POLITECNICO DI TORINO

Corso di Laurea Magistrale
in Sustainable Nuclear Energy

Nuclear Fusion Reactor Physics

Power Exhaust Modeling Project
Case 1

Professor
Fabio SUBBA
Haosheng WU

Student
Federico PATI s328987

2023/2024

Introduction

To realize controlled nuclear fusion plants, one of the biggest challenges is reducing the power flux on the plasma-facing components, such as the divertor targets. Achieving this goal remains an open question, but detachment presents a potential solution. When detachment occurs, there is a significant reduction in the flux of particles and power onto the target. Numerical tools for Plasma Exhaust (PEX) modeling are essential for studying this phenomenon. SOLPS-ITER is one of the most verified and validated codes for this purpose.

In this project, we will analyze data from numerical simulations conducted with SOLPS-ITER for a D+Ne case. Using MATLAB, we will evaluate important parameters and discuss divertor operation regimes.

Mesh

In SOLPS-ITER, quadrilateral elements are used for the plasma mesh, while triangular elements are used for the neutral particles (see Figure 1a). A topologically equivalent rectangular grid is constructed by cutting the grid in the bottom part, unfolding it, and distorting it, as illustrated in Figure 1b. The domain size is 98x38, including two additional guard cells considered for better representation.

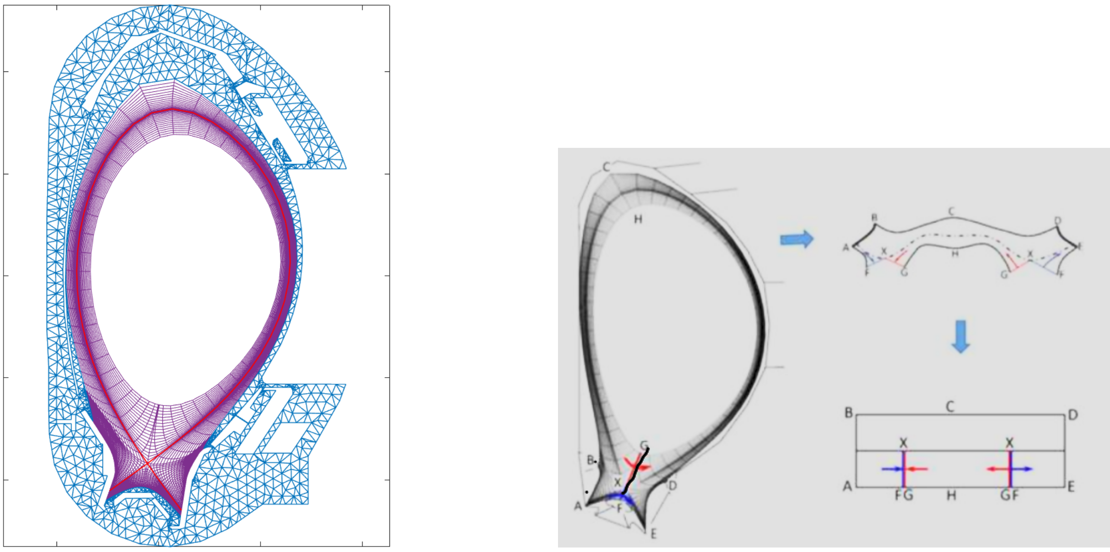

Figure 1: (a) Mesh in SOLPS-ITER. (b) Rectangular grid (S.I. Krasheninnikov Journal of Plasma Physics 83)

Integral Particle Flux

The first objective of this project is to evaluate of the integral particle flux for D+ and Neon ions in various regions: at the inner divertor entrance (IDE), inner divertor target (IT), outer divertor entrance (ODE), outer divertor target (OT), core boundary (CB) and separatrix (core-sol interface). Specifically, only D+ ion will be considered for deuterium, while the contribution of all ten ions up to Ne10+ will be considered for neon.

Assuming not relevant for the study the sign of the fluxes, the absolute values of the results are summarized in Table 1 below:

	D+ ion flux [s^{-1}]	Neon ion flux [s^{-1}]
IT	2.0751e23	4.6097e21
OT	2.9317e23	5.2337e21
IDE	4.5116e21	5.2544e20
ODE	7.8535e21	3.5484e20
CB	1.3008e21	2.5654e19
SEP	2.8775e21	5.8914e19

Table 1: Integral ion fluxes

It is noteworthy to observe that the D+ fluxes at the targets are two orders of magnitude higher than the values at the divertor entrance. This observation could be explained by considering that ions striking the wall recombine into neutral atoms, which are then released back and ionized very close to the wall.

The particle flux hitting the target is no directly related to the particle flux leaving the confined plasma. In fact, the particle balance of the whole system is completely concentrated in the thin region close to the target, where ionization of the recycled neutrals seems to be the dominant particle source. For this reason, the first hypothesis of regime operation might be detachment or conduction-limited regime, also called high-recycling regime.

Power Flux

To proceed with the analysis, the power flux will be evaluated in the same regions of interest of the previous point. In this case, In this case, the power fluxes deposited by ions and electrons are considered. As before, the absolute values of the results are summarized in Table 2 below:

	Electron Flux [MW]	Ion Flux [MW]
IT	0.2871	0.1426
OT	0.7066	0.4597
IDE	9.1302	1.0441
ODE	13.5765	1.8540
CB	18.0359	12.0675
SEP	18.7434	8.3419

Table 2: Power fluxes for electron and ions

It is worth to notice that the power flux at the targets is lower than at the divertor entrances. Considering the results of the previous point, it is seems reasonable to assume that could be due to radiative recombination and ionization. The reason why recombination removes power is that radiation is emitted isotropically, hence the power flux is spread in every direction, not focusing only on the target.

1D profiles

Due to the presence of plasma instabilities, turbulence, and complex geometry, a three-dimensional analysis may be necessary to fully understand the behavior of the system. However, even from a simpler one-dimensional (1D) model, valuable insights about trends of important parameters can be gained.

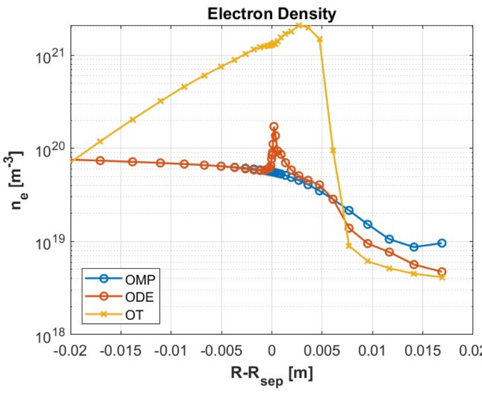

Figure 2: Electron Density

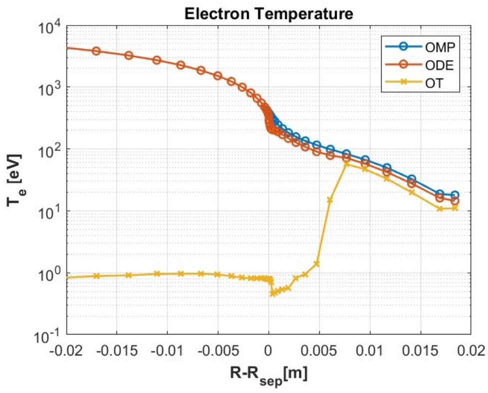

Figure 3: Electron Temperature

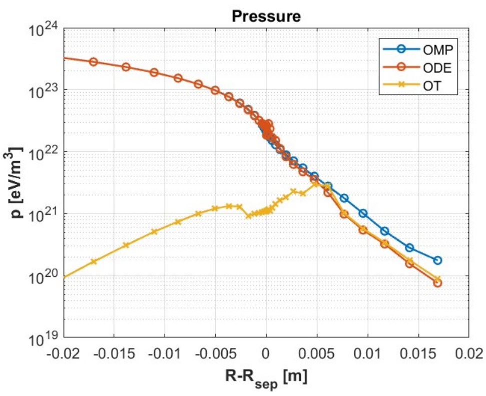

Figure 4: Pressure

Looking at Figure2, some interesting observations can be drawn. Firstly, at the separatrix, for the ODE and for the OT, there is a peak in density, which can be attributed to the higher confinement of magnetic forces. Additionally, at the separatrix, the density at the outer divertor target (OT) is significantly higher than in the other region. This is consistent with the earlier discussion on ion fluxes. Since after recombination they ionize really close to the target, it seems reasonable to have also a higher density of electron as well as ions.

Regarding what happens before and after the separatrix, a parallel analysis could be conducted for both the electron density and temperature (in Figure 3). In both the graphs is clear that moving radially outward the quantities decrease strongly. This reduction can be attributed to the expansion and cooling of the plasma, as it becomes less confined and particles diffuse radially due to plasma drifts and turbulence. On the left of the separatrix, could be pointed out two different behavior for the ODE and OMP compared to the OT. While a relatively regular behavior is represented for the former two, there is a sharp drop in density and temperature at the outer target. A reasonable explanation is that there, in the private flux zone, happened most of the recombination and is fed of electrons only by cross-field transport across the separatrix,

The pressure (as shown in Figure 4), depends on the two previous quantities and is computed as follow: For the pressure at the outer divertor entrance and at the outer middle plane, it is calculated as the product of the electron density and the electron temperature at that position. While the pressure at the outer target is twice that product evaluated on the target plate.

Power Flux Density

As anticipated at the beginning of this project, one of the biggest engineering challenges of a stable fusion reactor is the ability to manage the huge power flux on the target. Presently, current technologies limit power dissipation to $\approx 10MW/m^2$. In Figure 5, it is clear that the power flux density at the target is significantly smaller than the value at the divertor entrance. While this reduction is desirable, it is still insufficient: he data from this graph also indicates that the power at the target remains higher than the engineering limit.

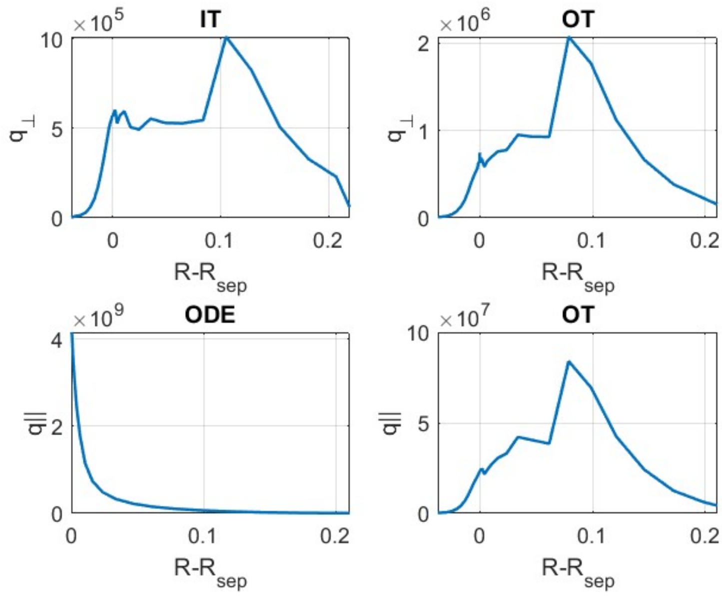

Figure 5: 1D Power Flux

2D plots

After the discussion on 1D profiles, undoubtedly the representation of some 2D distribution could be a matter of interest.

In Figure 6, 7, 8 are shown the 2D distribution of particle sources for D+, Ne+ and Ne5+. These plots provide a further validation of the previous argument. We can notice high positive and negative values:

- The first one, colored in dark red, represents the ionizations of the recombined neutrals, and are more relevant close to the target especially for D+;
- The negative values, colored in blue, represents the recombination, a sink for the ions.

Furthermore, focusing mainly on the D+ distribution, the graph is consistent with the temperature profile of the electrons.Recombination occurs where $T_e \lesssim 1eV$, such as on the separatrix and its left side, while ionizations dominate on the right side where the temperature peaks.

In Figure 9 is depicted the distribution of line radiation, considering all the Neon ions. Line radiation contributes to redistributing part of the incoming power to the surrounding walls, as radiation is emitted almost isotropically. As expected, the radiation is higher near the targets, where recombinations happen.

Finally, Figure 10 and 11 show the 2D distribution of neutral particle density for D, D_2 and Ne. Here again, we can verify the coherence of what was said. In fact, the density of neutrals is higher where recombinations occur, hence in the colder region. This zone coincides almost entirely with the private plasma region, where temperatures are below 1 eV. Outside this zone, high temperatures ionize neutrals almost immediately.

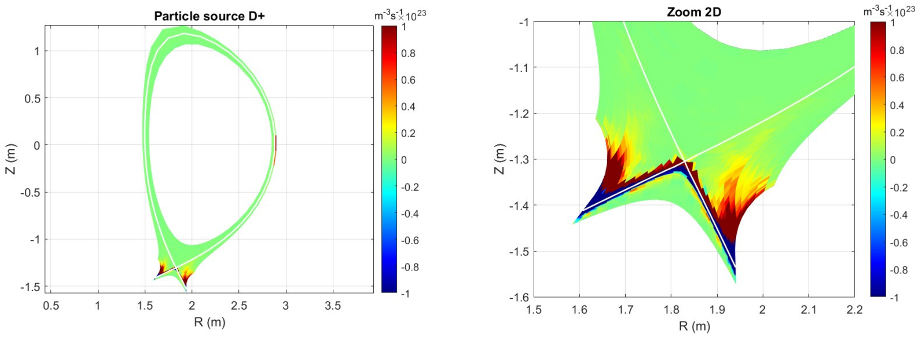

Figure 6: 2D distribution of D+ source

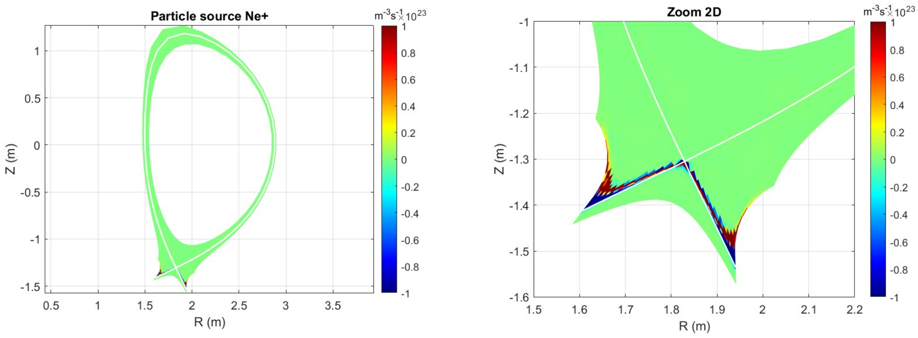

Figure 7: 2D distribution of Ne+ source

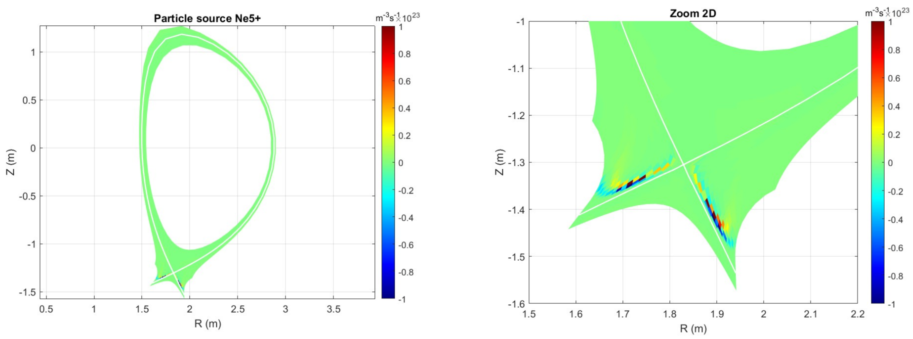

Figure 8: 2D distribution of Ne5+

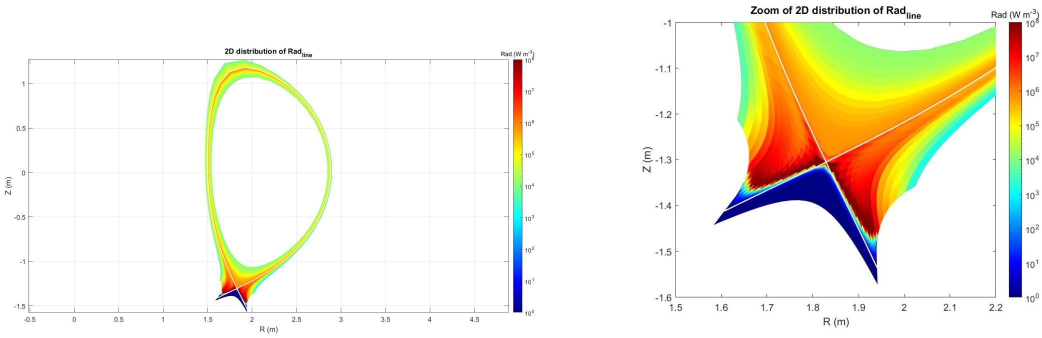

Figure 9: 2D distribution of line radiation

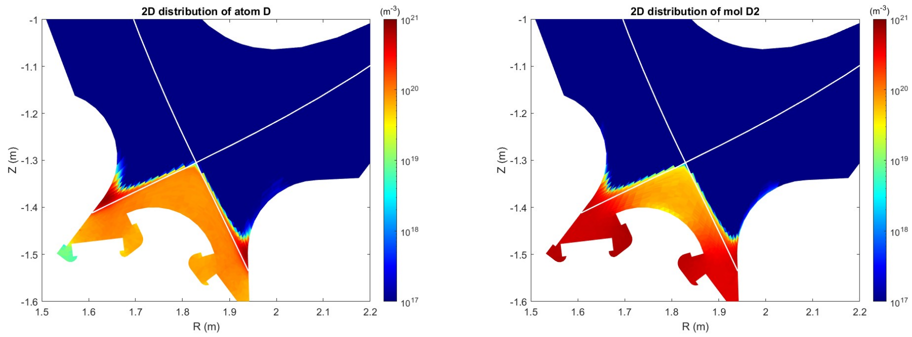

Figure 10: 2D distribution of D (a) and D2 (b)

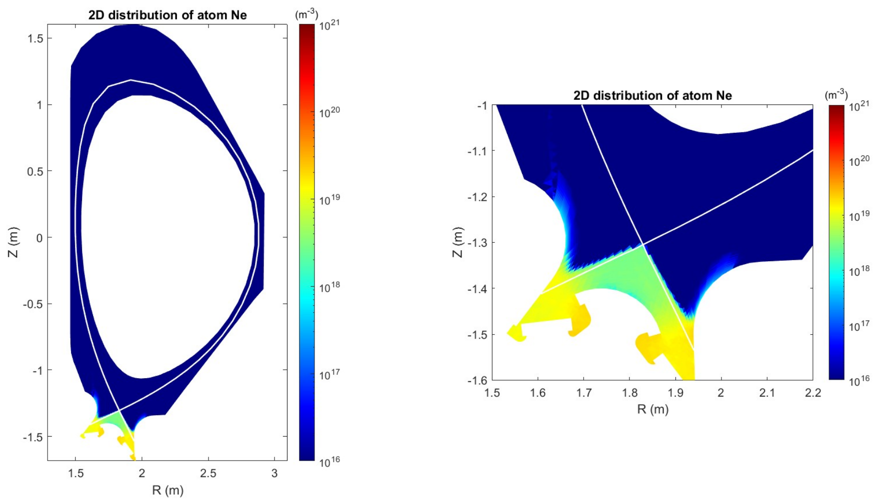

Figure 11: 2D distribution of Ne (a) and zoomed detail (b)

Divertor regime

Considering all the previous analysis and adding also the electron density and temperature along a flux tube in Figures 12 and 13, it is finally possible to define the divertor regime.

- First of all, it is clear that it isn't a **sheath-limited regime**. It has already been shown that we have high recycling and in Figure 13 can be observed that electron temperature is definitely not constant along flux tubes, for those reasons that regime could be excluded.
- The **conduction-limited regime** is more similar to this case: a temperature gradient along the magnetic field lines from upstream to target arises, and ionization is the dominant particle source. Nevertheless, some fundamental features of this regime are not present in this case, such as the constant pressure along the flux tubes and an increasing trend of electron density at the target. Hence, also this regime is discarded.
- The **detachment** regime fits better to the case described until now: not only large temperature gradient along each flux tubes and high recycling, but also a substantial pressure loss and a significant reduction heat flux. Moreover, not considering a total detachment because of the relatively high density at the target and high heat flux. However, the strong reduction of pressure and temperature for several power decays length, suggest the pronounced detachment rather than partial.

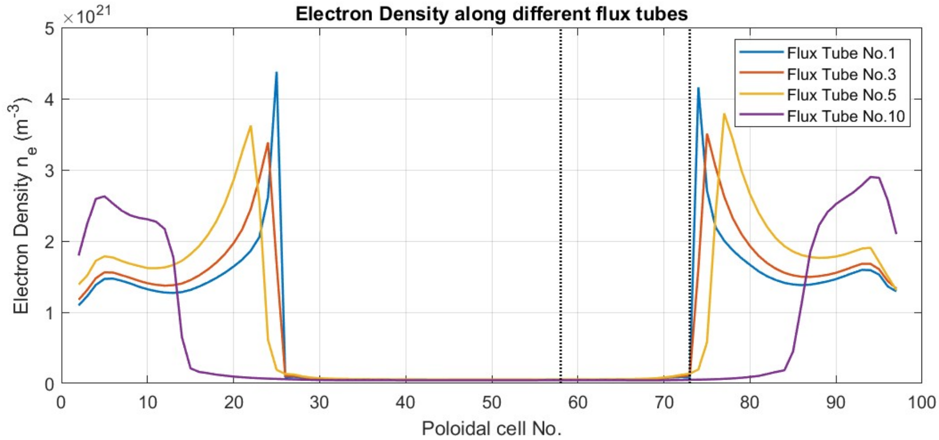

Figure 12: Electron density along flux tubes

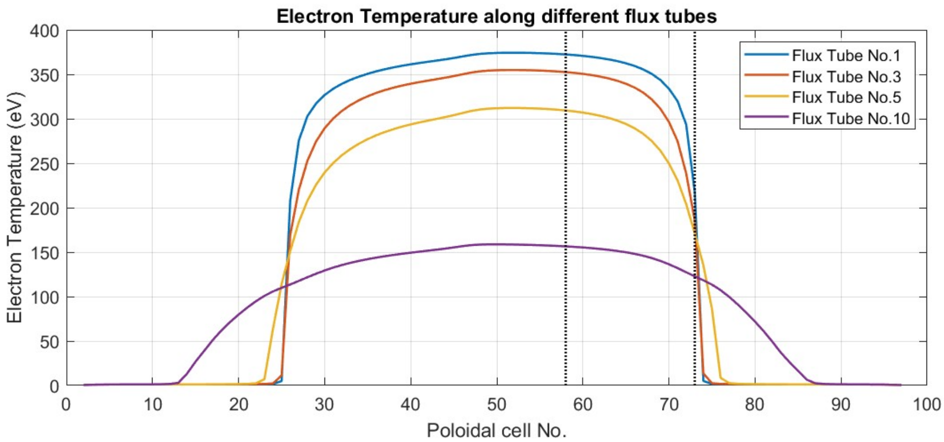

Figure 13: Electron temperature along different flux tubes