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Analysis of Heat and Particle Flows in the Scrape-Off Layer of a Field-Reversed Configuration

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Summary:

Plasma in the scrape-off layer (SOL) of a field-reversed configuration (FRC) was simulated in one dimension, using UEDGE. The goal was to understand the conditions upon which plasma detachment would occur, in order to better analyze plasma confinement mechanisms and the management of heat deposition. Specifically, the idea of a dense, neutral "gas blanket" was considered as a means for reducing power flux to the outer divertor region, by redistributing the heat flux over a larger surface area[1,2].

By varying rates of gas injection and power levels, it was observed that higher rates of gas injection, at fixed power input, corresponded to an overall drop in the maximum plasma temperature (of the SOL). This observation was further explored, and it was found that detachment-like behavior was associated with higher rates of gas injection. Specifically, the plasma temperature and plasma density would sharply drop near the divertor target, at the end of the axis.

At higher power levels, the overall maximum plasma temperature of the SOL was increased. However, for higher power levels, lower gas injection rates were required to observe detachment-like behavior. It can therefore be potentially concluded that at higher power levels, it may be proportionally easier to detach hot plasma in the FRC.

Motivation:

In a standard divertor scheme, the exterior region of a confined plasma- the scrape-off layer (SOL)- impinges on a collector plate (Hsu, Yamada), in the process depositing excessive power and heat. For example, in a system such as ITER[2], it is expected that these loads may rise to the order of 50 MW/m^2. These severe fluxes to the collector plate lead to erosion, sputtering, and heat load problems[1, 2, 3]. These issues not only damage the confining structure, but also lead to the undesirable introduction of impurities into the plasma.

In order to circumvent this problem, the idea of a gaseous divertor has been suggested[1, 2]- the idea being that the detrimental, localized heat deposition can be largely mitigated by a "neutral gas blanket," which redistributes the plasma energy over a larger surface area. Specifically, it has been experimentally observed that a flowing stream of plasma can be terminated without touching a material wall (Hsu, Yamada), and moderate neutral gas pressures have been shown to reduce the plasma temperature by more an order of magnitude, and plasma densities by several orders of magnitude[2].

With this past work in mind, potential applications to the FRC configuration are still to be explored, in order to make the device better suited for fusion reactions.

Model:

Mesh:

The scrape-off layer of the plasma was simulated using the UEDGE multi-fluid code [4], adapted for one dimension. In order to be consistent with the idea of a 1D simulation, the cylindrical geometry of the FRC was modified to that of a slab geometry, with a computational mesh (of the SOL) in the y-z plane[5]. For reference, the major axis of the FRC was along the z-axis. To that end, there was no variation considered in the x or y directions of the FRC. In order to normalize the 1D case, the code assumes that the slab is 1m thick in this x-direction.

In this y-z plane, despite the one-dimensional aspect of the simulation, there are 3 radial cells in the y direction, and a variable number of cells in the z direction. This setup corresponded to a main row of central cells, bounded on all sides by a perimeter of guard cells. The purpose of these guard cells is numerical: they are used to set radial flux boundary conditions, and to simulate the injection of power and/or particles into the system. The number of cells in the z direction, along the length of the row, was variable, and therefore provided a means by which the resolution of the simulation could be controlled. For these observations, 128 cells were simulated along the z-axis.

The main row (in the z direction) extended from two main axial boundaries of the FRC, simulating a closed end of the FRC and an open end of the FRC through which the high-speed exhaust passes. This configuration is highly suitable for a propulsory application, such as a rocket engine.

Parameters:

A plasma column of radius 0.01 m was simulated, in the presence of a constant axial 0.5 T magnetic field. The FRC was 2 m long.

Energy was volumetrically added to the system, via heated electrons. Ions were not heated for volumetric power addition, as this electron-specific type of heating is expected from the slowing-down of fusion products. This power injection was not uniform along the axis, in order to match the realistic condition that power could only be input through a boundary. The power in the cells varied as a Gaussian along the axis, with the center at the axial boundary of the FRC. The half-width of this Gaussian was set at 0.125 m. This power input was tuned, generally on the scale of 1 to 15 MW, in order to better understand the different conditions under which plasma detachment would occur.

Neutral gas injection was also simulated, with values ranging from approximately 1 to 50 equivalent-amps (the neutral analog of electric current amps). These values were tuned in order to see varying plasma behavior near the boundary.

Methodology:

In order to look for evidence of plasma detachment, simulations were run with variable power inputs and neutral gas flow rates. As a precipitous drop in plasma temperature is illustrative of plasma detachment, the electron temperature was recorded, as it was assumed that the electron temperature would be indicative of the plasma temperature. For these measurements, the plasma was considered approximately detached if the minimum plasma temperature was less than 10% of the maximum plasma temperature. Plasma density was also recorded, in order to better examine the density decrease characterized by detachment.

Additionally, in order to consider the gas-blanket effects on plasma detachment, the neutral gas density and pressure were recorded, in order to see if there were correlations between neutral gas density and/or pressure, and the temperature drop.

In order to determine the relationship between (1) the power input, and (2) the corresponding gas injection rate required to lower the plasma temperature by a certain proportion, trends were compared to the **ratio** of (1) and (2). This allowed for the comparison of data obtained at different power levels or gas flow rates. Additionally, the aforementioned variables (electron temperature, neutral gas density, etc.) were subdivided into groups according to the power input. This made it possible to see if different proportions of gas flow rate/power input were required at different power inputs, for the same temperature drop.

Results:

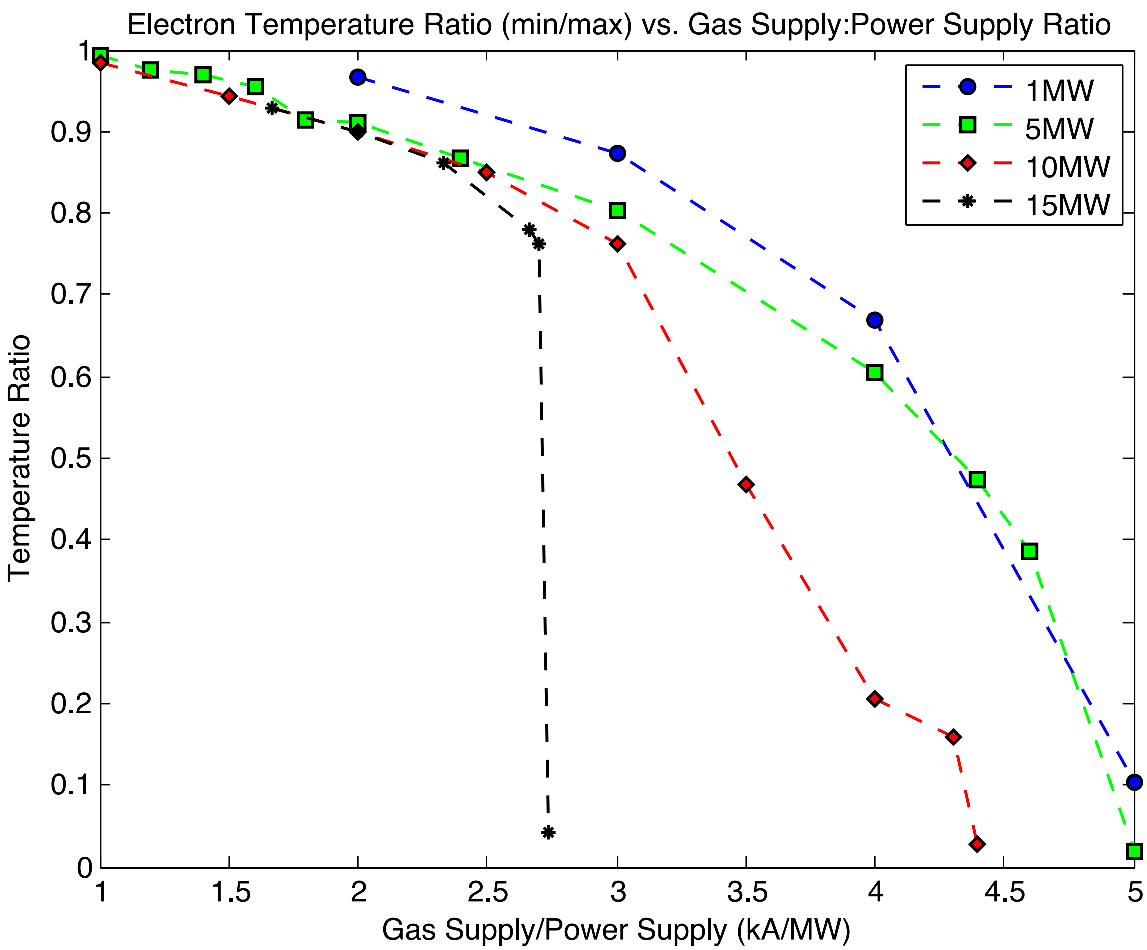


Figure 1: Illustrating the relationship between the ratio of the minimum and maximum electron temperatures, and the ratio of the gas flow rate and power input. Different markers indicate the trends for given power input values.

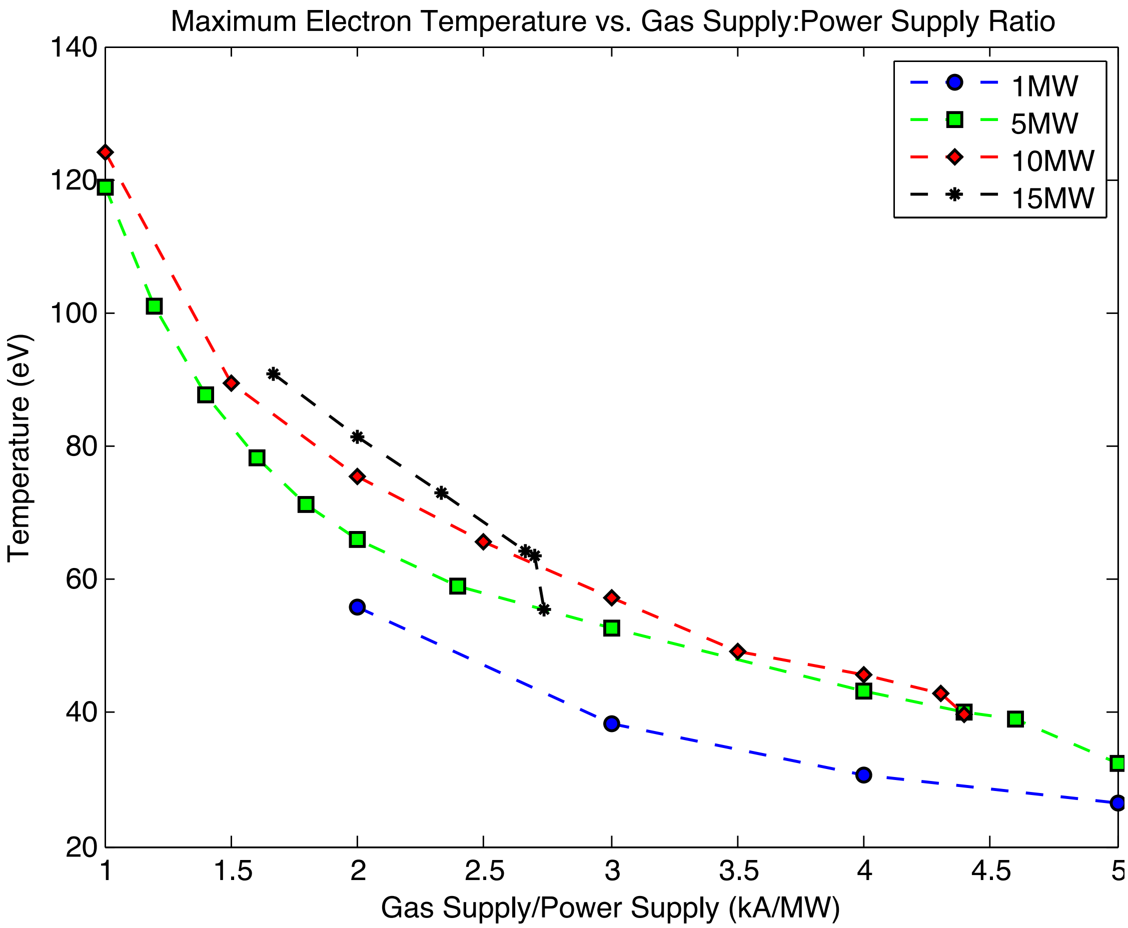


Figure 2: Showing maximum SOL electron temperature at various ratios between the gas flow rate and power input. Different markers indicate the trends for different power input values.

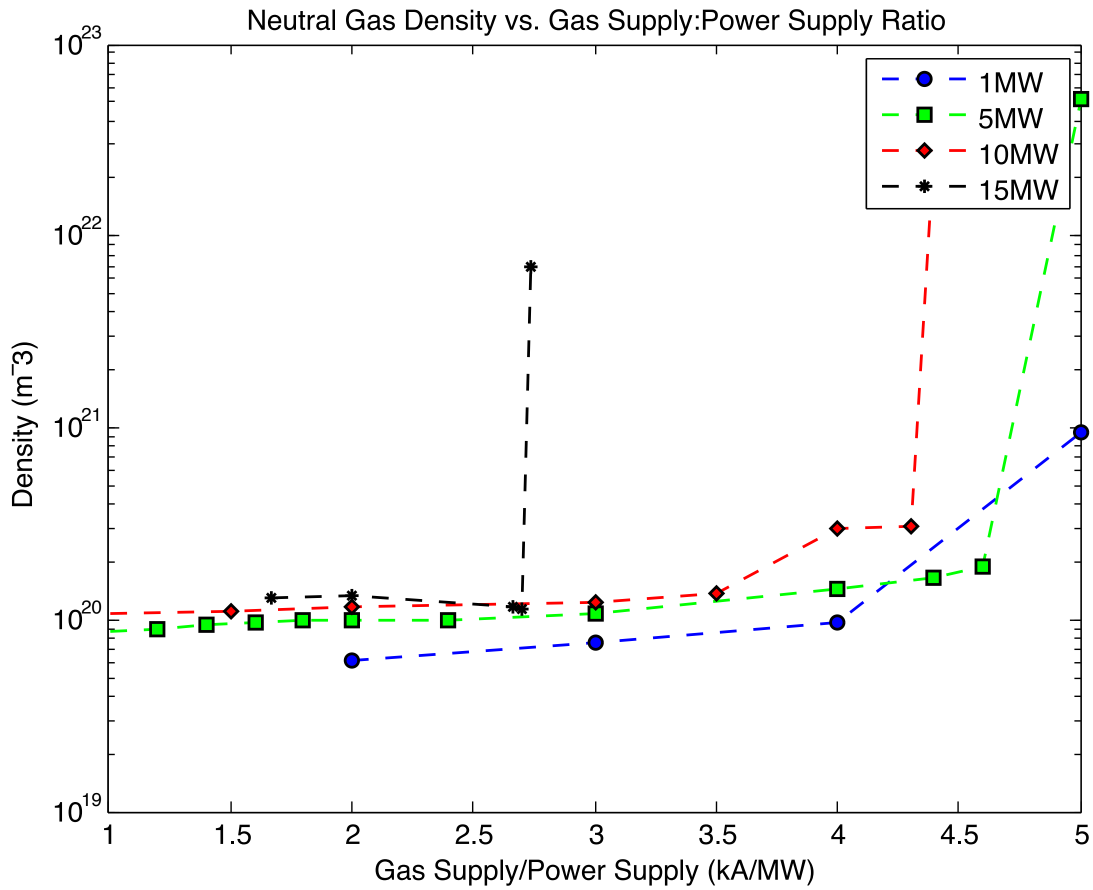


Figure 3: Showing neutral gas density at various ratios between the gas flow rate and power input. Different markers indicate the trends for different power input values.

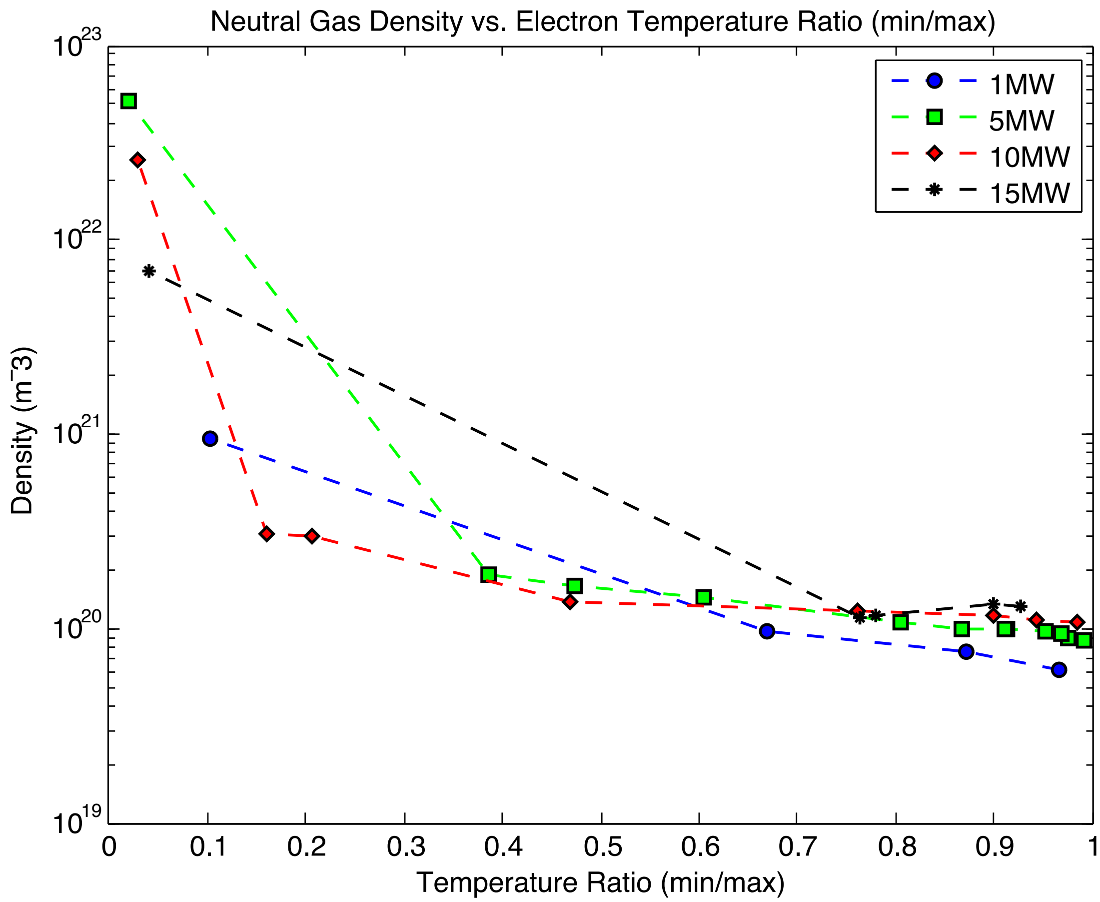
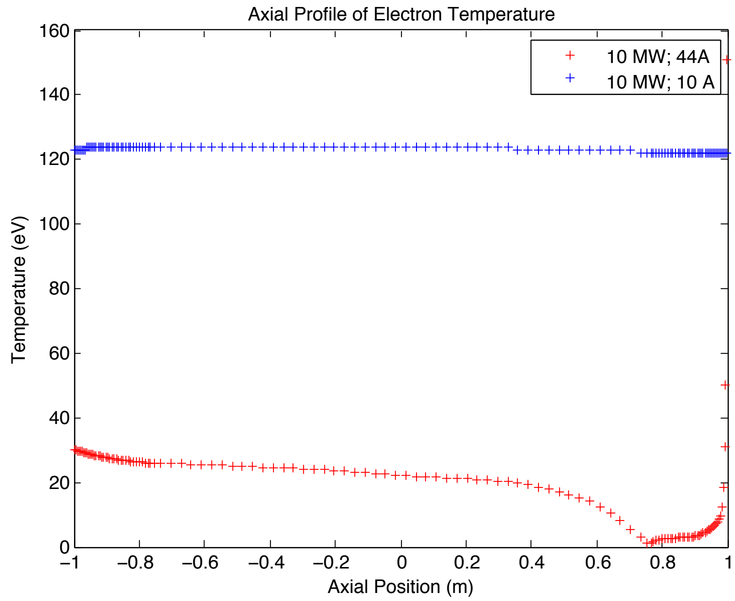


Figure 4: Showing the neutral gas density at various ratios between minimum and maximum SOL electron temperatures. Different markers indicate the trends for different power input values.

(a)



(b)

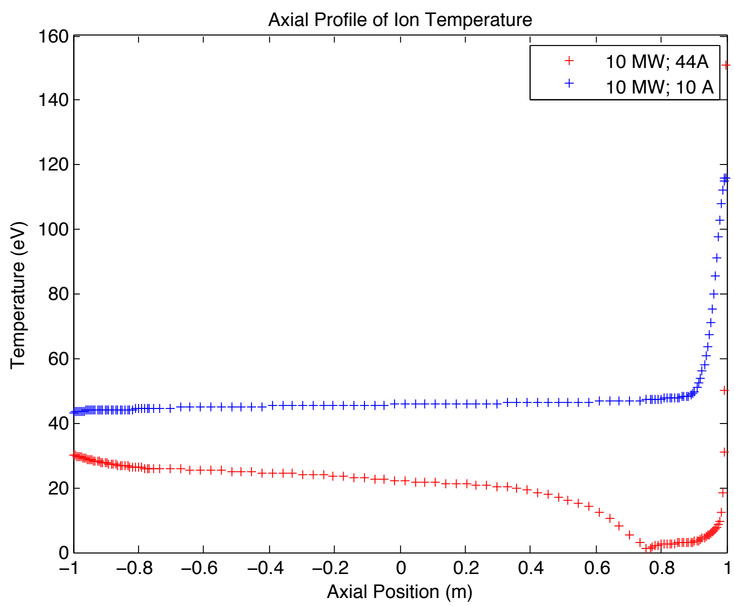


Figure 5: Showing the axial profiles of (a) electron temperature, and (b) ion temperature. Cases are shown to compare potentially detached (10MW, 44 A) and attached (10 MW, 10 A) scenarios.

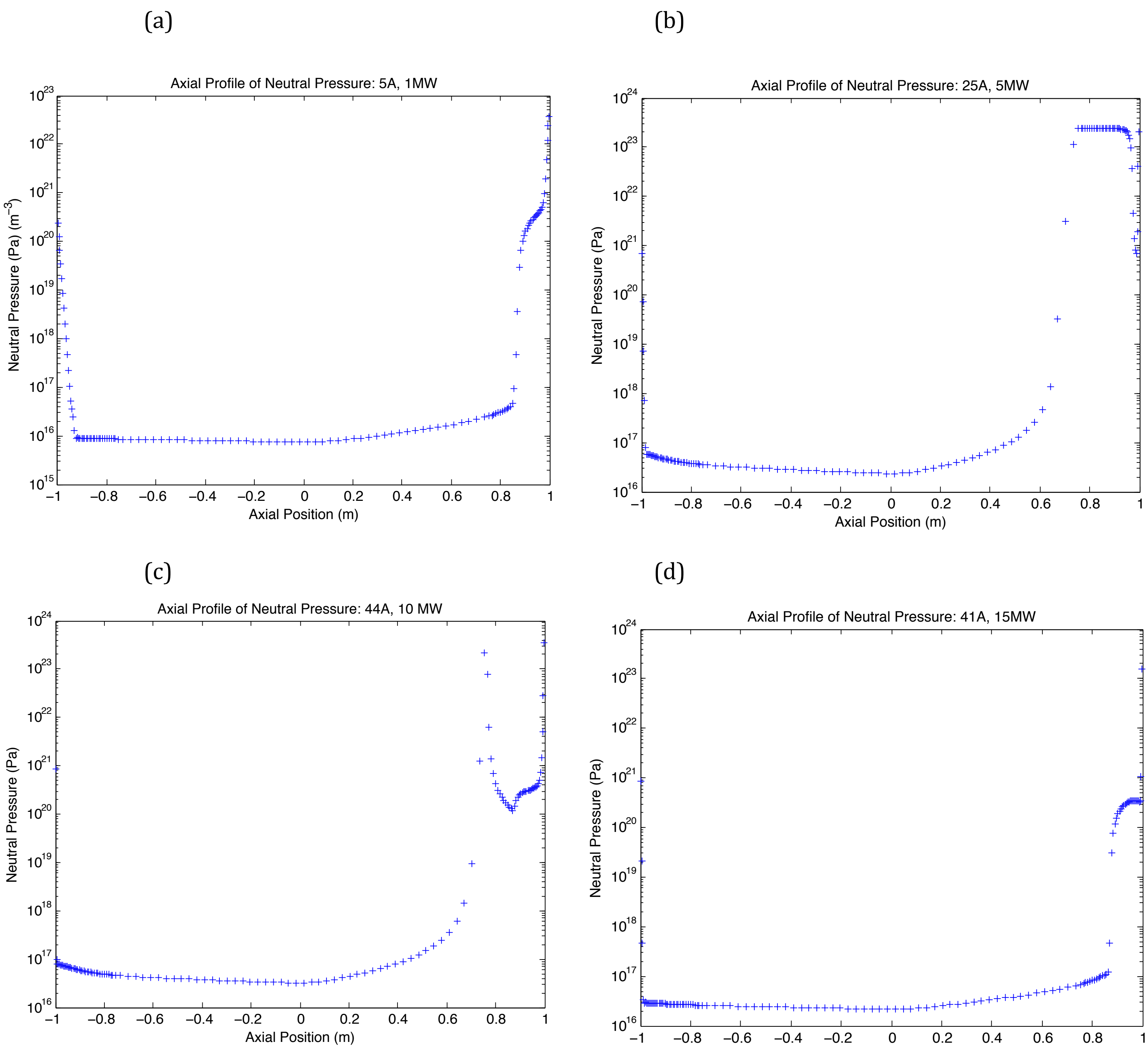


Figure 6: Showing axial profiles of neutral pressure. Shown for potentially detached profiles at (a) 1MW, (b) 5MW, (c) 10MW, and (d) 15MW.

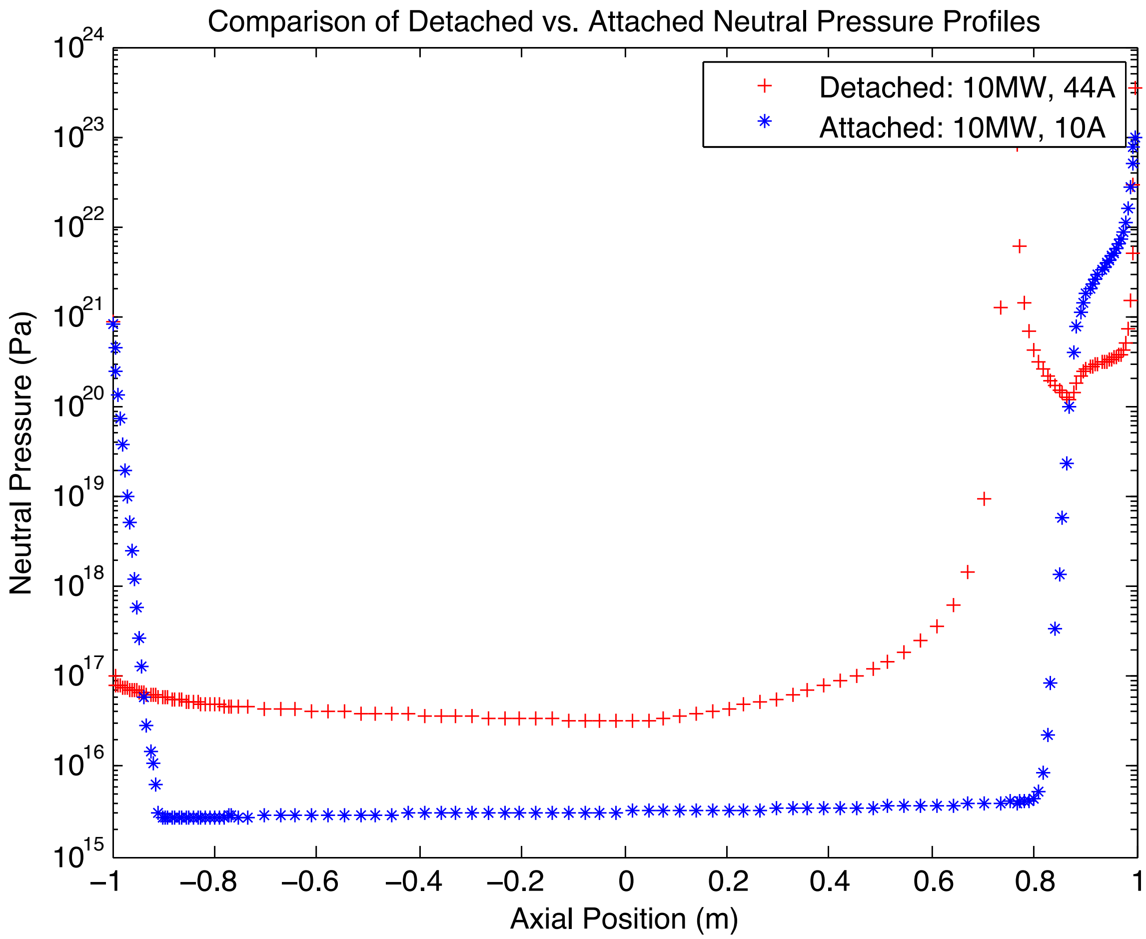


Figure 7: Comparing the neutral pressure profiles of potentially detached and attached cases, at 10 MW

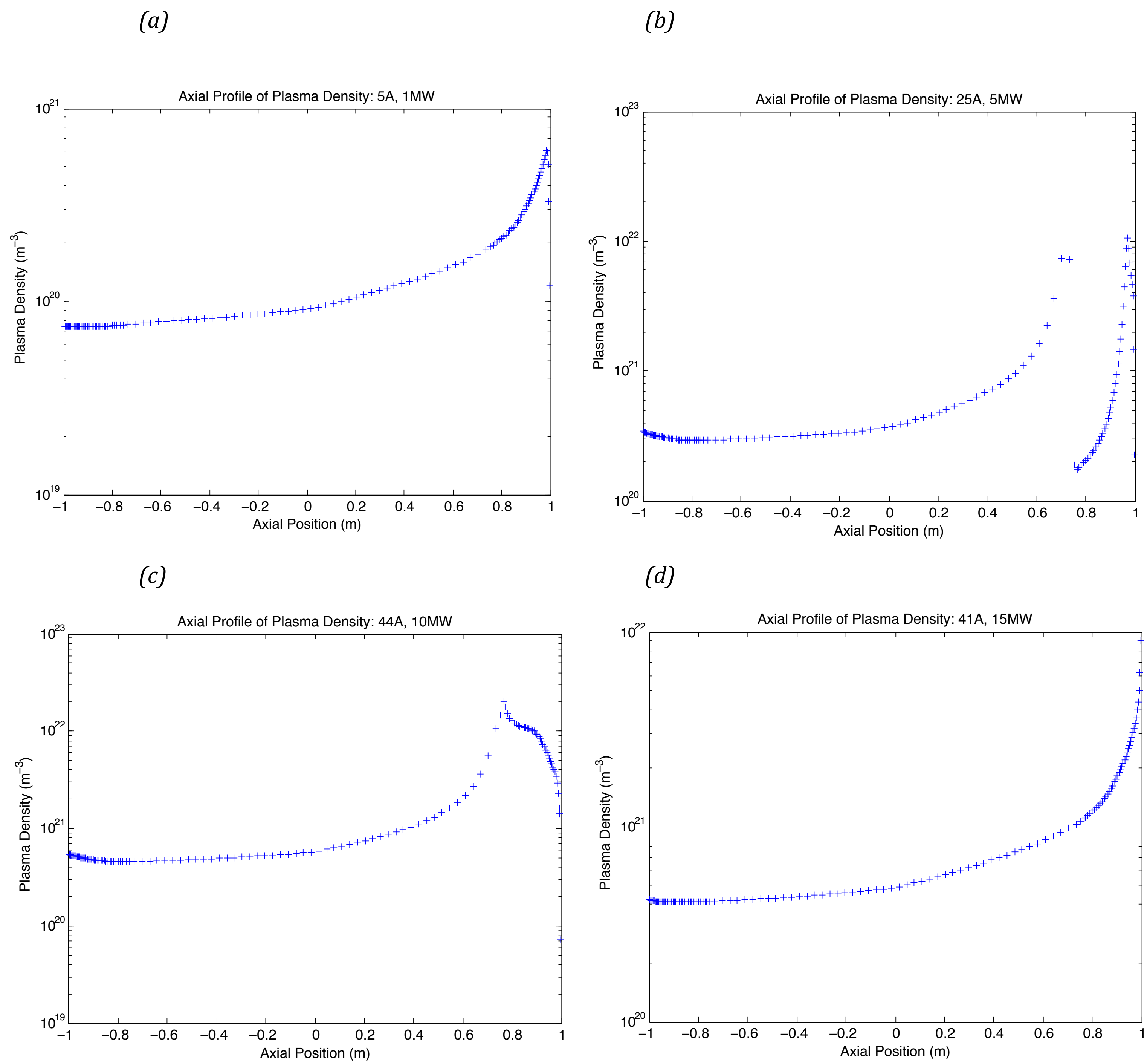


Figure 8: Showing the axial plasma density profiles. Shown for potentially detached profiles at (a) 1MW, (b) 5MW, (c) 10MW, and (d) 15MW.

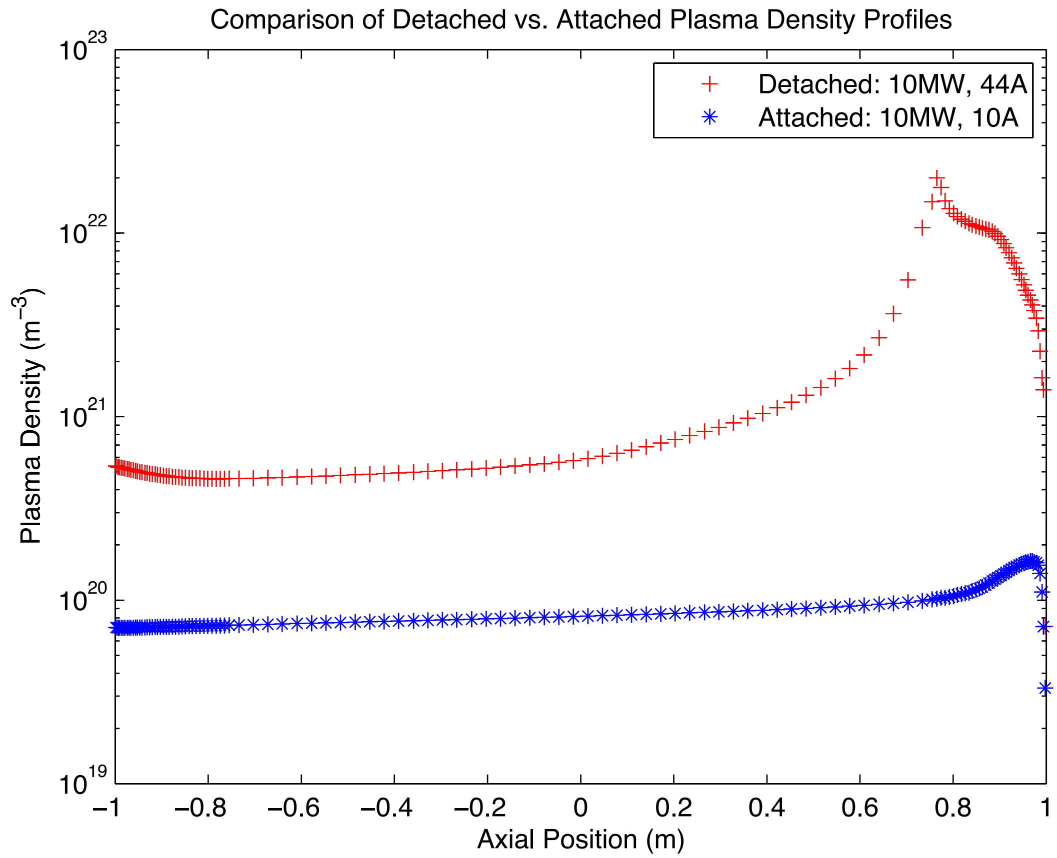


Figure 9: Comparing the plasma density profiles of a potentially detached and attached case, at 10 MW

Discussion:

For this discussion, a potential indicator of plasma detachment was considered when the minimum plasma temperature was observed to be approximately 10% or less of the maximum plasma temperature. Representative cases of potentially attached and detached plasmas can be seen in figure 5, where electron temperature and ion temperature profiles are markedly different. It should nevertheless be noted that there can exist other markers of plasma detachment.

With that said, it can be seen that when semblances of plasma detachment are observed, the neutral gas density is at least on the order of 10^{21} m^{-3}, which appears consistent with previous work[2]. This can be observed in figure 4.

Also to be expected from concept of plasma detachment is an observed drop in the plasma density, on the scale of several orders of magnitude[2]. Plasma density can be seen in figure 6, for seemingly detached cases, but this warrants further exploration, in order to determine where numerical issues were confounding results.

It can be seen that as more power is input to the system, it appears to become proportionally easier to detach the plasma. As seen in figure 1, when the power supply is 1 MW, potential plasma detachment can be seen at a gas supply-power supply ratio (GS/PS) of 5, leading to a temperature ratio of 0.10. However, as the power input is increased, as is the case at 15 MW, only 41 equivalent-amps are required (GS/PS = 2.73) for a temperature ratio of 0.04.

Accordingly, higher neutral gas densities are achieved for lower GS/PS values, as power supply is increased. This is consistent with the first observation, which directly linked neutral gas density and plasma detachment; if it is proportionally easier to attain a higher neutral gas density, then due to the heat-diffusing applications of a neutral gas blanket, it should be proportionally easier to detach the plasma.

Less explicitly related to detachment, the maximum SOL plasma temperatures were also recorded (figure 2)- a variable highly relevant for fusion confinement. It was noted that higher plasma temperatures were observed at lower GS/PS values; as more gas was injected into the system, the plasma grew cooler, eventually leading to potential detachment. However, for higher power levels, the maximum SOL plasma temperature was also higher, across all GS/PS ratios (figure 2). At GS/PS = 2, for example, the maximum SOL plasma temperature is 81.5 eV for 15 MW power addition, but only 55.7 eV for 1 MW power addition. Unlike the plasma core where a high temperature is desirable, the case is the opposite for the SOL, where the plasma is much closer to interacting with the confining device.

Therefore, by increasing the power level, there are potentially compromised benefits. Desirably, the plasma appears to be proportionally easier to detach, with lower GS/PS ratios required for an appreciable temperature decline (figure 1). However, at higher power levels, the maximum SOL temperatures are increased across all GS/PS ratios (figure 2). This can lead to more difficult confinement issues, and introduces the concept of the existence of a potentially optimal power input.

While excessively high power supplies and gas flow rates might never be “easy” in any sense, regardless of the proportion, hopefully this work can help provide direction for further experimental work, or for higher-dimensional models.

These results indicate that trends relevant to plasma detachment appear to be nonlinear, and can provide a useful preliminary for more complex analyses regarding a neutral gas blanket as an alternative to a standard divertor scheme.

Work Cited

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[2] Schmitz, L., Lehmer, R., Chevalier, G., Tynan, G., Chia, P., Doerner, R. and Conn, R.W. Experimental Simulation of the Gaseous Divertor Concept in PISCES-A. Journal of Nuclear Materials 176 & 177 (1990) 522-527

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