

Optimizing fuelling pellet injection geometry for COMPASS Upgrade using HPI2

Márton Vavrik¹, T. Szepesi¹, G. Kocsis¹, J. Cerovsky², F. Jaulmes², N. Panadero³

¹HUN-REN Centre for Energy Research, Institute for Atomic Energy Research, Budapest, Hungary

²Institute of Plasma Physics of the Czech Academy of Sciences, Prague, Czech Republic

³Laboratorio Nacional de Fusión, CIEMAT, Madrid, Spain

e-mail: vavrik.marton@ek.hun-ren.hu

COMPASS Upgrade [1] is a high-magnetic field (up to 5 T) tokamak, being built in Prague. The HUN-REN Centre for Energy Research plans to develop a fueling pellet injector for COMPASS-U. This work aims to optimize the pellet injector parameters, pellet velocity, size, injection direction, and investigates the pellet-plasma interaction, using various plasma scenarios of the Compass Upgrade tokamak with the HPI2 code [2].

A cryogenic pellet is formed by extruding a frozen rod of cryogenic material, then chopping it up into pieces. The extruder can have a continuous operation, but that is much more challenging to design, and for our purposes, a batch extruder is sufficient, which extrudes a rod with a certain length, and slowly pushes it out. Once the rod is fully pushed out and chopped into pellets, the freezing of a new rod and a new batch of pellets starts. Then the pellet is accelerated, which can be done several ways: a gas gun can produce large pellet launch speeds, which are advantageous for deeper penetration, but are effectively single shot. A blower gun [3] offers high repetition rate, but lower speeds and larger velocity scatter. A centrifuge has favorable speeds and repetition, but it is quite complex. A good reference for designing a centrifuge pellet injector can be the TATOP centrifuge [4].

	speed	v scatter	repetition	gas load	complexity	
Centrifuge	< 1 km/s	Negligible	10-80 Hz	Negligible	High	← Most likely on CU
Gas gun	2+ km/s	Low	Single shot	Medium	Medium	
Blower gun [3]	500 m/s	High	100-150 Hz	Med-High	Low	

Figure 1. advantages and disadvantages of pellet launch methods

Pellet transfer to the tokamak is typically done through guiding tubes, where the Leidenfrost effect helps reduce friction between the cold pellet and the warm tube wall. Efficient transfer requires good vacuum pumping, which can be enhanced using curved tubes with venting holes on one side. To maintain pellet integrity and speed, S-bent tracks should be avoided and impact angles at the tube exit must remain below 2° [5,6], as larger angles increase losses and risk of fragmentation and curvature significantly limits the maximum achievable pellet speed [7]:

$$v_{critical} (m/s) = 1150 \sqrt{\frac{R_{track}(m)}{L_{pellet}(mm)}}$$

HPI2 is a widely used, MATLAB-based 2D+ pellet injection simulation code that can handle 3D geometries and related secondary phenomena, such as inhomogeneous pellet ablation. It is based on an extended neutral gas and plasma shielding (NGPS) model. The simulation begins by calculating the pellet ablation: as the cryogenic pellet material sublimates, it forms a neutral cloud that temporarily protects it. Next step is ionization, creating a plasmoid around the pellet, which experiences drifts by the magnetic field. The plasmoid elongates along the field lines, and then the material spreads along magnetic surfaces, which is called homogenization. The material becomes part of the plasma, so the plasma profiles, such as density and temperature, can be updated accordingly. The pellet motion also accounts for the rocket effect, causing it to curve slightly outward radially [8].

The input of the HPI2 code includes a 2D magnetic geometry, and 1D quantities mapped through a_{flux} (to obtain full 2D data), and the pellet launch parameters. We found the simulation should be run so it makes around 50 plasmoid steps for optimal resolution, requiring 3–4 hours of runtime. The code's outputs include plasma profiles after homogenization, ablation and deposition profiles, and the drift distances of plasmoids along a_{flux} . Key quantities of interest are the penetration depth (the simulation stops when 99.9% of the pellet mass is ablated), and the resulting material deposition profiles.

The dependence of material deposition and penetration depth on pellet size and velocity were examined, and results show that for the desired 10^{21} D/s refueling material deposition rate, pellets with a radius of 0.75 mm should be injected into the plasma, assuming a repetition rate of 10 Hz. Higher injection velocity is advantageous, but based on technical considerations, the simulations were run using an injection velocity of 500 m/s.

In most cases, pellet injection into the high-performance H-mode scenario (#5400) was considered, since it has the highest temperature, density and magnetic field, resulting in the shallowest penetration. Analysing other H and L-mode scenarios, much larger penetration depths and larger deposition ratios were observed, so finding the best injection geometry in the high-performance H-mode yields adequate geometries for other lower-performance scenarios.

The properties of different injection directions from the five ports were explored, to define the optimal injection geometry, as it is seen in figure 2, where the length of the red lines is the penetration depth, and the width corresponds to the deposited percentage of the pellet material. While low-field side (LFS) injection is the easiest to realize

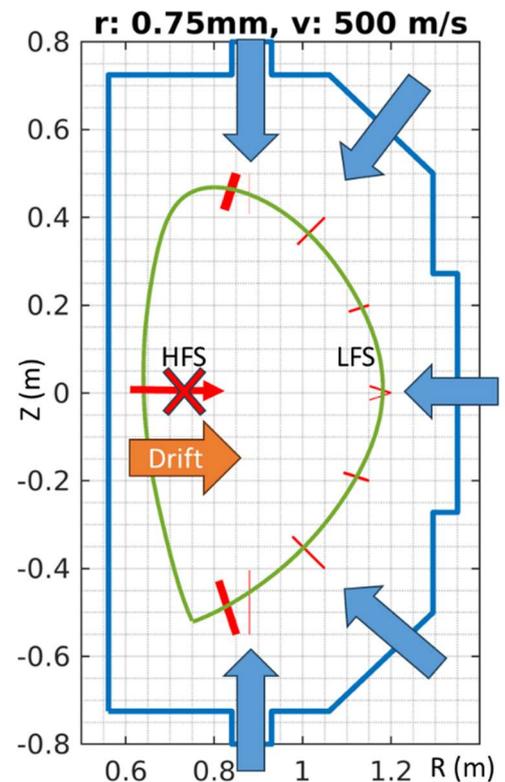


Figure 2. different launch geometries

technically, it results in the least efficient fuelling, as expected, as drift phenomena quickly accelerates the pellet cloud out from the plasma. The internal, high-field side (HFS) injection is the most efficient, where the drift direction points inward the plasma, but due to accessibility constraints, pellets cannot be delivered here.

A good compromise is the vertical high-field side (VHFS) injection, the optimal launch geometry can be iterated by a scan of varying geometries. As it can be seen in figure 3, vertical injections show higher deposition on the HFS where $R < 0.8$ m. Here, the pellet trajectory is shown with black, and the width of red line show the deposition profile. Although ablation rates and penetration depths were generally similar across the cases, strong drifts significantly influenced the material deposition. Notably, the total deposition fraction decreased from 100% to 0% within a narrow 3 cm radial range, highlighting the sensitivity of deposition to launch geometry.

Deposition profile of injection parameter scans can be visualized using heatmaps to help optimize injection depositions, particularly top and bottom VHFS cases. As seen in figure 4, deposition generally extends inward up to $a=0.6$, with minor differences between launch radii of $R=0.7$ m and $R=0.8$ m. On the LFS, a noticeable drop in deposition appears for $R > 0.82$ m, primarily due to ExB-driven drifts. A gap in the deposition profile at $R=0.75$ m is attributed to numerical errors near the X-point, but the divertor region should be avoided regardless.

Based on the findings of the parameter scan, two main injection location options were considered (see fig. 5). The first is an AUG-like vertical high-field side (VHFS) injection (1.), where the pellet guide could potentially enter through a small additional port. However, this route is obstructed by many vessel components, so installing a new dedicated port is not feasible. The second option involves using existing ports starting from $R=0.85$ m, with curved guiding tubes to reach

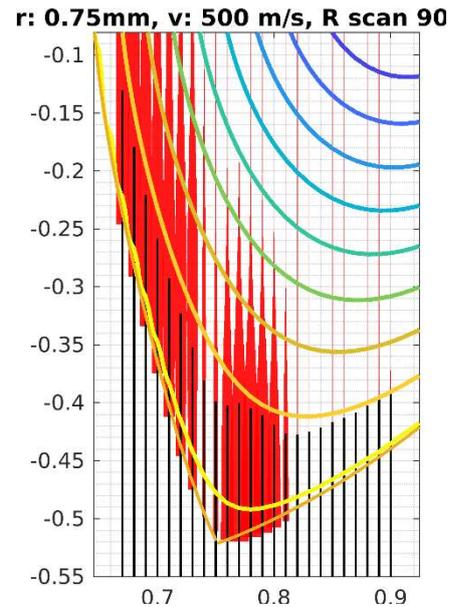


Figure 3. radial scan of VHFS

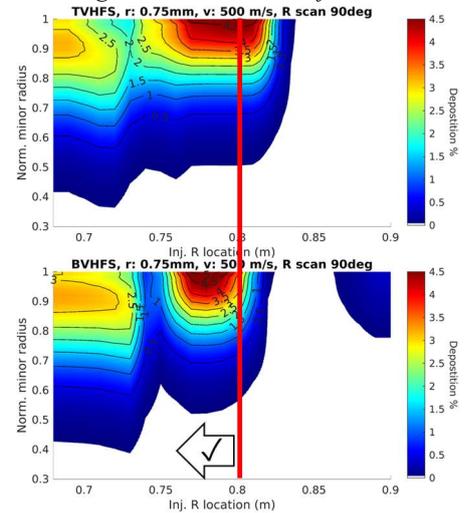


Figure 4. VHFS scan deposition heatmap

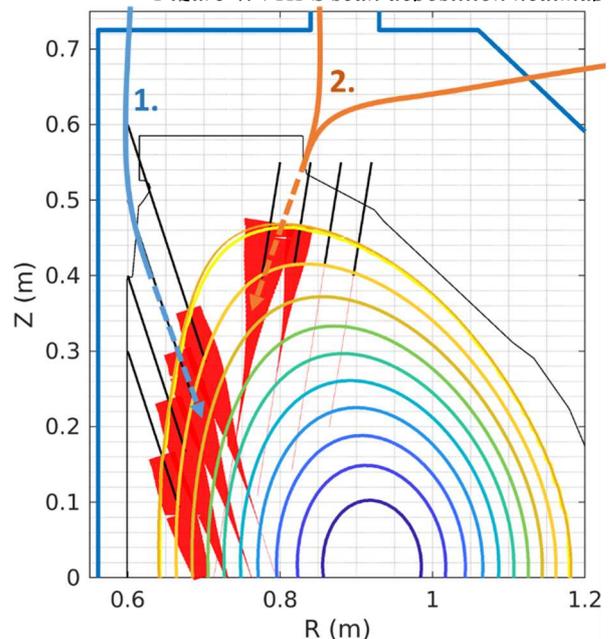


Figure 5. considered guide tube paths: 1-new, 2-existing port

inward toward $R < 0.8\text{m}$ (2.). This configuration can also achieve nearly 100% deposition, though with a slightly shallower profile, depositing more material toward the plasma edge.

Finally, the exact parameters of the injection were iterated (see figure 6, rocket effect also included). The top and bottom ports in sector 15 are currently reserved, for the pellet injection guide tube.

In conclusion, our optimization of pellet injection geometry for COMPASS Upgrade using the HPI2 code has identified the vertical high-field side (VHFS) injection as the most effective geometry for fuelling, even in high-performance H-mode scenarios, although

deposition profiles are highly sensitive to injection geometry due to magnetic field-driven drifts. An exact geometry has been identified using a curved guiding tube from an existing port, achieving complete deposition. Simulations confirm that $r=0.75\text{ mm}$ pellets launched at 500 m/s and 10 Hz meet the refuelling requirements. These results provide a strong foundation for the design and implementation of an efficient pellet fuelling system for COMPASS-U.

References

- [1] M. Komm *et al* 2024 *Nucl. Fusion* **64** 076028
- [2] N. Panadero, 2017, Ciemat report
- [3] T. Szepesi, PhD thesis (2009)
- [4] T. Szepesi, FED 96-97 (2015)
- [5] P. Lang, RSI 74 (2003) 3974
- [6] A. Lorenz *et al*, RSI 71 (2000) 3736
- [7] P. Lang, FED 96-97 (2015) 123
- [8] T. Szepesi, *Nucl. Materials*, Vol 390–391, 2009

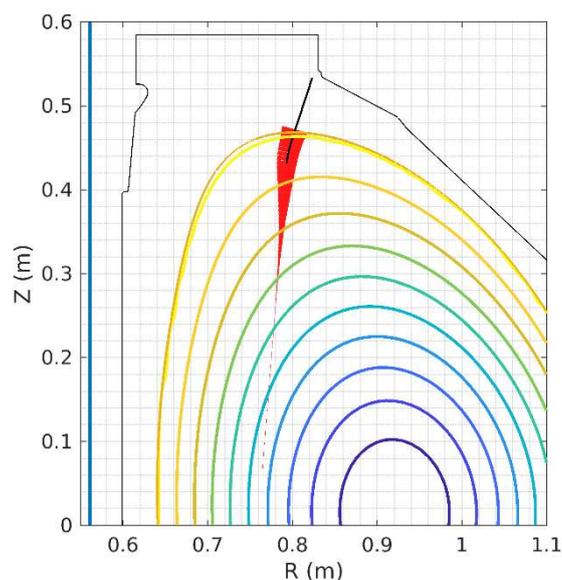


Figure 6. iterated proposed injection geometry