimit the channel of the device, i.e. the yellow, orange, purple, green, dark red and the permanent magnets shown in figure 4.2. Figure 4.4c shows the vacuum electric field, which is axial only at the exit plane. After the ignition, the plasma cannot close the circuit to the channel walls since they are made of quartz. The plasma is then forced to close the circuit at the bottom of the channel, where the gas injection occurs, as in a regular HT.

4.3 Diagnostics

4.3.1 Magnetic measurements

The ring-like disposition of the magnets has been shown in figure 4.3a. Since a finite number of permanent magnet disks affects the uniformity of the magnetic field, the intensity of the magnetic field has therefore been measured. Figure 4.8a shows the quasi-symmetry of the magnetic field along the azimuthal direction of the channel. The small difference in the intensity at the maximum is related to the uncertainty in the position of the probe. For the same reason, in figure 4.8b almost straight horizontal lines are obtained from azimuthal measurements. As a conclusion, the measurements have confirmed that there are no ripple effects.

4.3.2 Langmuir probe

In order to characterize the plasma generated by the device, a Langmuir probe is installed on a z-shifter manipulator to determine plasma density and the electron temperature along the axis of the device. The probe consists of a cylindrical tungsten rod, with a radius of 1mm and an exposed length of 4.5mm, so that the main collecting surface is the lateral one, which is parallel to the axis of the plume. Figure 4.6 shows the electrical scheme of the experiment. A Kepco supplies the bias voltage of the probe, scanning from a minimum of -100V to a maximum of 50V. A four parameter fitting code has been used to determine the density of the plasma



Figure 4.7: a) ATHENIS facility. b) 3D drawing of ATHENIS assembled parts. c) Avocado pressure simulation. d) Pressure line plot along the HET channel discharge.

and electronic temperature. The algorithm is based on the model described in [64], according to which the collecting area depends on temperature and mass of the ions and on local magnetic field. Figure 4.9 shows the superimposition of several I-V characteristics.

4.3.3 Retard Field Energy Analyzer

A Residual Field Energy Analyzer (RFEA) has been developed and installed to measure the energy of positive ions in the plasma plume (figure 4.10). It is a system



Figure 4.8: a) Axial profiles of magnetic field for several azimuthal positions. (b) Annular profiles of magnetic field for several axial positions.



Figure 4.9: Example of characteristic I-V curves acquired through the Langmuir probe.



Figure 4.10: a) RFEA electrical scheme. b) Example of collected measurements. c) Example of post processing from which the energy distribution function of the positive ions is derived.

of polarized grids as shown in figure 4.10a and its details are described in [65]. Figure 4.10c shows that the HET device can be used to tune the energy of positive ions. This new property of the device can be used for a further optimization of the alternative ion source because the positive Hydrogen ions play an important role in the generation of negative ions by means of the surface mechanism [66].

4.3.4 Spectroscopy

An optic fiber for spectroscopic measurements was added to characterize the plasma and check the absence of impurities during the plasma discharge (Figure 4.11). Figure 4.11b shows that there are resonances only for Hydrogen excitation lines confirming in this way that it is the only gas in the plasma.



Figure 4.11: a) Spectroscopic diagnostic system assembled on ATHENIS facility. b) Spectrum measured with H_{α} , H_{β} , H_{γ} excitation lines and no other impurities.

4.4 Plasma Characterization Data



Figure 4.12: a) Plasma density axial profile for several N2 mass flow rates. (b) Electron temperature axial profile for several N2 mass flow rates. Plasma voltage discharge varies from 65V to 95V with a fixed cathode current of 6.3A. The position of the filament (the cathode) is also shown

The device has been successfully operated in Nitrogen and Hydrogen. An extensive experimental campaign has been completed in Nitrogen because its ionization energy is similar to the Hydrogen. The thruster has still to be optimized to carry out an extensive experimental campaign in long pulsed modes. Nitrogen is the best solution to understand the plasma behavior changing operation parameters. Obviously, data for Hydrogen operations are reported too. The main results in Nitrogen are shown in figures 4.12 and 4.13. The temperature and density plots in the bulk plasma, spanning a distance of 4 cm from the ion source exit, show an almost constant temperature of the order of 3 eV except for the region near the cathode (see figure 4.12). Figure 4.13 shows that density and temperature values increase with the applied voltage and are uniform over the spatial range spanned by the probe. From these results it appears, that the voltage plasma discharge is the main drive of the plasma parameters. To control this parameter, both in Hydrogen and Nitrogen,



Figure 4.13: a) Plot of plasma density according to plasma voltage discharge. (b) Plot of electronic temperature according to plasma voltage discharge. Current plasma discharge varies from 0.4A (65V) to 1.2A (90V). Cathode current 5.8A.



Figure 4.14: a) Plasma density axial profile with different voltage discharge and similar mass flow rate. (b) Electronic temperature axial profile with different voltage discharge and similar mass flow. Current plasma discharge 1.312A with cathode current 5.6/5.8A.

it has been found that the cathode current has to decrease. For operation in Nitrogen an optimum value (60sccm) of mass flow rate has been found at which plasma density and electronic temperature reach their maximum value. For the Hydrogen case, only low values of mass flow rate were considered in order to keep the pressure low enough to guarantee a mean free path of the H_0 atoms of the order of some centimeters so to allow them to hit the caesiated target. It has been found that the plasma parameters keep the same trend for both values of mass flow rate studied, even though a more stable behavior has been observed for the higher one. In summary, the Hydrogen plasma density that can be assumed for negative current ion predictions is $2.5 \cdot 10^{1} 6m^{-3}$.

4.4.1 Estimate of the H^- current

In [67], a 0D balance in an extraction system is described. The mechanisms that generate negative ions and that have been taken into account for the 0D balance in terms of reaction rates $(\frac{1}{m^3s})$ are:

• surface production by means of atomic hydrogen $G_1 = \frac{1}{4}n_{H_0} \cdot \hat{v}_{H_0} \cdot \frac{A_{extr}}{V} \cdot \gamma_{H_0};$

- surface production by means of Hydrogen positive ions $G_2 = \frac{1}{4}n_{H^+} \cdot \hat{v}_{H^+} \cdot \frac{A_{extr}}{V} \cdot \gamma_{H^+};$
- dissociative attachment DA of the volume process $G_3 = n_{H_2^*} \cdot n_e \cdot \langle \sigma \cdot v \rangle$

where \hat{v}_i is the thermal velocity for the i-species, V is the volume considered for the 0D balance, A_{extr} is the extraction surface considered, γ_i is the success percentage of negative ion conversion for the i-species, n_i density of the i-species. The species considered are atomic Hydrogen H_0 , positive ion H^+ , excited state Hydrogen molecule H_2^* , electron e. As for the destruction mechanism, the following reactions have been considered as specific rate $\frac{1}{2}$:

- electron detachment DE $D_1 = n_e < \sigma \cdot v >_{DE};$
- mutual neutralization MN $D_2 = n_{H^+} < \sigma \cdot v >_{MN};$
- associative detachment AD $D_3 = n_{H_2} < \sigma \cdot v >_{AD}$.

Finally, the confinement time τ_{H^-} of the negative ions has to be considered. From the 0D balance final form, the expected negative ion density n_{H^-} is obtained:

$$n_{H^{-}} = \frac{G_1 + G_2 + G_3}{D_1 + D_2 + D_3 + 1/\tau_{H^{-}}}$$
(4.1)

The estimate has been done considering only the contribution given by the positive ions, not taking into account then the DA and the atomic surface production. Moreover, a corrective coefficient of 0.5 is applied after the considerations found in chapter 2 about the virtual cathode described by Mc Adams[44]. Taking from the experimental campaigns a pressure of 1Pa, the background molecular density is $n_{H_2} = 2.4 \cdot 10^{20} m^{-3}$ for T = 300 K. The plasma density is $n_e = n_{H^+} = 2.5 \cdot 10^{16} m^{-3}$. Then, from the plots in [46] and considering a minimum positive ion energy of 30eVfrom figure 4.10c, the resulting conversion percentage is $\gamma_{H^+} = 10\%$. The volume V considered for the process is a $2x2x4cm^3$ geometry after the cathode position of the device, while the extraction surface is $A_{extr} = 1cm^2$. The values of the destruction parameters have been found in ALADDIN database, while the confinement time τ_{H^-} has been determined considering an average acceleration of the negative ion generated of 5eV. In this way, the final value of n_{H^-} is:

$$n_{H^{-}} = \frac{G2 \cdot 0.5}{D_1 + D_2 + D_3 + 1/\tau_{H^{-}}} = \frac{1.67 \cdot 10^{22} \cdot 0.5}{3.75 \cdot 10^3 + 6.75 \cdot 10^3 + 2.42 \cdot 10^5 + 1/4.5 \cdot 10^{-7}} = (4.2)$$
$$= 6.72 \cdot 10^{15} m^{-3}$$

From this density, the maximum current density available can be determined by means of the following relation [68]:

$$j_{H^{-}} = n_{H^{-}} \cdot q \cdot \sqrt{\frac{k \cdot T_{H^{-}}}{m_{H^{-}}}} =$$

$$= 6.72 \cdot 10^{15} \cdot 1.6 \cdot 10^{-19} \cdot \sqrt{\frac{1.38 \cdot 10^{-23} \cdot 5 \cdot 11600}{1.67 \cdot 10^{-27}}} \approx 23 \frac{A}{m^{2}}$$

$$(4.3)$$

4.5 Extraction

The final step of this experiment is the design, manufacturing and operation of an extraction system for the Hall effect thruster. The three main components are the (i) plasma grid, (ii) the collector and (iii) the magnetic circuit to filter the co-extracted electrons. Figure 4.15a shows the scheme of both the plasma source



Figure 4.15: a) ATHENIS scheme with its extraction system . b) ATHENIS extraction system geometry for COMSOL simulation.

and the extraction system. This last component can be thought as the sum of cesium evaporation system, electrode plates and magnetic circuit. Cs deposits over a Molybdenum disk which covers the first part of the double conic extraction plate hole. Beyond this last component, there is the collector. It consists of an inner disk aimed to collect the negative ions while the outer ring should collect the electrons. Finally, two permanent magnets, with same polarization direction but opposite sign, impose the magnetic field perpendicular to the axial electric field set between the collector and the extraction plate. In this way, the electrons will be subjected to the $E \times B$ force and separated from the negative ions.

4.5.1 Electromagnetic simulations and trajectories analysis

Figure 4.16 shows the magnetic and electric field in the extraction region determined through COMSOL software. Using a simple Matlab code that determine particle motion under Lorentz force, that is, $\vec{F}_{E\times B} = q(\vec{E} + \vec{v} \times \vec{B})$, it is possible to integrate electron trajectories. Assuming from figures 4.16b-4.16d a uniform potential V =150V over a distance d = 10mm and a uniform magnetic field intensity B = 9mT, the distance along the electric field direction covered by the electron is less than 2mm, which is sufficiently low to allow the outer collector to stop them before they hit the inner plate. A more detailed study of these trajectories has been done by COMSOL simulations. Figure 4.17b shows that the electrons do not reach the inner collector, while the negative ions are not affected by the magnetic field (see figure 4.17a): in the simulations a plane meniscus has been positioned within the extraction hole thickness. Therefore, the final design has been sketched down and



Figure 4.16: a) Potential surface plot. b) Potential profile starting from the extraction hole. c) Magnetic flux surface plot. d) Magnetic flux profile.



Figure 4.17: a) Negative Hydrogen ion trajectories. b) Electron trajectories. Legend in eV.

manufactured. Figures 4.18a-4.18b show the extraction plate system mounted on a 150 DN-CF flange. Figure 4.18c shows the collector system, where the back and lateral surfaces are covered with Kapton tape to avoid signal interference with secondary emitted electrons. Figure 4.18d illustrated the two fixed permanent SmCo magnets. Both magnetic and collector systems have been installed on two different z-shifter manipulators, giving a lot of flexibility on the distance configuration respect between them and even respect to the extraction plate. The Kapton tape is useful also to avoid a short circuit contact in case the magnetic system accidentally touches the collector one.



Figure 4.18: a) Extraction plate. b) Extraction plate with cesium evaporation system. c) Outer and inner collector. d) Magnetic circuit system.

4.5.2 Cesium evaporation system

As already seen in figure 4.17b, the cesium system is completely different from the one used for the CATS experiment in chapter 3. Since the aim is to prove the possibility to extract negative ions and not to have an optimized system, the choice has fallen to the cesium dispenser produced by SAES getters company, which allows at least 20 minutes of operation. Moreover, it is a really simple device since it acts as an electric resistance, allowing to create an actual electrical circuit, even with more dispensers connected in series. The basic scheme is shown in figure 4.19a. It consists of a mixture of cesium chromate with a reducing agent. This reducing action is activated by the current supplied to the device: the cesium vapour is not affected by the active gases produced thanks to the absorption properties of the St 101 alloy used to build the container. Figure 4.19b illustrated the evaporation parameters according to the current supplied to the dispenser. Before getting into those operation regimes, though, it is necessary to increase the current by 0.1A/min steps. Finally, always referring to figure 4.17b, the quartz tubes circuit are shown



Figure 4.19: a) Cesium dispenser provided by SAES getters S.p.A. b) Cesium yeld in time according the current provided.



Figure 4.20: Comparison of Langmuir isotherm and BET isotherm for three temperatures, both with desorption energy variable with coverage. The dashed line indicates the vapour pressure, the dashed-dot line - the modified Langmuir isotherm, and the solid line - the BET isotherm [60].

too. It is a heating system to keep a constant temperature of $\approx 200^{\circ}C$ on the Molybdenum plate. According to [60], to obtain an atomic cesium deposition over a surface it is necessary to raise the temperature of the surface over $150^{\circ}C$, so there is the certainty of Cesium oxides or other impurities. Using four dispensers at time, the total amount of cesium evaporated is 20.8mg from SAES datasheets since each of them has 12mm of active length. Therefore, over a period of 20 minutes, the expected cesium emission rate for 6.5A of current supplied is $\dot{m}_{Cs} \approx 7mg/h$. The slit of the dispensers is a $0.1 \times 12mm^2$ rectangle, so for four devices the total emission area is $4.8mm^2$. Knowing that the atom cesium mass is $m_{Cs} = 2.22 \cdot 10^{-25} kg$, the specific flux Γ is:

$$\Gamma = \frac{\dot{m}_{Cs}}{A \cdot m_{Cs}} \approx 1.8 \cdot 10^{21} \frac{1}{m^2 s} \tag{4.4}$$

Using figure 4.20, it has been estimated a cesium coverage of the Molybdenum less than one mono-layer (≈ 0.8), not far from the optimum value of 0.64 found in [43], which corresponds to the minimum work function value for the surface considered.



4.5.3 Extraction campaign results

Figure 4.21: a) V-J characteristic curves of the inner (blue tones) and outer collector (red tones). b) 2 species Child-Langmuir fit on the higher voltage side.

Figure 4.21 shows an example of measurement without Caesium (cyan line) and with Caesium (blue one) collected by the inner collector. The decrease of current highlighted by the inner collector but not by the outer one is consistent with the presence of negative ions. Based on this first indication, to estimate the contribution to the total current detected, a Child-Langmuir law for the 2 species (negative ions and electrons) has been applied [69]:

$$j_{max} = \frac{2}{9} \frac{1}{\gamma_i} \frac{m_e \cdot \epsilon_0}{q} \frac{1}{s^2} \left(v_{0i} + \sqrt{v_{0i}^2 + 2\gamma_i \frac{q}{m_e} (V_d - V_{floating})} \right)^3 \tag{4.5}$$

where j_{max} is the maximum current density available, γ_i and γ_e are the contributions from negative ions and electrons respectively with $\gamma_i + \gamma_e = 1$ as a strict condition, m_e and q are the electron mass and charge, ϵ_0 is the dielectric permittivity in vacuum, s is the plasma sheath thickness, v_{0i} is the initial velocity of the negative ion, V_d is the collecting probe voltage and $V_f loating$ is the floating potential. From the fit, s(i.e. the distance between meniscus and inner plate collector), γ_i , v_{0i} and $V_{floating}$ have been obtained.

A summary of the results is shown in table 4.1. It can be concluded that:

- a fraction of the order of 10% of negative ions is measured in the inner collector;
- a fraction of electron current larger than expected (90%) is measured in the inner collector;

Shot	Cs [y/n]	Magnets Distance mm	Collector Distance mm	Cathode Power W	Plasma Power W	J electron contribution inner plate %	J neg ions contribution inner plate %	sheath thickness inner plate mm	J electron contribution external plate %	J neg ions contribution external plate %	sheath thickness external plate mm
99	n	23.5	2	114	194	99.51	0.49	1.07	98.81	1.19	2.80
100	n	13.5	2	115	193	99.48	0.52	1.12	99.29	0.71	2.45
102	n	16	7	115	190	99.12	0.88	0.88	98.83	1.17	2.82
106	у	16	8	120	177	88.89	11.11	2.09	98.97	1.03	2.69
107	у	16	8	120	175	89.56	10.44	2.23	99.05	0.95	2.66
112	у	16	8	124	175	91.93	8.07	2.11	99.83	0.17	1.76
113	у	16	2	124	176	90.75	9.25	2.02	99.11	0.89	2.58

Table 4.1: Summary of the results on negative ion collected. 99,100 and 102 without Cesium. 106,107,112 and 113 with Cesium.

• a sheath thickness of the order of 2mm is derived, different from that assumed in the COMSOL simulations where the distance of the meniscus from the collector was at least 6mm.



Figure 4.22: COMSOL simulation for the configuration with 2.5mm of distance between meniscus and collector. a) 2D plot line of potential between meniscus and collector b) 2D surface plot of the potential. c) Negative ion trajectories. d) Electron trajectories.

The discrepancy with the results expected from the simulations has been found

related to the extraction voltage limited by the available power supply which was not enough to generate a meniscus inside the extraction hole. As a consequence the plasma could expand through it and interact directly with the inner collector. The following COMSOL simulation using the experimental sheath thickness derived from the measurements and illustrated in figure 4.22, has shown that the magnetic field in the region of sheath was not sufficient to filter the electrons, therefore justifying the large fraction of electron current measured in the inner collector. However, a further optimization in the electromagnetic configuration of the extraction system is already under investigation.

4.6 Conclusions

Previous numerical analysis on Hall effect thrusters have shown that there is an interesting Hydrogen dissociation rate inside the channel device. The atomic population generated could be relevant for the surface mechanism process of the negative ions. This led to the attempt to transfer this aerospace technology into the neutral beam injector topic for fusion applications. The design, manufacturing and operation of a home-made Hall effect thruster has been successfully achieved. The plasma generated has been studied by a set of diagnostics a Langmuir probe, a Retard Field Energy Analyzer and a spectroscopic diagnostic. During this stage, another relevant contribution for the negative ion formation has been considered, that is, the positive Hydrogen ions. The possibility to tune the energy of these particles, acting upon the anode potential of the device, can influence the surface mechanism process efficiency. After the plasma characterization, a simple extractor system has been designed and developed. Moreover, a cesium evaporation device has been added to maximize the negative ion generation. The collector has not been able to screen all the electrons and acted as a big Langmuir probe. However, a contribution from negative ions has been confirmed through a two population fit. Though the detection of the negative ions has fulfilled the main goal of the project, i.e. the proof of principle that a system based on a Hall Thruster source can generate negative ions, the negative ion density achieved with the present configuration has been too low to meet the requirements of a DEMO alternative negative ion source. The fraction of electron current larger than expected seems to indicate that the insufficient voltage has not allowed the proper formation of a meniscus to take place. However, the increase of current density expected at higher plasma density and extraction voltage, indicate a possible way to improve the system performance. For this purpose an experimental upgrade has been suggested by adding a differential pumping to separate the pressure on the source from that on the extraction region and by increasing the extraction voltage by a suitable power supply with a related revision of the isolation requirements. Given the promising beneficial effects of these upgrades to achieve higher negative ion current densities such a system upgrade could be part of a proposal for a further extension of the investigation.

Chapter 5 RAID

All the present negative ion sources, including those for ITER and DEMO, use cesium to enhance the performances of the systems. However, cesium poses problems related to unwanted plasma dis-uniformity, unwanted breakdown discharges, contamination and maintenance procedures needed, such as the refueling. For this reason, R&D is looking for alternative sources to produce high negative ion current densities through the volume mechanism without cesium. One promising technology is the plasma source based on the helicon antenna concept. In this chapter, a present experiment is described and two potential solutions will be proposed to extract negative ions and successfully demonstrate that this type of source is DEMO relevant as proof of principle.

5.1 Introduction

5.1.1 Helicon Plasma Sources



Figure 5.1: Helicon Plasma Source scheme. The gas is injected through a cylinder surrounded by an antenna and a system of solenoids: the former generates and heats the plasma while the latter confines it. At the end of the cylinder, there is the plasma exhaust flow [70].

The Helicon Plasma Source (HPS) is the device which is responsible for the plasma ignition and production. Its components are the following (see figure 5.1):

- a feeding system which comprehends a gas tank and a pressure injector;
- a plasma cylinder;
- a Radio Frequency (RF) Antenna;

• a magnetic coil

Generally, a helicon source consists of a dielectric tube surrounded by coils which generate a weak magnetostatic field (up to 0.15 T) and an RF antenna working in the range of frequencies $w_{ci} \ll w_{lh} \ll w \ll w_{ce}$, where $w_{ci}(wce)$ is the ion(electron) cyclotron angular frequency, and w_{lh} is the lower-hybrid frequency. Helicon plasma sources were first investigated by Boswell, who found that the absorption of radiofrequency energy by the plasma could not be explained by only collisional theory since there was a huge discrepancy between analytical and experimental results [71]. The mechanism behind the plasma production is always the same: giving energy to a neutral gas in order to create the formation of charge carriers. The ways to maximize the efficiency of this process are still under analysis. F. F. Chen et al. in 1995 [72] figured out that Landau damping could play an important role in the plasma formation: they added, therefore, a collisionless mechanism since the charged particles are accelerated or damped according to the narrowness with the phase velocity with the exciting wave. Varying the operative parameters, such as magnetic field intensity or background pressure, it was still unknown the behaviour of the results obtained by the helicon sources: D. Arnush in 2000 [73] underlined the role of Trivelpiece-Gould (TG) waves coupled with helicon (H) ones. An important characteristic about this coupling is that the former waves have a short radial wavelength compared to the latter ones: TG waves damp really fast and deposit their energy in the near edge of the plasma cylinder, whilst H waves penetrate until its center. As for the other mechanism of energy deposition, the two main parameters which control the efficiency of this process are, as already written, the magnetic field intensity and the background pressure. Although everything was not so clear about the physics in HPS, the interest toward this new technology was caused by the advantages in confront to the previous plasma production systems, such as Reactive Ion Etching (RIE) discharge, Electron Cyclotron Resonance (ECR) source, the Radio-frequency Inductive (RFI) or Transformer Coupled Plasma (TCP) discharge [74]:

- High density: using general gases or higher powers than normally used, there is a gain in density of a factor 10;
- High efficiency: thanks to the high densities obtained through the previous mechanism mentioned, there is a rapid transfer of wave energy to the primary electrons;
- no internal electrodes: since the antenna is outside the vacuum chamber, the possibility of contamination or sputtering from the electrodes producing the plasma is eliminated.

5.1.2 RAID

Resonant Antenna Ion Device (RAID) is a helicon plasma source located at Swiss Plasma Center (SPC), EPFL in Lausanne. Figure 5.2a shows a picture of the facility. 6 coils determine the intrinsic axial magnetic field up to 800G and that it is necessary for the propagation of the helicon waves. These waves are emitted by means of a bird-cage antenna [76], whose geometry can be seen in figure 5.2b and its electrical diagram in figure 5.2c: technically, the antenna shown is a second antenna



Figure 5.2: a) RAID source [75]. b) 2^{nd} bird-cage antenna built during SPC experience for coupling test. Installed on the opposite side of the 1^{st} antenna. c) Electrical diagram of the birdcage antenna. Each leg divides the two external loops in a L-C circuit. Moreover, each leg can be represented as an inductance L, but they are omitted to make the diagram readable.

(c)

Kang

I built to operate RAID experiment with two devices contemporaneously. Indeed, the original experiment works with a main antenna on the left side of figure 5.2a and a target plate at the end of the plasma column. The second antenna has substitute the target plane for a quick experiment. However, the facility is deeply described in [77]-[75]. The interest on this type of source has risen because of the detection of a interest density profile of negative ions along the radius direction of the plasma column section [75]. A peak has been found on the external side of the column, where the electron temperature decrease, clear index of negative ion generation by means of the volume process.

Second Antenna During the staying at SPC, I contributed to the building and installation of a second antenna on the opposite side of the first antenna for RAID (see figure 5.2b). Despite a water cooling leak on the ceramic cylinder that separates the antenna from the vacuum chamber, the installation has been successful. The cooling has been done through forced air convection and no damage because of thermal power load has been detected. Figure 5.3 shows the plasma density and temperature axial profiles obtained through the Langmuir probe fit used in chapter 4 [64]. The total RF power used has been 1kW and the test has been carried out with 2 configurations: with both antenna operating, the power has been equally



Figure 5.3: Comparison of the results between the ones obtained with two helicon antennas contemporaneously and the ones obtained with the single antenna configuration, with the same level of total RF power required. a) Axial density profile. b)Axial temperature profile.

split while, in the second case, only the main antenna was working. The nominal value of temperature and density are almost equal in both cases while the profile is more uniform along all the magnetic field axis for the double antenna configuration than the one antenna configuration. This is an important plasma characteristic to take into account for a future optimization in terms of efficiency for the negative ion generation.

5.2 Extraction Problem Analysis

The intrinsic axial magnetic field of RAID is the main concern for the negative ion extraction application on this source. Its high value allows to confine the energetic electrons in the center of the plasma column. These particles excite Hydrogen molecules that are the main source of the volume process generation of the negative ions in the external side of the plasma column since the electrons there are colder. For this reason, the axial magnetic field cannot be perturbed by the magnetic field necessary to filter the co-extracted electrons.

Radial Extraction Model For the radial extraction, I developed and applied a 1D model using Mc Adams relations[44] and the diffusivity model in the plasma pre-sheath for three species by Lieberman [36]. In this way, assuming a negative ion density in the plasma bulk, a current density can be estimated knowing that a perpendicular magnetic field is applied to the direction of extraction, condition necessary for the diffusivity model. In summary, the hypothesis considered for this model in the pre-sheath are:

- influence of a magnetic field B perpendicular to the direction of the extraction electric field (radial direction for RAID);
- quasi neutrality with presence of negative ion;
- constant electric field.

The parameters known are the following:

- ion and electron temperature T_i, T_e ;
- Positive/Negative ion and electrons densities at the plasma bulk (n_{+0}, n_{-0}, n_{e0}) ;
- Plasma potential (ϕ_p) ;
- Imposed pre-sheath length $(x_{ps} \approx r_{ce} \text{ (electron gyration radius)})$

The equations therefore involved are:

- $n_{+ps} = n_{-ps} + n_{eps}$ (quasi-neutrality);
- from momentum conservation for each species $\Gamma_i = \pm \mu_i \cdot n_i \cdot E D_i \frac{dn_i}{dx}$, we have:

$$n_{+ps} = (n_{+0} - \frac{\Gamma_{+}}{\mu_{+} \cdot E})e^{\frac{\mu_{+}E}{D_{+}}x_{ps}} + \frac{\Gamma_{+}}{\mu_{+}E};$$

$$n_{eps} = (n_{e0} + \frac{\Gamma_{e}}{\mu_{e} \cdot E})e^{-\frac{\mu_{e}E}{D_{e}}x_{ps}} - \frac{\Gamma_{e}}{\mu_{e}E};$$

$$n_{-ps} = (n_{-0} + \frac{\Gamma_{-}}{\mu_{-} \cdot E})e^{-\frac{\mu_{-}E}{D_{-}}x_{ps}} - \frac{\Gamma_{-}}{\mu_{-}E}$$

where the diffusivity for the i-species is $D_i = \frac{kT_i}{m_i v_{mi}} \frac{1}{1 + (\frac{w_{ci}}{v_{mi}})^2}$ with w_{ci} the gyration frequency and v_{mi} the momentum transfer collision considering the hard sphere approach and Hydrogen density $n_{H_2} = 2 \cdot 10^{19} m^3$. The mobility of the i-species is $\mu_i = \frac{q}{m_i v_{mi}} \frac{1}{1 + (\frac{w_{ci}}{v_{mi}})^2}$. The "ps" subscript stands for pre-sheath region. Since there is a constant electric field E and that $\frac{d\phi}{dx} = -E$, the potential at the end of the pre-sheath ϕ_s , which means the beginning of the plasma sheath, is:

$$\phi_s = \phi_p - E \cdot x_{ps} \tag{5.1}$$

Figure 5.4 shows the potential profile for an electrode potential higher than the



Figure 5.4: a) Potential profile of 1D model Lieberman-Mc Adamas. b) Density profiles for electrons, positive and negative Hydrogen ions in the 1D model Liebermanmc Adams.

plasma potential (fig. 5.4a)) and the density profiles for electrons, negative and positive ions (fig. 5.4b). The values considered for these simulations are the ones found in RAID [77]: $T_e = 2.5eV$, $T_i = 0.3eV$, $n_e = 2 \cdot 10^{17}m^{-3}$, $n_{H^-} = 2 \cdot 10^{16}m^{-3}$ and B = 150G. The electrons mobility is reduced a lot by the magnetic field and therefore the quasi neutrality in the pre-sheath must be verified by the negative ions. The equations for the sheath model are described in chapter 2: the negative particle current density is considered constant in the sheath since the potential increases in this region. In this way, the expected negative ion current density found in the model, as $j_{H^-} = n_{H_s^-} \cdot v_{H^-} \cdot q$ is $\approx 0.8 \frac{A}{m^2}$ while the electron current density obtained is $j_e \approx 7.2 \frac{A}{m^2}$. To strength the reliability of this model, ELISE parameters have been used. The only thing different is the magnetic field, which is 30G [21]. The values obtained are $j_{H^-} \approx 5 \frac{A}{m^2}$ and $j_e \approx 110 \frac{A}{m^2}$, which are of the same order to the ones obtained in ELISE without cesium evaporation for similar [20]-[21].

5.3 Radial Extraction

5.3.1 First Conceptual Design



Figure 5.5: a) First draft radial extractor for RAID. b) Langmuir-Blodgett application to extraction draft ($2a = 10mm; w = 15mm; d = 10mm; l = 100mm; r = r_0 + d = 100mm$)

Figure 5.5a shows the first conceptual design for the radial extractor thought for RAID. It consists of a simple scheme to test if the intrinsic axial magnetic field is sufficient to filter the co-extracted electrons. Therefore, the first thought is to use a longitudinal slit on the plasma grid that approaches the plasma column along the radial direction. The design is simple because for a proof of principle experiment the aim is only to collect negative ions without the need to optimize the quality of the beam optic. To determine the final geometry configuration and to know the potential negative ion current density upper limit that can be extracted, RAID plasma parameters have been considered:

- experimental pressure operation p = 0.3Pa;
- considering a gas temperature T = 1000K, the density of the background molecular Hydrogen gas is $n_{H_2} = 2.2 \cdot 10^{19} m^{-3}$;
- the Hydrogen atomic density, as a result of the dissociation process thanks to the plasma discharge, can be assumed as 30% of the background pressure, therefore $n_H = 6.5 \cdot 10^{19} m^{-3}$;
- the electronic/plasma density has been estimated as $n_e = 10^{17} m^{-3}$ [77]

These values are associated to the main reactions that an extracted negative ion can incur to:



Figure 5.6: Paschen discharge curve for several gases [78]

- electron detachment by molecular collision $H^- + H_2 \rightarrow H + H_2 + e;$
- electron detachment by atomic collision $H^- + H \rightarrow H + H + e$;
- positive ionization $H^- + H_2 \rightarrow H^+ + H_2 + e + e;$
- electron detachment $H^- + e \rightarrow H + e + e;$
- molecular generation by atomic collision $H^- + H \rightarrow H_2 + e$

ALADDIN database provides the cross sections $\sigma[m^2]$ of the previously cited collisions. Then, the aim has been to find the mean free path λ defined as the reciprocal of the product of the cross section and density of the particle to which the negative ion impacts: $\lambda = \frac{1}{\sigma \cdot n_i}$. With the parameters listed previously, the minimum λ found is 40cm for the electron detachment by molecular collision. Imposing then a distance d = 10mm between the collector and the plasma grid is sufficient to avoid a high rate of H^- destruction. The processes regarding electron collisions have not been taken into account because all the cross sections were so small that all the mean free paths obtained were on the order of the meters. Another aspect to consider for the distances involved in the design is the Paschen-type discharge in vacuum. Considering always p = 0.3Pa and the distances in the extractor system (d = 10mm), the minimum voltage that can cause a discharge is really high for the Hydrogen case (left side of the cyan curve of figure 5.6), so there should not be issues from this point of view. As for the negative current density that can be extracted, figure 5.5b shows the application of Langmuir-Blodgett equations, explained in chapter 2, to RAID specific case, precisely the ones used for the cylindrical case because the extraction occurs using a slit. The voltage applied to the plasma grid is a few volts higher than the plasma potential, which is 12V at maximum according to last RAID campaign measurements for the Hydrogen case. The voltage imposed between the plasma grid and the collector is 1000V at maximum, so the safety requirement for the X-rays generation are met (the limit is 5000V). The meniscus is approximated to a rectangle surface because of the high radius r compared to the small angle subtended by the slit. For the Hydrogen case and with the geometry applied for the first conceptual design, eq.2.7 has the following parameters:



Figure 5.7: COMSOL geometry model for the first draft extractor.

- $D = 5.455 \cdot 10^{-8} \cdot V^{3/2}$
- $rr_0\beta^2 = 0.919cm^2$ from the tables in [35] knowing that $\frac{d}{r_0} = 0.1$

Using always eq.2.7, the maximum current density j limited by the space charge effect for this initial case is $15.9 \frac{A}{m^2}$ with a voltage applied of 1000V. Taking into account the geometry of the slit, that is, a $100 \times 10mm^2$ rectangle, the total current expected to be collected is $\approx 16mA$. Knowing the current and the voltage applied to the electrode, the proper power supply to collect the signal can be identified. As for the electrons, the space charge limits the current density to $679 \frac{A}{m^2}$ and, as a consequence, a current limit of 679A.

5.3.2 Electromagnetic Simulations

Once set the main geometrical requirements, it is necessary to simulate the electromagnetic field and the trajectories of electrons and negative ions. COMSOL has been the electromagnetic code used to simulate and verify whether the electrons are filtered by the extraction system and if the negative ions are collected. Keeping the same geometry parameters of figure 5.5b, a COMSOL model has been realized and it is visible in figure 5.7. To impose an axial and uniform magnetic field comparable to the one used in RAID, two magnetic surfaces acting as permanent magnets have been inserted. Figure 5.8 shows how in the extraction region a uniform axial magnetic field of $\approx 200G$ is present: the shape of the plot can mislead, but the y-axis values show that the magnetic field is constant. Figure 5.9 shows the potential behavior of the system with 1000V applied to the collector and 10V to the plasma grid. From the experience acquired from the HET experiment, there is the risk that the electric field is not high enough to penetrate in the plasma grid slit. The purpose of the study though is to show that RAID can be a source from which extract negative ions in terms of proof of principle. Anyway, in this stage there is still room to optimize the electric field configuration. Figure 5.10a shows the first important result for this prototype design. The electrons are completely deflected by the axial magnetic field. Another parameter studied in negative ion sources is the ratio between negative Hydrogen ions and co-extracted electrons. It is useful then to insert a biased plate as shown in figure 5.10b, plate that can also improve the electric field. As for the negative ions, figure 5.11a shows how they are not affected by the magnetic field. Particles that are not collected are a side effect of a not-closed system (see figure 5.11b), being in this way free to continue their path



Figure 5.8: a) 2D surface plot of the magnetic flux B. b) Plot of B along the line between collector and plasma grid (z-axis).)



Figure 5.9: a) 2D surface plot of the potential V. b) Plot of V along a line along the extraction direction.)



Figure 5.10: a) Electron trajectories simulation from an inlet surface 2mm far from the plasma grid. b) Possible plate solution to add in order to collect co-extracted electrons.)


Figure 5.11: a) Negative ion trajectories simulation shown in the x-y plane. b) Negative ion trajectories simulation shown in the y-z plane.)

without being collected. These results led then to the final design of sthe system: a compact structure where the extraction region is completely shielded from the rest of the vacuum chamber.

5.3.3 Final configuration



Figure 5.12: a) FEMM 4.2 plot of equipotential lines of the voltage value. b) Electric field along the red line of (a).)

A simple check on the electric field has been done through the FEMM 4.2 code simplifying the geometry shown in figure 5.14. In figure 5.12a, the presence of the biased plate can help to increase the electric field in the extraction region. Moreover, its particular shape impose a meniscus form to the equi-potential lines: this is of course a vacuum simulation without plasma, but it improves the success to extract negative ions. The final COMSOL model has been then simulated to see if the change of the electric field configuration can alter the previous results. From figure 5.13a, the voltage 2D map shows the same results illustrated in figure 5.12a, while in figure 5.13b the magnetic field can be considered uniform. Finally, figures 5.13c-5.13d demonstrate how the system is able to filter the electrons and collect only negative ions. Figure 5.14a shows the final 3D CAD of the radial extraction configuration. In figure 5.14b, three main components are visible, that is, the plasma grid, the biased plate as hypothesized in the previous subsection and the collector. Besides the electrical feedthroughs of the main flange, an important role has been assigned to the two cooling parts. The two components that are going to be subjected to high thermal load power are the plasma grid and the collector. Since the insulated



Figure 5.13: a) COMSOL Electric field surface plot for the final configuration. b) COMSOL Magnetic field surface plot for the final configuration. c) Electron filtering in the final configuration. All the particles are collected by the biased plate. d) Negative ions trajectories, all ending to the collector.



Figure 5.14: a) 3D view of the final radial extraction configuration. b) Exploded view of the final configuration.)

parts are made of Shapal, ceramic material with thermal conductivity comparable to the copper one, the cooling system should be able to withstand a pulsed mode operation. Thermocouples are planned to be inserted as further diagnostic to be sure to stop the experiment before damaging the system.

5.4 Axial Extraction

5.4.1 First conceptual design

The axial extraction is a complex matter because of the intrinsic axial magnetic field of RAID. It is mandatory to impose an electric field along the longitudinal direction but at the same time a perpendicular magnetic field, otherwise the co-extracted electrons are not filtered. Inside a cylinder vacuum vessel with 5 coils wrapped around, this could be an initial issue. Through FEMM 4.2, a thorough investigation has been carried out to find the right magnetic circuit configuration, using permanent mag-



nets and ferromagnetic materials. Figure 5.15a shows the position of the extractor

Figure 5.15: a) FEMM 4.2 cylindrical symmetric model of RAID. b) Equipotential B lines nearside the extraction region.)

in RAID experiment while figure 5.15b shows the first conceptual geometry of the extractor. Since it is a 2D simulation assuming cylindrical symmetry, the plasma grid is a two circular plate made of ferromagnetic material. Then, after the slit, there are two vertical rectangles, therefore constituting a two ring structure. They delimit the extraction region and, since they are made of ferromagnetic material too, they allow to have a defined volume with a radial magnetic field. In this way, B and E are perpendicular. The magnetic field intensity is guaranteed by the two permanent magnet ring beyond the main structure: their polarization is along the axis of symmetry but they have opposite sign. Another important result is that the intrinsic axial magnetic field in the plasma column side is not affected, as visible in figure 5.16b. Figure 5.16d shows the axial magnetic field in the region nearside the extractor: there is a slight decrease in the intensity of the magnetic field and the uniformity is not guaranteed anymore. However, this alteration should not affect the parameters of RAID column plasma since there is still an axial magnetic field component even near the extraction slit. Finally, figure 5.17 shows as a radial magnetic field is feasible in RAID experiment thanks to the coupling of permanent magnets and a ferromagnetic material structure. The results suggest that a further optimization could ensure a better uniformity than the one illustrated in figure 5.17b.

5.4.2 Final configuration

Figure 5.18 shows all the components represented in COMSOL model for the final check of the electromagnetic and particle tracing simulations. Except for the collector, all the components are made of ferromagnetic material, while the permanent magnets are made of the SmCo series since they can sustain high temperatures without being de-magnetized. Figure 5.19 shows a summary of the electromagnetic behavior of the axial extractor prototype. Specifically, it is important to highlight the equipotential lines of the electric field in figure 5.19c and of the magnetic field in figure 5.19f: in the former case the meniscus shape obtained is perfect for the vacuum stage; for the latter, the presence of the big lateral walls allow a uniform radial component of the magnetic field and can also be used as electrode to collect filtered particles. Finally, figure 5.20 illustrates the trajectories of electrons and negative ions predicted for the axial extraction prototype. Thanks to a COMSOL tool,



Figure 5.16: a) FEMM 4.2 equipotential B lines in RAID with axial extractor. b) Axial magnetic field B intensity along the radius direction far away from the extractor. (c) FEMM 4.2 equipotential B lines in RAID nearside axial extractor. (d) Axial magnetic field B intensity along the radius direction near the extractor.



Figure 5.17: a) FEMM 4.2 equipotential B lines in the extraction region. b) Radial magnetic field intensity along the extraction direction (red line).

several surfaces can be studied to record how many particles they have collected during the simulation. The results are reported in table 5.1. The values to look are the ones in the column of the relative percentage. As visible in figure 5.18b, the two parts that divide the ring shape slit into two C shape-like slit intersect the particles emitted from the inlet surface. Therefore, it is necessary to consider only the neat flux of particles overcoming the slit aperture. The results indicate that the system



Figure 5.18: COMSOL final axial extractor model. a) Inlet surface from which the particles are emitted in COMSOL. b) Plasma grid with C-shape slits. c) Extraction electrodes. d) Lateral wall electrodes. e) Collector and permanent magnet disks configuration.

design is able to collect the negative ions and the magnetic field is high enough to filter the electrons. Finally, figure 5.21 illustrates the 3D CAD drawings of the final configuration. Also the cooling parts are reported and, although the design is still under review by the technical SPC office due to its high level of complexity, the project has been generally approved by the SPC team. In chapter 1, NIO1, the experiment on negative ion source and acceleration located at Consorzio RFX has been briefly described. Thanks to the axial configuration just designed, the issue caused by the intrinsic axial magnetic field of a helicon source can be potentially overcome. Therefore, a helicon antenna as plasma source for NIO1 can be now

Surface	Negative ions	Nominal	Relative	Electrons	Nominal	Relative
	conected	70	70	conected	70	70
\mathbf{Inlet}	44	0.44%	—	23	1.15%	—
Extractor	0	0%	0%	866	43.3%	82.7%
Lateral	8	0.08%	0.14%	168	8.4%	16%
walls						
Collector	5543	55.43%	99.3%	0	0%	0%
\mathbf{PG}	4375	43.75%	—	930	46.5%	_
plasma side						
\mathbf{PG}	0	0%	—	9	0.45%	_
extraction side						

Table 5.1: Negative ions and electrons surface collection in the axial extraction prototype for RAID. 10000 negative ions and 2000 electrons have been emitted from the inlet.

proposed.

5.5 Conclusions

The volume generation optimization has been studied in the experiment RAID within a EuroFusion enabling research project. Subject of the thesis has been the development of an extraction system prototype to extract negative ions as a proof of principle. Electromagnetic simulations have been developed and analyzed in order to define a final design, taking into account the presence of the axial magnetic field intrinsic of the experiment. Moreover, a simple 1-D model has been developed to understand the effect of the magnetic field on the plasma sheath generated between the plasma column and the plasma grid. A first result from the model shows that the expected current density available for the extraction is of the same order of magnitude recorded in other negative ion sources experiments without cesium. Though the current obtained does not meet DEMO requirements yet, the low RF power needed to sustain the plasma, compared to other current experiments, is an encouraging aspect that justify the pursuing of negative ion extraction in this experiment. Two type of extractors have been designed. One to extract the negative ion current along the plasma column radius. It is a simple system since it should take advantage of the axial magnetic field to filter the co-extracted electrons. On the other hand, the second prototype is more complex because there is the necessity to shield the extraction region from the same axial magnetic field. To solve this issue, using a system of permanent magnets and ferromagnetic material, a perpendicular magnetic field has been optimized to filter the co-extracted electrons without affecting the performances of RAID experiment in terms of radial confinement. This research was aimed to demonstrate the potential of both concepts at a proof of principle level. Therefore, the purpose is to demonstrate the capability of collecting negative ions,

leaving the improvement of the system for future developments, among which is the cooling system, needed for both prototypes since they face the plasma. Simple conceptual designs without complete thermal analysis have been defined. Pulsed mode operations are then foreseen checking in any case the temperatures of critical parts by means of thermocouples. The first prototype is under construction and should be tested by the end of 2019. The second one should be completed during the first half of 2020.



Figure 5.19: a) 2D surface plot COMSOL result of the electric field in a section view of the axial extractor. b) Potential line plot from the slit to the collector. c) 2D surface plot COMSOL result of the magnetic field in a section view of the axial extractor. d) Radial component of the magnetic field along the line from the slit to the collector. e) FEMM4.2 plot of the equipotential lines fo the magnetic field.



Figure 5.20: a) COMSOL particle tracing for negative ions in the axial extraction prototype. b) COMSOL particle tracing for electrons in the axial extraction prototype.



Figure 5.21: a) SolidWorks 3D CAD of the final prototype. b) Exploding view of the axial extractor.

Chapter 6

Conclusions and Future Work

In this PhD thesis, the study of Hydrogen negative ion generation has been carried out integrated in the optimization of ion sources. The work can be inserted as part of the nuclear fusion R&D, focused to the neutral beam injector (NBI) physics and study of optimum extraction in an alternative ion source. The work is divided into three sections: (i) optimization of negative ion generation in SPIDER ITER source, (ii) study of optimization of an alternative plasma source for the negative ion surface generation mechanism and (iii) for the volume one. Chapter 3 deals with the first part of the work. The cesium behavior has been analyzed in SPIDER by using CATS facility. Aimed to an optimization of the system, the cesium behavior in SPIDER has been analyzed by using the ovens prototypes designed for SPIDER. During this stage, numerical simulations have been used to match experimental and numerical results on cesium density distribution. The sticking coefficient to apply to the vacuum chamber walls has been parameterized to predict the cesium distribution. A value around 2% has been found as the best match between CATS measurements and model results. This value has been applied later to a SPIDER plasma source model. The numerical code shows that $\approx 20\%$ of the cesium vapour emitted during the vacuum phase deposit in unwanted regions. To avoid risky and unwanted scenarios, it has been found that it is necessary to set a particular maintenance procedure during SPIDER shut-down periods and that there could be undesired break down discharges between the unwanted cesiated components and the rest of source parts. Chapter 4 and 5 deal with the optimization for two alternative ion sources of interest for DEMO. In chapter 4, an aerospace technology has been used. It is a home-made different Hall effect thruster (HET) concept built to generate negative ions through the surface process. In the thesis, the design procedure and the electromagnetic simulations have been carried out and the device has successfully operated in Nitrogen and Hydrogen. Moreover, the plasma has been characterized by means of several diagnostics showing a quasi uniform plasma density profile along the thruster axis with interesting nominal values. Moreover, by means of the Retard Field Energy Analyzer (RFEA) diagnostic, the role of positive ions for the operation of the source has been highlighted showing that they could provide a substantial and tunable contribution to the generation of negative ions. Indeed, acting on the power supply, it is possible to tune the energy of the ions which are going to impact on the cesiated extraction area, influencing in this way the surface generation mechanism. Successively, after electromagnetic and particle tracing simulations, the extraction system has been built. As for the cesium evaporation, the experience gained in

the cesium operation for SPIDER has helped to design the cesium injection for the source. Although the collector has not been able to screen all the co-extracted electrons, the signal has shown that negative ions were present therefore showing that a system based on a Hall Thruster source can generate negative ions. Being the experiment a proof of principle, to demonstrate the potential for DEMO, further R&D has been identified aimed to verify the maximum current density which can be extracted and, if this latter one meets the requirements for DEMO and future reactors, an optimization of the system can be envisaged. The second experiment is aimed to study the volume process mechanism. It is of DEMO interest to verify this alternative concept as it is a low power device and it is a cesium-free source: this alkali metal is important for the surface production, but it can also raise problems during experimental operations. In this case, the plasma source is operating at SPC-EPFL in Lausanne. It is a Radio-Frequency (RF) helicon antenna system and the name of the experiment is RAID (Resonant Antenna Ion Device). The plasma generated is confined by means of a strong axial magnetic field, forming in this way a long plasma column where the helicon waves propagate. The interest as a possible alternative negative ion source comes from the observation of a high H^- density found in the external part of the plasma column. The work of this thesis dealt with the design of two extraction system prototypes, one radial and one axial. Before that, a simple 1D model has been developed to take into account the effect of the intrinsic axial magnetic field on the H^- transport in the plasma sheath interface between the source and the extraction system. In this way, it has been possible to estimate the order of magnitude of the maximum negative ion current density achievable. In chapter 5, all the electromagnetic and particle tracing simulations have been carried on successfully thanks to the experience gained in the HET source. The radial extractor is the simplest design because it uses the intrinsic axial magnetic field of the system to filter the co-extracted electrons. The axial design has been much more difficult to obtain because of the same magnetic field. A particular permanent magnets-ferromagnetic material configuration has been designed so a final sketch has been drawn down. The two configurations have been considered worth of an experimental test and, since the purpose is to demonstrate the extraction capability without depleting the negative ion population, the initial test for both concepts will be pulsed. At present, the radial prototype is under construction and it is going to operate before the end of 2019. The axial prototype requires some technical iterations and it is going to be installed in the first half of 2020.

In summary, during this PhD project, several goals have been achieved. (i) The development of three type of diagnostics have allowed the study on cesium in CATS. It has been possible then to match the cesium distribution parameters with numerical model outputs. This comparison led to the simulation of a scenario that has given a better understanding of cesium deposition and procedure in SPIDER ITER ion source. (ii) Within a EuroFusion enabling research, an alternative concept of negative ion source based on HET has been developed. The plasma has been characterized by three types of diagnostic and an extraction system has been built. The device has been considered as a successful proof of principle alternative source for negative ion generation. Moreover, the possibility to regulate the positive ion energy of the plasma generated has been observed. So a further optimization of the device can be used to study and enhance the negative ion generation by means

of the surface mechanism. (iii) Within another EuroFusion enabling research, a promising cesium free helicon plasma source has been analyzed. The hurdle of the intrinsic high axial magnetic field of the device has been overcome by means of the development of two extractor prototypes. Both of the final configurations have been accepted for the experimental stage. The radial prototype will be tested by the end of 2019 and the axial one during 2020.

Bibliography

- [1] Luiz C. M. M. and Lima C. A. S. "On the forecasting of the challenging world future scenarios". In: *Technological Forecasting & Social Change* 78 (2011).
- [2] N. Abas et al. "Review of fossil fuels and future energy technologies". In: *Futures* 69 (2015). DOI: https://dx.doi.org/10.1016/j.futures.2015. 03.003.
- [3] Bilanovic D. et al. "Freshwater and marine microalgae sequestering of CO2 at different C and N concentrations. Response surface methodology analysis". In: *Energy Conversion Management* 50 (2009).
- [4] Solangi K. et al. "A review on global solar energy policy". In: Renewable and Sustainable Energy Reviews 15 (2011).
- [5] Herbert G. M. J. et al. "A review of wind energy technologies". In: *Renewable and Sustainable Energy Reviews* 11 (2007).
- [6] Moriarty P. et al. "Hydrogen's role in an uncertain energy future". In: International Journal of Hydrogen Energy 34 (2009).
- [7] Faaij A. P. C. "Bio-energy in Europe: Changing technology choices". In: *Energy Policy* 34 (2006).
- [8] Pearce J. M. "Photovoltaics A path to sustainable futures". In: *Futures* 34 (2002).
- [9] Duffey R. B. "Sustainable futures using nuclear energy". In: *Progress in Nuclear Energy* 47 (2005).
- [10] Shinzo S. "Role of nuclear energy to a future society of shortage of energy resources and global warming". In: *Journal of Nuclear Materials* 398 (2010).
- [11] R. G. Mills. "Lawson Criteria". In: *IEEE Transactions on Nuclear Science* 18 (1971).
- [12] ITER website. "www.iter.org". In: ().
- [13] O. Motojima. "The ITER project construction status". In: International Atomic Energy Agency 55 (2015).
- [14] N. Taylor et al. "Lessons learned from ITER safety and licensing for DEMO and future Nuclear Fusion Facilities". In: *Fusion Engineering and Design* 89 (2014).
- [15] ITER ED et al. "Plasma auxiliary heating and current drive". In: Nuclear Fusion 39 (1999).
- [16] B. Zaniol et al. "NIO1 Diagnostics". In: AIP Conference Proceedings 1655 (2015).

- [17] M. Cavenago et al. In: *Rev. Sci. Instrum.* 83 (2012).
- [18] M. Cavenago et al. "First experiments with the negative ion source NIO1". In: Review of Scientific Instruments 87 (2016).
- [19] B. Heinemann et al. "Design of the halfsize ITER Neutral Beam Source for the Test Facility ELISE". In: *Fusion Engineering and Design* 84 (2009).
- [20] M. Berger et al. "Cavity ring-down spectroscopy on a high power rf dirven source for negative hydrogen ions". In: *Plasma Sources Scientific Technology* 18 (2009). DOI: 10.1088/0963-0252/18/2/025004.
- [21] P. Franzen et al. "Commissioning and First Results of the ITER-Relevant Negative Ion Beam Test Facility ELISE". In: *Fusion Engineering and Design* 88 (2013).
- [22] V. Toigo et al. "The PRIMA Test Facility: SPIDER and MITICA test-beds for ITER neutral beam injectors". In: *New Journal of Physics* 19 (2017).
- [23] M. Bacal E. Nicolopoulou and H. J. Doucet. "Equilibrium density of h- in a low pressure hydrogen plasma". In: J. Phys. France 38.11 (1977), pp. 1399– 1404. DOI: https://doi.org/10.1051/jphys:0197700380110139900.
- [24] M. Bacal and G. W. Hamilton. "H- and D- Production in Plasmas". In: *Phys. Rev. Lett.* 42.23 (1979), p. 1538. DOI: https://doi.org/10.1103/ PhysRevLett.42.1538.
- [25] J. M. Wadehra and J. N. Bardsley. "Vibrational- and Rotational-State Dependence of Dissociative Attachment in e-H2 Collisions". In: *Phys. Rev. Lett.* 41.26 (1978), p. 1795. DOI: https://doi.org/10.1103/PhysRevLett.41.1795.
- [26] C. Bottcher and B. D. Buckley. "Dissociative electron attachment to the metastable c 3 Pi u state of molecular hydrogen". In: *Journal of Physics B: Atomic and Molecular Physics* 12.16 (1979), p. L497. DOI: https://doi.org/ 10.1088/0022-3700/12/16/004.
- [27] M. Bacal and M. Wada. "Negative hydrogen ion production mechanisms". In: *Applied Physics Reviews* 2 (2015). DOI: https://dx.doi.org/10.1063/1. 4921298.
- [28] M. Wada. "Formation and destruction processes of negative ions in abounded plasma". In: *Thin Solid Films* 316 (1998). DOI: https://doi.org/10.1016/ S0040-6090(98)00402-7.
- [29] K. S. Woodcock. "The Emission of Negative Ions under the Bombardment of Positive Ions". In: *Phys. Rev.* 38 (1931). DOI: https://doi.org/10.1103/ PhysRev.38.1696.
- [30] G. Cartry1 et al. "Alternative solutions to caesium in negative-ion sources: a study of negative-ion surface production on diamond in H2/D2 plasmas". In: New Journal of Physics 19 (2017). DOI: https://doi.org/10.1088/1367-2630/aa5f1f.
- [31] J. J. C. Geerlings J. Los. "Charge exchange in atom-surface collisions". In: *Physics Reports* 190 (1990). DOI: https://doi.org/10.1016/0370-1573(90) 90104-A.

- [32] J. Los B. Rasser J. N. M. Van Wunnik. "Theoretical models of the negative ionization of hydrogen on clean tungsten, cesiated tungsten and cesium surfaces at low energies". In: Surface Science 118 (1982). DOI: https://doi. org/10.1016/0039-6028(82)90216-3.
- [33] T. S. Green. "Intense ion beams". In: *Rep. Prog. Phys.* 37 (1974).
- [34] I.Langmuir and K. B. Blodgett. "Currents limited by space charge between concentric spheres". In: *Phys. Rev.* 24 (1924).
- [35] I.Langmuir and K. B. Blodgett. "Currents limited by space charge between coaxial cylinders". In: *Phys. Rev.* 22 (1923).
- [36] M. A. Lieberman and A. J. Lichtenberg. Principle of Plasma Discharges and Materials Processing. Hoboken, New Jersey: John Wiley and Sons, 2005.
- [37] V. Antoni R. S. Hemsworth A. Tanga. "Status of the ITER neutral beam injection system". In: *Review of Scientific Instruments* 79 (2008). DOI: https: //doi.org/10.1063/1.2814248.
- [38] K.H. Berkner, R.V Pyle, and J.W Stearns. "Intense, mixed-energy hydrogen beams for CTR injection". In: Nuclear Fusion 15 (1975). DOI: https://doi. org/10.1088/0029-5515/15/2/009.
- [39] M.Hanada et al. "Development of negative ion sources for the ITER neutral beam injector". In: *Fusion Engineering and Design* 56-57 (2001).
- [40] David R. Lide. *CRC Handbook of Chemistry and Physics*. Boca Raton, FL: Taylor and Francis, 2007.
- [41] H. B. Michaelson. "The work function of the elements and its periodicity". In: Journal of Applied Physics 48 (1977). DOI: https://doi.org/10.1063/1. 323539.
- [42] E. P. Gyftopoulos and J. D. Levine. "Work Function Variation of Metals Coated by Metallic Films". In: *Journal of Applied Physics* 33 (1962). DOI: 10.1063/1.1728530.
- [43] A. G. Naumovets A. G. Fedorus. "Cesium on Tungsten (011) face; Structure and Work Function". In: Surface Science 21 (1970). DOI: https://doi.org/ 10.1016/0039-6028(70)90244-X.
- [44] R. McAdams et al. "Transport of negative ions across a double sheath with a virtual cathode". In: *Plasma Sources Sci. Technol.* 20 (2011).
- [45] M. Bacal and M. Wada. "Negative ion production by plasma-surface interaction in caesiated negative ion sources". In: AIP Conference Proceedings 1515 (2013).
- [46] M. Seidl et al. "Negative surface ionization of hydrogen atoms and molecules". In: Journal of Applied Physics 79 (1996).
- [47] H. A. Jones et al. In: G. E. Rev. 30 (1927).
- [48] J. B. Taylor et al. "The evaporation of atoms, Ions and Electrons from Caesium Films on Tungsten". In: *The Physical Review* 44 (1933).
- [49] E. Sartori et al. "Modeling the cesium flow from a dispenser oven and the measurement by a surface ionization detector". In: *RFX Internal Technical Note* (RFXSPIDERTN450).

- [50] M. Barbisan et al. "Design and preliminary operation of a laser absorption diagnostic for the SPIDER RF source". In: *Fusion Engineering and Design* article in press (2019).
- [51] L. Bizzotto. Development of a movable probe to characterize the caesium emission from SPIDER caesium ovens. Bachelor Thesis. 2019. DOI: http://tesi.cab.unipd.it/.
- [52] E. Sartori et al. "AVOCADO: A numerical code to calculate gas pressure distribution". In: *Vacuum* 90 (2013).
- [53] K. Jousten. *Handbook of Vacuum Technology*. Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KGaA, 2016.
- [54] P. Agostinetti et al. "Detailed designed optimization of the MITICA negative ion accelerator in view of the ITER NBI". In: *Nuclear Fusion* 56 (2016).
- [55] L. Grisham et al. "Recent improvements to the ITER neutral beam system design". In: *Fusion Eng. Des.* 87 (2012). DOI: https://doi.org/10.1016/j. fusengdes.2012.08.001.
- [56] P. Franzen et al. "Progress of the ELISE test facility: results of caesium operation with low RF power". In: *Nuclear Fusion* 55 (2015).
- [57] R. S. Hemsworth et al. "Positive and negative ion sources for magnetic fusion". In: *IEEE Transactions on Plasma Science* 33 (2005).
- [58] J. P. Boeuf et al. "Model of an inductively coupled negative ion source: II. Application to an ITER type source". In: *Plasma Sources Science and Technology* 20 (2011).
- [59] L. Schiesko et al. "Magnetic field dependence of the plasma properties in a negative hydrogen ion source for fusion". In: *Plasma Physics and Controlled Fusion* 54 (2012).
- [60] E. Sartori et al. "Analytical study of caesium-wall interaction parameters within a hydrogen plasma". In: AIP Conference Proceedings 2052 (2018). DOI: https://doi.org/10.1063/1.5083724.
- [61] D.M. Goebel and I. Katz. Fundamentals of Electric Propulsion: Ion and Hall thrusterss. Hoboken, New Jersey: John Wiley & Sons, Inc., 2008.
- [62] F. Taccogna at al. "Three-dimensional particle-in-cell model of Hall thruster: The discharge channel". In: *Physics of Plasmas* 25 (2018).
- [63] T. Ito et al. "Experimental Characterization of a Micro-Hall Thruster". In: Journal of Propulsion and Power 23 (2007).
- [64] D. Desideri and G. Serianni. "Four parameter data fit for Langmuir probes with nonsaturation of ion current". In: *Rev. Sci. Instrum.* 69 (1998).
- [65] L.N. Mishra. "Retarded Field Energy Analyzer as a tool to Study the Ion Velocity Distribution Functions on Radio Frequency Argon Plasma in Expanding Magnetic Field at Low Pressures". In: Journal of Nepal Physical Societyr 3 (2015).
- [66] J. Hiskes. "Formation of hydrogen negative ions by surface and volume processes with applica-tion to negative ion sources". In: *Journal de Physique Colloques* 40.C7 (1979), pp. C7-179-C7-192. DOI: 10.1051/jphyscol:19797439.

- [67] B. Kakati et al. "Development of a novel surface assisted volume negative hydrogen ion source". In: *Scientific Reports* (2017).
- [68] B. Wolf. Handbook of Ion Sources. New York: CRC press, 1995.
- [69] F. Spinazzè. Theoretical and experimental investigations on the Child-Langmuirlimited current. Master Thesis. 2017. DOI: http://tesi.cab.unipd.it/ 54430/.
- [70] J. Navarro-Cavallè et al. "Helicon Plasma Thrusters: prototypes and advances on modeling". In: *International Electric Propulsion Conference* (2013).
- [71] R. W. Boswell. "Very efficient plasma generation by Whistler waves near the lower hybrid frequency Plasma". In: *Plasma Physics and Controlled Fusion* 26 (1984).
- [72] F. F. Chen et al. "Downstream physics of the helicon discharge". In: *Plasma Sources Science Technology* 5 (1996).
- [73] D. Arnush. "The role of Trivelpiece-Gould waves in antenna coupling to helicon waves". In: *Physics of Plasmas* 7 (2000).
- [74] F. F. Chen. "Helicon Plasma Sources". In: *High Density Plasma Sources* (1996).
- [75] R. Agnello et al. "Cavity Ring-Down Spectroscopy to measure negative ion density in a helicon plasma source for fusion neutral beams". In: *Review of Scientific Instruments* 89 (2018).
- [76] P. Guittienne et al. "Towards an optimal antenna for helicon waves excitation". In: Journal of Applied Physics 98 (2005).
- [77] I. Furno et al. "Helicon wave-generated plasmas for negative ion beams for fusion". In: *EPJ Web Conf.* 157 (2017).
- [78] S. P. Das et al. "A Dielectric Barrier Discharge (DBD) Plasma Reactor: An Efficient Tool to Measure the Sustainability of Non-Thermal Plasmas through the Electrical Breakdown of Gases". In: *IOP Conf. Ser.: Mater. Sci. Eng.* 410 (2018).