Injection of high-speed solid D_2 pellets using a “Direct-Line-of-Sight” (DLS) guide tube

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ABSTRACT

Extensive investigations, within the EUROfusion Work Package "Tritium, Fuelling and Vacuum", indicate that sufficiently deep fuel deposition inside H-mode plasmas of the EU-DEMO tokamak requires injection of fuel pellets from the High Field Side (HFS) at speeds ≳ 1 km/s. To implement this, two different approaches are being pursued: one makes use of “conventional” curved guide tubes, *featuring large bend radii (≳ 6 m), to transport 1 km/s pellets to the HFS while trying to preserve their mass and integrity; the other explores the feasibility of injecting high-speed (≳ 2 km/s) pellets from the HFS, along "Direct-Line-of-Sight" (DLS) paths. This paper focuses on the latter approach. Recent tests with an existing ENEA-ORNL high-speed injector have confirmed that the trajectories of free-flight pellets, travelling under vacuum at speeds up to 2.4 km/s, spread within an angle ≲ 0.68°. Despite their small scatter cone, free-flight pellets may require too much cut off volume of the Breeding Blanket (BB), due to the large distance between the injector and the plasma. The introduction of a straight DLS guiding tube transporting the high-speed pellets, to avoid significant loss of BB material, has been investigated. The existing ENEA-ORNL injector has been modified to accommodate a 10 mm i.d. DLS guide tube, and intact pellets have been consistently delivered downstream of the guide at speeds up to 2.6 km/s, with remarkably reduced scatter cone, thus showing the viability of this innovative approach.*

Keywords: EU-DEMO tokamak, Oblique High Field Side (OHFS) injection of high-speed pellets, straight DLS guide tubes

1. Introduction

Core fuelling of the EU-DEMO Tokamak is being investigated, as part of the EUROfusion Work Package Tritium, Fuelling and Vacuum (WP-TFV). An extensive analysis of fuelling requirements and available technologies, suggests that pellet injection still represents, to date, the most realistic option for deep fuel (or impurities) deposition in DEMO [1].

While in present-day tokamaks the pellet penetration can contribute to improve the fuel deposition depth, this seems to be no longer true in the case of a fusion reactor; simulations performed using the HPI2 pellet ablation-deposition code [2] indicate indeed that, in DEMO, the fuel deposition is strongly dominated by the outward displacement induced by the ∇B [3,4], so sufficiently deep particle deposition profiles can be achieved only launching pellets from the High Field Side (HFS) at speeds ≳ 1 km/s. In present tokamaks, curved guiding transfer systems are usually employed to inject pellets from the HFS. This injection scheme has been proposed, as a first approach, also for DEMO; however it suffers of many drawbacks that may hamper its use at speeds of ~ 1 km/s, as exhaustively discussed in ref. [5]. Indeed, when travelling inside a curved guide tube, pellets undergo centrifugal stress, which is proportional to their mass and to the square of their speed, and inversely proportional to the local curvature radius R of the guide; this stress may break the pellets, due to the poor mechanical strength of the deuterium ice, and may also cause mass erosion, speed losses and pressure build-up inside the tube [6,7]. Lacking a proper model, an empirical scaling law, calibrated on the ASDEX Upgrade (AUG) experiment for cubic shaped pellets [8,9], is commonly adopted to relate the maximum injection speed V_{inj} (m/s) that pellets can withstand without fracturing, to the curvature radius R (m) of the guide tube and to the pellet size L (m):

$$V_{inj}\ (m/s) \leq\ 36.4\sqrt{R\ /L} \tag{1}$$

Taking into account the substantial mass erosion (~ 80%) associated with the requested injection speed of ~ 1 km/s [7], eq. (1) predicts a minimum curvature radius of ~ 6 m for the guide track, in order the pellets can survive and be delivered intact at the plasma edge with the desired final mass [5]. It is unclear, however, whether the empirical law (1) can be safely extended to the considerably larger pellet size and to the higher injection speeds required for DEMO.

A dedicated R&D effort is ongoing within the TFV, aimed at optimizing the design of the pellet transfer system, to try filling the substantial gap between the performance of present curved guide tubes, and those needed for DEMO [10]. However, in case this technology will prove inadequate for DEMO, complementary approaches to implement HFS injection need to be investigated.

2. HFS injection of high-speed pellets along “direct-line-of-sight” (DLS) trajectories

The only realistic way to get rid of the issues related to curved guide tubes, consists in implementing inboard injection schemes that allow the pellets to travel along “direct-line-of-sight” (DLS) paths [5]. To assess the feasibility of this complementary approach, a preliminary analysis has been performed, aimed at identifying viable DLS injection lines accessing the plasma either vertically or from the HFS, compatible with present DEMO engineering constraints or requiring acceptable revision of the current design. Options using the upper vertical port have been explored first, since they represents by far the simplest approach. However, the position of the vertical port in DEMO is such that pellets injected through it are predicted to not yield sufficiently deep fuel deposition for the injections velocities available with current technologies [11,12], so HFS injection is being presently investigated, since this scheme is predicted to provide better fuelling performance [11]. Due to the interference with the central solenoid (CS), DLS injection paths from the HFS must be necessarily oblique, a configuration which is referred to as Oblique High Field Side (OHFS) injection, that might lead, as in the case of curved guide tubes, to make compromises on the possible injection configurations, particularly as the angle that the pellets trajectory forms with the magnetic surfaces is concerned. However, compared to conventional arrangements that make use of curved guide tubes, the DLS injection scheme allows in principle to inject pellets at significantly higher velocities; this peculiarity does indeed help to recover sufficient fuelling performance, despite a potentially less favorable layout. Preliminary simulations carried out using the HPI2 code indicate indeed that there are possible OHFS injection configurations providing performance (in terms of fuel deposition depths and fuelling efficiency) comparable to those achievable by pellets injected at 1.3 km/s through a curved guide tube featuring a curvature radius R = 6 m, provided that the OHFS injection location does not exceed a distance z_{inj} of ~ 2.5 m from the equatotial midplane [11]. A more detailed investigation is still ongoing, aimed at optimizing the injection location, and will be published elsewhere as soon as the results will become available.

Two-stage pneumatic launchers have already demonstrated their ability to reliably propel solid D_2 pellets in the 3 to 4 km/s range [13-14], if combined with suitable “pipe gun” cryogenic pellet sources (equipped with either one or more launching barrels) [15], as well as to accelerate sequences of extruded D_2 pellets, 2.7 mm in size, at speeds up to 2.5 km/s and frequency of 1 Hz [16,17]. Large D_2 pellets (6 mm) have also been launched at speed up to 2.5 km/s using a pipe-gun injector equipped with a two-stage driver [18]. Moreover, this technology has the potential to provide even higher speed performance, by adopting advanced layouts, such as the “double piston” configuration [19]. It represents, therefore, a realistic candidate for high-speed pellet launching.

3. Angular dispersion of free-flight high-speed pellets

In a pneumatic injector, once the pellets get out of the launching barrel, their free-flight trajectories spread within a given scatter cone. Experiments performed many years ago with the high-speed pellet injectors for the Frascati Tokamak Upgrade (FTU), have shown that the free-flight trajectories of 1.6 mm solid deuterium pellets, travelling at velocities up to ~ 3 km/s, are enclosed within a cone having a vertex angle of about 0.01 rad (~ 0.57°) [13]. Actually, the angular distribution width of free-flight high-speed pellets trajectories is an important information to derive a functional design for DEMO. Due to the many structures surrounding the plasma, such as the bio-shield, the cryostat, the breeding blanket (BB) and the vacuum vessel (VV), the pellet injector needs indeed to be placed many (~ 20) meters from the plasma. It is quite evident that the longer is the free-flight distance that the pellets have to travel to reach the plasma, the larger is the cross section of the apertures they need to get through the above mentioned structures. Recently, the angular distribution of the free-flight trajectories of high-speed pellets, having a size (4.4 mm) comparable to that required for DEMO core fuelling, has been measured, to consolidate the results of previous similar experiments with smaller pellets, as well as to provide a reference case for any successive investigation. These preliminary tests have been carried out using an existing high-speed pellet injector, originally designed for the Ignitor experiment and therefore named “IPI” (Ignitor Pellet Injector). This facility, developed in collaboration between ENEA and ORNL, has been described exhaustively elsewhere [20,21]; the four-barrels “pipe gun” cryostat of the IPI has been recently upgraded, resulting in a significant improvement of the injector performance [11,12]. The specific arrangement used for scatter cone measurement, the analysis of the experimental data, and the results are also reported in detail in ref. [12]. In summary, a total of 62 solid deuterium pellets (4.4 mm in diameter and aspect ratio 1.7) were consistently formed and launched at speeds ranging between 1.4 and 2.4 km/s, and the resulting impact pattern on a target placed about 3.77 m downstream of the gun muzzle was recorded. The impact position of each pellet was identified as the center of the roughly circular hole that the projectile had produced in the target; the two sets of x and y coordinates of all the impact positions were assumed to be statistically independent, and separately fitted using normal distributions, whose standard deviations were estimated to be respectively σ_x = 8.9 mm and σ_y = 6.8 mm. The angle at the vertex of the scatter cone was estimated to be within ~ 0.68° (or ± 0.34°), a result that does not differ so much from that previously obtained with the FTU injector, for significantly smaller pellets.

4. Preliminary experiments using a DLS guide tube

Though the dispersion cone of free-flight pellets turns out to be rather small in absolute terms, it still has a considerable impact on the reactor design, due to the considerable distance that the pellets have to travel in order to reach the plasma. For instance, after a free-flight of ~ 20 m (which is a realistic value for DEMO), a hole with a diameter of ~ 24 cm would be required in the BB. The adoption of a straight guide tube, able to confine the trajectories of the pellets within a much narrower DLS duct, could get rid of this issue [11]. So far, high-speed cryogenic pellets have always been launched across pipes featuring a sufficiently large cross section to ensure “free-flight” conditions, for fear of destroying the projectiles by collisions. It has been reported, indeed, that the impact of solid D_2 pellets against a surface may lead to fracturing if the component of the impact velocity normal to the surface exceeds a critical value ranging from ~ 20 m/s (for cylindrically shaped pellets with Ø2.7 or Ø10 mm) [22] up to ~ 40 m/s (for cylindrically shaped pellets Ø1.0 × 0.9 mm) [23]. However, D_2 pellets travelling inside a guide tube with a velocity vector that forms an angle α with the tube axis (and hence with the tube wall), equal to the maximum measured angular spread (± 0.34°), may hit the side wall of the tube with a velocity normal component $V_\perp > 20\div40$ m/s only provided that their speed exceeds $V_\perp/\sin\alpha > 20\div40/\sin(0.34°) \cong 3370\div6740$ m/s. For smaller values of α, even higher speeds are expected to be necessary to lead to fracturing of the pellets. These velocity limits are predicted starting from experiments carried out with relatively low speeds and represent just a rough estimate, however they are large enough for being expected to not induce any problems for 2.7 km/s pellets.

The feasibility of using DLS guide tubes is becoming increasingly relevant for a potential application in DEMO. A sound experimental plan, aimed at identifying, and possibly solving, potential issues that might hamper the viability of this highly innovative injection scheme, as well as at pointing out eventual criticalities that may limit its reliability and/or performance, is being outlined within the TFV. However, to identify a reasonable starting point, some preliminary experiments have already been performed using the existing ENEA/ORNL high-speed injector, which has been modified in order to further improve its speed performance and to accommodate a DLS guide tube. The experimental layout used and the very encouraging results of these initial tests are described in detail in the following paragraphs.

4.1. Recent further improvement of the IPI speed performance

The ENEA sub-system of the IPI includes four independent two-stage pneumatic guns (TSG), each equipped with a special valve that accommodates, in a single-body arrangement, both an electro-pneumatically driven cut-off ball valve, and a check valve, which is closed by the electromagnetic force generated by the electric current flowing through a coil [24,25].The normally closed (NC) ball valve separates the two-stage gun from the launching barrel during pellet formation and opens, for a very short time, just in order the high pressure propellant pulse produced by the two-stage gun can accelerate the pellet during a gunshot. The check valve opens only once the force exerted on the valve shutter by the increasing propellant pressure overcomes the electromagnetic closing force, thus protecting the piston that is prevented from hitting the end of the pump tube. This valve allows also adapting the shape of the rising edge of the pressure pulse produced at the gun breech, to optimize the acceleration of the projectile all along the gun barrel. A specific innovative arrangement, developed at a later time, allows accommodating on each barrel both a single-stage and a double-stage gun [24,25], thus gaining greater flexibility and conferring to this injector a further distinctive feature. As a first preliminary attempt to proof the functionality of this unique configuration, without introducing significant changes to the injector design, a rough-and-ready provisional layout was adopted, which however results in increasing the dead volume of the gun breech, likely limiting to some extent the speed performance. To overcome this issue, the ENEA team has recently built a new prototype of the valve complex at the interface between the two stage gun and the cryostat. The new design incorporates the earlier temporary layout so as to minimize undesired dead volumes, and decouples the ball valve from the check valve, which are now two distinct bodies featuring the same upstream and downstream connecting interfaces. This allows fitting either the cut-off ball valve only, the magnetic check valve only, or both (in series).

Preliminary tests have been recently performed using only the new ball valve (figure 1) in order to minimize the dead volume. These tests allowed consolidating and further improving the speed performance achieved during the previous experimental campaign (2.4 km/s) devoted to scatter cone measurement. With the new configuration, intact solid deuterium pellets, 4.4 mm in diameter and featuring a nominal aspect ratio of 1.7, have been accelerated at speeds up to ~ 2.76 km/s. Figure 2 shows the in-flight picture of a pellet (shot # 14399) travelling, from right to left, at 2604 m/s.

Figure 1. the new interface at the gun breech with the ball valve only

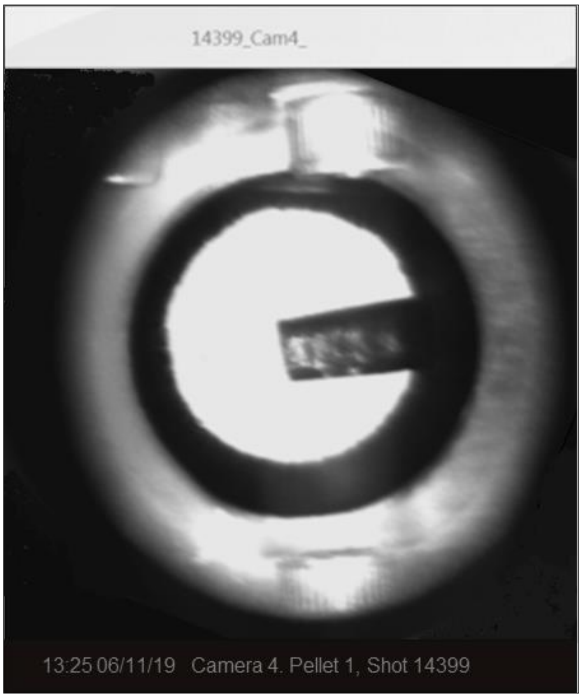

Figure 2. In-flight picture of a pellet travelling (from right to left) at 2604 m/s.

4.2. Experimental layout for preliminary tests with a DLS guide tube

The IPI has been further modified to accommodate a DLS guide tube, in order to preliminarily identify the potential issues, never addressed before, related to this configuration. Only barrel 4 (4.4

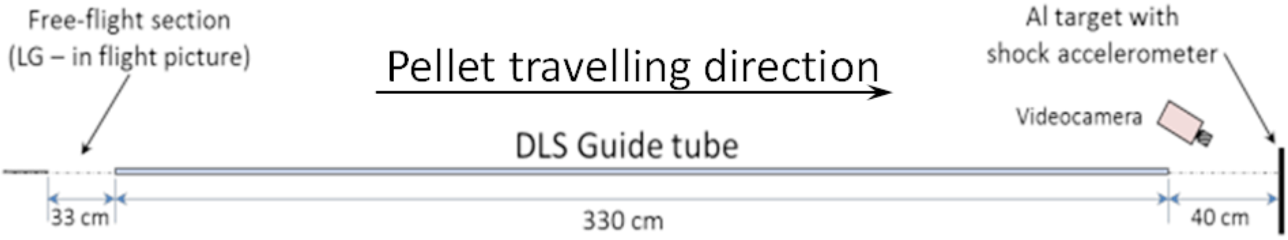

Figure 3. Schematics of the experimental layout with the DLS guide tube

mm bore) has been used for these tests. The very simple experimental layout used is schematically shown in figure 3. The large diameter (DN 150 ISO KF) tube used to ensure free-flight of the pellets during scatter cone measurement [12] was removed, and a stainless steel DLS guide tube, featuring inner and outer diameters of 10 mm and 12.5 mm respectively, and an overall length of 3.3 m, was fitted on barrel 4. The upstream end of this guide tube is located at a distance of ~ 33 cm from the gun muzzle; pellets travel this distance under free-flight conditions, across an evacuated diagnostic system including a light-gate (LG) and an in-flight photographic station (PHS), before entering the guide tube. The diagnostic apparatus of the IPI usually comprises also a microwave cavity (MWC) located 30 cm downstream of the LG, which provides a measurement of the pellet mass, and allows to evaluate the pellet speed by measuring the time of flight (TOF) between the LG and the MWC. This latter, however, was removed to allow the upstream end of the guide tube to get as close as possible to the gun muzzle, with just minor adaptation of the existing hardware. Indeed, the guide tube inlet must be placed, taken into account its diameter, within a corresponding maximum distance from the gun muzzle to ensure that the free-flight pellets can get into the guide despite the angular dispersion of their trajectories. Assuming, for simplicity, that the pellets, 4.4 mm in diameter, do not rotate at all after exiting the gun muzzle, their radial displacement after 330 mm of free-flight, must not exceed (10 - 4.4)/2 = 2.8 mm, in order they can get into the guide tube entrance (10 mm i.d.). This corresponds to a maximum scatter angle of the trajectories within about ± 0.49°. It is well known, on the other hand, that for a normal distribution with mean value μ and standard deviation σ, about 68.27% of values lie within the interval $\mu \pm \sigma$, about 95.45% lie within $\mu \pm 2\sigma$, and about 99.73% lie within $\mu \pm 3\sigma$. The former scatter cone measurement of free-flight trajectories indicates therefore that 99.73% of the pellets are expected to hit a target, placed 377 cm downstream of the gun muzzle, within $\pm 3\sigma_x \cong \pm 26.7$ mm along the x axis, and $\pm 3\sigma_y \cong \pm 20.4$ mm along the y axis, from the center (x_0, y_0) of the distribution [12]. We can therefore assume, conservatively, that even more than 99.73% of the pellets are expected to hit the above mentioned target, within a circle having a radius of $3\sigma_x \cong 26.7$ mm. By scaling down this radius over the shorter distance of 330 mm, instead of 3770 mm, we may expect that the center of mass of almost all the pellets will be confined, at the entrance of the guide tube, within a circle (centered in the guide tube axis) having a radius of ~ 2.34 mm (< 2.8 mm), with a free annular gap of ~ 2.66 mm with respect to the inner wall of the guide tube; simple geometrical considerations indicate that this gap, which is greater than the pellet radius (2.2 mm), should be sufficient to allow pellets travelling along a trajectory lying on the scatter cone surface (i.e. with the maximum angular spread given by $\arctan(2.34/330) = \arctan(26.7/3770) \cong \pm 0.4° < \pm 0.49°$), to get into the guide tube even in case they are slightly tilted (roughly within ± 33°). Pellets that move along trajectories inside the scatter cone, i.e. with an angle < ± 0.4°, so as to intercept the guide tube entrance within a circle of radius < 2.34 mm around the axis, should be able to get into the tube even if they are tilted to a larger extent; however, due to the short distance separating the guide tube inlet from the gun muzzle, pellets are unlikely to achieve very large tilting at the guide tube inlet (as clearly shown by figure 2). Moreover, since the pellets trajectories will preferably concentrate in the inner part of the scatter cone, where the normal distribution achieves its maximum, most of the pellets are expected to get into the guide tube, almost regardless of their tilting. This reasoning also indicates that using a funnel to facilitate routing of the pellets across the guide tube may not be necessary; therefore we decided to not include a funnel in this preliminary layout. The guide tube is sustained by a rigid aluminum structure standing on two metallic supports, as shown in figure 4, to prevent possible bending due to gravity.

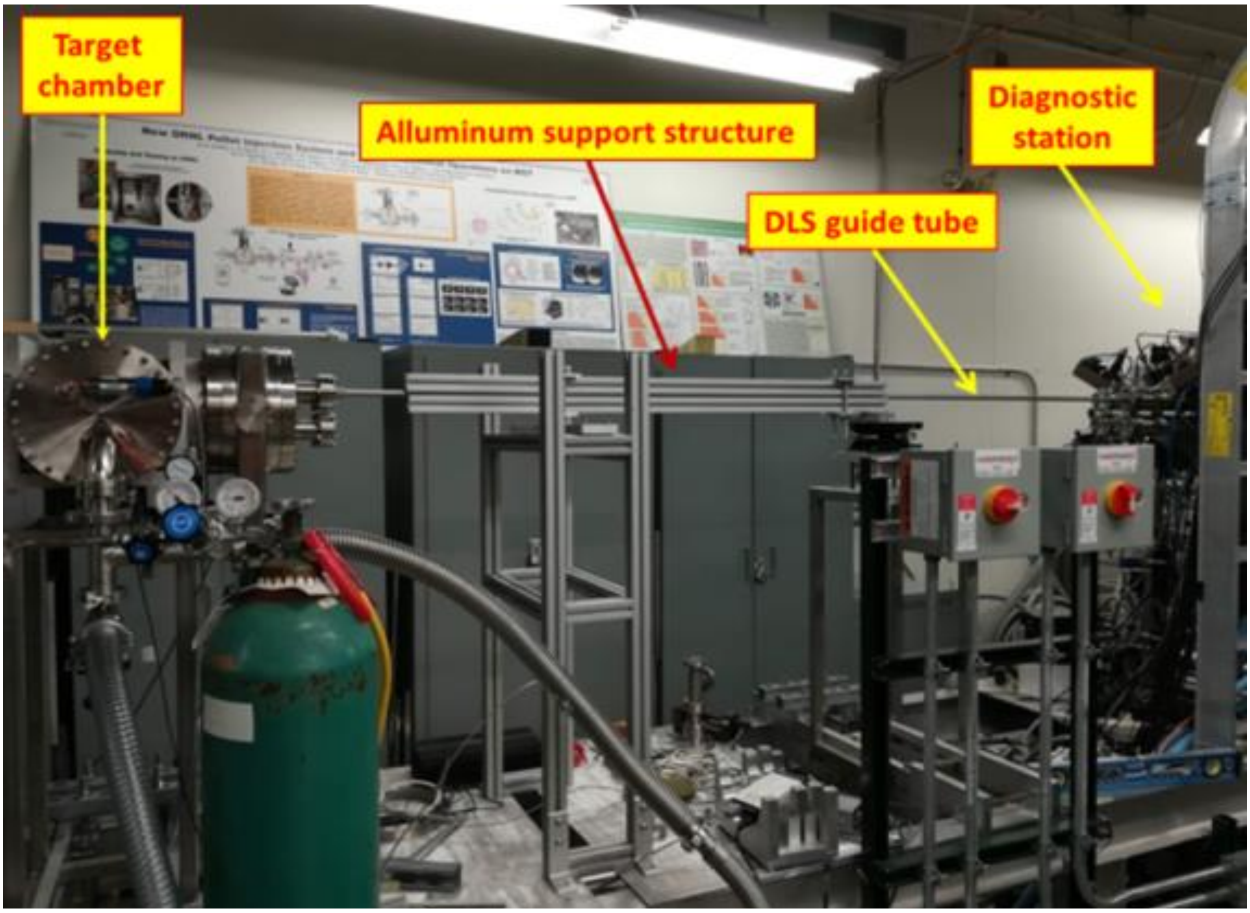

Figure 4. The guide tube assembly with the rigid aluminum support structure

A vacuum chamber, provided with an inlet gate valve and located downstream of the guide tube (figure 5), accommodates a target made out of an aluminum sheet fitted on a dedicated support at a distance of 40 cm from the guide tube exit, to either monitor the integrity and the impact position of each pellet. The target support is equipped with a shock accelerometer, to measure the speed of the pellets, which can be inferred by the time of flight between the light gate and the target, which are 375 cm apart. If desired, the aluminum target sheet can be easily replaced at any time between two shots. A side window in the target chamber allows capturing short videos of each pellet impact, by means of an external camera. The overall distance from the gun muzzle to the target is 33 + 330 + 40 = 403 cm, comparable to that used during scatter cone tests (377 cm).

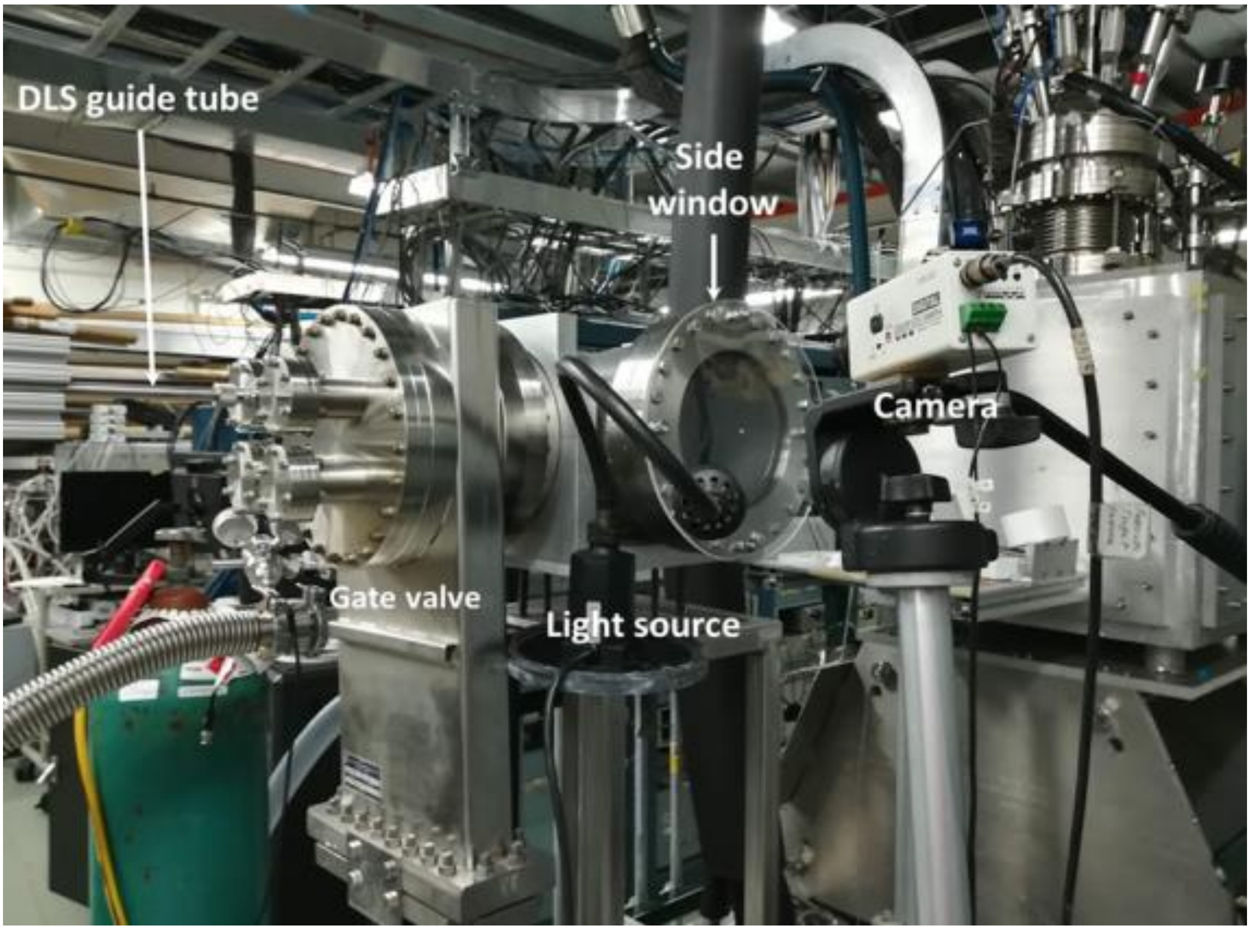

Figure 5. The target chamber and the external camera used to capture videos of the pellet impact

5. Experimental results

During the latest joint ENEA/ORNL experimental campaign (November 2019), a total of 40 pellets, having a diameter of 4.4 mm and an aspect ratio (length/diameter) of either 1.5 or 1.7, were systematically formed and launched at speeds ranging from 1.5 to 2.76 km/s; 30 out of 40 pellets had velocities in excess of 2 km/s (it is indeed good practice to start every day launching a few pellets at moderate speeds, just in order to check that everything is working properly, and then progressively increase the velocity). For speeds up to 2.2 km/s, all pellets have been systematically able to pass undamaged through the guide tube, regardless of their aspect ratio. At higher velocities, pellets formed with this parameter set to 1.7 have been regularly able to travel intact across the free-flight diagnostic station, upstream of the guide tube, except to some extent for shot 14386, where the in-flight image of the pellet, travelling at 2.76 km/s, revealed the presence of both a bulk piece and a very small fragment. Moreover, these pellets have been all able to survive across the guide tube and reach, still intact, the target, except for three cases (shots 13180, 13182, and 14416, with pellets travelling respectively at 2.45, 2.31 and 2.2 km/s). Pellets formed with the aspect ratio set to 1.5 were observed to sporadically break in two halves, almost longitudinally separated from each other, while still travelling across the free-flight section upstream of the guide tube, as clearly witnessed by their in-flight images. This was the case of shots 14382 and 14384, corresponding to pellets travelling respectively at 2.2 and 2.44 km/s; figure 6 shows, for instance, the in-flight pellet image captured on shot 14382. It is quite likely that the lower aspect ratio selected during the pellet formation, which actually results in a smaller amount of deuterium gas being frozen, may occasionally give rise to the grow up of projectiles with a somewhat hollow rear shape, thus causing the propellant pressure to exert a radial force in the outward direction that breaks them longitudinally in two parts as soon as they get out of the gun barrel. Nevertheless, some of the pellets formed with an aspect ratio of 1.5 (shots 14383, 14387, 14389, and 14390), have been anyway collected still intact on the target, after passing undamaged through the DLS guide tube, despite having speeds ranging from 2.3 up to 2.47 km/s.

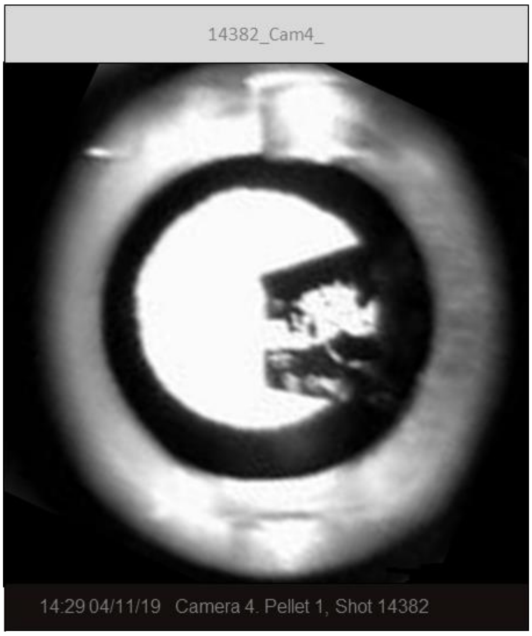

Figure 6. In-flight picture of a broken pellet with aspect ratio 1.5 (shot 14382) moving from right to left at 2.2 km/s

With the target placed at a distance of only 40 cm from the downstream end of the guide tube, no significant dispersion was observed; the impact positions of the pellets on the target turned out to be always very close to each other (often less distant than one pellet diameter), so as to be hardly distinguished at a glance. However, the comparison of the images of the target recorded just before and after each shot shows that a pellet hitting the target in a position just partially corresponding to an existing hole, widens it to a clearly perceptible extent, allowing to detect its impact with absolute certainty. Figure 7 shows, for instance, the impact pattern produced on the target by a rather long sequence of pellets (from shot 14395 to 14412), launched during the last day of experiments (November 6, 2019). All the pellets in this series were formed with the aspect ratio set to 1.7, and launched at speeds well in excess of 2 km/s (from a minimum of 2232 m/s for shot 14410, up to 2604 m/s for shot 14399), except for the first one (shot 14395), launched at ~1.56 km/s. Figure 7 reveals moreover that, compared to the impact pattern obtained during free-flight tests, all the pellets hit the target much closer to the expected position (represented, for each of the four barrels, by the intersection points of the four dashed lines), providing thus evidence that the guide tube is also effective in reducing the aiming error significantly. Of course, by increasing the distance between the downstream end of the guide tube and the target, the dispersion of the impact positions on the target might be appreciated much better than over the short gap used in these

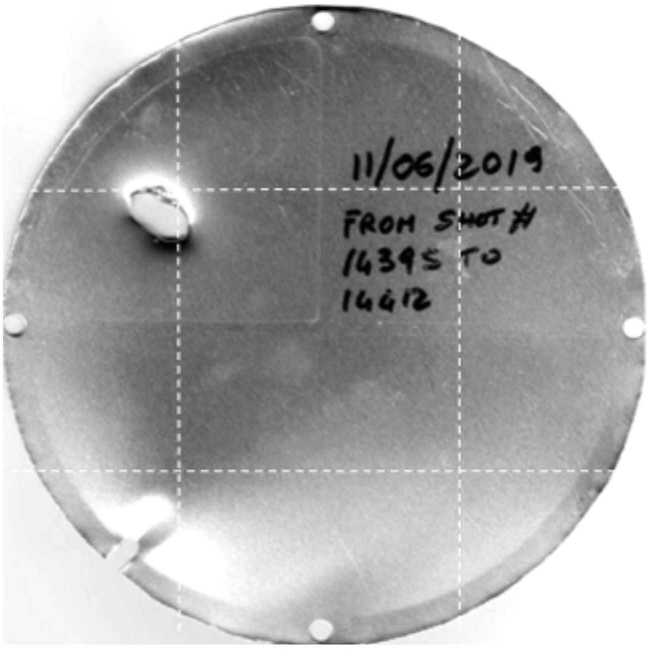

Figure 7. Impact pattern produced by a long sequence (shots 14395 – 14412) of high-speed pellets (aspect ratio 1.7)

preliminary experiments. Unfortunately, the presence of other equipment located on the IPI test bench prevented moving the target chamber more faraway; we plan however to further investigate this issue in the near future. Anyway, the results of these preliminary tests undoubtedly show that, over the total distance of 403 cm from the gun muzzle to the target, the DLS guide tube is able to strongly reduce both the aiming error and the scatter cone, as compared to those measured with free-flight pellets over a total distance of 377 cm.

On the last day of experiments, we also tried to set up a fast framing camera (figure 8), provided by ORNL, to record movies of the high-speed pellets exiting the guide tube and impacting on the target. After a few attempts, we were finally able to properly set the trigger delay of the fast framing camera, and capture images of the last three pellets (shots 14415-14417). Figure 9 shows, for instance, a sequence of images of an intact pellet (shot 14415) travelling (from left to right) at 1.7 km/s. The shape of the pellet looks to be quite cylindrical, indicating that perhaps negligible erosion occurs inside the guide tube.

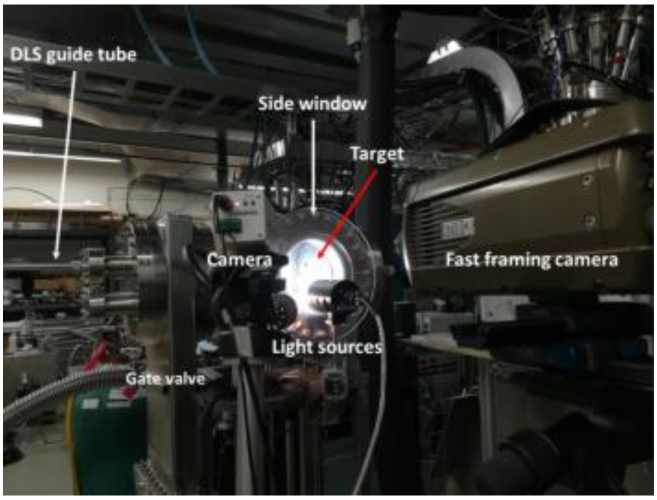

Figure 8. The fast framing camera setup

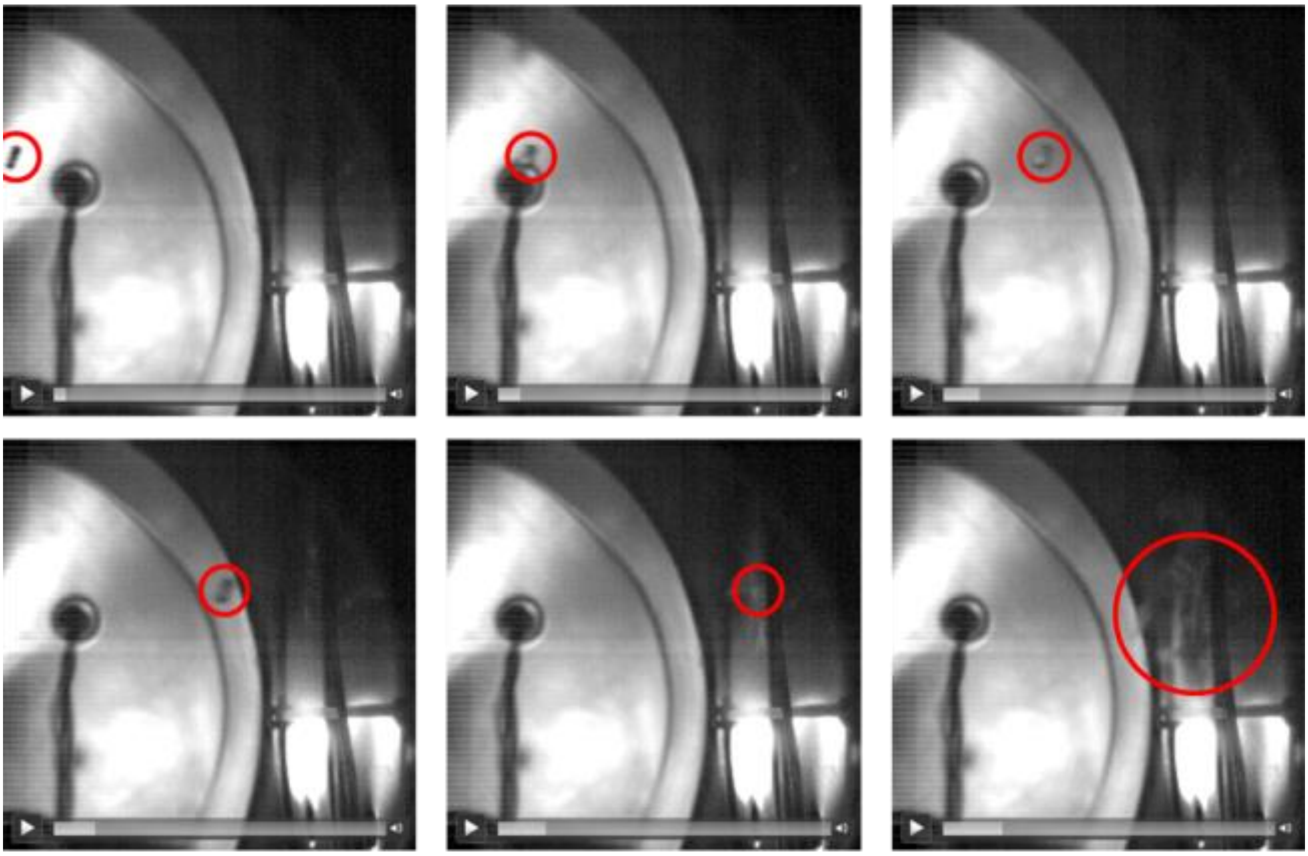

Figure 9. Sequence of images from a fast framing movie of an intact pellet travelling (from left to right) at 1.7 km/s (Shot 14417)

6. Discussion

The achievements of these pioneering tests are extremely encouraging, and go, in a certain sense, beyond any expectation. Despite the tentative arrangement used for these preliminary experiment was, to some extent, rather rough, the results already demonstrate, without any doubt, that high-speed pellets can in principle survive inside a DLS guide tube, and that this latter can moreover reduce the scatter cone remarkably, compared to a free-flight layout. We can therefore conclude, in the framework of the proposed complementary approach for DEMO core fuelling, based on the injection of high-speed fuel pellets from the HFS, that the potential use of DLS guide tubes to minimize the space required to penetrate the BB, is worth of being further explored.

A DLS guide tube with an internal diameter of 10 mm already seems to work rather satisfactorily, preserving the integrity of most of the pellets at speeds as high as 2,6 km/s, at least for the guide length tested so far (330 cm); we plan to perform further tests in the near future, using different combinations of the diameter and the length of the guide tube, as well as using guides having different shapes (for instance circular vs rectangular), in order to explore the sensitivity to these parameters of both the performance and the reliability of the injector, and possibly identify optimal configurations. Assessing the extrapolability of this scheme to 20 m long (or more) DLS guide tubes is not an easy task. The survival of the pellets may depend on how many impacts they undergo inside the guide (a number that presumably increases with the guide length), and on whether the stress they suffer at each impact may result in a cumulative solicitation or not. A dedicated experiment is perhaps the only way to address this issue; we plan to perform it in the near future.

The experiments also confirmed the prediction that no funnel is required in order the pellets, exiting the gun muzzle under free-flight conditions, can get through the 10 mm guide tube inlet located at a distance of 330 mm. Of course, due to the scatter cone of free-flight pellets, an increase of this distance is expected to require either a larger bore guide tube, or the use of a funnel to guide the pellets into the guide tube entrance, as gently as possible. However, the transition of the pellets into the tube, with particular regard to the alignment between the funnel exit and the tube entrance, represents a critical issue for the pellet survival even at relatively low speeds [26]. Therefore, avoiding the use of a funnel might be a preferable option. The preliminary results described above, indicate that this may be a viable solution, worth of being further explored to identify optimum combinations of distance and diameter of the guide tube inlet.

We also plan to equip the injector with two distinct diagnostic stations, each able to provide an independent measurement of both mass and speed of the pellets (as well as to capture their in-flight pictures), and fitted at the two extremities of the guide tube as shown schematically in figure 10, so

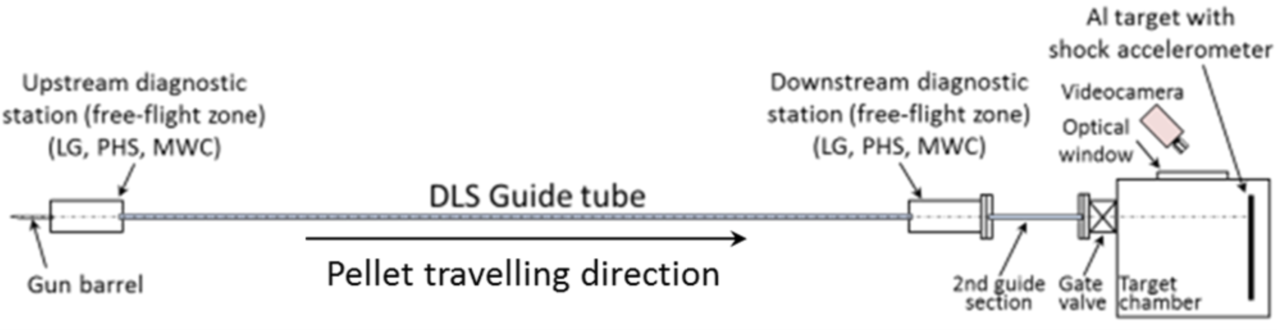

Figure 10. Schematics of the arrangement with two, upstream and downstream, diagnostic stations

as to detect whether the mass and the speed of the pellets passing through the tube undergo any significant reduction. Core fuelling of DEMO will require a pellet injection system capable of providing steady-state operation, i.e. able to deliver a very long sequence of high-speed pellets injected with a sufficiently high repetition rate; to accomplish this duty, a screw extruder [27,28,29,30] represents to date the only appropriate pellet source. In the 90's, ENEA and ORNL have already jointly developed an high-speed repeating pellet injector, by matching an existing ORNL piston extruder and an ENEA two-stage gun. This device has demonstrated the capability of launching sequences of up to 20 pellets (limited by the capacity of the solid deuterium reservoir of the batch extruder used for this pioneering experiment) at a frequency of 1 Hz (limited by the two-stage gun) and speed of 2.5 km/s [16,17]. Updating this concept from an old batch extruder to a modern screw extruder, can provide a virtually unlimited sequence of pellets. Moreover, ENEA and ORNL have developed a specific arrangement that allows accommodating both a single-stage and a two-stage gun on each of the four barrels of the IPI [24]; this configuration can be easily extended, in principle, to a configuration that accommodates more pneumatic guns (either single-stage and two-stage) on a single launching barrel, so as to improve the repetition rate. The two concepts above can be merged, resulting in a screw extruder equipped with several two-stage guns operating in parallel (with an appropriate time sequence) on the same launching barrel, as schematically shown in figure 11. Such a configuration could be a suitable solution for core fueling of DEMO, as well as of other long-pulse fusion devices, such as ITER and the Divertor Tokamak Test Facility (DTT), capable of providing at the same time steady state operation and adequate performance in terms of high injection speed and frequency, without requiring more than one DLS guide tube, thus preserving the advantages of this scheme in terms of reduced BB cut-off volume.

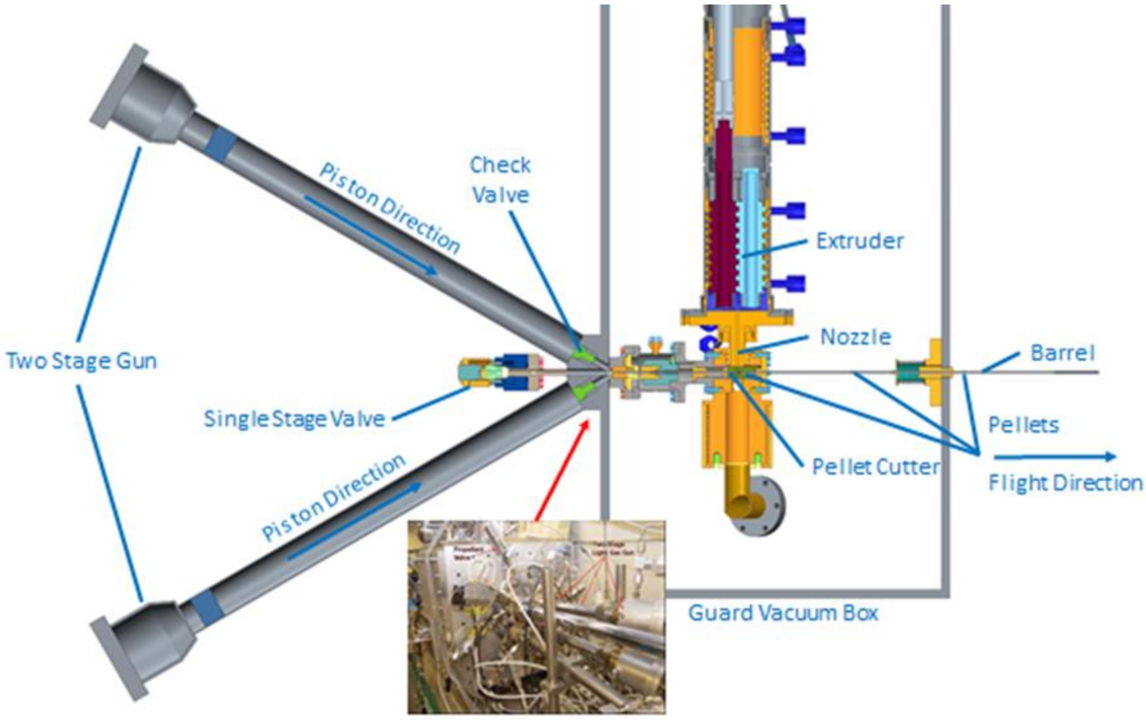

Figure 11. Schematics of the proposed driving propulsion system for a steady-state high-speed repeating injector, accommodating on the same barrel a multiple ENEA TSGs arrangement (only two are shown here); a single-stage propellant valve is also shown..

All the injectors and the pellet acceleration schemes described above, those already fully developed or presently under investigation, as well as those proposed as possible future technological developments, need to be made tritium compatible for use in DEMO, which will require the injection of T_2 or DT fuel pellets. Usually, all technological approaches are prior tested in the laboratory using deuterium pellets, since tritium handling involves many additional safety issues that require adequate radioprotection measures. Nonetheless, proof-of-principle experiments, aimed at demonstrating the feasibility of pneumatic T_2 or DT pellet launchers, either based on pipe-gun [31,32,33] or on piston-extruder concepts [34,35], have already been carried out successfully by the ORNL team, so this achievement seems to be now within reach.

Conclusions

A complementary approach for core fuelling of the EU-DEMO tokamak is being investigated within the EUROfusion WP-TFV, relying on the injection of high-speed fuel pellets from the HFS through oblique DLS paths (OHFS injection scheme). To minimize the BB cutoff volume required for pellet penetration, use of DLS straight guide tubes is being explored, which can reduce the scatter cone compared to free-flight options. Preliminary experiments have been recently carried out using the existing ENEA/ORNL high-speed pellet injector (IPI), which was modified to accommodate a DLS guide tube on barrel 4 (4.4 mm bore). A number of intact pellets have been consistently delivered downstream of the guide tube at speeds up to 2.6 km/s, with remarkably reduced scatter cone, thus showing the viability of this innovative approach.

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