Advanced neoclassical impurity transport modelling with its experimental comparison for TJ-II

Master Thesis
presented by

Mohamed Ezzat Fathi Mohamed Mostafa

Thesis Promoter
Prof. Luis Mario Fraile
Universidad Complutense de Madrid

Thesis Supervisor
Dr. Jose Manuel García Regaña
National Fusion Laboratory, CIEMAT

July 23, 2018
Advanced neoclassical impurity transport modelling with its experimental comparison for TJ-II

Master Thesis presented by

Mohamed Ezzat Fathi Mohamed Mostafa

Thesis Promoter
Prof. Luis Mario Fraile
Universidad Complutense de Madrid

Thesis Supervisor
Dr. Jose Manuel García Regaña
National Fusion Laboratory, CIEMAT

Erasmus Mundus Program on Nuclear Fusion Science and Engineering Physics

July 23, 2018
Abstract

The absence of the disruptive instabilities and the steady-state operation make the stellarator concept a promising candidate for future reactors together with the tokamaks. Impurity accumulation in the core is considered as one of the stellarator intrinsic drawbacks because it dilutes the plasma and increases the radiation losses contributing to the plasma collapse. Neoclassical theory predicts in stellarators a non-ambipolar transport of electrons and bulk ions due to magnetic field ripple produced by the three-dimensional coil structure. Non-ambipolar transport creates, depending on the collisionality of each species, radially inward (outward) radial electric field for ion (electron) root regime. Ion root regime is predicted for the future stellarator reactor scenarios, which implies very likely impurity accumulation. However, outward transport has been observed during the so-called HDH mode improved confinement regime int W7-AS (K. McCormick 2002) and the impurity hole at LHD (K. Ida 2009) but without satisfactory theoretical explanation. The standard neoclassical treatments consider only the radial component of the electric field, which is a good approximation for the bulk species, ions and electrons, but not for the highly charged impurities. Recent approaches have considered the tangential component of the electric field related to the electrostatic potential variation $\Phi_1$ on the flux surface and have shown to strongly modify the standard predictions of high-Z impurities (see e.g J. M. García-Regaña 2017 and reference therein). EUTERPE code has been used to solve the drift kinetic equation and the quasineutrality condition in both NBI and ECRH TJ-II plasmas and quantify its effect on the impurity distribution. The $\Phi_1$-driven impurity density variations have been compared with the Soft X-Rays and Bolometry asymmetric radiation for the whole effective radius. The comparison of the surface-averaged radial flux has been carried out between considering $\Phi_1$ and excluding it, and considering for the first time in EUTERPE the linearized impurity-ion collision operator (see e.g I. Calvo 2018-Arxiv) and the routinely pitch-angle scattering operator (see e.g C. D. Beidler 2011).
Contents

1 Introduction 5
  1.1 Energy resources .............................................. 5
  1.2 Why Fusion Energy? ........................................... 6
  1.3 Magnetic confinement ........................................ 8
    1.3.1 Lawson criterion ....................................... 8
    1.3.2 Confinement by toroidal magnetic field ............... 8
    1.3.3 Confinement by flux surfaces ........................... 9
  1.4 TJ-II Stellarator ............................................. 11
    1.4.1 Description ............................................. 11
    1.4.2 Bolometry systems ...................................... 12
  1.5 Impurity problem overview .................................. 14

2 Neoclassical Transport 17
  2.1 Fokker Planck equation ..................................... 18
  2.2 Drifts and the electrostatic potential .................... 19
  2.3 Neoclassical DKE version for EUTERPE ..................... 20
    2.3.1 Collision operator .................................... 22
    2.3.2 Ion root regime ....................................... 22
    2.3.3 Electron root regime .................................. 23
  2.4 The electrostatic potential with EUTERPE ................. 24

3 Numerical and Experimental analysis 27
  3.1 Numerical steps and analysis .............................. 27
    3.1.1 Numerical calculation of $\Phi_1(r, \theta, \phi)$ .......... 29
    3.1.2 Calculating radial particle flux ....................... 30
  3.2 Sources of EUTERPE input in TJ-II .......................... 30
  3.3 Emissivity tomography analysis scheme .................... 34

4 Results and discussions 37
  4.1 $\Phi_1$ asymmetry EUTERPE vs Experiment .................. 37
    4.1.1 Ion root case ....................................... 38
    4.1.2 Electron root case ................................... 42
  4.2 Influence of $\Phi_1$ on the impurity transport ............ 45
  4.3 Impurity-ion collision operator ............................ 46
5 Conclusion 49
Chapter 1

Introduction

1.1 Energy resources

Energy demands and necessary resources have continued growth since the industrial revolution and current estimation predicts the continuity with higher rates \cite{1}. Stable energy supplier should have multiple energy sources working together each of which has a participation ratio, as shown in figure 1.1 depending on the advantages and disadvantages of each, environmental factors and availability. Fossil fuels were and still are the main energy source on the earth, but its reservoirs are limited and according to the recent estimations it will last for a century at most\footnote{Quantitative estimations for the oil, coal, and gas are to last for 33, 104 and 34 years respectively \cite{2}}. Fossil fuels produce energy via chemical reactions that release a huge amount of CO2 which is considered as the main cause of the global warming \cite{3}. These two issues oblige us to innovate for alternative cleaner and safer sources with available fuel. Renewable sources such as wind and solar represent a solution, but they need to coexist with a backup system \cite{4} due to the intermittency problem and their low energy content. Nuclear energy has been considered as a solution since the 1950s. It can be released from the nucleus via one of two processes, the first is the fission in which a

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1.png}
\caption{The history and predicted world energy consumption indicating the ratio of each source}
\end{figure}
1. Introduction

Heavy nucleus is split for two light nuclei and energy, and the second is fusion in which two light nuclei fuse to form a heavier nucleus and energy. The released amount of energy comes from the change in the binding energy per nucleon of the reactants and the products. The binding energy curve in figure (1.2) represents the experimental data of the binding energy per nucleon in a nucleus versus its mass number. From this figure one can concludes that,

![Figure 1.2: The slope in the binding energy curve shows the energy released by a nucleon. Fusion slope, on the left, is seven times larger than the fission slope on the right. Arrows represent the direction in which each process release energy.](image)

Light nuclei with atomic masses less than Fe\(^{56}\) can produce energy by fusion and heavy nuclei with atomic masses higher than Fe\(^{56}\) can produce energy by fission. All available nuclear reactors are fission based and they are still have some unresolved issues such as incomplete safe operation, locality of the fuel mines at some countries and the manufacturing technology in some other countries, and has radioactive wastes with half-lifetime in few thousands of years range. Fission is a chain reaction and any lose of control system leads to a safety crisis. On the other hand, nuclear fusion can avoid all this problems, roughly speaking, but it is still under research and development for handling their technology challenges and more details come in the next section.

1.2 Why Fusion Energy?

Generally, nuclear energy is clean but fusion advantages makes it a superior to fission since it is safer\(^2\), has available fuel\(^3\), has wastes with half-life time in

---

\(^2\)Fusion can be achieved in a stable plasma which requires nonlinear control system on magnetic field shape, plasma current and cooling and any loss of control leads to a safe and instantaneous stop of the reactor

\(^3\)Deutrium exist in sea water and can be easily extracted while the tritium can be self-generated during fusion process via lithium that is common in the crust[5]
1.2 Why Fusion Energy?

Few decades range, and it is denser for energy content\textsuperscript{4}. Historically, the fusion as an energy source was theoretically postulated as the mechanism for energy production in stars by Edington in 1922 \cite{6}. Different fusion reactions can be achieved in stars depending on the star’s mass \textsuperscript{5}. On earth, an alternative reactions have been proposed since the achievable density and temperature on earth still far from the star’s conditions. Typical values of the predicted fusion reactor are \((10^{20} - 10^{22} \text{ m}^{-3})\) for the density and \((10 - 20 \text{ keV})\) for temperature that can accommodate the proposed reactions such as D-T, D-D, and D-He\textsuperscript{3} where D=H\textsuperscript{2}, T=H\textsuperscript{2} and He\textsuperscript{3} refer to deuterium, tritium and helium three.

D-T reaction

\[ \text{D + T} \rightarrow \text{H}_2^4 \ (3.5 \text{ MeV}) + \text{n} \ (14.1 \text{ MeV}) \]

has the highest cross section producing alpha particle and neutron, in the former predicted temperature window, among the possible reactions shown in figure (1.3).

\textbf{Figure 1.3:} Reaction rate for different fusion reactions in which D-T record the highest at the predicted energy window (10-25 kev) for future reactors.

\textsuperscript{4}Fusion is a very dense energy source as shown formerly in binding energy curve and this going to be obvious through the following example by rough estimation. Let us consider a household that consumes 18,000 kWh/year, this house can be lighted approximately for five hours, 1300 years and 5000 years by burning one Kg of coal, fissure one Kg of Uranium and one Kg of deuterium and tritium mixture respectively

\textsuperscript{5}Sun fusion cycle: Four hydrogen nucleus (H\textsuperscript{1}) converted to the helium nucleus, a couple of neutrinos, three gammas, and energy released as shown in \((4\text{H}_1^1 + 2 \text{e} \rightarrow \text{H}_2^4 + 2\nu_e + 3\gamma + 26.7 \text{ MeV})\) different stars fusion process occurring via different cycle depending on it mass, such as the group catalytic cycles names CNO which is dominated in stars that weight roughly 2.3 times the sun.
1.3 Magnetic confinement

1.3.1 Lawson criterion

Different approaches for fusion confinement had been developed through the last decade and the most relevant one for fusion reactor is the magnetic confinement due to its promising ability for achieving Lawson criteria,

\[
\begin{align*}
    nT\tau_E & \geq 1 \times 10^{21} \text{m}^{-3}\text{keVs for laboratory plasma,} \\
    & \geq 3 \times 10^{21} \text{m}^{-3}\text{keVs for reactor,}
\end{align*}
\]

where \( n, T \) and \( \tau_E \) represents the density, temperature and the confinement time and the left-hand side is so-called the triple product. To reach the relevant temperature, the fuel is ionized gradually reaching the plasma state which is a charged medium has the ability to stabilize the quasi-neutrality\(^6\) condition, and its charged particles behaves collectively. To study the dynamics of a system such as plasma, a simplified approach comes in the next section to declare two important concepts, the confinement, and the drift.

1.3.2 Confinement by toroidal magnetic field

If any particles with charge \( q \) enters a region with a magnetic field \( \mathbf{B} \) with a random velocity \( \mathbf{v} \), it will gyrate around the field lines with perpendicular velocity \( \mathbf{v}_\perp \) and travel along field lines with parallel velocity \( \mathbf{v}_\parallel \), as shown in figure (1.4) according to the equation of motion (1.1) without the influence of the electric field \( \mathbf{E} \).

\[
m\frac{d\mathbf{v}}{dt} = q (\mathbf{v} \times \mathbf{B} + \mathbf{E})
\]

Considering a perpendicular \( \mathbf{E} \) in the equation of motion, the particle will drifts perpendicular on both the \( \mathbf{B} \) and \( \mathbf{E} \) as shown in the red trajectory at figure (1.4) for the electron and the ions will drift in the same direction. Concept of drift can be generalized to any perpendicular forces to the magnetic field. The drift due to \( \mathbf{E} \) is in the same direction for ions and electrons since it is charge independent while the drift caused by the gradient of the magnetic field or the curvature introduces polarization. The total drifts by the electric and the magnetic inhomogeneity is given by this formula,

\[
\mathbf{v}_D = \frac{\mathbf{E} \times \mathbf{B}}{B^2} + \frac{m \mathbf{v}_\parallel + \mu B}{qB^3} (\mathbf{B} \times \nabla \mathbf{B})
\]

This simple analysis has lighted the confinement concept. However the open ends of such a system will make the particles escape through, and for this

\(^6\text{Quasineutrality means the system is neutral on macroscopic scale and charged on the microscopic scale, and this microscopic scale is determined by few Debye length which is a characteristic parameter for the plasma system } \lambda_D \propto \sqrt{\frac{T}{n}}.\)
1.3 Magnetic confinement

Figure 1.4: Gyromotion of the charged particles in the homogeneous magnetic field (---). Electron trajectory (—) and the ion (-----). Ion has larger Larmor radius and gyrates clockwise and the electron anticlockwise. The thick red trajectory (-----) represents the electron downward drift (-----) with velocity ($v_D$) because of the electric field $E$ toward the page.

reason two ideas had been presented, the first is the magnetic mirror \(^7\) and the second is the toroidal magnetic devices. The later based on closing the field lines on each others producing a torous shape, but the circular motion of the particles along the pure toroidal field produces a centrifugal force perpendicular the introduce polarized electric field due to upward and downward drift of the electrons and ion and the resultant electric field will drift both species outwardly or inwardly leading to the confinement loss at the end. Up to this end, one can conclude that, the pure toroidal magnetic field isn’t sufficient for confinement.

1.3.3 Confinement by flux surfaces

An additional poloidal magnetic field component is required to counteract the previous kind of drifts. The toroidal and the poloidal components together give twisted field lines that forming nested magnetic flux surfaces that accommodate the current and magnetic field lines on, and hence producing an inward magnetic pressure opposing the outward plasma pressure ($p$) fulfilling the free balance equation,

$$j \times B = \nabla p$$

(1.3)

Two designs have been developed through the last decades for producing the poloidal component, the first is driving toroidal plasma current as in the toka-

\(^7\)Mirror effect occurs when the magnetic field has a gradient along the field lines that increase the perpendicular velocity and decreases the parallel velocity up to reverse its direction because of the magnetic moment ($\mu = \frac{mv^2}{2\pi^2}$) conservation of the
1. Introduction

Tokamak 8 and its schematic is shown in figure(1.5) indicates the coils, the magnetic flux surfaces, and the blanket9. The second is through designing 3D coils to produce the both components as in stellarator 10 shown in figure(1.6).

Figure 1.5: Scheme for tokamak shows the toroidal field coils, the central solenoid, the twisted magnetic field lines forming a magnetic surface and the blanket.

![Figure 1.5: Scheme for tokamak](image)

Figure 1.6: Scheme for stellarator shows the three-dimensional coils, the flux surface whose shape as the same as plasma and couple of ports from many other ports used for diagnostics and operation tools.

![Figure 1.6: Scheme for stellarator](image)

Different models 11 are used to study plasma dynamics seeking the stability

---

8 *Tokamak* is a Russian acronym means toroidal chamber with an axial magnetic field. It had been invented by Igor Tomm and Andrei Sakharov [7, 8] and here is a review article [9]

9 The vacuum vessel will be covered by Blanket in the future reactor. The Blanket is a layer covering the internal side of the vacuum vessel first wall for both tokamak and stellarator. It has multifunctions such as shielding cooling pipes and the components in the first wall and also contains the lithium for breeding the tritium but the latter purpose will be in the future reactor DEMO, not ITER.

10 *Stellarator* is acronym for the *Stellar Generator* and had produced for first time as eight shape by Lyman Spitzer in Princeton, US [10]

11 Plasma can be studied using the single particle model, the fluid model or the kinetic
conditions at the highest possible density, temperature and longer confinement time for achieving the Lawson criteria. Half a century of research on both designs has shown the advantages and the drawbacks of each of them that can be summarized as the following. In the tokamak, the plasma current is generated by induction from the central solenoid that requires a pulsed operation, it is a strong nonlinear system because plasma current confines the plasma itself and so it requires a sensitive and fast feedback control systems. In stellerator the absence of this current leads to a steady state operation with higher stability. The tokamak has an operation density limit so-called Greenwaled limit while the stellarator hasn’t. On the other hand, the toroidal symmetry in tokamak simplify the transport formalism and decreases the magnetic islands and ripples in the magnetic surfaces to the lowest order than stellarator. Both of them have the same technology challenges such as the shortages in the ion heating sources, first wall and divertor materials, vacuum systems and the fuel cycle for future reactors. The brief preview has shown the competitions between the two concepts from the physics point of view and the reader can look to [11] for a detailed comparison.

1.4 TJ-II Stellarator

The absence of the disruptive instabilities, increasing of the confinement time with the ECRH heating and the steady-state operation make stellarators a competitive candidate for future reactors as tokamaks. In this section, we introduce the description and characteristics of TJ-II stellarator emphasizing on the required diagnostics for the thesis work. The first section assigned to a general description of TJ-II stellarator and the second for introducing the concept of bolometry and the technical descriptions of of the Bolometry and Soft X-Rays (SXR) systems at TJ-II which are used for the experimental validation of the modeling work.

1.4.1 Description

TJ-II is a helical stellerator with toroidal magnetic field period four generated by 32 poloidal coils and the plasma helicity formed by a combination of one circular and one helical coil and plasma vertical position is controlled by the vertical coils. Its design has been started by CIEMAT staff in cooperation with Oak Ridge National Laboratory by Euroatom fund for physics phase in 1986 and engineering phase in 1990 producing the first plasma in 1997. It targets to study many physics problems such as transport in three dimensions (3D) magnetic field for future design optimization, neoclassical transport in-
1. Introduction

Including impurity\textsuperscript{12}, the influence of 3D magnetic field on the L-H transition\textsuperscript{13}, stability and control, fast ion physics and some other technology-related topics. A schematic of TJ-II coils and port is shown in figure (1.7) and its design parameters are listed in table (1.1).

![Diagram of TJ-II coils and port](image.png)

Figure 1.7: TJ-II perspective view shows only the vertical, toroidal field coils and some access ports, the helical and circular coils can’t be seen from this view.

1.4.2 Bolometry systems

Bolometry is a system that records the plasma emission signals from different view angles around the plasma in order to tomographic them for toroidal plane emission. TJ-II implemented with many bolometry systems that are located around the vessel poloidally and toroidally aims to cover the full emission photon ranges from plasma. Observation of the asymmetric emission from plasma is a key to study its origin such as impurity asymmetric impurity distribution. Practically, Bolometry is a system looks to all energy range while the SXR looks to the soft x-rays energy window. Two systems in TJ-II figure(1.8) are essential for our work and their technical description will be introduced in the coming lines.

Bolometry technical description

TJ-II bolometry system had been installed at toroidal angle 215.5° that corresponds 75.5° primary toroidal angle due to the period four of the machine.

\textsuperscript{12}The thesis scope
\textsuperscript{13}L-H transition refers to the transition from the low to high confinement mode that happens at threshold power in which the confined power is doubled because of a pressure pedestal formation at the edge. Without this discovery in ASDEX tokamak on 4 February 1982 by F. Wagner \cite{12} there was no possibility for fusion research to sustain up today
### 1.4 TJ-II Stellarator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major radius (R)</td>
<td>1.50 m</td>
</tr>
<tr>
<td>Minor radius (a)</td>
<td>0.22 m</td>
</tr>
<tr>
<td>Plasma volume: V</td>
<td>$\sim 1$ m</td>
</tr>
<tr>
<td>Field periods</td>
<td>4</td>
</tr>
<tr>
<td>TF coils</td>
<td>32</td>
</tr>
<tr>
<td>Number of ports</td>
<td>104</td>
</tr>
<tr>
<td>Rotational transform ($\iota/2\pi$)</td>
<td>0.9 - 2.5</td>
</tr>
<tr>
<td>Magnetic field on axis ($B_0$)</td>
<td>$\sim 1$ T</td>
</tr>
<tr>
<td>ECRH heating power ($P_{ECRH}$)</td>
<td>$&lt; 600$ keV</td>
</tr>
<tr>
<td>NBI heating power ($P_{NBI}$)</td>
<td>$&lt; 2$ MW</td>
</tr>
<tr>
<td>Pulse length</td>
<td>$&lt; 200$ ms</td>
</tr>
</tbody>
</table>

Table 1.1: TJ-II stellarator design parameters.

[13]. It consists of three cameras BO1, BO2 and BO3 are located at three different poloidal positions and each of them has 20 lines record signals in TJ-II database as BO101, .., BO120 for the first camera and other cameras follow the same form; look figure(1.9). Sixty lines with different view angels are measuring the line integral emission from the plasma cross section simultaneously. These lines are subject to tomography process\(^\text{14}\) in order to determine the local emissivity for producing the radiation map of this cross section.

**Soft X-rays technical description**

Five pinhole cameras in TJ-II covered by Be foils measure the expected energy spectra by different detectors Si(Li) for (1-40 keV), Ge for (1-100 keV) and NaI(Tl) for the higher energy (see [14] and reference therein). The system is located at module A2 corresponding the toroidal angle $\phi=104.5^\circ$ and four of these cameras are located at $0^\circ$, $50^\circ$, $250^\circ$, $305^\circ$ poloidal angles with sixteen cord per each as shown in figure (1.10) with a 2 cm poloidal resolution and sampling rate 2 MHz.

\(^{14}\text{Tomography is a process that used to reconstruct the cross-section view from multiple-line integral signals at different view angles via mathematical transformation such as Radon transform with Fourier transform. It is used for different applications from medical imaging to fusion and detailed description is given in the analysis part at the last chapter.}\)
1.5 Impurity problem overview

Impurity is any kind of ions exist in fusion plasma except fuel ions and it can be classified generally into (i) light (low-Z impurity) such as alpha particles a fusion product, and (ii) heavy (high-Z impurity) that comes from the first wall via different processes because of the high thermal and neutron loads. Impurities are the main source of radiation losses and its density must be less than a critical value, especially at the core region, [15] to keep the fulfillment of the Lawson criterion. Otherwise, it will dilute the fuel and enhance the radiation losses contributing to plasma collapse. On the other hand, low-Z impurity distribution in the scrape off layer\textsuperscript{15} plays an essential role for preserving the first wall and the divertor by radiating the excessive heat flux load. First wall requires high-Z elements to survive against high heat flux and experiences a less irradiation under the high neutron flux. Impurity accumulation has an intrinsic characteristics on stellarators because they tends to accumulate due to the inward ambipolar electric field ($E_{\text{amb}} < 0$) and the absence of the ion temperature screening generally speaking. The $E_{\text{amb}}$ creation is due to the non-ambipolar transport in stellarator. The presence of the \textit{locally trapped particles} is a serious disadvantages in stellarators since it enhances the transport coefficient in low-collisionality regimes considerably than in tokamaks. Electrons and ions transport radially in different rates (non-ambipolarity) leading to $E_{\text{amb}} < 0$ inward (ion root) or $E_{\text{amb}} > 0$ outward (electron root) depending

\textsuperscript{15} \textit{Scrape off layer} is the layer extends from the last closed flux surface to the first wall and it is dynamics is crucial for confinement performance

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.8.png}
\caption{Top view of TJ-II machine with 4 fold symmetry in toroidal direction with $\phi = 0^\circ$ corresponds to the entrance from the control room. Soft X-Rays system is located at the A2 module with angle $\phi = 104.5^\circ$ and bolometry system at segment B7 with angle $\phi = 215.5^\circ$}
\end{figure}
1.5 Impurity problem overview

Figure 1.9: Cross section view of the bolometry System lines at B7 module ($\phi = 215.5^\circ$). Three cameras and each camera’s lines arranged in the anti-clockwise direction from 1 to 20. Photodiode from extreme ultraviolet type is located for different view angels.

on each species collisionality. Ion root is the predicted one for the fusion reactor paramters that leads to the accumulation in general according to the neoclassical predictions\footnote{Neoclassical is a kinetic theory approach considers the curvature of the magnetic field and studying transport processes that occurs on a scale less than the larmor radoius} and the routinely experimental observations except few cases\footnote{Unexpected outward transport has been observed during an improved confinement regime so-called HDH mode at W7-AS (K. McCormick 2002) and the impurity transport hole at LHD (K. Ida 2009) but without satisfactory theoretical explanation.}. Histrocally, neoclassical taken only the radial component of the electric field into account negelecting any tangential componentets which is a good approximation for the low collisional species such as bulk species ions and electrons. High-Z impurity is higher colloisional species because of its high electric charge ($Z$) and this voilates the previous approach and the tangential perturbation must be considered. Recent approach \cite{16} has considered the tangential perturbed componentets and defined the electric field $E$ using the electrostatic potential $\Phi$ in two parts; (i) the flux surface function part $\Phi_0 (r)$ and (ii) the asymmetric perturbation part $\Phi_1 (r, \theta, \phi)$

\begin{align*}
E &= E_r + \nabla \Phi_1 (r, \theta, \phi) \\
E_r &= \nabla_r \Phi_0 (r)
\end{align*}

where $r, \theta$ and $\phi$ denotes the flux surface label, the poloidal and toroidal directions respectively. We will drop $\Phi_0$ and $\Phi_1$ arguments for simple writing upto the end of the thesis except it is required for some explanation. Numerical \cite{16, 17, 18, 19} and analytical \cite{20, 21} studies have calculated $\Phi_1$ and studied
Figure 1.10: Cross section view of the soft x-rays system at A2 module ($\phi=104.5^\circ$). Five cameras are presented and each of them has sixteen cords.

its influence on the impurity transport. Their conclusions were $\Phi_1$ is important if and only if $Z_{a,e}^{\Phi_1} \sim 1$ that corresponds higher collisional species like high-Z impurity, where $\tilde{a}$, $Z$, $T$ and $e$ represents the species label, charge, temperature and the electron charge respectively. The expected asymmetry in impurity distribution on the flux surfaces because of the asymmetry in $\Phi_1$, according to the former neoclassical approach has been already shown in modelling but still lacking the experimental validation. Pedrosa has introduced the first reasonable direct measurmets of $\Phi_1$ [22] but it was limited to the edge region $0.87<r/a<1.0$ because of experimental constrains. In this thesis we introduces a parameter that we call $\alpha$ from $\Phi_1$ modelling as a quantity to be measured indirectly from the emission map at any toroidal plane covering the whole radial range. The calculated $\alpha$ parameter map indicates the asymmetry in $\Phi_1$ which is expected to be observed in the constructed radiation maps by the bolometry systems which intrinsically hold the impurity distribution information and $\Phi_1$. Usually EUTERPE\textsuperscript{18} solve the drift kinetic equation considering the pitch-angle scattering collision operator for the impurity (see e.g [23]) that neglects the impurity parallel velocity due to the impurity-ion friction which is a good approximation for the bulk species. Since the impurity-ion friction is non-trivial for the high-Z impurity, for the first time EUTERPE code considers a modified collision operator that is so-called linearized impurity-ion (see e.g [21]) for impurity including the ion friction contribution and its explicit formula comes in the next chapter.

\textsuperscript{18} EUTERPE is a neoclassical, gyrokinetic, particle in cell $\delta f$ and monte carlo. It solves the neoclassical version of the drift kinetic equation up to three different kinetic species electron, ions and heavy ions that corresponds the impurity.
Chapter 2

Neoclassical Transport

The classical transport theory has enough mathematical tools for handling such kinds of problems. A scientific satisfaction toward the transport theory mathematical tools, clearness, understanding, and its predictions have been established through years of applications in different fields. The swell was and still at many applications, but several shortages have appeared when it starts to treat the highly magnetized plasma since the middle of the last century. Considerable differences between the predictions and experiments of the particle and energy radial flux due to any slight spatial inhomogeneity in the magnetic field ($B$) since the classical transport counts only for the $B$ neglecting the raised drift due to its inhomogeneity (curvature and gradient). Elaborate studies on the former unexpected behavior considering $B$ inhomogeneity, through the last fifty years, have introduced a successful but not complete approach that is termed by the neoclassical theory of transport (NC).

Radial losses of the particles and energy in toroidal devices are caused by two different mean of transport, the collisional transport that is treated by NC while the second is due to turbulent fluctuations in electric and magnetic field. The former is dominated in stellarators inner plasma and treated by the NC theory as a kinetic approach while the later is sub-dominated [] and treated by the Gyrokinetic theory as a kinetic approach.

Minimization of the collisional transport to the lowest order is one of desired tasks to decrease the energy losses. Deuterium-tritium fusion requires collision and hence fusion plasma is a collisional with low collision frequency $\nu$.

Kinetic theory aims at solving for the distribution function $f(r, v)$ of an ensemble of particles each with a position $r$ and velocity $v$ at a certain instance of time. The observable quantities like the particle and heat fluxes $\Gamma$, $Q$ are expressed as the moments of the distribution function and reads, respectively,

$$\Gamma = \int v f(r, v) dv$$  \hspace{1cm} (2.1)

$$Q = \int \frac{mv_s^2}{2} v_s f(r, v) dv$$  \hspace{1cm} (2.2)

where $v_s$ is the particle velocity in the moving frame and $v_s = v - v_s$ is the
particle relative velocity with respect to the moving frame. The dependence of the distribution function on the independent variables $r$, $v$ and $t$ is governed by the known *Boltzmann equation*,

$$\frac{df (r,v,t)}{dt} = \left( \frac{df}{dt} \right)_{\text{coll}}$$

(2.3)

where the right-hand side is the collision operator, that contains the particles mutual interactions, which is vanishing if there is no collision, and in this case, the equation is so-called the *collisionless Boltzmann equation*. The collision term has different expressions depending on the underlying process in the system like the *Kronck model*, *Boltzmann collision integral* and *Fokker-Planck collision term*. Boltzmann collision operator is a good approximation for the strong binary collision\(^1\), while Fokker-Planck operator considers a series of successive weak binary collision\(^2\) and in that case the equation is named *Fokker-Planck equation*.

### 2.1 Fokker Planck equation

Regardless the collision operator, all these equations are a 6D problem and then it is problematic to solve. The task of neoclassical theory is indeed solving for the Fokker-Planck equation, i.e. the *Vlasov equation*\(^3\) incorporating a source term accounting for the collisions among particles, but instead of solving for the distribution function of the particles, it does it for the distribution function of their guiding centers $R = r + \bar{\rho}$:

$$\left( \frac{\partial}{\partial t} + \dot{R} \cdot \nabla + \dot{v} \cdot \nabla v \right) f = \left( \frac{\partial f}{\partial t} \right)_{\text{coll}}$$

(2.4)

where the gyromotion is represented as: $\bar{\rho} = \rho(x\cos(\omega) + y\sin(\omega))$. Here $\rho = \frac{v_{\perp}}{qB}$ is the larmor radius, $x$ and $y$ are the unit vectors in perpendicular velocity plane ($x \times y = b$) and $\omega$ is the gyrophase with fast evolution and the average over it leaded to the problem reduction from 6D to 5D. Fokker-Planck collision operator has two main terms represents the diffusion and the dynamic fricitions that works in oposite to retain the system to the theromdynamic equilibrium, and hence it vanishes if the distribution function is Maxwellian [24, p. 615]:

$$f_M (r,v) = n(r) \left[ \frac{m}{2\pi^4T} \right]^{3/2} \exp \left( -\frac{mv^2}{2T} \right)$$

(2.5)

---

\(^1\)Strong binary collision: is the particle-particle collision that makes a large deflection angle per each collision and it is dominated in the neutral gases collision

\(^2\)Weak binary collision: is a particle-particle collision but each collision has small deviation angle and a series of successive collision can make accumulative effect like the he coulomb collision in plasma. collisions is considered

\(^3\)Vlasov equation: is a modified version of the collisionless Boltzmann equation that includes the smoothed macroscopic average internal electromagnetic forces
which isn’t the case in fusion plasma, $m$ and $T$ represent the mass and the temperature respectively. Plasma departure from the thermal equilibrium can be expressed by $\delta f = f - f_M$ that represents the departure of the distribution function from the Maxwellian. Since the analytical solution of $f_M$ is known, the neoclassical solves for the $\delta f$, but before proceeding to the neoclassical drift kinetic equation that is deduced from the Fokker-Planck equation (2.4), let us briefly explain the neoclassical assumptions for the impurity problem, the origin of the non-constant part of the electrostatic potential $\Phi_1(r, \theta, \phi)$ and the aim of solving the drift kinetic equation.

### 2.2 Drifts and the electrostatic potential

One of stellarator intrinsic characteristic is the magnetic ripple on the flux surface figure(2.1) that trapped bulk species such as ions and electron with small pitch angels. Diffusion can free the trapped particles, but the diffusion coefficients according to [25, p. 239] is defined by

$$D_{1/\nu} \propto \left( \frac{ma^2\epsilon_h^2}{T_a^7} \right)^{1/2} \quad (2.6)$$

which is different for electrons and ions at the same temperature because of the mass difference and therefore a non-ambipolar transport. Here $a$ and $\epsilon_h$ refers to the kinetic species and the helical ripple depth. This regime is a so-called $1/\nu$ regime since the diffusion transport is inversely proportional to the collision frequency and it is exclusive for stellarators. Non-ambipolar transport creates a radial electric field ($E_r = -\nabla \Phi_0(r)$) to retain the ambipolarity. Historically, the neoclassical approaches consider only this radial electric field component $E_r$, neglecting the non-constant part $-\nabla \Phi_1(r, \theta, \phi)$ from the variation of the electrostatic potential on the flux surfaces. Recent approaches[16] has initiated to study the dynamics beyond the $\Phi_1$, its characteristics and its influence on the high-Z charge impurity dynamics specifically the radial transport. Since the radial electric field, the magnetic curvature and inhomogeneity in the 3D are unavoidable in the stellarator, an associated poloidal and toroidal drifts will perturb the radial dependence part $\Phi_0(r)$ by a radial, poloidal and toroidal dependence part $\Phi_1(r, \theta, \phi) << \Phi_0(r)$. This first order term is fruitless for the bulk species (ion and electrons), but it is supposed to be for higher charge species like the high-Z impurities. Figure (2.2) shows a rough schematic for the radial drifts $v_{E_1}, v_m$ due to the poloidal polarization from the radial electric
field and magnetic field inhomogeneity:

\[
v_{E_1} = -\frac{\nabla \Phi_1 \times B}{B^2},
\]

\[
v_m = \frac{m v_\parallel + \mu B}{Z} \left( B \times \nabla B \right) \quad \text{(2.8)}
\]

\[
v_D = v_{E_1} + v_m \quad \text{(2.9)}
\]

and important to note, \( v_{E_1} \) is the same for all species while \( v_m \) is much less for the high-Z impurity implicating the dominance of \( \Phi_1 \) drift.

Figure 2.1: This figure shows the poloidal small ripples and the toroidal large ripples in the magnetic surface. The smaller the width the less detrapping where the diffusion coefficient is proportional to the its width.

2.3 Neoclassical DKE version for EUTERPE

Fokker-Planck equation (2.4) is the starting point toward the neoclassical drift kinetic equation (DKE) that requires the guiding center trajectory equations. Taking into account the drifts in equations (2.7, 2.9), and the non-constant electrostatic potential part \( \Phi_1(r, \theta, \phi) \), the guiding center trajectory according to[17] is governed by:

\[
\dot{R} = v_\parallel b + \frac{b \times \nabla \Phi_0}{B},
\]

\[
\dot{v}_\parallel = -\frac{\mu}{m} b \cdot \nabla B - \frac{v_\parallel}{B^2} (b \times \nabla B) \cdot \nabla \Phi_0 - \frac{Z e}{m} b \cdot \nabla \Phi_1,
\]

\[
\dot{\mu} = 0
\]

Here, \( b \) is a unit vector in the magnetic field direction, equation (2.10) describes the parallel and perpendicular velocity, equation (2.11) contains the parallel

---

4The electric field in general drift ions and electrons in the same direction so no polarization is expected but here ions and electrons trapping play a role leading to a fluctuated poloidal drift.
forces normalized to the mass and equation (2.12) indicates the conservation of the magnetic moment \( (\mu = \frac{mv_{\perp}^2}{2B}) \). By recalling the definition of the distribution function \( f = f_0 + f_1 \) and the Fokker-Planck equation (2.4) with the guiding center trajectory (2.10 - 2.10) and then linearize the system to the first order in \( O(\frac{\delta}{\rho}) \) (\( \delta \) is the variation length scale), one can write the neoclassical DKE for \( f_1 \) according to [17] as:

\[
\left( \frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla + \mathbf{v}_{E} \cdot \frac{\partial}{\partial v_{\parallel}} \right) f_1 =
\]

\[
f_0(v_m + v_{E1}) \cdot \nabla r \left[ n' - \frac{Z_a \Phi_0}{T_a} + \left( \frac{mv^2}{2T_a} - \frac{3}{2} + \frac{Z \Phi_1}{T} \right) \frac{T'}{T} \right] + C(f) \tag{2.13}
\]

with an equilibrium distribution,

\[
f_0 = f_M \exp \left( -\frac{Z_a e \Phi_1}{T_a} \right) \tag{2.14}
\]

that departure from the Maxwellian \( f_M \) because of \( \Phi_1 \) and \( Z \) combination. Impurity accumulation is caused by the inward radial transport, therefore the surface-averaged radial particle flux:

\[
\frac{(\Gamma_a \cdot \nabla r)}{n_a} = -L_{11} \left( \frac{n'_a}{n_a} - \frac{Z_a e E_r}{T_a} + \frac{L_{12}^a}{L_{11}^a} \frac{T'_a}{T_a} \right) \tag{2.15}
\]

calculation is essential for impurity problem where, where \( L_{ij} \) is so-called thermal transport matrix coefficients that can be calculate with \( f_1 \). A particle in cell (PIC), Monte Carlo (MC), \( \delta f \equiv f_1 \) code called EUTERPE can solve the neoclassical DKE equation (2.13) up to three kinetic species ions, electrons, fast ions (impurity) simultaneously. According to equation (2.15), the

\( \textbf{Figure 2.2:} \) A schematic to show the origin of \( \Phi_1 \), where \( \mathbf{B} \) (---) represent the magnetic field, \( \mathbf{E}_r \) (-----) the radial electric field, \( \mathbf{v}_{E} \) (-----) the poloidal drift that causes \( \mathbf{E}_1 \) that provokes radial drift \( \mathbf{v}_{E} \) (-----). \( E_r \) direction is determined by the operation root if ion or electron. \( \mathbf{v}_{E} \) is a fluctuated part so some of ions go in clockwise and some anticlockwise. The magnetic drift is represented by (-----) and both direction represent the ion and electron drift since the \( \mathbf{v}_m \) is a charge dependent.
surface-avaged particle flux can be inward (outward) for $E_r < 0$ ($E_r > 0$) which is corresponding two operation regimes, the ion root and the electron root respectively.

### 2.3.1 Collision operator

EUTERPE always consider the pitch-angle scattering collision operator according to [23];

$$C(f_1) = \frac{1}{2} \frac{\partial}{\partial p} \left( (1 - p^2) \frac{\partial f_1}{\partial p} \right)$$  \hspace{1cm} (2.16)

for all species electron, ions and the high Z-impurity, however the validity of this approximation depends on the collosionality regime of the species that defined by the $\nu^* = g(Z)$ that means electrons and ions are in different regimes from the high Z-impurity. Pitch-angle approach is valid for the species in the low collisionality regime with a normalized frequency ($\nu^*$) less than their poloidal precession frequency by the $E_r \times B$ drift that reduces their trapping time in the ripples. This is hold for electrons and ions with a good approximation because both are typically located in $1/\nu$ or $\sqrt{\nu}$. On the other hand, since the $\nu^*_Z$ is higher for high Z-impurity and typically is located in the Pfirsch-Schluter regime this approximation is violated. The linearized impurity-ion collision operator

$$C(f_1; h_i) = \nu_{Zi} \left[ K f_1 + \frac{m_{Zi} A v_{\parallel}}{T} f_M \right]$$  \hspace{1cm} (2.17)

and the reader that considers that neglects the ion-ion collision in comparison with the impurity ion collision since the latter introduces a parallel friction force with ions leading to the momentum conservation.

### 2.3.2 Ion root regime

For $T_i \sim T_e$ as in NBI plasma$^5$ and since $m_i > m_e$ the ions diffusion coefficient (due to the $m$ dependence in equation 2.6) will be higher and hence the ion radial flux is larger than the electron flux which is called non-ambipolar transport. Furthermore, this radial polarization creates an inward electric field to retain the ambipolarity that is so called the ambipolar radial electric field $E_r > 0$. Inward $E_r$ enhances the inward transport of impurities and even higher for high-Z impurity causing an accumulation generally. For the reactor operation, $T_i \sim T_e$ is mandatory while the fusion cross section is higher with higher ion temperature. So, many studies in the regime seeking alternatives to counteract the influence of the $E_r$ on the impurity. However, the

---

$^5$NBI Plasma is the plasma initiated by the electron cyclotron resonance heating (ECRH), typical initiation in stellarators, and then the neutral beam injection starts to heat the plasma independently in the second phase which has a higher efficiency for ion heating. This scenario leads to plasma with a comparable ion and electron temperature.
2.3 Neoclassical DKE version for EUTERPE

routinely experimental observation of the accumulation, few cases with unexpected outward transport has been observed in the W7-AS [26] and th LHD [27] but leaking a complete theoretical explanation. The numerical calculation concluded the existence of one stable solution for the DKE in this regime [25, page. 243].

2.3.3 Electron root regime

For \( T_i \ll T_e \) as in ECRH plasma\(^6\) the electron diffusion coefficient will be higher (due to \( T_i^{7/2} \) dependence in equation 2.6) that means higher electrons flux than ions (non-ambipolarity) and hence an electric field pointing out \( E_r < 0 \) is created to retain the ambipolarity transport. Impurity accumulation is avoidable in the regime, however, it can be achieved in today stellarator because of the availability of higher power ECRH heating source but neither NBI nor ICRH heating.\(^7\) The numerical calculation concluded the existence of multiple solution for the DKE in this regime, but only one is stable [25, page. ].

---

\(^{6}\)ECRH plasma is the plasma heated by the electron cyclotron resonance heating (ECRH) that heats the electron directly that transfer some of its energy to ions through collision during the pulse length. This scenario leads to plasma with a small ion temperature in comparison with the electron temperature.

\(^{7}\)ICRH are the ion cyclotron resonance heating which is mandatory for reactor because it heats the fuel ions directly with higher efficiency. ICRH has a technology challenge since its antenna must be almost in contact with plasma for higher coupling because the ICRH wavelength is comparable to machine size and it attenuates in the vacuum.
2. Neoclassical Transport

2.4 The electrostatic potential with EUTERPE

The neoclassical DKE (2.13) requires the $\Phi'_0$ and $\Phi_1$ which can be obtained from the ambipolarity condition and the quasineutrality respectively. Different codes can precalculate $E_0 = \Phi'_0$ such as KNOSOS, GYRASKA or DKES and can also be measured experimentally by Doppler Reflectometry for the middle part and then fitted for the full radius. The experimental one is superior for the cases with unstable codes behavior that gives considerably different results from the measurements. In principle, EUTERPE can obtain $E_0$ but with a huge CPU hours consumption without major advantages than the former codes. Calculation of $\Phi_1(r, \theta, \phi)$ maps is one of EUTERPE main tasks with higher accuracy since it considers the nonlinear effects. Quasineutrality must be fulfilled locally within each flux surface which means the total charges, up to the first order, from electrons, ions and impurities must be zero. Hence, $\Phi_1$ can be calculated by solving this equation,

$$\sum_a Z_a e n_a = 0 \quad (2.18)$$

considering the following simplifications, (i) the electrons are adiabatic in the background leading to consider only the zero order density $n_{0e}$ and neglect the first order $n_{1e}$, (ii) cases with the low impurity density and therefore, both the zero $n_{0i}$ and the first $n_{1Z}$ impurity density orders tend to zero and (iii) the exponent factor for the ions as a kinetic species $e\Phi_1/T_i \ll 1$. These assumptions are true without losing the physics beyond the problem. Considering these simplifications (i-iii) after substituting the general density formula,

$$n_a \simeq n_{0a} \exp \left( -\frac{Z_a e \Phi_1}{T_a} \right) + n_{1a} \quad (2.19)$$

in the quasineutrality condition (2.18), leads to the manifestation of the explicit formula for the non-constant electrostatic potential

$$\Phi_1(r, \theta, \phi) = \frac{T_e}{e} \left( n_{0e} + n_{0i} \frac{T_e}{T_i} \right)^{-1} + n_{1i}, \quad (2.20)$$

and then the density map can be obtained for different species by substituting $\Phi_1$, which is a map of $\phi, \theta$ at each flux surface, in the density definition. The asymmetry in impurity density at each flux surface can be obtained by calculating the normalized density departure from the mean value,

$$\alpha_{nz} = \frac{n_Z - n_{0Z}}{n_Z} \quad (2.21)$$

$$= \exp \left( -\frac{Z e \Phi_1}{T_Z} \right) - 1 \quad (2.22)$$

whose correlation with the possible emissivity radiation from bolometry systems ($\alpha_{rad}$) is of interest in order to study the nature of the radiation asymmetry. The scheme provides an indirect check of the non-constant potential
characteristics of the neoclassical potential over the flux surfaces. The ability of this scheme to study $\Phi_1(r, \theta, \phi)$ characteristic for the full radius domain make it is superior to the direct measurement that restricted to $0.87 < r/a < 1.0$ domain [22].
2. Neoclassical Transport
Chapter 3

Numerical and Experimental analysis

In the previous chapter it has been introduced \((\alpha_{nz})\) parameter that refers to the asymmetry level of the impurity density distribution due to the flux surface electrostatic potential variation respect to the constant value over each surface \((\alpha_{nz}=0)\) means no variation and \(\alpha_{nz} = \pm 1\) means \(\pm 100\%\) variation in the \(\Phi_1\) but doesn’t mean it leads to \(\pm 100\\%\) in the density variation. Therefore, in the experiment, we are looking for the \(\alpha_{rad}\) that refers to the radiation asymmetry parameter that mainly due to the impurity asymmetric distribution in two different toroidal planes. It is apparently the comparison between \(\alpha_{nz}\), which is amplification of \(\Phi_1\) according to equation (2.22), and \(\alpha_{rad}\) is reasonable to study the \(\Phi_1\) asymmetry characteristics and its influence on the impurity transport on different levels of ionization. This chapter organized in three sections: section 3.1 review the calculation steps with EUTERPE to (i) calculate the \(\Phi_1(r, \theta, \phi)\) for an (ion root shot #45469) and an (electron root shot #45477) and (ii) calculate the \(\langle \Gamma_Z \cdot \nabla r \rangle\) for the ion root case with including \(\Phi_1\) versus excluding it, and considering the linearized impurity-ion collision versus pitch-angle scattering collision operator. Section 3.2 describes the required experimental profiles for EUTERPE and briefly introduces their diagnostics. Section 3.3 is dedicated to explain the emissivity tomographic reconstruction technique Tomography-code employed at TJ-II to follow the evolution of the radiation captured by Bolometry and SXR in order to reconstruct the asymmetry in the radiation maps \((\alpha_{rad})\).

3.1 Numerical steps and analysis

EUTERPE takes as input the radial profiles of density, temperature and the ambipolar radial electric field. In the present work, the numerical calculations targets three main tasks; (i) observing the asymmetry in the \(\alpha_{nz}\) in the toroidal plane where the radiation is measured for \(\alpha_{rad}\) reconstruction, (ii) studying the influence of \(\Phi_1\) asymmetry (included in \(\alpha_{nz}\)) on the impurity radial transport
3. Numerical and Experimental analysis

for different impurity types $C^{6+}$, $Fe^{10+}$ and $W^{20+}$, and (iii) comparing the effect of considering the linearized impurity-ion and pitch-angle scattering collision operator, including and excluding $\Phi_1$ for both, on the $\langle \Gamma_Z \cdot \nabla r \rangle$ for the impurity. EUTERPE typically requires High Performance Computing platforms and all simulations here has been performed on MARCONI, MARENostrum and the local CIEMAT cluster EULER has been used for testing. Many parameters are defined in the input file with multiple input choices, table (3.1) summarizes the most relevant parameters for the study presented in this work.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Name in the input</th>
<th>Used values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinetic species</td>
<td>kinspecies=<em>.</em>._.</td>
<td>t or f</td>
</tr>
<tr>
<td>Profiles</td>
<td>iprof_fname=____.dat</td>
<td>file name</td>
</tr>
<tr>
<td>$\Phi_1$ calculation</td>
<td>calc_pot=_.</td>
<td>0 or 1</td>
</tr>
<tr>
<td>$s_0=(r/a)^2$</td>
<td>load_s0=____</td>
<td>0 to 1</td>
</tr>
<tr>
<td>Collision operator</td>
<td>colop=_.</td>
<td>0 or 3</td>
</tr>
<tr>
<td>Consider $E_r$</td>
<td>neo_er=_.</td>
<td>0 or 1</td>
</tr>
<tr>
<td>Value of $E_r$</td>
<td>efield_r=____</td>
<td>$E_r$ kV/m</td>
</tr>
<tr>
<td>Consider $\Phi_1 (r, \theta, \phi)^2$</td>
<td>neo_eang=____</td>
<td>0 or 1</td>
</tr>
<tr>
<td>Impurity charge</td>
<td>qsde=_.</td>
<td>number</td>
</tr>
<tr>
<td>Impurity mass</td>
<td>msdp=_.</td>
<td>number</td>
</tr>
</tbody>
</table>

Table 3.1: Summary of the most relevant parameters used in the EUTERPE input file. $kinespecies=ions,electrons,impurity$ and $(t,f)$ stands for true and false. For $\Phi_1$ calculation $calc\_pot=0$ stands for no calculation while $calc\_pot=1$ does it. In the collision operator: $colop=0$ means the pitch-angle scattering [23] and $colop=3$ represents the linearized impurity-ion operator [21] that is only important for impurity, but neither for ions nor electrons. Consider $neo\_eang=0$ for neglecting $\Phi_1$ while $neo\_eang=1$ for including $\Phi_1$ in $\langle \Gamma_Z \cdot \nabla r \rangle$ calculation and this is only important for impurity. EUTERPE has many choices but the table represents the most relevant parameters for this work.

---

1By default it reads the maximum parallel velocity due to the impurity-ion friction at $A_{zi}.dat$ which is post-processed from the file diag2d.dat
2The $\Phi_1 (r, \theta, \phi)$ is read from phi2d.dat file that is post-processed from the flsurf_phi.dat that represents the 2D electrostatic potential $\Phi_1 (\phi, \theta)$ at radial pin
3Normalized to the magnitude of electron charge
4Normalized to the proton mass
3.1 Numerical steps and analysis

3.1.1 Numerical calculation of $\Phi_1(r, \theta, \phi)$

Typically in the ion root, the ion distribution is the main source of $\Phi_1$ since it scales with the Larmor radius $\rho = T m^{1/2}/(eB)$ of each species that is larger for the ion since the $\rho_\text{i} = \sqrt{m_i/m_e} \rho_\text{e}$. However in the electron root regime with $T_\text{i} \ll T_\text{e}$ the $\Phi_1$ scales with $\rho/\nu*$ and since the electrons are in the $1/\nu$ regimes with relatively small $\nu_\text{e}*$ the electrons contribution can count[18]. Therefore, the kinetic electrons has been neglected for the ion root simulation confidently and it is neglected for the electron root but due to the high CPU hours consumption and is left for future work. So, ions is considered the only kinetic species by setting $(\text{kinspecies}=t,f,f)$ when solving the quasi-neutrality and calculating $\Phi_1$. The like with profiles are fitted to the experimental one (obtained with TS and CNPA TJ-diagnostics) and arranged in column like $[s, T'_\text{i}/T_\text{i}, T_\text{i}, T'_\text{e}/T_\text{e}, T_\text{e}, n'_\text{i}/n_\text{i}, n_\text{i}, n'_\text{e}/n_\text{e}, n_\text{e}]$ with $X' = dX/ds$. For the bulk species that have low collision the pitch-angle scattering collision operator is a good approximation in stellarators and when the radial particle flux are calculated by defining $\text{colop}=1$ in the input file. The radial electric field has measured by the Doppler Reflectometry (DR) that shows rather constant value within the error margins. In order to calculate $\Phi_1$ $\text{neo_eang}=1$ parameter must be defined in the input file, and finally these parameters $\text{qsde}=1$ and $\text{msdp}=1$ since the normalized charge and mass are equal unity for the hydrogen ion. The simulation is launched at ten different $s = (r/a)^2$, one simulation per each radial pin. The potential is diagnosed using diagnostic libraries to plot the contour at the toroidal-poloidal plane at each radial pin as shown in figure (3.1).

![Figure 3.1: $\Phi_1$ 2D map for the shot #45469 at the flux surface with a normalized effective radius $r/a = 0.51$. The variation of $\Phi_1$ in order (-3 to 2 Volt) is apparent along the poloidal and toroidal coordinates $\phi$ and $\theta$ respectively. Note that, the angles are in radians and $\theta[0 \Rightarrow 2\pi]$ while $\phi[0 \Rightarrow \pi/2]$ only due to the four fold toroidal symmetry in TJ-II.](image-url)
3.1.2 Calculating radial particle flux

The impurity radial particle flux \( \langle \Gamma_Z \cdot \nabla r \rangle \) is calculated using the previous inputs considering the following changes. First the kinetic species here is the impurity while the ions and electrons are not kinetic and for that change from the previous \( \text{kinespecies}=t,f,f \) to \( \text{kinespecies}=f,f,t \). Then the profiles file is modified by adding four columns to the nine in the previous to include the impurity information \[ s_0, \ T'_i/T_i, \ T_i, \ T'_e/T_e, \ T_e, \ T'_z/T_z, \ T_z, \ n'_i/n_i, \ n_i, \ n'_e/n_e, \ n_e, \ n'_z/n_z, \ n_z \]. At this point we consider \( \text{colop}=0 \) for the pitch angle or \( \text{colop}=3 \) for the linearized impurity-ion collision operator and both has simulated in order to compare the difference of the latter operator which is more reliable for the impurity since it includes more processes like the friction of the impurity and ions which is important for high-Z impurity with higher collision. The calculated \( \Phi_1 \) in previous run can be neglected or considered too in order to study the effect of \( \Phi_1 \) on the impurity radial transport. Table (3.2) summarizes the performed simulations for studying the influence of \( \Phi_1 (r, \theta, \phi) \) on the \( \langle \Gamma_Z \cdot \nabla r \rangle \), and the two possible collision operator implemented.

<table>
<thead>
<tr>
<th>––</th>
<th>Pitch angle</th>
<th>Nr</th>
<th>Linearized impurity-ion</th>
<th>Nr</th>
</tr>
</thead>
<tbody>
<tr>
<td>w ( \Phi_1 )</td>
<td>for ( C^{6+}, \ Fe^{10+}, \ W^{20+} )</td>
<td>30</td>
<td>for ( C^{6+}, \ Fe^{10+}, \ W^{20+} )</td>
<td>30</td>
</tr>
<tr>
<td>w/o ( \Phi_1 )</td>
<td>for ( C^{6+}, \ Fe^{10+}, \ W^{20+} )</td>
<td>30</td>
<td>for ( C^{6+}, \ Fe^{10+}, \ W^{20+} )</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 3.2: Summary of the simulations to study the influence of the \( \Phi_1 \) on \( \langle \Gamma_Z \cdot \nabla r \rangle \) and the difference between pitch-angle scattering and the linearized impurity-ion collision operator. Nr refers to the total number of runs for the three impurities \( C^{6+}, \ Fe^{10+} \) and \( W^{6+} \) with and without \( \Phi_1 \). One simulation typically takes 512 CPU hours.

3.2 Sources of EUTERPE input in TJ-II

Ion root regimes is achieved typically in NBI heating scenarios while the electron root are in ECH heating. A Couple of TJ-II shots with different heating scenarios have then been used for the current study with two impurities seeding, Fe by Laser-Below-Off (LBO) and Ne by gas puffing. The shot #45469 is an ion root shot with NBI-heating and #45482 as an equivalent to #45477 \(^5\) is an electron root shot with ECRH heating. Two gyrotrons\(^6\) are used in TJ-II for ECRH that operates with 53.2 GHz and each of them can deliver up to

\(^5\)Both shots #45482 and #45477 has nearly the same profiles and heating scenarios but in modeling and comparison with the experiment we relied on the #45488 and #45477 since there was impurity injection which made the radiation signals more reliable too. So, treat both as equivalent through the thesis and don’t be confused by switching between them.

\(^6\)ECRH system can operate in a modulated mode for studying the perturbed transport and can drive current too.
300 kW power. Two quasi-optical transmission lines are used to transmit the beams which are launched to the plasma, through B3 and A6 sectors, with a help of a steerable mirror located inside the vacuum vessel which controlling the incidence angle. In addition, two NBI heating system with 40 keV acceleration energy is installed in TJ-II that can deliver up to 3.2 MW power for pulses shorter than 300 ms. NBI1 access the vessel through D8 sector while NBI2 through C1 sector. In NBI plasmas (#45469), the NBI can’t initiate the discharge at the first phase and though ECH system is used to start heating and then NBI starts to come in operation at the last 20 ms for ECH pulse to work independently afterwards delivering up to 0.5 MW as shown at the top part in figure (3.2). For the ECH plasma (#45482) the two gyrotrons are working exclusively for the whole discharge period delivering up to 0.45 MW which is divided equally between the two gyrotrons as shown at the down part in figure (3.2). Referring to the neoclassical DKE (2.13) which EUTERPE solves, it requires the three species temperature, density profiles, and their gradients. The next few lines introduce which measurements are considered and the approximation for poorly characterized profiles. After the ramping up phase and in the stable plasma profiles, the Thomson Scattering (TS) laser can reconstruct the electrons temperature $T_e$ and the electron density $n_e$ with high spatial resolution in one instant [28]. For the #45469 the TS time was 1208 ms while in #45482 was 1131 ms. Measuring the ion temperature $T_i$ profile in TJ-II is not intierly possible since only two radial points can be measured.

**Figure 3.2:** Heating scenarios: For the shot time trace of the delivered heating power of NBI and ECH plasma. **Top** for shot #45469 as a typical NBI plasma that starts with ECRH (two gyrotrons ECRH1 ( ) and ECRH2 ( )) up to $t=1265$ ms and the NBI ( ) starts at $t=1145$ ms and independence phase at $t=1258$ ms. The Thomson scattering (TS) ( ) constructs the profiles at $t=1208$ ms, and the density ( ) is till ramping due to NBI, but with lower rate than the initial ramping up. **Down** for the shot #45482 is a typical ECH Plasma with ECRH heating ( , ) in the time window 1160 - 1260 ms with stable density profile ( ) and th TS ( ) has constructed the profiles at $t=1131$ ms.
with the Compact Neutral Particle Analyzer (CNPA) during the shot. Some studies have scanned different different two positions from shot to shot with the same conditions for TJ-II plasmas concluding that, the $T_i$ and $T_e$ shapes are similar in NBI shots while the $T_i$ and $n_e$ shapes 1, 3 and five. are similar in the ECH plasmas [29]. The ion density profile $n_i$ has been taken the same as $n_e$ to satisfying the quasineutrality which is a good approximation unless the effective charge ($Z_{\text{eff}}$) is much larger than unity which isn’t the case in TJ-II, since current scenarios has $Z_{\text{eff}}$ 2 for the NBI plasma and much less for the cleaner ECH plasmas with outward ambipolar radial electric field. On the other hand, the impurity temperature profile is typically assumed as $T_i$ because of the collisional z-i coupling, while $n_Z$ is taken constant with five order of magnitude less than the bulk species since EUTERPE assumes trace impurity in $\Phi_1$ calculation. The #45469 and #45482 profiles are shown in figure (3.3, 3.4) respectively. TJ-II is implemented with a DR system operates in Q-band (33-

![Graph](image_url)

(a) The temperature profiles at $t=1208$ ms. The $T_e$ ( ), $T_i$ ( ), and $T_z$ ( ) is exactly as $T_i$. It is clearer that $T_e$ is almost twice $T_i$ satisfying the ion root condition.

(b) The density profiles at $t=1208$ ms. $n_e$ ( ) and $n_i$ ( ) are exactly the same, while the $n_z$ ( ) is five order of magnitude less than the $T_e$ and $T_i$.

**Figure 3.3:** Temperature and density profiles for the ion root shot #45469

50) MHz at sector C6 (toroidal angle=337°). It measures the fluctuations in plasma density and the velocity perpendicular spectra in the range $k_{\perp}^{-1}$=1-14 cm via different incidence angles with respect to the perpendicular reference. It has an ellipsoidal mirror for focusing the gaussian microwave beam in order to deliver plane wavefronts before backscattering and also gives different incidence angles accessibility covering the effective radius ($r/a$=0.6 to 0.9) range [30]. DR measures the radial electric field $E_r$ in the same range ($r/a$=0.6 to 0.9) as shown in figure (3.5), however a numerical estimation of $E_r$ can be a choice, but here that we have a poorly characterized $T_i$ and $Z_{\text{eff}}$ profiles, we

---

7 Trace impurity approach: is considered for the species that has small amount in comparison with the bulk species and hence a neglected contribution in the background force in comparison with the bulk species, so whatever the initial profile it will be reshaped according to the background forces.
3.2 Sources of EUTERPE input in TJ-II

(a) The temperature profiles at $t=1131$ ms. $T_e$ profile ( ), $T_i$ ( ), and $T_z$ ( ) is exactly as $T_i$. It is clear that $T_e$ is eleven times larger than $T_i$ satisfying the ion root condition.

(b) The density profiles at $t=1208$ ms. $n_e$ ( ) and $n_i$ ( ) are exactly the same, while the $n_z$ ( ) is five order of magnitude less than the $T_e$ and $T_i$.

Figure 3.4: Temperature and density profiles for the ion root shot #45482

have considered the $E_r$ profile on the accessible range of DR a more appropriate source for our input. Since DR measures the modulus of the local radial electric field, which is by definition $E_r = E_r \nabla r$, while EUTERPE requires $E_r$ at the input, the nearly constant value obtained from the measurements shown in figure (3.5) have been divided by a factor 1.5, which corresponds to an approximate value of $|\nabla r|$ at the measurement positions the DR microwave beam can access. Therefore the considered $E_r$ values for the two shots are ($E_r \sim -3000$) for the #45469 and ($E_r \sim 1300$) for #45482.

Figure 3.5: The ambipolar radial electric field $E_r$ measured by the DR from the left (•) and right (◆). (a) for the ion root shot #45469 and (b) for the electron root shot #45482 which is almost constant and equal within the error margins. Figs: courtesy of T. Estrada, CIEMAT.
3.3 Emissivity tomography analysis scheme

Tomography is a technique that reconstructs the local emissivity from the multiple collected integrated emission lines from different viewing angles. Medical and industrial tomography has higher efficiency because of the typical number of lines is very large in order $10^5$ with different viewing angles that allows to cover the whole poloidal view around the measured object. On the other hand, fusion devices have limited ports because each device has lots of diagnostic systems besides Bolometry and soft x-rays (SX). Typical fusion Bolometry system has around 100 lines that decrease the tomography reconstruction efficiency, but higher efficiency can be retained by intelligent mathematical tools and plasma symmetric properties which are higher in tokamak than stellarators[31]. One or two cameras in tokamak plasma together with the mathematical techniques and toroidal symmetry can achieve a reasonable efficiency but stellerator needs a higher number of cameras as described in section 1.4.2 for TJ-II and more powerful SX at W7-X with 360 lines from twenty pinhole cameras[32]. TJ-II counts with a Fortran Matlab tomography suit applicable for the Bolometry and SX data that is so-called Tomography. This section is devoted to explain the basics and one consideration like the calibration. In general, the reconstruction process can be achieved using a set of algebraic linear equations, in arbitrary coordinate system, which is formed by combining the integrated viewing emission lines and the crossing points of these lines. The numbers of equations is less than the number of unknowns that lead to multiple solutions and gives us only the local emissivity without information for interpolation process. Johnn Radon[33] introduced a transform

$$R_\mu (L) = \int_L \mu (x, y) \, dx\, dy \quad (3.1)$$

that calculate the line integral $R_\mu$ from the two dimension projections $\mu (x, y)$ and its inverse take the lines integral from different view angels and radial positions to give the local emissivity $\mu (x, y)$ where $x$ and $y$ are the coordinates of the viewed plane. This transform combined with Fourier transform of the underlying signal selecting the proper coordinate system to increase the efficiency and simplify the problem mathematically and therefore Tomography-code in TJ-II uses the VMEC coordinates\(^8\). The local emissivity is given by

$$E (\rho, \theta) = \sum_{n,m} C_{nm} f_n (\rho) \exp (im\theta) \quad (3.2)$$

where $C_{nm}$ is coefficient $f_n (\rho)$ is arbitrary function for radial variation, $\exp (im\theta)$ represents the poloidal variation, $(\rho = r/a, \theta)$ are the radial and poloidal variables, and $(n, m)$ are the radial and poloidal mode numbers. By expanding

\(^8\)VMEC is the coordinate system that the magnetohydrodynamic (MHD) code VMEC uses for solving the MHD ideal equilibrium and providing the magnetic equilibrium configurations.
equation (3.1) for the first poloidal mode number $m = 0$,

$$E(\rho, \theta) = \sum_{n=0}^{N} C_{n0} f_n(\rho) \sum_{n,m=0}^{N,M} f_{n}^1(\rho) \left[ C_{nm}^1 \cos(m\theta) + C_{nm}^2 \sin(m\theta) \right]$$  \hspace{1cm} (3.3)

The coefficients $C_{n0}$ (of poloidal symmetric terms), $C_{nm}^1$ (of the cosine terms), and $C_{nm}^2$ (of the sine terms) can be determined from the linear regression of the measured data. As mentioned formerly the selection of orthogonal sets of basis function $f_n$ is crucial for higher efficiency and optimal reconstruction and here Bessel is used since it satisfies this condition. The reconstruction quality is being tested by comparing the original signal by the fitted one as shown for example in the figure (3.6).

![Figure 3.6](image)

**Figure 3.6**: Original and fitted signal form the Soft x-rays three cameras which has sixteen line for each.
3. Numerical and Experimental analysis
Chapter 4

Results and discussions

4.1 $\Phi_1$ asymmetry EUTERPE vs Experiment

EUTERPE has been used to calculate the 2D map of $\Phi_1 (\theta, \phi)$ (see e.g figure 3.1) at ten different radial pins $r/a=\{0.12, 0.21, 0.33, 0.41, 0.51, 0.59, 0.69, 0.80, 0.91, 0.97\}$ covering the core, middle and the edge region and with them the reconstruction of the asymmetry parameter $\alpha_{nz}$ (see equation (2.19, 2.22)) at any arbitrary toroidal planes becomes possible with the diagnostic libraries. The $\alpha_{nz}$, as an amplifier of the $\Phi_1$ variation on the flux surface, has been reconstructed at two toroidal planes $\phi = 14.5^\circ$ and $75.5^\circ$ in the EUTERPE toroidal domain, which are the correspondents to the locations of Soft X-Rays (SXR) at $\phi = 114.5^\circ$ and the Bolometery at $\phi = 315.5^\circ$ for three impurity with $Z=6, 10$ and $20$. Since $\alpha_{nz}$ is a charge dependent and mass independent, the obtained numerical results for these three charges are valid for the comparison with any impurity in the experiment with the same charge state regardless its mass. The radiation asymmetry parameter $\alpha_{rad}$ map has been reconstructed by the Tomography-code from the SXR and Bolometery systems. A similar analysis has been carried out for a couple of shots, #45469 is the ion-root and #45482 is electron-root shot with central densities, temperatures and heating powers summarized in table (4.1). A trace of two impurity species Fe and Ne, that don’t exist in the plasma, are used for the study. Fe has been injected with BOL but it is being diffused rapidly to outward and stuck with the walls and hence it has no contribution in the impurity radiation while Ne has injected by gas puffing and it is being recycled back, because it is a noble gas and has low chemical interactions with the walls, and hence it is considered as the impurity species for the current study. Before proceeding, it is important to mention the replacement of the charge symbol from $Z$ to $Z_I$ and $Z$ switched to denote the cylindrical coordinate perpendicular to the horizontal plane of the machine.

$^1$Since TJ-II has four fold symmetry, EUTERPE calculates for one fourth of the toroidal domain $\phi[0 \Rightarrow \pi/2]$ which is applied to the other three identical parts. For example, the $[\phi = 1^\circ]$ in EUTERPE is equivalent to the toroidal planes $[\phi = 1^\circ, 91^\circ, 181^\circ$ and $271^\circ]$ in TJ-II.
4. Results and discussions

<table>
<thead>
<tr>
<th>Quantity</th>
<th>#45469</th>
<th>#45488</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_e$</td>
<td>0.32</td>
<td>1.10</td>
<td>keV</td>
</tr>
<tr>
<td>$T_{i,n}$</td>
<td>0.13</td>
<td>0.10</td>
<td>keV</td>
</tr>
<tr>
<td>$n_{e,i}$</td>
<td>2.20</td>
<td>0.58</td>
<td>$10^{19}$ m$^{-3}$</td>
</tr>
<tr>
<td>$n_z$</td>
<td>1.00</td>
<td>1.00</td>
<td>$10^{19}$ m$^{-3}$</td>
</tr>
<tr>
<td>ECRH-Power</td>
<td>–</td>
<td>0.4</td>
<td>MW</td>
</tr>
<tr>
<td>NBI-Power</td>
<td>0.5</td>
<td>–</td>
<td>MW</td>
</tr>
</tbody>
</table>

Table 4.1: Central temperature and density for the three species (electrons, ions and impurity) and the heating powers for the two shots. Note, for the shot #45482 ECRH is used only for plasma initiation and then NBI work independently for the interested time and therefore we put ECRH-power=0 (see e.g fig(3.2))

4.1.1 Ion root case

The ion-root discharge #45469 has input profiles shown in figures (3.3, 3.5) and summarized in the table (4.1). EUTERPE calculation of $\alpha_{nz}$ at the toroidal plane of the SXR system with angle $\phi = 14.5^\circ$ is shown in the figure 4.1 for three different impurity charges $Z_I = 6$, 10 and 20. It shows a higher variation on the outer and the core regions in comparison to the middle region. The upper right part shows higher positive variation while the lower left part represents negative variation. Positive and negative here refers to the variation which is larger and less than the variation average on the same flux surface where $\alpha_{nz}$ refers to the variation normalized to the average value on the the same flux surface. Since EUTERPE calculations provide the full 3D maps of

![Figure 4.1: Numerical results for #45469: The normalized asymmetry parameter of the impurity density $\alpha_{nz}$ considering $\Phi_1$ for three charges $Z_I = 6$, 10 and 20 from left to right at the SXR toroidal plane($\phi = 14.5^\circ$). Higher $Z_I$ shows higher asymmetry.](image)

the $\Phi_1$ from which $\alpha_{nz}$ is being calculated, we have used the benefits of the
4.1 $\Phi_1$ asymmetry EUTERPE vs Experiment

runs to produce $\alpha_{nz}$ map at the Bolometery toroidal plane with $\phi = 75.5^\circ$. However the Bolometery counts the whole energy spectrum that comes from different sources not only the impurity, but it is still an indicator for the impurity distribution to certain percentage since impurity is the main radiation source in TJ-II plasma. Figure (4.2) represent the $\alpha_{nz}$ for the three different charges $Z_I=6, 10, 20$. It shows a higher variation on the outer and the core regions in comparison to the middle region. The upper region shows more positive variation while the lower part represents negative variation. The indirect

![Figure 4.2: Numerical results for #45469: the normalized asymmetry parameter of the impurity density $\alpha_{nz}$ considering $\Phi_1$ for three charges $Z_I=6, 10$ and 20 from left to right at the Bolometery toroidal plane ($\phi = 75.5^\circ$). Higher $Z_I$ shows higher asymmetry](image)

measurement of the $\Phi_1$ that introduces impurity density asymmetry is based on the comparison of the $\alpha_{nz}$ with the radiation asymmetry from the SXR as the main system counts the impurity radiation and the Bolometery is considered too however it counts for other radiation in addition to the impurity. The radiation asymmetry parameter $\alpha_{rad}$ represent the radiation variation normalized to the averaged radiation on the same flux surface. Strictly speaking the normalization to the each flux surface radiation average that means higher you should look to the variation on each flux surface regardless others flux surface. Ne trace gas has puffed to the experiment at 1155 ms and it has selected because Ne isn’t exist in plasma and this guarantees the sureness of the impurity type in the plasma. The radiation background has been subtracted to focus one the radiation from Ne trace since theoretical approach consider the trace approximation. The reconstructed radiation maps from the SXR and Bolometery are shown in figure 4.3 on the left and right column respectively. The reconstruction of radiation poloidal symmetric part considered modes $m=0$ in the Tomography-code while the poloidal asymmetry has reconstructed by considering $m=1, 2$ and 3 where the SXR and Bolometery has three cameras. The $m=0$ shown in figures 4.3(a,d)represents the symmetric average radiation on each flux surface and $m>0$ up to three sown in figures 4.3(b,e)represents the poloidal symmetric part in addition to the variation that breaks the symmetry. The normalized variation of the radiation on each flux surface $\alpha_{rad}$ has
been calculated by subtracting the former ($m=0$) from the latter ($m>0$) and then dividing by the former ($m=0$). This $\alpha_{\text{rad}}$ is shown in figures 4.3(c,f) for SXR and Bolometery respectively. The symmetric part shows higher radiation

![Experimental results for #45469: left for the SXR and right for the Bolometery. (a,d) represents the symmetric radiation part without poloidal modes $m=0$, (b,e) is the asymmetric radiation maps with poloidal modes $m>0$ up to 3, and (c,f) represents the $\alpha_{\text{rad}}$ that is going to be compared with the impurity density parameter $\alpha_{nz}$ due to $\Phi_1$ from the core indicating impurity accumulation as expected by the NC for the ion-root discharge #45469 with $E_r < 0 \sim -3 \text{ kV/m}$ from DR in figure 3.5. The comparison between the numerical and experimental asymmetry parameters $\alpha_{nz}$ and $\alpha_{\text{rad}}$ is shown in figure (4.4) for both SXR at top in (a,b) and Bolometery at the bottom in (c,d). One can observe partial agreement at the SXR particularly the bottom part of the core and the top part of the...](image-url)
edge while the Bolometery shows partial agreement at the bottom part of the middle region. Up to this point we can’t argue there is a clear correlation between both $\alpha_{nz}$ and $\alpha_{rad}$ but at least there is a comparability of the variation scale and partial agreement at some regions. This discrepancy might be a

![Image](image_url)

**Figure 4.4:** Numerical vs Experiment for #45469: (a,b) represent the numerical impurity density asymmetry parameter $\alpha_{nz}$ and the experimental radiation asymmetry parameter $\alpha_{rad}$ respectively at the toroidal plane $\phi = 14.5^\circ$ that corresponds the SXR toroidal position. (c,d) represent the numerical impurity density asymmetry parameter $\alpha_{nz}$ and the experimental radiation asymmetry parameter $\alpha_{rad}$ respectively at the toroidal plane $\phi = 75.5^\circ$ that corresponds the Bolometery toroidal position. Note the numerical scale between $\pm 0.5$ while the experimental scale is between $\pm 0.9$ which are comparable. Since Ne is the puffed trace impurity, the numerical results in (a,c) has considered $Z_I = 10$ assuming fully ionization of Ne on the whole effective radius.

raised due too several reasons, (i) SXR shows relatively better results than the Bolometery because the latter measures wider energy window energies that count other radiations from plasma such as fast ions not only the impurity radiation, (ii) the numerical calculation assumes a stationary profile taken at a specific instance by TS in this ion shot #45469 which has NBI plasma in which the profiles are evolving and not stationary, (iii) in TJ-II even in the ion-root discharges the electron temperature still two times larger than the ion temperature that means the electron contribution in $\Phi_1$ is non-trivial, however
it has been neglected due to CPU hours, (iv) since the ionization degree of the
impurity has a radial distribution, different Z_I should be considered at different
flux surfaces, while simulation considers single Z_I and (v) the higher observed
\( \alpha_{\text{rad}} \) at the core than \( \alpha_{\text{n}} \) might be referred to the possibility of impurity accu-
mulation due to \( E_r < 0 \) (see e.g figure 3.5) that increases the impurity density
to be out of the assumed trace impurity limit.

### 4.1.2 Electron root case

A similar analysis of the ion-root discharge has been carried out to the electron-
root discharge \#45477 \( \equiv \#45482 \) with profiles shown in figures (3.4,3.5) and
summarized in table (4.1). EUTERPE calculation of \( \alpha_{n_z} \) \(^2\) at the toroidal plane
of the SXR system with angle \( \phi = 14.5^\circ \) is shown in the figure 4.5 for three
different impurity charges \( Z_I = 6, 10 \) and 20. It shows a higher variation on the

![Figure 4.5: Numerical results for \#45477: the normalized asymmetry parameter of the impurity density \( \alpha_{n_z} \) considering \( \Phi_1 \) for three charges \( Z_I = 6, 10 \) and 20 from left to right at the SXR toroidal plane(\( \phi = 14.5^\circ \)).](image)

\( \alpha_{n_z} \)

\( Z_I = 6 \quad Z_I = 10 \quad Z_I = 20 \)

<table>
<thead>
<tr>
<th>( Z_I = 6 )</th>
<th>( Z_I = 10 )</th>
<th>( Z_I = 20 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha_{n_z} )</td>
<td>( \alpha_{n_z} )</td>
<td>( \alpha_{n_z} )</td>
</tr>
</tbody>
</table>

![Figure 4.6: Numerical results for \#45477: the normalized asymmetry parameter of the impurity density \( \alpha_{n_z} \) considering \( \Phi_1 \) for three charges \( Z_I = 6, 10 \) and 20 from left to right at the Bolometery toroidal plane(\( \phi = 75.5^\circ \)).](image)

\( \alpha_{n_z} \)

\( Z_I = 6 \quad Z_I = 10 \quad Z_I = 20 \)

<table>
<thead>
<tr>
<th>( Z_I = 6 )</th>
<th>( Z_I = 10 )</th>
<th>( Z_I = 20 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha_{n_z} )</td>
<td>( \alpha_{n_z} )</td>
<td>( \alpha_{n_z} )</td>
</tr>
</tbody>
</table>

\(^2\)The definition of \( \alpha_{n_z} \) is defined in detail at the previous subsection ion-root case.
outer region, the variation is larger than the average at the bottom region and below the average at the top region. The variation increase with the charge until it reaches 35% at the core for $Z_I = 20$ while 15% for $Z_I = 6$. Figure (4.6) represent the $\alpha_{nx}$ for the three different charges $Z_I=6, 10, 20$. It shows a higher variation on the outer and the core regions in comparison to the middle region. The upper region shows more positive variation while the lower part represents negative variation. The indirect measurement of the $\Phi_1$ that intro-

![Image](image.jpg)

**Figure 4.7: Experimental results for #45477:** left and right represent the SXR and Bolometry respectively. (a,d) represents the symmetric radiation part without $m=0$ while (b,e) is the asymmetric radiation with poloidal modes $m>0$ up to 3, and (c,f) represents the $\alpha_{rad}$ that is going to be compared with $\alpha_{nx}$ due to $\Phi_1$

roduces impurity density asymmetry is explained in the ion root subsection. The same methodology has been employed for the electron-root discharge #45477.
Ne trace gas has puffed to the experiment at t=1100 ms and it has selected because Ne isn’t exist in plasma and this guarantees the sureness of the impurity type in the plasma. The radiation background has been subtracted to focus one the radiation from Ne trace since theoretical approach consider the trace approximation. The reconstructed radiation maps from the SXR and Bolometry are shown in figure 4.7 on the left and right column respectively. The reconstruction of radiation poloidal symmetric part considered modes m=0 in the Tomography-code while the poloidal asymmetry has reconstructed by considering m=1, 2 and 3 where the SXR and Bolometry has three cameras. The m=0 shown in figures 4.7(a,d) represents the symmetric average radiation on each flux surface and m=0 up to three sown in figures 4.7(b,e) represents the poloidal symmetric part in addition to the variation that breaks the symmetry. The normalized variation of the radiation on each flux surface $\alpha_{rad}$ has been calculated by subtracting the former (m=0) from the latter (m>0) and then dividing by the former (m=0). This $\alpha_{rad}$ is shown in figures 4.7(c,f) for SXR and Bolometry respectively. The simulated $\alpha_{nz}$ shows asymmetry order

![Radiation Maps](image)

**Figure 4.8: Numerical vs Experiment #45477:** (a,b) represent $\alpha_{nz}$ and $\alpha_{rad}$ respectively at the SXR toroidal plane. (c,d) represent $\alpha_{nz}$ and $\alpha_{rad}$ respectively at the Bolometry toroidal plane. Note the numerical scale between ±0.38 while the experimental scale is between ±0.9 which are comparable. Since Ne is the puffed trace impurity, the numerical results in (a,c) has considered $Z_I = 10$ assuming fully ionization of Ne on the whole effective radius.
range ±40% while the reconstructed $\alpha_{rad}$ recorded asymmetry range ±90%. Apart from the asymmetry order, one can still observe partial agreement in the patterns at the outer upper region at the SXR while at the lower right part with $R>1.35$ m, $Z<0.15$ m for the Bolometery but with opposite sign. The discrepancy between the numerical calculations and the experimental measurements at some regions could be explained by referring to (i) the decreasing of the impurity confinement time with ECRH power in TJ-II that reaches $\sim 4$ ms at the used ECH power 0.4 MW (see e.g table (4.1) and [34]) which comes with the increase of the modulus of $E_r$ that expulses the impurities and then weakness the analyzed signal, (ii) the radiation increases with the peak density square that $\sim 0.58 \times 10^{19}$ m$^{-3}$ for the ECRH plasma #45477 that is 4 times less than the NBI plasma in the discharge #45469. This can be solved in the future by constructing the TS profile at an instance after $\sim 2$ ms from the impurity puffing to make the simulation more relevant for the comparison with the SXR and the Bolometery reconstruction.

4.2 Influence of $\Phi_1$ on the impurity transport

This section presents the influence of the flux surface electrostatic potential variation $\Phi_1(\theta, \phi)$ on the surface-averaged radial particle flux of some selected impurities $C^{6+}$, $Fe^{10+}$ and $W^{20+}$. The comparison has been carried out in the ion root discharge #45469 with the profiles in figures 3.3, 3.2 and summarized in the table (4.1). The impurity trace approximation is considered since the density is five order of magnitude less than the bulk species density and the linearized-ion collision operator equation (2.17) has been considered, in EU-TERPE for the first time, to count the parallel friction force exerted by ions on the impurity [21]. It is important to note that the surface-averaged radial flux

![Graph](image-url)
(\(\mathbf{\Gamma}_Z \cdot \nabla r\)) is mass and charge dependent so, it is important to know the used atomic masses for the C\(^{6+}\), Fe\(^{10+}\) and W\(^{20+}\) are 12, 56 and 138 respectively. Figure (4.9(b)) shows the profiles with \(\Phi_1\) that have significant increase in the inward transport at the middle region \(0.2 < r/a < 0.6\) from excluding the \(\Phi_1\) in figure (4.9(a)). The negative peak increased by 60% for the C\(^{6+}\) with lower atomic mass 12 while 10% for the W\(^{20}\) whose atomic mass 183. Increasing of the transport profiles peaks supposed to reduce the impurity density in this region forming a hole in the density profile. This result is consistent with the results for the LHD simulation using SFINCS code\(^{[35]}\) and might be a preliminary results toward better theoretical understanding of the impurity hole formation in the LHD\(^{[27]}\).

4.3 Impurity-ion collision operator

The usual used pitch-angle scattering collision operator in equation\((2.16)\) that neglects the impurity-ion parallel friction force which has been considered in the linearized ion collision operator that is linearized to the mass ratio parameter \(\sqrt{m_i/m_Z} \ll 1\) where \(m_i\) and \(m_Z\) refers to the ion and impurity species mass. For the first time the latter collision operator has been employed in EUTERPE to be tested. Impurity-ion collision counts the increasing of the parallel velocity due to the parallel impurity-ion friction, implicating decreasing of the radial transport. Figure (4.10(b)) represent the the transport profile considering the linearized impurity-ion collision operator that shows a decreasing in the profile peak by 9% for C\(^{6+}\) and 25% for W\(^{20}\) from the pitch-angle approach at figure (4.10(a)). On the other hand, it doesn’t show much difference with excluding \(\Phi_1\) as shown in figure\((4.10(c))\) and \((4.10(d))\).
Figure 4.10: The surface-averaged impurity radial flux for the ion-root discharge # 45469 considering the pitch-angle scattering collision operator on the left and the linearized impurity-ion collision operator on the right. The top figures (a,b) excluding the $\Phi_1 (r, \theta, \phi)$ while the bottom figures (c,d) include the $\Phi_1 (r, \theta, \phi)$. 

(c) w/o $\Phi_1 (r, \theta, \phi)$ - Pitch-angle 
(d) w/o $\Phi_1 (r, \theta, \phi)$ - Ion-impurity collision
4. Results and discussions
Fusion energy is a promising safe energy source with available fuel facing few technology challenges under research and development. Stellarator is a potentially competitive magnetic confinement device due to its steady state operation but the magnetic ripple complicates its transport problem. Ion root regime with inward radial electric field is predicted for the fusion reactor parameters in which the impurity implicate to accumulate. The 3D magnetic field introduce different magnetic and $E \times B$ drift that produce a 3D electrostatic potential whose dependence on the poloidal and toroidal coordinates $\Phi_1(\theta, \phi)$ requires solving the quasineutrality. The influence of this departure on the impurity radial flux has been investigated considering the linearized impurity-ion collision operator (expansion parameter: $\sqrt{m_i/m_Z} \ll 1$) in TJ-II. Increasing in the inward transport peak by 60% for C$^{6+}$ and 10% for W$^{20+}$ of the inward flux has observed in EUTERPE simulation which is consistent with the recent simulation by SFINCS for the LHD plasma (see e.g A. Mollén et al., PPCF 2018). The visibility of the indirect measurement of the $\Phi_1(r, \theta, \phi)$ through comparing the density asymmetry parameter $\alpha_{nz}$ and the radiation asymmetry parameter $\alpha_{rad}$ at any toroidal plane has been investigated and applied for the SXR and Bolometery. This method can works as a testing bed for the numerical approaches aims the calculation of the non-constant electrostatic part. The ion root and the electron root cases have shown partial agreement between $al_{nz}$ and $\alpha_{rad}$ pattern with difference in the ranges by $\pm 40\%$. Neglecting the effect of the kinetic electrons which is large in TJ-II for the ion-root and even larger for the electron-root, the variation of impurity charge along the effective radius and the non-stationary profiles for NBI plasma can be a source of the discrepancy between $\alpha_{nz}$ and $\alpha_{rad}$ at some regions and should be considered for future studies. The discrepancy might be explained by the low confinement time of the impurity and the low central electron density in The ECRH plasma. Few modification are being considered for future to enhance the numerical results by considering the charge state distribution along the effective radius, considering earlier profile during the impurity confinement time for the electron root case with the ECRH plasma, considering the electron kinetic contribution in $\Phi_1$ and better estimation for the ion temperature profiles.
The linearized ion-impurity indicates a slight deviation from the pitch angle collision operator with $\Phi_1$, but has no influence with excluding the $\Phi_1$. 
Bibliography


Acknowledgements

This work is part of the EUROfusion work package S1 activity WP18.S1.A1 that offers the CPU hours of the entire work via MARCONI (EUROFusion) and MARENostrum (Barcelona Super Computing). The author receive the fund from the European Omission represented by EACEA under Erasmus+ Fusion-EP.

I would like to thanks specially to my supervisor Dr. Jose Manuel García Regaña who has devoted his valuable time and experience for guiding me through the thesis by referring to the proper literature, answering questions, demonstrating the new concepts patiently, reviewing the manuscript with valuable comments and introducing me smoothly for two high performance computing facilities MARCONI (EUROFusion) and MARENostrum (Barcelona Super Computing) to enable the delivery of the thesis at the proper time. In addition, his continues guiding to cooperate with other groups in CIEMAT, and I can’t forget to apologize for always disturbing during weekends that meet by all pleasure from his side.

I would like to thank CIEMAT people who helped me: firstly Dr. Boudewijn van Milligen the owner of Tomography-code at TJ-II for his continued support during the code adapting and his useful comments and discussion until getting the useful results for a month, secondly Dr. Paco Medina for his useful discussion on TJ-II database and technicality of the Bolometry and Soft X-Ray systems, thirdly Dr. Alvaro Cappa for providing the heating scenarios and the useful comments, fourthly Dr. Mariana Ochando for providing the calibration factors for Bolometry system and last but not least Dr. Teresa Estrada for providing the ambipolar electric field radial profiles.

I would like to thank Fusion-EP committee especially the secretary Mr. Frank Janssens for his administration since September 2015, my teachers at Stuttgart University, KIT and UC3M-Madrid, and an especial thanks to Dr. Jan Joracek from IPP, Prague and I would like to thank all my professors and teachers in Physics Dept., Mansoura University Egypt for continues support during the undergraduate and postgraduate studies.

I would like to thank my big family for encouragement and continues support through eighteen years of study. In particular, I would like to thank my Father Mr. Ezzat for his friendship and continues moral and ethics support through profitable discussion since my childhood, my mother Mrs. Asmaa for continues love, care and offering prosperity for my live, my brother Dr. Ehab for his
fruitful discussion that motivates me along the way and my brother Mr. Fathi and sister Manar for moral support and love.

I would like to thank my wife Tofy, the queen of my new family, for offering a calm climate, proper study environment, and love during the two years of MSc in Stuttgart and Madrid. I consider her as a co-owner of this thesis and my achievement since we have married, and all thanks to her parents Mr. Mostafa and Mrs. Boshra who growing her moral and ethic values.

...
Declaration in lieu of oath

Herewith I declare in lieu of oath that I have prepared this thesis exclusively with the help of my scientific teachers and the means quoted by them.

City, the

Mohamed Ezzat Fathi Mohamed Mostafa

Copyright Agreement

I hereby grant the FUSION-EP consortium the non-exclusive right to publish this work.

I declare that this work is free of copyright claims of third parties.

City, the

Mohamed Ezzat Fathi Mohamed Mostafa