Study of the pellet rocket effect in magnetized plasmas

Pellet injection is an effective tool for modifying the density profile in fusion devices, and can be used for both fuelling and plasma control. It has been employed successfully to mitigate transient events in tokamaks, e.g. disruptions. The use of pellets to control such events is also planned for ITER.

In order to assess the performance of pellet injection schemes for future fusion devices, such as ITER, it is important that accurate estimates of the modified density profile created by the pellets are included in the modelling tools used to simulate such events. This can only be achieved through an understanding of the underlying physics of the mass deposition after pellet injection. Estimating the material deposition profile of a pellet is strongly affected by the pellet's trajectory and changing velocity.

When a pellet is injected into a hot, magnetically confined plasma, it travels through the plasma in solid form while the outer layers are continuously ablated by the energy flux from the hot background plasma, resulting in material being deposited along the pellet trajectory. The cloud of ablated material initially has a cold dense structure – a plasmoid – which drifts towards the low-field side of the torus. This is caused by the charge separation that takes place due to electron and ion drifts in the inhomogeneous magnetic field, leading to the build-up of a vertical electric field, and the resulting $\mathbf{E} \times \mathbf{B}$-drift moves the ablated material across magnetic field lines, where $\mathbf{E}$ and $\mathbf{B}$ denote the electric and magnetic field, respectively. This drift creates asymmetry and non-uniform heating of the ablation cloud. The asymmetry results in a less efficient shielding on the pellet's high field side region, where the enhanced ablation pushes the pellet towards the low field side, like a rocket. The rocket effect may strongly influence trajectories and penetration of pellets in fusion plasmas.

Rocket model The aim of this project is to develop a semi-analytical model to study this effect and estimate pellet rocket acceleration in fusion devices. The rocket effect is driven by the difference in the cloud pressure on the low field side and high field side of the pellet. Simpler estimates to explain existing observations in medium-sized tokamaks exist, see e.g. [1, 2], but they are not widely used in the community. Only recently it has become apparent that this effect can be significant in future tokamaks with higher temperatures.

The questions we would like to know the answer to are:

- What is the order of magnitude of the acceleration from the rocket effect?
- How does that depend on the pellet size, composition and background plasma parameters?
- Is this effect in agreement with the observed acceleration in existing tokamaks (within reasonable margins)?
- Is this effect strong enough to influence disruption mitigation plans for ITER?
- Can we derive a self-contained model for the rocket-acceleration that can be implemented in simulation tools?

Phase I – Reading about pellet ablation, expansion of pellet cloud and understanding the current state of modelling of drifts and rocket effect

In this phase the student is introduced to the fundamental concepts. After this phase, the student will have a general knowledge of the ideas, models, as well as experimental observations, that underlie the study of pellet ablation. This phase is expected to take 4-5 weeks of the available 20. The work-plan is as follows:

1. Read through section 2.1, 2.2 and 3.1, 3.2 in Pegourie [3].

2. Read relevant parts of the papers by Senichenkov et al [1] and Szepesi et al [2].

3. Read relevant parts of O Vallhagen's drift paper [4].

As a whole this phase will be assessed by weekly meetings with the supervisors and by the student's record of the work in the final thesis. It should comprise between a third and half of the finished thesis.

Phase II –Constructing a numerical tool that estimate pellet rocket effect

The aim of this part is to develop a set of equations that describe the acceleration of the pellet. This phase of the project will take 8-10 weeks, depending on the level of sophistication the student aims for.

1. Formulate a set of differential equations describing the fluid dynamics around the pellet given a weakly asymmetric heat source. The symmetric part of the dynamics is analogous to the so called Neutral Gas Shielding (NGS) model [5] calculation, around wich the asymmetric part is to be treated as a perturbation.

2. Solve the obtained equation system numerically.

3. Calculate the heat source given an asymmetric electron heat flux into the neutral pellet cloud.

4. Finally, to make the model self-contained, calculate the shape of the ionized pellet cloud to be able to compute the heat flux into the neutral pellet cloud.

5. Estimate the order of magnitude off the acceleration for different pellet sizes and compositions and background plasma parameters. Compare the obtained pressure asymmetry values reported by by Szepesi et al [2].

6. Make estimates for ITER scenarios.

At this point, several options may present themselves, and it will be part of the project to decide, with detailed input from the supervisor, upon what should be pursued for any remaining time. The rationale for choosing any remaining problem will be part of the final report on the work.

The total duration of a MSc project is approximately 20 weeks (full time). In addition to the research detailed above, the students will need to write a thesis detailing the work conducted during this project. The writing is expected to take *at least* 6 weeks (full time) of the allotted 20. This should be distributed during the full duration of the project (continuous documentation of the results), but naturally the writing part will be most intense toward the end.

The examiner is Tünde Fülöp and the supervisors are PhD student Oskar Vallhagen and senior researcher István Pusztai. The project will be done in collaboration with Prof Per Helander (Max-Planck Institute, Greifswald) and Sarah Newton (Culham Centre for Fusion Energy). Collaboration with other colleagues in the EUROfusion community that are interested in this problem is also foreseen.

References

[1] Senichenkov et al, *Proceedings of 34th EPS Conference on Plasma Physics*, Warsaw, 2007, Paper No. P-4.094, 2007

[2] Szepesi et al, *Journal of Nuclear Materials* **390391** (2009) 507-510

[3] Pegourie, *Plasma Phys. Control. Fus.* **49** (2007) R87

[4] Vallhagen et al *Journal of Plasma Physics* **89** (2023) 905890306

[5] Parks and Turnbull, *The Physics of Fluids* **21** (1978) 1735