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An innovative approach for DEMO core fuelling by inboard injection of high-speed pellets

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Core fuelling of DEMO fusion reactor is under investigation within the EUROfusion Work Package "Tritium, Fuelling and Vacuum". An extensive analysis of fuelling requirements and technologies, suggests that pellet injection still represents, to date, the most realistic option. Modelling of both pellet penetration and fuel deposition profiles for different injection locations, assuming a specific plasma reference scenario and the ITER reference pellet mass (6×10^{21} atoms), indicates that: 1) Low Field Side (LFS) injection is inadequate, even at speeds ≥ 10 km/s; 2) Vertical injection may be effective only provided that pellets are injected at ~ 10 km/s from a radial position ≤ ~8 m, so this injection scheme is not presently considered as a practical option, unless such high injection speeds will become available; 3) effective core fuelling can be achieved launching pellets from the High Field Side (HFS) at ~1 km/s. Guiding tracks with a bend radius ≥ 6 m are envisaged to deliver intact pellets at 1 km/s. HFS injection was therefore selected as the reference scheme, though scenarios featuring less steep density and temperature gradients at the plasma edge could induce to reconsider vertical injection at speeds in the range of 4 to 5 km/s. The results of above simulations rely, of course, on the hypothesis that pellets are delivered at the plasma edge with the desired mass and speed. However, mass erosion and fracturing of pellets inside the track, severely limiting the transfer speed, as well as pressure build up and speed losses at relevant injection rates, might hamper the use of curved guide tubes. An additional innovative approach, aimed at individuating inboard straight "free flight" injection paths, to inject pellets from the HFS at significantly higher speeds, is proposed and discussed as a backup solution. Outboard high-speed injection is still being considered, instead, for JT-60SA.

Keywords: DEMO, Tokamak, pellet fuelling

1. Introduction

Core fuelling of the Demonstration Fusion Power Reactor (DEMO) is being investigated, as part of the Eurofusion work package Tritium, Fuelling and Vacuum (WP-TFV) [1]. An extensive analysis of fuelling requirements and technologies, suggests that pellet injection still represents, to date, the most realistic option for deep matter deposition in DEMO.

Modelling of both pellet penetration and fuel deposition profiles, for pellets launched from different injection locations, has been performed using the pellet ablation-deposition code HP12 [2]. For these simulation, the DEMO1noCD scenario (June 2014) [3] has been adopted, featuring a very narrow pedestal width Δ (5% of the normalized minor radius). For the pellet mass, the ITER reference value of $N_p = 6\times10^{21}$ D-atoms has been assumed.

While in present day tokamaks the pellet penetration λ_p can contribute to the fuel deposition depth, in DEMO the simulations indicate that, for the adopted reference scenario, the fuel deposition is dominated by the ∇B-induced displacement, thus leading to the following conclusions [4]:

1. Low Field Side (LFS) injection is inadequate, even at speeds ≥ 10 km/s, due to the unfavourable drift;
2. Suitable particle deposition profiles can be achieved launching pellets from the High Field Side (HFS) at speeds of ~1 km/s, almost regardless of the vertical injection position z_{inj}.
3. Vertical injection at ~1 km/s can grant significant particle deposition inside the pedestal area only provided that pellets are injected from a radial position R_{inj} ≤ ~8 m. Such an injection scheme is referred to as Vertical-HFS (VHFS).

To inject pellets from the HFS, use of guiding transfer systems is envisaged. At the state of the art, however, this technology suffers of many issues, which might hamper its use at speeds of ~ 1 km/s.

2. Performance limits of present HFS injection technology.

In present tokamaks, HFS pellet injection is commonly performed by means of special transfer systems, redirecting the cryogenic projectiles delivered by the launcher to their inboard injection locations. Such systems constrain the pellets to travel inside a guiding tube or alongside a kind of rail, usually featuring several bends having different curvature radii. Due to centrifugal stress and to friction, as well as to the poor mechanical properties of the hydrogen isotopes ice, the cryogenic projectiles may break and partially vaporize inside the track, causing severe restriction to the injection speed. Even a very short section of the guide, featuring a too small curvature radius, has dramatic effects on the pellet integrity. Depending on the minimum curvature radius

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all along the track, the speed limit may be as low as a few hundred m/s [5-6]. Lacking a proper model, this speed limit is usually estimated using the empirical AUG scaling low:

$$v_p\ (m/s) = 1150\sqrt{R\ (m)/L\ (mm)} \qquad (1)$$

relating the minimum curvature radius R (m) of the guiding track to the maximum speed $v_p\ (m/s)$ that a cubic pellet, having side length L (mm), can withstand without fracturing [7]. At speeds v > v_p, the fraction of pellets that are delivered intact downstream of the transfer system, gradually drops to zero within a few hundred m/s (transition region) [5-6]. Eq. (1) suggests that large curvature radii may help improving to some extent the speed limit, but such an option also leads to increase the track length. However, increasing the launching speed and the distance to be travelled by the pellet inside the track, are both factors that contribute to intensify the mass erosion. In experiments carried out at Oak Ridge National Laboratory (ORNL) with a 15 m long ITER mock-up test tube with a minimum curvature radius of 800 mm, the fraction of pellet mass that vaporizes inside the guide is found to range from ~ 10% at 300 m/s (where the pellet survivability is ~100%) up to ~20% at 450-500 m/s (survivability ~ 10%), [5] but grows up to about 80% at speeds approaching 1000 m/s, in the case of a 17 m long system for ASDEX Upgrade, featuring significantly larger bend radii [8]. It should be noted, however, that in this latter case, the increased curvature radius essentially results in a wider transition region, which extends toward higher speeds as compared to results of ORNL experiment. Nonetheless, its lower limit (corresponding to 100% pellets survivability) is still in the order of 300 m/s, while at ~1 km/s only ~ 55% of launched pellets are delivered intact.

Moreover, to ensure an adequate fuel flux, pellets are to be injected at some suitable rate (usually in the order of several Hz up to a few tens of Hz). Consequently, due to mass erosion, pressure may build up inside the transfer system, unless sufficiently fast evacuation is ensured. This is, however, a rather challenging issue, due to the high impedance commonly associated with such long and narrow ducts, and represents in any case a substantial additional load for the vacuum system. In the case of a D-T burning reactor, such as DEMO, this also burdens the fuel cycle systems and generates an undesired significant growth of the overall tritium inventory. Pressure build up, on the other hand, further limits the performance of guiding systems. Experiments at ORNL [5] show that increasing the base pressure from 10^{-4} torr to 10 torr, besides slightly decreasing the speed limit (with a transition region going from ~250 to ~450 m/s), makes the mass loss unpredictable; at a base pressure of 100 torr, these effects further grow up and, moreover, a significant speed loss (ranging from ~15% at 100 m/s to ~10% at 350 m/s) is observed.

Finally, when pellets are launched at suitable repetition rates, fragments of a broken pellet inside the guiding track may cause fragmentation of subsequent pellets, perhaps resulting in a sort of avalanche effect. To avoid this problem, the launching speed should not exceed the lower limit of the transition region (~ 250 - 300 m/s), to ensure 100% pellet integrity.

Modelling indicates that, in DEMO, pellets should be delivered at the inboard plasma edge (i.e. downstream of the transfer system) with final speed and mass respectively of ~ 1 km/s and 6×10^{21} atoms; this pellet size corresponds, for D_2 ice, to a cube with a side length of ~ 4.7 mm. Therefore, for a speed limit of 1 km/s, eq. (1) predicts a minimum curvature radius of ~ 3.5 m. Due to mass erosion, however, pellets have to be injected, upstream of the transfer system, with a correspondingly larger mass. Since experiments indicate that, at speeds of ~ 1 km/s, about 80% of the pellet vaporizes in the transfer system [8], its original mass (upstream of the guide) should be 5 times larger, i.e. ~ 3×10^{22} D atoms, corresponding to a side length L ~ 8 mm. For the same speed limit, eq. (1) then predicts a minimum curvature radius of ~ 6 m. About 2.4×10^{22} D atoms (1.2×10^{22} D_2 molecules corresponding to ~ 48 Pa m^3_{NTP}) are expected to be vaporized inside the track for each launched pellet. On the other hand, in DEMO, the requested fuel replenishment flux at the SOL, may be as high as 1.2×10^{23} atoms/s [9], so that pellets injection rates of up to 20 Hz may be required. If so, the average amount of D_2 gas vaporized per unit time inside the track, can be estimated in the order of up to ~ 1kPa m^3/s. If we finally consider speed losses, pellets should be launched at a somewhat higher upstream velocity, resulting in a further increase of mass erosion and curvature radius R.

It is quite evident that a dedicated R&D effort will be necessary, to try filling the substantial gap between the performance of present transfer systems and DEMO requirements. However, in case this technology will prove inadequate for DEMO, alternative approaches to implement HFS injection should be investigated as backup solutions.

3. An innovative approach for high-speed HFS pellet injection in DEMO.

As a matter of fact, injection along straight "free-flight" lines is the only realistic alternative to guiding tracks that inherently gets rid of all related issues. Possible straight paths accessing the plasma from the HFS (or from the VHFS), compatible with present DEMO engineering constraints or involving an acceptable revision of current DEMO design, are still to be identified. This may lead, as in the case of curved tracks, to compromise on the injection configurations; however, such a "free-flight" launching scheme allows injecting pellets at significantly higher speeds, that could partially compensate for less favourable arrangements. The technology of two-stage pneumatic launchers has already demonstrated its ability to reliably accelerate solid D_2 pellets in the 3 to 4 km/s range [10,11], and has perhaps the potential to provide even better performance with some suitable and simple improvements [12]. It represents, therefore, a realistic candidate for high-speed pellet launching.

To briefly address the potential of this innovative proposal, we will make use once again of the results of modelling, including those of a comparative study aimed at identifying optimal solutions for the inboard track system, compatible with constraints of present DEMO

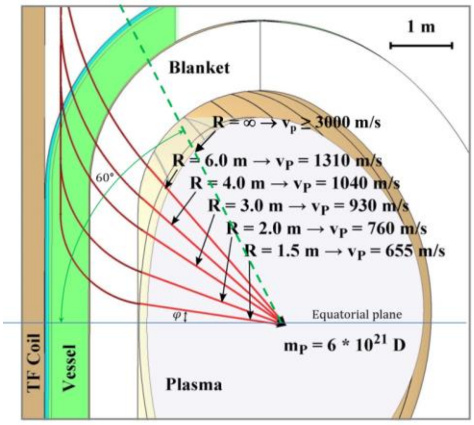


Figure 1. First set of HFS injection tracks (continuous red lines) considered for DEMO. For each option, the minimum bend radius R and the maximum expected transfer speed v_p (estimated by eq. 1) are indicated. A pellet mass of $6{\times}10^{21}$ D atoms is assumed.
The green dashed line refers to an hypothetical free-flight injection path, aiming at plasma center

design. Five different possible options (Fig. 1) have been first considered, but no significant impact of the specific injection solution is predicted. This can be ascribed to several factors:

i. At speeds in the range considered here ($\leq$ 1300 m/s), the penetration of pellets is too small to contribute to the fuel deposition depth in DEMO;

ii. All five proposed injection tracks aim at the plasma centre, so that the projection V_R of the pellet velocity along the major radius is roughly constant ($\leq$ 800 m/s) for all the considered injection lines (first five points in Fig. 2);

iii. The HFS drift displacement is almost independent on z_{inj} for pellets having the same radial speed.

Actually, the only parameter which seems to play an important role in determining the fuel deposition profile for pellets injected from the HFS and aiming at the plasma centre, is the radial component v_R of the injection speed.

As an example, figure 1 also shows an additional hypothetical straight injection path (green dashed line), still aiming at the plasma centre, and forming an angle of 60° (or possibly less) with the horizontal mid-plane. Pellets injected along this line at speeds $\geq$ 3 km/s would have a radial velocity $v_R \geq 1.5$ km/s (last point in fig. 2), i.e. more than twice than achievable by the previous five curved tracks.

In present tokamaks pellet penetration is comparable or even larger than the drift displacement, so that aiming at the plasma centre may help improving the fuel deposition depth; in the case of DEMO, however, this is no more true, so this constraint can be released. It is instead more convenient that pellets are injected from a vertical injection position z_{inj} distant less than ±2a/3 from the equatorial plane, in order the drift displacement, which is directed outward along the major radius, can pass through the flux surfaces almost perpendicularly, and thus perform more efficiently. Similarly, pellet penetration improves, to some little extent, if pellets are injected almost perpendicularly to flux surfaces. An example of an hypothetical free-flight path, complying with this latter constraint and compromising on z_{inj}, is shown in figure 3.

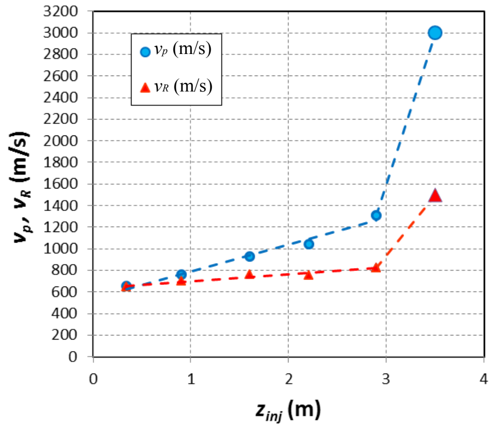


Figure 2. The pellet speed v_p and its projection v_R along the major radius, for the first set of five different injection tracks considered for DEMO, and (last point on the right) for the additional hypothetical free-flight path (green dashed line in figure 1).

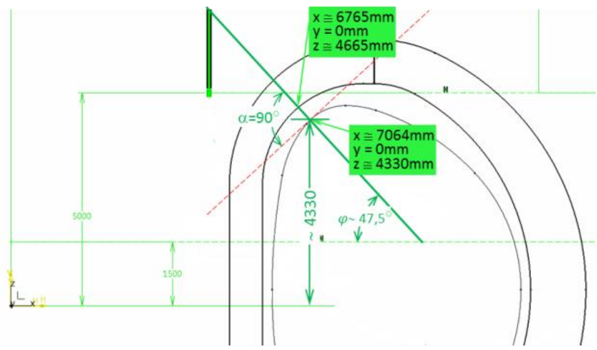


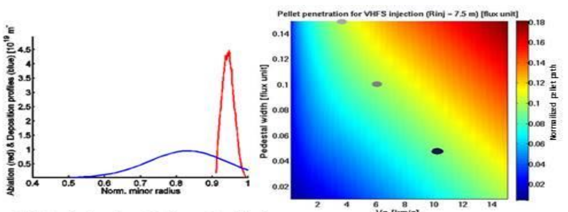
Figure 3. An example of a straight injection path almost perpendicular to the flux surfaces (compromising on z_{inj}). The coordinates of the intersection point with the separatrix and the angle φ are roughly estimated.

The coordinates of the intersection point with the separatrix may be allowed to change within some suitable range, trying to keep the angle α as close as possible to 90°. The angle φ that the injection pattern forms with the horizontal mid plane, will also change accordingly. For the case shown, $\varphi \sim 47.5°$ so that, assuming once again a pellet speed $v_p \geq 3$ km/s, the radial component v_R of the velocity is roughly given by $v_R = v_p \times \cos\varphi \geq 3{\times}0.676 \cong 2{,}03$ km/s.

4. Potential of high-speed VHFS pellet injection.

VHFS launch option also allows the pellets to travel along a straight path, with no other restriction on the injection velocity than that imposed by the launching technology. The results of modelling [4] indicate that pellets launched from the VHFS at ~ 1 km/s can achieve a penetration $\lambda_p \sim 0.95$, comparable to that of pellets injected at the same speed from the HFS. The barycentre

$\lambda_{<D>}$ of the fuel deposition profile may instead be worse, due to the lower efficiency of drift displacement (which, in this case, is almost tangential to the flux surfaces), unless pellets are injected from a radial position R_{inj} < 8m. The best performance is predicted for R_{inj} = 7.5 m, where $\lambda_{<D>}$ exhibits the same maximum of ~ 0.84, as compared to pellets launched from the HFS with z_{inj} < 1.4 m. VHFS injection from R_{inj} = 7.5 m has therefore, in principle, the potential to provide deeper fuel deposition than optimal (i.e z_{inj} ≤ 1.5 m) HFS arrangements, since pellets can be injected from the VHFS at significantly higher speeds. One could rise the objection that, in this case, the pellet penetration is not expected to increase appreciably with the speed, being penalized by the plasma elongation. Modelling indeed shows that, for the very narrow pedestal (Δ = 0.05) adopted as reference case, the injection velocity required in order a pellet, launched from the VHFS with R_{inj} = 7.5 m, can penetrate up to λ_p ~ 0.9 (i.e. a pellet path of ~ 0.1), is of the order of ~ 10 km/s, out of the performance of present injectors (figure 4). However, the pedestal width turns out to be a key parameter in determining the pellet penetration, and the above value of Δ may be rather pessimistic. Figure 4 shows, on the other hand, that the injection speed required to achieve λ_p ~ 0.9 drops down to ~ 6 km/s for Δ = 0.1, and becomes less than ~ 4 km/s for Δ = 0.15. So, particularly for scenarios featuring less steep temperature and density gradients at the plasma edge, high-speed VHFS injection may still represent a practical option.



Ablation (red) and particle deposition (blue) profiles for a pellet speed of 10 km/s, and Δ = 0,05

Map of the pellet penetration calculated for VHFS injection (R_{inj} = 7.5 m)

Figure 4. Pellet penetration for VHFS injection (R_{inj} 0 7.5 m)

5. Outboard high-speed injection for JT60-SA

Evidently, it appears eligible to make proper use of a technology already at hand allowing access to a pellet speed range of 3-4 km/s, currently even progressing with the aim to provide even better performance. On the one hand it is desirable to use this technology in actual projects in order to apply pellet performance parameters at the ultimate achievable limits. Thus, it is expected to gain insight into physics processes not accessible so far, in particular the interaction of pellets with very hot core plasmas. In turn, a project aiming on the application of such an advanced high speed system under the real harsh operational conditions of a fusion oriented research device could significantly foster the according technology robustness and gain practical experience.

As a possible project suitable for such an approach, the superconducting coil tokamak JT-60SA [13] has been chosen. Currently already under construction, JT-60SA is a project with the mission to contribute to early realization of fusion energy by supporting the exploitation of ITER and by resolving key physics and engineering issues for DEMO reactors. The project therefore necessitates a suitable pellet injection system serving for efficient particle fuelling and for control and mitigation of edge localized modes (ELMs).

A conceptual design for a suitable JT-60SA pellet injection system will be worked out in the time period 2015-2017, taking into account the status of the torus vessel assembly [14]. It is proposed to consist basically of components already routinely used for conventional pellet systems. For the main unit serving all requirements expressed in the JT-60SA research program, a steady state fuel ice extruder feeding a mechanical centrifuge launching pellets finally through a guiding system from the torus inboard side is proposed. However, since the guiding tube system is expected to impose rather pronounced speed restrictions, as an additional option a dedicated system is suggested for high speed outboard launch, covering the potential for an injection of different pellet species at a speed significantly beyond 2000 m/s. The only technical feasible solution considered for this option is the two-stage pneumatic launchers, however requested to cover the need for a suitable pellet repetition rate in the range of about 10 Hz.

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