



UNIVERSITÀ
DEGLI STUDI DELLA
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**Department of Economics, Engineering, Society and
Business Organization**

**PhD in Engineering for Energy and Environment
XXXVI Cycle**

Scientific-disciplinary area: IIET-01/A

**Engineering aspects of new generation
tokamak devices: spectroscopic diagnostics and
vacuum auxiliary system**

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Abstract

This thesis is conducted within the framework of nuclear fusion research, a promising alternative energy source which aims to generate sustainable and clean power. It is the process by which two light atomic nuclei combine to form a heavier nucleus, releasing a significant amount of energy. The European roadmap for fusion energy focuses on achieving controlled fusion reactions using toroidal devices known as tokamaks, which are the subject of intensive scientific research supported by advanced diagnostics and complex auxiliary systems. Advances in scientific research and technological innovation are driving the development of larger superconducting tokamaks, as increasing their size improves plasma confinement, enhances energy retention. Unlike earlier designs, where diagnostics were largely external, the new-generation superconductive tokamaks integrate diagnostic systems directly into the vacuum vessels where the fusion reactions occur. These harsh nuclear environments, characterized by high neutron fluxes, high vacuum, and intense heat loads, demand increased complexity, robustness, and reliability of diagnostic systems as well as complex integration with other tokamak components. Within this context, the work presented in this thesis focuses on the design of spectroscopy diagnostics and the pumping systems for two new superconducting tokamaks: DTT and JT-60SA.

Part I firstly introduce the global energy landscape and the fundamentals of nuclear fusion, emphasizing the urgent need for low-carbon energy alternatives and detailing the plasma confinement methods used in fusion research. The section concludes with an overview of DTT and JT60-SA which are the devices on which the thesis work is focused.

Part II of this work focuses on the Visible Spectroscopy diagnostic system designed to measure the effective charge (Z_{eff}) radial profile time evolution and the visible imaging diagnostic of the DTT's divertor. This system is integrated to fit within limited vessel space and includes a setup for Bremsstrahlung radiation measurement along ten lines of sight in the poloidal plane, a toroidal line of sight for average Z_{eff} evaluation and a dual-telescope to observe the divertor. In both systems the collected light is transmitted to external spectrometers and filter devices for flexible monitoring of impurity influx, plasma positioning, and detachment evolution. The conceptual design was completed, incorporating both the mechanical and optical structures, along with an estimation of the laboratory setup required for data acquisition and post-processing.

Part III presents the preliminary design of the DTT vacuum system. This section presents the study undertaken to develop a layout capable of achieving the required pressure levels inside the vacuum vessel. The analysis begin with an evaluation of the vessel geometry in terms of pumping capacity to identify the optimal configuration, taking into account the integration of other subsystems such as additional heating systems and diagnostic equipment. The conceptual design is then finalized, incorporating the technical specifications necessary to prepare a tender document for the facility's procurement.

Part IV introduces the Vacuum Ultraviolet Spectrometer (VUV) specifically designed to monitor the JT-60SA divertor region. This diagnostic supports the broader objectives of ITER and DEMO by investigating impurity-induced radiation and plasma detachment in the divertor region. The spectrometer is based on the double SPRED system originally used on Textor which has been significantly upgraded with two new toroidal gratings for 1D imaging detection, 2D CCD detectors, a dual pair of gold-coated toroidal mirrors, and a new pumping system. Additionally, a custom-designed chassis was developed to integrate the spectrometer into the tokamak structure, ensuring precise alignment of the line of sight (LoS). The gratings have been installed within the spectrometer vessel, and their performance has been verified through a dedicated calibration setup.

Questa tesi è condotta nell'ambito della ricerca sulla fusione nucleare, una fonte di alternativa energia che mira a generare energia sostenibile e pulita fondendo nuclei atomici leggeri. La ricerca Europea mira a realizzare un processo controllato di fusione utilizzando dispositivi toroidali noti come tokamak, che si basano su un avanzato sistema diagnostico e diversi sistemi ausiliari. A differenza delle prime versioni di tokamak, dove le diagnostiche erano per lo più installate esternamente, i tokamak di nuova generazione integrano le diagnostiche direttamente all'interno vacuum vessel. Questi ambienti nucleari estremi, caratterizzati da flusso di neutroni, alto vuoto e carichi termici intensi, richiedono alle diagnostiche una maggiore complessità, robustezza e affidabilità. Questo lavoro di tesi si concentra sul progetto di alcune diagnostiche spettroscopiche e sul sistema di pompaggio per due nuovi tokamak superconduttori: DTT e JT-60SA.

Part I inizia con una panoramica del contesto energetico globale e con un'introduzione ai fondamenti della fusione nucleare, evidenziando l'urgenza di alternative energetiche a basse emissioni di carbonio e descrivendo i diversi filoni di ricerca sulla fusione. La sezione si conclude con una panoramica di DTT e JT-60SA, i tokamak di nuova generazione su cui si concentra il lavoro di tesi.

Part II si concentra sul sistema diagnostico di spettroscopia visibile progettato per misurare l'evoluzione temporale del profilo radiale della carica efficace (Z_{eff}) e imaging spettroscopico nella regione del divertore di DTT. Questo sistema è integrato per adattarsi nel poco spazio disponibile nel vacuum vessel. Integrata in un design compatto è stato disegnato un sistema per ottenere una misurazione della radiazione Bremsstrahlung lungo dieci linee di vista nel piano poloidale, più un'aggiuntiva linea di vista toroidale per avere una valutazione più robusta della carica effettiva media. Per massimizzare la copertura del divertore si è sviluppata una configurazione a doppio telescopio che trasmette la luce raccolta a un set-up di spettrometri e filtri interferenziali posizionati esternamente alla tokamak hall. Il sistema mira ad essere flessibile permettendo una vasta gamma di misure che mirano allo studio della distribuzione delle impurità, della posizione del plasma e dell'evoluzione del detachment. Il progetto concettuale della struttura meccanica ed ottica è stato completato ed è stata fatta una prima stima dell'allestimento del laboratorio necessario per l'acquisizione dei dati e il post-processamento.

Part III riporta il progetto preliminare del sistema da vuoto di DTT. Questa parte analizza le dimensioni dei tubi e la configurazione delle pompe, sul sistema di pre-vuoto, con il fine di ottenere la pressione desiderata nel vacuum vessel. È stata effettuata una comparazione tra due possibili configurazioni di accessi al vessel per determinare la soluzione ottimale in termini di pompaggio anche tenendo conto dell'integrazione dei sistemi di riscaldamento aggiuntivi e delle diagnostiche. Successivamente i sotto-componenti, inclusi i sistemi di pre-vuoto e alto vuoto, sono stati ottimizzati al fine di ottenere una gestione efficace della pressione, insieme a uno studio dettagliato della rigenerazione della pompa criogenica dedicata al divertore. Il progetto concettuale è stato completato, fornendo le specifiche tecniche necessarie per la redazione di un documento di gara per la fornitura dell'intero sistema.

La Part IV presenta lo spettrometro a ultravioletti (VUV) dedicato al monitoraggio della regione del divertore di JT-60SA. Questa diagnostica contribuisce agli obiettivi più ampi di ITER e DEMO studiando la radiazione indotta dalle impurità nella zona del divertore e mira ad approfondire lo studio della fisica del detachment. Lo spettrometro si basa sul doppio SPRED originariamente utilizzato su Textor, che è stato aggiornato con due nuovi reticoli toroidali con la capacità di risoluzione spettrale 1D, nuovi rilevatori CCD, una doppia coppia di specchi toroidali rivestiti in oro e un nuovo sistema di pompaggio. Inoltre, è stato sviluppato un telaio personalizzato per integrare lo spettrometro nella struttura del tokamak e un sistema che consenta un allineamento preciso delle linee di vista. I nuovi reticoli che consentono la ricostruzione spettrale dell'immagine del divertore sono stati installati nello spettrometro e le loro prestazioni sono state verificate tramite un set-up dedicato.

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List of abbreviation

Abbreviation

CCD	Charge coupled device
CF	Kind of flange (ConFlat) characterized by a knife-edge flange to achieve an ultrahigh vacuum seal
DEMO	DEMONstration fusion power plant
DIV	Divertor
DIO	Digital input - output
DTT	Divertor Tokamak Test
FWHM	Full Width at Half Maximum
GDC	Glow discharge cleaning
HC	Hollow Cathode source
ICF	Inertial Confinement Fusion
IPCC	Intergovernmental Panel for Climate Change
ITER	International Thermonuclear Experimental Reactor
JT60-SA	Japan Tokamak-60 Super Advance
K-STAR	Korea Superconducting Tokamak Advanced Research
LoS	Line of sight
MCF	Magnetic Confinement Fusion
MCP	Microchannel plate
MOS	Metal-Oxide-Semiconductor
RFP	Reverse Field Pinch
RFX	Reverse Field pinch eXperiment
ROI	Region of interest
SPRED	(survey, poor resolution, extended domain) spectrometer configuration
VV	Vacuum vessel
VUV	Vacuum UltraViolet wavelength range
Z	The atomic number Z of a chemical element is the positive charge number of an atomic nucleus
Z_{eff}	Plasma effective charge
PFC	Plasma-Facing Component
DIS	Diverto Imaging System
HFS	High Field side
LFS	Low Field side
FW	First wall

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Part I

Introduction

This part of the thesis serves as a comprehensive introduction to the field of nuclear fusion, beginning with an exploration of the global energy landscape in Sec. 1. The current energy challenges, including the growing demand for sustainable and low-carbon energy sources is summarized. It highlights the limitations of existing energy technologies and the urgent need for alternatives that can meet future energy needs without exacerbating environmental issues. Following this, the Sec. 2 delves into the fundamentals of nuclear fusion, explaining the processes that the fusion research aim to replicate. The discussion then moves to the various methods of plasma confinement, a critical aspect of maintaining the extreme conditions necessary for fusion. This includes an examination of magnetic confinement approaches in Sec. 3. The final Sec. 4 introduce two experiment objective of this thesis work: DTT and JT-60SA. This section provide an overview of their design, objectives, and contributions to advancing our understanding of plasma behavior and fusion technology.

1.1 Energy context

The growing of world population and improvement of the life quality of last century was followed by a more and more request of energy. An overview of current world energy consumption can be seen in Fig. 1.2. The bulk of this energy is obtained at the expense of a great emission of greenhouse gases. The IPCC (Intergovernmental Panel for Climate Change) published a report about the impacts of a 1.5 °C average temperature increase with respect to the pre-industrial level [63]. The study of Earth temperature change suggests that the latter scenario is likely to be reached within the 2030-2050 years. The last decades trend of world CO₂ emission is reported in Fig. 1.1a, whereas the overview of the world consumption made explicit for the different types of source is shown in Fig. 1.2. This request of energy is set to increase also with growing of world population (see Fig. 1.1b) that already in 2022 has crossed eight billion of people. As a result, there has been a growing awareness that humanity needs to greatly reduce its dependence on fossil fuels for energy production but, at the same time, people are unwilling to compromise their quality of life.

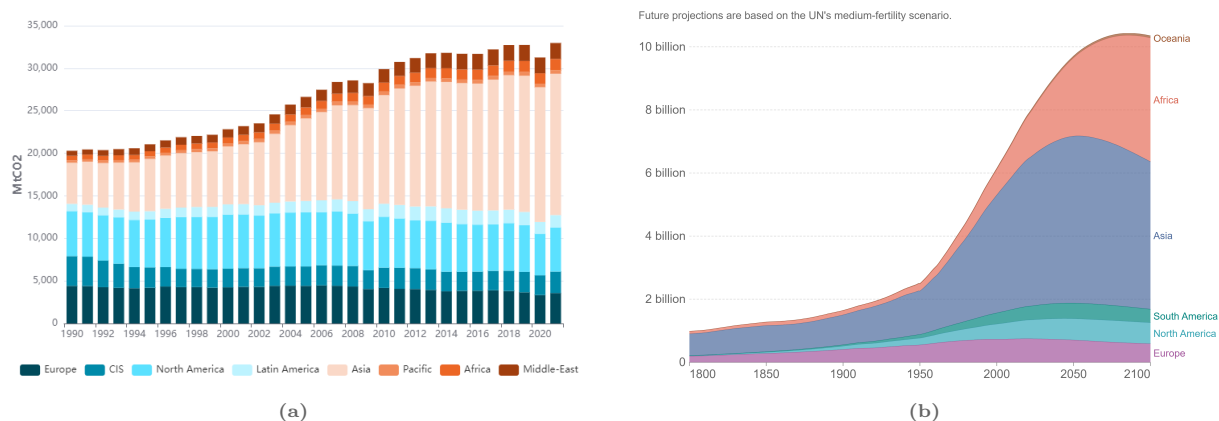


Fig. 1.1: World last decades evolution: (a) trend over 1990-2021 of CO₂ emission expressed in Mt [27]; (b) world population by region with projection [90]

Many governments are strongly investing in renewable energy sources such as wind and solar, but due to the intermittent nature of these sources, in combination with the lack of efficient storage options, the share of these sources in the energy mix is limited. The first issues behind the renewable energy is their intrinsic intermittence and seasonality. An easy example is the solar energy that is limited during the daylight hours and sunny weather. Developing proper storage options for this intermittent sources that can cope with both the nocturnal as well as the seasonal variations will certainly improve the situation. Nevertheless, even with the best possible storage means and making use of super grid the relative contribution of renewables to the electricity mix is estimated to be limited to 60% [36].

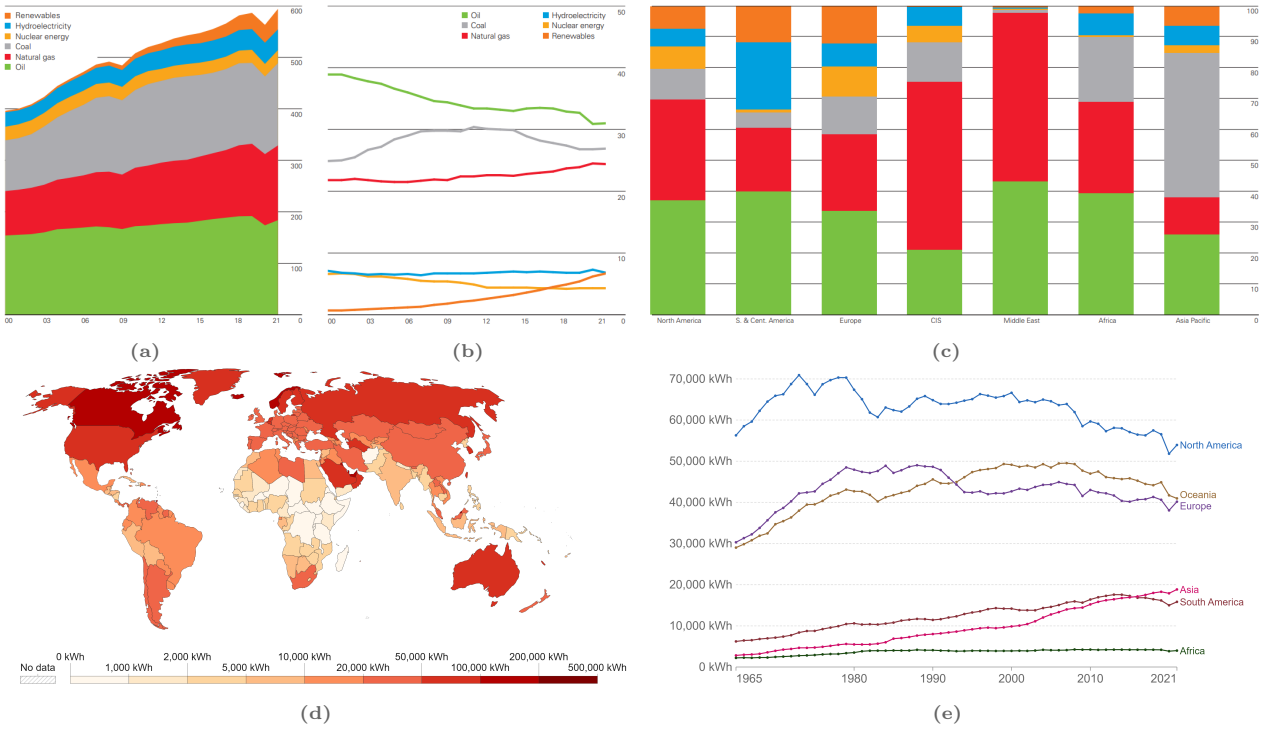


Fig. 1.2: Overview of the world consumption [81][88]: (a) world consumption in EJ (10^{18} Joule); (b) shares of global primary energy in percentage; (c) regional consumption pattern in 2021 in percentage; (d) energy used per person 2021; (e) trend of energy use per person by country

The demand is expected to increase substantially more in the second part of this century, to perhaps 10 TW [31] but at the same time the green house gases emissions must be drastically reduced, in order to avoid further long terms climate changes, in addition to the already existing ones. In this context nuclear fission, for those countries where it is accepted, see Fig. 1.3a, can complement renewables in cutting power sector emissions while also contributing to electricity security as a available power source [49]. This kind of energy has been regularly exploited as a controlled source in nuclear power plants or in form of weapon since several decades how shown in Fig. 1.3. It can produce enormous amount of energy however it presents a series of disadvantages like the production of long-lasting radioactive waste which requires special storage. In addition, in this kind of plant awful accidents can occur when the chain reaction control fails (URSS, Chernobyl 1986) or the cooling system does not work properly (Japan, Fukushima 2011).

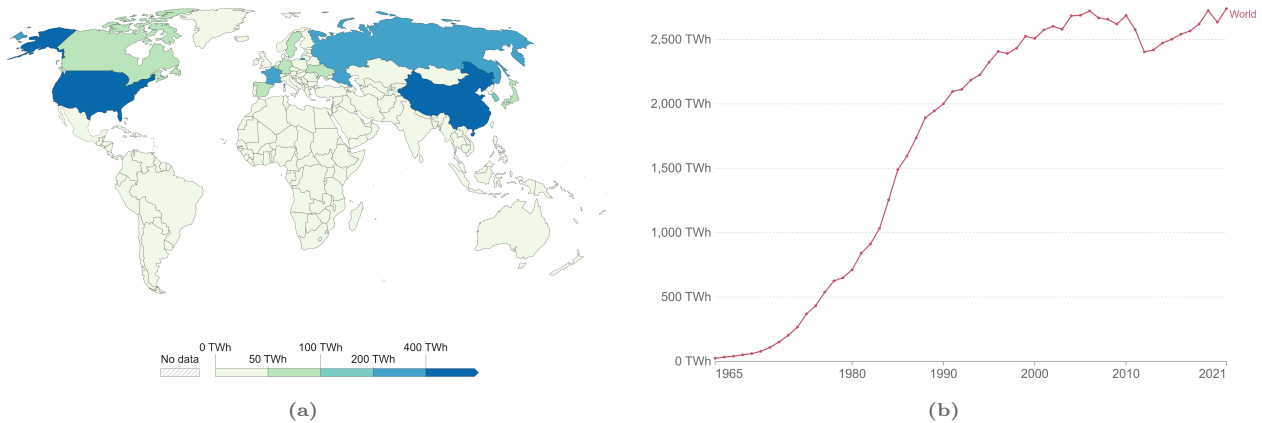


Fig. 1.3: Overview of the world nuclear fusion energy production: (a) Map of nuclear energy generation by country in 2021; (b) Evolution of global generation of nuclear energy

1.2 Roadmap to fusion energy

In this context the fusion energy represent the best alternative to other source of energy with its intrinsic security and zero CO₂ emission. In addition, unlike renewable energy sources, fusion does not depend on weather conditions and does not require huge energy storage systems. Today, Europe is a leader in fusion research and development following several steps in order to achieve this goal [31]:

- Technical demonstration of large scale fusion power - this is the first goal of ITER¹ (500 MW for 400 seconds)
- Electricity delivered to the grid via a DEMOnstration² fusion power plant (DEMO) which would do the following:
 - generate, early in the second part of this century, hundreds of MW of electricity for at least several hours at a time
 - operate with a closed fuel cycle
 - have other features that could be extrapolated to early commercial fusion power plants
- In parallel, a science, technology, innovation and industry basis to allow the transition from the demonstration fusion plant to affordable devices suitable for large scale commercial deployment (stellarators might prove particularly attractive)
- Large scale industrial production of fusion plants

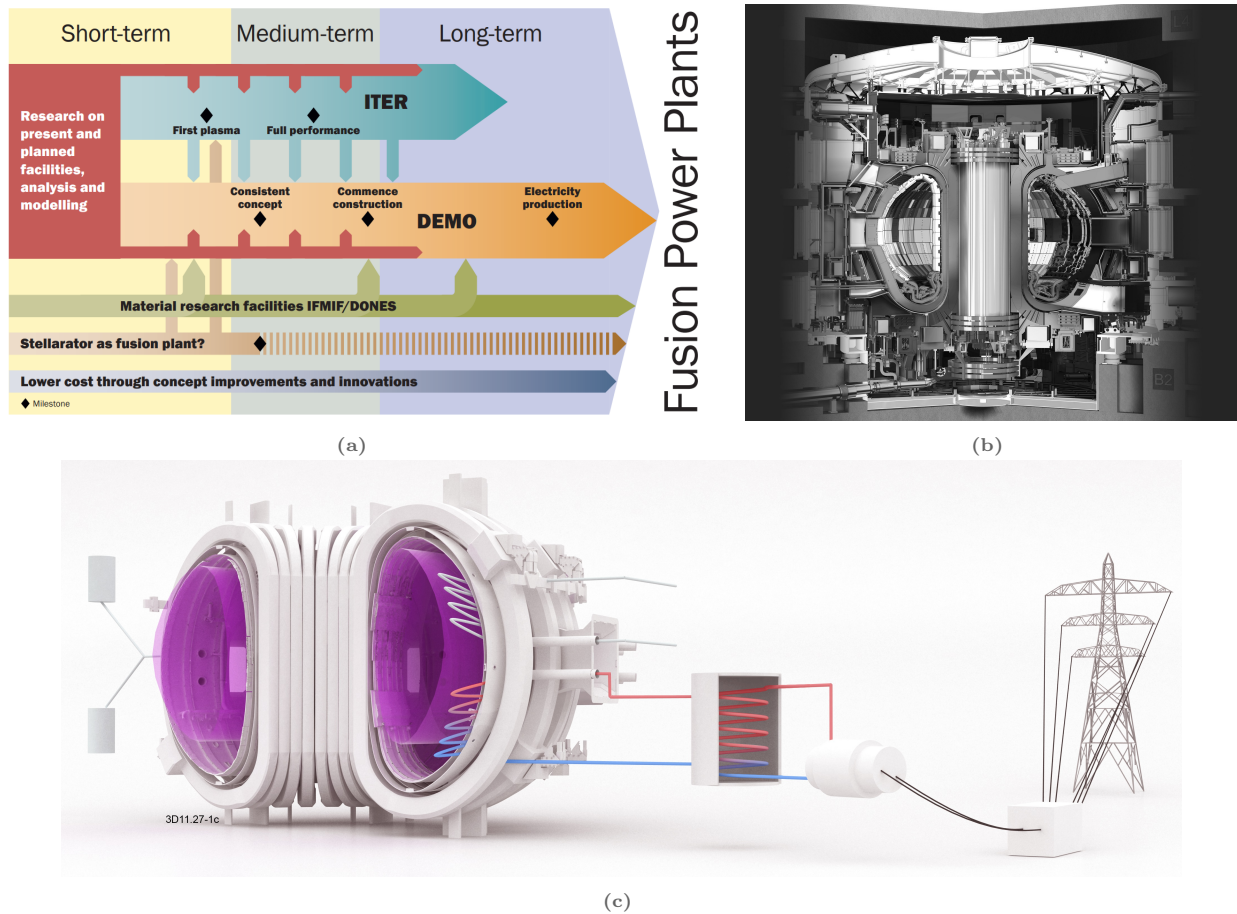


Fig. 1.4: EuroFusion programme: (a) EUROfusion roadmatto for the realization of fusion power plant; (b) ITER (International Thermonuclear Experimental Reactor) drawing; (c) DEMOnstrative reactor power plant drawing

In Fig. 1.4a long-term EUROfusion program is shown whereas Fig. 1.4b reports an cross-section of the fusion reactor ITER currently under construction in Cadarache (France). ITER will be a tokamak configuration device and it si predicted to start the operations within the end of this decade and aims to reach the full performance in the 2040's. Parallel to ITER, different projects aimed at solving technological problems in material research will be operated such as DTT, JT60-SA, Wendelstein 7-X, etc. The final goal is the construction of DEMO represented in Fig. 1.4c, which will prove the technological feasibility of fusion energy directly producing electrical power for the grid.

¹ITER: International Thermonuclear Experimental Reactor - <https://www.iter.org/>

²DEMO: DEMOnstration fusion power plant - <https://euro-fusion.org/programme/demo/>

The atom is the basic structure in which matter is organized and it is the fundamental units which constitute the chemical elements. Every atom is composed of a nucleus and one or more electrons¹ bound to the nucleus. The nucleus is made of one or more protons² and a number of neutrons³ hold together by the nuclear force. The characteristics of atomic elements can be found in [39]. The atom nucleus is characterized by a mass less than the sum of the masses of sub atomic elements that compose the nucleus itself. This gap of mass Δm is directly related to the binding energy with the Einstein formula $E = \Delta mc^2$. The controlled process in which two light nuclei are fused together, generating a heavier nucleus, with the aim of producing energy as consequence of this gap of mass is the Fusion reaction.

2.1 Binding energy

The key concept behind the release of energy in fusion (and fission) reactions is the binding energy, which is the energy released when a nucleus is formed from protons and neutrons, or vice versa the energy released when an nucleus is split into two (or more) lighter nuclei. Fig. 2.1a shows the binding energy, expressed in MeV⁴, as function of the atomic mass number. The maximum of the curve is in correspondence of the iron (Fe), with a mass number of 56, and it is a threshold that separates the two fields on nuclear energy: fusion and fission (see Fig. 2.1b). The reactions of nuclear fission consist of the subdivision of a heavy nucleus (mass number > 56) into two or more lighter nuclei and fragments, instead fusion is the opposite process in which two light nuclei are fused together generating a heavier nucleus.

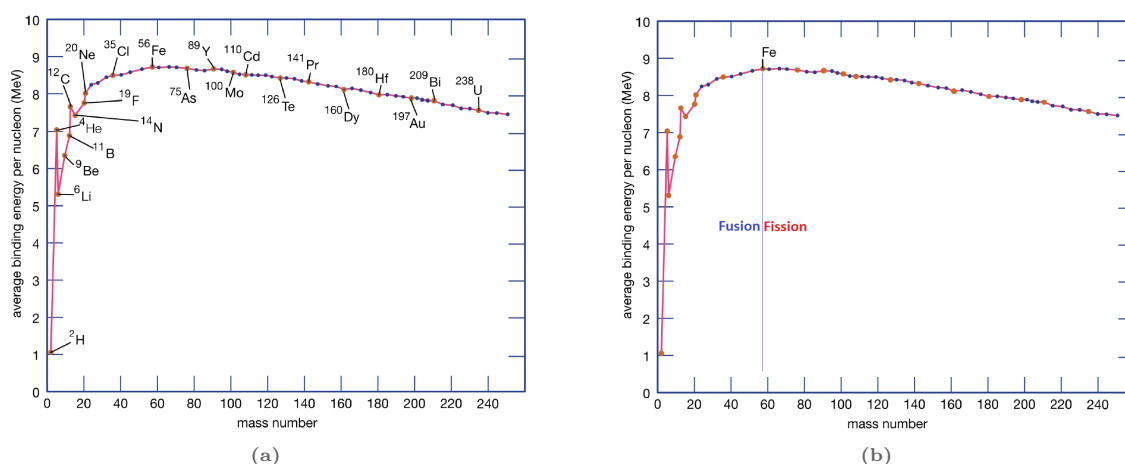


Fig. 2.1: Elements binding energy: (a) binding energy as function of the atomic mass; (b) nuclear binding subdivided in fusion and fission reaction

¹**Electron:** stable subatomic particle with a negative charge $-e$ of $-1.6 \cdot 10^{-19}$ C and a mass of $9.11 \cdot 10^{-31}$ kg

²**Proton:** stable subatomic particle that has a positive charge equal in magnitude to a unit of electron charge ($+e$) and a rest mass of $1.67 \cdot 10^{-27}$ kg

³**Neutron:** subatomic particle with neutral charge and a mass slightly greater than that of a proton

⁴**eV:** electron-volts is a unit of energy obtained multiply the value of an electron charge ($1.6 \cdot 10^{-19}$ C) for 1 V. As consequence of this $1 \text{ eV} = 1.6 \cdot 10^{-19} \text{ J}$. Electron-volts is also used to describe the temperature because they are related by the Boltzmann constant k ($1.38 \cdot 10^{-23} \text{ J/K}$) as $T(\text{eV}) = k \cdot T(\text{K})/e$ where e is the electronic charge while $T(\text{K})$ and $T(\text{eV})$ are respectively the temperature in Kelvin and eV. It follows that $1 \text{ eV} = 11.604,5 \text{ K}$

2.2 Fusion reactions

With fusion is indicated the controlled process in which two light nuclei are fused together, generating a heavier nucleus, with production of energy. They occur naturally in the core of the stars because of the extremely high pressures generated by the gravitational confinement. It is a very slow process (due to the extremely small cross-section of the proton-proton fusion reaction) and it allows a small star like the Sun to live for several billion years [79].

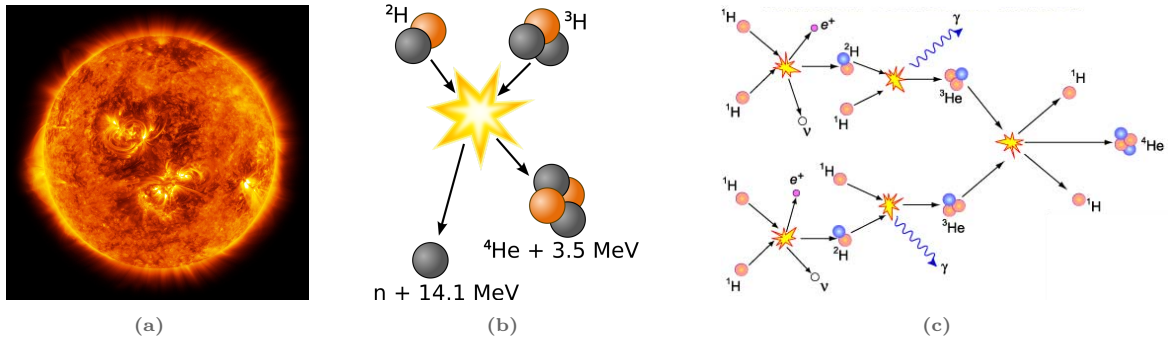
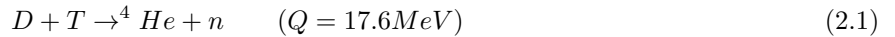
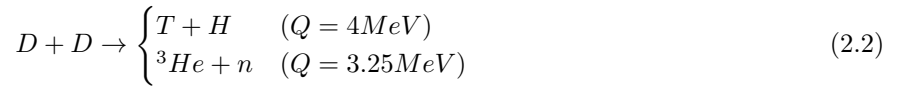


Fig. 2.2: Examples of fusion reaction: (a) Suggestive picture of the our sun powered by nuclear fusion; (b) Fusion reaction $^2\text{H} - ^3\text{H}$; (c) Dominant fusion reaction in stars

In the stars the dominant process begins from hydrogen nuclei (see Fig. 2.2c), which have only one protons and at the end of the fusion process the total energy released is $6 \cdot 10^8$ MJ per kg of hydrogen (60 million times the energy per kg available from chemical fuels). However, in a practical system the reactions could not proceed at the rate of those in the stars, where this process results extremely slow taking million of years. This problem is solved by starting with deuterium⁵, either alone or in a mixture with the heavier hydrogen isotope tritium⁶, like in the example reported in Fig. 2.2b. This fusion reaction can be expressed in the way reported in (2.1).



where D indicates the deuterium and T the tritium. From the reaction (2.1) 17.6 MeV of energy is produced. Others promising fusion reactions are the ones reported in (2.2) and (2.3) [98].



In order for a fusion reaction to occur, the two nuclei must have enough energy to overcome the repulsive Coulomb force acting between them and approach each other sufficiently close so that the short-range attractive nuclear force becomes dominant. To achieve this condition, the fusion fuel must be heated to temperatures exceeding 10^7 K. At such temperature the gas exists as a microscopically neutral collection of ions and unbound electrons which is called plasma [98]. In this thermonuclear condition the likelihood of a fusion reaction is expressed in terms of a cross-section of the particles. The fusion rate (cross section) as function of the plasma temperature for the main fusion reactions is reported in Fig. 2.3.

⁵**Deuterium:** is one of the stable isotopes of hydrogen and it is composed by one proton and one neutron (atomic mass of 3). Deuterium is frequently represented by the chemical symbol D but also ^2H can be used.

⁶**Tritium:** tritium is a rare and radioactive isotope of hydrogen. The nucleus of tritium contains one proton and two neutrons (atomic mass of 3). Tritium is frequently represented by the chemical symbol T but also ^3H can be used.

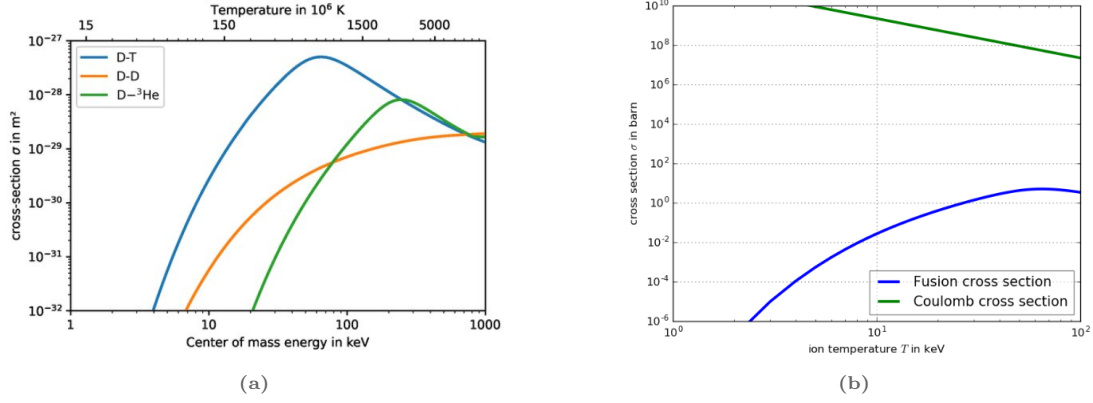


Fig. 2.3: Cross section of main fusion reaction: (a) cross section as function of the center of mass energy; (b) comparison between Coulomb scattering and deuterium-tritium fusion cross sections

Fig. 2.3 shows D-T fusion reactivity, blue line, is much greater than that for other potential fusion reactants. Following this evidence, the present plan for the first fusion reactor is, therefore, based on this kind of reaction [33]. Current experiments aim at the investigation of the Deuterium-Tritium fusion reaction, however, often use Deuterium only. This is because T is radioactive, whereas D is a stable isotope [79]. Like just said the fusion reaction takes place when two nuclei combine in a heavier nucleus. But this reaction occurs when the nuclei are very close such that the strong interaction dominates. For larger distances the electromagnetic interaction dominates and since both nuclei are positive there is a large repelling force that must be overcome. Even in terms of cross section, from Fig. 2.3b, it can be seen that the Coulomb scattering cross section is larger than the fusion cross-section so, in other words, the probability that two nuclei repel each other is greater than the probability that they fuse together [58]. So to overcome the electrostatic repulsion and come close enough to fuse the nuclei, it is required that the mixture of the reagent nuclei be heated to a temperature of the order of millions of K. When gases (hydrogen isotopes) reach this temperature an appreciable number of the gas atoms are ionized and a high temperature gaseous state is achieved, in which the charge numbers of ions and electrons are almost the same and charge neutrality is satisfied only on a macroscopic scale. The word *plasma* is used to designate this high temperature ionized gaseous state with charge neutrality and collective interaction between the charged particles and waves [69].

Methods of confinement

The gravitational confinement represents the natural way of confining plasma in stars. To achieve fusion on Earth, it is needed to maintain the fusion reactants to sufficiently high temperature and density, and also hold it confined for a sufficiently long time away from any surrounding material walls. In other words, it is necessary to reproduce the core stars environment. There are two different lines of research that try to deal with this problem. One is based on the rapid compression, and heating of a solid fuel pellet through the use of laser or particle beams. In this approach, the fusion reaction is obtained trying to reproduce the huge pressure on the nuclei stars. This approach is called inertial confinement fusion (ICF) and it is exposed in Sec. 3.2. The other approach, known as magnetic confinement (MCF), uses a magnetic field to confine the plasma. This second approach here is only introduced and it will be discussed in Sec. 3.3 with more details.

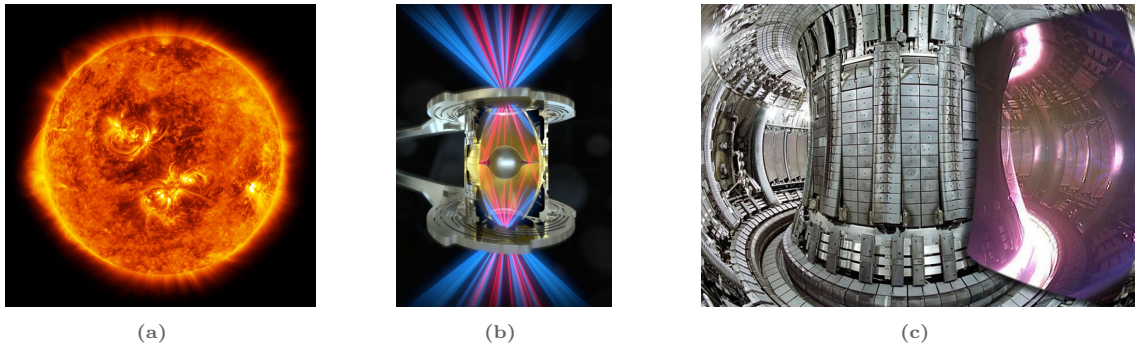


Fig. 3.1: Method of confinement: (a) suggestive picture of the our sun powered by nuclear fusion with gravitational confinement; (b) an artist's rendering shows NIF's 192 laser beams towards the fuel capsule that try to obtain the fusion by means of inertial confinement; (c) vacuum vessel of JET torus, a device based on magnetic confinement of plasma

3.1 Gravitation

The gravitational confinement represents the natural way in which the fusion energy is obtained in the cores of stars. A star is a massive celestial object, made up of plasma held together by its self-gravitational interaction. The celestial body life-cycle is ruled by the balance of gravitational force (generating the star collapse) and pressure force (generating the star expansion) sustained by the large amount of fusion reactions that power the star. The dominant process begins from hydrogen nuclei (Fig. 2.2c), which are simply protons, and it proceeds in three stages [108]:

1. In the first stage two protons fuse, releasing a positron¹ (violet ball in Fig. 2.2c) and forming a deuteron (pink ball in Fig. 2.2c).
2. This is an extremely slow process (point 1.), but once the deuteron is formed it lasts only a few seconds before a further proton is added to form the light isotope of helium (^3He).
3. The ^3He nuclei then wait about a million years before that two of them fuse to form ^4He with the release of two protons.

This sequence of fusion reactions illustrates the interplay of gravitational forces and nuclear processes that govern stellar evolution and energy generation.

¹**Positron:** the positron or antielectron is the antiparticle or the antimatter counterpart of the electron. It has an electric charge of +e, a spin of 1/2 (the same as the electron) and the same mass as an electron

3.2 Inertial confinement

The Inertial Confinement Fusion (ICF) is a method of achieving nuclear fusion by rapidly compressing and heating a small pellet of fusion fuel, typically a mixture of deuterium and tritium. If a pellet of solid fusion fuel is compressed to very high densities and a portion of it is heated to the temperatures required for ignition, it is possible to generate net fusion power before the pellet blows itself apart in a micro-explosion [58]. This is done by using a capsule consisting of a spherical shell filled with deuterium-tritium gas. The shell itself consists of a high-Z material at the outside and an inner region of D-T, which forms the bulk of the fuel [82] like can be seen in Fig. 3.2a.

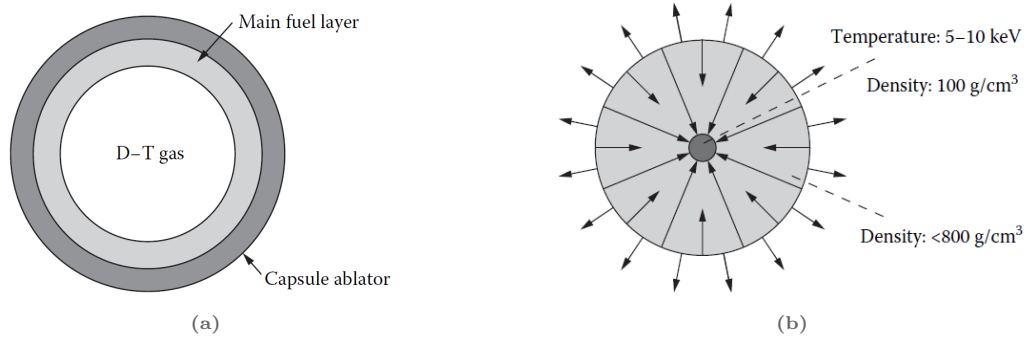


Fig. 3.2: Inertial confinement[82]: (a) Schematic picture of target capsule; (b) Schematic picture of implosion of the fuel capsule

On pellet fuel is applied an enormous burst of energy in a very short time. Because of this burst of energy the outer part of the target shell (dark gray in Fig. 3.2a) ionizes and vaporizes immediately. Due to this explosion, the fuel implodes toward the center of the capsule and compress the D-T gas to high densities and thermonuclear temperatures like schematized in Fig. 3.2b. The most relevant experiment in this field is the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (see Fig. 3.3a) which are developing a precision laser system now capable of delivering 1.8 MJ at 500 TW of 0.35 μ m light to a target. A primary goal of the NIF is to demonstrate fusion ignition and burn via inertial confinement fusion (ICF). The NIF approach to ignition utilizes indirect drive, wherein the DT filled capsule is placed inside a cylindrical cavity of a high-Z metal, see Fig. 3.3c), and the implosion drive (pressure) is provided by focusing laser energy onto the interior walls of the capsule [26]. All this process takes place inside an insulated chamber that is shown in Fig. 3.3b. A new record of energy production in NIF was reached in December 2023, when the facility focused 2.05 MJ of laser light on the fuel producing 3.15 MJ of energy. This was the first laser-driven fusion demonstration in which the reaction produced more energy than the laser light used to start it [110].

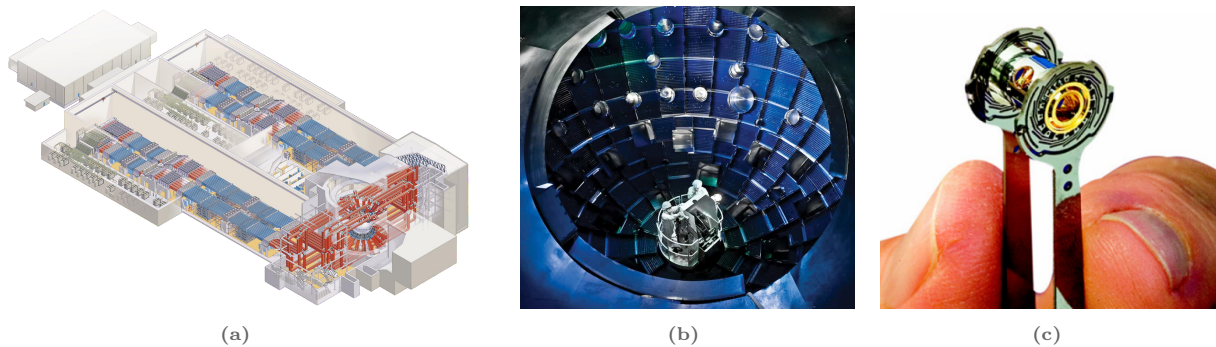


Fig. 3.3: NIF facilities [71]: (a) floor plan of the experiment building; (b) insulated chamber for the test; (c) picture of fuel capsule

3.3 Magnetic confinement

The second line of research seeks to achieve fusion by confining plasma through the generation of a controlled magnetic field. The idea at the basis of magnetic confinement is that no material surface is able to support direct contact with the high temperature plasma, so a magnetic field is generated in order to maintain the plasma away from the reactor wall. Early 20th-century research identified fusion as a potential energy source, leading to various experimental approaches. In the 1950s, the tokamak design emerged in the Soviet Union, utilizing powerful magnetic fields to confine hot plasma. Today, it remains the most promising configuration for achieving energy production. In parallel to tokamak configuration, the stellarator had been developed employing

twisted magnetic fields to stabilize the plasma instabilities typical of tokamaks. In opposite approach the pinch was developed to try to confine the plasma thanks to magnetic fields self-generated within the plasma itself. Relevant in this approach is the reversed field pinch (RFP) concept, which involves reversing the magnetic field within the plasma to achieve the conditions needed for fusion. Also open/linear fusion experiments, such as magnetic mirror machines, in which the plasma is reflected from a high-end-density to a low-end-density magnetic field, has been explored to test alternative confinement methods [8].

3.3.1 Tokamak

A charged particle q in movement with a speed $\mathbf{v}$ inside a uniform magnetic field $\mathbf{B}$ experiences the Lorentz force, which bounds the particle to the field lines. According to the Lorentz force, expressed as $\mathbf{F} = q\mathbf{v} \times \mathbf{B}$, a charged particle can move freely in the direction parallel to the field ($\mathbf{v} \parallel \mathbf{B}$); however, in the transverse direction the Lorentz forces confine the particle into a circular orbit [107]. Under these conditions, a particle with initial velocity will start to rotate around the field line defining a spiral or helical path. The radius of this transverse motion is known as the Larmor radius, typically indicated with ρ , and it depends on the charge, mass, and velocity of the particle as well as the strength of the magnetic field $\mathbf{B}$ [64]. In Fig. 3.4a the movement of an generic ion and an electron, along a linear magnetic field line, is illustrated [75].

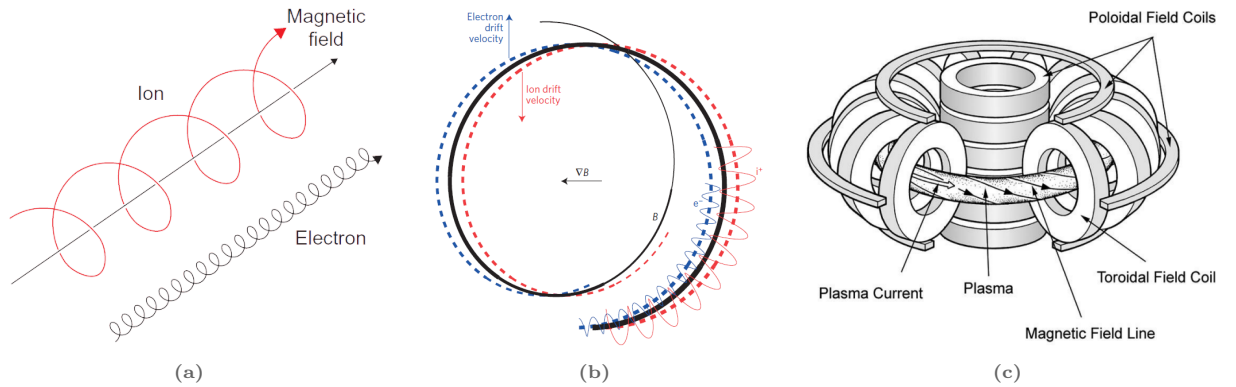


Fig. 3.4: Physics of tokamaks: (a) schematization of an ion and an electron rotating around a magnetic line of view [64]; (b) trajectory of charged particles in the non-uniform typical tokamak magnetic field; (c) overview of a generic tokamak configuration

By configuring a magnetic field, the plasma can be confined within a designated space, preventing contact with the chamber wall. This enables the maintenance of the thermonuclear temperature required to initiate the fusion reaction [44]. The magnetic field in a tokamak is obtained combining two main fields: the toroidal magnetic field, typically indicated with $\mathbf{B}_\phi$ and the poloidal one, $\mathbf{B}_\theta$. The toroidal magnetic field is generated by a series of magnetic coils that encircle the tokamak vacuum vessel, running along its circular path. On the other hand, the poloidal magnetic field is produced by a current driven through the plasma itself, which generates a field perpendicular to the toroidal one. The combination of these two fields results in a helical magnetic field structure that effectively confines the plasma away from the walls of the vacuum vessel [108]. An example of the particle orbit is reported in Fig. 3.4b while Fig. 3.4c shows a schematization of a tokamak structure.

3.3.2 Stellarator

The stability of the plasma is a critical challenge in tokamak operation. Various instabilities can cause the plasma to lose confinement, potentially damaging the tokamak. To control these instabilities, the stellarator configuration was proposed in the 1950's by [97] and nowadays is one of the goals of the Eurofusion roadmap like can be seen in Fig. 1.4a. The goal of the stellarator is to obtain the plasma performance of advanced tokamaks without the issues associated with driving the plasma current and disruptive plasma phenomena. The main characteristic of this device is the absence of a significant plasma current and the presence of specially designed magnetic field coils able to generate both the components of the field (poloidal and toroidal components). The absence of the current prevents the development of current driven instabilities and makes the stellarator intrinsically capable to sustain a plasma steady-state. On the other hand the overall experiment design becomes engineeringly more complicated because of the magnetic field coils and the massive use of additional heating systems, necessary to compensate the absence of ohmic heating [13].

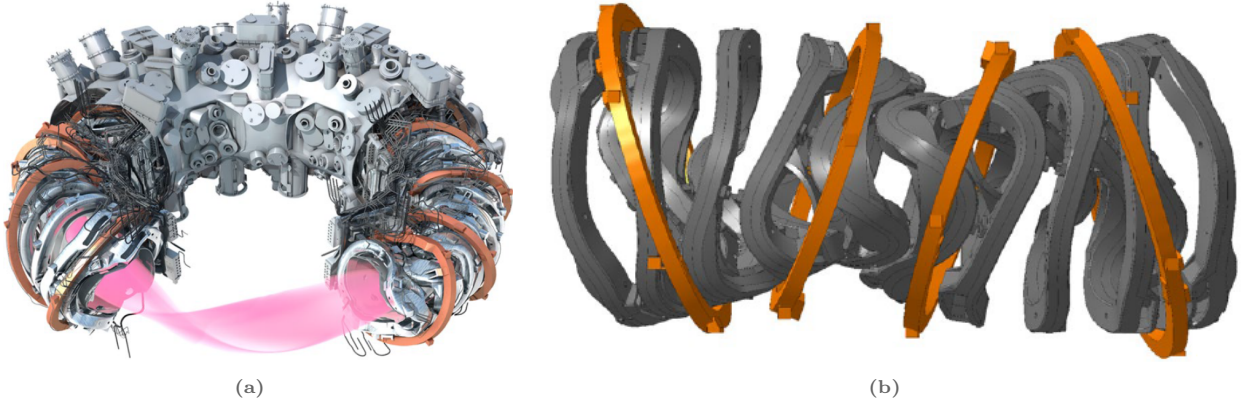


Fig. 3.5: Outline of Wendelstein 7-X and its magnet system[25]: (a) Schematic CAD drawing; (b) Arrangement of the non-planar, modular coils (in dark grey) and planar coils in orange

The largest stellarator operating devices are: the Large Helical Device (LHD) in Japan [50] and the Wendelstein 7-X (W7-X) in Germany [59]. In Fig. 3.5 an overview of W7-X is reported also with a details of the complex coils.

3.3.3 RFP

As an alternative magnetic configuration device, the Reversed Field Pinch (RFP) is a device designed to achieve the conditions necessary for nuclear fusion reactions by reversing the direction of the magnetic field within the plasma itself enhancing plasma stability. In an RFP, the magnetic field lines twist in a helical pattern, with the toroidal magnetic field (running along the circumference of the device) reversing direction near the edge of the plasma. This reversal is achieved through the self-organization of the plasma, driven by the currents within it.

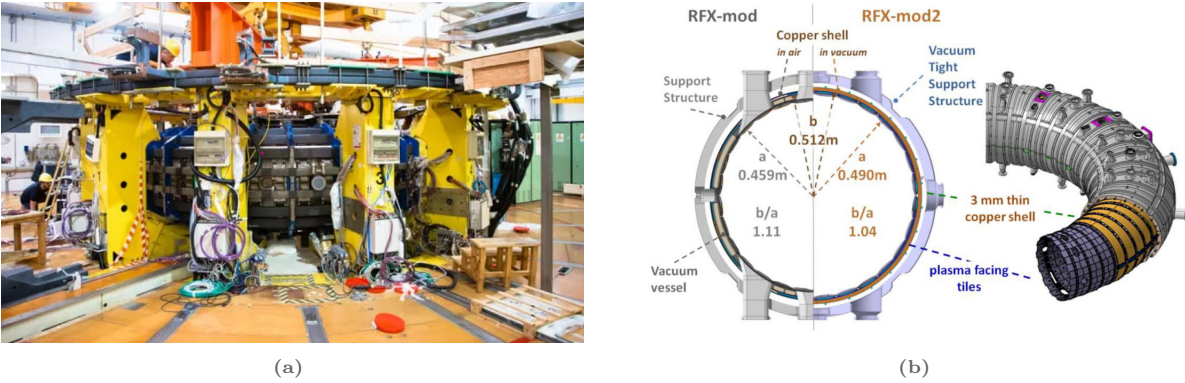


Fig. 3.6: Reverse Field pinch eXperiment (RFX): (a) pic of the experiment, (b) schematization of the last updated from RFX mod to RFX mod2.

The RFX-mod (Reversed Field Experiment) is one of the most advanced RFP experiments in the world, located in Padua, Italy [96]. The RFX-mod experiment is designed to explore and enhance the understanding of plasma behavior in an RFP configuration. It aims to investigate the stability and confinement properties of the plasma, addressing key challenges such as magnetic turbulence and relaxation events that can lead to the loss of confinement. Currently it is under updating to a new version, called RFX-mod 2, which aims to improve machine performance reducing the ratio between the vessel and plasma radius [16].

This work is dedicated to mechanical aspects of the new Italian project DTT which aims to investigate alternative power dissipation solutions in perspective of DEMO and to JT60-SA currently operating in Japan to be a support for ITER by following a complementary research and development programme. To better understand the work exposed in the following parts, this section has been dedicated to give an overview of these facilities. In particular Sec. 4.1 introduces the DTT experiment while Sec. 4.2 is dedicated to JT60-SA.

4.1 DTT

One of the main effort of fusion community is focused to develop a heat and power exhaust system able to withstand the large loads expected in the divertor of DEMO. Indeed, the power released by the nuclear fusion reactions of deuterium and tritium in the plasma will be in part spread over the so-called blanket that surrounds the plasma, in part will be directed towards the divertor. Furthermore, the divertor must fulfill other critical functions: nuclear shielding, channeling of exhaust gas for pumping and assuring the structural integrity of the neutron-irradiated components [111]. In this context a new Italian facility, called Divertor Tokamak Test (DTT), has been proposed [3].

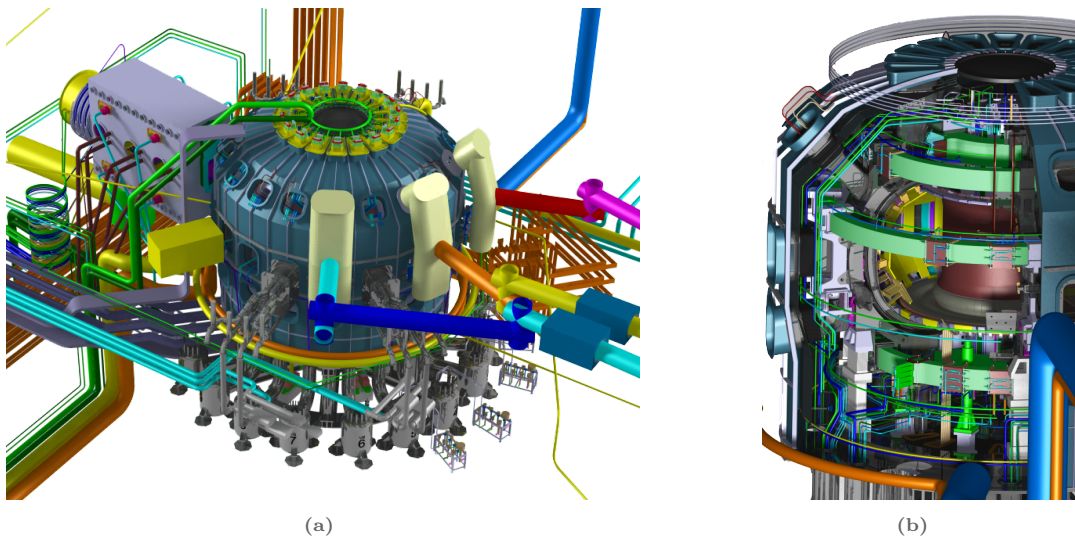


Fig. 4.1: Overview Divertor Tokamak Test (DTT) facility: (a) Render of the tokamak; (b) open view of the cryostat and vessel

In Fig. 4.1 an overview of the DTT is given. More mechanical details will be given in Part II. DTT is a fully superconducting tokamak characterized by 5.85 T on-axis of maximum toroidal magnetic field, which aims to carrying plasma current up to 5.5 MA. It is designed to work in pulses with total duration up to 100 s each one. The D-shaped vacuum chamber is able to host a plasma with major radius $R=2.19$ m, minor radius $a=0.70$ m and average triangularity of 0.3 [89].

Tab. 4.1 summarizes the main parameter of DTT. The heating power is subdivided in 28.8MW by ECRH, 9.5 MW by NBI and 6.7 by ICRH, for a total heating power of 45 MW.

Table 4.1: DTT main parameters [22]

Plasma current	5.5 MA
Toroidal field	5.85 T
Major radius	2.19 m
Minor radius	0.70 m
Plasma volume	35 m ³
Elongation	1.78
Triangularity	0.45
Aspect ratio	3.1
Flattop Duration	100 s
Heating and CD power	45 MW

4.2 JT60-SA

JT-60SA is a superconducting tokamak developed under the Satellite Tokamak Program, part of the Broader Approach Agreement between the EU and Japan, and in conjunction with the Japanese national program [102]. Its scientific aim is to contribute to the early realization of fusion energy by supporting the ITER project and future DEMO devices, addressing key engineering and physical issues for advanced plasma operation. It was developed with a medium-sized design as an update to the JT-60U experiment, reusing its infrastructure. JT-60SA is currently undergoing commissioning in Naka, Ibaraki, Japan, at the QST¹ site. The JT-60SA plasma features a major radius of 2.96 m, minor radius of 1.18 m and typical values for elongation and triangularity within the range of 1.9 and 0.5 for the design basis scenarios. The inductive current is expected to reach up to 5.5 MA, to support the primary focus of the device, which is to extend the pulse length towards a steady state, with a target duration of approximately 100 seconds. One notable strength of JT-60SA is its robust heating system, featuring 34 MW of neutral beam (NB) and 7 MW of electron cyclotron (EC) installations. The main parameters of the tokamak are summarized in Tab. 4.2.

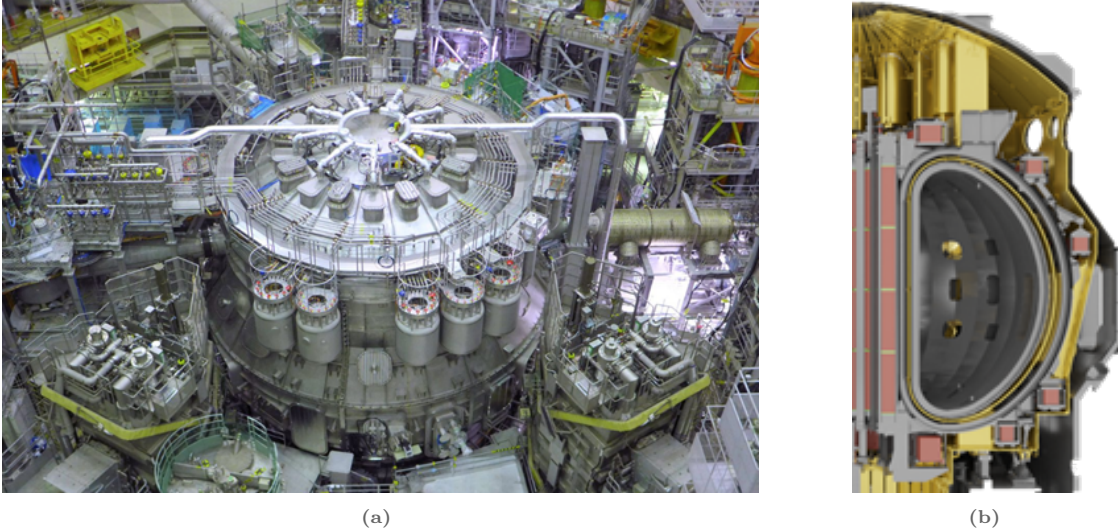


Fig. 4.2: Overview JT-60SA facility: (a) Picture of the tokamak; (b) open view of the cryostat and vessel

At the beginning JT-60SA will operate with carbon wall and will explore the ITER and DEMO plasma regimes with the primary mission of achieving high- β steady state operations. The later stages of the project will involve a complete replacement of the divertor target and of the first wall with tungsten-coated carbon [18][102]. In Fig. 4.3 the drawing and the manufactured divertor cassette can be seen.

¹QST: Japanese National Institutes for Quantum and Radiological Science and Technology - URL: <https://www.qst.go.jp/site/qst-english/>

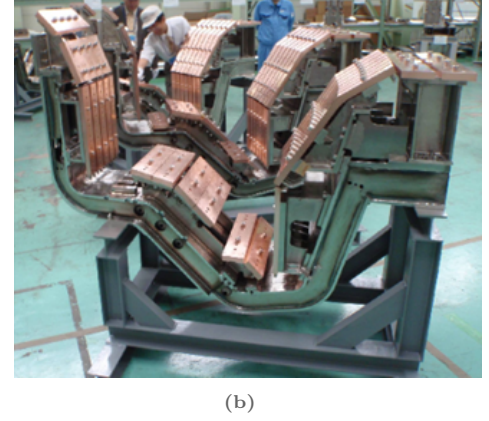
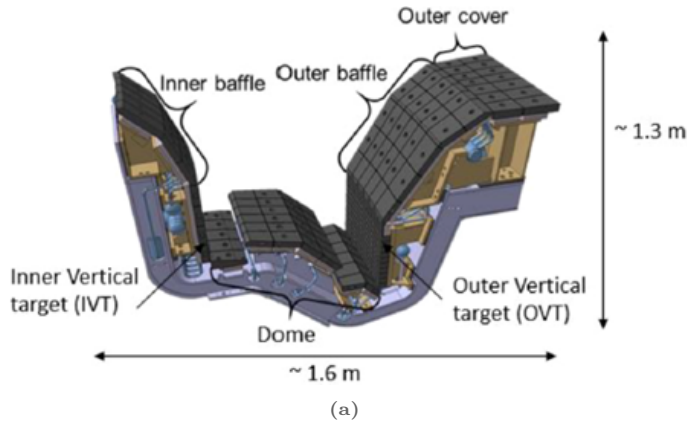


Fig. 4.3: Overview JT-60SA divertor cassette: (a) drawing of the cassette [18] ; (b) picture of the manufactured divertor

The first plasma of JT60-SA was achieved in 23 October 2023 with a plasma current of 130 kA. In early November a diverted plasma configuration was produced. During the Inauguration Ceremony on 01 December 2023 a divertor plasma with 1 MA of current was demonstrated (from QST website URL:<https://www.jt60sa.org/wp/1-ma-plasma-current/>).

Table 4.2: JT-60SA main parameters [102]

Plasma current	5.5 MA
Toroidal field	2.25 T
Major radius	2.96 m
Minor radius	1.18 m
Plasma volume	133 ³
Elongation	1.95
Triangularity	0.53
Aspect ratio	2.5
Shape parameter	6.7
Flattop Duration	100 s
Heating and CD power	41 MW

Part II

Visible Spectrometer system for DTT

The project of the Visible Spectroscopy diagnostics for the Z_{eff} radial profile measurement and for the divertor visible imaging spectroscopy, designed for the new tokamak DTT (Divertor Tokamak Test), is presented. To deal with the geometrical constraints of DTT and to minimize the diagnostics volume inside the access port, an integrated and compact solution hosting the two systems has been proposed. The Z_{eff} radial profile will be evaluated from the Bremsstrahlung radiation measurement in the visible spectral range, acquiring light along ten Lines of Sight (LoS) in the upper part of the poloidal plane. The plasma emission will be focused on optical fibers, which will carry it to the spectroscopy laboratory. A second equipment, with a single toroidal LoS crossing the plasma centre and laying on the equatorial plane, will measure the average Z_{eff} on a longer path, minimizing the incidental continuum spectrum contaminations by lines/bands emitted from the plasma edge. An overview of the boundary condition and on the installation are given in Sec. 5 while the effective charge profile system design is explored in depth in Sec. 6. On the other hand, the divertor imaging system is designed to measure impurity and main gas influxes, to monitor the plasma position and kinetics of impurities, and to follow the plasma detachment evolution. The project aims at obtaining the maximum coverage of the divertor region. The collected light can be shared among different spectrometers and interferential filter devices placed outside the torus hall to easily change their setup. The system is composed of two telescopes, an upper and a lower one, allowing both a perpendicular and a tangential view of the divertor. The design is presented in Sec. 7.

Overview of the system

5.1 Overview

In the roadmap of the European program toward nuclear fusion [31], one of the most critical challenges is the design of an adequate power exhaust solution that can work in the harsh environment of the Demonstration Fusion Power Plant (DEMO). Within this context, the new Italian project DTT (Divertor Tokamak Test) [3], which is under construction at the ENEA Frascati research center, near Rome, aims to explore alternative divertor solutions and to optimize the configuration foreseen for DEMO. To fulfill this scientific objective the device will be equipped with a dedicated set of diagnostics for the study of the edge and divertor regions, focusing on the measurement of impurity level, thermal characterization, plasma detachment and power exhaust [2]. In line with these goals, during the initial plasma operation, DTT will feature a first group of machine and plasma diagnostics, the so-called DAY0 systems [83], which include the spectroscopy diagnostics presented in this work. The presented Visible Spectroscopy diagnostic serves as a versatile and multi-purpose tool for characterizing various aspects of tokamak operation, encompassing detachment states, plasma position, impurity kinetics, and main gas behaviour. The system integrates a double divertor visible spectrometer, named Divertor Imaging system (DIS), and an effective charge (Z_{eff}) radial profile setup.

5.1.1 Z_{eff}

Another important application of the diagnostic is the measurement of Bremsstrahlung radiation¹, aimed at evaluating the effective charge Z_{eff} . This assessment is crucial to understand and possibly control the impurity behavior within the plasma, since impurity accumulation can lead to radiative losses, radiative collapse, enhanced plasma resistance and fuel dilution. The Z_{eff} measurement technique, which exploits Bremsstrahlung emission in a wavelength region free from spectral lines, is a widely used approach. It was tested for the first time in JIPP T-II [57], and now employed in main fusion machine such as EAST [19], K-STAR [91], TEXTOR [104], W-7X [78], JET and ASDEX [66]. This passive spectroscopy system has been chosen for DTT for its simplicity, robustness, versatility and independence by the ion species. During the second phase of DTT (DAY2), it will be supported by a Charge Exchange Recombination system devoted to the ion temperature evaluation and measurement of the fully stripped population of injected gasses [14]. In this project the emitted light from plasma is directed to the telescope outside the cryostat with an optic relay composed by two mirrors for each LoS located inside the port, and then conveyed to the laboratory via fiber optics. Narrow band Interference filters (1 nm) at a proper line-free wavelength in the visible range and photomultiplier detectors are foreseen to assure high time resolutions (in the order of 100 kHz).

5.1.2 Divertor imaging system

To monitor the plasma-facing component (PFC) in the divertor and identify the source of impurities from that region, multi lines of sight (LoS) observing systems may be used, as in WEST [68] and EAST [62], or imaging setups, such as in Wendelstein 7-X [109], JET and ITER [45]. Following this last approach, a double imaging system based on the JET solution is adopted, complying with the stringent DTT spatial constrain. A key feature of this divertor spectroscopy diagnostic revolves around studying high quantum number states of the Balmer series of deuterium. This enables the evaluation of electron density, temperature, and neutral deuterium density in the cold region near the divertor [1][100]. The optical layout consists in two identical heads that host two in-vacuum mirrors. The aim is to have both the tangential observation of the divertor (for detachment

¹Bremsstrahlung is electromagnetic radiation produced by the deceleration of a charged particle when deflected by another charged particle, typically an electron by an atomic nucleus

evolution monitoring) and the vertical observation of it (for throat observation). The light from the vessel will be directed to the laboratory to be shared among a multispectral imaging system [80], high and low-resolution spectrometers and interference filters. The detailed configuration of the laboratory set-up is not yet defined, but during the DAY0 operation (first machine start-up) it is foreseen to set the multispectral imaging system and a couple of High-Resolution spectrometers in the torus hall, close to the vessel.

5.2 DTT vessel ports

DTT is a tokamak device with a D-shaped cross section characterized by a major radius of 2.19 m and a minor radius of 0.7 m [3]. In order to be ITER and DEMO relevant it will be equipped with fully metallic first wall made of tungsten. The vacuum vessel contains the plasma, which can be observed through five ports (for each sector), as depicted in Fig. 5.1a. The ports are numbered from top to bottom. The device has a toroidal shape divided into 18 sectors each spanning 20° . The first part of the diagnostic project involved selecting the optimal sector and port for installing the system. The details regarding the port selection analysis will be presented in Sec. 6 for the Z_{eff} and in Sec. 7 for the DIS.

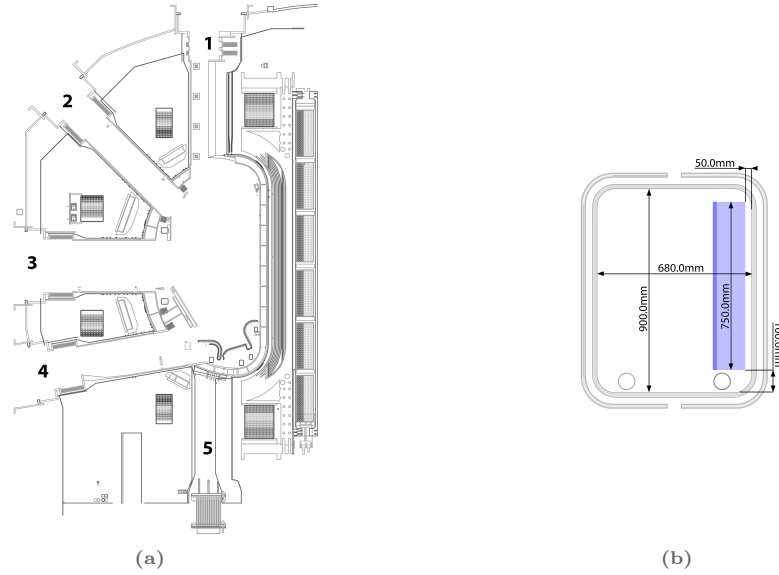


Fig. 5.1: DTT vessel duct: (a) poloidal cross section of DTT with the duct numbered; (b) equatorial port (indicate as Port 3) cross section.

After examination, it was determined that the optimal location for installation is the equatorial port 3 in sector 3. The equatorial position is one of the most desired locations for many diagnostics, and the large number of equatorial ports allocated heating devices makes the integration of diagnostics challenging. Therefore, a study was conducted to explore the available space and developing a solution to coexist with other systems. The port features a rectangular shape with a height of 900 mm, a width of 680 mm, and a length of about 2500 mm from the cryostat to the vessel. The presence of cooling pipes for the plasma-facing components requires a 100 mm free space at the bottom of the port. The entire diagnostic assembly should be installable from the outside of the cryostat as a plug-in module. To ensure a secure installation and to prevent any potential impact between the diagnostic equipment and the port wall during installation procedure and during possible vibrations, a distance of 50 mm is assumed from the side wall and from the top. In Fig. 5.1b, a schematic representation of the equatorial port is presented, the light purple area highlights the area available for the diagnostics, while the dark purple area schematizes the interface chassis available for other diagnostic systems. The disposition is chosen by considering the current configuration of the tungsten limiter tiles, which serves as initial PFC of the inner first wall during the plasma ramp-up. The inner first wall, positioned centrally within the torus and facing the ports (referred to as the High Field Side, HFS, due to the highest magnetic field magnitude), is equally subdivided into limiter and vessel sections. The Z_{eff} system requires the use of dumps, not compatible with the limiter, to minimize reflections from the first wall which can overlap the Bremsstrahlung brightness altering the measurement. Therefore, the diagnostic must be arranged ensuring that the Z_{eff} line of sight footprints on the HFS wall are in positions allowing the installation of dumps, while remaining on the same poloidal plane. This is a key aspect to take into account in order to apply the assumption of toroidal symmetry for Z_{eff} evaluations that need density and temperature profile measurements on DTT [48] (the evaluation details and its correlation with the toroidal symmetry hypothesis are deepened in Sec. 6).

6.1 Physical principle

The measurement of the effective charge Z_{eff} is crucial to quantify impurities detrimental effects on energy confinement, dilution of the fusion fuel, plasma cooling and reduced fusion yield. Z_{eff} is defined as (6.1).

$$Z_{eff} = \frac{\sum_i n_i Z_i^2}{\sum_i n_i Z_i} \quad (6.1)$$

where i denotes the ion species of density n_i and charge Z_i . It can be derived from absolutely calibrated measurements of the continue emission of electrons due to collisions with ions in the plasma, known as Bremsstrahlung radiation. The measured Bremsstrahlung emissivity, in a line-free visible spectral region, is combined with the profiles of electron density n_e and temperature T_e , measured respectively by interferometer polarimeter [29] and Thomson scattering [73]. In the usual assumption of toroidal symmetry, if the recombination radiation can be neglected (good assumption in the visible spectral range), the LoS lies on a poloidal plane and T_e , n_e and Z_{eff} can be considered constant on a flux surface ρ , the Bremsstrahlung emissivity ϵ on the flux surface ρ at a wavelength $\lambda(\text{\AA})$ and time t can be written as (6.2).

$$\epsilon(\rho; t) = 1.89 \cdot 10^{-28} Z_{eff}(\rho; t) g_{ff} e^{-12400/(T_e(\rho; t)\lambda)} n_e(\rho; t)^2 \quad (6.2)$$

The free-free Gaunt factor g_{ff} in (6.2) is a multiplicative correction factor to the continuous emission that depends weakly from T_e , λ and Z_{eff} and can be calculated and used in the deconvolution [67] or approximated as $1.35 \cdot T_e^{0.15}$ [19][70]. In DTT, at DAY0, the emissivity will be measured along 10 LoS on the upper part of the poloidal plane (as much as possible avoiding the huge background emission from the divertor) by telescopes and interference filters centred at a specific wavelength λ with a well-defined spectral range $\Delta\lambda$. λ must be in a line-free spectral range, to measure only the Bremsstrahlung continuum, and typically it is set between 523 and 570 nm, to avoid recombination radiation and contamination from thermal radiation emitted by hot vessel components in the infrared spectral range. Narrow band interference filters (i.e. 1 nm) centered at 523 nm is used in KSTAR, JET and DIII-D, whereas on ASDEX, ALCATOR and FTU Z_{eff} is evaluated at 537 nm [91] and on EAST at 570 nm [19]. For DTT application, a wavelength of $523.5 \text{ nm} \pm 0.5 \text{ nm}$ is chosen [15] [17], to be confirmed by checking the line absence coupling the system with a spectrometer. In Fig. 6.1 the LoS, in green, cross the plasma and must hit the dump installed on the high field side first wall (FW-HFS). The mirrors installed in the port (behind the low field side first wall FW-LFS) convey the emission toward the telescope lenses mounted outside the cryostat. The lens focusses the light into a fiber that drive the emission to the lab.

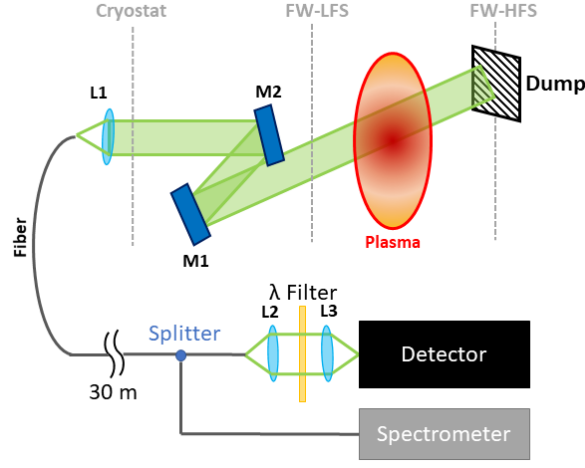


Fig. 6.1: Z_{eff} structure schematization

The local Bremsstrahlung emissivity and the Z_{eff} profile, once available the Te and ne profile, will be obtained with a generalized Abel inversion technique [20] that can be applied to elongated plasma such as those in DTT.

6.2 Assessment of positioning

The potential viewing options for the two systems were investigated to determine the optimal position in the ports. As already pointed out, the LoS disposition is selected to obtain a comprehensive scan of the plasma while avoiding the colder area in close proximity to the divertor where the molecular pseudo-continuum and lines emitted can contaminate the Bremsstrahlung spectrum and compromise the measurement. Therefore, the line of sight (LOS) should be positioned as far from the divertor as possible. Fig. 6.2 shows a series of possible configurations for each port, except for port 5, which is obstructed by the divertor.

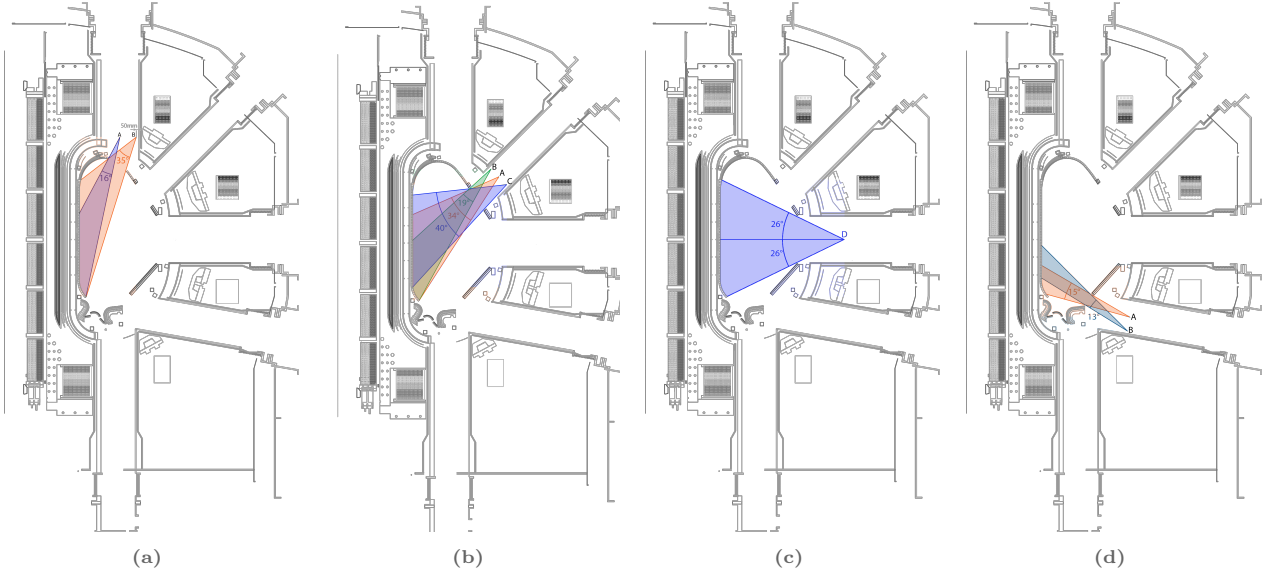


Fig. 6.2: Analysis of possible Z_{eff} profiles: (a) Port 1; (b) Port 2; (b) Port 3; (b) Port 4.

Fig. 6.2a shows that Port 1 covers only the high-field side of the plasma and captures data from a region very close to the divertor. A similar condition exists for Port 4, where the view passes through the area just above the divertor, as shown in Fig. 6.2d. In contrast, Port 3 and Port 2, illustrated in Fig. 6.2b and Fig. 6.2c, respectively, present more suitable configurations. However, Port 2 offers less flexibility due to its smaller aperture and the adjacent first wall (FW), which restricts the view of the plasma. Additionally, the view from Port 2 is closer to the divertor compared to Port 3, making the latter the best position for diagnostics. The aperture of the view from Port 3 can also be expanded by adjusting the position of the pinhole (point D in Fig. 6.2c). To improve the viewing angle, point D was repositioned to achieve 45° coverage, focusing exclusively on the upper side of the plasma (the area above the equatorial plane), as shown in Fig. 6.3a.

6.3 Poloidal effective charge profile

The emitted light from the plasma is directed to the telescope outside the cryostat with an optic relay composed by two mirrors for each line of sight located inside the port, and then conveyed to the laboratory via fibreoptics 30 m long (telescope described in Sec. 6.5). The mechanical structure of the system is designed to be flexible, enabling potential upgrades or modifications to the optics (installed outside the cryostat) that may become necessary following the initial period of DTT operations. The ten LoS will cover the upper part of the vacuum vessel as shown in Fig. 6.3a. These lines span a range of 45° starting from the equatorial plane of the machine. Each line of sight is spaced 5° from the previous one. As already pointed out, the LoS disposition is selected to obtain a comprehensive scan of the plasma while avoiding the colder area in close proximity to the divertor where the molecular pseudo-continuum and lines emitted can contaminate the Bremsstrahlung spectrum and compromise the measurement

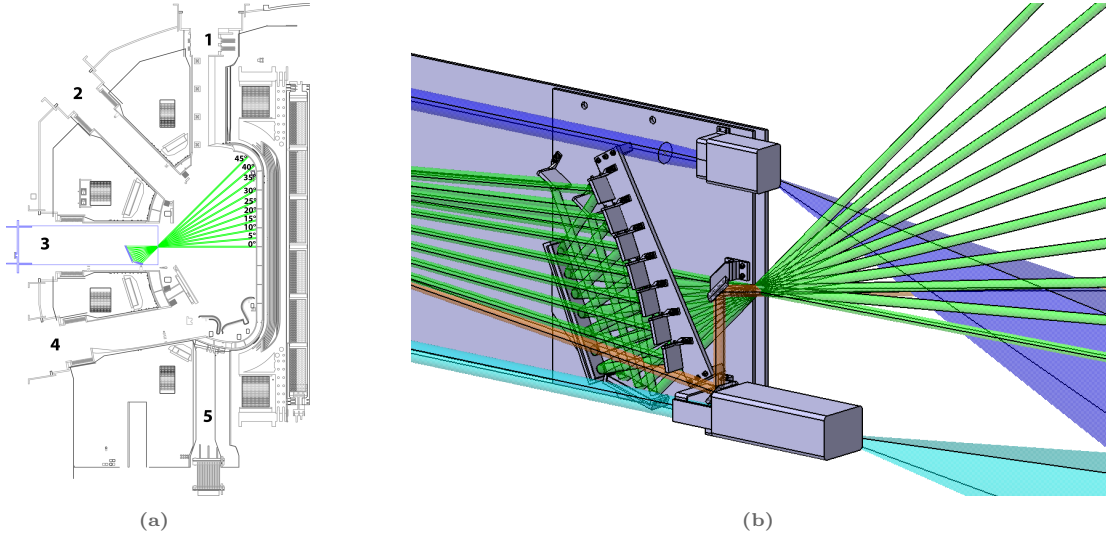


Fig. 6.3: Poloidal effective charge profile configuration: (a) cross section with highlighted in green the LoSs; (b) mechanical configuration

The harsh environment expected in DTT makes impractical to place windows close to the plasma, they must be placed on the cryostat. An in-vessel mirror setup has been chosen to address the limited view angle of the plasma, as the window on the cryostat offers only a restricted perspective due to the small ratio between the section and duct length. Moreover, telescopes cannot be placed in vessel because their optical properties would rapidly degrade due to the intense plasma emission. To minimize the needed space a design with two large flat mirrors that divide the LoS into two different planes is selected. The first large flat mirror handles seven lines, covering the angle range from 0° to 30° , redirecting them towards a shelf where smaller flat mirrors for each LoS are installed. The second large mirror manages the lines at 35° , 40° and 45° , directing them towards their respective smaller flat mirrors located below the shelf. In Fig. 6.1, these two mirrors are schematized with M1 and the second, smaller one, as M2. This approach minimizes the space occupied by the initial two large mirrors while allowing for precise control of each LoS using the smaller mirrors. Since the hardware is not in the centre of the duct, the optical relay has to adjust the tilt of the LoS in order to have the Z_{eff} LoS in a poloidal plane. In more detail, the LoS plane must be tilted at an angle of 1.4° relative to the port axis to remain on a poloidal plane, for accurately reconstructing the magnetic surfaces intersected by the line of sight. This configuration can be observed in Fig. 6.4, where the angle between the green line (representing the poloidal Z_{eff} LoS) and the chassis, which is parallel to the port axis, is visible. As a precaution, all mirrors have dimensions exceeding the expected footprint of the line of sight by a factor greater than 2. The smaller mirrors are square-shaped, measuring 60×60 mm, while the larger ones are longer, at 340 and 140 mm respectively, but still maintain a width of 60 mm. The expected footprint corresponds to a circular area with a diameter of approximately 25 mm. The selection of the mirror dimensions aims at facilitating alignment by allowing movements of the telescopes outside the cryostat, while keeping the mirrors as fixed as possible. The telescopes (schematized with single lens L1 in Fig. 6.1) will be in air and installed on a remotely movable support for a facilitated maintenance and easy alignment control.

6.4 Toroidal effective charge line of sight

A further line of sight (the 11th) on the equatorial plane integrates the described poloidal setup. This line crosses the centre of the plasma along a longer path to minimize the potential contamination of Bremsstrahlung

emission by lines/molecular bands at the plasma edge. This approach allows for a more robust assessment of the averaged Z_{eff} . The system follows the same structure of the poloidal one, but with the utilization of the port wall as dump element to mitigate reflections.

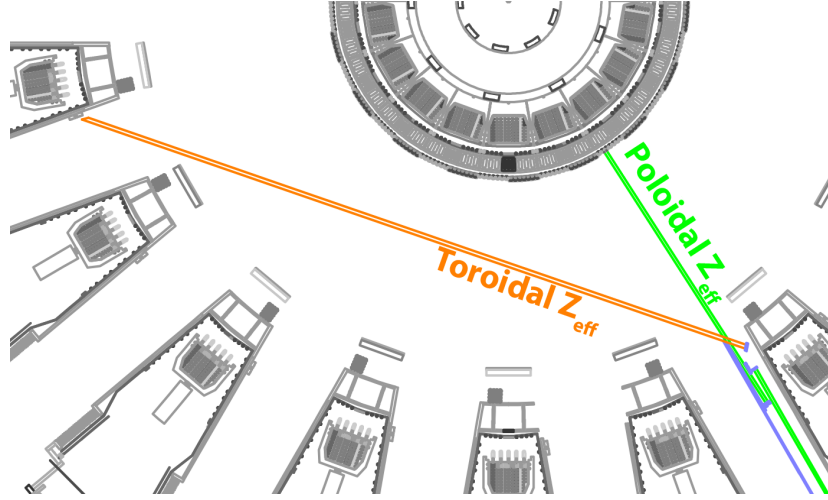


Fig. 6.4: Equatorial cross section. The central solenoid, the high field side first-wall (FW-HFS) and the different equatorial port of DTT are shown. In green the Z_{eff} poloidal LoS path from the equatorial port to the dump located in the FW-HFS. In orange the additional Z_{eff} toroidal LoS on the equatorial plane.

6.5 Laboratory set-up

Both system, poloidal (described in Sec. 6.3) and the toroidal one (in Sec. 6.4) are based on the same acquisition set-up. As a first hypothesis, at the telescope (one for each line of measure) the light is focused onto a fiber using a plano-convex lens with an optical diameter of 24.5 mm and a focal length of 75 mm, resulting in an F# of 3. The selected quartz fiber has an optical diameter of 1000 μm (F# of 1.3) and extends for approximately 30 m to transport the emission to the laboratory. Upon reaching the laboratory, a couple of lenses filter light using interference filters centred at $523.5 \text{ nm} \pm 0.5 \text{ nm}$ (see Sec. 6.3). A schematization of the structure can be seen in Fig. 6.1 where the green line represents the line of sight, the red circle the plasma and the black square the dump on the first wall.

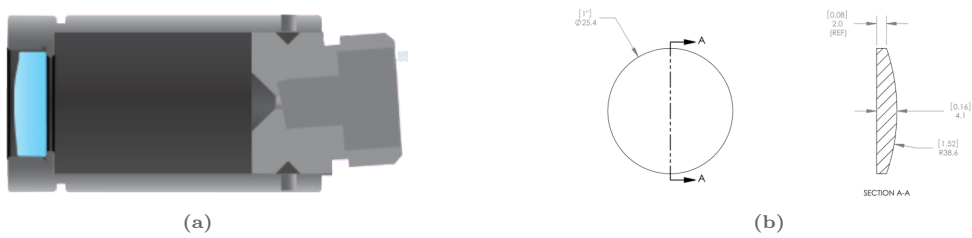


Fig. 6.5: Telescope for the Z_{eff} system: (a) schematization of a telescope; (b) lens.

The optical setup has been simulated using ray tracing with Optical Studio Zemax. As already mentioned in the previous section, the Z_{eff} system requires the use of dumps on the first wall high field side in order to minimize reflections from the wall itself which can overlap the Bremsstrahlung brightness altering the measurement. The optical setup was thoroughly analyzed using ray-tracing simulations in Optical Studio Zemax. As mentioned in the previous section, the Z_{eff} system requires the use of dumps on the high-field side of the first wall to minimize reflections that could interfere with Bremsstrahlung brightness, thus distorting the measurements. The dump will be implemented on a section of the first wall, not used as limiter, by machining it into a sawtooth profile. The wall will be machined to its full height with a width of 40 mm. To ensure a conservative design, the system was optimized with a simulated field of view of 25 mm, as shown in Fig. 6.6. Based on commercially available optical components, the characteristics outlined earlier and summarized in Tab. 6.1 were selected.

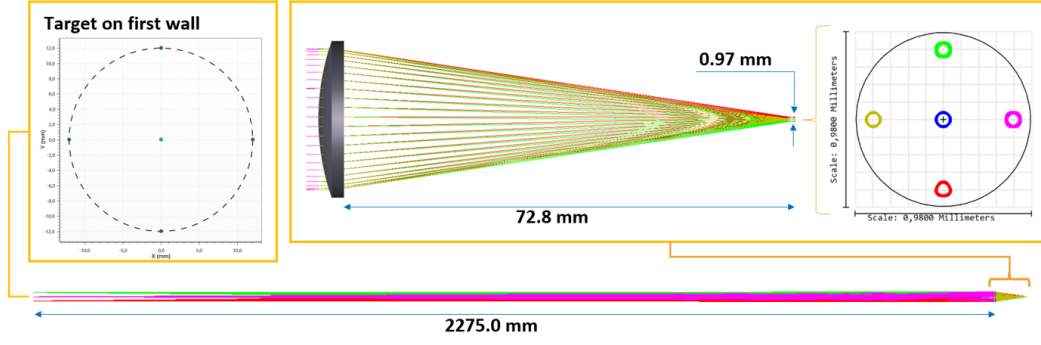


Fig. 6.6: Zemax simulation of the telescope lens

Telescope parameter	
Focal length [mm]	75.00
Optical diameter [mm]	24.50
F. number [1]	3.00
Numerical aperture [1]	0.17
Image height [mm]	0.98
Fiber distance [mm]	72.80
Fiber parameter	
Optical diameter [μm]	1000
Numerical aperture [1]	0.39
F. number [1]	1.28
Signal attenuation [dB/km]	18.00

Table 6.1: Z_{eff} acquisition system

A conservative assessment of light losses in the optical chain along the route to the laboratory gives an attenuation of about 50%, as explained in the following. A reflectivity of 95% might be assumed for the mirrors; along the optical fiber an attenuation around 18 dB/km, translates into a loss of about 12% over a 30 m distance. The windows on the cryostat will likely be commercial double glass in sapphire, with a transmittance about 90% at the wavelength of interest. The interference filter introduces a loss of 10% and the three lenses involved (one on the telescope and two after and before the filter) have a transmittance of approximately 90%. It is foreseen to split the signal between the filters for Z_{eff} (discussed above), spectrometers or other filters as in [68] or [62], to quantify the impurity presence in the upper region of the vessel. Fig. 6.7 shows the decrescent trend of the signal from plasma to the laboratory (the element on x-axis make reference to Fig. 6.1).

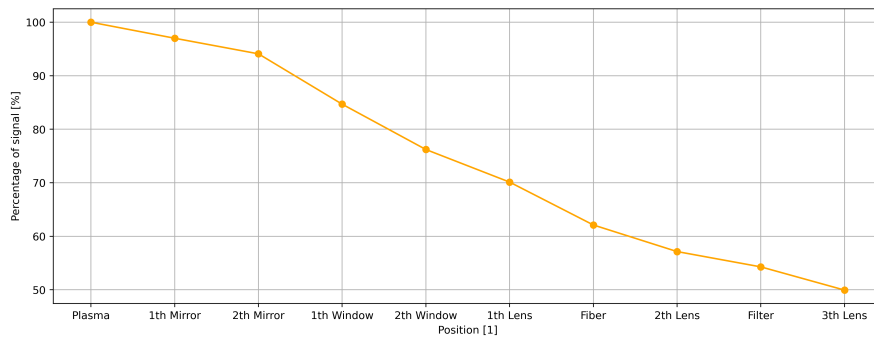


Fig. 6.7: Intensity losses along the optical chain of the Z_{eff} signal

Divertor imaging system

7.1 Physical principle

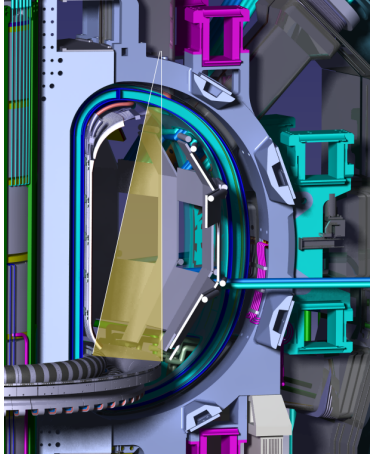
In the perspective of ITER and DEMO, DTT is designed with a complete tungsten first wall. The tungsten released from the divertor plate components and first wall can diffuse into the main plasma, leading to the degradation of its performance, and even cause it to disrupt. The high cooling factors of tungsten [85], resulting from its partial ionization within the confined plasma, remains significant even at temperatures relevant to a reactor, ranging from 10 to 20 keV [72]. For this reason, the new generation tokamak devices, characterized by metallic PFC, are now equipped with dedicated systems for the spectroscopic investigation of the tungsten distribution at the divertor region. This new diagnostic system, considering the strict constraints of the DTT vessel port, use the same approach adopted in JET and that will be repropose for ITER [45]. This divertor imaging system, called DIS, aims at measuring the impurity and main gas influx from the divertor plasma facing components and to spectroscopically investigate the divertor region to monitor detachment phenomena. The system is composed by two endoscopes that drive the visible light emission from the vacuum vessel toward the outside of the torus. The collected emissions will be investigated in the spectral region $\sim 350\text{--}800\text{ nm}$, in order to quantify the volume recombination, experimentally represented by the high quantum number state of the deuterium Balmer series behaviour (between 360 and 670 nm) [101][46]. The neutral Balmer series line ratios and the series limit recombination edge (at 364.5 nm) behaviors are connected to the ionization front movement and detachment onset/evolution/settlement. Moreover, those ratios allow the local deuterium neutral concentration and electron temperature and density evaluation [1] [46] [105] [61]. Being nitrogen foreseen to give rise to detachment in DTT for the DAY0 scenario, it is possible to follow N ions distribution [87] and to measure T_e and n_e from N-II/N-III line ratios [42]. Contiguous N-II, N-III and N-IV emission can be followed in the range 460–464 nm, and the strong N-IV triplet at $\sim 347\text{ nm}$ [87] is interesting if the optical elements will allow measurements at this low λ . Moreover, including W influx measurement among the mandatory measurement on DTT, it would be useful to detect the 364.1 nm W II emission line [84].

7.2 Assessment of positioning

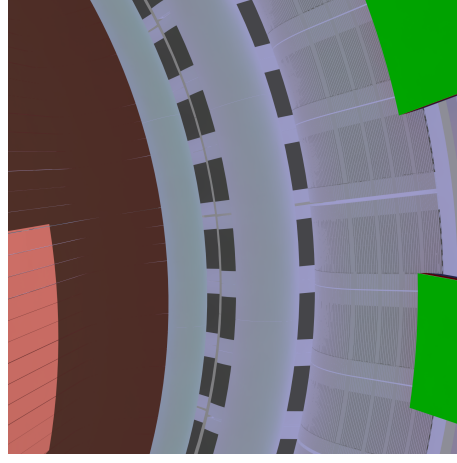
As done for the Z_{eff} diagnostic (Sec. 6.2), an analysis to select the correct position of the imaging system was carried out. Camera library ¹ from DS Catia V5 ² has been used to simulate the view of the divertor from different points on the vacuum vessel. Then each image obtained was compared with the cross section of the divertor to understand roughly which parts can be seen from every position. The view from port 5 is neglected because this port is completely closed by the divertor.

¹The camera tools enables you to specify a viewpoint from which a photorealistic image will be computed. The official document is reported here http://catiadoc.free.fr/online/cfyugrendering_C2/cfyugrenderingcreatecamera.htm

²Dassault System Catia V5: <https://www.3ds.com/it/prodotti-e-servizi/catia/>

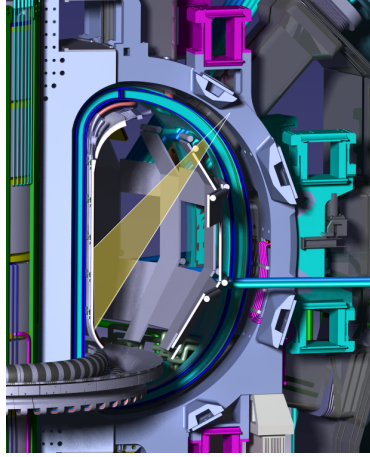


(a)

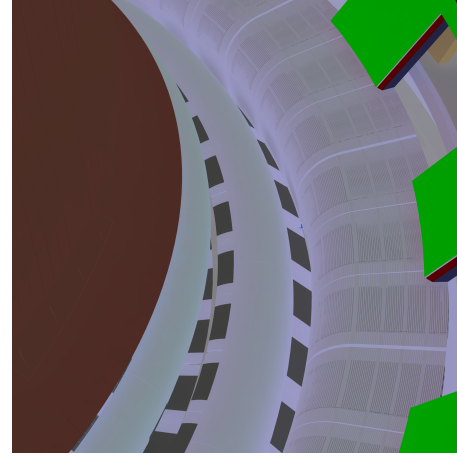


(b)

Fig. 7.1: Simulation of the possible view of the imaging spectroscopy system from port 1: (a) field of view; (b) image simulated.

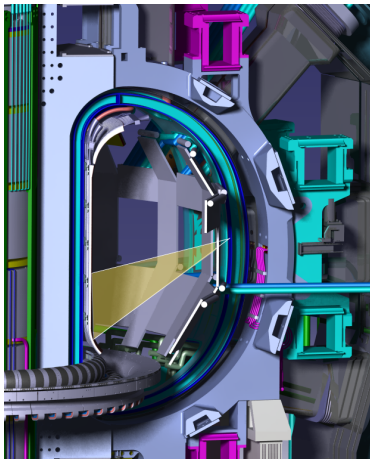


(a)

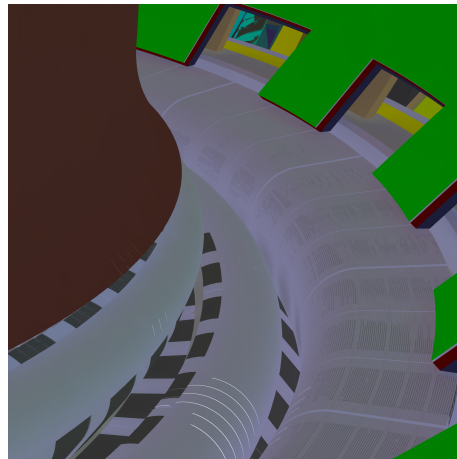


(b)

Fig. 7.2: Simulation of the possible view of the imaging spectroscopy system from port 2: (a) field of view; (b) image simulated.



(a)



(b)

Fig. 7.3: Simulation of the possible view of the imaging spectroscopy system from port 3: (a) field of view; (b) image simulated.



Fig. 7.4: Simulation of the possible view of the imaging spectroscopy system from port 4: (a) field of view; (b) image simulated.

Observing Fig. 7.1, we note that from Port 1, a tangential view of the divertor region is not achievable. While all areas of the divertor are visible, it is not possible to examine events occurring in the region above it. In contrast, both Ports 2 and 3 allow a tangential view, facilitating the study of both the divertor and the area above it. The view from Port 2 is restricted by the first wall, more so than Port 3, which offers greater adjustability due to its wider duct. The views accessible from Port 2 are shown in Fig. 7.2, while those from Port 3 are depicted in Fig. 7.3. Examining the perspective from Port 4 in Fig. 7.4, we can see that this port is unsuitable for use; the view it provides is excessively tangential to the divertor, making it challenging to correlate the image accurately with the 3D CAD model.

In evaluating the positioning, a possible DTT configuration with a double divertor was also considered [53]. This configuration, however, ruled out the use of Port 2. As shown in Fig. 7.5a, to observe the upper divertor, the diagnostic system would need to be moved closer to the first wall, so nearer to the plasma, where the heat flux becomes prohibitive. Additionally, as with Port 4, the view is overly tangential to the divertor, making tomographic reconstruction impossible. Conversely, Port 3 provides a suitable view of the upper divertor, as illustrated in Fig. 7.5b.

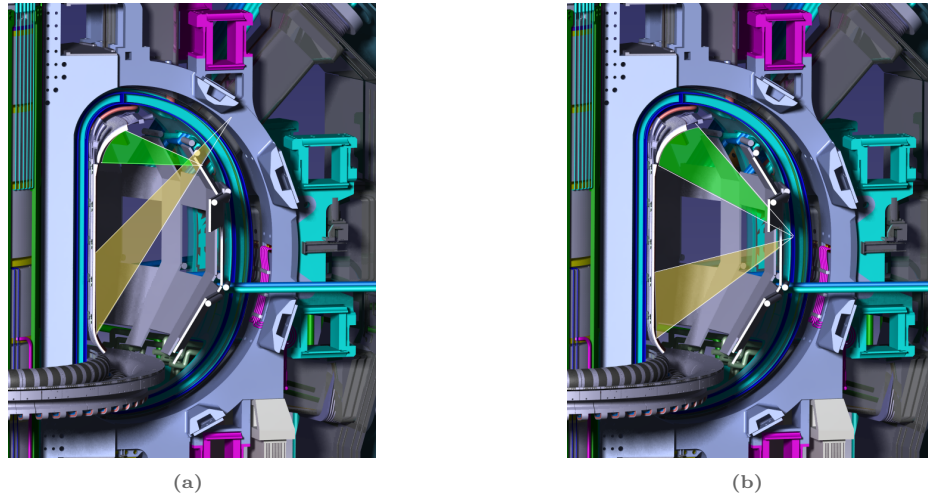


Fig. 7.5: Simulation of the possible views in double divertor configuration: (a) field of view from port 2; (b) field of view from port 3.

Figures Fig. 7.6, Fig. 7.7, and Fig. 7.8 compare the divertor cross-section with the simulated view from Port 3. The initial choice was based on an earlier divertor configuration [6]. Recently, the final divertor configuration has been decided; the configuration selected and presented in this work is optically the most complex due to its irregular shape. New proposed divertor configurations, one example shown in Figure 7.9, have a more regular shape [52], making them easier to investigate using the proposed diagnostic system. In summary, the preliminary evaluation conducted is conservative, ensuring that future divertor designs can be effectively studied. The simulation results show that even the deepest regions of the divertor can be observed in images obtained from Port 3. i

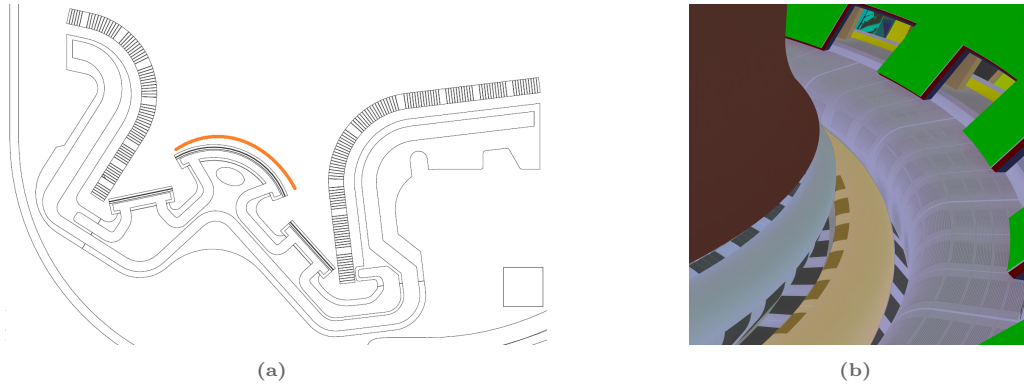


Fig. 7.6: Comparison between the divertor cross section and the simulated view from port 3 (example 1): (a) divertor example cross section; (b) simulated view.

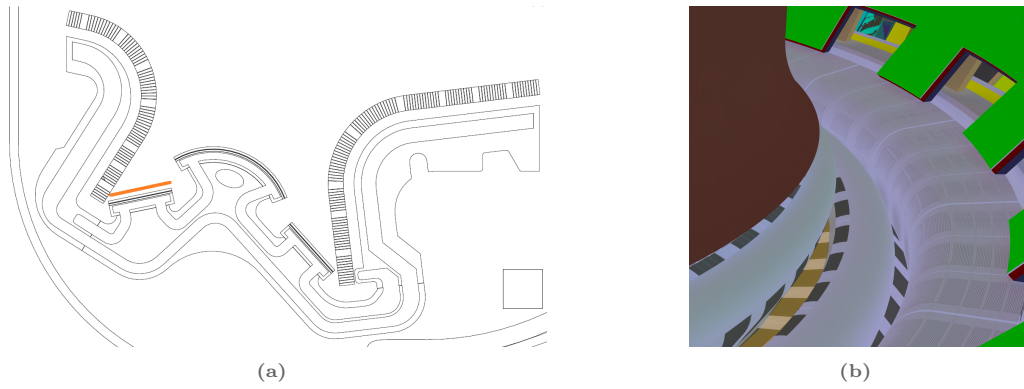


Fig. 7.7: Comparison between the divertor cross section and the simulated view from port 3 (example 2): (a) divertor example cross section; (b) simulated view.

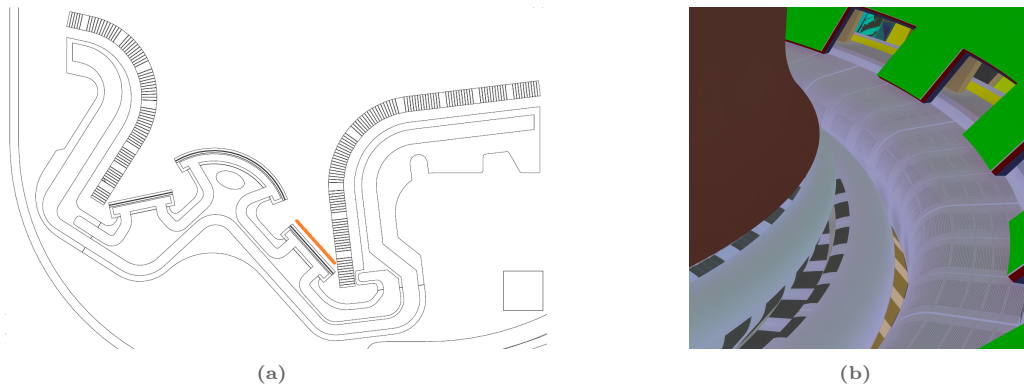


Fig. 7.8: Comparison between the divertor cross section and the simulated view from port 3 (example 3): (a) divertor example cross section; (b) simulated view.

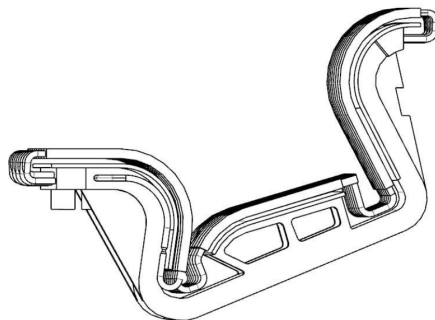


Fig. 7.9: Current divertor configuration

In conclusion, Port 3 was selected for imaging spectroscopy as it provides the best view of the divertor, including the case of a double-divertor configuration. This port allows a comprehensive view along the divertor, even within the throats. Additionally, the perspective from Port 3 is not excessively tangential, enabling accurate reconstruction between the captured image and the 3D CAD model with acceptable reconstruction error.

7.3 Design

The diagnostic is designed to provide a double view, to study the area above the divertor and the divertor itself. The overall configuration can be seen in Fig. 7.10a where the views are indicated in blue and light blue. The upper view (blue beam in Fig. 7.10a) observes the divertor from a sloped view (to see the divertor throats). The lower view, in light blue, offers a wider, more tangential view for monitoring the detachment front movement. The simulated view of the divertor for both lines of view is reported in Fig. 7.11.

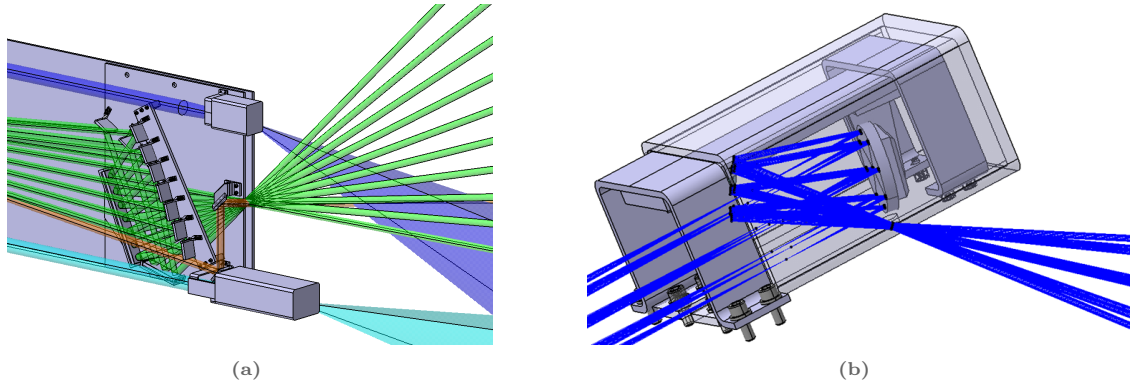


Fig. 7.10: Overview of the divertor imaging system: (a) optic head installed above and below the Z_{eff} system; (b) details of the optical head.

Both heads share the same structure consisting of a metallic cover that protect the identical optical. A detailed view of this structure can be seen in Fig. 7.10b. The chassis of the heads is composed of a sturdy framework that securely holds the two mirrors in place and it is fixed to the base plate of the overall structure. It also includes a shutter system to safeguard the mirrors during wall conditioning operations and is equipped with a cooling system to manage the intense plasma thermal load. The first mirror (M1) is flat while the second one (M2) is a concave parabolic mirror on axis ($k = -1$) with a focal length of 495 mm allowing a spatial resolution better than 5 mm. The optical diameter of M1 is 30 mm, while M2 has a larger optical diameter of 50 mm. 7.10b shows the optical head details where the blue line beam being the ray tracing simulation carried out using Ansys Zemax³

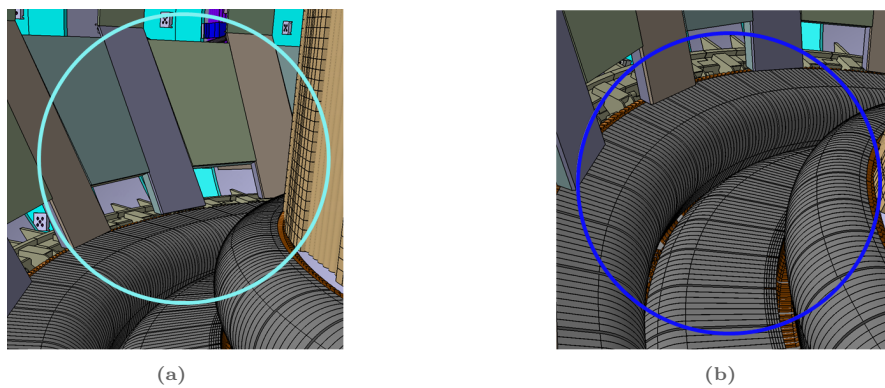


Fig. 7.11: Simulated view of the Divertor imaging system, with the circles color matching the notation in 7.10a): (a) Lower optical head perspective; (b) Upper optical head perspective.

The ray tracing simulation was configured to optimize the optical layout for the wavelength range of 350–800 nm. This involved resolving the optical path for nine points within the field of view: one for the chief ray (central point of the field of view), and eight circular points arranged along the edge of the region of interest (Fig. 7.11).

³Ansys Zemax OpticStudio - URL: <https://www.ansys.com/it-it/products/optics/ansys-zemax-opticstudio>

7.4 Laboratory set-up

To enhance the flexibility of the system, the possibility to place instruments outside the torus hall is pursued, as done in JET [65]. This approach allows efficient sharing of light among different spectrometers and interferential filter devices facilitating easy modification of the instrument setup as needed. In Fig. 7.12a, the overview of the torus hall is reported with underlined the path of the light from the sector 3 (orange) to the spectroscopy laboratory (green). The visual representation in Fig. 7.12b summarize the intended arrangement of the optical path from the plasma to the laboratory through the biological shield, which is designed to protect personnel and the environment from radiation emitted during fusion reactions. The details of the dog-leg, a curve pathway in the wall designed to eliminate a direct path for the radiation, are under definition and Fig. 7.12b shows a likely configuration.

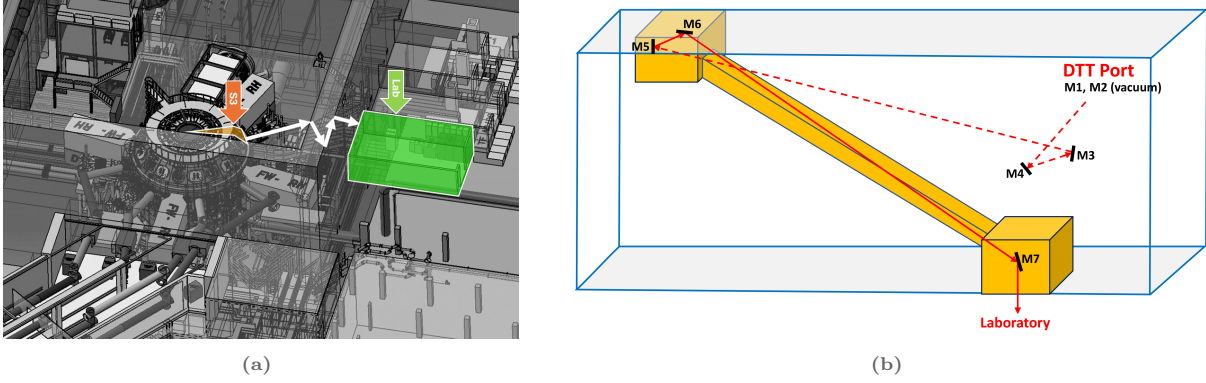


Fig. 7.12: Path from the tokamak to the laboratory: (a) overview of the torus hall illustrating the optical path to the laboratory; (b) schematization of the optical path to the laboratory through the dog-leg of the bio-shield.

To avoid chromatic aberration, a mirror-based solution has been chosen. M1, located in the optical head, captures the divertor image from the vacuum vessel and redirects it to the second mirror, M2. This last then guides the ray along the port, directing it towards the outside of the tokamak. The path of the light beam in the vessel is depicted in blue and light blue in Fig. 7.11a. Upon passing through the double vacuum windows, the light encounters a pair of mirrors, M3 and M4, close to the cryostat, which focus it across the torus hall. Subsequently, another pair of mirrors, M5 and M6, positioned near the inlet of the bio shield dog-leg, further guide the light. This final pair of mirrors directs the ray inside the bio-shield wall, ultimately guiding it towards the laboratory. This sequence of mirrors and redirection steps ensure to maintain image quality and avoid chromatic aberration throughout the optical pathway. This structure is duplicated with one for each imaging divertor system. Adequate screens and checkpoints are foreseen to verify the optical alignment, along the 25 m path length. The assumed checkpoints are three: inside the port to verify the view on the divertor, after M4 on the wall, after M6 to check the mirrors combination to pass the bio-shield inside the laboratory. The checkpoint in the torus hall is assumed also to allow the possibility to intercept the light with a multispectral imaging system [68][80] during DAY0 operations. Optical elements outside the tokamak port must be shielded with a black box to minimize the background light from the tokamak hall. To ensure safety and accommodate radiation hazards, each mirror will be installed within a 6-axis stages with nanometric positioning capability for the mirrors. Given the presence of a strong electromagnetic field, these stages will be equipped with piezoelectric motors for remote control. In the laboratory, a CCD camera will be employed to verify the alignment of the optical chain. Each optical element within the torus hall will be installed using this method to ensure maximum flexibility for the system.

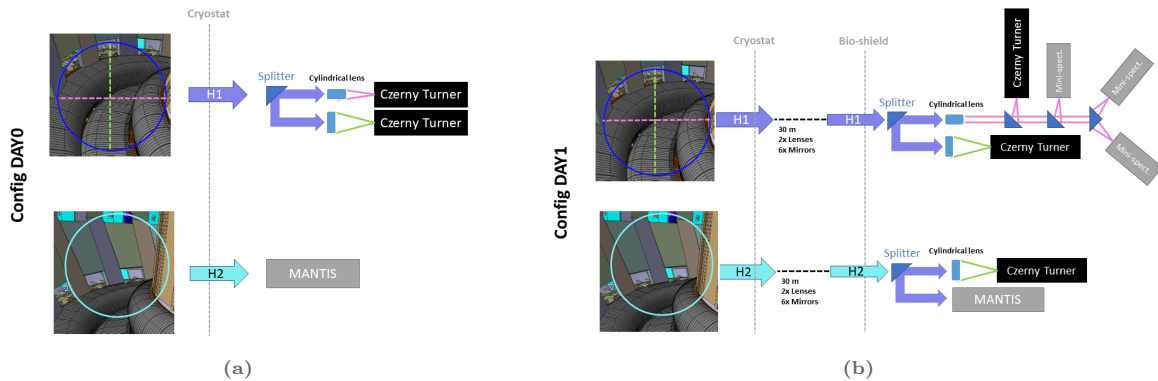


Fig. 7.13: Acquisition set-up of the divertor imaging system: (a) DAY 0 configuration; (b) DAY 1 configuration.

The imaging system aims to observe the plasma facing components (PFC) and to spectroscopically investigate the divertor region to monitor detachment phenomena. The system is composed by two endoscopes that drive the visible light emission from the vacuum vessel toward the outside of the torus. Two different configuration are taken into account: The DAY0 configuration foresees spectrometers in the torus hall: 2 Czerny Turner spectrometer and 3 LR spectrometer (mini-spectrometer) 1 for the inner, 1 for the outer, 1 for the dome. The details of the optical coupling are to be defined with tests in laboratory, in principle a beam splitter will direct the light towards two cylindrical lens in order to integrate the divertor image along the vertical and horizontal direction respectively. The horizontally integrated image will then direct directly in a High resolution (HR) CT spectrometer spectrometer while the vertically integrated image is further split between HR and Low Resolution spectrometers. At the DAY2 the system will be moved in the laboratory bringing the light from the cryostat to the dogleg with a custom optical relay. The image collected with the more tangential observation will be conveyed also to a multispectral imaging system [80] to study the plasma detachment through a tomographic reconstruction. In order to maximize the signal it is under study the possibility of image transfer with an optical relay, still keeping the possibility of using a more versatile fiber bundle.

Conclusion

The conceptual design of the main visible spectroscopy diagnostic systems for the DTT facility has been presented and discussed. The diagnostic tools comprise a dual imaging spectroscopy system focused on the divertor region, along with effective charge measurements using poloidal and toroidal LoS. The optical in-vessel components capture the plasma emission and direct it outside the vessel through the equatorial port. The Zeff system utilizes quartz fibers to transport the emitted signals from the device to the laboratory. The imaging system employs a mirror-based setup to relay the plasma emission from tokamak to the lab, traversing the torus hall and crossing the laboratory bio-shield. This flexible solution has been developed to ensure the required performance of various spectroscopy systems within the geometric constraints of the device port. The chosen design takes into account the harsh operating environment of the system, including wall conditioning operations. The mechanical layout not only ensures port compatibility but also facilitates easy coexistence and integration with other diagnostics and auxiliary systems within the DTT facility. This work demonstrates the feasibility of a compact and versatile spectroscopy diagnostic system that meets the performance targets of its different subsystems while fitting the constraints of the device port. The proposed solution is presently under evaluation by the DTT project team to ensure its compatibility with the machine design requirements and other possible interferences. To enhance flexibility, the possibility to set the instruments outside the torus hall is pursued. This approach enables efficient sharing of light among different spectrometers and interferential filter devices, facilitating easy modification of the instrument setup as needed. The optical layout, anyway, takes into account also the possibility to share the light with instrumentation that can be installed in the torus hall, if needed, such as a multispectral imaging system. The next steps in finalizing the diagnostic system include the installation of support components in the torus hall, and designing the cooling system and the mirror-based relay system to bring the divertor image from the vessel to the laboratory. As a part of the scheduled work, the crucial contribute of the reflection of metal vessel components on the collected emission, will be modelled, with particular reference to the divertor region.

Part III

Vacuum system for DTT

This part presents the pre-design of the DTT vacuum system. The primary objective is to assess the impact of pipe size on the system's performance and to estimate both the final pressure within the vacuum vessel and the time required to achieve this pressure. Special attention is given to the fore-vacuum side of the system due to its longer pipes, which result in the most significant pressure drops. The system consists of two subsystems: one dedicated to the cryostat and the other to the vacuum vessel. However, only the vacuum vessel subsystem is analyzed in this document, as the same technical evaluations are applied to the cryostat. Sec. 9 begins with an overview of the main parameters of DTT, along with a summary of the key characteristics of the gases studied. The first step in the analysis was selecting the vacuum vessel ports to be used for pumping. Due to the requirements of additional heating systems and diagnostics, only port 4 and port 5 are available. A comparison between these two options is provided in Sec. 10. Sec. 11 offers an overview of the system layout, and a detailed analysis of the subsystems in the subsequent sections: fore-vacuum components in Sec. 12, and high-vacuum components in Sec. 13. Finally, Sec. 14 examines the regeneration process of the cryopanel [38] of the divertor pumping system.

Boundary conditions

9.1 DTT Vacuum parameters

In this section, the main geometrical characteristics of DTT are recalled. In particular, in Tab. 9.1 the volume and the surface of the vacuum vessel are reported, while Tab. 9.2 shows the cryostat parameters. Lastly, in the Tab. 9.3 the geometrical parameters of the access ducts are summarized.

Items	Symbols	Value
Vacuum vessel volume [m^3]	V_{vv}	99.7
Ports without bellows [m^3]	V_p	45.2
Global volume [m^3]	V	145.2
Surface no ports [m^2]	S_{vnp}	81.1
First wall W surface [m^2]	S_w	66.8
First wall steel plate [m^2]	S_p	233.8
Divertor surface (Hp) [m^2]	S_d	100.0
Inner ports surface (no bellows) [m^2]	S_p	341.3
Bellows surfaces [m^2]	S_b	755.8
Total inner surface + 20% margin [m^2]	S	1894.6
Target pressure [Pa]	P_t	$<5 \times 10^{-5}$

Table 9.1: Vacuum vessel parameters

Items	Symbols	Value
Total volume [m^3]	V_{vv}	TBD
Empty volume [m^3]	V_p	TBD
Surface [m^2]	S_{vnp}	TBD
Target pressure [Pa]	P_t	$<5 \times 10^{-2}$

Table 9.2: Cryostat parameters

	Port 1	Port 2	Port 3	Port 4	Port 5
A [m^2]	0.176	0.292	0.613	0.329	0.147
h [m]	2.112	2.168	3.162	2.332	1.800
Lmax [m]	3.665	3.162	2.492	3.258	3.764
Lmin [m]	3.355	3.002	2.492	2.764	3.569
L [m]	3.510	3.082	2.492	3.011	3.667
S [m^2]	7.415	6.682	7.879	7.022	6.599
D _{eq} [m]	0.333	0.538	0.775	0.564	0.326

Table 9.3: Port geometrical parameters

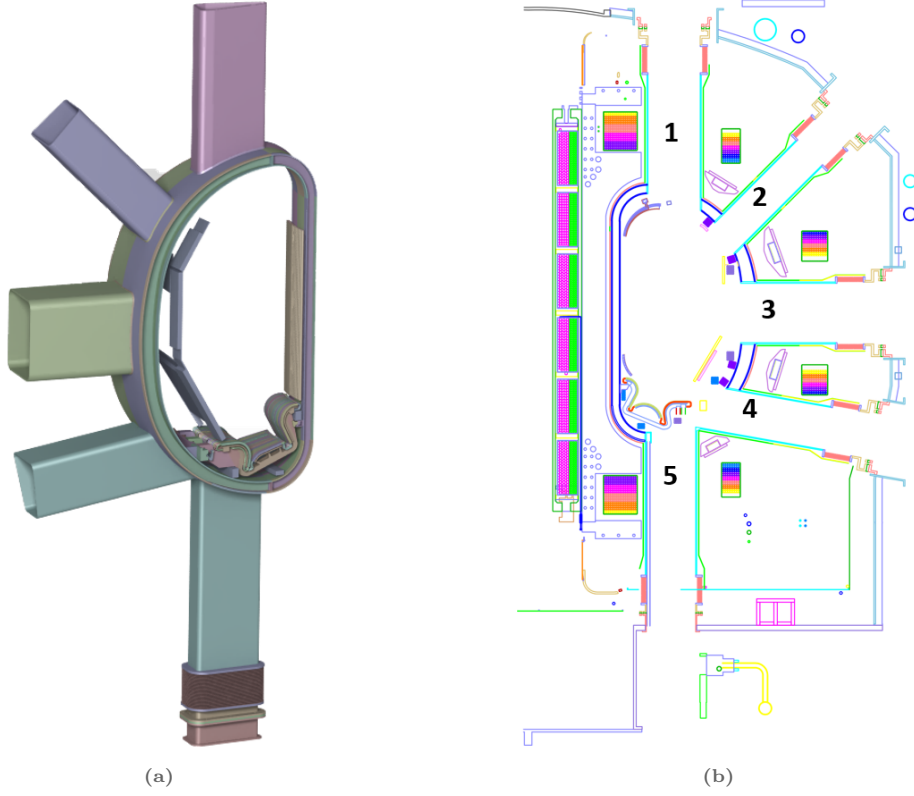


Fig. 9.1: Overview of DTT sector: (a) render of the CAD ; (b) cross section with indicated the port number identification

In Tab. 9.3 $\mathbf{A}$ is the cross section of the port while $\mathbf{h}$ is the perimeter. $\mathbf{L}_{min}$ and $\mathbf{L}_{max}$ are respectively the minimum and the maximum length inside the port while $\mathbf{L}$ is the mean length. $\mathbf{S}$ is the internal lateral surface of the duct, while $\mathbf{D}_{eq}$ is the equivalent diameter calculated as $4 \cdot \mathbf{A}/\mathbf{h}$. At the top of port 5 internally in the vessel there is the divertor which have a series of holes between cooling pipes to connect the sub-divertor region (and ports #5) to the vacuum vessel. The geometrical characteristics of the divertor are reported in the following Tab. 9.4 where $\mathbf{A}_{hole}$ is the section of a one hole on the divertor and $\mathbf{N}_{holes}$ is the number of the holes.

$R_{div} [m]$	1.813
$L_{mono} [m]$	0.022
$N_{mono} [1]$	517
$L_{open} [m]$	0.007
$H_{open} [m]$	0.07
$A_{hole} [m^2]$	0.00049
$N_{holes} [1]$	1034

Table 9.4: Divertor holes configuration

9.2 Gasses parameters

In Tab. 9.5 the main gas parameters are reported. $\mathbf{m}$ is the mass of the elements, the σ is the cross-section radius [40], $\mathbf{c}$ is the mean particle speed calculated using relation (9.1) while the mean free path λ is obtained by (9.2)[55]

	$\mathbf{m} [\cdot 10^{-27} \text{ kg}]$	$\sigma [\cdot 10^{-10} \text{ m}]$	$\mathbf{c} [\text{m/s}]$	$\lambda [\cdot 10^{-8} \text{ m}]$
$\mathbf{H}_2$	3.30	2.71	1781	12.4
$\mathbf{D}_2$	3.35	-	1770	-
$\mathbf{H}_e$	6.60	2.15	1259	19.8
$\mathbf{H}_2\mathbf{O}$	29.9	-	591	-
$\mathbf{N}_2$	46.2	3.70	476	6.67
$\mathbf{O}_2$	52.8	3.55	445	7.25
$\mathbf{Ar}$	61.0	3.58	414	7.13

Table 9.5: Gasses parameters

$$c = \sqrt{\frac{8}{\pi} \frac{kT}{m}} \quad (9.1)$$

$$P\lambda = \frac{kT}{\sqrt{2}\pi\sigma} \quad (9.2)$$

In (9.1) and (9.2) k is the Stephan Boltzmann constant ¹, T is the temperature assumed of 273 K and P is the pressure expressed in Pa. For the results reported in Tab. 9.5 the pressure is assumed equal to the atmospheric value (10^5 Pa).

¹The Boltzmann constant is a physical constant that relates the average kinetic energy of particles in a gas with the temperature of the gas and it values $1.38 \cdot 10^{-23}$ J/K

Vacuum vessel pumping port selection

The integration in the vacuum vessel of the additional heating systems, diagnostics and auxiliary system such as vacuum, fueling and remote handling represent a crucial point in the design of DTT. The heating systems and diagnostics require or take advantage of the position and wide cross section of ports 2 and 3, so these access cannot be dedicated exclusively to the pumping system. The small section of port 1 makes it unserviceable for an efficient pumping system. These considerations reduce to only two possible configurations of connection:

1. Connection through two ports 4. At least 2 of ports 4 are reserved to remote handling system, it is considered feasible to easily remove vacuum components when remote handling operations will be needed. The same could not be true for diagnostics or other components.
2. Connection through 10 bottom ports 5. Nine of ports 5 are reserved to the installation of divertor pumping systems cryopannels, while one port 5 could allocate a few mirrors for an optical diagnostics. Being below the divertor, ports 5 are not suited for diagnostics or other systems.

To analyze the relative advantage of the two options in terms of vacuum pumping efficiency we compared the conductance of the port 4 and the port 5. Fig. 10.1 reports the empty space inside the duct for the two ports.

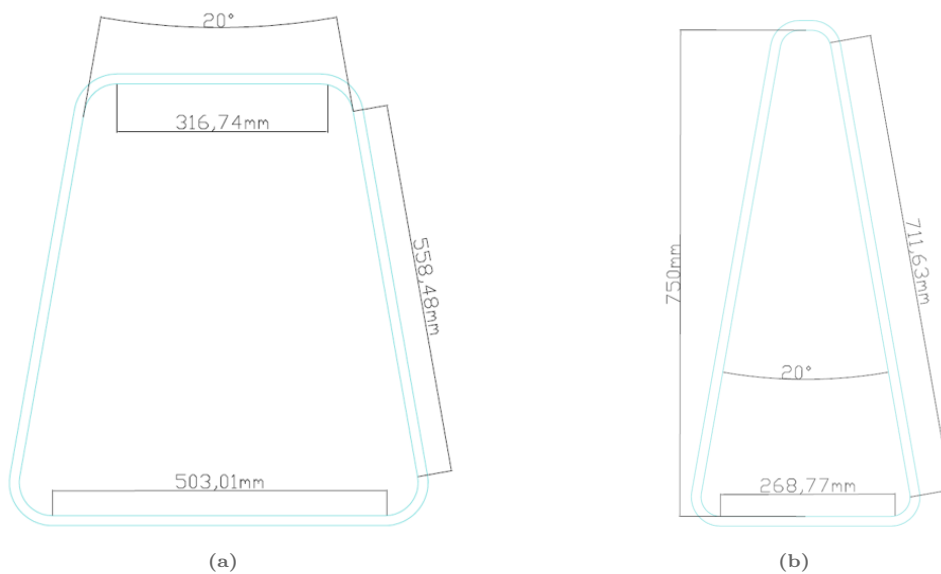


Fig. 10.1: DTT ports cross section: (a) cross section of port 4; (b) cross section of port 5

Fig. 10.2 illustrates the elements located inside the ports. In particular the pipes located inside the port 4 and the pipes and the cryopannels inside the port 5. For the estimation of the conductance the geometry of the free section of the ports has been simplified as show in Fig. 10.3.

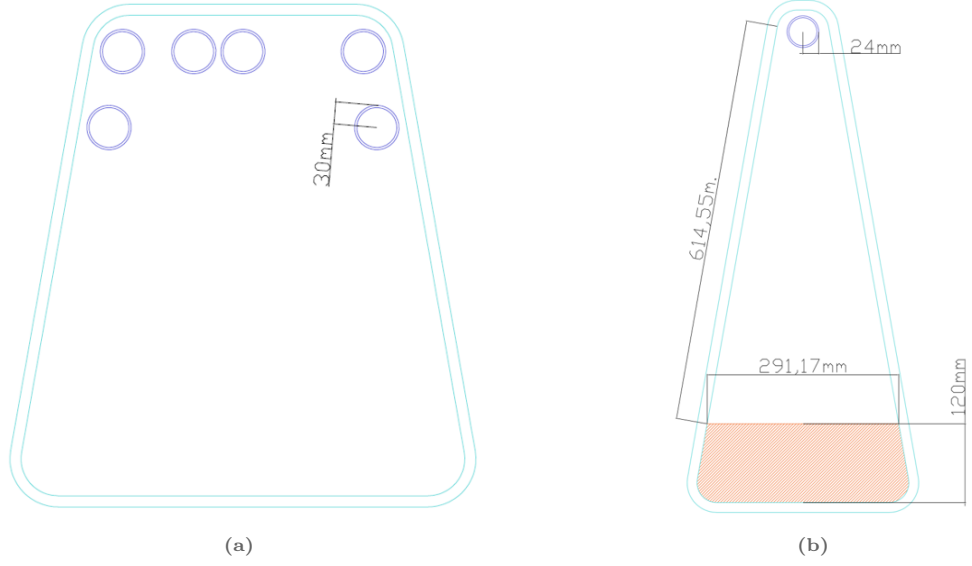


Fig. 10.2: DTT ports cross section with pipes: (a) cross section of port 4; (b) cross section of port 5

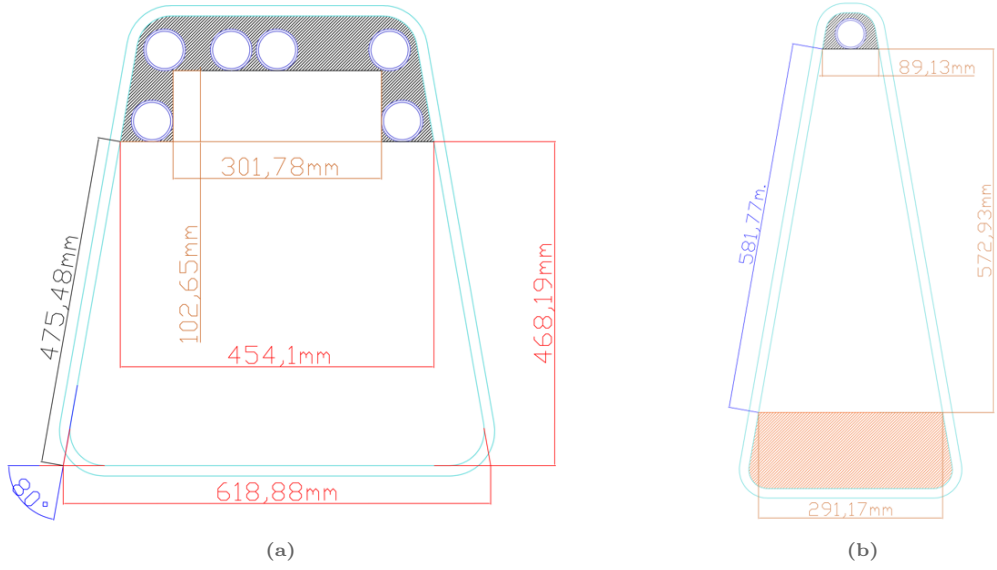


Fig. 10.3: DTT ports cross section with pipes and simplified geometry: (a) port 4 cross section with pipes; (b) port 5 cross section with pipes and cryopanel

	Port 4	Port 4 with pipes	Port 5	Port 5 with cryopanel
A [m^2]	0.33	0.28	0.15	0,11
h [m]	2.33	2.23	1.80	1.54
L_{max} [m]	3.26	3.26	3.76	3.76
L_{min} [m]	2.76	2.76	3.57	3.57
L [m]	3.01	3.01	3.67	3.67
S [m^2]	7.02	6.72	6.60	5.66
D_{eq} [m]	0.56	0.17	0.33	0.08

Table 10.1: Size of port 4 and port 5

N. Ducts	2		10	
Port	P4 [m3/s]	P4 with pipes [m3/s]	P5 [m3/s]	P5 with cryop. [m3/s]
H ₂	58.5	46.0	69.3	45.2
D ₂	58.1	45.7	68.8	44.8
He	41.4	32.6	48.9	31.9
H ₂ O	19.4	15.3	23.0	15.0
N ₂	15.6	12.3	18.5	12.0
O ₂	14.6	11.5	17.3	11.3
Ar	13.6	10.7	16.1	10.5

Table 10.2: Comparison between the conductance of port 4 and port 5

The conductance of the a generic pipe in molecular pressure condition can be approximately estimated by (10.1)

$$C = \alpha \cdot C_A \quad (10.1)$$

where C is the conductance, α is the transmission probability and C_A is the conductance of the aperture (in this case the cross section of the port). The transmission probability can be calculated using the equation (10.2) [32]

$$\alpha = \frac{1}{1 + \frac{3}{4} \frac{L}{D}} \quad (10.2)$$

whereas the aperture conductance with the (10.3):

$$C_A = \frac{1}{4} c \cdot A \quad (10.3)$$

In (10.2) and (10.3) L is the length of the pipe, D is the hydraulic diameter that in this case is $4 \cdot A/h$ and A is the cross section. All these terms can be found in Tab. 10.1. The terms c is the gas speed and this value is calculate using the equation (9.1) and its value can be found in Tab. 9.5. From Tab. 10.2 it is possible to see that 10 ports 5 provide slightly lower conductance then 2 ports 4. Finally, the conductance is also influenced by the presence of the divertor. In the port 4 case the divertor cuts the 50% of the port aperture. Instead, in the port 5 the gasses must flow through the divertor holes. The final conductance is the combinations of ports and holes/divertor conductance which is reported in Tab. 10.3, where **Div. Cross** is the conductance of the section reduction for 1 port 4, **P4 x 2** are the conductance of 2 ports 4 and **Total P4** is the combination of the conductance of the divertor and the 2 ports 4. For the port 5 case, **Div. Holes** is the conductance of all divertor holes, **P5 x 10** is the conductance of 10 ports 5 and **Total P5** is the combination of divertor and all ports 5. Considering the influence of the divertor the 10 ports 5 option provides a slightly higher conductance than the 2 ports 4 option and taking into account that port 5 is less useful for other systems (diagnostics, remote handling, etc) it has been decided to proceed on a vacuum vessel pumping system design based on the port 5 option.

	Port 4 [m ₃ /s]			Port 5 [m ₃ /s]		
	Div. Cross	P4 x 2	Total P4	Div. Holes	P5 x 10	Total P5
H ₂	62.8	46.0	33.7	225.7	45.2	37.6
D ₂	62.4	45.7	33.5	224.2	44.8	37.4
He	44.4	32.6	23.8	159.6	31.9	26.6
H ₂ O	20.9	15.3	11.2	75.0	15.0	12.5
N ₂	16.8	12.3	9.0	60.3	12.0	10.1
O ₂	15.7	11.5	8.4	56.4	11.3	9.4
Ar	14.6	10.7	7.8	52.5	10.5	8.8

Table 10.3: Global conductance of the system

Pumping system over view

The pumping system is divided into two sub-systems: one for the vacuum vessel and one for the cryostat. In Fig. 11.1 the layout of the system is reported. For the scope of this document, it will be presented only the details about the pumps whereas the valves and pressure gauge are not considered.

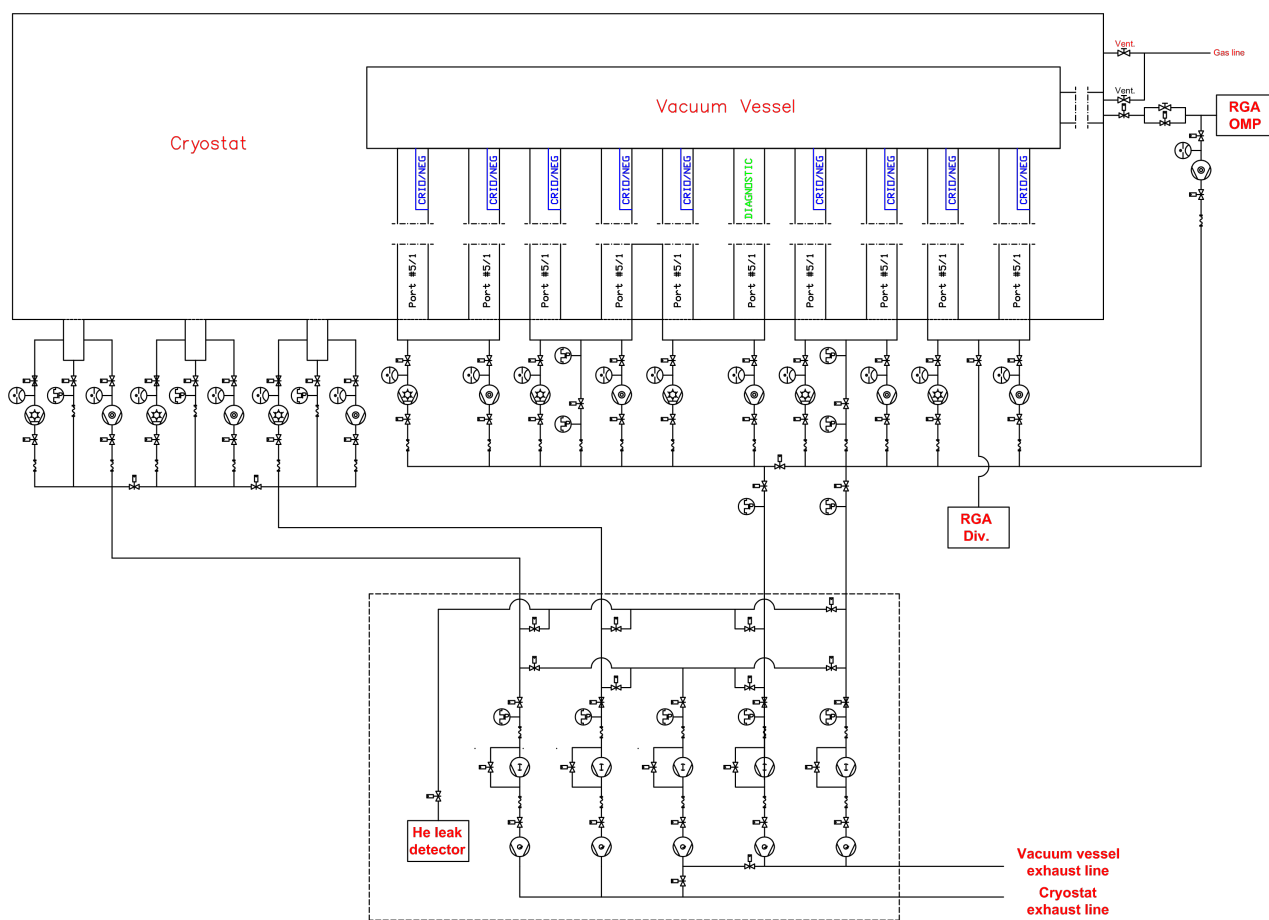


Fig. 11.1: Layout pumping system

The system is composed by the following components:

1. Vacuum vessel:

- Fore-vacuum:
 - 3 screw pumps model **Pfeiffer Hepta 100**¹ The characteristic curve is reported in Fig. 11.2b
 - 3 roots pumps model **Pfeiffer Okta 500**². The characteristic curve is reported in Fig. 11.2a
- High-vacuum:

¹Pfeiffer Hepta 100: <https://www.pfeiffer-vacuum.com/products/screw-pumps/hepta-100>

²Pfeiffer Okta 500: <https://www.pfeiffer-vacuum.com/en/products/oktaline/okta-500/3216/okta-500-roots-vacuum>

- 5 turbo molecular pumps model **Pfeiffer HiPance 2300**³. The characteristic curve is reported in Fig. 11.2c
- 5 cryopumps model **Marathon CP-250LP Cryopump**⁴. The main parameters are shown in Fig. 11.2d

2. Cryostat:

- Fore-vacuum:
 - 2 screw pumps model **Pfeiffer Hepta 100**. The characteristic curve is reported in Fig. 11.2b
 - 2 roots pumps model **Pfeiffer Okta 500**. The characteristic curve is reported in Fig. 11.2a
- High-vacuum:
 - 3 turbo molecular pumps model **Pfeiffer HiPance 2300**. The characteristic curve is reported in Fig. 11.2c
 - 3 cryopumps model **Marathon CP-250LP Cryopump**. The main parameters are shown in Fig. 11.2d

It is important to underline that listed components are used as an example of what is commercially available to provide a preliminary design of the vacuum pumping system. The final components selection will be the result of the procurement tender in which only the technical requirements and performance parameters will be specified.

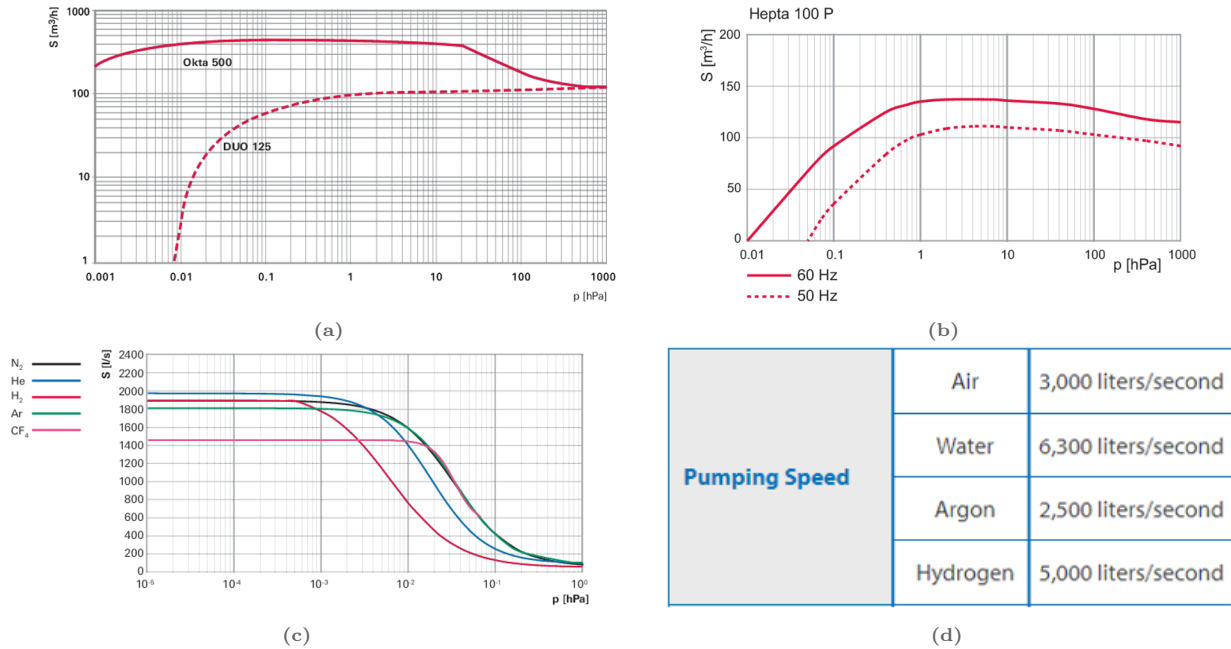


Fig. 11.2: Characteristics of the pumps: (a) Pfeiffer Okta 500 characteristic curve; (b) Pfeiffer Hepta 100 characteristic curve; (c) Pfeiffer HiPance 2300 characteristic curve; (d) Maraton CP-250LP characteristics;

The procedure to achieve the vacuum inside the tokamak vessel or cryostat is composed by four steps:

1. **Only fore pumps on:** to obtain a low vacuum using the screw and the roots pumps. In this case the pressure range is between 10^5 Pa (about 1 atm) and 1 Pa (0.01 hPa);
2. **Only fore pumps on:** The second range, laminar flow, is between 1 Pa and 0.1 Pa;
3. **Fore and turbo-molecular pumps on:** When the pressure of about 0.1 Pa is achieved the turbo-molecular pumps are turned on. The pressure drops to a limit value that is determined by the baking process and/or by the turbo-molecular pumps compress ratio;
4. **Fore pumps, turbo-molecular pumps and cryopumps on:** The last step provides the ignition of the cryopumps that drops the pressure towards the target pressure.

³Pfeiffer HiPance 2300: <https://www.pfeiffer-vacuum.com/en/products/turbopumps/hybrid-bearing/hipace-2300>

⁴Marathon CP-250LP: <https://www.shicryogenics.com/product/marathon-cp-250lp-cryopump/>

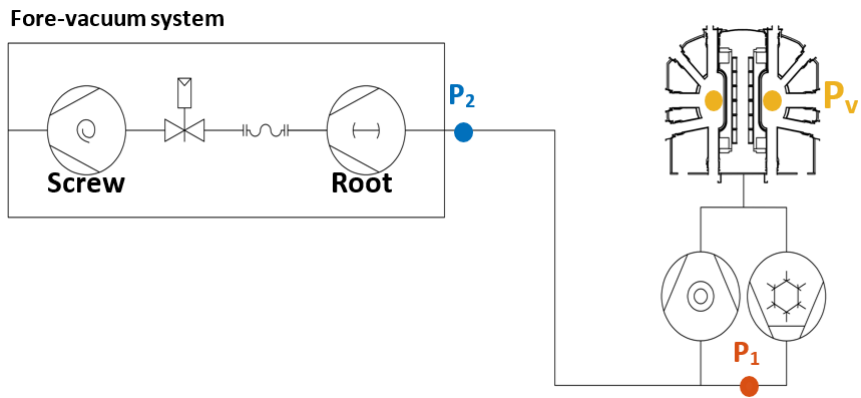


Fig. 11.3: Scheme of vacuum system

In the following sections will be analysed the pumping performance (time to achieve the requested vacuum pressure) of fore-vacuum and then of the high-vacuum parts.

12.1 Analytic calculation

In the following the nomenclature is based on the scheme shown in Fig. 11.3 P_2 is the pressure in the inlet of the fore-vacuum pumps, P_1 is pressure in the outlet of the high-vacuum pumps and P_v is the pressure in the vacuum vessel. The process from atmospheric pressure to the high-vacuum covers three different flow regimes: turbulent flow, laminar flow and molecular flow. The first step listed above is in turbulent flow and the pressure follows the equation (12.1):

$$P(t) = P_0 e^{-\frac{S}{V}t} + P_1 \quad (12.1)$$

where P_0 is the initial pressure (namely atmospheric pressure), V is the vacuum vessel volume from Tab. 9.1, and S is the total pumping speed. This last one is function of the pressure because it depends by the speed of the roots+screw (when backing pumps like the roots+screw are used) following the function reported in Fig. 11.2a:

$$S(P) = N_r S_r(P) \quad (12.2)$$

where N_r is the number of roots+screw pumps and, S_r is the pumping speed function reported in Fig. 11.2a. In the second step the flow becomes laminar and the pipes plays a key role in the effective pumping speed. In laminar flow the conductance C is a function of the pressure at the edge point of the pipes following the equation (12.3) [55]

$$C = \frac{\pi \cdot d^4}{256 \cdot l \eta} (P_1 + P_2) = A(d;l) \cdot (P_1 + P_2) \quad (12.3)$$

Where l and d are the sizes of the pipes (length and diameter), η is the gas viscosity. P_1 and P_2 are the pressure at the edge of the pipe (see Fig. 11.3). The flux Q can be expressed as function of the conductance of the system:

$$Q = C \delta P \quad (12.4)$$

or in function of the pumping speed and of the pressure in a point of the system:

$$Q = S P \quad (12.5)$$

Merging the equations (12.4) and (12.5) it is possible to define the pressure in the outlet of the high-vacuum components as a function of the fore-vacuum pumps characteristic (P_2) and of the pipes configuration (parameter $A(d;l)$ of (12.3))

$$S \cdot P_2 = C \cdot \delta P \quad (12.6)$$

$$S \cdot P_2 = A \cdot (P_1 + P_2)(P_1 - P_2) \quad (12.7)$$

$$P_1 = \sqrt{\frac{S \cdot P_2 + A \cdot P_2^2}{A}} \quad (12.8)$$

The (12.8) equation allows calculating P_1 . From the (12.7) it is possible to evaluate also the P_2 (the negative solution of the second order equation is neglected):

$$P_2 = \frac{-S + \sqrt{S^2 + 4A^2 P_1^2}}{2A} \quad (12.9)$$

Considering the continuity equation on turbo-molecular pump it is possible to define the condition that must be respected in order to ensure the correct behaviour of the turbo pump:

$$S_{eff}P_1 = S_t P_v \quad (12.10)$$

In (12.10) the S_{eff} is the effective pumping speed of the roots+screw pumps in correspondence of the turbo outlet and S_t is the turbo pumping speed. This last one can be rewritten considering the compression ratio K .

$$S_{eff}P_1 = S_t \frac{P_1}{K} \quad (12.11)$$

$$S_{eff} = S_t \frac{1}{K} \quad (12.12)$$

The continuity along the pipe can be expressed by.

$$SP_2 = S_{eff}P_1 \quad (12.13)$$

Merging (12.12) with (12.13) and considering that the mass flow generated by the roots+screw must be higher than the outlet flow of the turbo-molecular pump the following condition must be satisfied:

$$K \frac{S}{S_t} \frac{P_1}{P_2} > 1 \quad (12.14)$$

P_1 and P_2 must satisfy (12.14) in order to ensure the correct behavior of the turbo-molecular pump. Replacing P_1 in the equation (12.14), with its definition given by (12.8)), the condition on the pressure P_2 can be defined:

$$K \frac{S}{S_t} \sqrt{\frac{A^2 P_2^2}{P_2 S + A P_2^2}} > 1 \quad (12.15)$$

Using the same method with P_2 the condition on P_1 can be written as:

$$K \frac{S}{S_t} \frac{-S + \sqrt{S^2 + 4A^2 P_1^2}}{2A P_1} > 1 \quad (12.16)$$

The (12.16) and the (12.15) represent the condition on the pressure P_2 (defined by the roots+screw chosen) and P_1 (pressure on the fore-vacuum side of the turbo-molecular pump). The roots+screw pump Okta 500+ Hepta 100 (see Fig. 11.2a) ensures a pressure of 0.1 Pa (0.001 hPa) with a pumping speed of 200 m³/h. The pipes are assumed with a length of 100.0 m and a diameter of 0.2 m. With this configuration both (12.16) and (12.15) are satisfied.

	$\eta[10 - 6Pa \cdot s]$	$A[10^{-3}m^3/Pa \cdot s]$	$P_1[Pa]$	$K[10^6]$	$P_v [10^{-6} Pa]$
H₂	8.8	22.3	0.51	0.02	25.4
D₂	11.8	16.6	0.59	-	-
He	19.6	10.0	0.75	0.30	2.5
H₂O	9.7	20.2	0.53	-	-
N₂	17.6	11.2	0.71	100.00	0.007
O₂	20.4	9.6	0.77	-	-
Ar	22.3	8.8	0.80	100.00	0.008

Table 12.1: Pressure fore-vacuum side of turbo molecular pump (K is not available for every gas)

It is important to underline the value of P_v obtained for the hydrogen in Tab. 12.1. In a vacuum application, typically the pressure limit is determined by the leak of the system and by the outgassing of the vessel inner wall. The pressure limit due to the outgassing reduces with time allowing reaching higher level of vacuum but in this case (H₂) the limit is due to the compression ratio of the turbo pumps. The turbo will work in combination with cryopumps and in addition the turbo is not predisposed to evacuate the hydrogen, so it is not a critical problem. However, it is an aspect that must be deeper studied (see Sec. 13).

In Fig. 12.1 the relationship between the fore-vacuum pipe diameter and the pressure P_1 (outlet of high vacuum components) is investigated (the length of the pipe is 100 m). From the chart it can be seen that increasing the diameter over 200 mm does not provide a important reduction in the pressure. The detailed data are reported in Tab. 12.2.

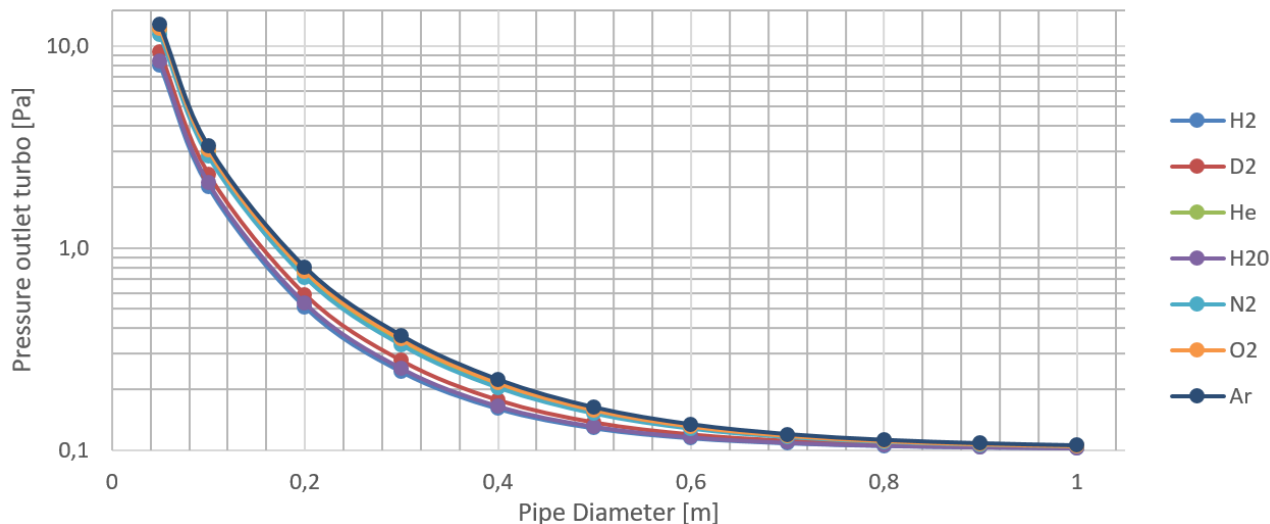


Fig. 12.1: Dependence of the P_1 by the pipe diameter

d[m]	$H_2[Pa]$	$D_2[Pa]$	$He[Pa]$	$H_2O[Pa]$	$N_2[Pa]$	$O_2[Pa]$	$Ar[Pa]$
0,05	7,984	9,246	11,915	8,383	11,291	12,156	12,710
0,1	1,998	2,313	2,980	2,098	2,824	3,041	3,179
0,2	0,509	0,586	0,751	0,533	0,713	0,766	0,801
0,3	0,243	0,276	0,346	0,253	0,329	0,352	0,367
0,4	0,160	0,176	0,211	0,165	0,203	0,215	0,222
0,5	0,128	0,136	0,156	0,130	0,151	0,157	0,162
0,6	0,114	0,119	0,130	0,116	0,127	0,131	0,133
0,7	0,108	0,111	0,117	0,109	0,115	0,118	0,119
0,8	0,105	0,106	0,110	0,105	0,109	0,111	0,112
0,9	0,103	0,104	0,107	0,103	0,106	0,107	0,107
1,0	0,102	0,103	0,104	0,102	0,104	0,105	0,105

Table 12.2: Relationship between diameter and pressure P_1

12.2 Analysys with a numeric tool

To validate the result obtained in Sec. 12.1 the same analysis has been carried out using an online tool from Leybold¹. On the tool, obviously, there are available only Leybold components so pumps similar to the previous ones are selected: root pump model ROVAC WA 5011² coupled with a screw model VARODRY VD 100³. In Fig. 12.2 the layout built with the tool is drawn. The target pressure is set to 0.1 Pa that is the minimum pressure achievable by fore-vacuum elements. The behaviour of this system was studied as a function of the pipe diameter while the length is fixed to 100 m (this is a safety value, probably the pipe length will be about 50 m). The tool allows calculating the effective speed in the chamber (the vacuum vessel in this case) in function of the pressure. The solution for the different diameters under analysis is drawn in Fig. 12.3. It is clear that increasing the diameter from 50 mm to 300 mm generates a great increment of the system performance, this improvement is drastically reduced when the diameter is increased above 300 mm.

¹Leybold online vacuum calculator: <https://calc.leybold.com/en/>

²Leybold ROVAC WA 501: <https://www.leyboldproducts.com/products/roots-vacuum-pumps/ruvac-wa-wau/pumps/644/ruvac-wa-501?number=11734>

³Leybold VARODRY VD 100: <https://www.leyboldproducts.com/products/dry-compressing-vacuum-pumps/varodry/pumps/3022/varodry-vd100?number=111100V10>

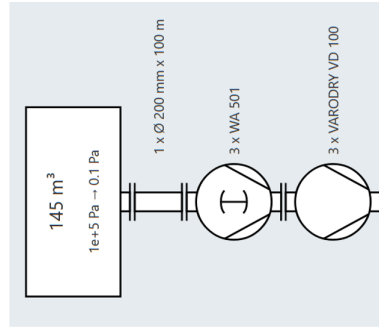


Fig. 12.2: Leybold layout

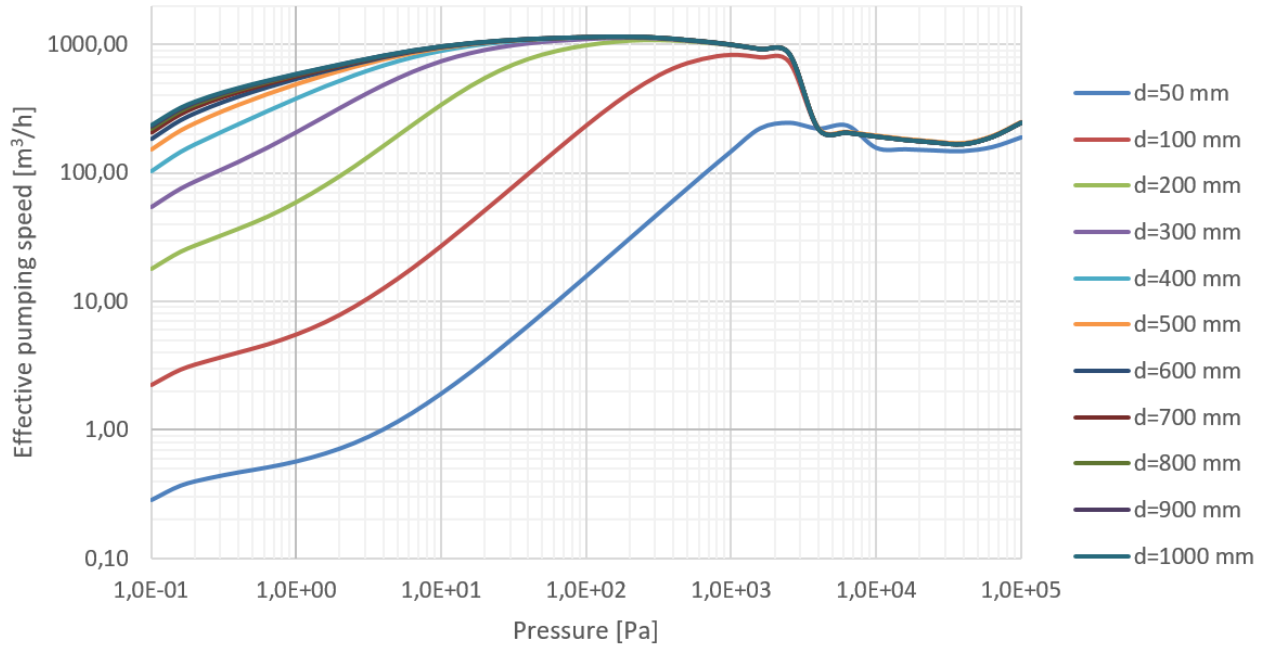


Fig. 12.3: Pumping speed for different fore-vacuum pipe diameter

The tool allows also calculating the time to achieve the target pressure. The result in function of the diameters is reported in Fig. 12.4.

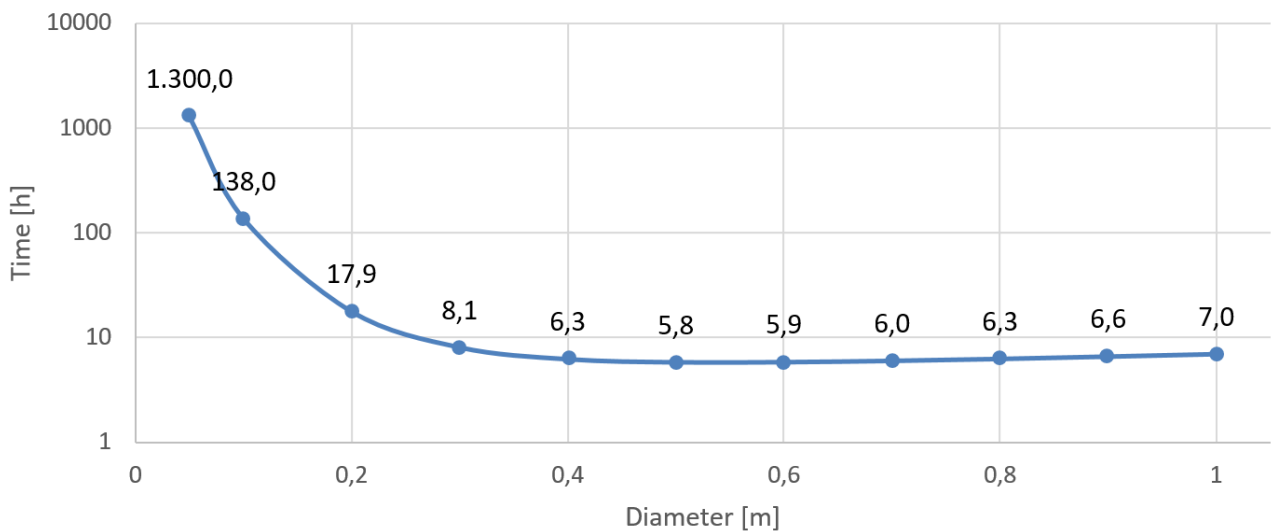


Fig. 12.4: Time as function of the pipe diameter

The data obtained are compatible with the ones presented in Sec. 12.1. The system performance strongly increases by about a two orders of magnitude reduction of the time when the pipe diameter rises from 50 mm

to 200 mm. The Leybold software shows that the performance has a good improvement also increasing from 200 mm to 300 mm (factor of two time reduction). However, considering the time requested to achieve the pressure to activate the turbo molecular pumps (see Fig. 12.4) the cost to increase the diameter above 200 mm is not justified by the improvements obtained. The slight increase in the timing that can be seen for diameter over 0.6 m is caused by the volume increase (vessel and pipe) without an improvement of the performance. It is important to underline that the Leybold tool can perform the calculation only with air so the behaviour of the system in presence of the hydrogen (the most critical case) cannot be investigated. In addition, the other parameters of the system (gas parameters, temperature, etc.) cannot be extrapolated by the system so these results must be used only as a reference for the global behavior of this kind of system. It can be concluded that the analytic approach match with the result obtained by the Leybold tool. So, pipe with diameter of 200 mm and a length up to 100 m can be accepted in the system and these values will be used in the following because they meet both the vacuum system performance target that the torus hall build constrains.

12.3 Timing

In Fig. 12.5 the time evolution of the vacuum vessel pressure obtained with the method presented in Sec. 12.1 for the gasses under analysis is shown. The final pressure (outlet of high-vacuum elements) for each gas is reported in Tab. 12.1 in P_1 column. Starting from the atmospheric pressure the target pressure is achieved in about 1.65 h. It is important underline that for this analysis the assumption is that only a single gas fills the vacuum vessels at atmospheric pressure. This is the most conservative approach, also if not fully realistic. By considering N_2 , which is the best approximation of air, it can be concluded that the time needed to reach the target pressure is about two hours with a pressure drop along the pipes of about 0.5 Pa.

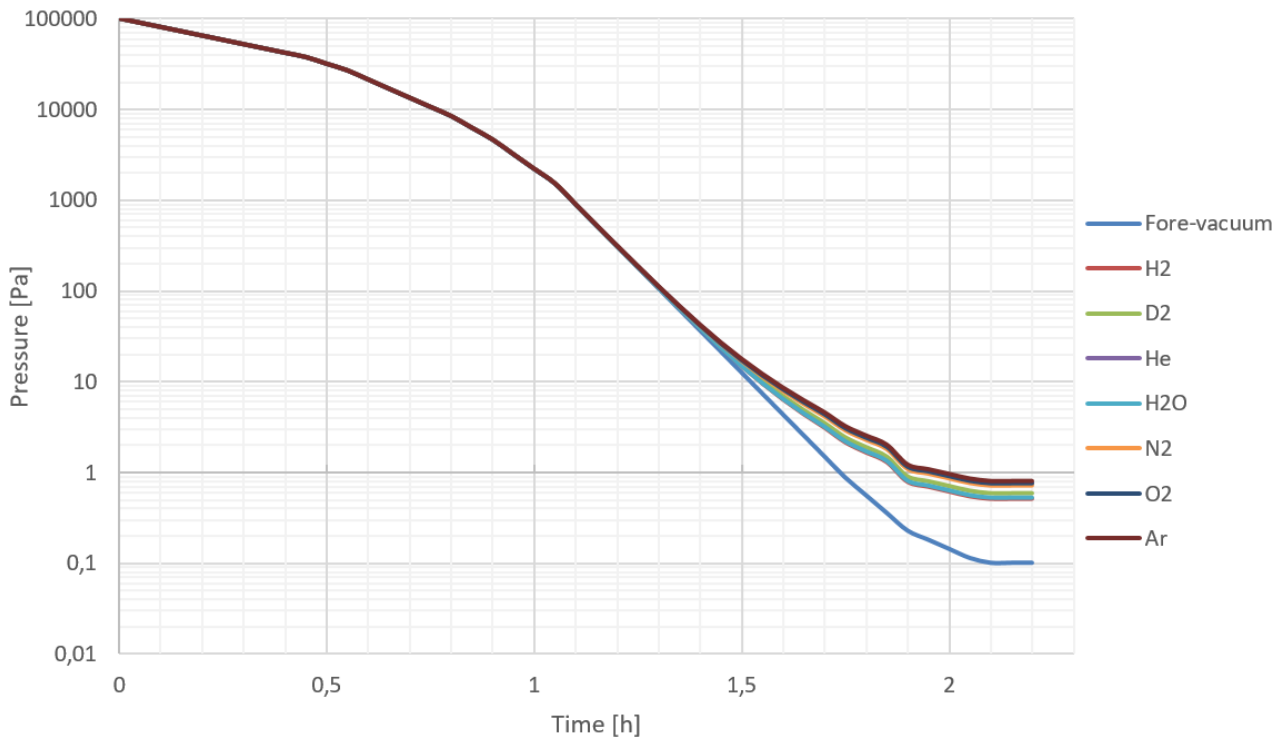


Fig. 12.5: Pressure trend

12.4 Number of pipes

In the vacuum system layout of Fig. 11.1 two pipes for the fore vacuum are considered for redundancy but in the previous computation only one pipe was used to have a safe margin. In this section the impact of more pipes is investigated. Fig. 12.6 shows the time evolution of the pressure in function of the number of pipes. It can be seen that the increasing of the performances is progressively reduced with the number of pipes. Observing the equation (12.3) it is evident that the most relevant parameter for the efficiency of the pipe is the diameter. Doubling the number of pipes increases the performance of a factor 2 (conductance of parallel elements) whereas doubling the diameter the performance rises by a factor 16 (in (12.3) the diameter contribute with an exponent of 4). The best solution is to have only two pipes to provide redundancy in the system. It is better to use space and budget to increase as much possible the diameter of the pipes.

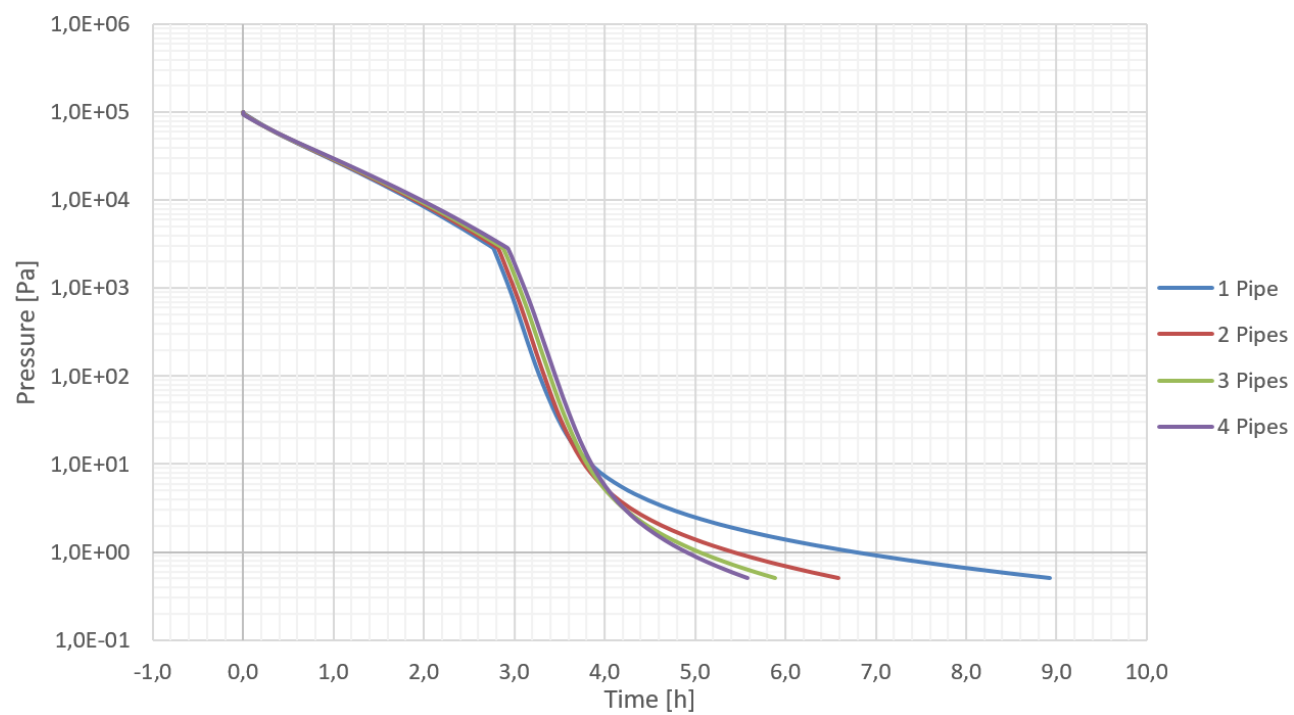


Fig. 12.6: Pressure trend as function of number of pipes

High-vacuum operation

The configuration chosen is composed by a turbo-molecular and a cryopump installed on a manifold that connects two ports 5 as shown in Fig. 11.1. Considering what obtained in Sec. 12 (see Tab. 12.1) in the Sec. 13.1 the hydrogen case (the most critical) is analysed. Instead, water which is the main species in the vessel after venting, is studied in Sec. 13.2.

13.1 Hydrogen case

The procedure, presented in Sec. 12, foresees that when the fore-vacuum system has reached the target pressure the turbo molecular pumps are turned on. The effective pumping speed of the turbo pumps depends on the global conductance of ports 5 and divertor (data in Tab. 10.3).

	N. speed 1 turbo [m ³ /s]	Total n. speed [m ³ /s]	Conductance [m ³ /s]	Eff. speed [m ³ /s]
H₂	1.85	9.25	47.25	7.74
D₂	1.85	9.25	46.94	7.73
He	2.00	10.00	33.41	7.70
H₂O	1.85	9.25	15.69	5.82
N₂	1.85	9.25	12.63	5.34
O₂	1.85	9.25	11.81	5.19
Ar	1.80	9.00	10.99	4.95

Table 13.1: Effective speed of turbo system

In Tab. 13.1 the column **N. speed 1 turbo** is the nominal speed of only one HiPance. The **Total n. speed** is just the nominal speed multiplied by the number of turbos (in this case 5). The **Conductance** column is the global conductance of the system composed by 10 ports 5 and by the divertor (see Sec. 11 or Fig. 11.1). The last column called **Eff. speed** reports the effective speed of the system calculated using the equation (13.1):

$$S_{t-eff} = \frac{S_t \cdot C}{S_t + C} \quad (13.1)$$

where S_t are the data in the **Total n. speed** columns and C are the ones in **Conductance** columns. The pressure is described by the equation (13.2):

$$P(t) = P_0 \cdot e^{-\frac{S_{t-eff}}{V}t} + P_{lim} \quad (13.2)$$

where S_{t-eff} is the effective pumping speed. In this case the study is focused on the one for the hydrogen (for the water see Sec. 13.2). In the equation P_0 is the initial pressure that is the one achieved by the fore-vacuum system (calculated by (12.8)) which is the final pressure in Tab. 12.1). P_{lim} is the limit pressure that can be reached by the turbo-molecular pumps and it depends on the characteristic of the pumps and on the treatment (desorption) of the vacuum vessel. A turbo-molecular pump is defined by the compression ratio between the outlet pressure (fore-vacuum) and the inlet pressure (high-vacuum). The minimum pressure obtained by the turbo-pump is calculated by (13.3)

$$P_v = \frac{P_1}{K} \quad (13.3)$$

From the (13.3) the minimum achievable pressure with the HiPance 2300 pump ($K=2000$) and the foreseen pipes system ($P_1 = 0.5$ Pa) is $2.5 \cdot 10^{-5}$ Pa (for H₂). The other parameters that affects the limit pressure is the

desorption of the vessel material (and leaks not considered here). This limit pressure depends on the outgassing rate q_a that is function of the vessel treatment. In Tab. 13.2 are shown the outgassing rates for the main gasses involved in DTT for the stainless steel AISI 316 LN.

	Outgassing vacuum [*10 ⁻⁶ Pa m ³ /(m ² s)]	Outgassing baking 110°C for 24h [*10 ⁻⁸ Pa m ³ /(m ² s)]	Outgassing baking 200°C for 24h [*10 ⁻⁸ Pa m ³ /(m ² s)]
H₂	0.00	9.6	4.8
H₂O	5.00	80.0	2.4

Table 13.2: Outgassing of AISI 316 LN

The limit pressure depends on the parameter q_a , on the leak rate λ (that presently is considered zero) and the effective speed of the turbo pumps system (value in Tab. 13.1).

$$P_{lim} = \frac{q_a \cdot S + \lambda}{S_{t-eff}} \quad (13.4)$$

From Tab. 12.1 it can be seen that in the hydrogen cases the pressure limit due to the compression of the turbo is higher than the pressure limit caused by the outgassing of the inner vessel surfaces. In Tab. 13.3 a comparison between the pressure limit due to the turbo compression ratio and the limit caused by the outgassing is shown. The limit pressure for hydrogen is of $2.5 \cdot 10^{-5}$ Pa due to the compression ratio.

	Limit compress ratio [*10 ⁻⁵ Pa]	Limit baking 110°C [*10 ⁻⁵ Pa]	Limit baking 200°C [*10 ⁻⁵ Pa]
H₂	2.5	2.35	1.18
H₂O	-	26.00	0.78

Table 13.3: Limit pressure for turbo

It is important to remember that in this case the system is assumed with fore-vacuum pipes 100.0 m length and with a diameter of 0.2 m (see Sec. 12.1). Once the limit pressure has been reached, which is $2.5 \cdot 10^{-5}$ Pa, the cryopumps will be turned on. The cryopumps installation is equal to that of turbo pump, so the effective speed of the cryopumps can be calculated in the same way (see Fig. 11.1). The data are presented in Tab. 13.4.

	N. speed 1 cryo [m ³ /s]	Total n. speed [m ³ /s]	Conductance [m ³ /s]	Eff. speed [m ³ /s]
H₂	5.0	25.0	47.3	16.4
D₂	5.0	25.0	46.9	16.3
He	5.0	25.0	33.4	14.3
H₂O	6.3	31.5	15.7	10.5
N₂	3.0	15.0	12.6	6.9
O₂	3.0	15.0	11.8	6.6
Ar	2.5	12.5	11.0	5.9

Table 13.4: Effective speed of cryo system

	Limit baking 110°C [*10 ⁻⁵ Pa]	Limit baking 200°C [*10 ⁻⁵ Pa]
H₂	1.11	0.56
H₂O	14.5	0.43

Table 13.5: Limit pressure for cryo

The limit pressure collected in Tab. 13.3 and Tab. 13.5 are determined by the initial value of outgassing. These values of pressure limit drop linearly with the time because the outgassing is reduced (the particle trapped in the material progressively decrease). With this consideration the pressure can be calculated using the relation (13.5)

$$P(t) = \frac{t_0 P_{lim}}{t + t_0} \quad (13.5)$$

where t_0 is a reference time in which the decrease of the outgassing is measured. From the literature typically it is considered of 1 hour. In Fig. 13.1 the evolution in time of pressure starting from the atmospheric to the target pressure is reported. For the color of the chart the scheme in Fig. 11.3 must be taken as reference.

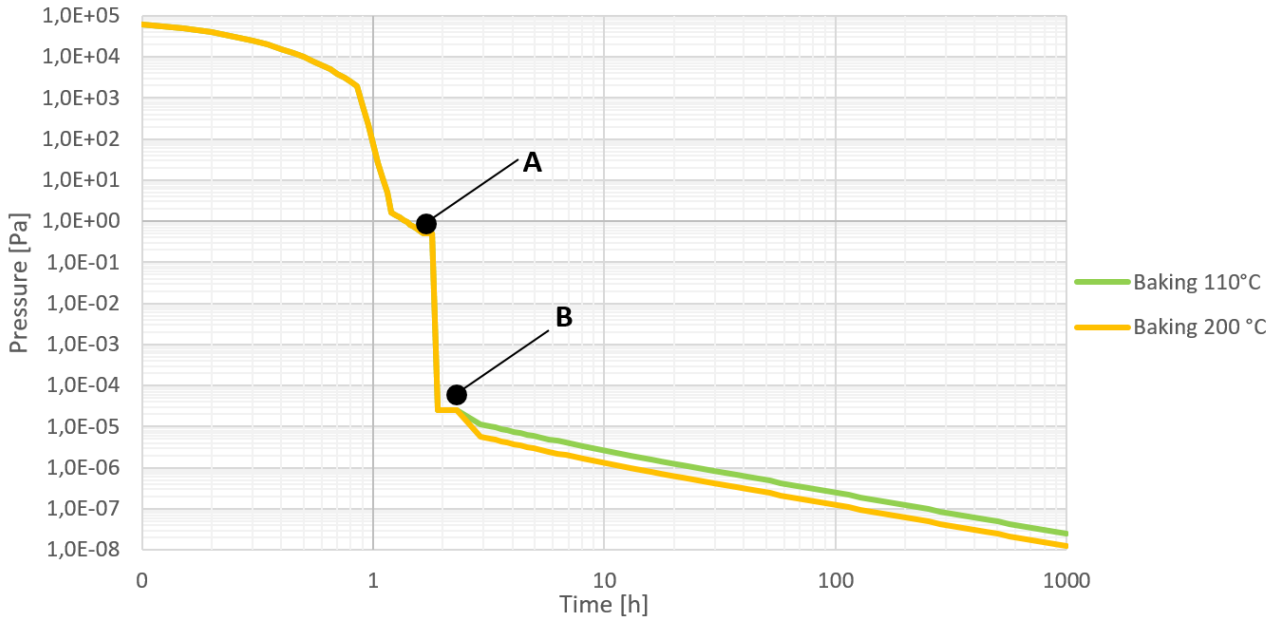


Fig. 13.1: Pressure trend for H₂

With green and light orange are indicated the pressure curve inside DTT vacuum vessel respectively with 110°C and 200°C baking process. At the point **A** the turbos are turned on and the pressure drops very quickly to the value of $2.5 \cdot 10^{-5}$ Pa that is the structural limit of the system. Instead, at the point **B** the cryo pumps are turned on. The amount of gasses trapped inside the surface progressively is reduced so also the limit pressure is reduced. This is possible because the cryo pumps have not the limitation of turbo related the compression, but the pressure is limited by the outgassing only.

Pressure with Baking @ 110°C [Pa]	Pressure with Baking @ 200°C [Pa]	Time [h]
10^5	10^5	0
0.58	0.58	1.8
$2.56 \cdot 10^{-5}$	$2.56 \cdot 10^{-5}$	2
$2.31 \cdot 10^{-6}$	$1.20 \cdot 10^{-6}$	10
$2.33 \cdot 10^{-7}$	$1.63 \cdot 10^{-7}$	100

Table 13.6: Resume of pressure trend case H₂

13.2 H₂O Case

In this section the case of water (H₂O), that is the most relevant after vessel venting, is considered. As reported in Tab. 13.2 and Tab. 13.3 the H₂O outgassing is the maximum between the gasses involved. The compress ratio for H₂O for the HiPace is not available but considering that the turbos show low compression ration for small molecules the worst case is in any case the hydrogen analysed in the previous section. So, in the H₂O case the pressure is limited only by the outgassing of the surface.

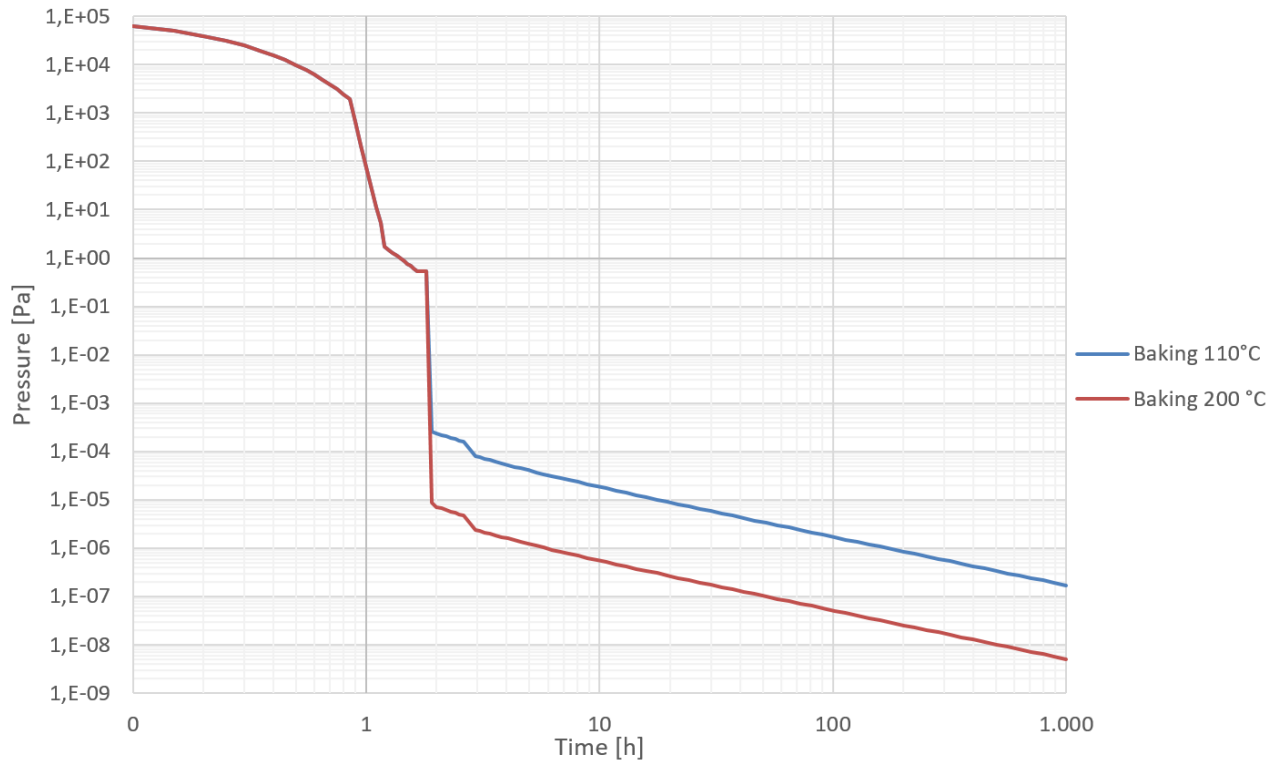


Fig. 13.2: Pressure trend for H₂O

In Fig. 13.2 the time evolution of the pressure is shown. The blue line is the case with baking at 110°C for 24h whereas the orange line is the case at 200°C. In Tab. 13.7 the main points of the pressure trend are summed.

Pressure Baking 110°C[Pa]	Pressure Baking 200°C[Pa]	Time [h]
10^5	10^5	0
0.53	0.53	1.8
$1.45 \cdot 10^{-4}$	$4.34 \cdot 10^{-6}$	2.6
$1.32 \cdot 10^{-5}$	$3.95 \cdot 10^{-7}$	10
$1.43 \cdot 10^{-6}$	$4.30 \cdot 10^{-8}$	100

Table 13.7: Resume of pressure trend case H₂O

13.3 Analysis with numerical tool

As for the previous case in order to have a check of the result an equivalent system was simulated using the Leybold tool described in Sec. 12. In Fig. 13.3 the equivalent layout created for the simulation is reported. The target pressure is set to 10^{-6} Pa and a desorption rate of 10^{-4} Pa·m³/(s·m²) (steel clean from Leybold datasheet).

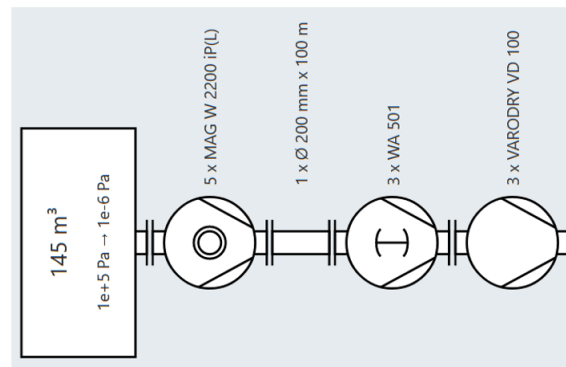


Fig. 13.3: Pressure trend for H₂O

The tool estimated the pressure considering an optimistic case and a pessimistic case, the results are shown

in Fig. 13.4. From Fig. 13.5 it can be seen that there is a gap between the result obtained in Sec. 13.2 and the ones calculated using the Leybold tools. Comparison between the two curves is difficult because the Leybold software gives only few points to draw the chart. In any case, the difference can be found principally in the difference between the outgassing values: $10^{-4} \text{ Pa}\cdot\text{m}^3/(\text{s}\cdot\text{m}^2)$ from the library of the Leybold software and $8.0\cdot 10^{-7} \text{ Pa}\cdot\text{m}^3/(\text{s}\cdot\text{m}^2)$ (see Tab. 13.2 for baking at 110°C) for the calculation in Sec. 13.2. In Fig. 13.6 the pressure obtained with the Leybold tool but using the data from Tab. 13.2 is reported. The comparison between this new Leybold case and the H_2O case is shown in Fig. 13.7. In this case it is evident that the two cases matched very well.

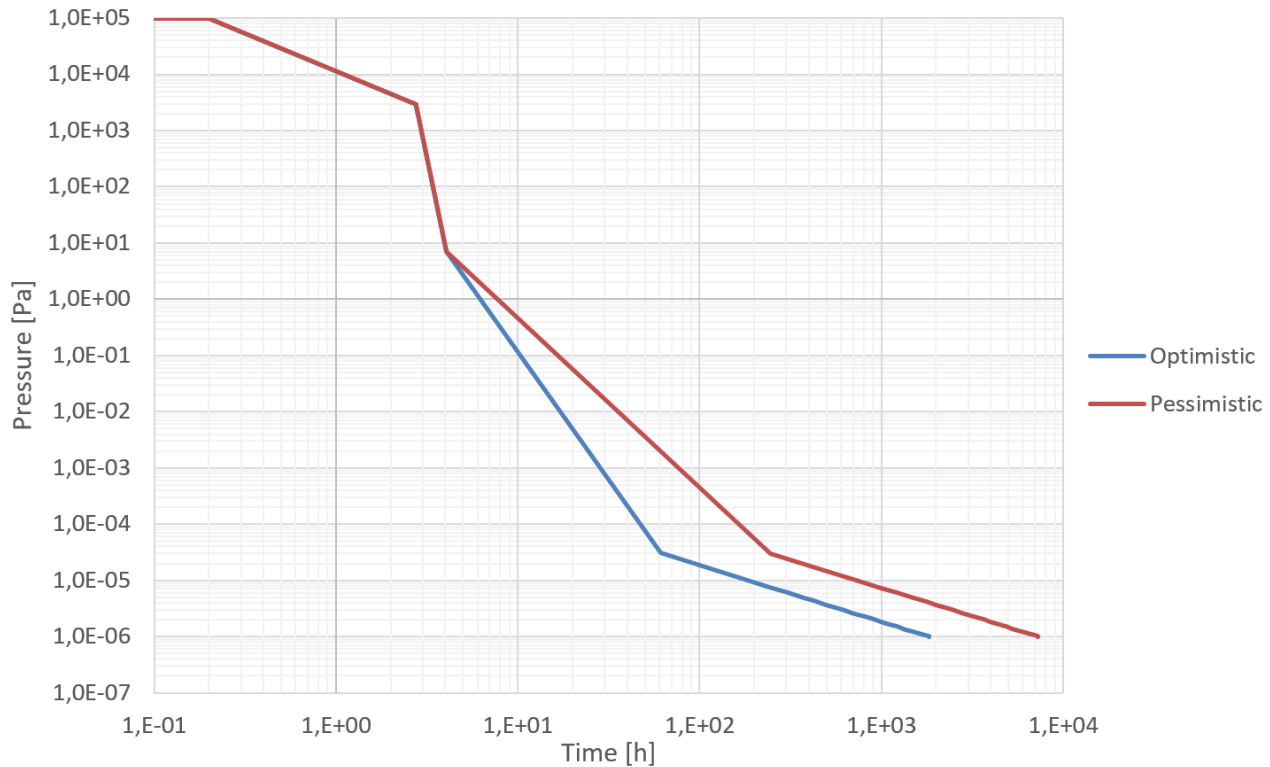


Fig. 13.4: Pressure trend from Leybold tool

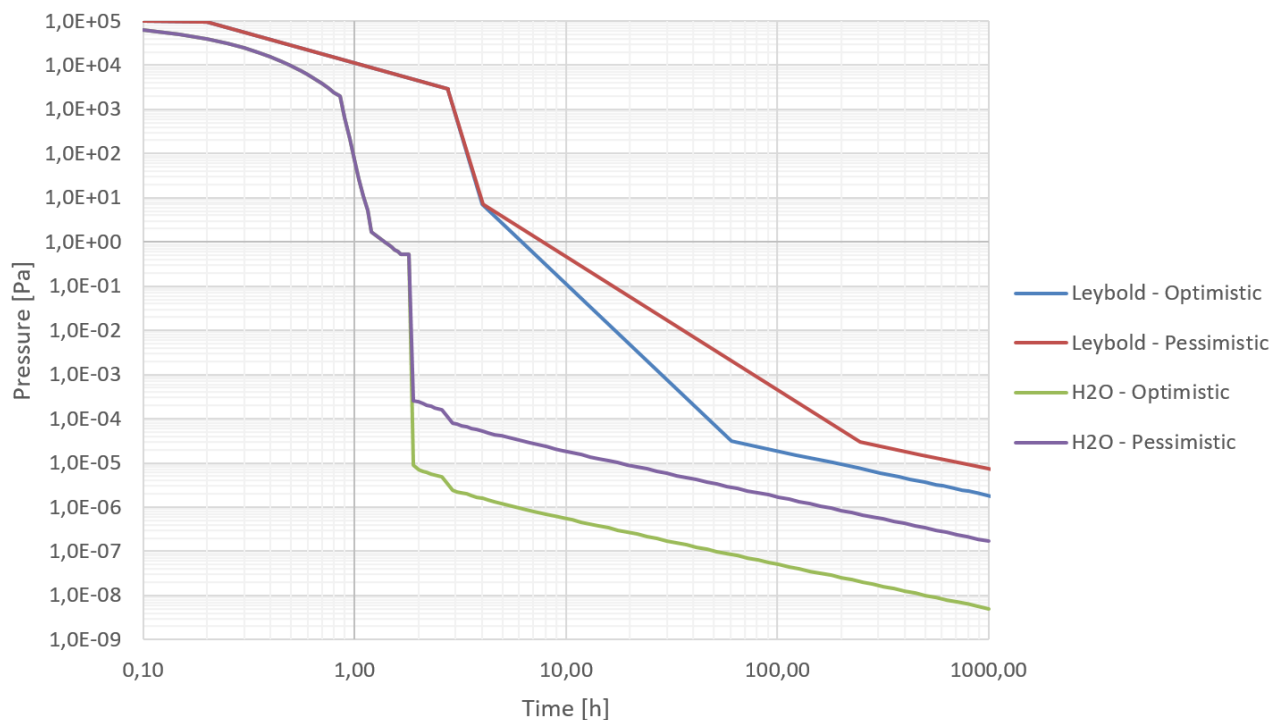


Fig. 13.5: Comparison of pressure trend

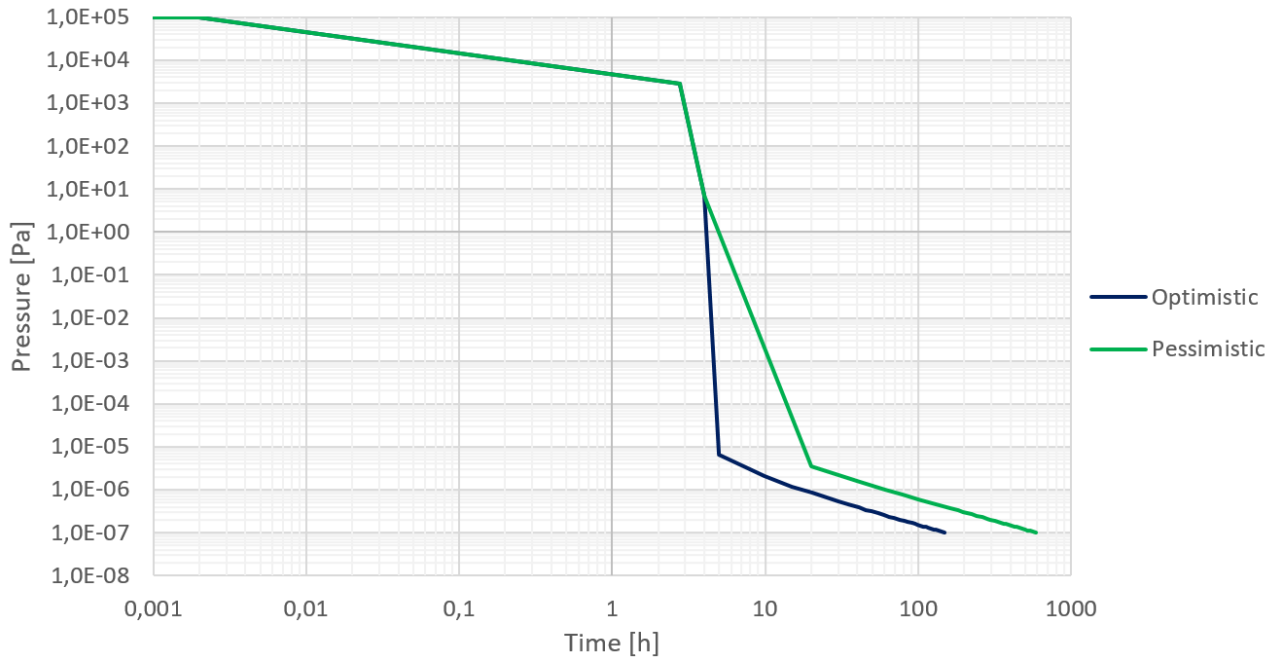


Fig. 13.6: Pressure from Leybold tool with new desorption rate

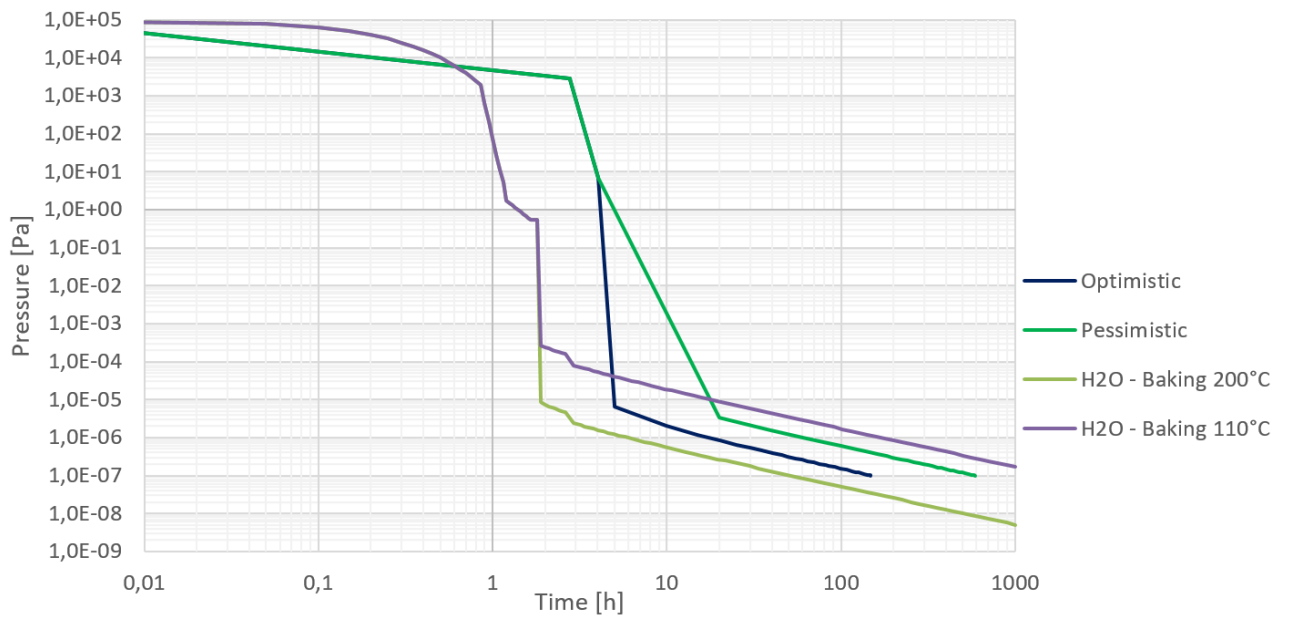


Fig. 13.7: Comparison between the Lybold (new desorption rate) and H₂O case

This analysis has underlined that the procedure used to the design of the system is in agreement with the numerical tools and that the most critical element is the value of the out-gassing. Considering the Fig. 13.7 the most pessimistic case shows that the target pressure of $5 \cdot 10^{-5}$ Pa can be achieved in about 20 h of pumping. The procedure of pumping after the venting requires at least two days of continuous pumping to achieve a pressure of 10^{-6} Pa. It is important underline that the procedure presented doesn't take into account possible leaks in the system.

Regeneration of the divertor pumping system

During DTT pulse operation the cryopanel of divertor pumping system absorb and trap nearly all gasses injected in the vessel by gas puffing, pellet injection and neutral beam injection. For safety reasons, it is essential to prevent the accumulation of large amounts of potentially explosive hydrogen on the panel surfaces. For this reason, a typical operating procedure includes regenerating the cryopanel at the end of each day. During regeneration, the temperature of the cryopanel is increased to release absorbed and trapped particles, which are then removed by the vacuum vessel pumping system. In this section, we estimate the time required for regeneration; however, the time needed to increase the cryopanel temperature is not considered, as it depends on the specific cryopanel design. The pumping time depends on the amount of gas captured by the cryopanel, which is influenced by the gas pressure at the cryopanel, their pumping speed, and the total loading time. To estimate the upper limit of captured gas, we consider full-power detached pulses. Edge modeling has indicated a pressure of approximately 1 Pa for H₂ at the entrance of port 5. DTT is nominally designed to perform 10 full-power pulses lasting 100 seconds each day; however, to provide a safety margin, we have assumed 20 pulses lasting 120 seconds. Assuming constant pressure, the captured gas can be calculated using equation (14.1).

$$Q_t = N_s \cdot \delta t \cdot P \cdot S_{cryop} \quad (14.1)$$

Tab. 14.1 summarized previous parameters and the estimated amount of captured hydrogen (much smaller amount of seeding gases like N, Ne, Ar, or impurity like O are also captured).

Number of shoots	N_s	20
Total pulse length	[s]	120
Pressure [Pa]	P	1
Cryo pumping speed [m³/s³]	S_{cryop}	120
Gas trapped in the cryo [kPa m³]	Q_t	288

Table 14.1: Operating parameters of cryopanel

The pressure reached in the vacuum vessel after heating the cryopanel depends on the Q_t and the volume of the vacuum vessel. In this case a pressure of $\simeq 2$ kPa (or about 0.02 Atm) is reached. Using the same method applied in the previous section the time evolution of pressure during pumping can be computed, Fig. 14.1 shows the pressure during the regeneration. The result shows that pumping time during regeneration is relatively short also in case of extreme loading conditions. After the regeneration it is not request a high-vacuum level so in order to improve the efficiency of the system only the fore-vacuum elements can be used to dispose the major part of the hydrogen released by the cryopanel. Anyway, if a lower level of pressure is requested the turbos can be used to drop the pressure below $5 \cdot 10^{-5}$ Pa. The pressure under 10^{-5} Pa request for the shots is obtained easily using the cryopanel that are turned on at the start of the working day.

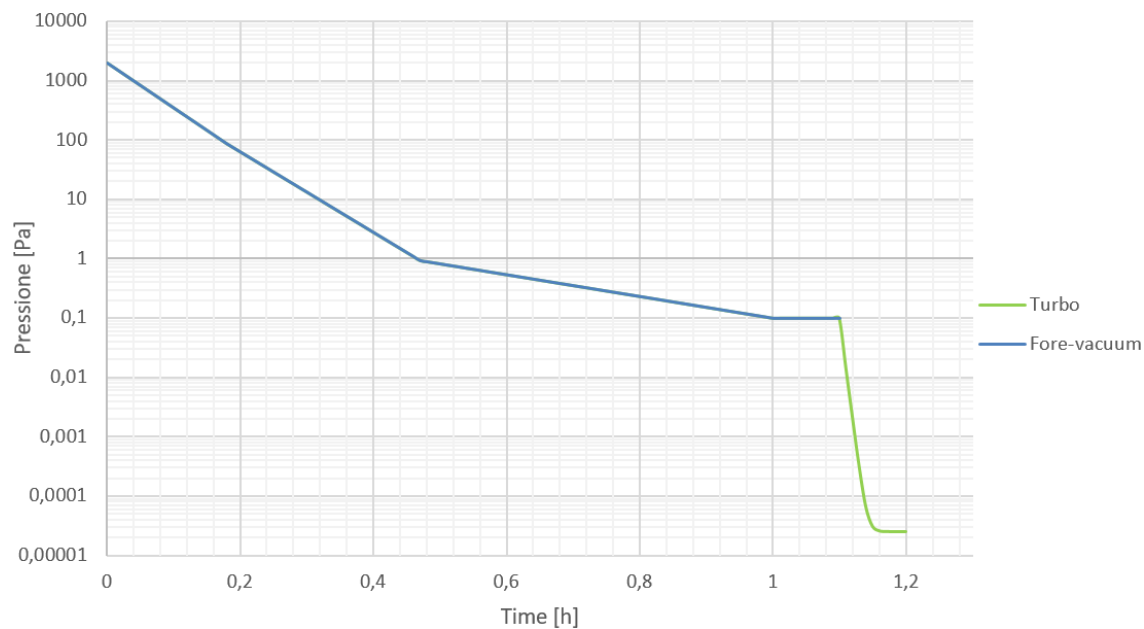


Fig. 14.1: Time evolution of in-vessel pressure during the regeneration process (slope variation at 0,5 h is due to the simplified transition between laminar flow and molecular flow)

Pressure [Pa]	Time [h]
1983	0
0,1	1,1
$2,5 \cdot 10^{-5}$	1,2
$3,6 \cdot 10^{-6}$	2

Table 14.2: Summary of the pressure evolution during the regeneration

Firstly, the two port connection solutions available are analysed in terms of global conductance (ports and divertor) and the results are reported in Tab. 10.3. The values estimated in molecular flow regimes show that the configuration based on the port 5 provide a slightly higher conductance allowing a better utilization of pumping system. Considering also that port 5 is less useful for other systems (diagnostic systems, remote handling, etc.) than port 4 the vacuum vessel pumping system has been designed to be connected to port 5. The fore-vacuum elements are stored in a fire-protected zone in the torus hall at about 50 m from the vacuum vessel. While, the high-vacuum pumps are installed on manifolds which connects two ports 5. The system is composed by two sub-systems: one dedicated to the cryostat and one for the vacuum vessel. In this document only the vacuum vessel side is analysed. A preliminary design and study of the performance of the vacuum system has been done using commercial components from Pfeifer as an example. The effect of pipes that connect the fore-vacuum components to the high-vacuum ones has been analysed and pipes diameter has been selected to avoid an important deterioration of pumping performance. Analytically the pressure drop has been calculated in function of the pipes diameter and the results obtained have been compared with a commercial tool by Leybold. Using a pipe length twice than the expected one it was shown that the system performance increases when the pipe diameter increases from 50 mm to 300 mm. However, considering the pumping timing the cost to increase the diameter over 200 mm are not justified by the improvements obtained. For this reason, a diameter of 200 mm has been considered reasonable because it meets both the vacuum system performance target that the torus hall build constrains. The pressure drop introduces for the H_2 a structural limitation on the reachable pressure due to the compress ratio. In the H_2 case the target pressure can be achieved with the cryopumps or introducing a second small turbo molecular pump behind the first one (as in JT-60SA), the last solution is less expensive than adding commercial cryopumps but provide less pumping speed which are useful in case of strong desorption or small leakages. In term of achieving the target pressure the most relevant case is the one with water because these molecules are desorbed by the inner surface of the vessel limiting the pressure achieved. From the analysis carried out it is obtained that, the target value can be reached in about 20 h. It is important underline that this timing is obtained using the value of outgassing in case of baking so to the 20 hours must be added the timing for the baking process (about 24 hours). It can be concluded that, also considering a safety margin, in about 100 h a pressure under 10^{-5} Pa can be reached. This result is also validated by comparison with the result obtained by the Leybold tool. Vacuum vessel pumping system will be also used to regenerate the divertor pumping system composed by nine cryopanel. Considering a typical DTT workday the regeneration process is analysed. After that the gasses trapped in the panel is released the system can restore the target pressure in about 2 hours making easy the regeneration at the end of the working days.

Part IV

**Vacuum Ultraviolet Spectrometer for
JT60-SA**

Given the key role of the divertor in the new generation fusion devices, JT60-SA is set to be equipped with a suite of divertor dedicated diagnostic systems. One of these systems is a double channel VUV spectrometer, which is presented in this part of the thesis. The spectrometer is based on the double SPRED spectrometer employed on Textor [9], refurbished with new specially designed gratings to maximize the spectral resolution for the given etendue [10], and two new CCD detectors. The spectrometer will be positioned on an upper port with a vertical line of sight, will complement the divertor monitoring activity by measuring the relative contribution of the various impurities to the radiation losses and by studying the physics of the plasma- detachment mechanism. The ongoing activity aims to complete the commissioning of the instrument. It involves designing, manufacturing, installing and testing of the remaining sub-systems to complete the instrument. This encompasses components such as the 0-order, electrical panel, limit sensor for in-vessel mirrors, chassis for the laser used for alignment of the spectrometer view on the divertor, etc. The installation and tests of the new toroidal gratings and, the wavelength calibration of the two channels of the instrument is included in the activity. To describe the carried out work, in Sec. 16 and Sec. 17 respectively a brief overview the physical principle of this kind of diagnostic and the specific requirement of this system are reported. Sec. 18 and Sec. 19 report the design of the instrument and finally Sec. 20 illustrate the calibration of the spectrometer.

Plasma spectroscopy is a very powerful and not perturbing diagnostic tool, especially for hot and high density plasmas where no material probe can be inserted. At high electron temperatures impurity emission lines are mainly in the the vacuum ultraviolet (VUV) /SXR spectral region, and , VUV spectroscopy is widely employed to track impurity species and gather information about their distribution [99]. Recognizing its importance major machines such as JET [60], K-Star [93], Alcator C-MOD [86], Textor [9], West [34], EAST [41], ASDEX [28], DIII-D [54] and stellarator like Wendelstein 7X [10] and LHD [74] or reversed field pinch experiment as RFX [5] are equipped with this system. The new generation fusion device like ITER [94], DTT [2] and JT60-SA will be equipped with similar diagnostics. In conclusion a thorough understanding and control of impurity content in the plasma are crucial for ensuring the device's safety, especially with regard to the load on and lifespan of plasma-facing components. Spectroscopic monitoring of emission lines is an effective and widely adopted method for investigating impurity behavior without significant perturbation. In the fusion devices plasma typical conditions, the strongest spectral lines for most relevant impurity ions are located in the vacuum ultraviolet (VUV, 80 to 200 nm) and extreme ultraviolet (XUV, 1 to 100 nm) spectral h range [9]. A visualization of the different wavelength ranges is reported in Fig. 16.1. The VUV light is heavily absorbed by the components of air, such as oxygen and nitrogen [106] [4]. This absorption is due to the high energy of VUV photons, which can ionize or excite these molecules, effectively preventing VUV light from traveling long distances through the atmosphere. This strong absorption means that VUV radiation can only propagate in a vacuum or very low-pressure environments. In general, pressures of about 0.01-0.001 Pa are maintained in the spectrograph, thus minimizing any absorption due to residual atmospheric gases, especially below 100 nm [51]. For this reason the range below 100 nm is dubbed vacuum ultraviolet wavelength range (VUV).

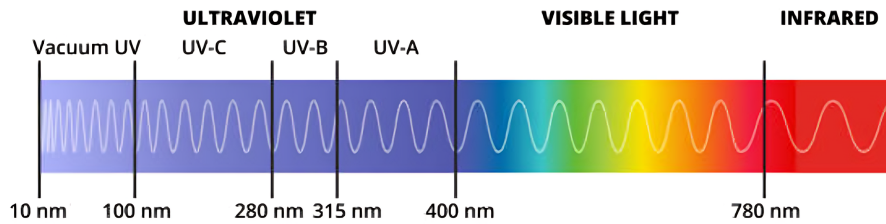


Fig. 16.1: Nomenclature of the different wavelength range.

Three key optical components make a spectrometer: the entrance slit, the diffraction grating and the detector. Radiation entering through a narrow slit is dispersed by a grating, and the spectrum is then brought to a focus plane where the sensors are located. The electromagnetic radiation is diffracted in its wavelength components according to the gratings equation (16.1) [77][30].

$$d(\sin \alpha + \sin \beta) = m\lambda \quad (16.1)$$

where d is the spacing between adjacent rulings of the grating, α and β are respectively the angles of incidence and diffraction, λ is the wavelength, and m is an integer known as "the order number". Typically, instruments are designed to measure the first order ($m=1$) because it is the most intense. In first order condition the light is deflected with an angle determined by the grating characteristic d and by the wavelength λ , resulting in an angular dispersion of the spectral components. A schematization of this configuration is shown in Fig. 16.2. A part of the light is not diffracted but simply reflected. This condition is called 0-order, i.e for $m=0$. According to (16.1), with $m=0$, the angles α and β are equal and independent by the wavelength. In other words, the grating behaves like a mirror. This feature is used as a valuable tool for instrument alignment (further details on its application in the spectrometer object of this work is given in Sec. 20.2).

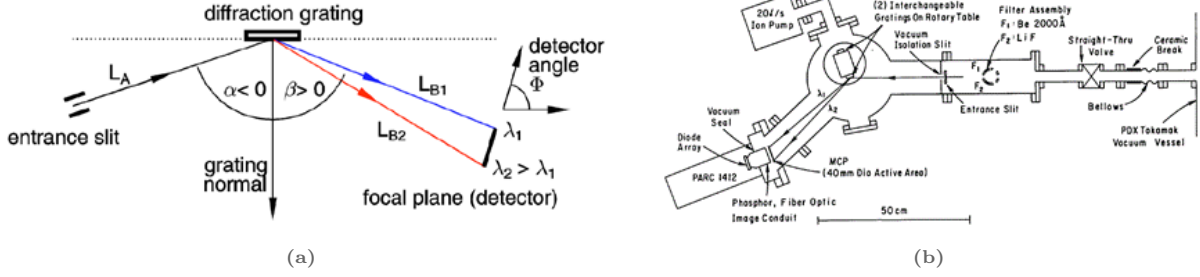


Fig. 16.2: Classic set-up of a VUV spectrometer: (a) schematization of a spectrometer, which consists of an entrance slit, a grating, and a detector [10]; (b) equatorial cross section of a SPRED spectrometer [30]

The spectrum obtained consists of a series of displaced spot of the entrance slit, corresponding to the different spectral components of the incident radiation. The instrument's ability to distinguish closely spaced spectral lines is referred to as the spectrometer resolution. Assuming a sufficiently narrow slit and negligible aberrations of the auxiliary optics, the width of the slit image for truly monochromatic light is determined by Fraunhofer¹ diffraction from the grating [77], so the slit aperture must be chosen in compromise between the resolution and the throughput of the system with a typical value between 0.025 and 0.25 mm [11][74]. JT60-SA VUV spectrometer (the diagnostic discussed in this work), a slit of 0.05 mm will likely be used during the initial operating period. The power of a grating is defined as

$$RP = \frac{\lambda}{\delta\lambda} \quad (16.2)$$

where $\delta\lambda$ is the smallest wavelength interval that can be resolved at a wavelength λ . On the basis of the Rayleigh criterion and from equation (16.1), the equation (16.2) can be rewritten in the form of [77]

$$RP = mN = \frac{mW}{d} = \left(\frac{W}{\lambda}\right) (\sin \alpha + \sin \beta) \quad (16.3)$$

Where N is the total number of grooves and W is the width of the grating, The grating is typically employed in the first diffracted order, i.e., $m=1$, resulting in a resolving power equal to the total number of grooves N from equation (16.2). As consequence, the resolution can be increased by increasing the width W and/or the grating groove density d . So it can be concluded that high resolutions may be achieved with gratings having relatively small values of d . Of course, this reasoning is limited by the manufacturing limit. Actually, the previous discussion primarily applies to plane gratings, as the resolving power of concave gratings is typically limited not only by groove density and width but also by geometric and optical considerations [77]. The gratings can be divided in two classes: reflection and transmission grating. Many materials are opaque in the VUV wavelength range (typically wavelengths shorter than 200 nm). This opacity prevents the use of transmission gratings because the grating material would absorb or block the VUV light instead of diffracting. The reflective gratings can further subdivided into mechanically or optically produced: ruled gratings are mechanically scribed resulting in a triangular shape of the groove as illustrated in Fig. 16.3a; the grooves in holographic gratings are optically obtained exposing the substrate to a laser interference pattern [76]. A holographic manufacturing shows generally sinusoidal grooves, as shown in Fig. 16.3b.

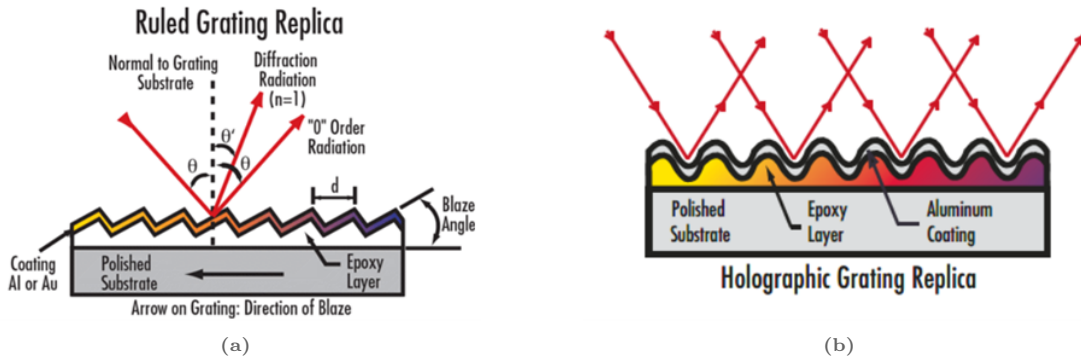


Fig. 16.3: Different kind of gratins [76]: (a) ruled grating obtained with mechanical procedure that results in triangular shape of the grooves; (b) holographic grating optically obtained exposing the substrate to a laser interference pattern

In order to optimize the performance, the optical element involved in the VUV spectrometer (grating included)

¹The Fraunhofer diffraction equation is used to model the diffraction of waves when the diffraction pattern is viewed at a long distance from the diffracting object

are typically gold or platinum coated, assuring higher reflectivity than other metals (i.e. aluminum), at wavelengths below 100 nm.

Physical requirements

The definition of wavelength ranges for the new instruments in JT60-SA depends on expected particle species present in the plasma and their most intense resonance lines. Under typical plasma conditions in magnetic fusion experiments, the strongest spectral lines of most relevant impurity ions are located in the vacuum ultraviolet (VUV) range, spanning from 10 to 200 nm [9] [11]. During its Initial Research Phase, JT-60SA will be equipped with an inertially cooled CFC/graphite divertor [18]. However, it is foreseen, upon achieving the integrated long-pulse high- β operation with the CFC monoblock divertor, that JT-60SA will explore more ITER and DEMO relevant configurations by adopting actively cooled plasma-facing components fully covered with tungsten [102]. As a consequence, the VUV divertor system must be capable of detecting both carbon and metal species, with a particular emphasis on tungsten. Due to the topological complexity of the radiation pattern, the VUV divertor spectrometer requires imaging capabilities to resolve the inner leg, outer leg, and X-point regions of the divertor [103]. The wavelengths of scientific interest are detailed in Table 17.1. To meet these scientific objectives, the VUV Spectrometer must be capable of capturing the entire Lyman series, starting from Ly- α (121.53 nm). The grating's wavelength resolution should also effectively separate Ly- γ (97.23 nm) from the strong C III emission line at 97.7 nm. Two gratings have been chosen to cover the ranges of 10-48 nm and 44-125 nm, with an overlapping region that includes the 45.96 nm C III line for cross-calibration.

Ionization stage	Wavelength [nm]	Note
D I	97,227	
	102,544	'Branching ratio' calibration
	121,534	Lyman-alpha giving ~90% of D radiation
He I	53,703	Branching ratio calibration
	58,433	
He II	24,303	Branching ratio calibration
	25,632	
	30,378	Lyman-alpha giving ~90% of He II radiation
C II	90,410	
C III	37,173	
	38,620	
	45,960	
	53,826	
	57,428	Branching ratio calibration
	97,702	
C IV	31,243	Branching ratio calibration
	38,413	
	41,965	
C VI	18,223	Balmer-alpha
N III	68,570	
	76,400	
N IV	28,350	
	32,270	
	76,515	Neighbouring weaker N III line at 76,400 nm
N IV	92,320	
N V	20,929	
	26,632	
	123,882	

	124,280	
N VII	13,387	Balmer-alpha
O IV	55,440	
O V	19,287	
	62,973	
O VI	17,303	
	103,191	
	103,761	
O VIII	10,249	Balmer-alpha
Ne III	48,960	
Ne IV	46,984	Neighbouring weaker Ne VII line at 46,522 nm
	54,330	Multiplet components at 54,113 and 54,207 and 54,388 nm
Ne V	36,559	
	41,621	
	48,250	
	57,100	Neighbouring Ne VII line. Multiplet components at 55,860 and 56,272 and 56,281 nm
Ne VI	40,170	
	56,100	Neighbouring Ne VII line. Multiplet components at 55,860 and 56,272 and 56,281 nm
Ne VII	46,522	
	56,160	Neighbouring Ne VI line. Multiplet components at 56,138 and 56,173 and 56,299 and 56,453 nm
Ne VIII	77,041	
	78,032	
Ar VII	58,575	
Ar VIII	70,024	
	71,380	
Ar XV	22,115	
Ar XVI	35,385	
	38,907	Blend with Cr XIV at 38,986 nm and neighbouring C IV line at 38,413 nm
Cr XIII	32,827	
Cr XIV	38,986	
	41,205	
Cr XXI	14,991	
Cr XXII	22,302	
	27,974	
Fe XV	28,416	
Fe XVI	33,541	
	36,076	
Fe XXIII	13,291	
Fe XXIV	19,203	
	25,511	
Ni XVII	24,919	
Ni XVIII	29,199	
	32,056	
Ni XXV	11,799	
Ni XXVI	16,541	
	23,342	

Table 17.1: Wavelength of interest for the VUV spectrometer of JT60-SA

18.1 Mechanical layout

The optical components of the VUV spectrometer are integrated within a vacuum vessel, which is installed into a chassis designed for mounting the instrument onto the tokamak cryostat. Fig. 18.1 provides an overview of the system, while Fig. 18.2 illustrates the installation of the spectrometer on JT-60SA. Specifically, the spectrometer will be positioned on the upper port of sector 12 and installed and connected to the vacuum environment of the tokamak. Given the high vacuum level required for minimizing air VUV absorption, the system is further equipped with a dedicate vacuum pumping system which is detailed in Sec. 18.2. The diagnostic vessel is divided into two smaller chambers. The first one, cylindrically shaped, is named spectrometer and hosts the gratings and the CCD detectors. Whereas, the second one has a spherical shape and houses the small mirrors that direct the light from the larger ones towards the slits (Fig. 19.1 shows the position inside the structure of the different optical components). The two chambers arrangement is indicated in Fig. 18.1. The slits, width between 0.005 and 0.3 mm, are situated on the flange connecting the two vessels.

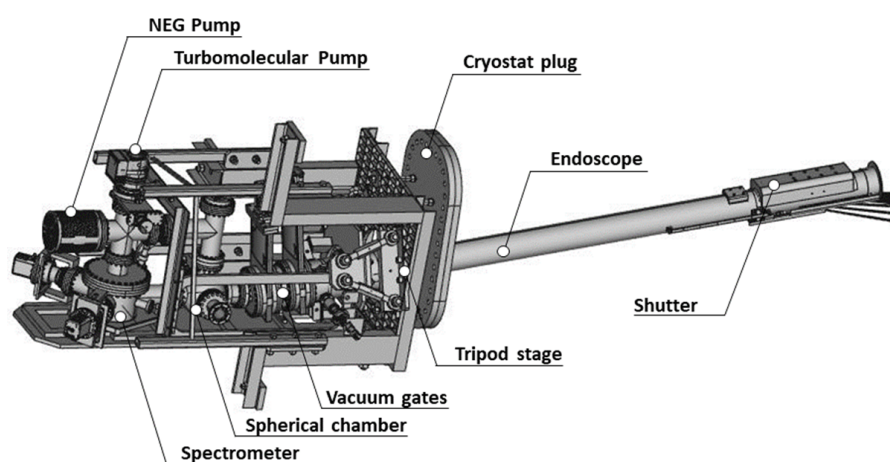


Fig. 18.1: Nomenclature of the different wavelength range.

The slits width and position behave as a closed path when the pressure in the vessel is enough low to be in molecular flow regime (high vacuum). So, to ensure a more efficient pumping and an uniform pressure distribution, the two chambers (spectrometer and spherical) are further connected by a C-shaped pipe.

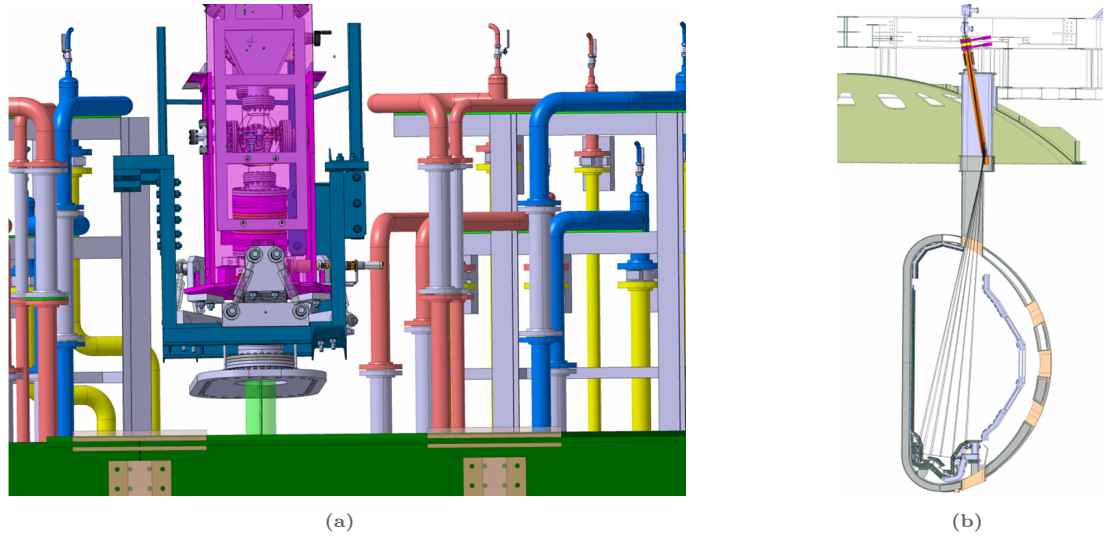


Fig. 18.2: The diagnostic installation of the VUV: (a) the VUV spectrometer is shown installed on the cryostat. The system, bolted to the surrounding structure, includes the cryostat (green), the mezzanine (light gray), the spectrometer (pink), and the cooling pipe of the tokamak (red and blue); (b) the instrument, highlighted in orange, is mounted on the cryostat, with an endoscope visibly penetrating the vessel duct. The Line of Sight (LoS) traces the path from the first cylindrical mirrors to the divertor.

The system is connected to the tokamak by means of a flange, referred to as Cryostat plug in Fig. 18.4a, acting as an air-vacuum interface for the JT-60SA vacuum vessel. Once the cryostat plug is sealed, the diagnostic chassis is bolted to the mezzanine surrounding the tokamak (depicted in light grey in Fig. 18.2a). The relative position between the structure and the spectrometer can be optimized using the tripod stage installed behind the spectrometer. A bellows installed between the cryostat plug and the first gate valve allows for displacement, via tripod, between the three components: spectrometer, cryostat plug, and mezzanine. Once the final position is achieved, the spectrometer is fixed to the mezzanine by tightening the tripod stage, which is itself secured to the diagnostic chassis.

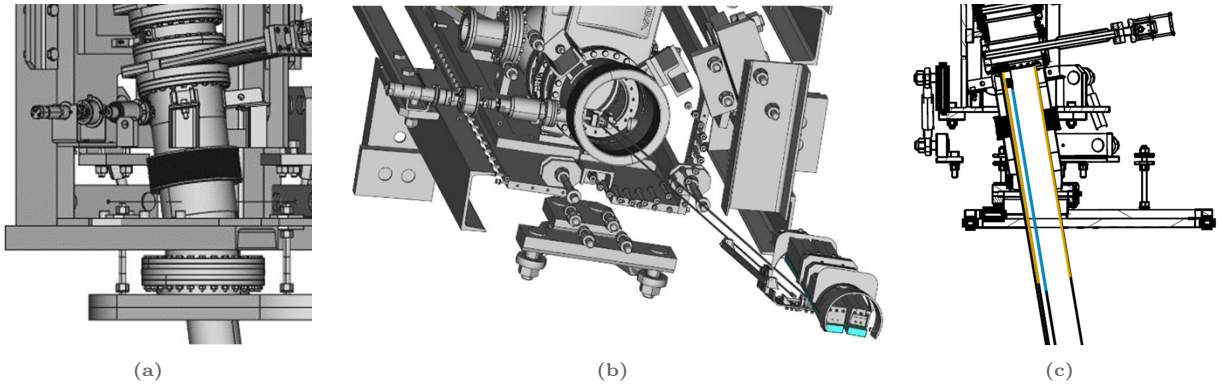


Fig. 18.3: Detail of the structure: (a) the pneumatic rotary throughput which moves a rope that open/close the shutter that covers the bigger mirrors at the end of the endoscope; (b) prospective image where the rope that moves the shutter can be seen. In light blue the lower mirrors; (c) cross section of the instrument. In orange the endoscope pipe while in light blue the shutter rope.

The endoscope is fixed after the second vacuum gate (closer to the cryostat) to ensure rigid connection to the spectrometer (see Fig. 18.3c). It passes through the bellow and cryostat plug, terminating near the vacuum vessel as shown in Fig. 18.2b. At the end of the endoscope, two larger mirrors are installed to reflect plasma emissions towards the spherical chamber, which houses smaller mirrors along the endoscope. These smaller mirrors further focus the light onto the slits (specific details are given in Section 19). The larger mirrors are protected by a shutter controlled via a pneumatic rotary feedthrough installed before the bellow (see Fig. 18.3). The shutter's movement is actuated by a rope fixed to it. Rotation of the feedthrough causes the rope to push the shutter, thereby adjusting its position to either cover or open the mirrors' line of sight. Fig. 18.3 provides two prospective views showing the rope mechanism.

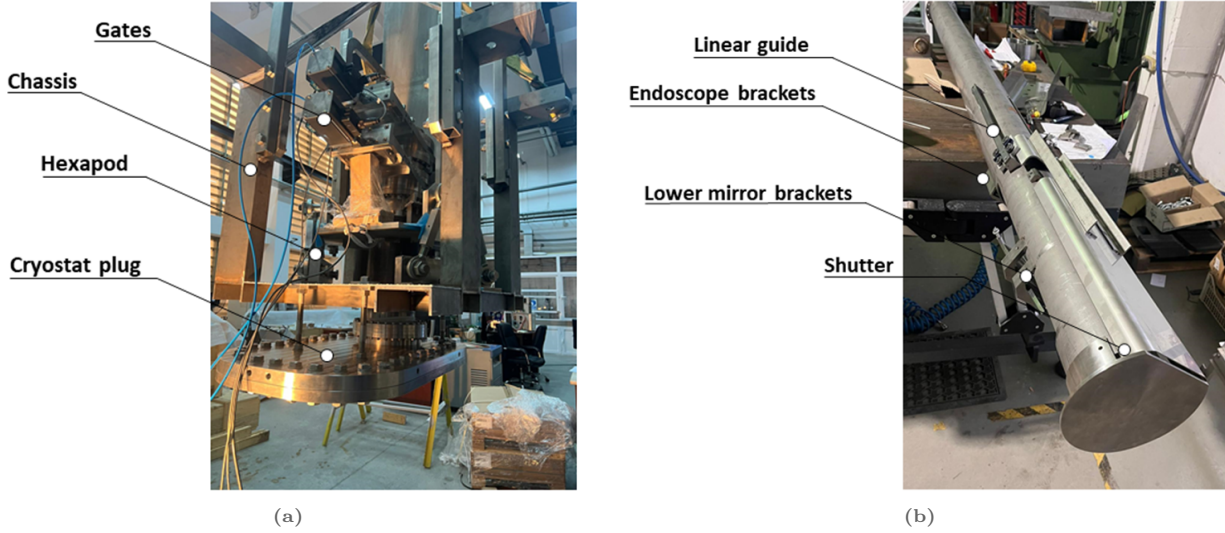


Fig. 18.4: Pictures of the components: (a) spectrometer chassis during the leak test. From the bottom, the cryostat plug, the hexapod for the alignment and the double gates. The structure is inserted in the chassis that will be bolted on the tokamak mezzanine; (b) endoscope picture. On the top the linear guide that drives the movement of the shutter, instead at the bottom the bracket of the lower mirrors and of the endoscope mirrors.

18.2 Vacuum system

As mentioned in Sec. 18.1, the system is composed by a vacuum vessel that will be installed and connected to the vacuum environment of the tokamak. Due to the high vacuum level required for minimizing air VUV absorption, the system is equipped with a dedicate vacuum pumping system. The diagnostic vessel is divided into two smaller chambers. The first, with a cylindrical shape, named spectrometer, hosts the gratings and the CCD detectors. On the other hand, the second chamber has a spherical shape and houses the smaller mirrors. The global structure is shown in Fig. 18.1 while a detailed view is given in Fig. 18.5.

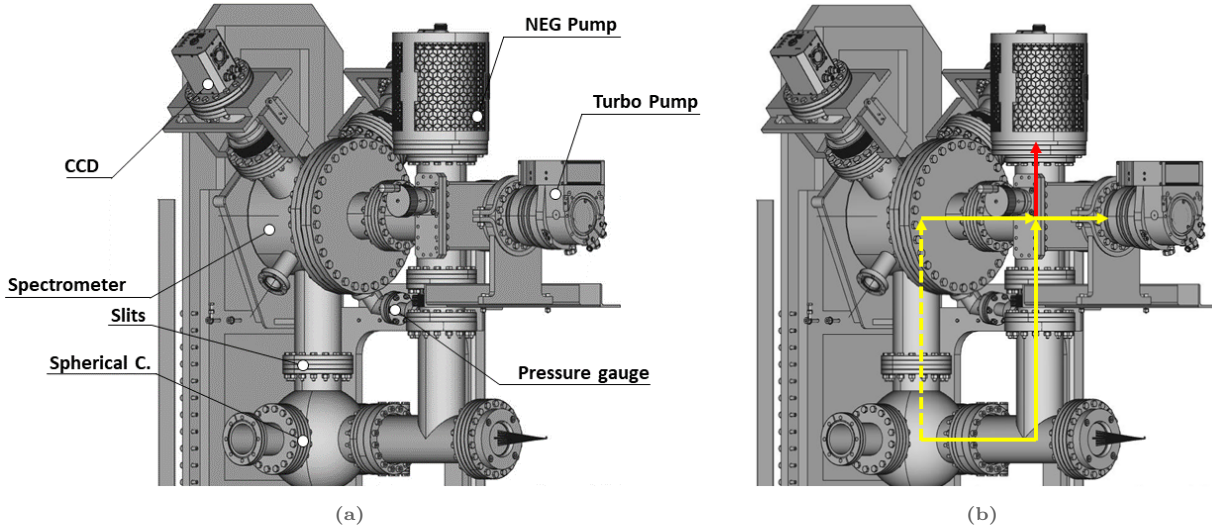


Fig. 18.5: Detail of the vacuum pumping system:(a) with indicated the different elements involved in the pumping system; (b) Path of the flow during the pumping. The yellow arrows indicate the path of the air. During the molecular flow (high vacuum) the path indicate with the dash line is closed due to the geometry. In red the arrow, towards the NEG pumps, indicated that only the hydrogen is pumped.

The vacuum pumping system is composed by two pumps: a getter pump model NEG SAES CapaciTorr HV 1600 ¹ and a turbomolecular pump model Leybold TurboVac 350 IR DN100 ². The two pumps are installed in a cross-way pipe bolted on the spectrometer chamber as shown in Fig. 18.5a. Fig. 18.5b shows the path of the flow during the pumping. The continue yellow arrows indicate the path of the air during the pumping while the dashed arrow indicate the path that cannot be used in molecular flow. When the pressure decreases the air flow changes from turbulent regime to molecular flow (Knudsen number lower than 0.5), condition in which

¹SAES CapaciTor 1600 HV – URL:<https://www.saesgetters.com/highvacuum/solution/capacitorr-hv/>

²LEYBOLD TurboVac 350 IR – URL: <https://www.leyboldproducts.it/prodotti/pompe-da-alto-vuototecnologia-crio/turbovac-turbovac-mag/turbovac-i-ix-cuscinetti-ibridi/pompa/678/turbovac-350-i/ix>

the capacity of a system to evacuate a volume is uniquely determined by the geometry of the volume [56]. It is evident that the pipe hosting the slits (dashed line in Fig. 18.5b) is not enough to evacuate the sphere volume. To address this limitation, the system is designed with an additional pipe, that connects the sphere to another volume, as shown with continue yellow arrows in Fig. 18.5b. Once the spectrometer is in vacuum and connected to the JT60-SA vessel, also possible hydrogen fluxes from the fueling system during the experimental campaign have to be evacuated. Since the presence of strong magnetic field doesn't allow to use the turbomolecular pump, a getter NEG pump has been foreseen. The pumping of the hydrogen is schematized with the red arrow in Fig. 18.5b.

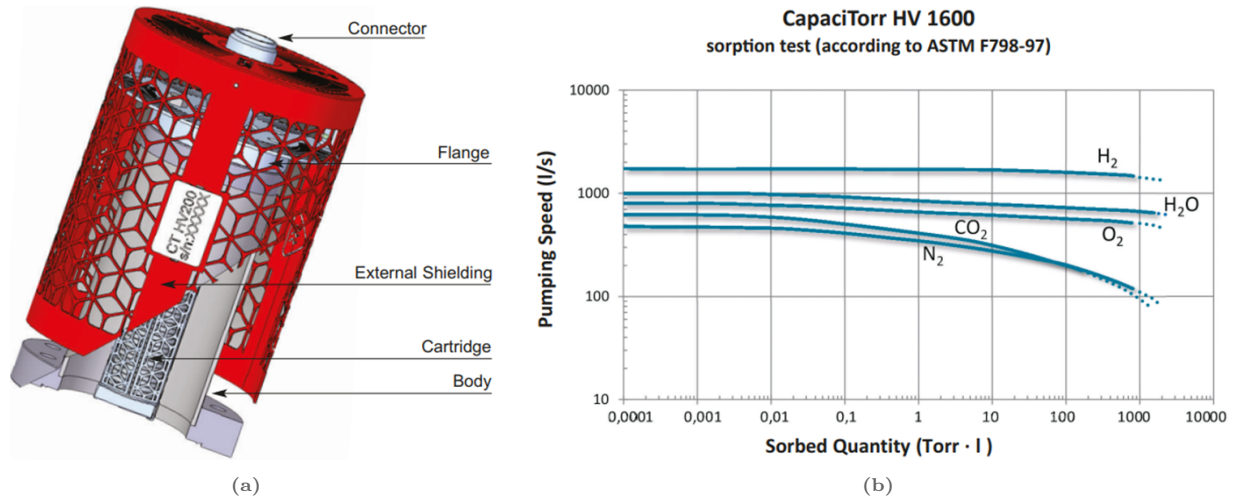


Fig. 18.6: Getter pump model NEG SAES CapaciTorr HV 1600: (a) schematization of the pump (b) pumping speed as a function of the saturation level of the NEG pump.

The getter pump is a SAES model CapaciTorr HV 1600 NEG pump. Fig. 18.6 reports the mechanical model of the pump and the pumping speed as a function of the neg pump saturation level. Instead, the turbomolecular pump is a model TurboVac 350 IR DN100 from Leybold shown in Fig. 18.7a. Its characteristic pumping speed as a function of the inlet pressure is plotted in 18.7b.

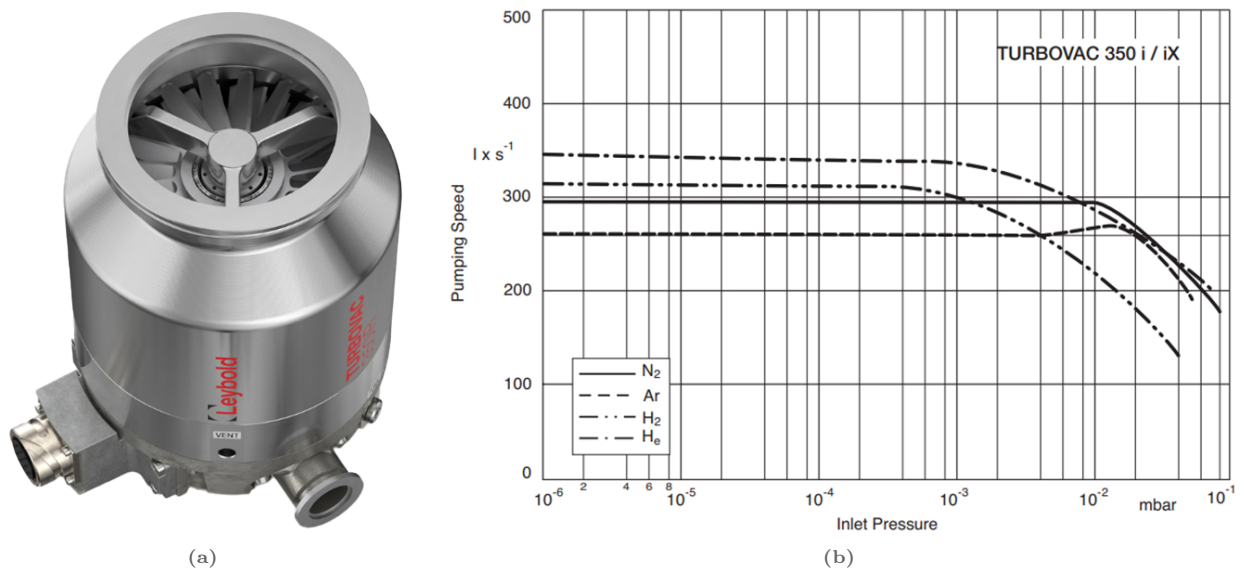


Fig. 18.7: Turbo pump model TurboVac 350: (a) picture of the turbomolecular pump; (b) - Pumping speed as a function of the inlet pressure.

19.1 Overview of the optical layout

The system is composed by a double channel spectrometer designed to cover the wavelength range 10 nm - 125 nm. The first channel, named SA (SPRED A) operate swithin 10 nm to 48 nm, while the second named SB (SPRED B) covers the 44 to 125 nm. Positioned on an upper port to have a vertical line of sight directed towards the divertor (see Fig. 18.2), each channel of the spectrometer is based on a SPRED configuration (survey, poor resolution, extended domain) [30]. Consequently, both channels has the same optical layout that share a unique vacuum chamber. The optical layout of the spectrometer is composed by five main elements: two couple of mirrors indicated as lower and upper mirror, two narrow slits, the toroidal gratings and the CCD detectors. In Fig. 19.1a a schematization of the optical layout is shown, while the position on the structure of the different optical elements is reported in Fig. 19.1b.

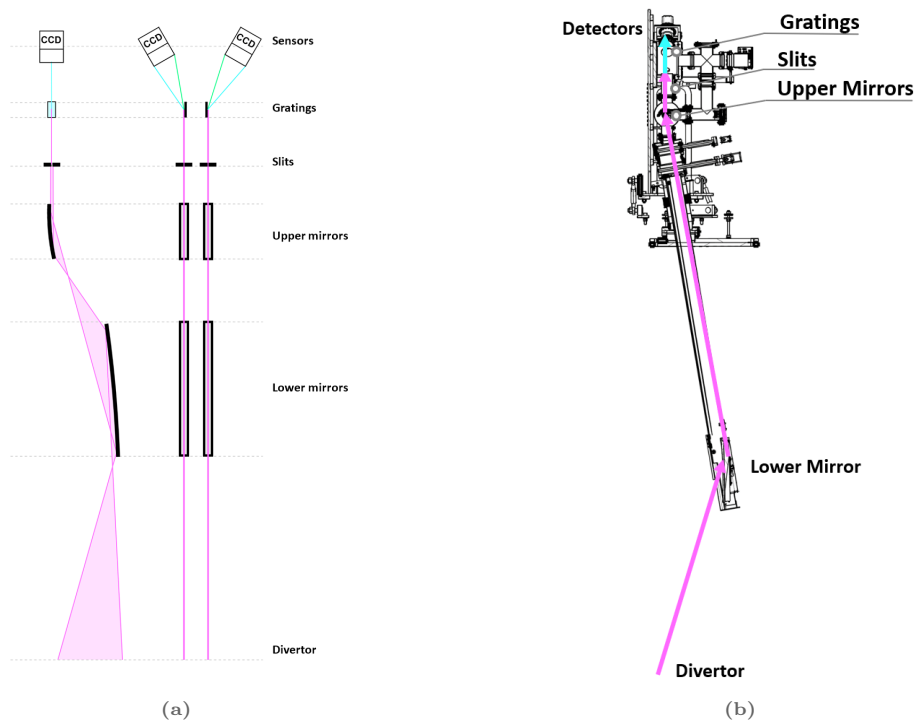


Fig. 19.1: Optical layout of the instrument: (a) left and right represent respectively the side view and the frontal view; (b) section of the diagnostic with the indication of the optical components.

Emissions originating from the divertor region are directed outside the cryostat by the lower toroidal mirrors. Subsequently, the light is focused onto the slits by the second pair of toroidal mirrors located within the spherical chamber. After passing through the slits, the light reaches the toroidal gratings, where it is dispersed into its spectral components (see Sec. 16). The gratings focus these light components onto the Charge Coupled Device (CCD) detectors which are positioned in correspondence of the focal planes of the gratings.

19.2 Lower mirrors

The two set of mirrors, referred to as lower and upper, are fabricated using the same method. They consist of a substrate made of ZERODUR[®], a glass ceramic material developed by Schott¹, which is composed of lithium-aluminum-silicate (LAS) glass ceramic. This material is characterized by an extremely low thermal expansion making it highly suitable for optical components [37]. The substrate is then coated with gold in order to enhance reflectivity in the vacuum-ultraviolet range (Fig. 19.5c is a picture of the mirrors where the gold coating is clear visible). Both mirrors are identical, with a first radius (long side) of 4500 mm, and a second radius that can be effectively considered infinite.

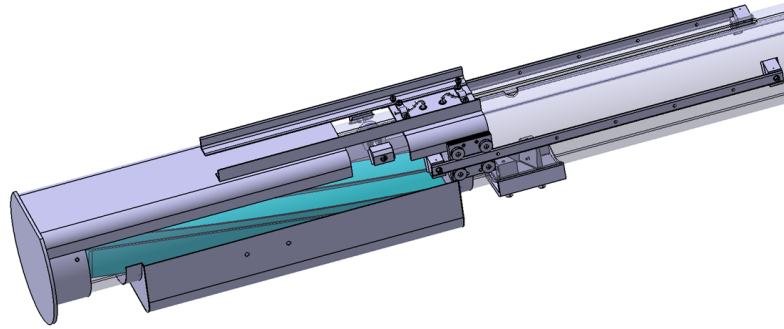


Fig. 19.2: Detail of the shutter mechanism. The mirrors are depicted in light blue, in dark gray the mechanical components. the endoscope is transparent.

When the diagnostic is installed, the lower mirrors will be located in the vacuum vessel as illustrated in Fig. 18.1. Giving the harsh environment, a shutter protection for the mirrors has been designed. The goal is to protect the mirrors, and particularly their gold coating, during wall condition procedures such as baking at 200°C and He GDC [7]. The shutter consists of a metallic cover that can slide along two linear guides to open or close the instrument's line of sight. The closed position is shown in Fig. 19.2. The cover is controlled by a pneumatic rotary motor installed before the bellow outside the cryostat (see Fig. 18.3). As the feed-through rotates, the rope moves the shutter to either cover or open the mirrors' line of sight. The assembled component is depicted in Fig. 19.5b.

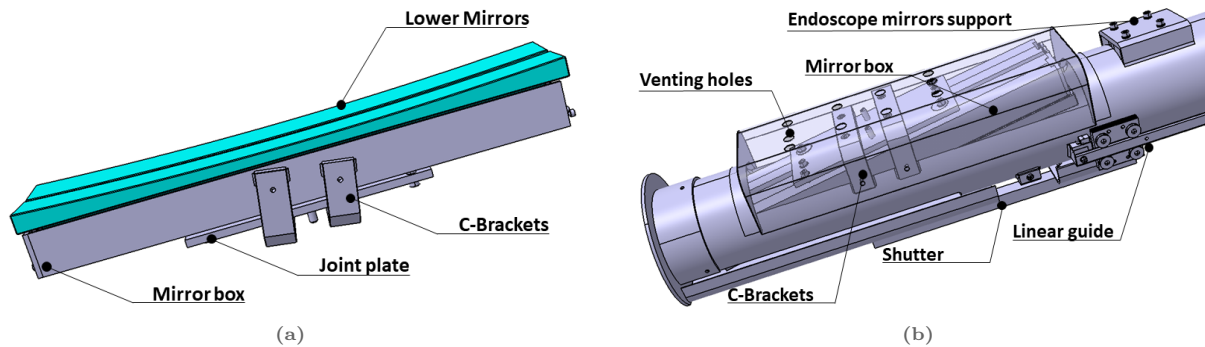


Fig. 19.3: Lower mirrors support assembly: (a) support of the mirrors; (b) Lower mirrors installed at the end of the pipe. The transparent element is the rectangular box, welded on the pipe, in which the mirrors assembly is bolted.

The mirrors are anchored at the end of the pipe, which is cut, to create a rectangular aperture where a box (see Fig. 19.3b) is welded to serve as the mirrors' chassis housing. The box is designed with a series of holes to ensure the pumping of the volume inside the tube, even with the shutter closed. Each mirror's base is encased within its respective box, providing an anchorage point for the c-brackets. Additionally, the relative positioning of the two mirrors is maintained by a joint plate mounted directly on the C-brackets. The overall structure and its installation on the pipe are shown in Fig. 19.3, while a detailed view on the lower mirrors chassis is provided in Fig. 19.5.

¹Schoot:<https://www.schott.com/en-no/products/zerodur-p1000269>

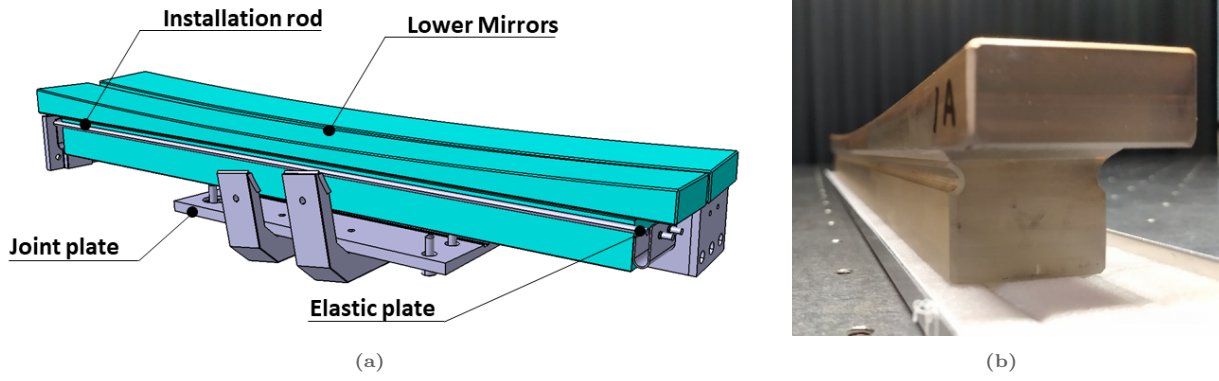


Fig. 19.4: Lower mirrors assembly: (a) assembly without the protective box of one of the mirrors; (b) picture where the double grooves on the side of the mirror base can be seen.

The mirrors bulk has a rectangular shape with grooves located on each side, as shown in Fig. 19.4b. These two grooves serve as attachment points for connecting the mirrors to their support box, as illustrated in Fig. 19.4a. Two metal rods flank the groove on the base of the mirror, and the threaded ends of these metal rods are bolted onto end-plates as shown in Fig. 19.4a (left side). To accommodate potential thermal deformations between the mirror and its chassis, C-shaped elastic sheets are positioned on either side of the mirror, between the mirror and the end plates (referred to as elastic plate in Fig. 19.4a). The end-plates are integral to the box that covers the mirror (see Fig. 19.3a), which in turn is bolted onto the joint plate and C-brackets, ensuring a robust installation of the mirrors into the pipe.

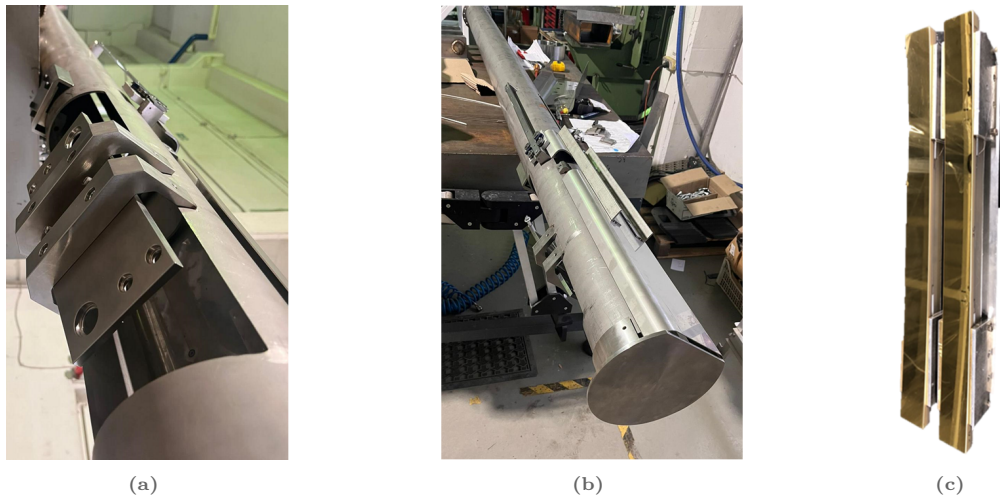


Fig. 19.5: Picture of the mechanical structure of the assembly: (a) lower mirrors chassis installation; (b) picture of endoscope with installed the shutter; (c) picture of the lower mirror.

19.3 Upper mirror

The second optical element comprises a smaller toroidal mirror positioned in the first chamber outside the cryostat (see Fig. 19.1). Similarly, to the lower mirrors (see Sec. 19.2), also these ones are constructed with ZERODUR with a gold coating. Both mirrors are toroidal with major radius equal to 4550 mm and minor radius of 50 mm. Alignment adjustments are achieved by a custom structure providing four degrees of freedom: two translations and two rotations. The alignment structure is identical for both mirrors, and incorporates two Thorlab² MS1S/M linear stages³ arranged orthogonally, moved by a in-vacuum piezoelectric motor model 8353-V⁴ by MKS⁵ (one motor for each stage). A kinematic support, utilizing a Thorlabs KM100PM/M kinematic mount⁶, is affixed to the second linear stage to adjust the mirrors orientation (two motors for each support). The configuration of this structure is depicted in Fig. 19.6a while Fig. 19.6b showcasing a photograph of the installed support (not all piezoelectric motors are installed).

²ThorLabs – URL: <https://www.thorlabs.com/>

³MS1S/M by Thorlabs – URL: <https://www.thorlabs.com/thorproduct.cfm?partnumber=MS1S/M>

⁴Picomotor Actuar 8353-V - URL: <https://www.newport.com/p/8353-V>

⁵MKS Newport – URL: <https://www.newport.com/>

⁶KM100PM/M by ThorLabs – URL: <https://www.thorlabs.com/thorproduct.cfm?partnumber=KM100PM/M>

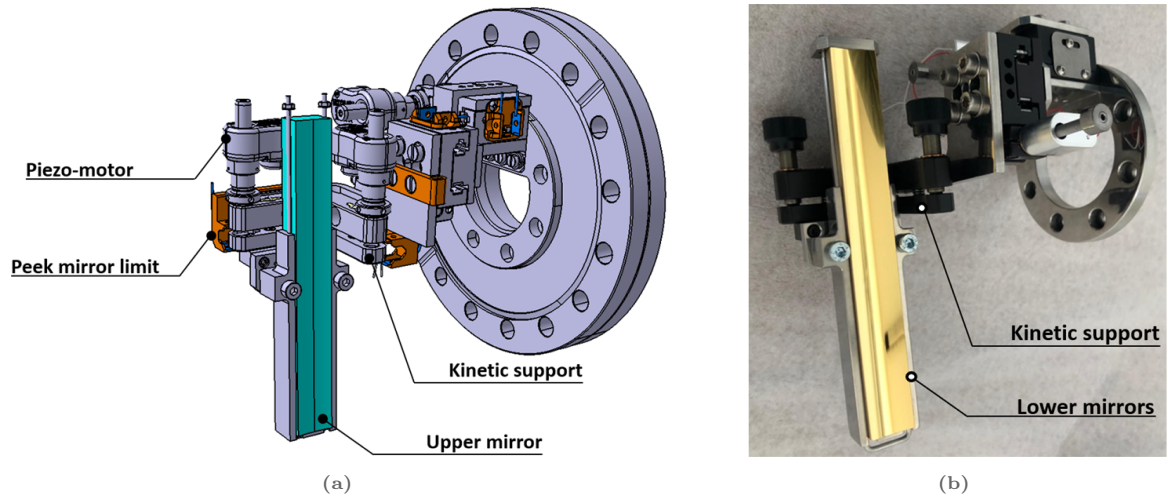


Fig. 19.6: Assembly of one kinematic support of the upper toroidal mirror: (a) mechanical structure; (b) picture of the assembled kinematic support.

The mirrors' positions are monitored using a set of sensors installed on both the linear stages and the kinematic support. These sensors consist of plastic insulators housing metallic plates. Any short-circuit caused by the contact between the support or a stage and the metallic plate, is measured using the digital input-output module, providing information on the mirror's position (end of stroke). The kinematic support is equipped with four limit sensors, two sensors for each motor. Depicted in Fig. 19.7a the conductive plates (blue) bolted onto the insulator supports (orange), which are installed on the kinematic support (black). Exploded view of the conductive plate is given in Fig. 19.7b.

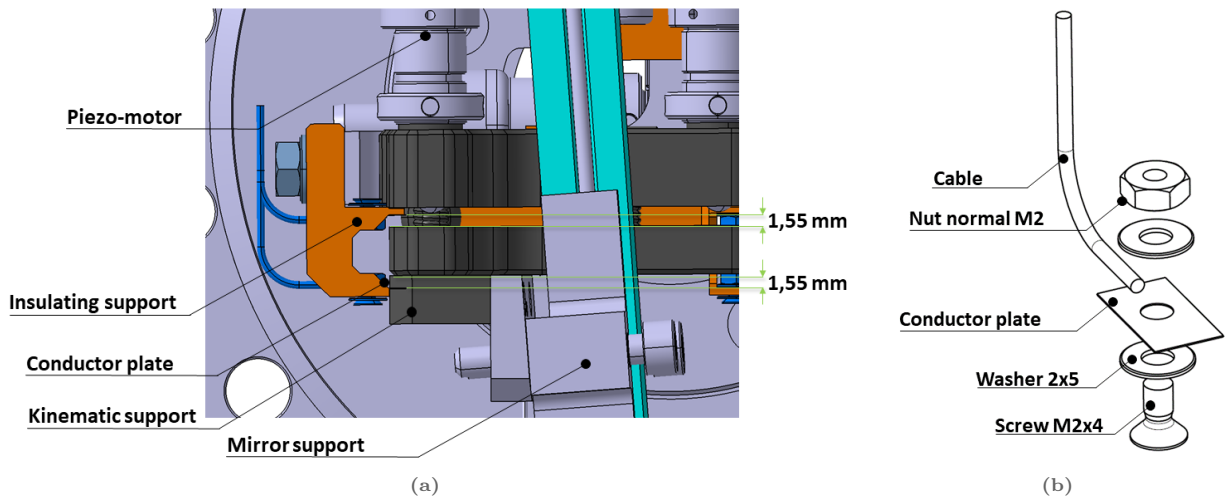


Fig. 19.7: Detail of the limit sensor for the kinematic support movement: (a) mechanical structure whit indicated the all components; (b) exploded view of the connector plate.

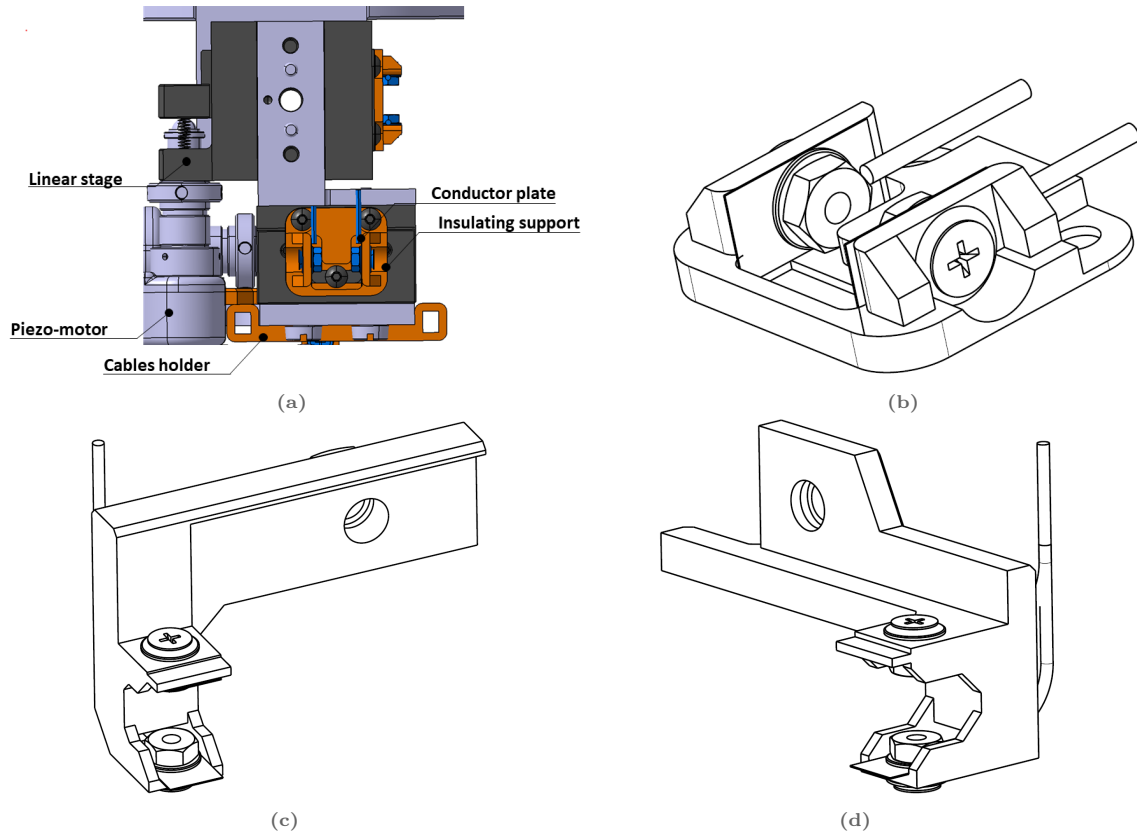


Fig. 19.8: Detail of the limit sensors for the linear stage: (a) mechanical structure whit indicated the all components; (b) drawing of the insulator support for the limit sensor of the linear stage; (c) drawing of the first type of insulator support for the limit sensor of the kinematic support; (d) drawing of the second type of insulator support for the limit sensor of the kinematic support.

The structure supporting the mirrors, described earlier, remains consistent for both channels. It is mounted on a custom flange design to accommodate the cables from the motors and the conductive plate to the electrical feed-through located on the flanges on the arms of the spherical vacuum chamber. Fig. 19.9 shows an overview of the sphere vessel installation. The free space between the two mirror structures, inside the sphere, is sufficient to the inclusion of the endoscope mirror. The design must guarantee that the light from the plasma reach the endoscope viewport along the pipe (see Fig. 19.9) and at the same time that the endoscope support does ‘not vignette the light reflected by the toroidal mirror. More details about the endoscope design are given in Sec. 20

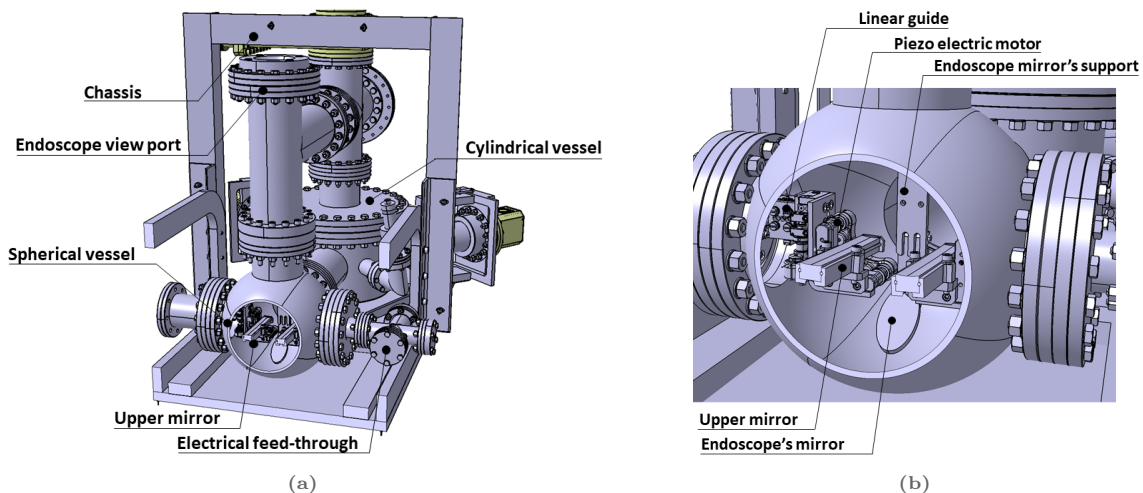


Fig. 19.9: Detail of the limit sensor for the kinematic support movement: (a) mechanical structure whit indicated the all components; (b) exploded view of the connector plate.

19.4 Gratings

The third optical elements, in the cylindrical vessel, is the grating, as shown in Fig. 19.1. Emissions from the divertor region are directed outside the cryostat by the lower toroidal mirrors, the second pair of toroidal mirrors within the spherical chamber will then focus the light on the slits. After the slits, the light reaches the toroidal gratings, where it is dispersed into its spectral components. The physical principle has been explained in Sec. 16. Fig. 19.1 shows the slits positioned within the pipe connecting the spherical vessel to the cylindrical one. A metal ring housing the slits is welded, close to the CF flange along the pipe, as illustrated in Fig. 19.10b. The slits themselves are made by two plates, each featuring a sharp edge, bolted onto a fixed metal flap. The two sharp plates are brought together onto a calibrated sheet metal and secured with screws to determine the width of the slit. A zoomed view of the slits is depicted in Fig. 19.10a. The metal flap is locked in position by a tier manufactured on the base flange and an elastic metal sheet.

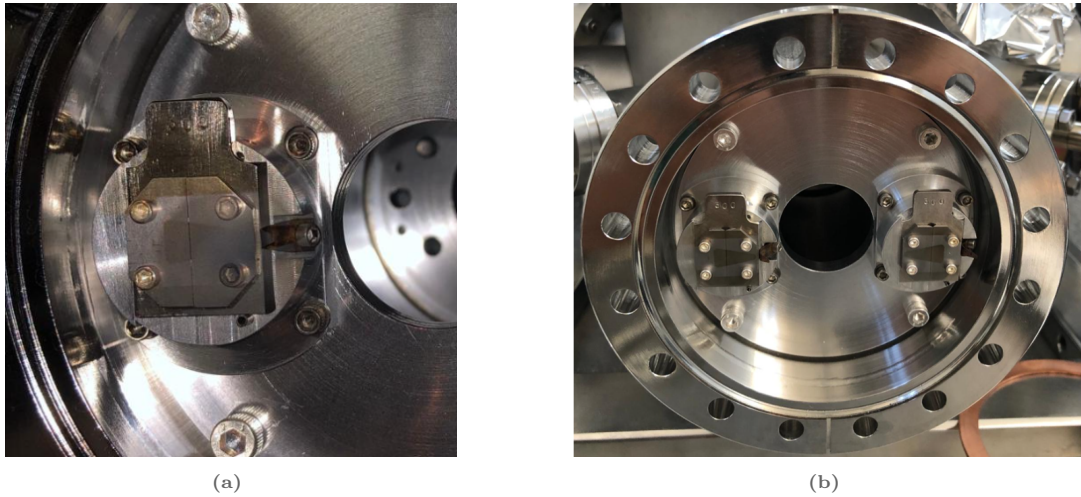


Fig. 19.10: Installation of the slit : (a) slit of 300 μm of channel B; (b) installation of the slit in the flange of the cylindrical vessel.

The two gratings are installed on custom holders, shown in Fig. 19.12, located inside the cylindrical vessel of the instrument (see Fig. 19.11c). At the bottom of the vessel, a shaped plate with three conical slots is bolted as reported in Fig. 19.11a. These slots secure the position of the plate hosting the gratings' holders, and allow its removal for maintenance without losing the alignment relative to the vessel. Fig. 19.11b represents the bottom view of the base depicted in Fig. 19.12a and it is shown installed in Fig. 19.11c.

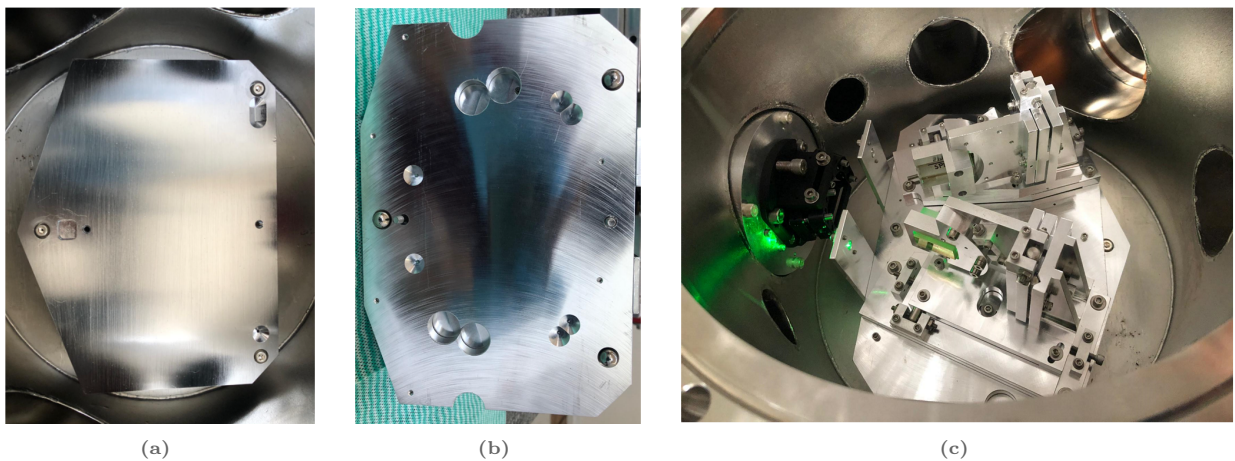
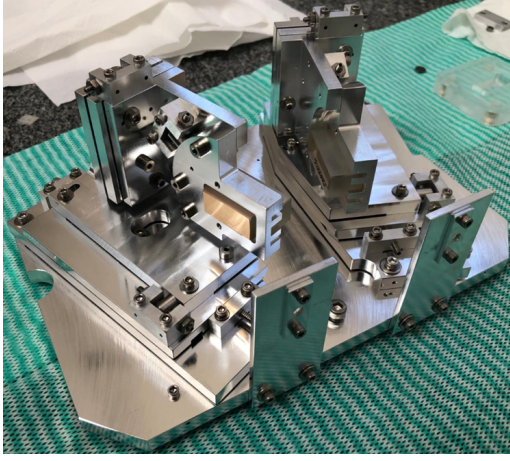
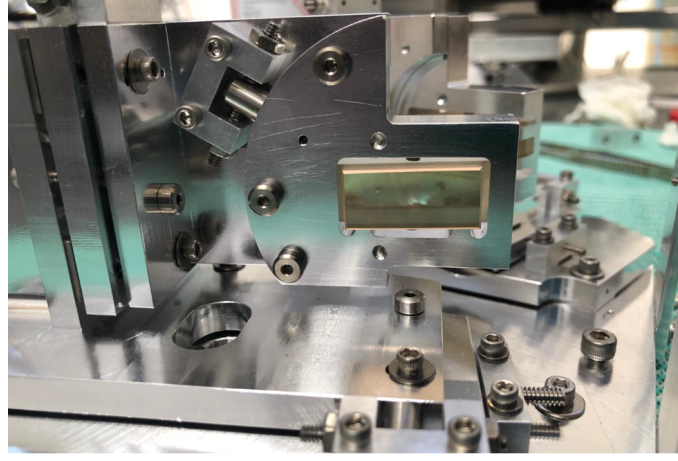


Fig. 19.11: Grating installation: (a) base plate installed on the bottom of the cylindrical vessel; (b) bottom view of the plate that hosts the gratings. The three metallic sphere match with the cylindrical holes of the base plate; (c) fully installation of the gratings inside the cylindrical vacuum chamber

The gratings are installed in the holder with three springs. Two springs push the gratings vertically and horizontally fixing its position, the third one pushes the grating in the perpendicular direction bringing the two branches of the T gratings (the T shape can be seen in Fig. 19.13) to lean on the holder, which is composed by a series of plates that can be finely adjusted to regulate the orientation of the grating.



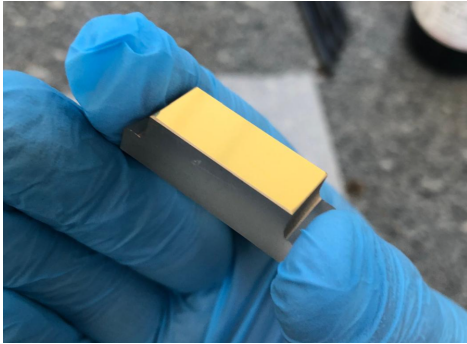
(a)



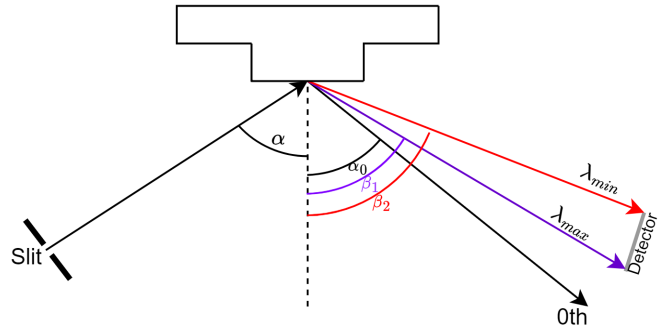
(b)

Fig. 19.12: Grating holders: (a) Pictures of the grating's holder; (b) details of the grating's holder.

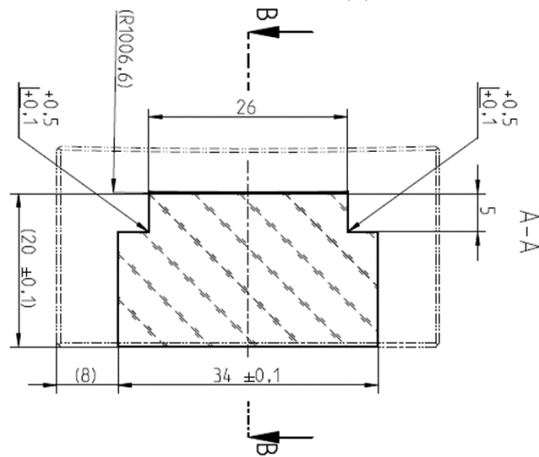
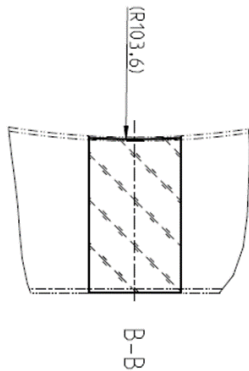
Based on the solution adopted in the stellarator W-7X [10], the gratings present a toroidal shape. Both gratings have been designed by Wolfgang Biel [12] with a toroidal shape, which can correct astigmatism at larger deviation angles and over larger wavelength ranges than the holographic concave spherical gratings [95]. The first channel, (SPRED A), covers a wavelength range between 10 to 48 nm and its toroidal shape is characterized by radii 1006.6 mm and 103.6 mm. The grooved area (clear aperture) is 10 mm high and 24 mm wide, on a bulk area of 12x26 mm². The second channel (SPRED B) instead covers a wavelength range from 44 to 125 nm and it is characterized by a radii of 1039.0 mm and 100.0 mm. The grooved and the bulk area are the same of SPRED A. More detailed characteristics of the two gratings are listed in Tab. 19.1.



(a)



(b)



(c)

Fig. 19.13: Grating: (a) grating before the installation; (b) schematization of the gratings; (c) mechanical drawing.

	Spred A	Spred B
Wavelength rang [nm]	10-48	44-125
Type [1]	Toroidal	Toroidal
First radius [mm]	103.6	100.0
Second radius [mm]	1000.6	1039.0
Height of grooved area [mm]	10.0	10.0
Width of grooved area [mm]	24.0	24.0
Grooves over millimeter [1/mm]	712.97	344.37
Mean etendue [mm ² sr]	$5.015 \cdot 10^5$	$5.019 \cdot 10^5$
Incident angle α [deg]	71.164	71.855
Diffractive angle [deg] of minor wavelength [nm]	69.938	69.247
Diffractive angle [deg] of major wavelength [nm]	65.815	65.124
Detector angle [deg]	87.25	86.56
Mean line width [pixel]	5.537	5.378
Wavelength resolution [nm]	0.08	0.16

Table 19.1: Summary of the grating's characteristics

These new gratings have been designed with 1-D imaging capabilities. Their performance has been simulated [12] and Fig. 19.14 illustrates the spot diagram and the profile instrument for wavelengths 10 nm and 48 nm (edges of wavelength range) for the channel SPRED A. The slit dimensions assumed for the simulation is width 50 μm and height 5.0 mm. From the spot diagrams, red dots Fig. 19.14, the spherical aberration on the x-direction expected due the shape of the grating can be seen. Note less evident spherical aberration on the y-direction, which can be neglected because it is evident only on the marginal ray of the spot. From this analysis, it can be concluded that the optimal vertical dimension for illuminating the gratings, in order to achieve the best imaging capability, is approximately 6 mm. This corresponds to the area where the dots are least dispersed. To limit the illumination to this area, two optical stops are placed in front of the gratings that can be seen in Fig. 19.12a or in Fig. 19.11c.

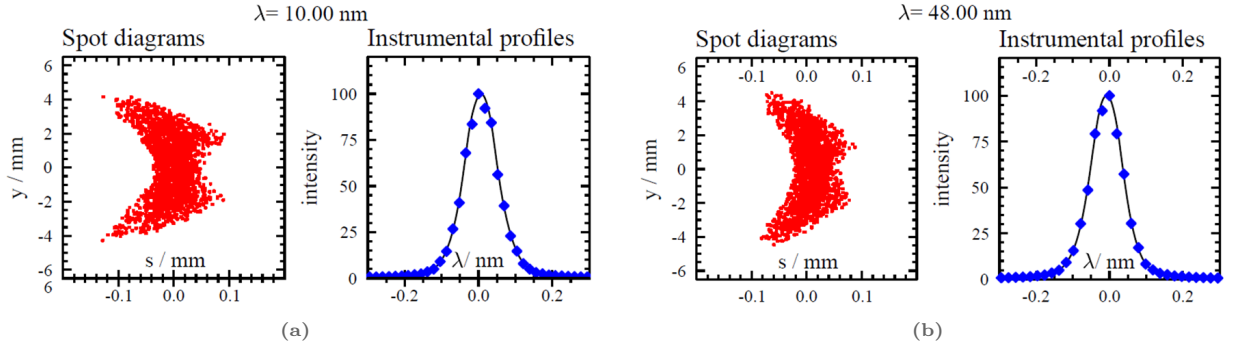


Fig. 19.14: Spot diagram and instrument profiles for Spred A : (a) $\lambda = 10$ nm; (b) $\lambda = 48$ nm.

19.5 Detector

MCP (microchannel plates) have been used as detectors in spectrometers for many years in many fusion devices such as JET [60], ALCATOR [86] or TEXTOR [9]. A MCP consists of a plate with numerous microscopic photomultiplier channels. When a photon or particle strikes a photocathode for detection, it generates photoelectrons, which enter in the channels of the MCP stack and collide against the channel wall releasing secondary electrons. An applied electric field accelerates these electrons within the stack, their collisions with the walls release other electrons in a cascading effect. This multiplication process significantly amplifies the original signal, making MCPs highly sensitive and capable of detecting faint signals in applications such as night vision, scientific instrumentation, and particle detection [21][35]. A schematization of the MCP structure can be seen in Fig. 19.15a. As an alternative, the Charged Coupled Devices (CCD) are composed of an array of metal-oxide-semiconductor (MOS) pixels that convert incoming light into electrical charges when a voltage is applied on them. These charges are then transferred across the chip and read out sequentially to produce a digital image. Each pixel, orange in Fig. 19.15b, is installed on silicon dioxide insulating layer (light gray). The voltage applied on the electrode repels holes⁷ away from the area underneath the electrode, creating a depletion region (Fig. 19.15b.A). Incoming photons are able to generate photoelectrons in the depletion region as illustrated in Fig. 19.15b.B. These photon-induced charges are then shifted to one side of the array so that they can be

⁷In semiconductor physics, a hole is essentially a positively charged carrier that acts as if it were a vacancy created by the absence of an electron in a filled electron state

electrically amplified and collected. Charge shifting can be accomplished by progressively shifting the applied voltage along the array as shown from Fig. 19.15b.C to Fig. 19.15b.F [47].

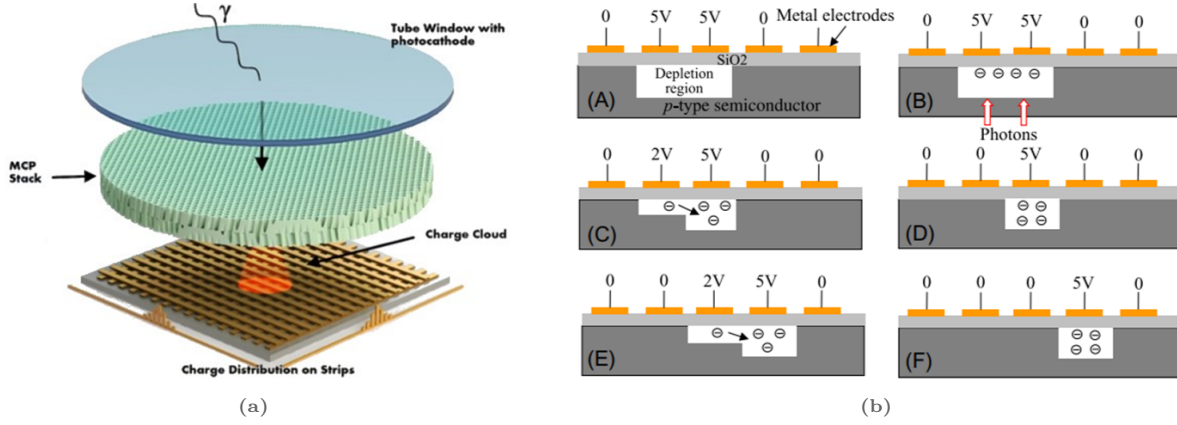


Fig. 19.15: Schematization of tipe of VUV detectors: (a) Microchanel plate (MCP); (b) Charged Coupled Device sensor (CCD).

The CCD technology is progressively replacing the MCP in new devices such as EAST [41] or K-STAR [93] and it will be implemented in ITER [94]. The comparison between the two kind of technologies demonstrates that the back-illuminated CCD has a higher spectral resolution than the MCP and similar sensitivity in the VUV wavelength ranges [92], promoting CCD as the ideal candidate for VUV spectrometer sensors when high time resolution (of the order or less of 1 ms) is not required. To achieve higher time resolution, the MCP is still used, and an example can be J-TEXT Tokamak where the CCD detector was replaced with a new detector system consisting of a one-stage MCP, a lens relay, and an EMCCD camera [112]. In our case, for both the VUV spectrometer channels, a commercial back-illuminated CCD has been chosen: ANDOR⁸ model Newton SO A-DO920-BEN⁹. It is characterized by a sensor of 1024 x 255 pixel of 26 x 26 μm^2 each, optimized to have high dynamic range high speed and high spatial spectroscopy resolution in the VUV and soft X-ray range. The efficiency curve of the CCD, in blue, is reported in Fig. 19.16a, while its general characteristics are summarized in Tab. 19.2.

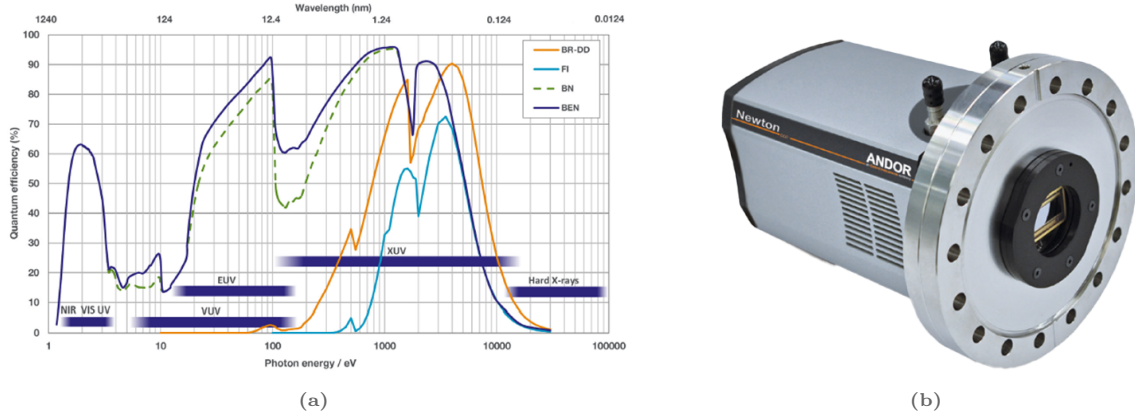


Fig. 19.16: ANDOR CCD Newton model: (a) quantum efficiency curve fo the sensor; (b) picture of the camera.

Sensor option	BEN: Back-Illuminated CCD
Active pixels	1024 x 255
Pixel size	26 x 26 μm^2
Image area	26.7 x 6.7 mm with 100% fill factor
Linearity	Better than 99%
Digitization	16 bit (all speeds)
Mounting flange	DN100CF
Vacuum compatibility	$>10^{-8}$ mbar

Table 19.2: CCD ANDRO Newton model characteristics

⁸ANDOR - <https://andor.oxinst.com/>

⁹ANDOR SO CCD model - <https://andor.oxinst.com/products/high-energy-detection/newton-so>

The CCDS are installed on the arms of the cylindrical vessel of the instrument. The optical layout is schematized in Fig. 20.5, while the position the sensors with respect to the structure can be seen in Fig. 18.1. The CCD is equipped with CF100 vacuum flange with a PEEK¹⁰ spacer (light brown in Fig. 19.17b) positioned between the CCD flange and the spectrometer one, to electrically insulate the CCD from the instrument body. The peek spacer is also used in both channel as support for the 0-order mirrors (more details about the 0-order are given in Sec. 20.2). The CCD is installed in a spectrometer arm with an angle of 45° with respect to the cylindrical vessel axis (see Fig. 20.5a). The arms connected to CCD are composed by an aluminum chassis that, with a bellow, allows a fine regulation of the CCD with respect to the spectrometer. The chassis and the bellow are reported in Fig. 19.17b, while a photograph of the sensor is shown in Fig. 19.17a.



Fig. 19.17: CCD installation: (a) picture of the CCD sensor; (b) picture of the CCD installed. The peek insulator between the camera and the bellow can be seen (light brown).

¹⁰PEEK: Polyether ether ketone is a high-performance thermoplastic valued in vacuum applications for its low outgassing, high thermal stability, and resistance to radiation.

20.1 Alignment endoscope

As already mentioned in Sec. 18, the instrument will be installed on the top port of JT60-SA, like reported in Fig. 18.2b, and after the main flange is bolted on the cryostat flange and the chassis bolted on the mezzanine surrounding the tokamak, the instrument must be oriented with respect to the machine to set the LoS view on the divertor. To perform the alignment, the spectrometer is back illuminated with a green laser through the 0-order system (see Sec. 20.2). The laser light path is reversed with respect to the plasma light during the measurements and, it shows the LoS footprint on the divertor. The alignment procedure imply moving the instrument with the tripod, to settle footprint on the divertor's point of interest. To verify the alignment, it is needed to check the position of the laser footprint, and for this reason, the spectrometer has been equipped with a custom endoscope object of this section. The optical layout and the position in the spectrometer chassis can be seen in Fig. 20.1.

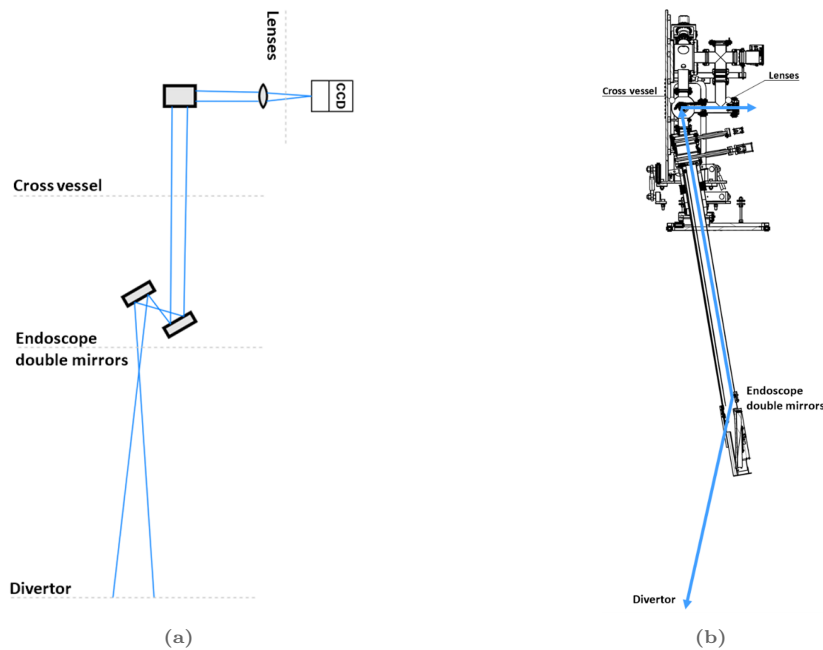


Fig. 20.1: Optical layout of the endoscope: (a) two mirrors direct the light outside the tokamak vessel towards the spectrometer cross vessel where another mirrors deflect the light outside the instrument; (b) section of the spectrometer with underlined in light blue the path of the light.

The light from the divertor region is directed outside the cryostat along the pipe with two opposing cylindrical mirrors. Both the cylindrical mirrors have a bulk of BK7¹ and a coating in aluminum, a radius of 700 mm, and are located in the pipe above the lower mirrors. Their disposition is shown in Fig. 20.2b. The mirrors are bolted on two blocks in turn fixed onto a C-shape bracket welded on the pipe structure (Fig. 20.2a).

¹Borosilicate Crown glass used for a wide variety of visible applications

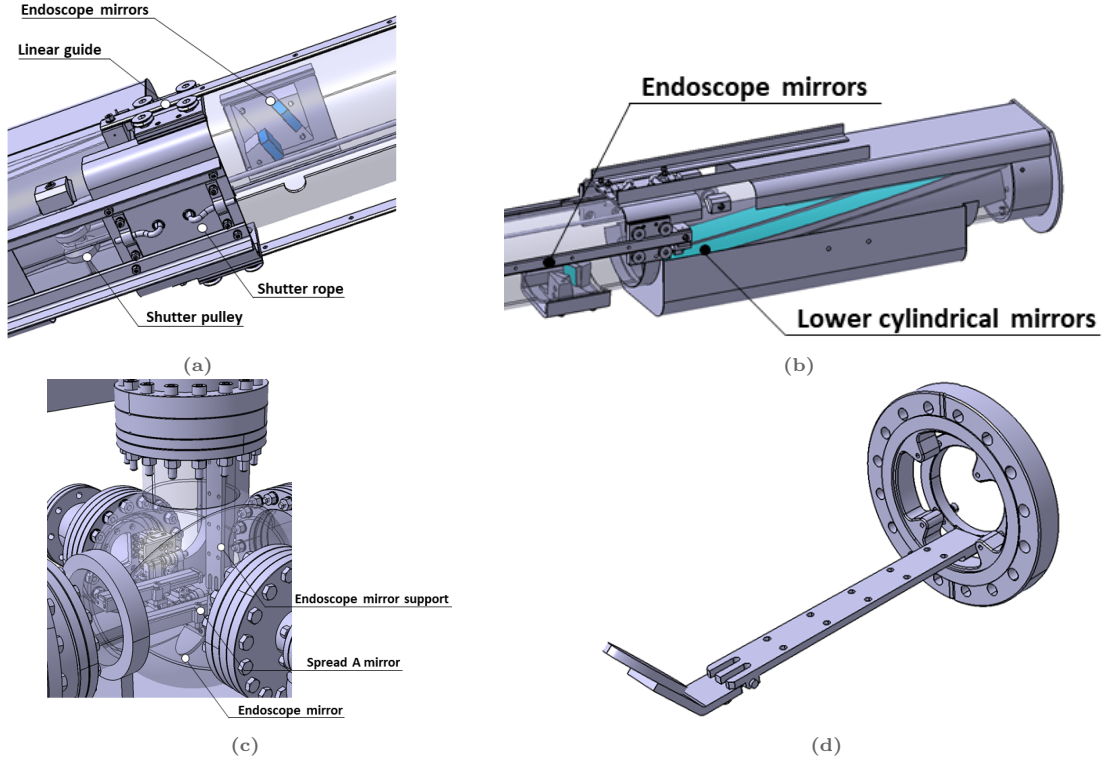


Fig. 20.2: Detail of the endoscope: (a) mirrors located and the end of the pipe (in blue); (b) position of the endoscope mirrors with respect to the lower mirrors; (c) detail of the installation inside the sphere chamber; (d) support for the mirror located in the spherical vessel.

The light from the two cylindrical mirrors during the the measurement, reaches the spherical chamber outside the cryostat plug. There a dedicated flat mirror, illustrated in Fig. 20.2c and Fig. 20.2d, drives the light outside the vessel along the pumping pipe (see Sec. 18.2) where a camera is positioned to follow in real time the position of the laser footprints on the divertor. The flat mirror is installed on a support fixed on a custom flange used as support reported in Fig. 20.2d. The flange is machined to ensure the support of the mirror without reducing the pipe conductance. The image reflected by the mirror is focalized on a CCD by series of in-vacuum lenses, which are installed directly on the view port like reported in Fig. 20.3 . The position of the view port with respect to the spherical chamber is clearly indicated in Fig. 19.9a. The objective is composed by a sequence of three lenses with optical characteristics given in Tab. 20.1. The label R1 and R2 in Tab. 20.1 refer respectively to the radius of the first and second surface of the lens according to the light propagation direction (from the divertor to the CCD camera). When the surface geometric center is beyond the surface the radius is considered positive, when the center is before instead it is negative. All lenses have optical diameter of 48 mm and a maximum thickness of 8 mm and are coated with an anti-reflection for the range 400-900 nm.

Lens	R1 [mm]	R2 [mm]	Optical diameter [mm]	Thickness [mm]	Material
1	-230	100	48	8	BK7 + A.R. 400-900nm
2	95	inf	48	8	F2 + A.R. 400-900nm
3	-140	625	48	8	BK7 + A.R. 400-900nm

Table 20.1: In-vacuum lenses endoscope characteristics

The lens holder is made of five components screwed together to hold the optical elements in position. Elastic metallic rings are placed between the components and the lenses to secure the lenses and prevent their movement. The last component is welded directly onto the CF-63 view-port flange. The view port has a sapphire glass with an anti-reflective coating. The flange is machined to have two threaded holes in which a support rod for the CCD camera is installed. The installation is clearer shown in Fig. 20.3

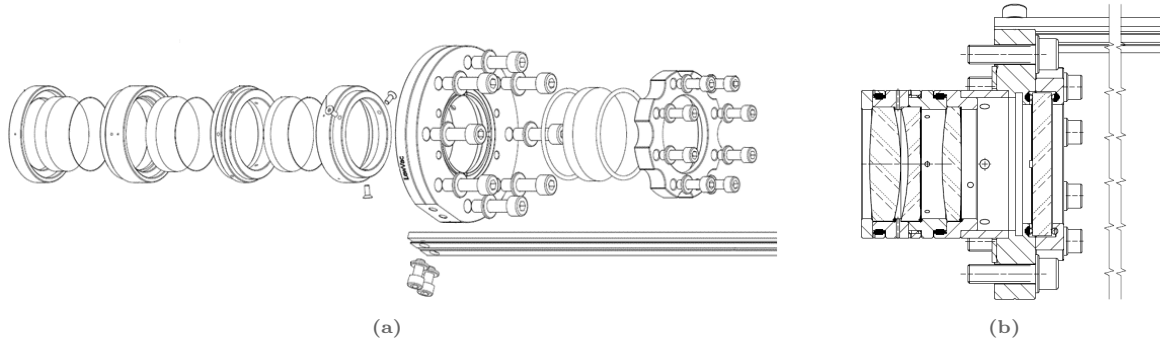


Fig. 20.3: In-vacuum lens holder for the endoscope: (a) exploded view; (b) cross section of the assembly.

Fig. 20.4 reports the pictures of the assembly components.



Fig. 20.4: Picture of the components: (a) support for the flat mirror installed inside the spherical vessel; (b) lenses holder and CF-63 viewport

20.2 0 order

A grating diffracts the light component according with the grating law (16.1). In this equation d represent the spacing between adjacent rulings, α and β are respectively the incident and the diffractive angle, λ the wavelength and finally m is the order. A more detailed explanation is given in Sec. 16. For sake of clarity the grating law is reported below.

$$d(\sin \alpha + \sin \beta) = m\lambda \quad (20.1)$$

According with (16.1), when m is equal to zero, the 0-order, the incident and diffractive angle are equal and all the spectral component are reflected. This fact can be used to align the instrument with a back illumination of the grating or can be exploited to look at the same emission region with a visible spectrometer. In our case, it is foreseen to use the 0-order in this way to couple with the VUV spectrometer a visible one to perform an absolute calibration of via the branching ratio technique [23][103]. A ray tracing schematization of the two gratings is reported in Fig. 20.5b. The gratings are located in the cylindrical vessel of the instrument symmetrically with respect to the longitudinal axis of the vessel (detailed description of the gratings' installation is reported in Sec. 19.4). To bring outside the vessel the 0-order light a couple of mirrors for each channel is installed inside the spherical vessel. A schematization of the path is reported in Fig. 20.5a.

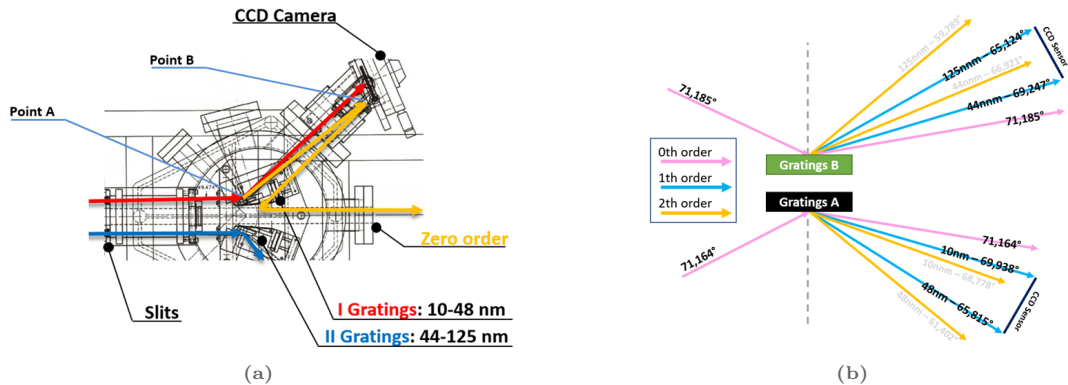


Fig. 20.5: Schematization of the 0-order: (a) the 0-order ray path (orange arrow); (b) ray for 0-order ($m=0$), first ($m=1$) and second order ($m=2$).

The first mirror of the 0-order is installed in the same flange of the CCD sensors (Point B of Fig. 20.5a) supported by a commercial kinematic support (Thorlab model STANDA 5MBM23-05-3SH, depicted in Fig. 20.7c). A custom anodized aluminum chassis is bolted onto the insulating PEEK flange, which is situated between the structure and the CCD (further details in Sec. 19.5). The design of this support is illustrated in Fig. 20.6a, while Fig. 20.7b and Fig. 20.8b shows the cad model of the assembly and a photograph of the component respectively. Fig. 20.8c displays a picture of the sensor taken during a 0-order test, where the final installation of the support is visible. In this image, the green laser spot on the mirror, the kinematic mount and the CCD sensor are clearly distinguishable.

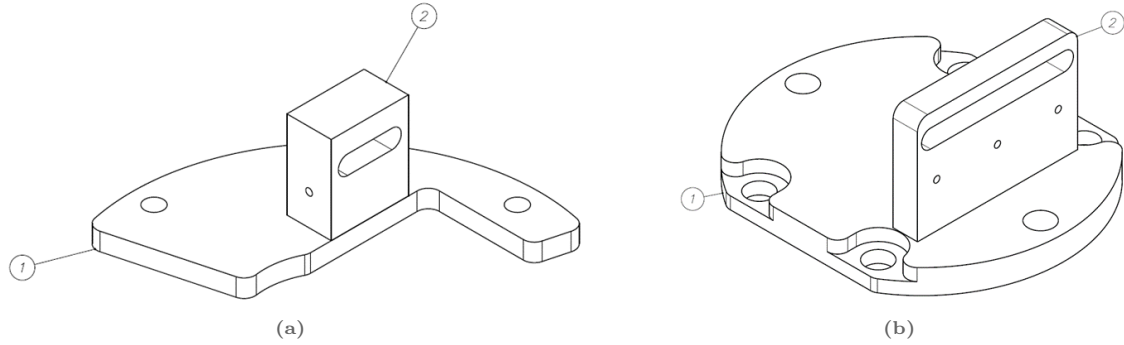


Fig. 20.6: 0-order mirror supports: (a) support located near the CCD sensor. It is composed by two elements, (1) and (2), bolted between them. On the elements (2) it is installed the Thorlab support; (b) support installed in the main vacuum chamber. It is composed by a base (1) bolted between the two gratings and a shelf (2) in which the Thorlab support are installed.

This mirror's focal length is 250 mm and an optical diameter of 12.7 mm (0.5 in). It focuses the 0-order light from the gratings towards a second flat mirror installed in a chassis located in the middle of the vacuum chamber (point A of Fig. 20.5a). This chassis, illustrated in Fig. 20.6b, is shared between the two channels and it is composed of a flange and an additional support in which the Thorlabs kinematic supports are bolted. The drawing of this components is show in Fig. 20.7a while Fig. 20.8a reports a picture of the component.

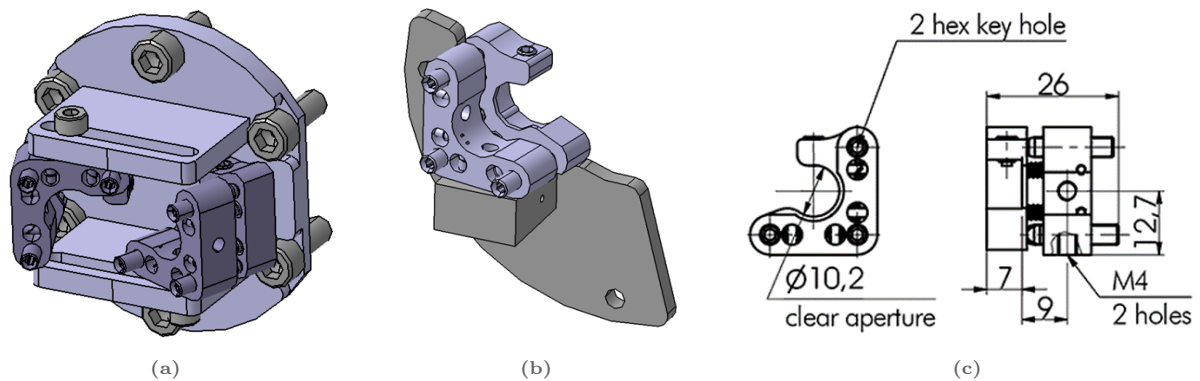


Fig. 20.7: 0-order mirror supports: (a) support installed in the cylindrical vessel; (b) support installed on the same flange of the CCD sensor; (c) drawing of the kinematic support for the mirror of the 0-order. Model STANDA 5MBM23-05-3SH.

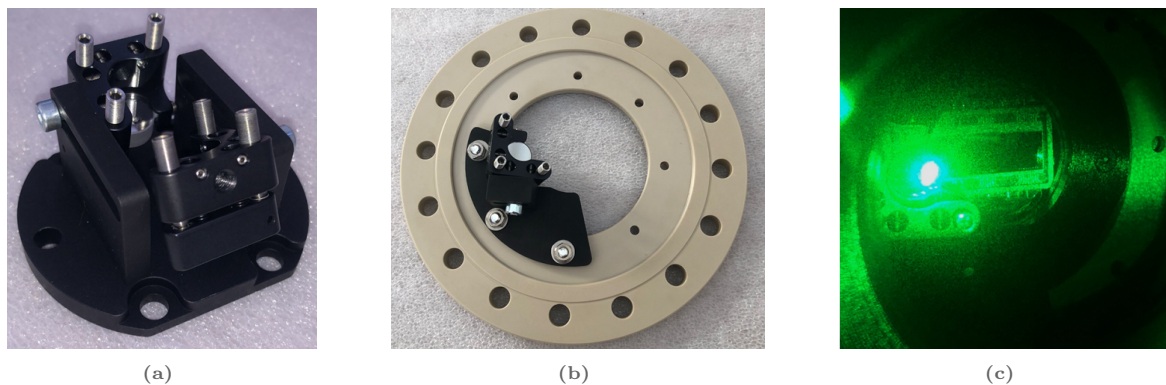


Fig. 20.8: Pictures of the components: (a) upport installed in the cylindrical vessel; (b) support installed on the same flange of the CCD sensor; (c) support installed near sensor illuminated by the green laser.

The alignment of the instrument is achieved by back-illuminating the instrument through the 0-order system. A laser green light is used to visualize the LoS footprint, which are then used to adjust the position of the spectrometer with respect to the divertor. The lasers, one for channel, are mounted on a breadboard bolted on the 0-order view-port, as shown in Fig. 20.10. For each channel the laser light alignment is made with a couple of laser-mirrors installed on a dedicated kinematic support. This assembly is covered by a black box, as illustrated in Fig. 20.10b, to prevent disturbances from the ambient light. From the vacuum view-port the laser light is directed towards the structure (Fig. 20.8a) that houses the first mirrors of both channels. There the flat mirrors deflect the light towards the second ones close to the CDD sensor (Fig. 20.8b), which in turn focus the laser on the gratings. The gratings reflect the light towards the slit and further towards the other optical element of the diagnostic, ultimately reaching the divertor. This procedure will be used, during the installation to align the instrument with respect to the JT60-SA divertor (other details of the alignment procedure are given in Sec. 18.1 and Sec. 20.1). This global path is underlined with white arrows on Fig. 20.9.

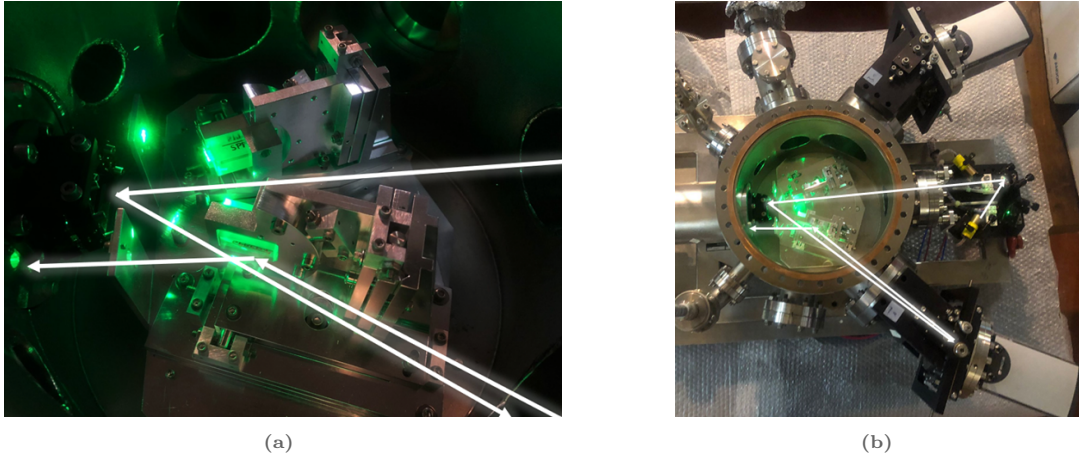


Fig. 20.9: Pictures of the 0-order laser test: (a) path of the 0-order ray inside the spherical vessel; (b) global path of the 0-order ray.

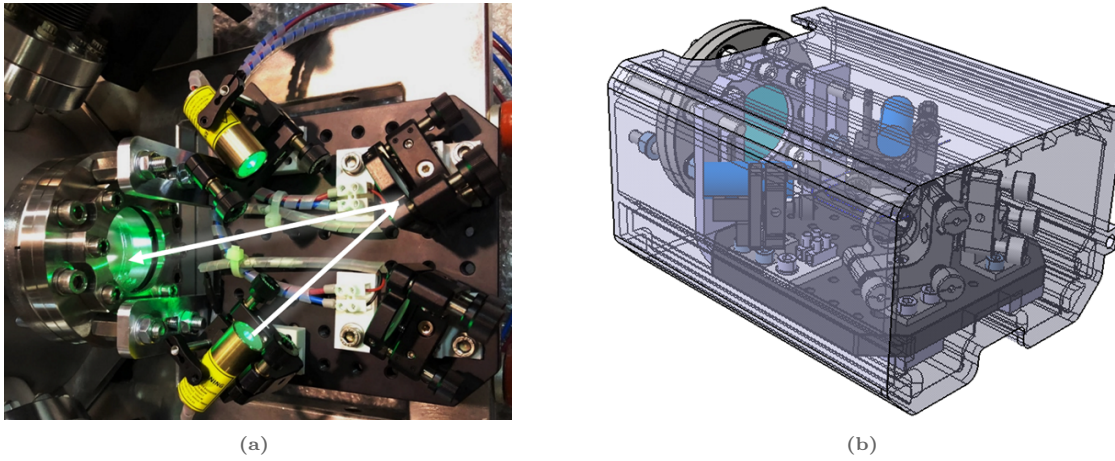


Fig. 20.10: 0-order laser support: (a) picture of the laser installed outside the viewport; (c) Cad of the 0-order support in which the protective box in transparency.

21.1 Calibration set-up

The calibration procedure involves measuring a well-known spectrum with the instrument and the associate every specific wavelengths with the corresponding pixels. By mapping these correspondences across the CCD pixels, it is possible to create a calibration function used then to recognize plasma emissions. This known wavelength emission can be obtained by creating a plasma discharge in a specialized system called a Hollow Cathode source (HC). In the calibration procedure for the spectrometer object of this work a source designed and built by Physikalisch-Technische Bundesanstalt ¹ and the Institut für Plasmaphysik of the University of Hannover² has been used [43][24]. The hollow cathode is composed by two anodes and one cathode, electrically insulated using glass spacers. The cathode itself is designed as a hollow aluminum cylinder, measuring 60 mm in length with a central bore diameter of 8 mm. This mechanical structure is depicted in Fig. 21.1a. Each of the anodes features central bores with a diameter of 4 mm which allow the observation of light emitted by the discharge. The anodes are installed on square aluminum vessels, which are connected to a differential pumping system via CKF flanges. The flux-limiting aperture stop, which has a diameter of 1.2 mm, drastically reduces the conductance between the two vessels forcing to adopt a differential pumping system. From the optical point of view, the aperture stop effectively restricts the solid angle through which radiation emitted by the source plasma can be observed to . It values approximately 3×10^{-4} sr. To enable controlled plasma generation and detailed observation, the system must be maintained at a good vacuum level, requiring a turbomolecular pump with a minimum pumping speed of 50 L/s, mounted on differential pumping system.

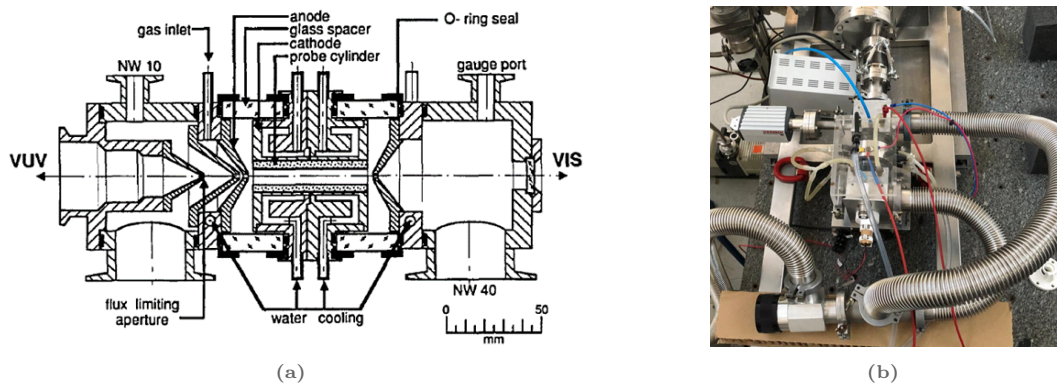


Fig. 21.1: Hollow cathode source: (a) longitudinal cross section [43]; (b) picture of the source used.

The spectral emission of the HC depends on the gas species (usually a noble gas), Voltage applied and current flowing through the gas. When the discharge is initiated, the radiance of spectral lines exhibits approximately linear dependence on the current for noble gases and quadratic dependence for metal ions sputtered off the hollow cathode wall [24]. Once the pressure inside the vessel (puffing of noble gasses) has the correct level, order of mBar, the voltage applied on the electrodes must be progressively increased until the discharge is triggered. This voltage is supplied by a linearized DC power source capable of adjusting between 0 and 1000V and distributing up to 2A. The supply includes a ballast resistor circuit ($700 \, \Omega$) to stabilize the current flow. The cathode is maintained at a high negative voltage, while the anodes are short-circuited to protective earth at ground potential. The gas flow is controlled using a needle valve and the pressure is monitored using an ionic

¹Physikalisch-Technische Bundesanstalt - <https://www.ptb.de/cms/>

²Institut für Plasmaphysik of the University of Hannover - <https://www.iop.uni-hannover.de/en/>

gauge installed on the source. To manage the circulating current levels, typically around 1A, the electrodes are actively cooled by a water at 25 °C circuit supplied by a commercial chiller. During the calibration procedure three gasses (helium, neon, and argon) has been utilized and the discharges are illustrated in Fig. 21.2.

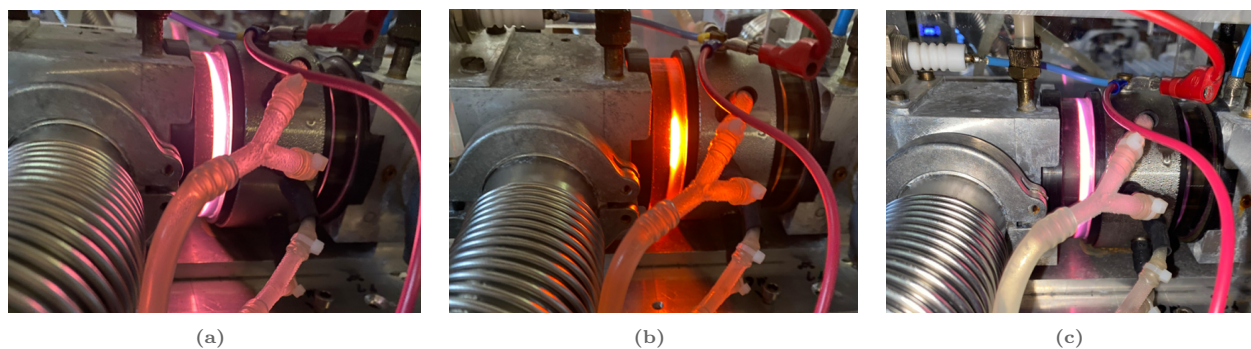


Fig. 21.2: Hollow cathode source discharge: (a) He; (b) Ne; (c) Ar.

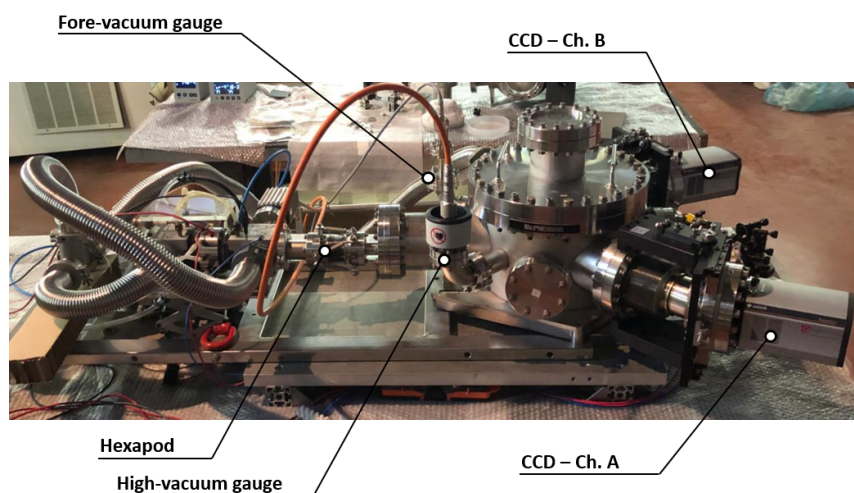


Fig. 21.3: Overview of the calibration set-up

21.2 Calibration SPRED A

With reference to Fig. 21.4a, SPRED A has the lowest wavelength of 10 nm at the first x-pixel, labeled as 0. Instead, the highest wavelength, 48 nm, corresponds to the last x-pixel, labeled as 1024 px. Due to the system's symmetry, the other channel (ranging from 44 nm to 125 nm and named SPRED B) has an opposite x-pixel/wavelength correspondence: the first x-pixel (0 px) corresponds to 125 nm, while the last x-pixel (1024 px) corresponds to 44 nm as shown in Fig. 21.4a. Instead, Fig. 21.4b illustrates the 1-D imaging capability of the system. It shows that the vertical axis of the sensors (y-pixel) corresponds to different positions along the divertor. The high-field side of the divertor is associated with y-pixel 255, while the low-field side corresponds to y-pixel 0. In summary Fig. 21.4 shows a schematization of the system showing that the horizontal dimension of the sensors is associated to the wavelength, while the vertical dimension represents different positions along the divertor.

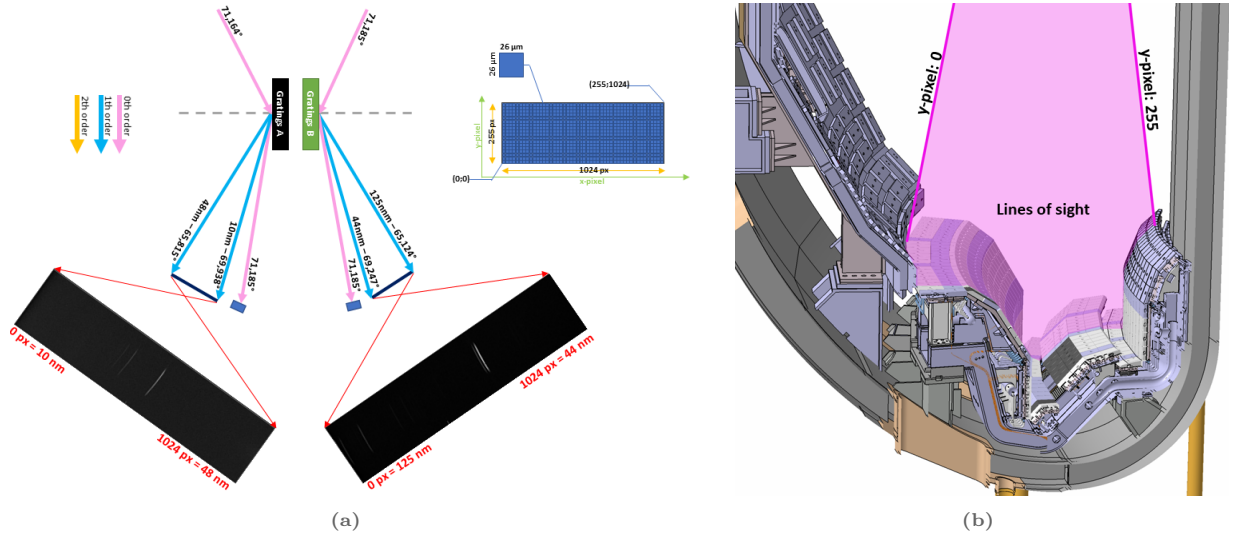


Fig. 21.4: Schematization of the acquisition: of both channels: (a) wavelength resolution scheme; (b) 1-D imaging capability scheme.

The hollow cathode source discharge loaded with helium (He) can emit well known wavelengths in the range suitable to calibrate the SPRED A. Fig. 21.5 shows the He spectrum acquired with hollow cathode source loaded with He at 0.8 mBar and powered with 700V and 0.9 A. The CDD sensor is cooled down to -10 °C and configured with an exposure time of 1500 ms. Fig. 21.5 is obtained with the sensor configured in binning mode ³ with a region of interest located in the middle of the sensor, between y-pixel 120 and 130. In this case binning configuration is indicated as 10 x 1024, which means that the data array dimension is 1024 values (horizontal dimension of the sensor) where each value is the sum of the y-pixel column from 120 to 130. To better understand the correspondence between the pixel notation and the acquisition set-up see the sensor reference system reported in Fig. 21.4.

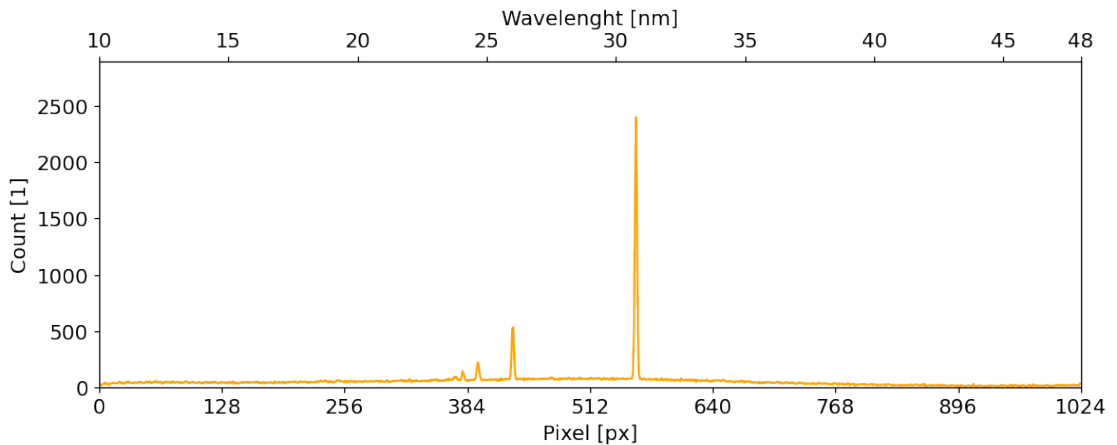


Fig. 21.5: Acquisition SPRED A with binning mode 10 x 1024 (ROI 130-140), exposure time of 1500 ms, temperature at -10°C. Hollow cathode with He at 0.8 mBar and supply at 700V and 0.9A

³Binning mode in a CCD refers to the process of combining charge from adjacent pixels into a single output signal. This enhances the signal-to-noise ratio and increases sensitivity at expense the image resolution.

He I emission lines are clearly visible in the reordered spectrum shown in Fig. 21.5 and listed in Tab. 21.1. The expected wavelength resolution of channel A is 0.08 nm, equivalent to 0.037 nm per pixel, as calculated using equation (21.1).

$$R = \frac{\Delta\lambda}{\Delta X_{pixel}} \quad (21.1)$$

where $\Delta\lambda$ represents the distance between two wavelengths, and ΔX_{pixel} is the distance between them expressed in x-pixels. Considering the entire spectrum range, $\Delta\lambda$ is 38 nm (from 10 nm to 48 nm), and ΔX_{pixel} is 1024 px, which corresponds to the full width of the sensor. This results in the resolution of 0.037 nm per pixel, or alternatively a wavelength resolution of ~ 0.08 nm.

Index	Species	Wavelength [nm]	Pixel [px]
1	He I	23.7	379
2	He I	24.3	395
3	He I	25.6	430
4	He I	30.4	560

Table 21.1: Spectrum acquired with SPREA A. Sensor in binning mode 10 x 1024 (ROI 130-140), exposure time of 1500 ms, temperature at -10°C. Hollow cathode with He at 0.8 mBar and supply at 700V and 0.9A

The nominal resolution of 0.037 nm/px can be experimentally verified by applying equation (21.1) to the measured values listed in Tab. 21.1.

$$\begin{aligned} R(30.4 \text{ nm}; 25.6 \text{ nm}) &= 0.036 \text{ nm/px} \\ R(30.4 \text{ nm}; 24.3 \text{ nm}) &= 0.036 \text{ nm/px} \\ R(30.4 \text{ nm}; 23.7 \text{ nm}) &= 0.037 \text{ nm/px} \end{aligned} \quad (21.2)$$

From (21.2), it is evident that the experimental test confirmed the expected resolution for the system. Further analysis can be conducted by examining the full width at half maximum (FWHM⁴) of the wavelengths. Fig. 21.6a displays the acquired signal (orange) and its Gaussian fit (blue) for the He I (30.4 nm). The FWHM is determined to be 2.91 px, which corresponds to 0.1 nm, based on the result from (21.2). This value aligns with the specification [12] shown in Fig. 21.6b (in figure it is reported the instrument profile simulated for the wavelength 38.5 nm). Same results are obtained for the other He I lines.

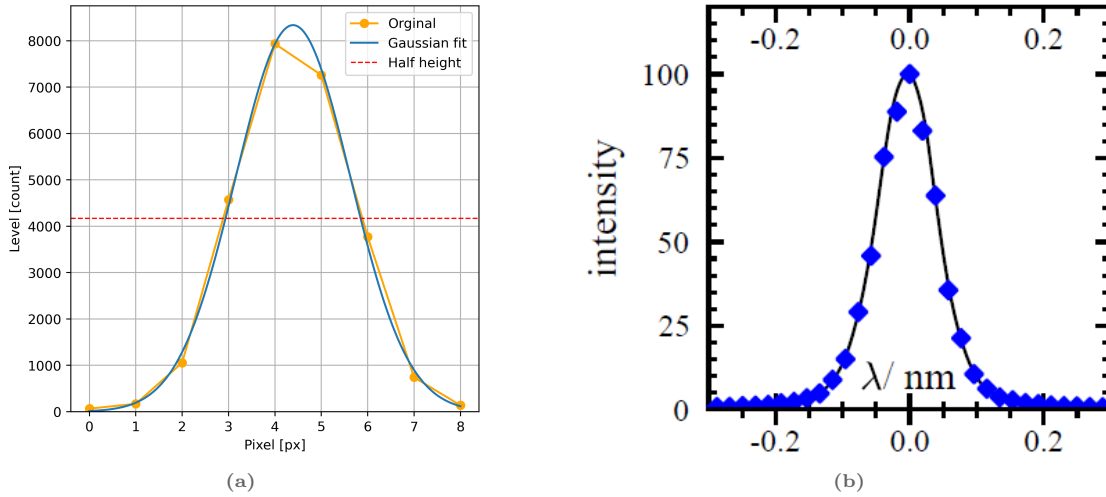


Fig. 21.6: Comparison between instrument line width: (a) Gaussian fit of He I (30.4 nm); (b) simulated instrument profile for 29.0 nm [12].

Since, the spectrometer is designed to operate in an imaging configuration, it has to resolve the spectrum at various points along the divertor as shown in Fig. 21.4b. In this setup, different vertical positions of the sensor correspond to different areas of the divertor, while different horizontal positions correspond to different wavelengths (as shown in Fig. 21.4). Fig. 21.7 illustrates an acquisition in imaging configuration with a resolution of 255 x 1024 pixels. The exposure time is set to 1500 ms, and the sensor is maintained at -10 °C. The hollow cathode is loaded with helium at 0.8 mBar and the discharge is at 700 V and 0.9 A. The height of the image in this calibration tests is limited by the optical configuration of the hollow cathode, which does not cover the

⁴The FWHM is a measure of the width of a peak in a signal, defined as the distance between the points on the curve where the intensity falls to half of its maximum value. This parameter is often used to characterize the resolution of an instrument.

entire height of the slit. When the instrument will be installed and used with plasma, the optical configuration will be adjusted to ensure full coverage of the sensor's vertical direction.

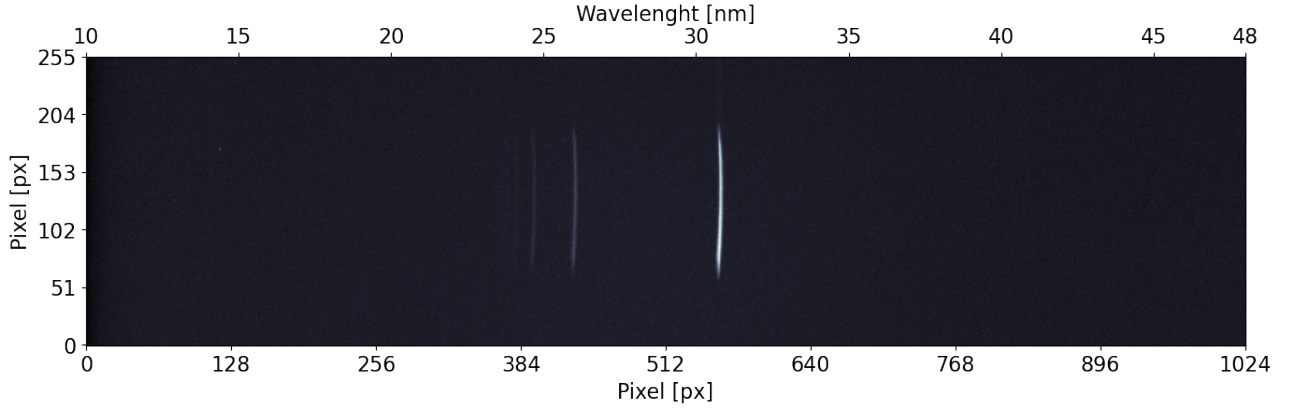


Fig. 21.7: Acquisition SPRED A with imaging mode 255 x 1024 (no ROI), exposure time of 1500 ms, temperature at -10°C . Hollow cathode with He at 0.8 mBar and supply at 700V and 0.9A

Observing the slit image in Fig. 21.7, a main distortion can be identified. A spherical aberration caused by the curvature radius of the gratings, highlighted in orange in Fig. 21.8a. This spherical aberration matches the expected distortion shown in Fig. 21.8b [12]. However this distortion can be solved during the post-processing procedure applying an offset to the wavelength identification for each row of the sensor.

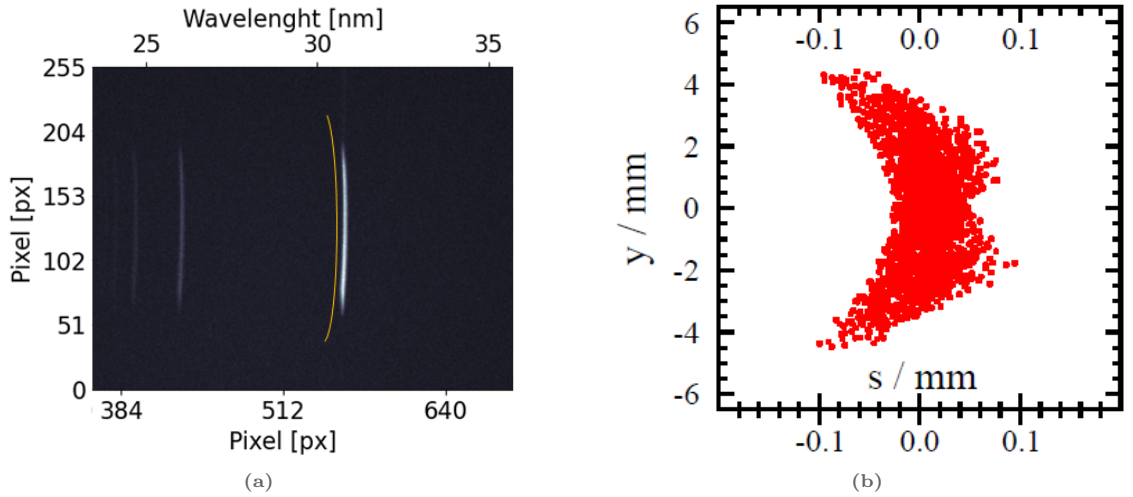


Fig. 21.8: Comparison between line distortions: (a) acquired signal with underlined the spherical aberration (orange); (b) simulated ray tracing for 29.0 nm [12].

The most promising configuration will likely involve a compromise between imaging and binning modes. To maximize signal and reduce noise, the sensor can be divided into bands where binning is applied. The optimal configuration should be determined through dedicated testing once the sensor is installed on the tokamak. Fig. 21.9 shows an example where the sensor is subdivided into 24 bands, each consisting of 10 pixels (10 x 1024). The signal of each band can also be plotted, as shown in Fig. 21.10.

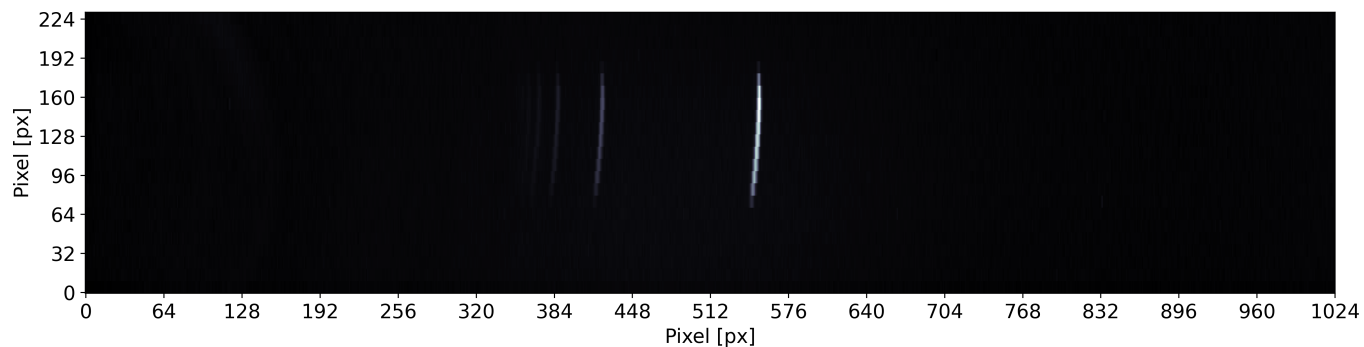


Fig. 21.9: Acquisition SPRED A with imaging mode 10 x 1024 (no ROI), exposure time of 1500 ms, temperature at -10°C . Hollow cathode with He at 0.8 mBar and supply at 700V and 0.9A

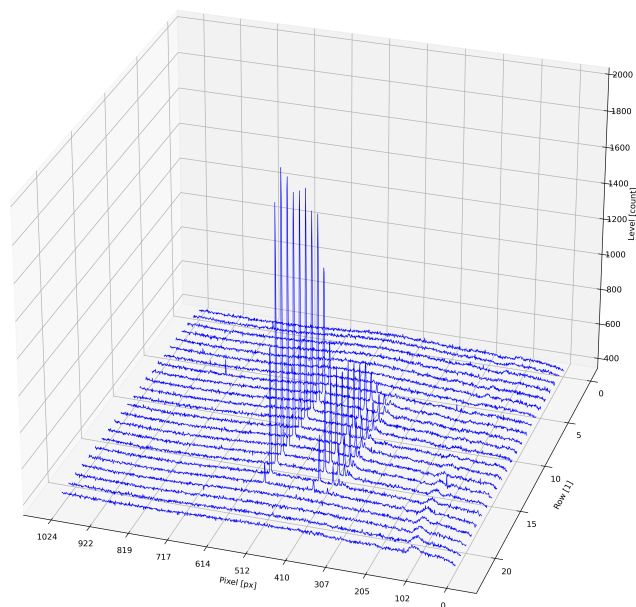


Fig. 21.10: Acquisition SPRED A with imaging mode 10 x 1024 (no ROI), exposure time of 1500 ms, temperature at -10°C . Hollow cathode with He at 0.8 mBar and supply at 700V and 0.9A

Based on the tests performed, it can be concluded that the gratings and the sensor are in compliance with the project.

21.3 Calibration SPRED B

The second channel of the spectrometer is designed to cover the wavelength range between 44 nm and 125 nm. The test has been conducted by using the calibration setup described in Sec. 21.1, following the same approach used for SPRED A as outlined in Sec. 21.2. Within the 44 nm to 125 nm range, there are well-known wavelengths for helium (He), neon (Ne), and argon (Ar) that can be identified and used for calibration purposes. Fig. 21.11 shows the results obtained in binning configuration mode 10 x 1024 with a region of interest (ROI) of 130–140 (see Sec. 21.2 for an explanation of the nomenclature). The plot was created by merging the data from three different tests performed with the sensor at -10°C and an exposure time of 1000 ms. During these tests, the hollow cathode has been loaded with Ne, He, and Ar, all at 0.9 mBar, and supplied with 800 V and 1.0 A.

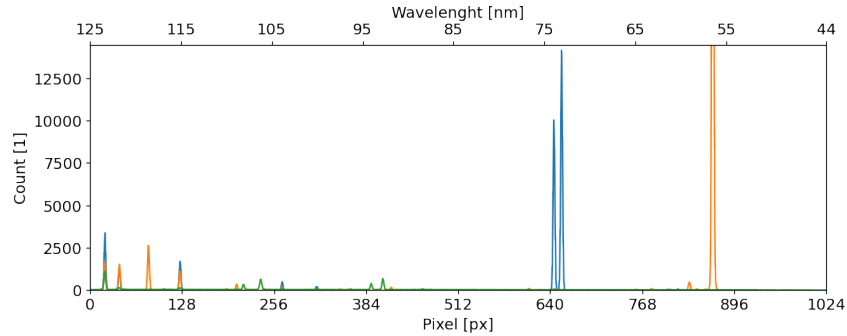


Fig. 21.11: Acquisition SPRED B with imaging mode 10 x 1024 (ROI 130-140), exposure time of 1000 ms, temperature at -10°C. Hollow cathode with He (orange), Ne(blue) and Ar(green) at 0.8 mBar and supply at 800V and 1.0A

Index	Species	Wavelength [nm]	Pixel [px]
1	Ar I	106.6	213
2	Ar I	104.8	237
3	Ne I	74.3	645
4	Ne I	73.5	656
5	He I	58.4	866

Table 21.2: Spectrum acquired with SPREA B. Sensor in binning mode 10 x 1024 (ROI 130-140), exposure time of 1000 ms, temperature at -10°C. Hollow cathode with He, Ne and Ar at 0.9 mBar and supply at 800V and 1.0A

In Tab. 21.2, the data from the acquisition plotted in Fig. 21.11 are summarized. For this second channel, a resolution of 0.16 nm or 0.079 nm/px is expected, according to equation (21.1). Using this equation with the data tabulated in Tab. 21.2, the resolution obtained is given by (21.3).

$$\begin{aligned}
 R(106.6 \text{ nm}; 104.8 \text{ nm}) &= 0.075 \text{ nm/px} \\
 R(104.8 \text{ nm}; 74.3 \text{ nm}) &= 0.074 \text{ nm/px} \\
 R(74.3 \text{ nm}; 73.5 \text{ nm}) &= 0.073 \text{ nm/px} \\
 R(73.5 \text{ nm}; 58.4 \text{ nm}) &= 0.0719 \text{ nm/px}
 \end{aligned} \tag{21.3}$$

From Fig. 21.3, it can be seen that the gratings behave with a resolution that aligns with the designed specifications, showing an average resolution of 0.073 nm/px. The analysis of the line width for different spectra, compared to the simulated ones, is reported in Fig. 21.12. Fig. 21.12a shows the Ne I line (73.5 nm) with a FWHM of 2.90 px, Fig. 21.12b shows the He I line (58.4 nm) with an FWHM of 2.97 px, and Fig. 21.12c reports the Ar I line (104.8 nm) with an FWHM of 3.01 px. The average FWHM is therefore 2.96 px, which corresponds to 0.23 nm, closely matching the simulated profile shown in Fig. 21.12d for the wavelength of 84.5 nm.

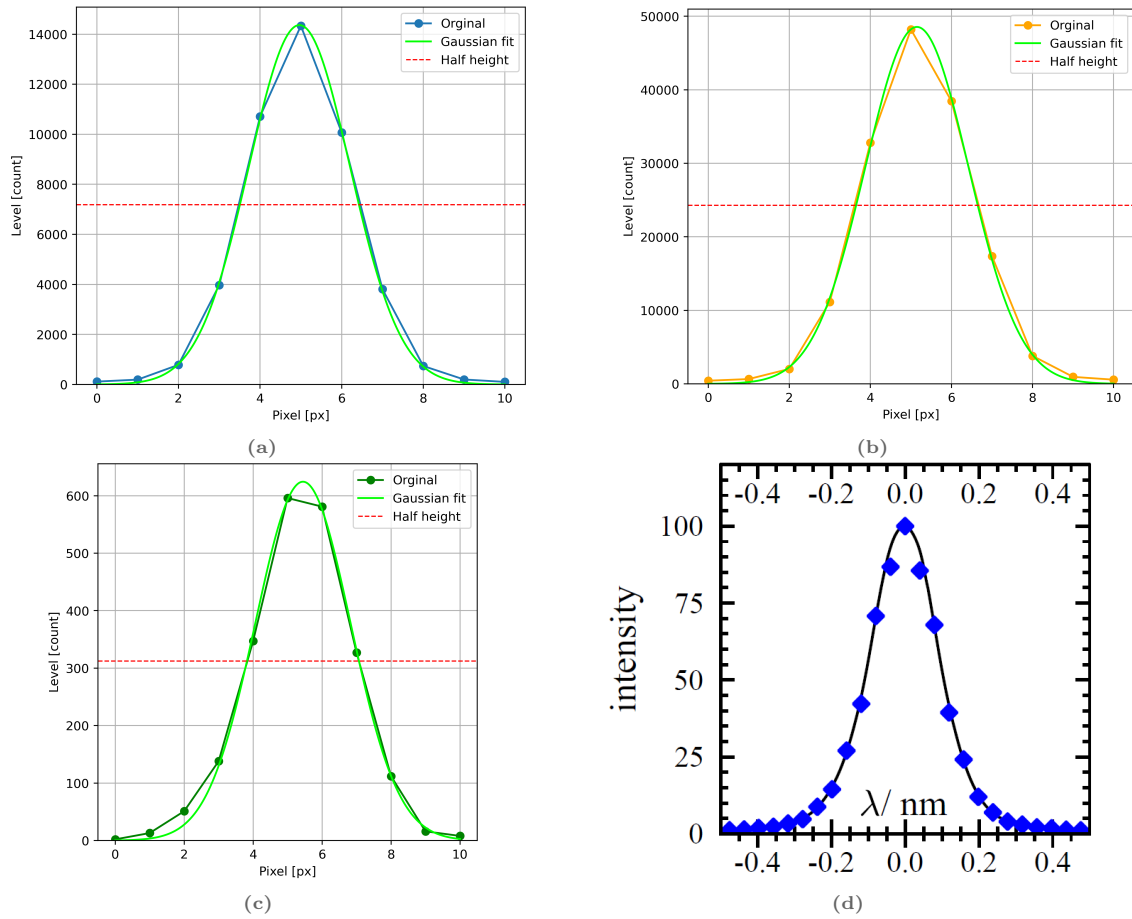


Fig. 21.12: Comparison between line width: (a) Gaussian fit of Ne I (73.5 nm); (b) Gaussian fit of He I (58.4 nm); (c) Gaussian fit of Ar I (104.8 nm); (d) simulated instrument profile for 84.5 nm [12].

In Fig. 21.13, the acquisition of the different gas spectra (Ne, He, and Ar) in imaging mode is shown. The acquisition for each gas is performed with the sensor at -10°C , in full imaging configuration (255×1024). The hollow cathode is supplied with 800 V and 1.0 A, and the gases are at 0.9 mBar. As in the SPRED A cases (see Sec. 21.2), spherical aberration and an inclination are present. The shape of the spherical aberration is consistent with the ray tracing simulation. The inclination is of the same magnitude and direction as that of SPRED A, suggesting a mechanical offset on the flange that hosts both slits (see Fig. 19.10). However, as with SPRED A, the inclination and the aberration can be corrected during data post-processing.

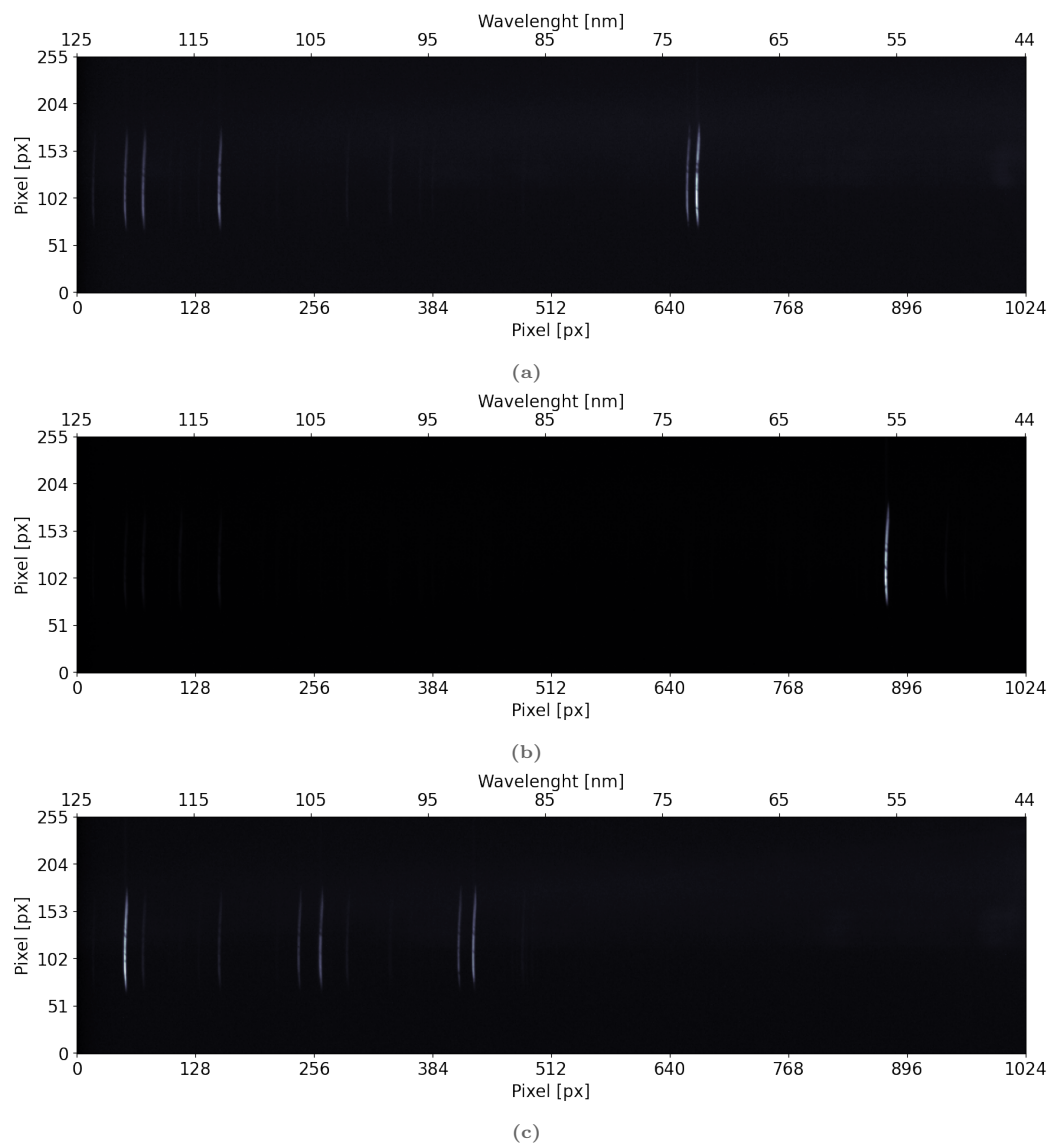


Fig. 21.13: Acquisition SPRED B with imaging mode 255 x 1024 (no ROI), exposure time of 1000 ms, temperature at -10°C . Hollow cathode with several gasses at 0.9 mBar and supply at 800V and 1.0A : (a) Ne; (b) He; (c) Ar.

This chapter presented the Imaging Vacuum Ultraviolet Spectrometer (VUV) designed to monitor the divertor region of JT-60SA which is starting its activity in support of the exploitation of ITER and by complementing it in resolving key physics and engineering issues for DEMO. The aim of the spectrometer is to characterize the contribution of impurities to the radiation emitted in the divertor region in different scenarios and to study the divertor physics including the plasma detachment. Positioned on an upper port with a vertical line of sight aiming at the divertor, the spectrometer is based on the double SPRED (survey, poor resolution, extended domain) spectrometer originally employed on Textor. It has been refurbished with two new toroidal gratings specially designed to compensate the aberration, to allow 1D imaging detection and to maximize the spectral resolution. The instrument covers a wavelength range from 10 nm to 125 nm separated in two ranges of 10-48 nm and 44-125 nm, with an overlapping region to perform the cross calibration. These two ranges are measured simultaneously using the two separate channels, enabling the instrument to resolve the emission across the entire range. The gratings have been installed in spectrometer vessel and tested using a dedicated setup. The spectrometer chamber has been connected to an hollow cathode source, which, when loaded with different gases, generated a known spectrum. Analyzing the emitted spectra enables the establishment of a reliable pixel-to-wavelength mapping and allows to evaluate the gratings performance. The resolution and line width for both channels have been also analyzed, confirming that the gratings, sensors, and optical system function properly and meet the design specifications. By acquiring data in binning mode, the distance between spectral lines have been compared to determine the resolution of both channels. Channel A (10-48 nm) demonstrated a resolution of 0.037 nm/px, which allows for the distinction of lines spaced at 0.074 nm, aligning perfectly with the designed characteristics of this grating. Furthermore, by reconstructing the wavelengths using a Gaussian interpolation fit, the full width at half maximum (FWHM) has been calculated, revealing that the average line width is approximately 2.91 px. This corresponds to a line width of 0.21 nm, which matches the expected value allowing to resolve the wavelengths of scientific interest. The same approach has been used for the second channel (44-125 nm), revealing a resolution of 0.075 nm/px, which allows for distinguishing lines spaced at 0.16 nm, in accordance with the designed resolution. The Gaussian fit had revealed a FWHM of 2.98 px for this channel, consistent with the expected value from the instrument profile simulations. On the other hand, by changing the sensor configuration to imaging mode, slit images at different wavelengths had been captured for both channels. These images revealed two types of deformation: spherical aberration, which has been predicted by the ray tracing simulation, and a tilt in the lines caused by the mechanical installation of the slit flange. These distortions can be corrected in post-processing by adjusting the wavelength identification for each row of the sensor, ensuring they do not affect the instrument's performance. However, dedicated tests are planned to further minimize these effects. The next step in investigating grating performance involves testing the 1-D imaging resolution of the system. The plan is to move the hollow cathode to simulate an extended source and use this setup to illuminate a custom slit composed of a series of holes. This test will utilize the entire height of the sensor aiming to characterize the system capacity of resolve the spectrum in different locations on the divertor.

Once installed on the tokamak, to perform the alignment, and so observe the divertor location of interest, it is foreseen to back-illuminate the spectrometer with a green laser through the 0-order system of the grating. The laser light path is reversed relative to the plasma light ones, revealing the Line of Sight (LoS) footprint on the divertor. The alignment procedure involves moving the instrument using a tripod to position the laser footprint accurately on the divertor's point of interest. To verify the alignment, it is necessary to check the position of this laser footprint. For this purpose, the spectrometer has been equipped with a custom endoscope. The 0-order system, which consists of three mirrors (two in-vessel and one out-vessel) and a laser, has been installed and successfully tested for aligning the calibration system. Once the gold-coated mirrors are installed, this system will be used to align the entire optical chain. The different components of the endoscope have been designed and manufactured but they are not yet installed.

Given the extended length of the JT-60SA port ducts, the system is equipped with custom-designed optical relays featuring gold-coated toroidal mirrors with remote alignment capabilities. These mirrors focus plasma emission from the divertor onto the two slits. Both mirrors the upper and lower mirrors, have been designed and manufactured. The upper mirror has been installed in the spherical chamber, while the lower mirror is yet to be installed. To test these optical elements, an upgrade of the vacuum chamber designed for leak testing has been proposed. This upgrade will allow the installation of the hollow cathode in front of the lower mirror. The goal is to replicate the calibration tests with the hollow cathode by using the entire optical chain. To perform this final test the complete system must be assembled including also the chassis. This last has been manufactured and it is under quality test at the laboratory of ICSI in Romania. The assembly of the entire system and the shipping to QST (Japan, Naka) it is foreseen for the second half of 2025.

Bibliography

- [1] M Agostini et al. “Neutral density estimation in the ASDEX upgrade divertor from deuterium emissivity measurements during detachment and shoulder formation”. In: *Plasma Physics and Controlled Fusion* 61.11 (Sept. 2019), p. 115001. ISSN: 1361-6587. DOI: [10.1088/1361-6587/ab4122](https://doi.org/10.1088/1361-6587/ab4122). URL: <http://dx.doi.org/10.1088/1361-6587/ab4122>.
- [2] R. Albanese et al. “Diagnostics, data acquisition and control of the divertor test tokamak experiment”. In: *Fusion Engineering and Design* 122 (Nov. 2017), pp. 365–374. ISSN: 0920-3796. DOI: [10.1016/j.fusengdes.2017.05.118](https://doi.org/10.1016/j.fusengdes.2017.05.118). URL: <http://dx.doi.org/10.1016/j.fusengdes.2017.05.118>.
- [3] R. Ambrosino. “DTT - Divertor Tokamak Test facility: A testbed for DEMO”. In: *Fusion Engineering and Design* 167 (June 2021), p. 112330. ISSN: 0920-3796. DOI: [10.1016/j.fusengdes.2021.112330](https://doi.org/10.1016/j.fusengdes.2021.112330). URL: <http://dx.doi.org/10.1016/j.fusengdes.2021.112330>.
- [4] J. P. Appleton and M. Steinberg. “Vacuum-Ultraviolet Absorption of Shock-Heated Vibrationally Excited Nitrogen”. In: *The Journal of Chemical Physics* 46.4 (Feb. 1967), pp. 1521–1529. ISSN: 1089-7690. DOI: [10.1063/1.1840883](https://doi.org/10.1063/1.1840883). URL: <http://dx.doi.org/10.1063/1.1840883>.
- [5] M Bagatin et al. “RFX diagnostics”. In: *Fusion Engineering and Design* 25.4 (Jan. 1995), pp. 425–460. ISSN: 0920-3796. DOI: [10.1016/0920-3796\(94\)00283-d](https://doi.org/10.1016/0920-3796(94)00283-d). URL: [http://dx.doi.org/10.1016/0920-3796\(94\)00283-d](http://dx.doi.org/10.1016/0920-3796(94)00283-d).
- [6] L. Balbinot, G. Rubino, and P. Innocente. “Development of DTT single null divertor scenario”. In: *Nuclear Materials and Energy* 27 (June 2021), p. 100952. ISSN: 2352-1791. DOI: [10.1016/j.nme.2021.100952](https://doi.org/10.1016/j.nme.2021.100952). URL: <http://dx.doi.org/10.1016/j.nme.2021.100952>.
- [7] P. Barabaschi, Y. Kamada, and H. Shirai. “Progress of the JT-60SA project”. In: *Nuclear Fusion* 59.11 (June 2019), p. 112005. ISSN: 1741-4326. DOI: [10.1088/1741-4326/ab03f6](https://doi.org/10.1088/1741-4326/ab03f6). URL: <http://dx.doi.org/10.1088/1741-4326/ab03f6>.
- [8] M. Barbarino. “A brief history of nuclear fusion”. In: *Nature Physics* 16.9 (June 2020), pp. 890–893. ISSN: 1745-2481. DOI: [10.1038/s41567-020-0940-7](https://doi.org/10.1038/s41567-020-0940-7). URL: <http://dx.doi.org/10.1038/s41567-020-0940-7>.
- [9] W. Biel. “Vacuum Ultraviolet Spectroscopy at TEXTOR”. In: *Fusion Science and Technology* 47.2 (Feb. 2005), pp. 246–252. ISSN: 1943-7641. DOI: [10.13182/fst05-a703](https://doi.org/10.13182/fst05-a703). URL: <http://dx.doi.org/10.13182/fst05-a703>.
- [10] W. Biel et al. “Design of a high-efficiency extreme ultraviolet overview spectrometer system for plasma impurity studies on the stellarator experiment Wendelstein 7-X”. In: *Review of Scientific Instruments* 75.10 (Oct. 2004), pp. 3268–3275. ISSN: 1089-7623. DOI: [10.1063/1.1784557](https://doi.org/10.1063/1.1784557). URL: <http://dx.doi.org/10.1063/1.1784557>.
- [11] W. Biel et al. “High efficiency extreme ultraviolet overview spectrometer: Construction and laboratory testing”. In: *Review of Scientific Instruments* 77.10 (Sept. 2006). ISSN: 1089-7623. DOI: [10.1063/1.2221659](https://doi.org/10.1063/1.2221659). URL: <http://dx.doi.org/10.1063/1.2221659>.
- [12] Wolfgang Biel. “Method for determining optimum grating parameters for producing a diffraction grating for a VUV spectrometer”. In: (Apr. 2003). URL: <https://patents.google.com/patent/US7420736# citedBy>.
- [13] Allen H. Boozer. “What is a stellarator?” In: *Physics of Plasmas* 5.5 (1998), pp. 1647–1655. DOI: [10.1063/1.872833](https://doi.org/10.1063/1.872833). eprint: <https://doi.org/10.1063/1.872833>. URL: <https://doi.org/10.1063/1.872833>.

- [14] K.J Callahan et al. “Integrated Zeff analysis on the DIII-D Tokamak”. In: *Journal of Instrumentation* 14.10 (Oct. 2019), pp. C10002–C10002. ISSN: 1748-0221. DOI: [10.1088/1748-0221/14/10/c10002](https://doi.org/10.1088/1748-0221/14/10/c10002). URL: <http://dx.doi.org/10.1088/1748-0221/14/10/C10002>.
- [15] L. Carraro et al. “Impurity screening in the RFX reversed field pinch”. In: *Journal of Nuclear Materials* 266–269 (Mar. 1999), pp. 446–451. ISSN: 0022-3115. DOI: [10.1016/S0022-3115\(98\)00827-7](https://doi.org/10.1016/S0022-3115(98)00827-7). URL: [http://dx.doi.org/10.1016/S0022-3115\(98\)00827-7](http://dx.doi.org/10.1016/S0022-3115(98)00827-7).
- [16] L. Carraro et al. “RFX-mod2 diagnostic capability enhancements for the exploration of multi-magnetic-configurations”. In: *Nuclear Fusion* 64.7 (June 2024), p. 076032. ISSN: 1741-4326. DOI: [10.1088/1741-4326/ad490a](https://doi.org/10.1088/1741-4326/ad490a). URL: <http://dx.doi.org/10.1088/1741-4326/ad490a>.
- [17] L. Carraro et al. “Zeff measurements on the reversed field pinch REX”. In: *24th European Physical Society Conference on Fusion and Plasma Physics*. IEEE, June 1997. URL: <http://libero.ipp.mpg.de/libero/PDF/EPS.24.Vol1.1997.pdf>.
- [18] Francesca Cau et al. “Analysis and design of the actively cooled JT-60 SA divertor”. In: *Fusion Engineering and Design* 193 (Aug. 2023), p. 113605. ISSN: 0920-3796. DOI: [10.1016/j.fusengdes.2023.113605](https://doi.org/10.1016/j.fusengdes.2023.113605). URL: <http://dx.doi.org/10.1016/j.fusengdes.2023.113605>.
- [19] Yingjie Chen et al. “Zeff first measurements in EAST with a multi-channel visible bremsstrahlung new system”. In: *Fusion Engineering and Design* 88.11 (Nov. 2013), pp. 2825–2829. ISSN: 0920-3796. DOI: [10.1016/j.fusengdes.2013.05.003](https://doi.org/10.1016/j.fusengdes.2013.05.003). URL: <http://dx.doi.org/10.1016/j.fusengdes.2013.05.003>.
- [20] A. M. Cormack. “Representation of a Function by Its Line Integrals, with Some Radiological Applications”. In: *Journal of Applied Physics* 34.9 (Sept. 1963), pp. 2722–2727. ISSN: 1089-7550. DOI: [10.1063/1.1729798](https://doi.org/10.1063/1.1729798). URL: <http://dx.doi.org/10.1063/1.1729798>.
- [21] Till Cremer et al. “Recent developments on next-generation microchannel plates for particle identification applications”. In: *UV, X-Ray, and Gamma-Ray Space Instrumentation for Astronomy XXI*. Ed. by Oswald H. Siegmund. SPIE, Sept. 2019. DOI: [10.1117/12.2530037](https://doi.org/10.1117/12.2530037). URL: <http://dx.doi.org/10.1117/12.2530037>.
- [22] F. Crisanti et al. *Divertor Tokamak Test facility Research Plan Version 1.0*. May 2024. URL: <https://www.pubblicazioni.enea.it/le-pubblicazioni-enea/edizioni-enea/anno-2024/divertor-tokamak-test-facility-research-plan-version-1-0.html.html>.
- [23] A.M. Daltrini and M. Machida. “Modified branching ratio method for absolute intensity calibration in VUV spectroscopy”. In: *IEEE Transactions on Plasma Science* 33.6 (Dec. 2005), pp. 1961–1967. ISSN: 0093-3813. DOI: [10.1109/tps.2005.860115](https://doi.org/10.1109/tps.2005.860115). URL: <http://dx.doi.org/10.1109/TPS.2005.860115>.
- [24] Karsten Danzmann et al. “High current hollow cathode as a radiometric transfer standard source for the extreme vacuum ultraviolet”. In: *Applied Optics* 27.23 (Dec. 1988), p. 4947. ISSN: 1539-4522. DOI: [10.1364/ao.27.004947](https://doi.org/10.1364/ao.27.004947). URL: <http://dx.doi.org/10.1364/AO.27.004947>.
- [25] A. Dinklage et al. “Magnetic configuration effects on the Wendelstein 7-X stellarator”. In: *Nature Physics* 49.14 (Sept. 2018). DOI: [10.1038/s41567-018-0141-9](https://doi.org/10.1038/s41567-018-0141-9). URL: <https://www.nature.com/articles/s41567-018-0141-9#citeas>.
- [26] M. J. Edwards et al. “Progress towards ignition on the National Ignition Facility”. In: *Physics of Plasmas* (Mar. 2013). DOI: [10.1063/1.4816115](https://doi.org/10.1063/1.4816115). URL: <https://aip.scitation.org/doi/10.1063/1.4816115>.
- [27] Enerdata. “CO2 emissions from fuel combustion”. In: *Enerdata website* (Dec. 2022). URL: <https://yearbook.enerdata.net/co2/emissions-co2-data-from-fuel-combustion.html>.
- [28] A. R. Field et al. “A spatially scanning vacuum ultraviolet and visible range spectrometer for spectroscopy of tokamak plasmas in ASDEX-Upgrade”. In: *Review of Scientific Instruments* 66.12 (Dec. 1995), pp. 5433–5441. ISSN: 1089-7623. DOI: [10.1063/1.1146065](https://doi.org/10.1063/1.1146065). URL: <http://dx.doi.org/10.1063/1.1146065>.
- [29] D. Fiorucci et al. “Design of an interferometer/polarimeter for DTT”. In: *Journal of Instrumentation* 15.02 (Feb. 2020), pp. C02041–C02041. ISSN: 1748-0221. DOI: [10.1088/1748-0221/15/02/c02041](https://doi.org/10.1088/1748-0221/15/02/c02041). URL: <http://dx.doi.org/10.1088/1748-0221/15/02/C02041>.
- [30] R. J. Fonck, A. T. Ramsey, and R. V. Yelle. “Multichannel grazing-incidence spectrometer for plasma impurity diagnosis: SPRED”. In: *Applied Optics* 21.12 (June 1982), p. 2115. ISSN: 1539-4522. DOI: [10.1364/ao.21.002115](https://doi.org/10.1364/ao.21.002115). URL: <http://dx.doi.org/10.1364/AO.21.002115>.
- [31] EURO Fusion. “Road map long version”. In: *EUROFusion website* (Sept. 2018). URL: <https://www.euro-fusion.org/eurofusion/roadmap/>.
- [32] G.Vandoni. *The basis of vacuum*. University lecture. 2012. URL: <https://indico.cern.ch/event/264020/attachments/467855/648232/CERN-Basic-Vacuum-2012-lecture.pdf>.

- [33] M. Glugla et al. “The ITER tritium systems”. In: *Fusion Engineering and Design* 82.5–14 (Oct. 2007), pp. 472–487. ISSN: 0920-3796. DOI: [10.1016/j.fusengdes.2007.02.025](https://doi.org/10.1016/j.fusengdes.2007.02.025). URL: <http://dx.doi.org/10.1016/j.fusengdes.2007.02.025>.
- [34] R. Guirlet et al. “Extreme UV spectroscopy measurements and analysis for tungsten density studies in the WEST tokamak”. In: *Plasma Physics and Controlled Fusion* 64.10 (Sept. 2022), p. 105024. ISSN: 1361-6587. DOI: [10.1088/1361-6587/ac8d2c](https://doi.org/10.1088/1361-6587/ac8d2c). URL: <http://dx.doi.org/10.1088/1361-6587/ac8d2c>.
- [35] T. Gys. “Micro-channel plates and vacuum detectors”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 787 (July 2015), pp. 254–260. ISSN: 0168-9002. DOI: [10.1016/j.nima.2014.12.044](https://doi.org/10.1016/j.nima.2014.12.044). URL: <http://dx.doi.org/10.1016/j.nima.2014.12.044>.
- [36] Donné A. J. H. “The European roadmap towards fusion electricity”. In: *Philosophical transactions of the royal society* 377 (Feb. 2019). DOI: <https://doi.org/10.1098/rsta.2017.0432>. URL: <https://royalsocietypublishing.org/doi/10.1098/rsta.2017.0432>.
- [37] Peter Hartmann et al. “Glass ceramic ZERODUR®: Even closer to zero thermal expansion: a review, part 1”. In: *Journal of Astronomical Telescopes, Instruments, and Systems* 7.02 (June 2021). ISSN: 2329-4124. DOI: [10.1117/1.jatis.7.2.020901](https://doi.org/10.1117/1.jatis.7.2.020901). URL: <http://dx.doi.org/10.1117/1.jatis.7.2.020901>.
- [38] Hauer and Volke. “Concept design proposals for the DTT divertor pumpingsystem”. In: *DTT* (Mar. 2022). DOI: <https://www.dtt-dms.enea.it/share/page/site/dtt/document-details?nodeRef=workspace://SpacesStore/5f12604d-a070-44b8-9e8b-5883604f42e9>.
- [39] W. M. Haynes, David R. Lide, and Thomas J. Bruno. *CRC Handbook of Chemistry and Physics - 95th Edition*. Mar. 2014. URL: https://edisciplinas.usp.br/pluginfile.php/4557662/mod_resource/content/1/CRC%5C%20Handbook%5C%20of%5C%20Chemistry%5C%20and%5C%20Physics%5C%2095th%5C%20Edition.pdf.
- [40] William M. Haynes. *Handbook of Chemistry and Physics*. July 2016. DOI: <https://doi.org/10.1201/9781315380476>.
- [41] Liang HE et al. “Space-resolved vacuum-ultraviolet spectroscopy for measuring impurity emission from divertor region of EAST tokamak”. In: *Plasma Science and Technology* 24.6 (May 2022), p. 064003. ISSN: 1009-0630. DOI: [10.1088/2058-6272/ac5f81](https://doi.org/10.1088/2058-6272/ac5f81). URL: <http://dx.doi.org/10.1088/2058-6272/ac5f81>.
- [42] S.S. Henderson et al. “Determination of volumetric plasma parameters from spectroscopic N II and N III line ratio measurements in the ASDEX Upgrade divertor”. In: *Nuclear Fusion* 58.1 (Dec. 2017), p. 016047. ISSN: 1741-4326. DOI: [10.1088/1741-4326/aa96be](https://doi.org/10.1088/1741-4326/aa96be). URL: <http://dx.doi.org/10.1088/1741-4326/aa96be>.
- [43] Jörg Hollandt, Michael Kühne, and Burkhard Wende. “High-current hollow-cathode source as a radiant intensity standard in the 40–125-nm wavelength range”. In: *Applied Optics* 33.1 (Jan. 1994), p. 68. ISSN: 1539-4522. DOI: [10.1364/ao.33.000068](https://doi.org/10.1364/ao.33.000068). URL: <http://dx.doi.org/10.1364/AO.33.000068>.
- [44] Chuanjun Huang and Laifeng Li. “Magnetic confinement fusion: a brief review”. In: *Frontiers in Energy* 12 (2018), pp. 305–313. DOI: <https://doi.org/10.1007/s11708-018-0539-1>.
- [45] A. Huber et al. “Development of a mirror-based endoscope for divertor spectroscopy on JET with the new ITER-like wall (invited)”. In: *Review of Scientific Instruments* 83.10 (July 2012). ISSN: 1089-7623. DOI: [10.1063/1.4731759](https://doi.org/10.1063/1.4731759). URL: <http://dx.doi.org/10.1063/1.4731759>.
- [46] A. Huber et al. “Impact of the ITER-like wall on divertor detachment and on the density limit in the JET tokamak”. In: *Journal of Nuclear Materials* 438 (July 2013), S139–S147. ISSN: 0022-3115. DOI: [10.1016/j.jnucmat.2013.01.022](https://doi.org/10.1016/j.jnucmat.2013.01.022). URL: <http://dx.doi.org/10.1016/j.jnucmat.2013.01.022>.
- [47] Rongqing Hui. “Photodetectors”. In: *Introduction to Fiber-Optic Communications*. Elsevier, 2020, pp. 125–154. ISBN: 9780128053454. DOI: [10.1016/b978-0-12-805345-4.00004-4](https://doi.org/10.1016/b978-0-12-805345-4.00004-4). URL: <http://dx.doi.org/10.1016/b978-0-12-805345-4.00004-4>.
- [48] I. H. Hutchinson. *Principles of Plasma Diagnostics*. Cambridge University Press, July 2002. ISBN: 9780511613630. DOI: [10.1017/cbo9780511613630](https://doi.org/10.1017/cbo9780511613630). URL: <http://dx.doi.org/10.1017/CBO9780511613630>.
- [49] IEA. “Nuclear Electricity”. In: *International Energy Agency* (2022). URL: <https://www.iea.org/reports/nuclear-electricity>.
- [50] A Iiyoshi et al. “Overview of the Large Helical Device project”. In: *Nuclear Fusion* 39.9Y (Sept. 1999), pp. 1245–1256. DOI: [10.1088/0029-5515/39/9y/313](https://doi.org/10.1088/0029-5515/39/9y/313). URL: <https://doi.org/10.1088/0029-5515/39/9y/313>.
- [51] Edward C.Y. Inn. “Vacuum ultraviolet spectroscopy”. In: *Spectrochimica Acta* 7 (1955), pp. 65–87. ISSN: 0371-1951. DOI: [10.1016/0371-1951\(55\)80009-4](https://doi.org/10.1016/0371-1951(55)80009-4). URL: [http://dx.doi.org/10.1016/0371-1951\(55\)80009-4](http://dx.doi.org/10.1016/0371-1951(55)80009-4).
- [52] P. Innocente et al. “Design of a multi-configurations divertor for the DTT facility”. In: *Nuclear Materials and Energy* 33 (Oct. 2022), p. 101276. ISSN: 2352-1791. DOI: [10.1016/j.nme.2022.101276](https://doi.org/10.1016/j.nme.2022.101276). URL: <http://dx.doi.org/10.1016/j.nme.2022.101276>.

- [53] P. Innocente et al. “Study of the double null divertor configuration in DTT”. In: *Nuclear Materials and Energy* 27 (June 2021), p. 100985. ISSN: 2352-1791. DOI: [10.1016/j.nme.2021.100985](https://doi.org/10.1016/j.nme.2021.100985). URL: <http://dx.doi.org/10.1016/j.nme.2021.100985>.
- [54] R. C. Isler et al. “Spectroscopic characterization of the DIII-D divertor”. In: *Physics of Plasmas* 4.2 (Feb. 1997), pp. 355–368. ISSN: 1089-7674. DOI: [10.1063/1.872095](https://doi.org/10.1063/1.872095). URL: <http://dx.doi.org/10.1063/1.872095>.
- [55] Karl Jousten. *Handbook of Vacuum Technology*. July 2016. DOI: <https://doi.org/10.1002/9783527688265.fmatter>. URL: <https://onlinelibrary.wiley.com/doi/abs/10.1002/9783527688265.fmatter>.
- [56] Karl Jousten. *Handbook of Vacuum Technology*. Wiley, June 2016. ISBN: 9783527688265. DOI: [10.1002/9783527688265](https://doi.org/10.1002/9783527688265). URL: <http://dx.doi.org/10.1002/9783527688265>.
- [57] K. Kadota, M. Otsuka, and J. Fujita. “Space- and time-resolved study of impurities by visible spectroscopy in the high-density regime of JIPP T-II tokamak plasma”. In: *Nuclear Fusion* 20.2 (Feb. 1980), pp. 209–212. ISSN: 1741-4326. DOI: [10.1088/0029-5515/20/2/010](https://doi.org/10.1088/0029-5515/20/2/010). URL: <http://dx.doi.org/10.1088/0029-5515/20/2/010>.
- [58] Mitsuru Kikuchi, Karl Lackner, and Minh Quang Tran. *Fusion Physics*. Non-serial Publications. Vienna: International Atomic Energy Agency (IAEA), Mar. 2012. ISBN: 978-92-0-130410-0. URL: <https://www.iaea.org/publications/8879/fusion-physics>.
- [59] T. Klinger et al. “Overview of first Wendelstein 7-X high-performance operation”. In: *Fusion Technology* 17.1 (2019), pp. 148–168. DOI: [10.1088/1741-4326/ab03a7](https://doi.org/10.1088/1741-4326/ab03a7). URL: <https://iopscience.iop.org/article/10.1088/1741-4326/ab03a7#back-to-top-target>.
- [60] K. D. Lawson et al. “Enhancements to the JET poloidally scanning vacuum ultraviolet/visible spectrometers”. In: *Review of Scientific Instruments* 83.10 (Aug. 2012). ISSN: 1089-7623. DOI: [10.1063/1.4745213](https://doi.org/10.1063/1.4745213). URL: <http://dx.doi.org/10.1063/1.4745213>.
- [61] B.A. Lomanowski et al. “Inferring divertor plasma properties from hydrogen Balmer and Paschen series spectroscopy in JET-ILW”. In: *Nuclear Fusion* 55.12 (Nov. 2015), p. 123028. ISSN: 1741-4326. DOI: [10.1088/0029-5515/55/12/123028](https://doi.org/10.1088/0029-5515/55/12/123028). URL: <http://dx.doi.org/10.1088/0029-5515/55/12/123028>.
- [62] Hongmin Mao et al. “A multichannel visible spectroscopy system for the ITER-like W divertor on EAST”. In: *Review of Scientific Instruments* 88.4 (Apr. 2017). ISSN: 1089-7623. DOI: [10.1063/1.4979406](https://doi.org/10.1063/1.4979406). URL: <http://dx.doi.org/10.1063/1.4979406>.
- [63] Masson-Delmotte et al. “Global Warming of 1.5°C”. In: *IPCC* (2018). DOI: [10.1017/9781009157940.008](https://doi.org/10.1017/9781009157940.008). URL: <https://www.ipcc.ch/sr15/>.
- [64] Garry McCracken and Peter Stott. “Magnetic Confinement”. In: *Fusion* 17 (2013), pp. 45–58. DOI: <https://doi.org/10.1016/B978-0-12-384656-3.00005-2>.
- [65] A. Meigs et al. “Enhancement of JET’s mirror-link near-ultraviolet to near-infrared divertor spectroscopy system”. In: *Review of Scientific Instruments* 81.10 (Oct. 2010). ISSN: 1089-7623. DOI: [10.1063/1.3502322](https://doi.org/10.1063/1.3502322). URL: <http://dx.doi.org/10.1063/1.3502322>.
- [66] H. Meister et al. “An integrated system to measure the effective charge of fusion plasmas in the ASDEX Upgrade tokamak”. In: *Review of Scientific Instruments* 74.11 (Oct. 2003), pp. 4625–4633. ISSN: 1089-7623. DOI: [10.1063/1.1605265](https://doi.org/10.1063/1.1605265). URL: <http://dx.doi.org/10.1063/1.1605265>.
- [67] H. Meister et al. “Zeff from spectroscopic bremsstrahlung measurements at ASDEX Upgrade and JET”. In: *Review of Scientific Instruments* 75.10 (Oct. 2004), pp. 4097–4099. ISSN: 1089-7623. DOI: [10.1063/1.1787167](https://doi.org/10.1063/1.1787167). URL: <http://dx.doi.org/10.1063/1.1787167>.
- [68] O. Meyer et al. “Visible spectroscopy diagnostics for tungsten source assessment in the WEST tokamak: First measurements”. In: *Review of Scientific Instruments* 89.10 (July 2018). ISSN: 1089-7623. DOI: [10.1063/1.5035566](https://doi.org/10.1063/1.5035566). URL: <http://dx.doi.org/10.1063/1.5035566>.
- [69] Kenro Miyamoto. *Plasma Physics and Controlled Nuclear Fusion*. Jan. 2004. DOI: <https://doi.org/10.1007/3-540-28097-9>. URL: <https://link.springer.com/book/10.1007/3-540-28097-9>.
- [70] S. Morita and J. Baldzuhn. “Zeff measurement and analysis of reheat-mode discharges in W7-AS”. In: *Als Ms. gedr* 75.10 (Oct. 1994). ISSN: 1089-7623. URL: <https://search.worldcat.org/title/Zeff-measurement-and-analysis-of-reheat-mode-discharges-in-W7-AS/oclc/832636895>.
- [71] Edward I. Moses. “Ignition on the National Ignition Facility: a path towards inertial fusion energy”. In: *Nuclear Fusion* 49.10 (Sept. 2009), p. 104022. DOI: [10.1088/0029-5515/49/10/104022](https://doi.org/10.1088/0029-5515/49/10/104022). URL: <https://dx.doi.org/10.1088/0029-5515/49/10/104022>.
- [72] R. Neu and Sadruddin Benkadda. “Benefits and Challenges of the Use of High-Z Plasma Facing Materials in Fusion Devices”. In: *AIP Conference Proceedings*. AIP, 2010, pp. 62–77. DOI: [10.1063/1.3447994](https://doi.org/10.1063/1.3447994). URL: <http://dx.doi.org/10.1063/1.3447994>.

- [73] P. Nielsen et al. “A LIDAR Thomson Scattering System for the Divertor Tokamak Test (DTT) facility”. In: *Journal of Instrumentation* 14.11 (Nov. 2019), pp. C11018–C11018. ISSN: 1748-0221. DOI: [10.1088/1748-0221/14/11/c11018](https://doi.org/10.1088/1748-0221/14/11/c11018). URL: <http://dx.doi.org/10.1088/1748-0221/14/11/C11018>.
- [74] Tetsutarou Oishi et al. “Space-resolved 3 m normal incidence spectrometer for edge impurity diagnostics in the large helical device”. In: *Applied Optics* 53.29 (Oct. 2014), p. 6900. ISSN: 2155-3165. DOI: [10.1364/ao.53.006900](https://doi.org/10.1364/ao.53.006900). URL: <http://dx.doi.org/10.1364/ao.53.006900>.
- [75] J. Ongena et al. “Magnetic-confinement fusion”. In: *Nature Physics* 12 (2016), pp. 398–410. DOI: <https://doi.org/10.1038/nphys3745>.
- [76] [Edmund Optics. *All about diffraction gratings*. 2024. URL: <https://www.edmundoptics.eu/knowledge-center/application-notes/optics/all-about-diffraction-gratings/>.
- [77] E W Palmer et al. “Diffraction gratings (manufacture)”. In: *Reports on Progress in Physics* 38.8 (Aug. 1975), pp. 975–1048. ISSN: 1361-6633. DOI: [10.1088/0034-4885/38/8/002](https://doi.org/10.1088/0034-4885/38/8/002). URL: <http://dx.doi.org/10.1088/0034-4885/38/8/002>.
- [78] A. Pavone et al. “Measurements of visible bremsstrahlung and automatic Bayesian inference of the effective plasma charge Z_{eff} at W7-X”. In: *Journal of Instrumentation* 14.10 (Oct. 2019), pp. C10003–C10003. ISSN: 1748-0221. DOI: [10.1088/1748-0221/14/10/c10003](https://doi.org/10.1088/1748-0221/14/10/c10003). URL: <http://dx.doi.org/10.1088/1748-0221/14/10/C10003>.
- [79] A.G. Peeters. *The physics of fusion power*. Mar. 2008. URL: <https://warwick.ac.uk/fac/sci/physics/research/cfsa/people/pastmembers/peeters/teaching/lnw.pdf>.
- [80] A. Perek et al. “MANTIS: A real-time quantitative multispectral imaging system for fusion plasmas”. In: *Review of Scientific Instruments* 90.12 (Dec. 2019). ISSN: 1089-7623. DOI: [10.1063/1.5115569](https://doi.org/10.1063/1.5115569). URL: <http://dx.doi.org/10.1063/1.5115569>.
- [81] British Petroleum. “BP Statistical Review of World Energy 2022 | 71st edition”. In: *Statistical Review of World Energy* 1 (Feb. 2022), p. 10. URL: <https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2022-full-report.pdf>.
- [82] Susanne Pfalzner. *An Introduction to Inertial Confinement Fusion*. Mar. 2006, p. 248. DOI: <https://doi.org/10.1201/9781420011845>. URL: <https://www.taylorfrancis.com/books/mono/10.1201/9781420011845/introduction-inertial-confinement-fusion-susanne-pfalzner>.
- [83] Gian Mario Polli et al. “Status of design and procurement activities in DTT tokamak project area”. In: *2022 IEEE 21st Mediterranean Electrotechnical Conference (MELECON)*. IEEE, June 2022. DOI: [10.1109/melecon53508.2022.9843123](https://doi.org/10.1109/melecon53508.2022.9843123). URL: <http://dx.doi.org/10.1109/MELECON53508.2022.9843123>.
- [84] A Pospieszczyk et al. “Determination of rate coefficients for fusion-relevant atoms and molecules by modelling and measurement in the boundary layer of TEXTOR”. In: *Journal of Physics B: Atomic, Molecular and Optical Physics* 43.14 (July 2010), p. 144017. ISSN: 1361-6455. DOI: [10.1088/0953-4075/43/14/144017](https://doi.org/10.1088/0953-4075/43/14/144017). URL: <http://dx.doi.org/10.1088/0953-4075/43/14/144017>.
- [85] T. Pütterich et al. “Calculation and experimental test of the cooling factor of tungsten”. In: *Nuclear Fusion* 50.2 (Jan. 2010), p. 025012. ISSN: 1741-4326. DOI: [10.1088/0029-5515/50/2/025012](https://doi.org/10.1088/0029-5515/50/2/025012). URL: <http://dx.doi.org/10.1088/0029-5515/50/2/025012>.
- [86] M. L. Reinke et al. “Vacuum ultraviolet impurity spectroscopy on the Alcator C-Mod tokamak”. In: *Review of Scientific Instruments* 81.10 (Oct. 2010). ISSN: 1089-7623. DOI: [10.1063/1.3494380](https://doi.org/10.1063/1.3494380). URL: <http://dx.doi.org/10.1063/1.3494380>.
- [87] M.L. Reinke et al. “Expanding the role of impurity spectroscopy for investigating the physics of high-Z dissipative divertors”. In: *Nuclear Materials and Energy* 12 (Aug. 2017), pp. 91–99. ISSN: 2352-1791. DOI: [10.1016/j.nme.2016.12.003](https://doi.org/10.1016/j.nme.2016.12.003). URL: <http://dx.doi.org/10.1016/j.nme.2016.12.003>.
- [88] Hannah Ritchie, Max Roser, and Pablo Rosado. “Energy”. In: *Our World in Data* (2022). URL: <https://ourworldindata.org/energy>.
- [89] Francesco Romanelli. “Divertor Tokamak Test facility Project: Status of Design and Implementation”. In: *Nuclear Fusion* (June 2024). ISSN: 1741-4326. DOI: [10.1088/1741-4326/ad5740](https://doi.org/10.1088/1741-4326/ad5740). URL: <http://dx.doi.org/10.1088/1741-4326/ad5740>.
- [90] Max Roser et al. “World Population Growth”. In: *Our World in Data* (2019). URL: <https://ourworldindata.org/world-population-growth>.
- [91] S. Sarwar, H. K. Na, and J. M. Park. “Effective ion charge (Z_{eff}) measurements and impurity behavior in KSTAR”. In: *Review of Scientific Instruments* 89.4 (Apr. 2018). ISSN: 1089-7623. DOI: [10.1063/1.5004217](https://doi.org/10.1063/1.5004217). URL: <http://dx.doi.org/10.1063/1.5004217>.

- [92] C. R. Seon et al. “Development of two-channel prototype ITER vacuum ultraviolet spectrometer with back-illuminated charge-coupled device and microchannel plate detectors”. In: *Review of Scientific Instruments* 81.10 (Oct. 2010). ISSN: 1089-7623. DOI: [10.1063/1.3478550](https://doi.org/10.1063/1.3478550). URL: <http://dx.doi.org/10.1063/1.3478550>.
- [93] C. R. Seon et al. “VUV spectroscopy in impurity injection experiments at KSTAR using prototype ITER VUV spectrometer”. In: *Review of Scientific Instruments* 88.8 (Aug. 2017). ISSN: 1089-7623. DOI: [10.1063/1.4998970](https://doi.org/10.1063/1.4998970). URL: <http://dx.doi.org/10.1063/1.4998970>.
- [94] Changrae Seon et al. “Design of ITER divertor VUV spectrometer and prototype test at KSTAR tokamak”. In: *The European Physical Journal D* 71.12 (Dec. 2017). ISSN: 1434-6079. DOI: [10.1140/epjd/e2017-70825-3](https://doi.org/10.1140/epjd/e2017-70825-3). URL: <http://dx.doi.org/10.1140/epjd/e2017-70825-3>.
- [95] Shyam Singh. “Diffraction gratings: aberrations and applications”. In: *Optics & Laser Technology* 31.3 (Apr. 1999), pp. 195–218. ISSN: 0030-3992. DOI: [10.1016/S0030-3992\(99\)00019-5](https://doi.org/10.1016/S0030-3992(99)00019-5). URL: [http://dx.doi.org/10.1016/S0030-3992\(99\)00019-5](http://dx.doi.org/10.1016/S0030-3992(99)00019-5).
- [96] P. Sonato et al. “Machine modification for active MHD control in RFX”. In: *Fusion Engineering and Design* 66–68 (Sept. 2003), pp. 161–168. ISSN: 0920-3796. DOI: [10.1016/S0920-3796\(03\)00177-7](https://doi.org/10.1016/S0920-3796(03)00177-7). URL: [http://dx.doi.org/10.1016/S0920-3796\(03\)00177-7](http://dx.doi.org/10.1016/S0920-3796(03)00177-7).
- [97] Lyman Spitzer. “The Stellarator Concept”. In: *The Physics of Fluids* 1.4 (1958), pp. 253–264. DOI: [10.1063/1.1705883](https://doi.org/10.1063/1.1705883). eprint: <https://aip.scitation.org/doi/pdf/10.1063/1.1705883>. URL: <https://aip.scitation.org/doi/abs/10.1063/1.1705883>.
- [98] Weston M. Stacey. *Fusion: An Introduction to the Physics and Technology of Magnetic Confinement Fusion*. 2011. DOI: [10.1080/00107514.2011.583690](https://doi.org/10.1080/00107514.2011.583690).
- [99] B. C. Stratton et al. “Chapter 5: Passive Spectroscopic Diagnostics for Magnetically Confined Fusion Plasmas”. In: *Fusion Science and Technology* 53.2 (Feb. 2008), pp. 431–486. ISSN: 1943-7641. DOI: [10.13182/fst08-a1677](https://doi.org/10.13182/fst08-a1677). URL: <http://dx.doi.org/10.13182/fst08-a1677>.
- [100] J L Terry and M L Reinke. “Diagnostic tools for studying divertor detachment: bolometry, spectroscopy, and thermography for surface heat-flux”. In: *Plasma Physics and Controlled Fusion* 59.4 (Feb. 2017), p. 044004. ISSN: 1361-6587. DOI: [10.1088/1361-6587/aa5997](https://doi.org/10.1088/1361-6587/aa5997). URL: <http://dx.doi.org/10.1088/1361-6587/aa5997>.
- [101] J. L. Terry et al. “Volume recombination and opacity in Alcator C-Mod divertor plasmas”. In: *Physics of Plasmas* 5.5 (May 1998), pp. 1759–1766. ISSN: 1089-7674. DOI: [10.1063/1.872845](https://doi.org/10.1063/1.872845). URL: <http://dx.doi.org/10.1063/1.872845>.
- [102] V. Tomarchio et al. “Status of the JT-60SA project: An overview on fabrication, assembly and future exploitation”. In: *Fusion Engineering and Design* 123 (Nov. 2017), pp. 3–10. ISSN: 0920-3796. DOI: [10.1016/j.fusengdes.2017.05.041](https://doi.org/10.1016/j.fusengdes.2017.05.041). URL: <http://dx.doi.org/10.1016/j.fusengdes.2017.05.041>.
- [103] Marco Valisa and et al. “Physics requirements for the VUV survey spectrometer intended for the divertor radiation monitoring on JT-60SA”. In: *Europhysics Conference Abstracts Volume 43C 46* (2009). URL: <http://ocs.ciemat.es/EPS2019PAP/pdf/P1.1012.pdf>.
- [104] G. Verdoolaege et al. “Design and commissioning of a new diagnostic for routine determination of Zeff from visible bremsstrahlung measurements on TEXTOR”. In: *Review of Scientific Instruments* 77.10 (Sept. 2006). ISSN: 1089-7623. DOI: [10.1063/1.2221895](https://doi.org/10.1063/1.2221895). URL: <http://dx.doi.org/10.1063/1.2221895>.
- [105] K Verhaegh et al. “Novel inferences of ionisation and recombination for particle/power balance during detached discharges using deuterium Balmer line spectroscopy”. In: *Plasma Physics and Controlled Fusion* 61.12 (Nov. 2019), p. 125018. ISSN: 1361-6587. DOI: [10.1088/1361-6587/ab4f1e](https://doi.org/10.1088/1361-6587/ab4f1e). URL: <http://dx.doi.org/10.1088/1361-6587/ab4f1e>.
- [106] K. Watanabe, Edward C. Y. Inn, and Murray Zelikoff. “Absorption Coefficients of Oxygen in the Vacuum Ultraviolet”. In: *The Journal of Chemical Physics* 21.6 (June 1953), pp. 1026–1030. ISSN: 1089-7690. DOI: [10.1063/1.1699104](https://doi.org/10.1063/1.1699104). URL: <http://dx.doi.org/10.1063/1.1699104>.
- [107] J. Wesson and D. Campbell. *Tokamaks*. 2011. ISBN: 9780199592234. URL: <https://books.google.be/books?id=XJssMXjHU0C>.
- [108] John Wesson. *The science of JET*. 2000. URL: https://www.euro-fusion.org/fileadmin/user_upload/Archive/wp-content/uploads/2012/01/the-science-of-jet-2000.pdf.
- [109] G. A. Wurden et al. “A divertor scraper observation system for the Wendelstein 7-X stellarator”. In: *Review of Scientific Instruments* 89.10 (Oct. 2018), 10E102. ISSN: 1089-7623. DOI: [10.1063/1.5035078](https://doi.org/10.1063/1.5035078). URL: <http://dx.doi.org/10.1063/1.5035078>.
- [110] Jake S. Yeston, Valda Vinson, and H. Holden Thorp. “Energy in 2023”. In: *Science* 379.6627 (2023), pp. 7–7. DOI: [10.1126/science.adg4111](https://doi.org/10.1126/science.adg4111). eprint: <https://www.science.org/doi/pdf/10.1126/science.adg4111>. URL: <https://www.science.org/doi/abs/10.1126/science.adg4111>.

- [111] J.H. You et al. “Divertor of the European DEMO: Engineering and technologies for power exhaust”. In: *Fusion Engineering and Design* 175 (Feb. 2022), p. 113010. ISSN: 0920-3796. DOI: [10.1016/j.fusengdes.2022.113010](https://doi.org/10.1016/j.fusengdes.2022.113010). URL: <http://dx.doi.org/10.1016/j.fusengdes.2022.113010>.
- [112] X. Y. Zhang et al. “Upgrade of vacuum ultraviolet spectroscopy system on J-TEXT tokamak”. In: *Review of Scientific Instruments* 92.7 (July 2021). ISSN: 1089-7623. DOI: [10.1063/5.0043449](https://doi.org/10.1063/5.0043449). URL: <http://dx.doi.org/10.1063/5.0043449>.