Extended Summary
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Introduction to fusion energy

The research I conducted in my PhD studies is motivated by the current worldwide energy crisis. On the one hand, forecasts indicate that, closely linked to population and economic growth, energy demand will continue to increase, as it has done in the past (world primary energy consumption exceeded 580 EJ for the first time in 2019, assuming a growth of 1.3% with respect to the previous year). On the other hand, the climate emergency requires an urgent reduction CO_2 emission, in an energy system that is based on the consumption of fossil fuels. In this context, fusion appears as one of the great technological options to cover the energy demand of future societies. This thesis contributes to the development of nuclear fusion as a technology to produce electrical energy.

Fusion is a clean energy source that consists of the union of two light atomic nuclei to form a heavier one, with a great release of energy in the process. To achieve fusion, it is necessary to overcome the Coulomb barrier (the strong electrical repulsion between atomic nuclei). For this, it is necessary that the particles have very high energies. At the high temperatures necessary for fusion (on the order of 100 million degrees), atoms dissociate into ions (positively charged atomic nuclei) and electrons (negatively charged). Under these conditions, matter is in its fourth state and forms a plasma, an ionized gas that shows collective behavior.

Nuclear fusion is a process that we observe in nature: it is the source of energy for stars. In space, the confinement of plasma, which is the fuel for fusion, is achieved by gravitational forces. On Earth, this strong gravity force is not an option, and we need to find other means to confine the plasma. Nuclear fusion can be achieved in Earth in two ways: by magnetic confinement or by inertial confinement. Magnetic confinement devices are currently the most developed experimental fusion reactors. Specifically, this thesis is focused on the so-called tokamak device. Tokamaks use strong magnetic fields to confine plasma to a limited volume in space.

In particular, the fusion reaction between deuterium and tritium, two isotopes of hydrogen, is the one that has the most interest on Earth:

$$D + T \rightarrow He + n + 17.6 \text{ MeV} \tag{1}$$

This reaction has a high cross section at relatively low temperatures, and releases a large amount of energy. Since a neutron (causing activation of materials) is produced in this reaction and tritium is radioactive (half-life of 12.3 years), experimental plasmas are typically composed of D or H only. This species forms what we call the main ion species since it dominates the composition of plasmas.

Research in magnetic confinement fusion focuses on understanding the behavior of plasma, and seeks to maximize its confinement. Current experimental research is focused on the development of high-confinement modes of operation, while theoretical research provides models that describe the nature of transport mechanisms in plasmas. Validation of theoretical models against experimental measurements in current experimental reactors is essential for progress. Likewise, knowing in detail the transport processes in experimental reactors is crucial to reliably predict and optimize the operation and performance of the next generations of fusion reactors.

To maximize plasma confinement, it is essential to understand and optimize the transport of energy and particles in the plasma. In turn, for this, an accurate diagnosis of the properties of the plasma is essential. Specifically, we refer by properties to temperature (*T*), density (*n*) and rotation speed (*v*) of the plasma.

The properties of deuterium and tritium (D and T, the main ions in plasma) are especially important since energy is released in their fusion reaction (according to Equation 1). However, the direct measurement of the properties of D and T is complex, so historically, it has not been carried out. Traditionally, the properties of D and T have been assumed to be the same as those of other minority ion species (impurities, found in low concentration in the plasma), or have been derived by a combination of impurity measurements and theoretical models, such as the neoclassical theory of transport. In recent years, advances in diagnostics and computational resources have made direct measurement of main ion properties feasible (early developments have been carried out by the DIII-D tokamak[1] team [1] and references therein).

In this thesis the edge of the plasma has been specifically studied. The plasma edge is a particularly important region, as it prescribes the boundary conditions that determine the overall performance of the plasma. In addition, the conditions in this region must be compatible with the thermomechanical limits established by current day materials. Understanding and controlling the physical processes and transport at the plasma edge is one of the most crucial tasks for the success of fusion reactors.

Goals of the project

The main objective of this thesis is to study the integration of future fusion power plants with power conversion cycles. To achieve this goal, three phases have been defined:

1. **Development of a new diagnostic system** based on spectroscopy technology (Figure 1) for the main ions (deuterium). This diagnostic is installed on the ASDEX Upgrade tokamak. In my PhD, I have installed and improved hardware to achieve a high spatiotemporal resolution (3 mm and 1.5 ms, respectively) and I have developed advanced analysis techniques that allow to determine the temperature, density and deuterium velocity from radiation measurements. These measurements are unique in Europe and are in the state of the art of instrumentation in the field of nuclear fusion.

2. **Characterization of energy and matter transport at the edge of the plasma based on the new measurements.** This stage is important because, once we know the nature of transport in current experimental reactors, it allows the prediction of plasma properties in future reactors.

3. **Study of the integration of a future fusion reactor and the power production cycle.** It includes estimating what will be the energy available in the plasma in future fusion plants based on density and temperature predictions for future reactors. Based on the energy production and the temperature of the different sources of heat,

[1] Medium sized tokamak (major radius of R_0 = 1.67 m) with a carbon wall located in General Atomics, in San Diego (California)..

the integration of the power production cycles with the fusion plants is optimized, with the aim of maximizing efficiency and electricity production.

During my PhD, I have enjoyed the close collaboration that exists between the University of Seville and the Max Planck Institute for Plasma Physics, where the ASDEX Upgrade (AUG) tokamak[2] is located. The AUG tokamak is one of the world's leading facilities and a big reference in the study of plasma physics and fusion technology. The AUG reactor has an all-metal tungsten wall, and this makes it a relevant device, as it replicates the conditions that will occur in future fusion reactors (where high heat fluxes are expected and it is not possible to use carbon walls as in current devices at smaller scale).

Breakdown of objectives and contributions to the state-of-the-art

In this context, the following research needs and opportunities to contribute to the state-of-the-art of nuclear fusion are identified:

1. The need for accurate characterization of the main ions properties. The achievement of this goal requires:
    a. The direct experimental determination of the main ion properties in current fusion devices.
    b. The comparison of the main ion measurements against:
        i. Experimental measurements of other plasma species (impurity ions and electrons).
        ii. Theoretical models.
2. The need to study the integration of future fusion devices with power cycles, which comprises:
    a. The evaluation of the integration of thermodynamic (in terms of the power cycle efficiency) and economic performance.
    b. The assessment of the impact of the boundary conditions (set by the nuclear fusion reactor) on the plant performance.
3. The need to investigate opportunities that promote the role of fusion in the energy market. In particular, the deployment of fusion may be affected by:
    a. The efficiency, and consequently, economic aspects of the fusion power plant.
    b. The opportunities for diversification of fusion applications.

To respond to these needs, this thesis contributes to:

1. The accurate characterization of the main ion properties in a current experimental reactor, which consists of:
    a. The exploitation of a new spectroscopic diagnostic for the main ion species at the ASDEX Upgrade tokamak, which includes:
        i. The installation of a new optical head.
        ii. The calibration and characterization of the diagnostic system.
        iii. The development of data analysis tools and a forward model for the interpretation of the measurements.

[2] Medium sized tokamak (major radius of R_0 = 1.65 m) with a tungsten wall located in the Max Planck Institute for Plasma Physics, in Garching bei München.

   b. The execution of dedicated experiments at the ASDEX Upgrade tokamak.
   c. The comparison of the new main ion measurements against impurity ion and electron measurements and theoretical models (in this case, neoclassical theory).
2. The study of various integration layouts for future fusion devices with power cycles, which requires:
   a. The simulation of the performance of future fusion devices based on present day physics and engineering understanding.
   b. Numerical modelling of a portfolio of Rankine and Brayton power cycles which are compatible with the boundary conditions imposed by the fusion reactor. The impact of the fusion reactor coolant and power cycle working fluid have been studied.
   c. The evaluation of the economic aspects of the integration.
3. The investigation of opportunities to maximize the role of fusion in future energy markets.
   a. Investigation of the feasibility of boosting the efficiency of fusion power plants via cogeneration of electricity and heat.
   b. The scalability of fusion power plants and opportunities for small aspect ratio tokamaks (the so-called spherical tokamaks, which are more compact than conventional tokamaks).

Description of the work and results

The energy released by nuclear fusion depends on the properties of the fusion fuel: deuterium and tritium ions, which constitute the main ion species. In particular, the properties of the deuterium at the plasma edge are important because they establish the boundary conditions that determine the overall performance of the plasma. Understanding the processes that govern ion transport at the plasma edge is critical to the success of future fusion devices. The development of theoretical models that describe the relevant transport processes and the definition of the conditions for their valid applicability are crucial for the reliable prediction of the operation of future fusion plants. The validation of theoretical models requires high-precision experimental measurements, with which to compare the theoretical results.

The temperature and rotation velocity of deuterium have rarely been directly measured in current experimental fusion devices and are usually inferred from measurements of impurity ions (minority species). The temperature of the deuterium is often assumed to be equal to the temperature of the impurities since thermodynamic equilibrium between ions is expected to be reached on very short time scales (on the order of a fraction of a millisecond). At the plasma edge, the toroidal velocity of deuterium is usually estimated by combining impurity measurements with neoclassical transport theory. Direct diagnosis of the properties of deuterium is crucial to verify if, and under what conditions, these assumptions are valid.

This thesis contributes to the study and characterization of the main ion temperature and the toroidal rotation velocity at the edge of the plasma in a tokamak. For this, a new diagnostic has been developed and exploited at the ASDEX Upgrade tokamak (see Figure 1). The new diagnostic is based on the charge exchange recombination spectroscopy technique. Within the framework of this thesis, a new optical system has been installed in the reactor and the hardware of the spectrometer has been improved, which allows the simultaneous measurement of the properties of deuterium and impurities. The state-of-the-art diagnostic provides measurements with a temporal resolution of 1.5 ms and spatial resolution of up to 3 mm, which allows to characterize the main ion species with high precision.

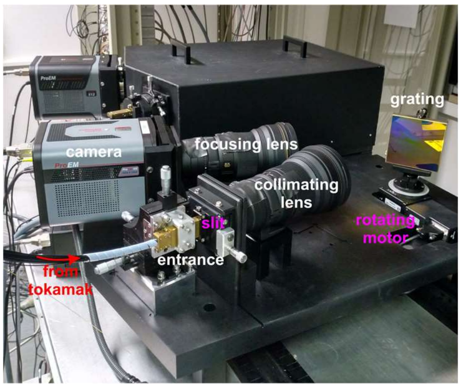

Figure 1 Spectrometer for the main ion (deuterium measurements)

Spectroscopy techniques rely on the detection of radiation (light) emitted by the plasma species. The measured emission spectrum contains information about the observed species. The spectrum is fitted using Gaussian functions to extract the temperature, density, and velocity of the ion species. Fitting of impurity spectra is relatively simple (see Figure 2), and it is a widely used and established diagnostic technique. The complex interpretation of deuterium spectra has historically prevented routine evaluation of deuterium properties, despite the great importance of this ion species. This is due on the one hand to multiple contributions to the spectrum (see Figure 3), and on the other hand to atomic effects affecting the deuterium spectrum.

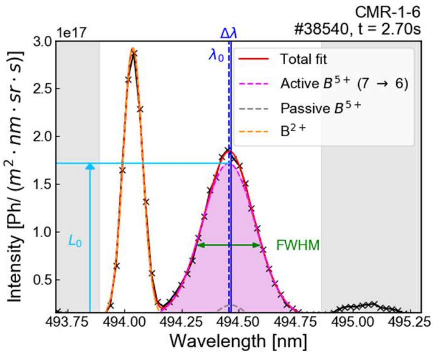

Figure 2 Boron spectrum (impurity species)

In this work, analysis tools and an advanced iterative model have been developed for the accurate interpretation of deuterium spectra. The model is based on the radiative-collisional model implemented in the Monte Carlo FIDASIM code [2]. The true underlying deuterium properties are found by comparing the experimental spectra and the synthetic spectra produced with FIDASIM. Correction factors are applied iteratively until convergency is reached, and the real deuterium properties are recovered (see Figure 4).

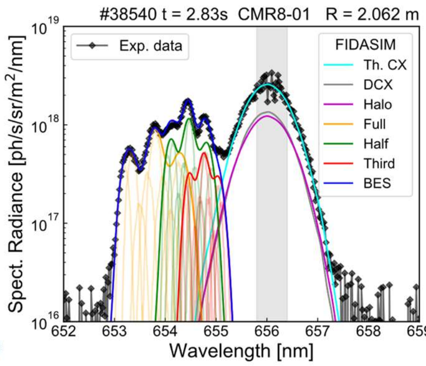

Figure 3 Deuterium (main ion) spectrum.

In the framework of my thesis, I have planned and executed several experiments to characterize the profiles of temperature (T_D) and toroidal rotation velocity ($v_{tor,D}$) of deuterium ions in high confinement plasmas (H-mode or high confinement mode). These profiles have been compared with the properties of impurities and electrons. The technique and forward model have been validated in a reference scenario. The temperature of deuterium (T_D), impurities (T_z) and electrons (T_e) have been compared to one another, and it has been obtained, in accordance with what was expected theoretically, that the three species are in thermal equilibrium within the experimental uncertainty (see the Figure 5), in a baseline scenario.

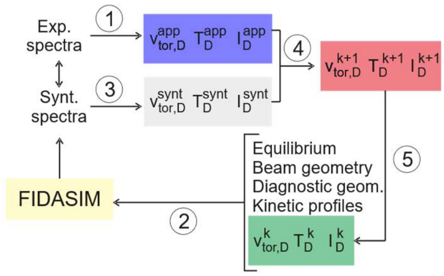

Figure 4 Forward model developed in the thesis to evaluate deuterium properties.

The effect of plasma collisionality (which is a parameter that represents the frequency of collision between particles, and with it the efficiency of energy exchange between different species) and heating schemes. An important result of this study is that it has been found that the impurity temperature is not always a good approximation for the deuterium temperature at the plasma edge (see Figure 6, from ρ_{pol} = 0.85-0.95, $T_D > T_z$). Another important result is that the heating scheme (and therefore, the heat fluxes in the ion and electron channel) seems to play a more relevant role than collisionality. In plasmas dominated by direct heating of the electrons, reducing the collisionality results in a greater difference between the temperature of the deuterium and that of the impurities. In plasmas dominated by direct ion heating, deuterium and impurities reach thermal equilibrium as collisionality is reduced. The experimental condition has been derived that deuterium is in thermal equilibrium with impurities and electrons regardless of collisionality in the pedestal when the power deposited in the ions (P_i) is more than twice the power deposited in the electrons (P_e), that is, $P_i > 2 P_e$.

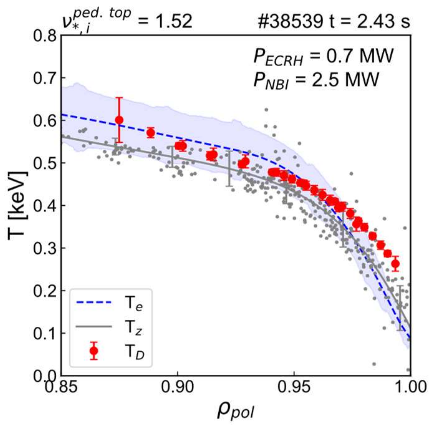

Figure 4 Deuterium, impurity and electron temperature when $P_i > P_e$.

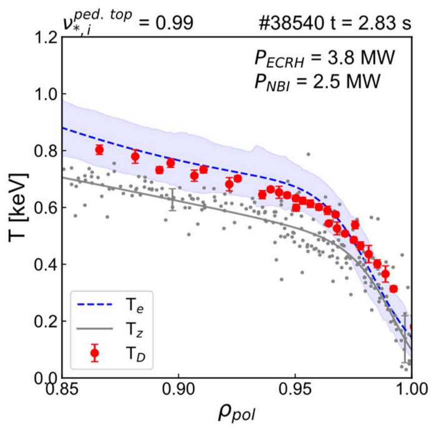

Figura 5 Deuterium, impurity and electron temperature when $P_e > P_i$.

The toroidal velocity of deuterium has been compared with neoclassical transport theory, using the ion differential toroidal rotation calculated with the neoclassical code NEOART [3] and the experimental impurity toroidal velocity profile. The measurements are consistent with neoclassical theory at the edge of high confinement plasmas. The toroidal velocity of the deuterium in the pedestal is faster than the neoclassical prediction in cases where the impurities and deuterium are not in thermal equilibrium. In the cases with high power deposited in the ions, the characteristic well shape expected from neoclassical theory is not recovered, and instead $v_{tor,D}$ is monotonically decreasing. In the outermost region of the confined plasma, the neoclassical theory does not describe the measurement, possibly due to the breakdown of the neoclassical order (the ion pressure gradient is greater than the ion Larmour radius). Furthermore, the experimentally inferred poloidal velocity of deuterium is consistent with neoclassical calculations within measurement uncertainty.

The H-mode is the expected mode of operation for future fusion plants, so the properties of deuterium in H-mode plasmas have been characterized in detail. However, there are some instabilities inherent to the H-mode, which motivate the investigation of alternative high confinement modes. To contribute to these developments, the properties of deuterium have been documented, in addition to H-mode, in other high and low confinement modes of operation, such as L-mode (low confinement mode), I-mode (improved energy confinement mode) and QH-mode (quiescent high confinement mode).

The measurements obtained in this thesis provide the first data on deuterium in an environment relevant to a future fusion power plant (in a reactor in which the inner wall of the reactor is completely metallic, in this case, tungsten). The absence of thermal equilibrium between the deuterium and the impurities is an unexpected observation, since thermal equilibrium was expected due to the collisions. These new measurements motivate the need to model in detail the ion thermal transport. For this, simulation codes that consistently allow to include several ion species to be modeled simultaneously are required. In this way, the heat exchange between the different species can be modelled accurately. These new measurements are an excellent test-bed for validating models and advancing in our current knowledge.

In addition, the performance of a future fusion power plant has been evaluated in a framework that combines the development of power conversion cycle models using the Engineering Equation Solver package and the PROCESS systems code [4,5]. A portfolio of Rankine (see Figure 7) and Brayton (helium and supercritical carbon dioxide, s-CO_2) cycles have been coupled to the DEMO Baseline 2018 [6] fusion reactor to study the thermodynamic and economic performance of the integrations. The suitability of different working fluids depends on the temperature boundary condition, since the maximum efficiencies for each working fluid are found in different temperature ranges. In the intermediate temperature range predicted for the DEMO Baseline 2018, of 500ºC, the s-CO_2 cycle is a very promising candidate. The impact of the temperature boundary conditions and power distribution between the components (blanket, divertor and inner wall of the reactor) on the performance has been evaluated.

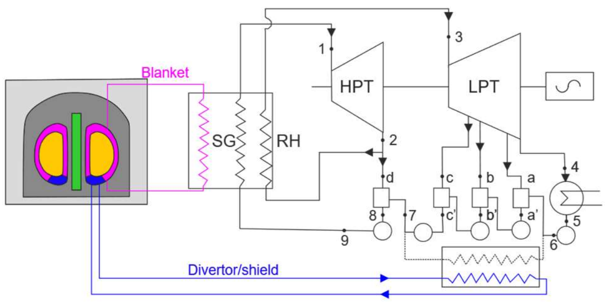

Figura 6 Rankine cycle coupled to the DEMO Baseline 2018 fusion reactor

In this thesis, hybrid heat and power production has also been studied as a strategy to increase the efficiency of future fusion power plants. The impact of using low-temperature heat to feed a district heating network on the thermodynamic and economic performance of the system has been evaluated and compared with a fission reactor. An important result is that efficiency improvements have been obtained for all designs: the efficiency of Rankine cycles improves by 20%, while the efficiency improvement for Brayton cycles is more modest (3-5%), as can be seen in Figure 8.

An economic parameter, the *Levelized Cost of Hybrid Production* has been defined, which combines the cost estimates obtained with PROCESS code with estimates of production and distribution costs. This parameter has been used as figure of merit to assess the economic feasibility of the cogeneration. Improvements in economic parameters compared to the pure electric mode have been obtained for the Rankine and supercritical carbon dioxide cycles. The evaluation of primary energy savings is only favorable for fission plants, since the high internal consumption of fusion plants distorts the evaluation of this indicator. In general, cogeneration schemes result in an improvement in efficiency, a reduction in costs and greenhouse gas emissions (which can potentially mean a significant reduction in costs due to the economic penalties associated with emissions). These cogeneration schemes extend the opportunities of fusion beyond its use to produce electricity and expand its potential for penetration in the future energy market.

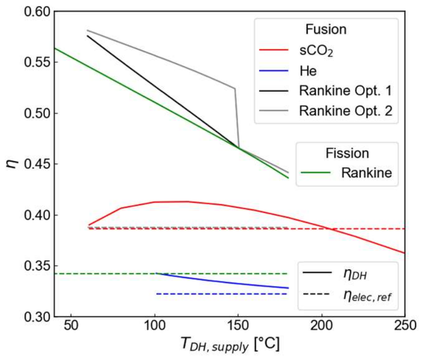

Figure 7 Cycle efficiency (η) against the district heating supply temperature for different technologies.

The diagnostic system and models developed in this thesis constitute a powerful tool for the study of fusion plasmas. In addition to the transport studies and comparisons with the neoclassical theory that have been carried out in the thesis, these measurements can contribute and provide relevant information in other research fields of nuclear fusion and plasma physics. This new diagnostic also offers the possibility of evaluating the density of deuterium. The extension of this diagnostic technique to other regions of the plasma is also very interesting. Likewise, studies of cogeneration by fusion for other alternative low-temperature applications, such as the production of cold (through, for example, absorption machines), water desalination and hydrogen production constitute interesting lines of research. In addition, the development of advanced scenarios from the point of view of technology and plasma physics, in which higher temperatures can be reached, expands the potential application of fusion energy to fields such as the production of industrial heat, which would help maximize the role of fusion energy in society.

References

[1] S R Haskey *et al Plasma Phys. Control. Fusion* **60** 105001 (2018)
[2] B Geiger *et al Plasma Phys. Control. Fusion* **62** 105008 (2020)
[3] AG Peeters, *Physics of Plasmas* **7** 268 (2000)
[4] M Kovari *et al*, *Fusion Engineering and Design* **89** 3054–306 (2014)
[5] M Kovari *et al, Fusion Engineering and Design* **104** 9–20 (2016)
[6] M Siccinio *et al, Fusion Engineering and Design* **176** 113047 (2022)