Plasma modelization: from space propulsion to fusion reactors

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About me

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- BEng in Aeronautical Engineering (EUITA) 2007-2011.
- Master in Aerospace Engineering (ETSIA) 2011-2013 (with *Honors* in final project).
- PhD in Aerospace Engineering (ETSIAE) 2013-2017 (with *cum laude*).
- Long term stays in international research centers.
- Started working in plasma simulation for my Master Thesis (2013) at the UPM PlasmaLab.
- Main research topics: Low temperature plasma, plasma-wall interaction, space propulsion (*alphie*) and plasma edge modeling for fusion devices.

Kinetic Theory for modelization of plasma

Ways to simulate plasma

- Two main approaches: fluid and kinetic methods.
  - **Fluid** = high density (high collisional regime).
  - **Kinetic** = low density (low collisional regime).
- Equations for the different species (regardless if fluid or kinetic) are coupled with the **electromagnetic** field.
- Multiple species: electrons, ions and neutrals.
  - Interaction between **N-N** and **N-C** species: collisions.
  - Interaction between **C-C** species: collisions and electromagnetic field.
- Where are kinetic descriptions relevant?
  - Low density plasmas (space propulsion, astrophysics, small tokamaks).
  - Reduced volume.
  - Distribution function far from Maxwellian equilibrium.
  - Relevance of complex collisional processes (difficult to model witn fluid models).

Bases of kinetic theory

- Computes (or approximates) the distribution function for each species.
- This needs to include the effect of the self-consistent electromagnetic field, boundary conditions and collisions among species.
- A very popular method is **particle-in-cell**.
- A set of **macro-particles** (representing a large number of real particles) are followed in a grid.
- The electromagnetic field is calculated in the grid and interpolated to the macro-particle position.
- Particle properties (charge, mass and velocity) are deposited in the grid nodes.
- Only collisions between particles in a cell are accounted for.

Plasma edge modeling in fusion reactors

Fusion as a source of energy

- Fusing Deuterium and Tritium to generate **huge** amounts of **energy** (17.59MeV).
- In the process, Helium and Neutrons are also generated.
- Neutrons interact with the device wall, heating it.
- Helium is important for achieving a burning plasma.
- Clean energy, with quasi-infinity fuel, and constant production.

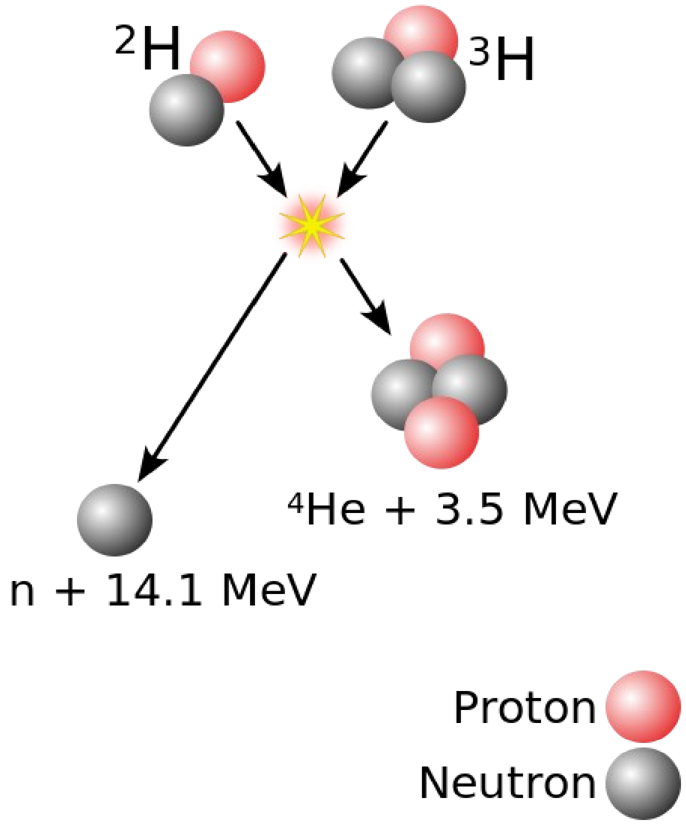

Fig. 1: Fusion Process. *J.K. Shultis & R. E. Faw. Fundamentals of nuclear science and engineering. CRC Press. (2002).*

An overview of fusion reactors

- Plasma is magnetically confined.
- Huge temperatures are reached (> 100e6ºC).
- Due to collisional processes, part of the plasma diffuse to the Scrape-Off Layer (SOL).
- The SOL is responsible of directing the plasma heat to the **divertor** and pumping away impurities.
- For **ITER**, it is expected to reach a heat flux of 10-20MW/m^{-2} in steady state operation.
- This high heat has the capability of **destroying** the W surfaces of the divertor.
- Moreover, there can be effects of **sputtering** that can contaminate the plasma core and hinder the fusion reaction.

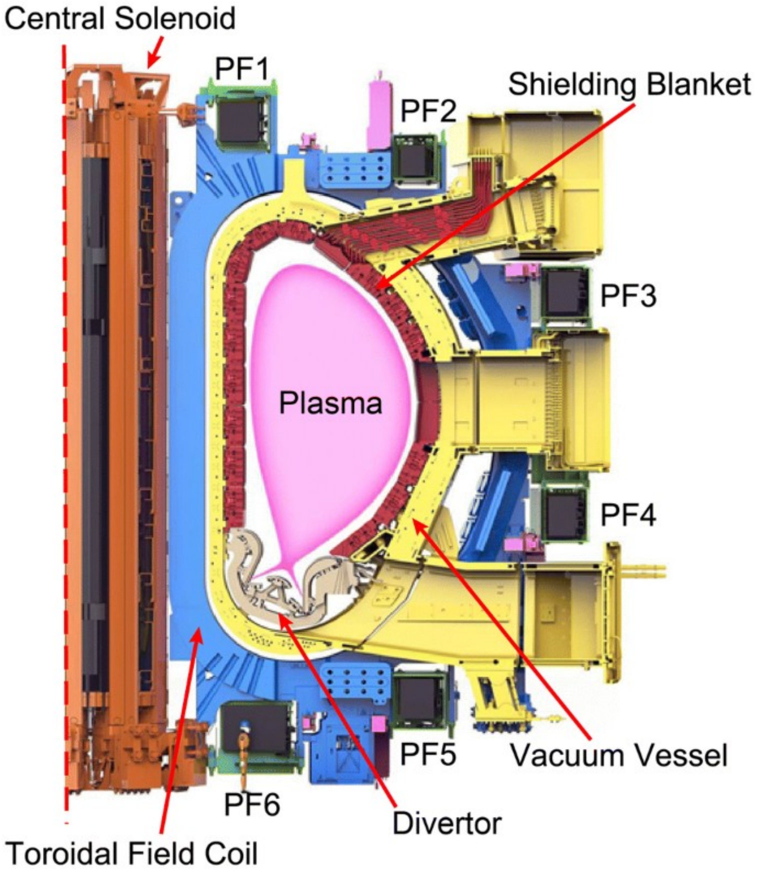

Fig. 2: ITER Section. Figure taken from *D. J. Campbell, et al. J. Fusion Energ. 38, 11–71 (2019).*

Importance of plasma edge modeling

Thus, **control mechanisms** need to be developed to reduce the heat flux to the divertor walls.

  - Currently, gas puffing and liquid metal walls seems to be the best options.

- This will become especially important in the next generation of fusion reactors (DEMO), aimed to continuous operation and electricity production.
- The modelization of an incoming high energy plasma to a material of similar properties that the divertor is of huge importance for the design of future divertors.
- At DIFFER, the plasma linear device Magnum-PSI was developed to generated plasmas in similar conditions to those expected to be reached at ITER.

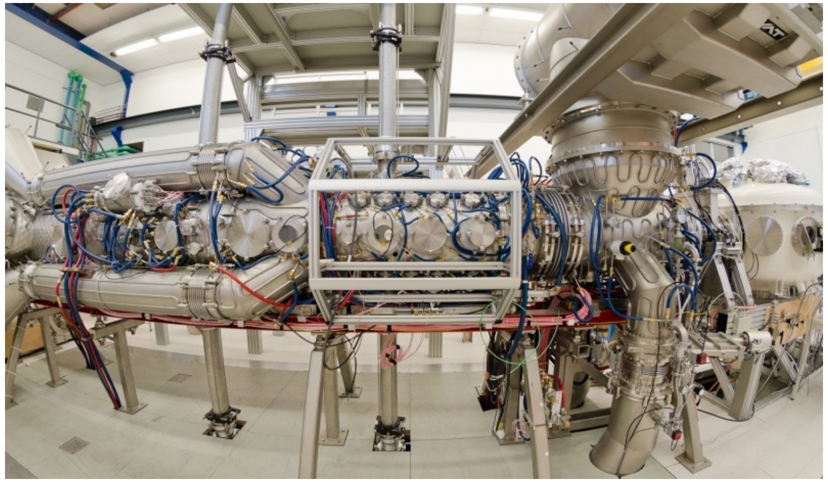

Fig. 3: The plasma Linear Device Magnum-PSI.

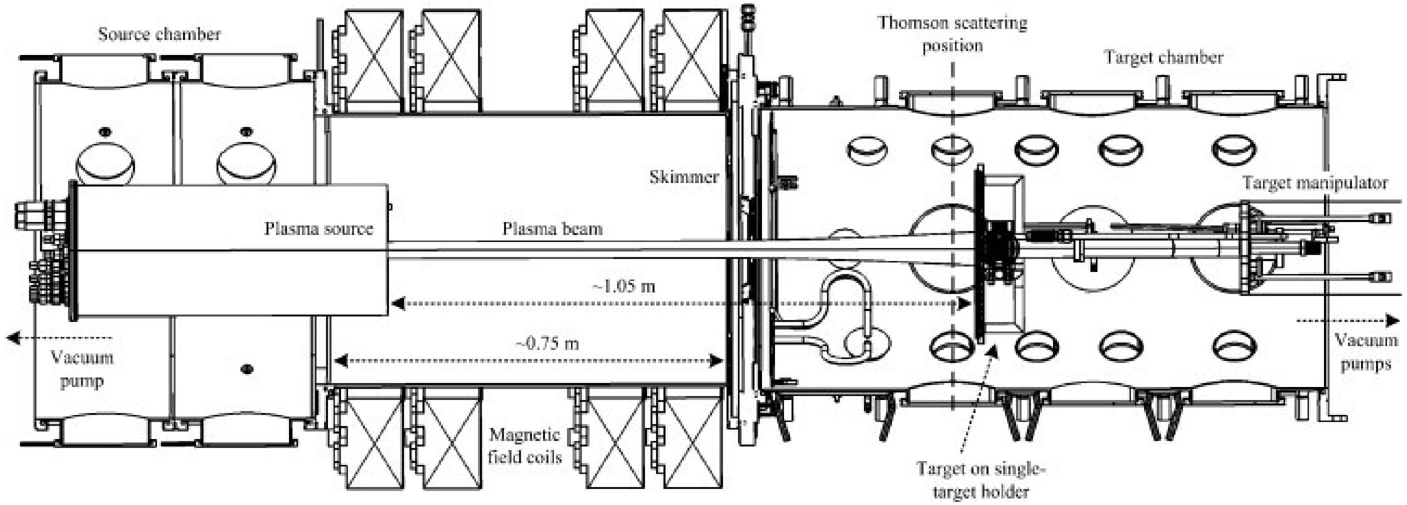

Fig. 4: Section of Magnum-PSI.

Why is important simulations then?

- Interaction between the high energy plasma, neutrals and the wall is a very **complex process**.
- The amount of data able to obtain with each Magnum-PSI shot is huge, but still limited.
- Thus, we need to have the capability to simulate Magnum-PSI to improve our knowledge of the Plasma-Wall interaction and understand the relevant processes that can lead to heat flux reduction and control.
- Useful information for designing **future divertors**.
- Currently, we use a hybrid code:
  - Plasma is simulated as a fluid due to its high density.
  - Neutrals are treated with kinetic models.
- Interaction between the plasma and the neutrals is accounted for:
  - Kinetic neutrals collide with the plasma background.
  - Source/sink of particles, momentum and energy for the plasma are calculated.

What do we simulate?

- We study different ways to reduce the heat flux.
- For example, **increasing the neutral density** in the target chamber by injecting a large number of neutral particles (gas puffing).
- Via collisions, part of the plasma energy is transferred to the neutrals, which are then pumped.
- Another, more complex (and interesting approach) is using a liquid metal (usually Li or Sn) in the material surface.
- This liquid metal evaporates forming a **vapor shielding** in front of the target.
- The advantages are multiple: **self-repairing** target, self-controlling via evaporating/condensation processes and **high heat absorption** capabilities.
- Our main tasks is to perform simulations in these extreme situations, validate them against experimental data from Magnum-PSI and then use this knowledge to predict future behaviors and improve divertor designs.

Simulation of detachment

- Detachment refers to when the plasma *detach* from the divertor, reducing the heat flux to it.
- This can be achieved by recombining the plasma before it reaches the divertor.
- Usually, a gas is injected to increase recombination.
- I simulate Magnum-PSI to see if simulations match experimental data and we are able to extract more information from the data.
- Still some discrepancies appear (molecular vibrational states? Incorrect cross sections at low temperature?)

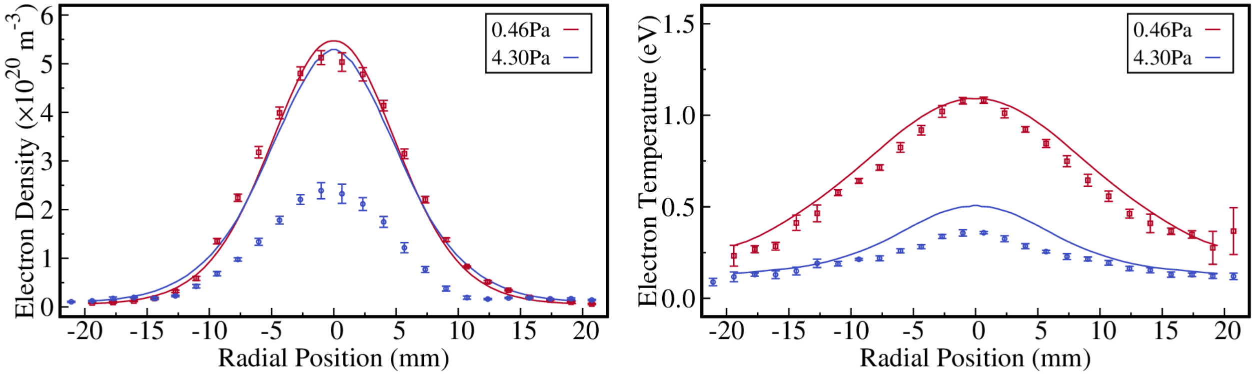

Fig. 5: Comparison of electron density (left) and temperature (right) of simulations (solid line) with experiments (data points) for a low and a high pressure case.

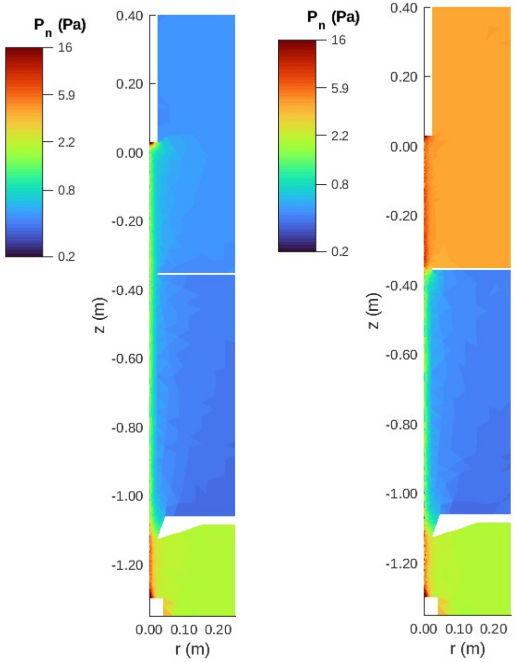

Fig. 6: Neutral pressure in the cases of low (left) and high (right) target chamber pressure.

Liquid metals at the divertor

- A possible way to reduce heat flux to a divertor walls is to use liquid metals (usually Li or Sn).
- The hot plasma will evaporate the metal from a porous structure (CPS) and create a cloud.
- This cloud helps to reduce plasma heat, but issues appear: contamination of the core, deposition of the metal in the device walls, retention of fuel, difficulty of measurements.
- Simulations help us identify the change in plasma and the dynamic of the evaporated metal.

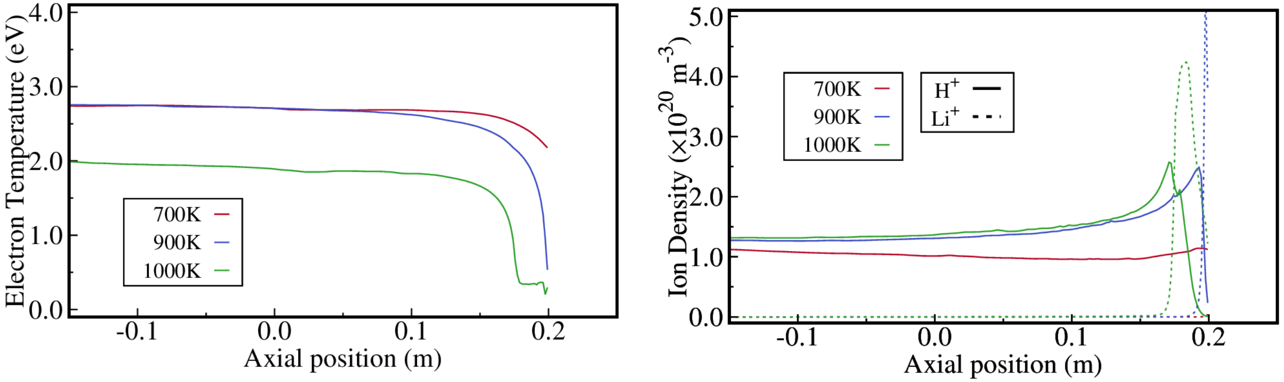

Fig. 7: Axial profile of the electron temperature (left) and the ion density (right) for proton (solid line) and lithium (dashed lines) for three temperatures of evaporation.

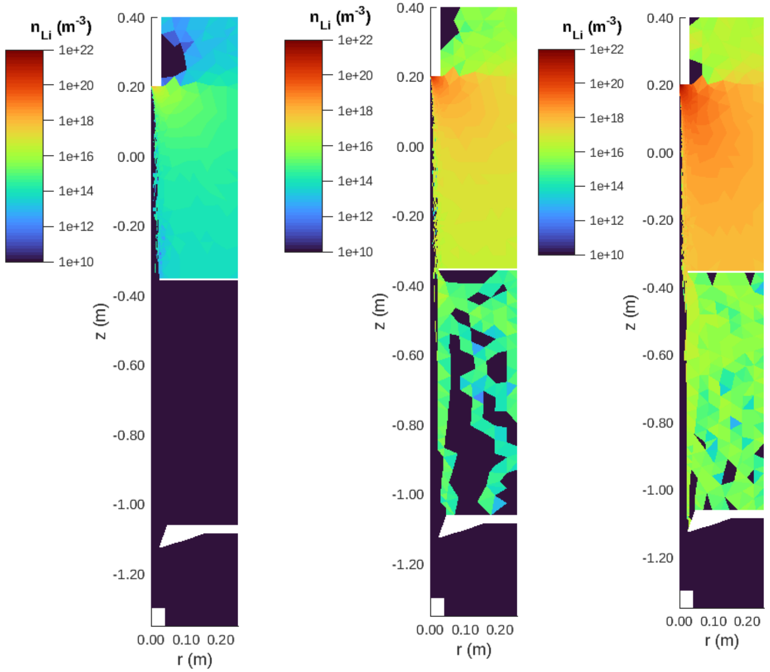

Fig. 8: Neutral Lithium distribution for the three evaporation temperatures studied. As evaporation of Li increases, larger amount reaches the middle chamber and the pump in the target chamber.

Vapour Box experiment

- Another method to extinguish a plasma that is being developed is the use of a *vapour box* or a *closed divertor*.
- This design retains the neutral particles coming from recycling, recombination and gas puffing, increasing collisionality with the plasma.
- The concept currently being studied at DIFFER also allows to evaporate lithium.
- Experiments to come soon. Future simulations and experiments in a closed configuration will arrive soon too.

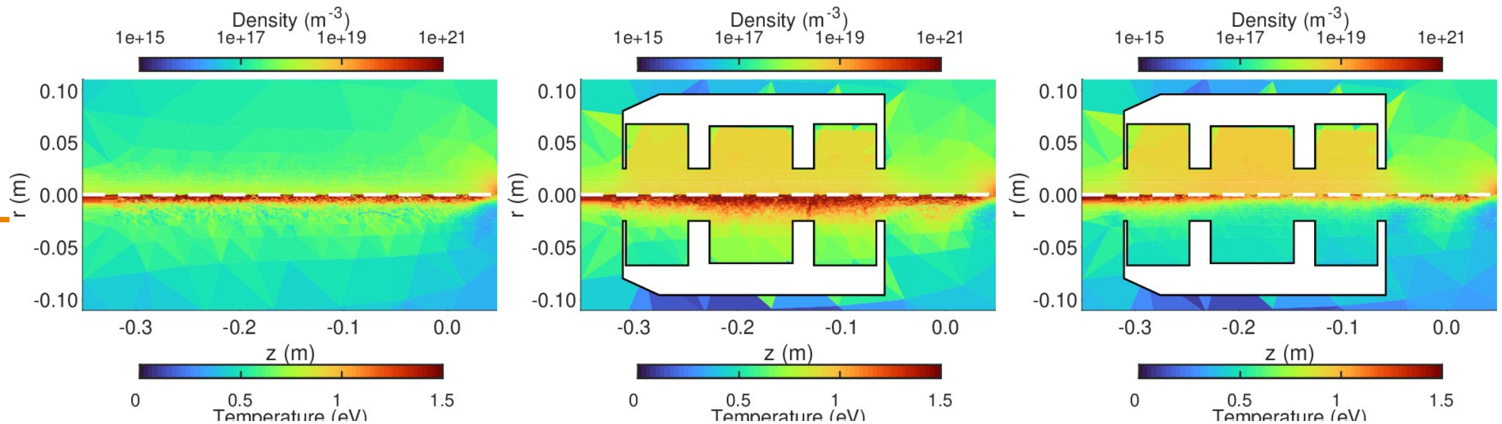

Fig. 9: Distribution of neutral density (top) and temperature (right) in the region of the VB for: no box (left) with box (middle) and with Li evaporation (right). Higher hydrogen temperature indicates higher collisionality. When Li is evaporated, it gains a large portion of energy from plasma and neutrals and contributes to recombination.

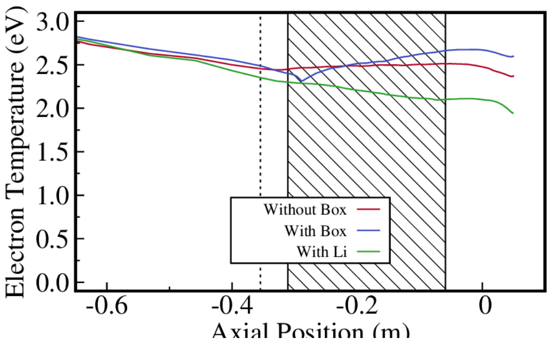

Fig. 10: Electron temperature in the region of the VB (dashed) without box, with box and with evaporation of Li. A lithium cloud is an excellent way to reduce the plasma temperature.

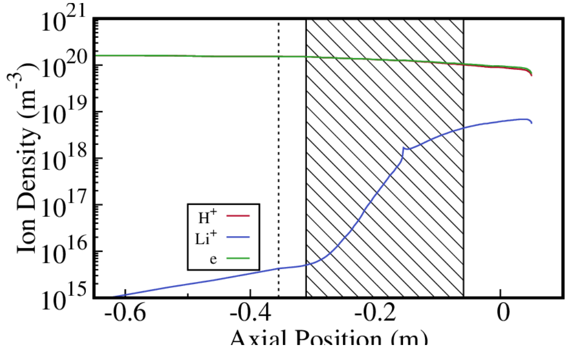

Fig. 11: Distribution of ions per species and electrons. The high energy protons are replaced by low energy Li^{+}.

Simulation of ALPHIE

What is ALPHIE?

- The Alternative Low Power Hybrid Ion Engine (***alphie***) is a new concept of plasma thruster developed at the UPM PlasmaLab.
- It differs from classical gridded thrusters as a **counterflow** of charges passes through the grid system.
- Although a lot of experimental measurements are being carried out to characterize the new thruster, simulations are key to explain the **high thrust** and **specific impulse** achieved by *alphie*.
- Fully kinetic particle-in-cell code, named *fpakc*, is being developed to, among other things, simulate *alphie.*

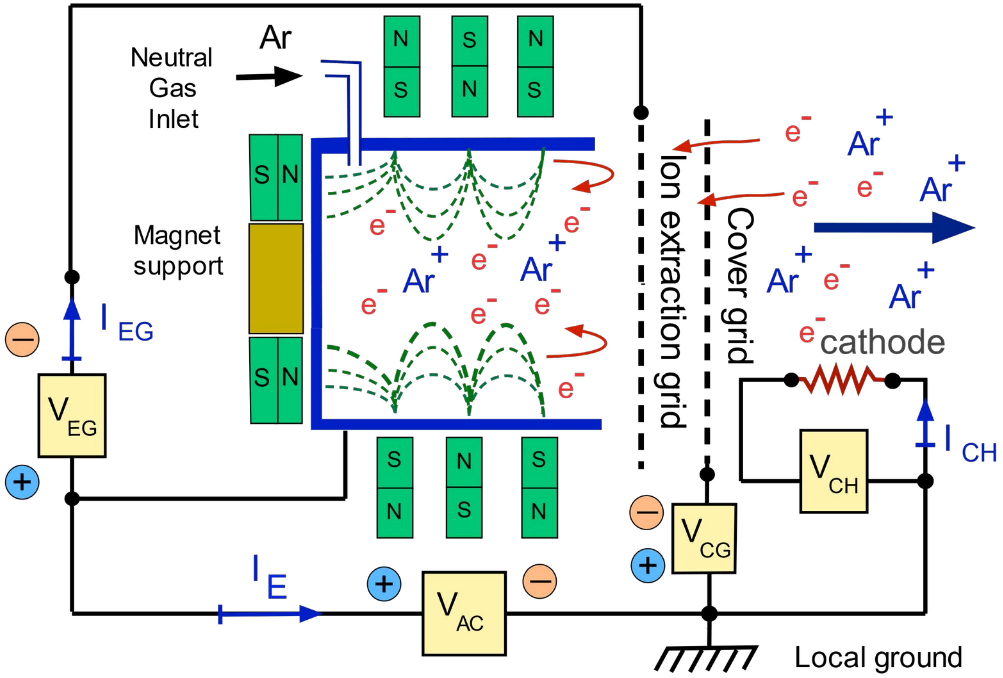

Fig. 12: ALPHIE electrical scheme.

Simulation of grid holes

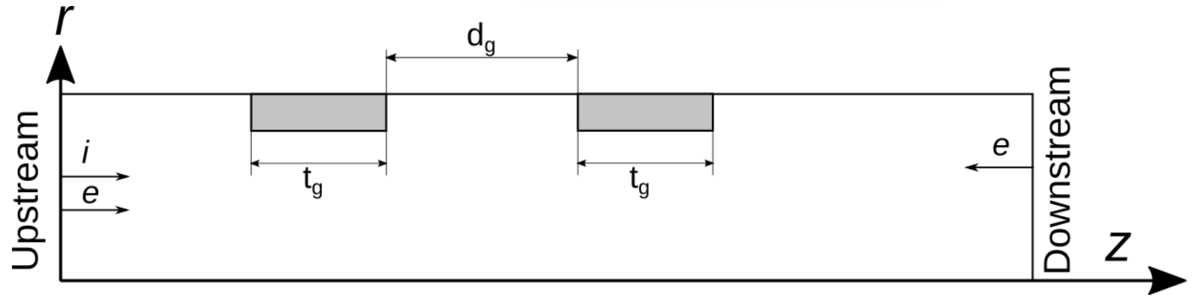

Fig. 13: Simulation domain. A counterflow between electrons from the *downstream* region and ions from the *upstream* region will form.

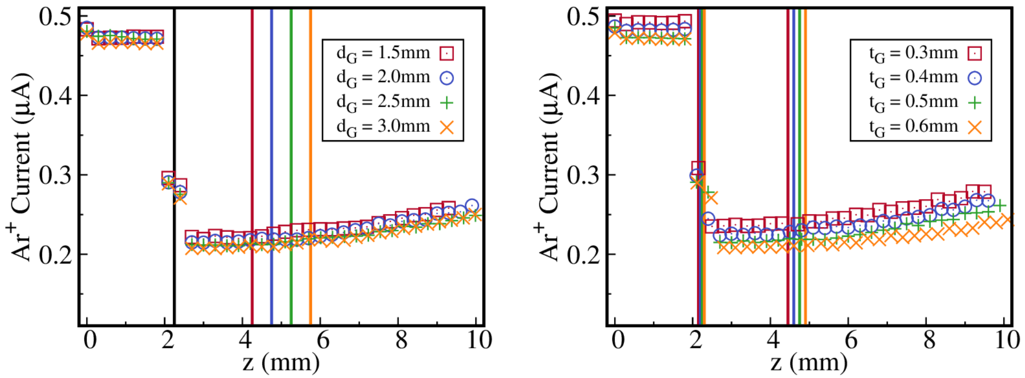

Fig. 14: Argon current through the grids modifying the separation between grids (left) and the thickness of the grids (right). Small changes in the extracted current are observable.

- We need to understand how the counterflow of charges affects the operation of ALPHIE.
- Also, different configurations of the grid system geometry can be tested to improve ALPHIE performance.
- With simulations we can understand and improve a new technology that has the potential to disrupt the plasma propulsion state of art.
- Simulations and measurements show ALPHIE as a high thrust, high specific impulse and low power new type of thruster.
- These properties do not change with small modifications of the grid geometry, which is good for manufacturing and erosion.
- Future analysis of collision processes in the ionization chamber.

Interactions in the plasma plume (I)

- The **plasma plume** is the exhaust of ions, electrons and neutral particles generated by a plasma engine.
- For any plasma thruster, the processes that occur in the plasma plume are crucial.
- Backflow of ions can interact with the spacecraft and also cause grid erosion, which limits the lifetime of the thruster.
- Main mechanism of this backflow is due to **Charge-Exchange** processes:

$$A_{slow} + A^+_{fast} \rightarrow A^+_{slow} + A_{fast}$$

- This results in a “slow” ion that can go back to the spaceship.

Interactions in the plasma plume (II)

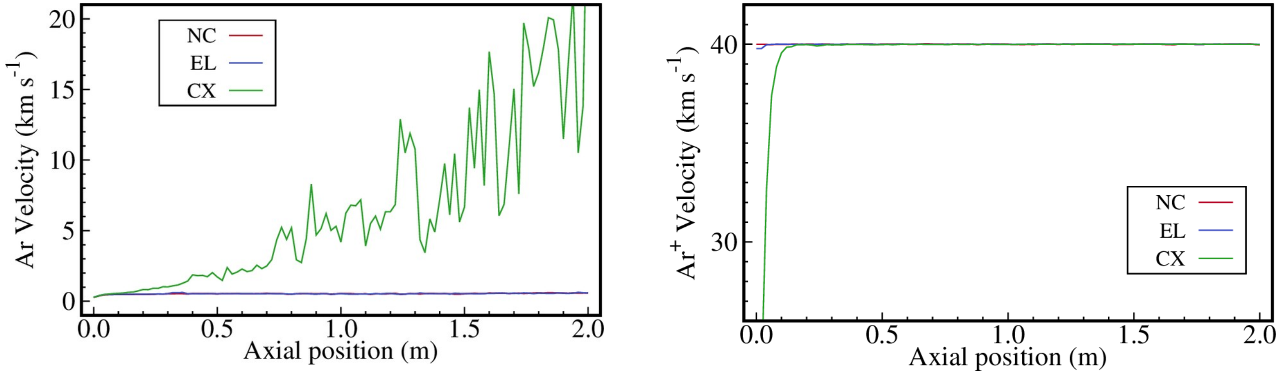

Fig. 15: Axial profile of the neutral velocity (left) and ion velocity (right) for a case without collisions (NC), only elastic interactions (EL) and charge exchange (CX). Charge exchange is responsible of transferring momentum from the fast ions to the slow neutrals.

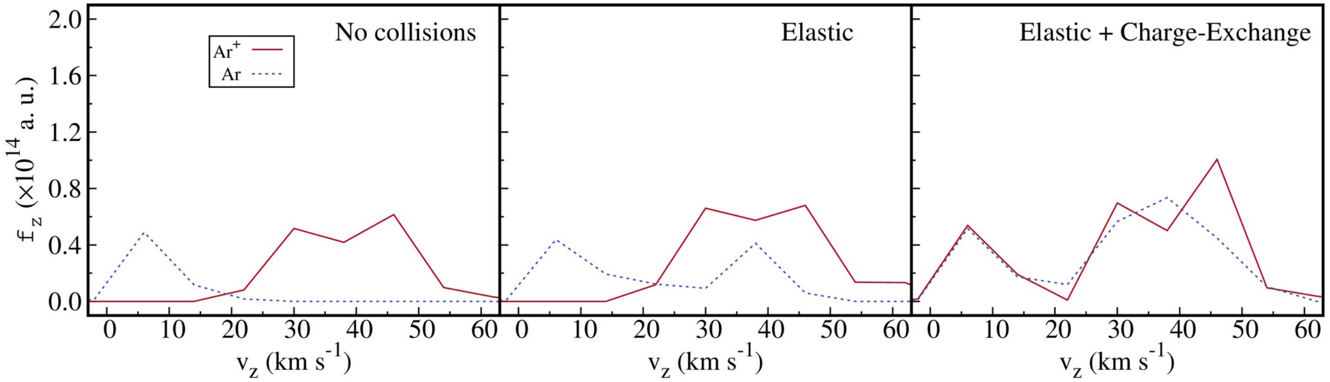

Fig. 16: Distribution function obtained numerically for neutral and ions. Charge exchange creates the two peaked profile observed in the experiments.

- We see how the introduction of charge-exchange between ions and neutrals produce a more disperse field of velocity for the ions, as well as creating a population of high velocity neutrals in the plasma beam.
- In the future, we will introduce electrons in the simulations and the self-consistent electric field to further explore the possible backflow of ions back to the spaceship.

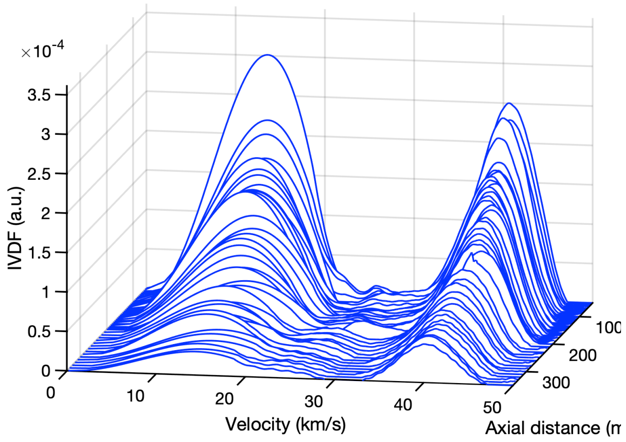

Fig. 17: Experimental measurements of the ion velocity distribution in the axial direction. Two populations are clearly observed.

Conclusions

Conclusions

- Kinetic descriptions of plasma and neutrals (either standalone or coupled with fluid models) are of mayor importance in state-of-the-art simulations.
- Plasma wall interaction in fusion devices is of major importance to increase the lifetime of divertors and improve the energy production in the next generation of fusion reactors.
  - The interaction between neutrals and the high heat flux incoming plasma is used to reduce heat load to the walls.
  - Liquid metals are currently being tested for this purpose.
- Simulations help us understand and improve new technologies, like ALPHIE.
  - New geometries can be tested.
  - Typical problems in plasma propulsion can be analyzed and mitigated.
  - Explanation to experimental data can be found.

Thank you for your attention

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DIFFER