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Addressing the feasibility of inboard direct-line injection of high-speed pellets, for core fueling of DEMO

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Core fuelling of the EU-DEMO tokamak is under investigation within the EUROfusion Work Package "Tritium, Fuelling and Vacuum" (WP-TFV). Pellet injection represents the most promising option, however simulations indicate that effective fuelling requires High Field Side (HFS) injection at velocities $\gtrsim$1 km/s. Two complementary approaches are being considered for inboard injection: i) using guide tubes with curvature radii ≥ 6 m to preserve pellet integrity, and ii) investigating the feasibility of injecting high-speed (~ 3 km/s) pellets along "direct line of sight" (DLS) trajectories, from either the HFS or a vertical port. Options using the upper vertical port have been explored first; however, simulations indicate that vertical injection may be effective only if pellets are injected well inboard the magnetic axis. High-speed injection through oblique inboard "DLS" paths, not interfering with the Central Solenoid (CS), are instead predicted to grant good performance, provided that the injection location is $\lesssim$ 2.5 m from the equatorial mid-plane. The angular spread of high-speed free-flight pellets, and/or the suitability of straight guide tubes to reduce the scatter cone, are being explored using an existing facility, in collaboration with Oak Ridge National Laboratory. The neutron flux across DLS injection paths is also being investigated.

Keywords: EU-DEMO tokamak, High Field Side high-speed pellet injection, straight guide tubes.

1. Introduction

Core fuelling of the EU-DEMO (DEMOnstrating fusion power reactor) tokamak is under investigation within the EUROfusion Work Package "Tritium, Fuelling and Vacuum" (WP-TFV). Pellet injection still represents, to date, the prime candidate option [1]. Pellet penetration and fuel deposition profiles have been simulated, for different injection locations, using the HPI2 pellet ablation-deposition code [2], and assuming specific EU-DEMO 2017 H-mode plasma scenarios and the ITER reference pellet mass (6×10^{21} atoms). The results indicate that injection from the Low Field Side (LFS) is ineffective, regardless of the pellet speed, whereas efficient fuelling can be achieved launching pellets from the High Field Side (HFS) at velocities $\gtrsim$ 1 km/s [3]. To implement suitable inboard injection schemes for the EU-DEMO, two complementary approaches are being considered: one is aimed at improving the design of guide tubes, using curvature radii ≥ 6 m in the attempt to preserve pellet integrity at ~ 1 km/s; the other is investigating the feasibility of injecting high-speed (~ 3 km/s) pellets along "direct line of sight" (DLS) trajectories, from either the HFS or a vertical port [4]. The identification and integration of suitable oblique HFS straight injection paths, compatible with existing constraints and, in particular, avoiding interferences with the central solenoid (CS), is really challenging and requires careful investigation. Options using the upper vertical port have therefore been explored first; the results of this analysis are reported in section 2. The angular spread of the trajectories of high-speed free-flight pellets, and/or the suitability of straight guide tubes to reduce the scatter cone and the corresponding open cross section on breeding blanket penetration, are being explored using an existing facility (described in section 3), developed in collaboration between the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) and the Oak Ridge National Laboratory (ORNL), As a first step, the scatter cone of high-speed free-flight pellets has been measured; the results are reported in section 4. The neutron flux across typical DLS injection paths is also being investigated and the results of preliminary analyses are presented.

2. Identification of DLS injection paths using the vertical upper port

The EU-DEMO design includes a vertical upper port (chimney), designed to grant suitable access to the Vacuum Vessel (VV) for Remote Maintenance (RM). The upper entrance of this wide rectangular port (1.5 m × 0.7 m) is at the level of the bio-shield top lid (12.78 m

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author's email: antonio.frattolillo@enea.it above the VV entrance and 18 m above the machine equatorial mid-plane). Its radial position is schematically shown in figure 1, with a minimum distance of 9 m from the machine axis. Unfortunately, pellet deposition simulations performed using the HPI2 code predict that vertical injection may be effective, to some extent, only if pellets are injected from radial positions well inboard the magnetic axis of the plasma [5], so that DLS injection paths routed across this vertical duct are expected to result in very poor fueling efficiency. High-speed injection through oblique inboard “DLS” paths, not interfering with the CS, are instead predicted to yield good fueling performance, provided that the trajectories intercept the separatrix at a distance from the equatorial mid-plane $\lesssim 2.5$ m [5]. Their integration in the design of DEMO, as well as the reduction of the cross section on BB penetration, need therefore to be investigated.

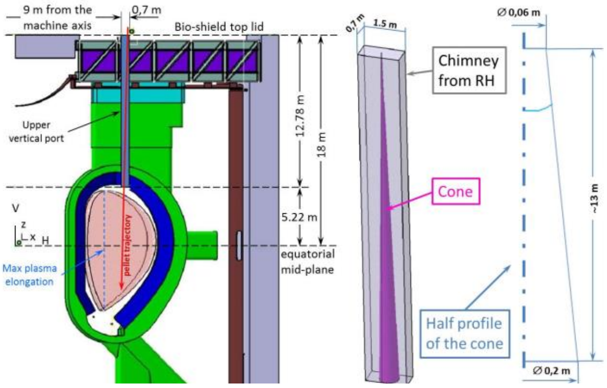

Fig. 1. Schematics of EU-DEMO upper vertical port

3. The ENEA-ORNL facility

The high-speed four-barrel prototype pellet injector, developed in collaboration between ENEA and ORNL, was originally designed for the Ignitor experiment [6], to produce sufficiently peaked density profiles during the current ramp-up phase and to sustain them during the flat top phase. This facility, named IPI (Ignitor Pellet Injector), consists of two independent sub-systems, each equipped with its own Control and Data acquisition system (C&DAS), which have been separately built and tested by ENEA and ORNL and finally integrated at ORNL for joint testing and operation (figure 2). The ORNL sub-system consists of the cryogen-free cryostat, fitted out with four pipe-gun barrels (1.9, 2.6, 3.2 and 4.4 mm in diameter), four single-stage propellant valves, a ballast chamber, located at the downstream end of the injector, accommodating a replaceable metal-foil target equipped with a shock accelerometer, and the diagnostic set-up positioned immediately downstream of the cryostat and incorporating four light-gates and four photographic stations (for measuring the speed and capturing in-flight picture of the pellets), as well as a common (ring-shaped) microwave-cavity mass probe [7]. The ENEA sub-system includes four independent Two-Stage Guns (TSG), each equipped with a (electromagnetically driven) pulse-shaping valve [5,6] and two ballistic pressure transducers (to measure the propellant pressure pulses produced respectively upstream and downstream of the shaping valve), a set of four small vacuum chambers, placed immediately downstream of the diagnostic station, each equipped with a removable insert accommodating a shock accelerometer and a replaceable aluminum target [8], and an innovative propellant gas removal system, consisting of four independent injection lines equipped with fast-closing (~ 9 ms) gate valves [7,9], that connect the injector with the final downstream ORNL target-chamber. A specific novel arrangement has also been developed, that accommodates both a single-stage and a double-stage gun on each barrel [8,10]. As a further distinctive feature, the injector located at ORNL can also be operated via the internet from a remote control station at ENEA Frascati [5,11]. Recently, the existing two-stage pulse tube cryo-generator used for initial tests (Cryomech PT810, cooling power of 80 W @ 80K on the first stage and 14 W @ 20K on the second), has been replaced by a similar but more powerful unit (Cryomech PT415, featuring a refrigerating power of 40 W @ 45 K on the first stage and 1.5 W @ 4.2 K on the second, with a nominal minimum temperature of ~ 2.8 K with no thermal input). Cooling tests with the PT415 have shown a significant drop of the temperatures achieved at both the radiation shield (from ~100 K down to ~54 K) and the freezing region (from ~10 K to ~8 K), with a consistent reduction of the overall time required to cool down the cryostat [11]. However, the temperature measured at the second cooling stage (~ 5 K) turns out to be ~ 3 K lower than that achieved by the freezing zone, suggesting that the latter is prevented from getting even colder because of an excessive heat load, perhaps due to thermal conduction along the barrels. To substantiate this analysis, the diode sensors of barrels 2 and 3 have been relocated to measure the temperatures at about 2.5 cm upstream (breech side) and downstream (muzzle side) of the freezing zone of barrel 4; as a matter of fact, temperature as high as ~200 K and ~146 K have been measured respectively, thus validating our hypothesis. The cryostat configuration has therefore been modified, adding thermal shorts on both the breech and the muzzle sides of the freezing zone, to redirect the incoming heat flow toward the 1st stage of the cryo-cooler (figure 3).

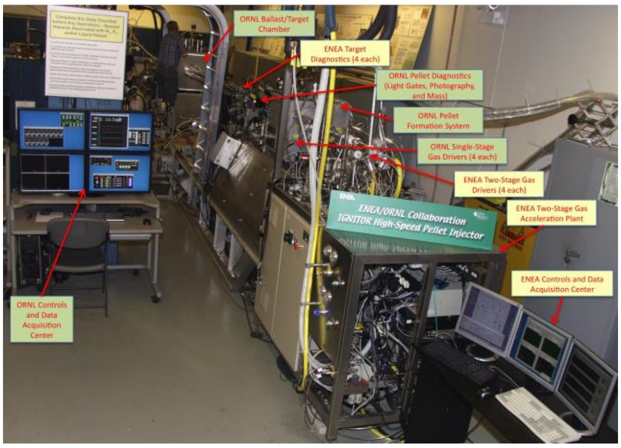

Fig. 2. The IPI facility at ORNL

With this new barrel arrangement (and the addition of multilayer insulation on the radiation shield), the temperatures measured both upstream and downstream of the freezing zone are drastically reduced (to ~ 40 K), while those measured at the second-stage cold head and

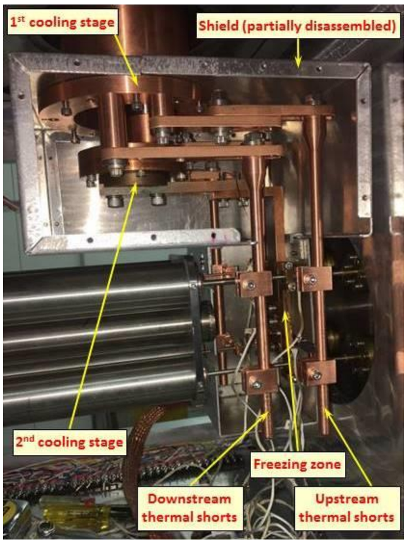

Fig. 3. The new cryostat configuration with added upstream and downstream thermal links to the first cooling stage

at the freezing zone can reach steady state values as low as 4.2 K and 5.7 K respectively, thus allowing very stable control of the freezing zone temperature during pellet formation, and removing the unwanted oscillation that are usually observed when the desired temperature set point approaches the lowest temperature that the system can achieve (due to the balance of residual refrigerating power and thermal inputs).

After performing several remote operation sessions, aimed at identifying suitable pellet formation parameters with this new configuration, a joint experimental campaign at ORNL was carried out in December 2016, that demonstrated the improvement in injector performance of intact pellets at speed up to 2.4 km/s.

4. Dispersion data of high-speed free-flight pellets

In order to ensure free-flight of the pellets from the gun muzzle to the final target, placed 3772 mm downstream, the microwave cavity has been removed, while a single large-diameter (∅ 150 mm) tube has been used to connect the injector to the final target tank, as shown in figure 4. A further short joint experimental campaign has been carried out at ORNL in July 2018, using only the largest bore barrel (4.4 mm); this pellet size has been selected since it more closely approaches that required for DEMO core fueling. After preliminary testing the new injector configuration at low speeds ($\lesssim$ 1 km/s), using ORNL propellant valves, high-speed tests using the ENEA TSG have been finally carried out. The aluminum targets were replaced frequently (no more than four shots with the same target), to facilitate the subsequent analysis. Moreover, the impact of each pellet on the target has been monitored by means of a video camera, providing an easy way to record a short video of each impact and to capture an image of the target after every single shot. This has turned out to be a very useful tool to precisely identify the imprint of each pellet. A total of 62 pellets were launched at speed ranging from 1.4 up to 2.44 km/s. The resulting overall impact pattern is shown in figure 5, where the intersection of the red dashed lines identify the projection of the four barrel's axes. Black and red dots refer to intact pellets travelling at different speeds; the three empty dots represent the imprints of the main piece of high-speed pellets associated with a couple of much smaller fragments (as witnessed by their traces on the target). The (x,y) coordinates of each point have been measured with respect to the reference system shown in fig. 5, and the two sets of values (assumed to be statistically independent from each other) have been separately fitted using a normal distribution, in order to identify the center of the impact pattern on the target, given by the average values (x_0, y_0), and the scatter cone width, associated with the standard deviations of the two normal distributions. The results are reported in table 1.

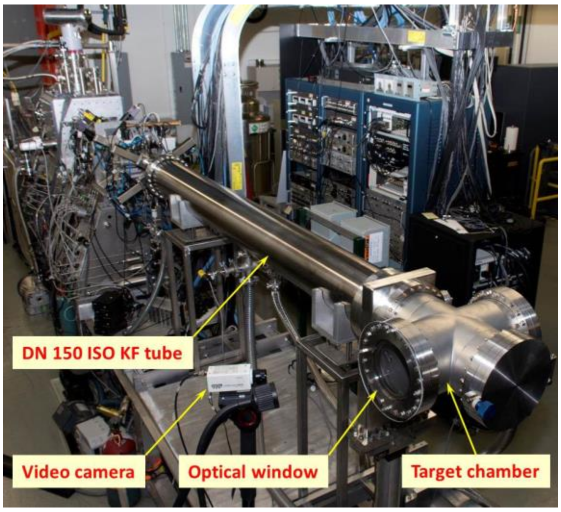

Fig. 4. The new IPI arrangement ensuring pellet's free-flight

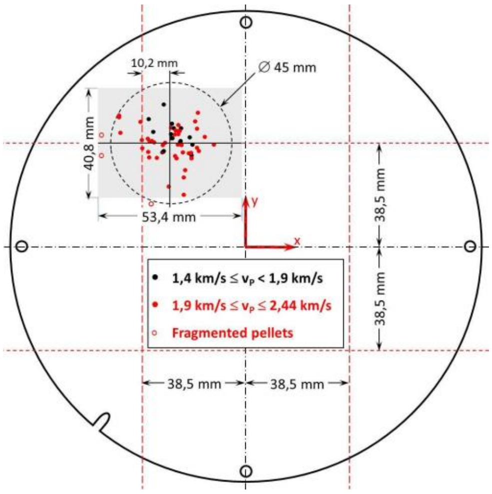

Fig. 5. Impact pattern of free-flight high-speed pellets

Table 1. normal distribution parameters of impact points

x_0 (mm)	y_0 (mm)	σ_x (mm)	σ_y (mm)
-28.30	38.47	8.9	6.8

This analysis indicates that the injector is pointing about 10.2 mm to the right, as compared to the expected aiming position. About 99.7% of values drawn from a normal distribution are within three standard deviations. This means that 99.7% of the pellets are expected to hit the target within a distance of about ± 26.7 mm from x_0 and about ± 20.4 mm from y_0, as shown by the shadowed area in fig. 5. This figure also shows that, except for the three fragmented pellets, all the impacts fall within a circle of $\approx$ 45 mm in diameter, centered in (x_0, y_0). If one takes into account the distance of the target from the gun muzzle, the angular scattering of intact pellets trajectories turns out to be about 0.7° (0.012 rad), which is the same value that had been previously measured for this barrel at speeds of ~ 1 km/s, using the ORNL propellant valve [12]. Moreover, this angular spread is not far from that measured (0.57°) many years ago using the high-speed multiple-barrels pellet injectors for the Frascati Tokamak Upgrade (FTU) [13].

5. The neutron flux across DLS injection paths

A preliminary assessment of the neutron flux through a vertical DLS injection path has been performed using the Monte Carlo N-Particle (MCNP) code [14] and the JEFF 3.2 nuclear data libraries [15]. The free flight fueling assembly with conical aperture (as shown in figure 1) has been defined in a 20° DEMO model integrating the WCLL (Water Cooled Lithium Lead) Single-Module-Segment breeding blanket [16]. As a first step, the neutron flux has been calculated for two different configurations:

- Free flight injection line completely open
- Free flight injection line with VV-like plug

In both cases, calculation has been carried out for two locations along the injection path: 1) outside the VV, 7.3 m from the plasma core, and 2) above the external surface of the Bio-shield, at 18.5 m from the core, (figure 6).

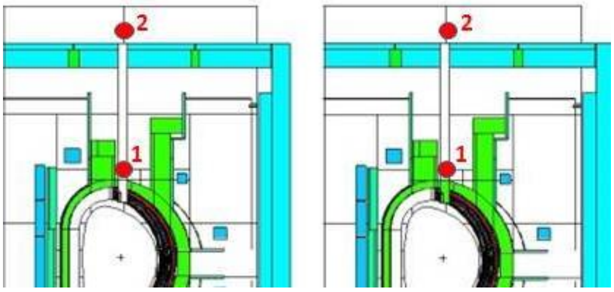

Fig. 6. Poloidal section of the MCNP DEMO model with chimney completely open (left panel), model with VV-like plug (right panel). Red dots specify the scoring positions.

The neutron fluxes estimated with the open injection line are $5.05\mathrm{x}10^{12}$ and $7.28\mathrm{x}10^{10}$ n/cm^2/s respectively. The integration of the VV-like plug ensures a substantial reduction of the scattered neutron flux across the conical penetration (∅ 200 mm): respectively $6.01\mathrm{x}10^{9}$ and $9.15\mathrm{x}10^{8}$ n/cm^2/s outside the VV and the Bio-shield. This preliminary assessment highlights the necessity to develop a dedicated shielding strategy to further reduce the radiation streaming along the free flight injection path, such as introducing an additional upper plug. If the use of straight guide-tubes will reveal a suitable option, the resulting neutron flux is expected to further decrease.

Acknowledgments

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