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Simulation and developments for large pellet formation and acceleration for shattered pellet injection of the ITER DMS

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Among the technological developments needed for ITER, the disruption mitigation system (DMS) is one of the most challenging since it has to mitigate the consequences of high-energy plasma disruptions to ensure the lifetime of ITER's structure and in-vessel components. ITER DMS is using Shattered Pellet Injection, whose technology needs to be developed for ITER specific requirements.

In the framework of the "Technology Fundamental Studies for DMS" contract with ITER Organization, as part of the ITER DMS Task Force activities, and CEA, the DSBT (Low Temperature Systems Department) designed and operates a pellet injection test bench to produce and accelerate large cryogenic pellets with diameters from 10 to 28.5 mm and length/diameter ratios up to two. The objective of this activity is to study and to optimise the pellet formation and acceleration process using pure Protium, Deuterium, Neon and mixtures of these gases.

Analytic and numerical studies were used to define the geometrical and cryogenic parameters for the pellet desublimation in the in-situ condensation cell of the cryostat. An analytical model has also been developed for the pellet acceleration in the single stage gas gun to validate the propellant valve design aiming at achieving velocities of up to 500 m/s for 28.5 mm protium pellets and 200 m/s for neon pellets.

The complete test bench is composed of the gas propulsion system, the cryostat with its key component the pellet formation cell, the flight tube and the target chamber with viewing ports. The mechanical assembly is completed with specific instrumentation and fast data acquisition systems for the observation of the pellet formation and acceleration. The pellet integrity and trajectory are characterised by shadowgraphy with high resolution, high-speed cameras located at 1 m and 3 m after the barrel exit and with an accelerometer and a target foil in the target chamber.

This document details the simulation studies, the selected test bench design and first obtained results.

Keywords: Disruption Mitigation System, Shattered Pellet Injection, In-situ pellet desublimation, ITER DMS.

1 Introduction

The design of the ITER's disruption mitigation system is based on shattered pellet injection (SPI). Although this technic is now widely tested on tokamaks [1], [2], [3] using in-situ condensation principle for the pellet production, the SPI technology poses for the ITER DMS a number of challenges, which are addressed through a dedicated ITER DMS Task Force programme [4]. For instance, the ITER DMS requires the use of large pellets made of protium, neon and protium/neon mixtures, with dimensions of $\text{Ø}28.5 \times 57$ mm. Based on past CEA designs [5] which demonstrate the capacities for high quality strength ice for high-speed pellet injection, CEA/DSBT developed and now operates, in the framework of the "Technology Fundamental Studies for DMS" contract with ITER Organization, a pellet injection test bench to produce and accelerate $\text{Ø}10$, $\text{Ø}19$ and $\text{Ø}28.5$ mm pellets. To support the design and operation, extensive analytical and numerical simulation works have been performed to predict and control the pellet formation and acceleration.

2 CEA/DSBT test bench for the technology fundamental studies for ITER-DMS

Figure 1 shows the test bench, installed and operated at CEA/DSBT laboratory. It is composed of, the high-

pressure propulsion valve (1), the cryostat (2), an expansion volume (3), the diagnostics line (4) and the target chamber (5) where the pellet is fragmented and sublimated (from right to left on the layout). Vacuum systems provide secondary vacuum in the whole desublimation cell, diagnostic line and target chamber prior to pellet production and firing. Two sets of light barriers measure the pellet speeds in two positions: just after the barrel exit and just before the target chamber. At the same positions, horizontal and vertical cameras provide pellet characterization such as pellet integrity, speed, sizes and trajectory.

2.1 Propulsion valve for single stage gas gun

A pneumatic actuated fast valve (Figure 1 ref. 1), designed by THIOT Engineering, provides high-pressure gas (H_2 or He gas up to 15 MPa) behind the pellet to accelerate it up to 200 to 500 m/s for the $\text{Ø}28.5$ mm pellets and up to 1000 m/s for the $\text{Ø}10$ mm pellets. The breech volume and the barrel pressure behind the pellet (136 mm after the rear side of the pellet for $\text{Ø}28.5$ cell, 61 mm for $\text{Ø}10$ mm cell) are recorded by piezoelectric fast pressure sensors and shown on Figure 2 for a $\text{Ø}10 \times 23$ mm H_2 pellet (320 mg) exiting the 0.7 m long barrel at 450 m/s. The pressures remain constant because the propellant valve remains open.

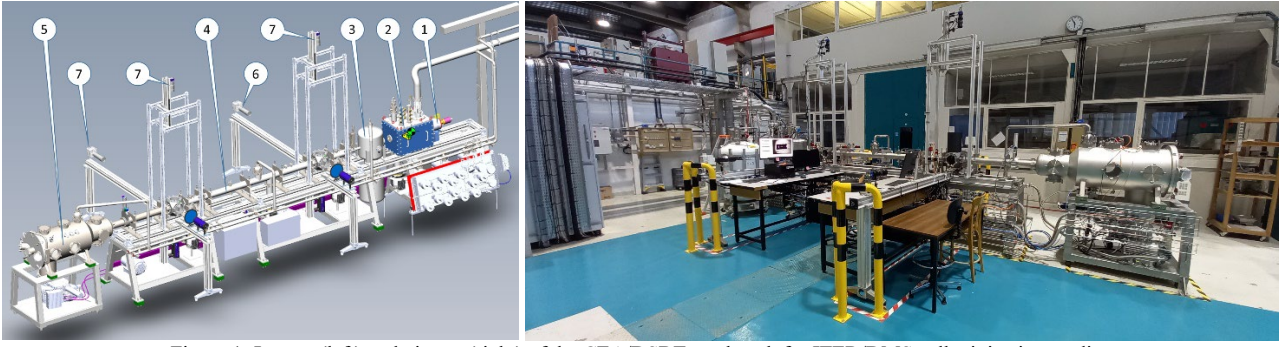


Figure 1: Layout (left) and picture (right) of the CEA/DSBT test bench for ITER/DMS pellet injection studies

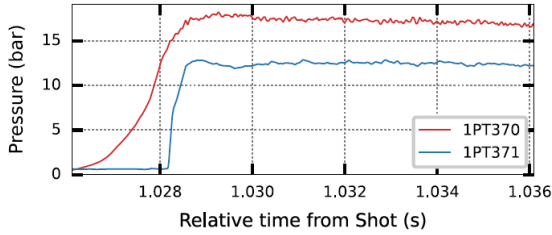


Figure 2: Breech volume pressure (red) and downstream barrel pressure (blue) at 61 mm of the cold cell for Ø10mm H₂ pellet

2.2 Cryostat and in-situ desublimation Cells

The cryostat shown in Figure 3 is a cubicle type cryostat to ease access to the components and to mimic the foreseen ITER-DMS cryostat shape, which shall include six in-situ desublimation cells.

A single liquid helium circuit supplied from a mobile LHe Dewar cools the cold cell (1), then the gradient heat sinks (2) and finally the thermal shield (3) before exiting the cryostat through an electrical heater to warm up the helium gas to ambient temperature.

The injected gas goes through two independent feeding circuits, up-stream and downstream of the cell. The copper cell is vacuum brazed on the thin wall barrel to minimize the temperature difference between helium cooling and the desublimation zone.

For the Ø19 and Ø28.5 mm cells, an additional precooler (4) cools the injected gas to be desublimated prior its injection in the barrel, in order to reduce the heat loads on the cold cell and to achieve shorter desublimation duration, as ITER duty cycle request a pellet production within 30 min.

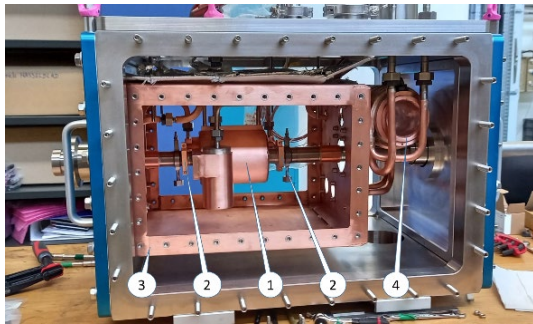


Figure 3: Ø28.5 mm in-situ desublimation cell in the cryostat

2.3 Diagnostics line

The pellet exits the barrel into a 50 L propellant gas expansion volume (as in the ITER-DMS design to limit

gas injection in the plasma) and flies then through a DN 100 and 4.5 m long tube before entering to the target chamber (simulating the plasma chamber) where the pellet is stopped and sublimated. Three sets of turbo-molecular and scroll pumps provide a pressure range of 10⁻⁷ to 10⁻⁶ mbar in the diagnostics line and the target volume before the pellet production and firing as required by ITER-DMS specifications.

2.4 High speed and high resolution cameras

One high-speed Phantom VEO1310 camera is installed horizontally (Figure 1 ref. 6) at 1.1 m from the barrel exit. This 1.2 M-Pixel @ 10 kHz camera provides low-resolution images but record during about two seconds the events prior and after the pellet passing.

Three LaVision SX 6M long exposure cameras set vertically and horizontally (Figure 1 ref. 7) provide high-resolution images. A double frame mode allows to determine the pellet speed. All the cameras are equipped with a LED flash lamp with a Fresnel's lens to backlight the pellet with minimum flash duration of 100 ns, which seize the object at 500 m/s with 50 µm resolution. These cameras provide typical pictures as shown in Figure 8 for Ø28.5 mm pellets.

3 In-situ desublimation Simulation

To support the design and the exploitation phases, CEA/DSBT developed a numerical desublimation model. The model aims at simulating the pellet formation process inside the barrel taking into account the actual cell geometry and material and the properties of the pellet material. The model is based on finite elements model as implemented in the COMSOL software.

The outputs of the model are the pellet shape as well as the time evolutions of the mass flow and the power to be extracted at the cold head.

The numerical simulation is based on the Hertz-Knudsen expression for sublimation/desublimation mass flow [6], [7] and simplified as followed:

$$\dot{m}_{HK} = \sigma \sqrt{\frac{M}{2\pi RT}} (P - P_{sat}(T)) \text{ [kg/m}^2\text{/s]}$$

In this expression, it is assumed that there is no difference between the gas and the pellet temperatures at the solid/gas interface; $T_{gas} = T_{pellet} = T$.

The parameter σ is an empirical coefficient to reflect the probability of a molecule to stick to the solid. Since the incoming gas is assumed to be pre-cooled between 50 and 70 K, $\sigma = 1$ has been used according to the reference [8].

3.1 Thermal numerical setup

The thermal boundary conditions of the model are shown in Figure 4. The simulation is split into three domains: the wall of the cell, the solid, and the feeding gas.

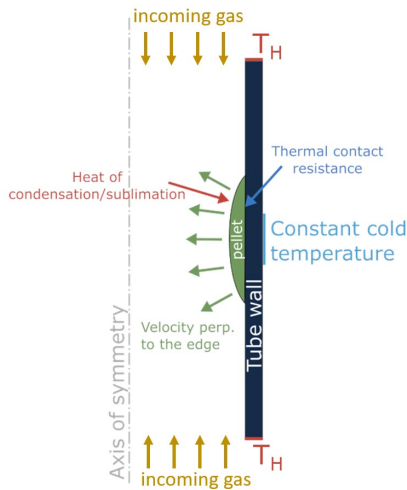


Figure 4: Model thermal conditions

The cell wall has imposed temperatures. The cold temperature set at the cell central part mimics the cooling power of the experimental setup while the so-called “hot” temperature is imposed at the cell extremities to control the length of the pellet.

The temperature-dependent properties of the material (H_2 , D_2 , Ne or mixtures and the cell wall steel) are used. A heat source condition is also imposed at the surface of the pellet to take into account the heat of sublimation/desublimation and the gas cooling prior to desublimation.

The pellet domain grows at the rate imposed by the Hertz-Knudsen mass flow. A remesh of the domain is performed whenever the mesh quality falls below a fixed threshold.

3.2 Model benchmark at the design phase

The model was benchmarked against existing measurements in CEA/DSBT lab on $\varnothing 6$ mm D_2 pellets [5] for the same operating conditions (desublimation duration, temperature and pressure).

Figure 5 shows the dependence of the D_2 pellet mass on the hot temperature T_H as measured (blue points) and as simulated (red line) in the same operating conditions (duration and pressure). The difference remains within 10% and the evolution of the mass is correctly modelled. The mass is experimentally measured by the amount of injected gas from a given volume. This method has been counter checked by the pressure raise after static sublimation of the pellet. Mass measurements from the images treatments are less reliable due to pellet tilt, deviation and fragmentation (mass loss).

Using the benchmarked model, the required cooling powers for the pellet formation process were estimated to design the relevant DMS cells fulfilling the ITER needs.

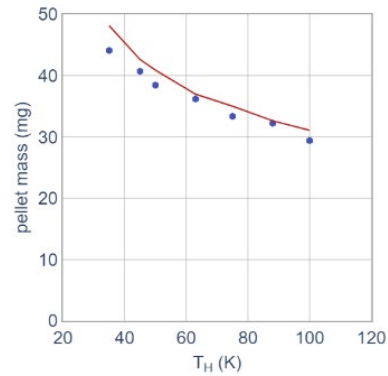


Figure 5: Model (solid line) benchmark against D_2 measurements (points) for $\varnothing 6$ mm D_2 , cold zone at 15 K and desublimation pressure at 70 mbar.

3.3 $\varnothing 10$ mm pellet model comparison

The formation model is also compared to the measurements of the produced 10 mm H_2 pellets.

Figure 6 shows the computed mass of the pellet as a function of the temperature together with the mass of pellets obtained for different formation durations for a formation pressure of 12 mbar. The model is overestimating the mass obtained for a given formation duration of less than 10 %.

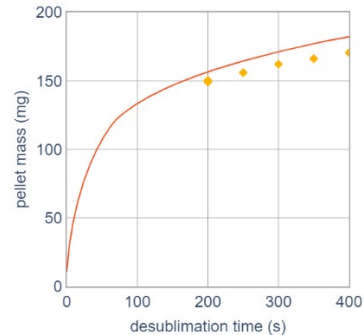


Figure 6: Model (solid line) and measurements (diamonds) comparison for 10 mm H_2 pellets, cold zone at 5 K and desub. pres. at 12 mbar.

Comparison of the model with the pellet obtained in the 28.5 mm cell is on-going. The first results confirm the same tendencies observed for the 10 mm cell.

4 First experimental results

4.1 Results on $\varnothing 10$ mm in-situ desublimation cell

Following the commissioning of the test bench, the experiments started in March 2022 with the 10 mm cell. With more than 140 shots having intact pellets, protium and deuterium pellets have been extensively characterized.

The main studied parameters were:

- The desublimation cell temperature from 4.5 to 9 K,
- The desublimation pressure from 12 to 60 mbar,
- The desublimation duration from 60 to 900 seconds.

Figure 7 shows typical time traces of the cold head temperature, pressure and flow during the pellet

formation phase for Ø10 mm H₂ pellet formed at 8 K and 12 mbar.

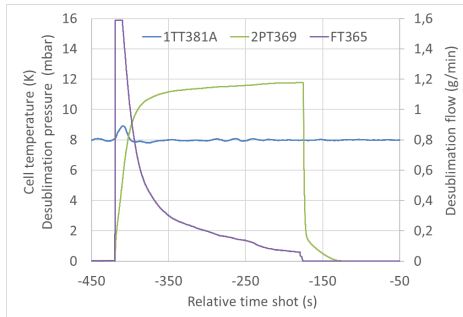


Figure 7: Typical cell temperature (blue – 8K), desublimation pressure (green – 12 mbar) and flow rate (purple) for Ø10 mm H₂ pellets

4.2 Results on Ø28.5 mm in-situ desublimation cell

Experimental works on the Ø28.5 mm cell started in July 2022. More than 90 intact pellets have been already produced and fired. Preliminary results are illustrated on Figure 8 for protium and neon pellets.

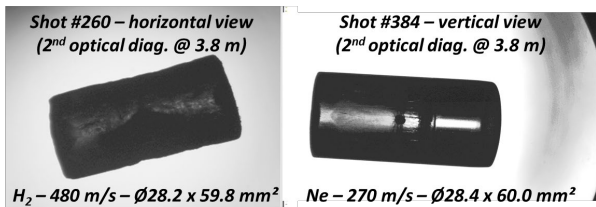


Figure 8: Protium (left) and Neon (right) pellets both formed at 5 K

Figure 9 shows typical time traces of the cold head temperature, pressure and flow during the pellet formation phase for Ø28.5 mm H₂ pellet formed at 5 K and 72 mbar. At the beginning of the pellet formation, the desublimation flow is largely larger than the flowmeter range. The experimental measurements, as predicted by the simulation design works, demonstrate the specified protium pellet formation duration in less than 30 min.

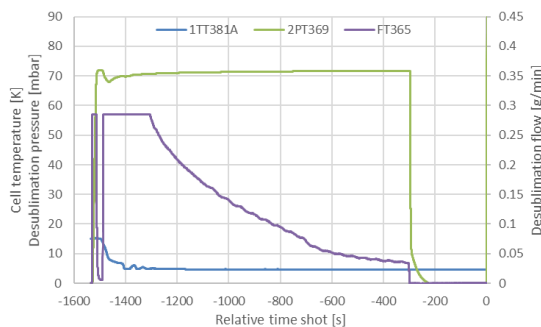


Figure 9: Typical cell temperatures (blue – 5K), desublimation pressure (green – 72 mbar) and flow rate (purple) for Ø28.5 mm H₂ pellets

5 Conclusion

The CEA/DSBT test bench is operational and first pellet shot results are available for the ITER DMS Task Force to guide the design of the ITER DMS. Pellet formation parameters for Ø10 mm H₂ and D₂ pellets have been extensively characterised in temperatures, pressures and durations. The measurements are promising and confirm the reliability of the desublimation simulation model. The preliminary results on Ø28.5 mm pellets in H₂, D₂ and Ne prove their feasibility and are encouraging

to fulfil the ITER DMS constraints for pellet formation duration and pellet speed. Experimental campaigns are now on going to complete the characterization of the pellet formation and acceleration and to define the optimum parameters for pellet formation and acceleration of the Shattered Pellet Injectors of the ITER DMS.

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Disclaimer

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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