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To cite this article: B. Ploeckl, P. T. Lang, A. Frattolillo, Y. Igitkhanov, B. Pégourié, E. Fable, Chr. Day & C. Gliss (2021) Matter Injection in EU-DEMO: The Preconceptual Design, Fusion Science and Technology, 77:4, 266-278, DOI: [10.1080/15361055.2021.1903784](https://doi.org/10.1080/15361055.2021.1903784)

To link to this article: <https://doi.org/10.1080/15361055.2021.1903784>



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Published online: 24 May 2021.



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Matter Injection in EU-DEMO: The Preconceptual Design

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Received February 25, 2021

Accepted for Publication March 12, 2021

Abstract — *EU-DEMO will be the next step in Europe after ITER on the path toward a fusion power plant. The matter injection systems have to provide the requested material in order to establish, maintain, and terminate the burning plasma. Their main function is to fuel the plasma, but other tasks are addressed as well like delivering matter for generating sufficient core radiation and divertor buffering. In the preconceptual design phase performed from 2014 to 2020, the matter injection systems, in particular pellet injection and gas injection, have been assessed. This work describes the main findings and state of the art of the matter injection systems at the transition from the preconceptual design phase to the conceptual design phase.*

Keywords — *EU-DEMO, pellet, plasma control, fueling.*

Note — *Some figures may be in color only in the electronic version.*

I. INTRODUCTION

EU-DEMO will be the first European fusion device that delivers electric energy to the grid. The fuel for the fusion reaction is a mixture of deuterium and tritium. This fuel has to be provided in the right amount and mixture, as well as at the right time. Only a small fraction of the provided fuel is burnt; the majority does not participate in the fusion process and is pumped away. Economic and ecological reasons require recirculating the redundant fuel. In particular, the tritium is a rare resource generated in the breeding blankets using neutrons of the fusion reaction.

A dedicated project, called the Work Package Tritium Fuelling and Vacuum was set up in the framework of EUROfusion to investigate this fuel cycle: storage and fuel delivery, exhaust, isotope separation, and restore of fuel. It seems to be feasible to arrange the system blocks in three fuel loops: direct internal recycling (DIR), inner loop, and outer loop.¹

The “fueling” part of the project was renamed Matter Injection in order to take into account all purposes of matter injection on a fusion plasma.

There are two main purposes: plasma core fueling and plasma edge control. The latter includes divertor buffering, application of plasma enhancement gases (PEGs), and maybe pacing of edge-localized modes (ELMs). It is obvious that these are very different purposes, which are creating different requirements for the technical systems designed for the respective application. The matter injection system has to serve for ramp up and down of the plasma discharge as well.

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II. CORE FUELING

II.A. Interface Definition

All matter injection processes transport particles across interfaces. In this case, it is from the fuel storage to the plasma core, passing the scrape-off layer (SOL). The result of a detailed analysis of the interfaces is presented in Fig. 1. Each interface has the potential to cause issues in terms of efficiency (e.g., mass loss) or safety (e.g., penetrating the bioshield).

On each interface there is an impact on the matter transport with respect to mass loss (e.g., on free-flight sections with subsequent funnels to refeed in the guiding tube). This mass loss directly affects the overall efficiency and the tritium inventory of the fuel cycle. Great care is needed to minimize

these losses; the overall efficiency is the product of all the interface efficiencies. A special feature of the interface SOL is its bidirectional nature; particles are entering and leaving the plasma through this interface. In order to assess the efficiency of the matter injection system as a whole, deposition processes and density built up in the plasma must be considered as well.

Inevitably, the fueling system must penetrate the bioshield along its way from fuel storage to the plasma. For this penetration, special consideration is required in order to keep the functionality of the bioshield.

II.B. Design Approach

The basic approach for all considerations is to look at the plasma need. All requirements are derived from that,

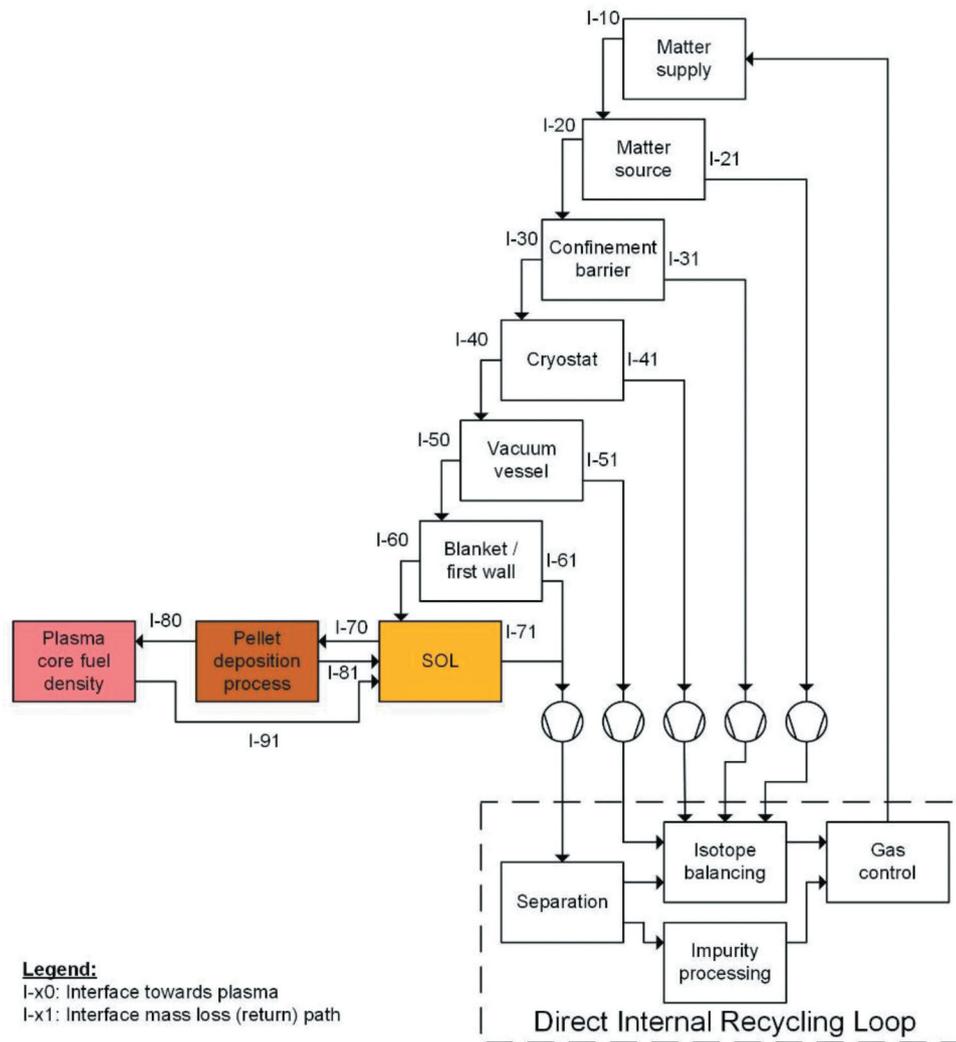


Fig. 1. Core matter injection system components with interfaces embedded in the fuel cycle comprising also parts of the vacuum system and the DIR loop.² The interfaces are labeled according to technical components. On each interface, some mass loss may occur, to be directed to the DIR loop.

and all system properties are benchmarked to it. The plasma scenario development for EU-DEMO is still evolving. Nevertheless, for this investigation the EU-DEMO basic scenario DEMO1noCD was taken as the basis.

The first design approach is to refer to the parameters considered for ITER. This is a particle inventory of $m_p = 6 \times 10^{21}$ D/T atoms per injection event (pellet). For cryogenic pellets, this corresponds to a cube with a side length of 4.6 mm. The minimum repetition rate is assumed to be 4 to 16 Hz depending on deposition profile. A minimum pellet speed of 300 m/s is selected, representing the speed range covered by blower gun solution.

In order to assess potential fueling techniques, a set of requirements has been set up. The basic requirements are

1. ability to deliver the required deuterium/tritium (DT) fuel mix to establish optimum burn conditions (correct DT-ratio at sufficient low impurity level)
2. sufficient particle flux to achieve fueling requirements
3. safe operation (radiation resistance, seismic events, explosion protection).

Beyond the basic requirements mandatory for any technique considered suitable for core fueling, a list of criteria for prioritization was carried out. These criteria are weighted by their importance, evaluated using a strength, weakness, opportunities, and treats³ analysis.

The most important criteria are

1. high fueling efficiency
2. high operational reliability
3. compatibility with injection geometries
4. low tritium inventory
5. precision of pellet parameters.

Moderate or minor importance for ranking is referred to in this stage of the project to e.g., maintainability, operational efforts, widely accessible pellet parameter range, or total cost of ownership.

Gas puff is not suitable for core fueling purposes due to its poor fueling efficiency.

Hence, conventional pellet technology using cryogenic hydrogen is selected for further investigation. Such pellet injection systems are composed of a pellet source, the acceleration unit, and the guiding tube, which guides the pellets to the point where they are requested.

The investigations follow the plasma need; hence, the first decision is where to inject the pellets. The results of the corresponding modeling activities are presented in [Sec. II.C](#). The input parameters for these activities are pellet size, pellet

speed, penetration point of SOL and direction. Three speed ranges represent different acceleration technologies:

1. 300 m/s: blower gun
2. 1200 m/s: centrifuge/single-stage gas gun
3. 3000 m/s: double-stage gas gun.

II.C. High Field Side Injection

In this explorative approach, three different poloidal launch positions have been considered: torus inboard [from the magnetic high field side (HFS)], torus outboard [from the magnetic low field side (LFS)], and vertical (parallel to the magnetic major axis). The result is clear: Injecting pellets from the magnetic HFS is the only way to set up a technically feasible system.

In order to transport pellets to this designated point of injection, guiding tubes are required. There are two options: straight guiding tubes or curved ones. Due to geometrical constraints, curved guiding tubes are more flexible in respect to injection point and direction. For straight tubes, it seems difficult to get the pellets into favorable areas. Furthermore, the injection angle in respect to the SOL is smaller, resulting in a reduced penetration depth of the pellet. This could be compensated for within a certain range using high-speed acceleration techniques.

Both solutions need guiding tubes; hence, some mass loss is to be expected. This mass loss turned out to be high for unfavorable geometries and speed. Indeed, the design of the tube defines the maximum pellet speed, particularly the bending radius and the transitions between geometrical elements.⁴ It must take into account all aspects (mass loss and survival probability) in order to keep the full performance of the pellet sources and to minimize the fuel inventory. Free-flight sections in between guiding tubes (e.g., for gate valves) require special care because of the scatter cone of free-flight pellets. They have to be trapped again using suitable funnels and fed into the subsequent guiding tube section.

Pellet injection into the plasma causes a strong impact on the latter. Initially, the size of a fueling pellet in ITER was considered as a reasonable choice (6×10^{21} atoms). Modeling activities taking into account the feedback from the plasma (closed loop) indicated this is unfavorably strong for EU-DEMO due to control issues.⁵ Hence, the design size was adapted accordingly to 2×10^{21} atoms. This is still a considerable impact, challenging the diagnostics and the plasma control system.

The first interface from the plasma edge is the penetration of the breeding blanket (BB). As the BB

serves for the production of tritium, the impact of the guiding tube to the BB should be as low as possible. The conditions in the BB space region are harsh, in particular on the plasma-facing side. Strong heat load and radiation are present. Therefore, three variants for the BB penetration are considered: full, partial, and no penetration. The deeper the penetration, the lower the required cutoff due to the scatter cone (see Fig. 2). This cutoff reduces the performance of the BB. On the other hand, the heat load on the guiding tube structure is higher. A no-penetration solution minimizes the load on this structure.

This obvious conflict is dissolved by a partial penetrating solution using dedicated modeling activities during the assessment of injection points and directions. Once the BB type is selected, a more thorough analysis is required to find the optimum solution (see Table I).

II.C.1. Issues of the Curved Guiding Tube

Initially, pellet injection systems were designed to inject from the outboard of the torus. This corresponds on tokamaks to the magnetic LFS. In the course of time, injection to the magnetic HFS turned out to be more effective (inboard launch).⁶ This design is more complicated; straight injection is very difficult due to geometrical constraints caused, in particular, by the magnets. In a new-built device, some options for a direct-line-of-sight (DLS) injection could be realized.

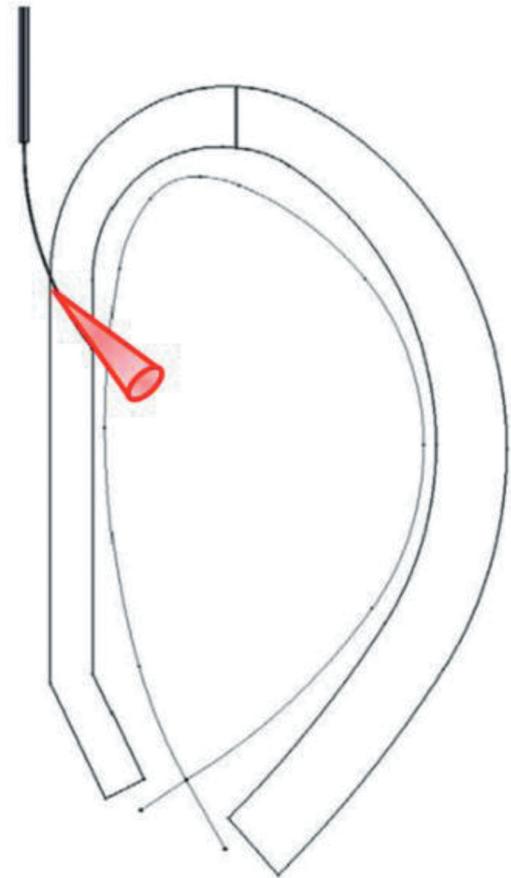


Fig. 2. Schematic setup of the solution with the guide tube ending at the rear end of the BB, not penetrating at all. This solution was expected to have a quite deleterious impact on the fueling performance but is considered to be the least practicable.

TABLE I
Assessment of BB Penetration Options

	Pro	Con
No penetration of BB	<ol style="list-style-type: none"> 1. Low heat load on guiding tube 2. Reduced complexity of mechanical design 3. Less interface to remote handling operation of BB 	<ol style="list-style-type: none"> 1. Reduced BB performance with regard to tritium breeding rate due to large scatter cone 2. Enhanced heat and radiation load on vacuum vessel wall due to reduced shielding of BB 3. Pellet trajectories scatter raises potential issues on control system. 4. Reduced path length for bending to the right direction due to straight free flight
Full penetration of BB	<ol style="list-style-type: none"> 1. Minimized impact on BB performance 2. Precise pellet trajectories 3. Optimum pellet performance 	<ol style="list-style-type: none"> 1. High heat load on guiding tube requires active cooling. 2. Complex interface to BB remote handling process

ASDEX Upgrade and JET are equipped with HFS pellet injection using curved guiding tubes. The ITER pellet injection system is designed to provide either LFS or HFS pellet injection using curved guiding tubes for both options, as well. In order to assess the maximum performance of these two options, a dedicated analysis on a mockup was carried out.⁷ The main parameter for the survival probability at a given pellet size and speed is the bending radius. The relation between the critical speed, pellet size, and bending radius for a cubic pellet is

$$v_c = \sqrt{\frac{\sigma_c R}{\rho L}}$$

where

- v_c = critical speed
- σ_c = yield strength
- R = bending radius
- ρ = pellet density
- L = side length of cubic pellet.

It is widely assumed that pellets are sliding on a gas cushion that is generated by the Leidenfrost effect. This reduces the friction a lot. If the centrifugal force becomes too high, this effect disappears; the friction increases and the pellets lose a lot of mass or are even destroyed.

Real pellets are not perfect in respect to mechanical stability, hence the “AUG calibrated” relation of pellet

size and bending radii was derived in order to provide the critical pellet speed of a given geometry. This critical speed defines the input parameter “pellet speed” for the corresponding modeling activities:

$$v_c = 36.4 \frac{\text{m}}{\text{s}} \sqrt{\frac{R}{L}}$$

This formula is benchmarked against data from the JET high-frequency pellet injector (HFPI), the Oak Ridge National Laboratory (ORNL) database, and the ITER mockup. The perfect fit to AUG data is intrinsic. The JET HFPI and ITER mockup match well. For the ORNL database, only a reasonable agreement can be claimed. However, the accordance is good, considering the wide span of data from DIII-D, JET, LHD, and FIRE (see Fig. 3).

The initial step of the modeling procedure was to find the most appropriate injection configuration. It turned out that only pellets launched from the torus inboard with a separatrix crossing sufficiently close to the horizontal midplane can achieve efficient fueling.⁸ The absolute pellet speed does not play the major role; what matters is the speed component perpendicular to the separatrix. This was adopted as a term of reference for the optimization of the injection geometry when taking into account further boundary conditions from the reactor design, in particular, the magnets. Obviously, pellet launch from the torus inside imposes the need to design a proper access to the vacuum vessel, a task hampered by its tight construction. Two basic solutions were derived: one

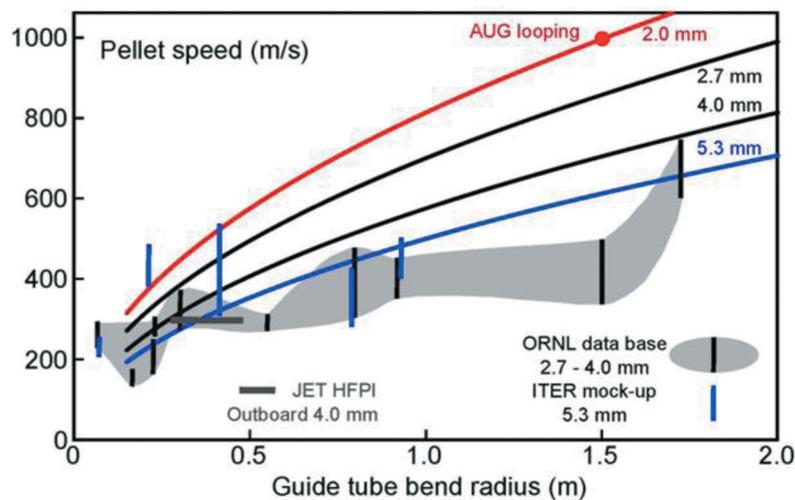


Fig. 3. Comparison of experimental data for maximum pellet transfer speeds in guide systems with characteristic bend radii. Data are from the ORNL database (black vertical lines, data range span indicated by shaded area), the ITER mockup (blue vertical lines), the JET HFPI inboard track (gray horizontal line), and the AUG looping system (red dot). Critical transfer speeds are calculated by the empirical “AUG calibrated” relation for different pellet sizes (2.0 mm, referring to the AUG data in red; 2.7 and 4.0 mm, referring to the ORNL database and the JET PLS HFPI in black; and 5.3 mm, referring to the ITER mockup in blue).

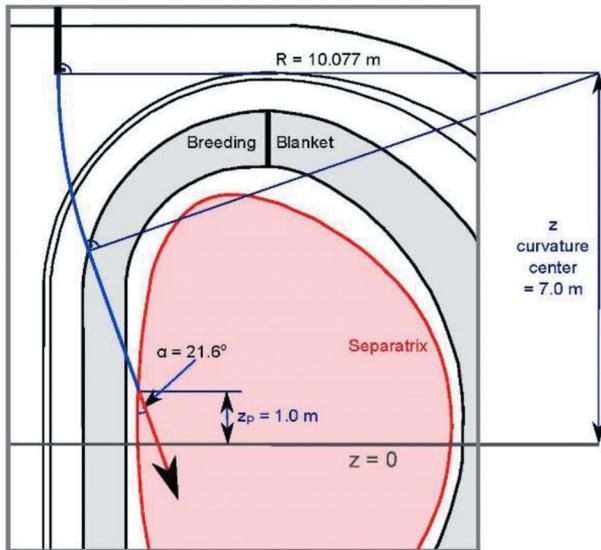


Fig. 4. Poloidal cross section of the injection geometry. The guide tube enters the vessel vertically at a fixed position and then enters a curved section following a segment of a circle up to the outer boundary of the BB. Keeping the direction at this point, the pellet leaves the guide tube resuming free flight toward the separatrix. For the example shown here, prescribing $z_p = 1.0$ m and a z curvature center = 7.0 m, it yields $R = 10.077$ and $\alpha = 21.6$ deg. From this, $v_c = 1702$ m/s and $v_{(P\perp)} = 627$ m/s is obtained.

relying on a guiding system with bent tubes, and a second considering no or only straight guiding tubes.

For the first option, appropriate space and location for several pellet launchers were identified and reserved on top of the cryostat. The guiding tube enters the vessel vertically at a narrow gap between the poloidal field (PF) and toroidal field (TF) coils at the upper part of the vessel. A gentle 90-deg bend outside the magnets causes no limitations on the operational parameters in the speed range of up to 1200 m/s. This gap is an almost fixed point; hence, the optimization task is to deal with the layout below the entrance section, as shown in Figs. 4 and 5.

Enforcing a very horizontal injection trajectory (and hence, an almost perpendicular penetration of the separatrix) increases the perpendicular pellet speed fraction, however, at the expense of a narrow bending radius and hence a lower absolute pellet speed. Going for bigger bending radii allows pellet launch with higher speed, which results in a tilted trajectory lowering the perpendicular speed component.

Taking the magnet geometry as a basis, the pellet penetration through the BB turned out to be a major issue for integration. Two effects have to be balanced in the course of the optimization: technical complexity of the solution versus system performance.

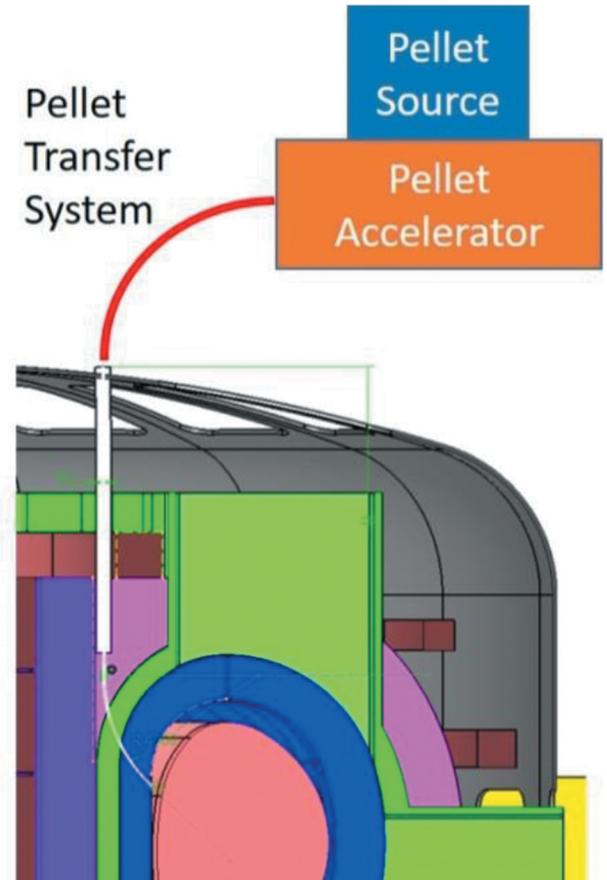


Fig. 5. Generic view of subsystem core fueling composed of pellet source, pellet accelerator, and pellet transfer system aiming at the magnetic HFS of the plasma. The speed range is at least 1200 m/s, hence centrifuge or single-gas gun is regarded to be suitable.

The least complex solution is to let the guiding tube end just on the rear surface of the BB. Then the pellets pass the BB straight in free flight, creating a scatter cone due to the scatter angle at the guiding tube exit (~ 1 deg). This cone enforces a significant cutout, reducing the BB performance while raising neutron and heat radiation issues on the vacuum vessel.⁹ This setup is expected to provide the lowest pellet performance of the variants investigated. Extending the guiding tube into the BB reduces the adverse effects but requires higher technology efforts. Two more setups are under consideration in addition to the no-penetration case: partial penetration with passive cooling (heat load drain via thermal conductance to the vacuum vessel) and partial penetration with active water cooling. Full penetration of the guiding tube is disregarded due to intolerable heat load.

In order to assess these three options, fully closed-loop modeling is applied. In a first step, pellet ablation and particle deposition are calculated by the HPI2 code, assuming this

takes place as an instant event with the initial target plasma parameters as boundary conditions. Second, the temporal plasma evolution of this delta-like pellet impact is computed by the ASTRA transport code. The final step is to adjust the pellet repetition rate to deliver pellet fueling just sufficient for achieving the required core density. The optimization strategy is to minimize the pellet particle flux required to meet a given core density target value.

A detailed investigation unveiled that the actively cooled solution shows the best fueling performance of the three guiding tube solutions, but also in respect to a comparative DLS configuration. However, the relative gain in respect to the passive-cooled option is only marginal and does not justify the huge effort to establish active cooling.¹⁰

At first modeling activities were performed still assuming an ITER pellet size. There are strong indications that accordingly the resulting pellet perturbation caused problems for burn control. This assumption was confirmed by a more detailed modeling of plasma and burn control with realistic pellet parameters resulting in the already mentioned adaptation of the pellet design mass. For the planned next steps (optimization taking adjusted pellet parameters into account) a well-established modeling strategy and tools are now at hand.

Future fusion devices will need appropriate fueling systems, providing pellets made from a mixture of tritium and deuterium. Material properties are different from nontritium pellets. The characteristics of these pellets are to be addressed in the upcoming conceptual design phase.

II.C.2. Issues of DLS: Straight Guiding Tube

An alternative injection scheme is proposed in order to avoid the mass loss of pellets using curved guiding tubes.¹¹ The main issue is to find a straight injection line to the magnetic HFS. The biggest barrier is the central solenoid, but other magnets define strong boundary conditions as well. A DLS geometry was carried out by a dedicated computer-aided design survey using a gap between the TF and PF coils (see Fig. 6). The initial intention to launch pellets in free flight was abandoned due to the big cutoff structure of the BB required to provide ample space for the scatter cone of pellets in free flight. The introduction of a straight guiding tube minimizes the interference to BB geometry. This option is labeled DLS.

The first metric of fueling efficiency is the value of the speed component perpendicular to the magnetic field at the penetration point of the SOL. The gap between the TF and PF coils is a pivot point, hence a target point with

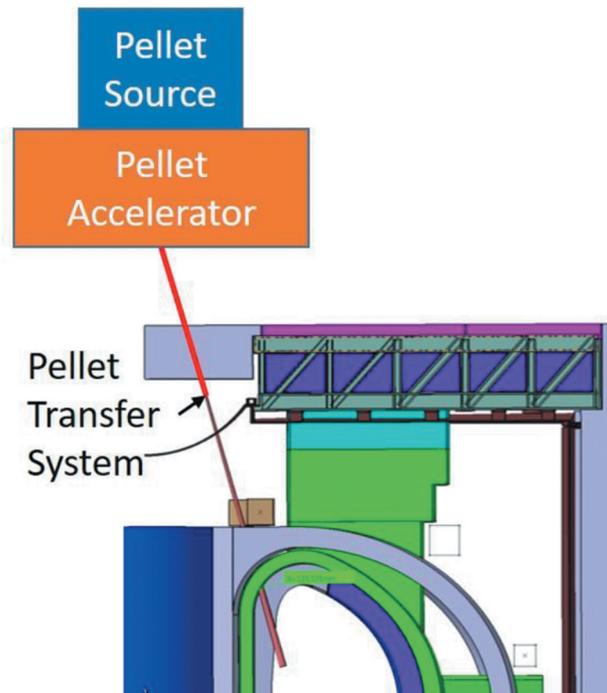


Fig. 6. Alternative variant using a DLS transfer system. High speeds up to 3000 m/s is required. Only double-stage gas gun technology will be able to reach this speed range.

higher z value (vertical distance to the torus midplane) provides a higher speed component and deposition depth.

In order to achieve sufficient penetration depth, the pellet speed should be much higher as assumed for the curved guiding tube concept. The target speed must be as high as 3000 m/s, requiring the use of double-stage gas guns.

In today's fusion devices, systems are installed either using curved guiding tubes at pellet speeds below 1200 m/s or using a free-flight setup at speeds up to 3000 m/s. The compatibility of straight guiding tubes with pellets at a speed of up to 3000 m/s in respect to survival probability and mass loss is under investigation. First results can be found elsewhere.¹¹

II.D. Pellet Acceleration

The main parameters of moving pellets are the speed and their accuracy. Any variation of the muzzle speed causes a jitter of pellet arrival time on plasma. For a given length of guiding tube, speed range, and scatter, there is a limit for the repetition rate. The upper limit is an arrival time jitter in the range of the period of the repetition rate. Pellets cannot pass in the guiding tube. Furthermore, the plasma control system requires the arrival of pellets on a regular basis.

The speed scatter is characteristic for the acceleration principle. Conventional pellet technology accelerates cryogenic pellets either using the force of an expanding gas volume (perhaps combined with some accelerated mechanic parts) or the guiding through an acceleration arm.

Gas guns are widely used in today's fusion devices, covering a speed range from 300 up to 3000 m/s. The lowest speed range guns apply a gas pulse to a pellet in a slightly bigger barrel, hence, some amount of the gas escapes through the gap between the pellet and the barrel. The speed range is up to 500 m/s.

High-speed guns (single stage) apply a gas pulse to a pellet frozen in the barrel, hence, initially there is no gap between the pellet and the barrel until the breakaway. The speed range is up to 1500 m/s.

Very high-speed gas guns (double stage) improve the gas pressure by applying a puncher that compresses the propellant gas to a higher level. Pellet speeds of up to 3.8 km/s are reported.^{12,13}

Pellet acceleration using a gas pulse is a force closure process, intrinsically with some existing slip (e.g., some bypassing gas). A second attribute of this acceleration principle is its mass dependence. Hence, any variation of pellet mass (e.g., due to some mass loss during the breakaway or acceleration process) affects the muzzle speed and the pellet arrival time accordingly.

The maximum repetition rates reported are decreasing for systems with a higher pellet speed range. Usually, the propellant gas is to be separated, injection to the plasma vessel not intended.^{14–16}

Centrifuge-based pellet systems require a more complex mechanical design due to the high kinetic parts that are to be integrated into the high-vacuum environment. The acceleration principle is form closure, hence, there is no slip. In addition, the acceleration is not mass dependent. The acceleration arm length and the rotation frequency define the speed. The jitter of pellet muzzle speed is very low, even for pellets with different sizes. This opens the way to integrating pellet sources for different purposes on one acceleration system, e.g., for fueling and ELM pacing. An according system is under construction for JT-60SA. The centrifuge provides a clock for the pellet launch that the plasma control system can rely on. The low-speed jitter offers the application of high pellet repetition rates, e.g., required for ELM pacing purposes. The speed range of existing systems is reported to be up to 1200 m/s (Refs. 17, 18, and 19).

II.E. Pellet Source

The pellet source delivers pellets of the right size and consistency and at the right time to the acceleration system. Most likely, the pellets should be made from a mixture of deuterium and tritium, e.g., 1:1. There are two pellet formation principles: extrusion and desublimation. The extrusion principle is usually applied to centrifuges and blower guns and the desublimation for gas guns (single and double stage). For fueling purposes, only the extrusion principle provides sufficient material throughput in order to achieve the requested high repetition rates. The latter is essential in terms of being a plasma actuator, following the plasma control system request. Extrusion systems are described elsewhere.^{12,15,20}

On ASDEX Upgrade a set of experiments was carried out injecting pellets with an isotope mixture (H/D) or admixed elements (N₂ or Xe in a deuterium pellet) into an H-mode plasma. The mixed hydrogen isotope experiments aimed to mimic the deuterium/tritium mixture in a future fusion device in terms of isotope control in the extruded ice as well as in the plasma.²¹

The admixing of xenon or nitrogen to deuterium pellets could help to inject PEGs into the plasma core. Dedicated technical demonstrations and plasma experiments were performed on ASDEX Upgrade.^{22,23}

The admixing of such gases results in the higher ice extrusion force needed and slows down the extrusion speed, and hence, the mass throughput. Therefore, this option does not come free of charge. Depending on species and confinement, the fraction of admixed species could range up to a few percent. A possible technical solution would be a dedicated extruder for efficient auxiliary species delivery in the host pellet integrated in the multisource centrifuge launcher concept currently planned for JT-60SA.

Early in the upcoming conceptual design phase of EU-DEMO there must be a decision about the injection scheme. This comprises the acceleration principle as well as the kind of guiding tubes (curved versus straight ones). A dedicated pellet test bed is proposed and envisaged in order to address these open questions and provide the basis for the conceptual design of the pellet system. The plasma scenario development for EU-DEMO is evolving and fueling technology has to follow this development and provide some headroom for the variation of requirements at a later stage. A design optimized to one point in parameter space is currently regarded as not suitable.

III. GAS INJECTION

Despite its use on today’s fusion devices, gas injection will not be suitable for serving the fueling purposes on EU-DEMO. The injected neutrals will be ionized at the very plasma boundary and will not be able to penetrate deep enough to contribute to the plasma core density. Gas puffing affects mainly the plasma edge, well desired for some purposes like divertor buffering.

Despite its uselessness for core fueling in the burning phase of operation, gas injection is required to provide matter injection in the ramp-up and ramp-down phases.

III.A. Purpose

The pump-down time for EU-DEMO in the dwell phase should not add on top of the recharge time. This is why a target time of 600 s was defined, which, however, requires the use of the electron cyclotron–assisted breakdown at pressures of typically 1 MPa. Hence, no prefill of gas is required.

Investigations for the ramp-up phase are on hand, indicating the required fueling rate, electron temperature, and electron density.²⁴ Effective pellet fueling requires appropriate target plasma that is hot and dense enough to absorb the injected pellet. Below this threshold, matter injection has to be provided by gas injection.

One useful characteristic number to assess the fueling property of injected pellets is the penetration depth. This depth is usually expressed as a fraction of the minor plasma radius (λ/a). The international pellet ablation database, collected by L. R. Baylor et al., provides a method to estimate the penetration depth as a function of electron temperature, electron density, pellet mass, and velocity perpendicular to the flux surfaces²⁵:

$$\lambda/a = 0.079 \cdot T_e(\text{keV})^{-0.51} \cdot n_e(10^{20} \text{m}^{-3})^{-0.03} \cdot m_p(10^{20} \text{atoms})^{0.12} \cdot v_p(\text{m/s})^{0.32},$$

where

λ = penetration depth

a = minor plasma radius

T_e = central electron temperature

n_e = electron density

m_p = pellet mass

v_p = pellet speed.

The units are indicated in brackets. Note, this scaling is valid only for LFS injection, while DEMO will

be HFS injection. Nevertheless, it is useful to get a first guess.

The penetration depth must meet a certain range. Values greater than 0.5 will cause severe plasma instabilities and are considered not useful. Pellets with a penetration depth lower than 0.1 are prone to not get over the pedestal; hence, a significant fraction of its material content is immediately rejected. These values are the subject of ongoing modeling activities that will follow the plasma scenario development.

Considering a crossover point from gas injection to pellet fueling at a penetration depth of 0.3, the gas injection system must be able to provide a particle flow ramp from 5×10^{21} 1/s (9.4 Pam³/s) up to 7×10^{21} 1/s (13.2 Pam³/s) within 70 s, resulting in a gradient of 2.86×10^{19} 1/s² (0.05 Pam³/s²). After the crossover point, the same gradient but decreasing should be sufficient (see Fig. 7).

For ramp down, the gas injection takes over from the pellet injection at a particle flux of 1×10^{21} atoms/s, which is much lower than the crossover value for the ramp up. A possible sequence is displayed in Fig. 8.

We developed a method to define this crossover point. In the course of the conceptual design phase, this exercise should be performed by applying the HPI2 code on the EU-DEMO plasma scenario, which is still evolving, as well as the ramp-up and ramp-down scenarios. This procedure provides results that are more precise and relevant.

III.A.1. Auxiliary Gases

There are some reasons to inject gases into the plasma beyond fueling purposes. The most important reason for this is to enhance the plasma performance by profile

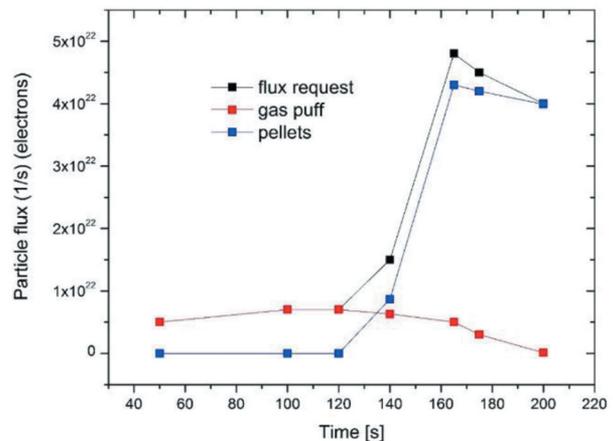


Fig. 7. Development of the particle fluxes for gas injection and pellet injection during the ramp-up phase estimated according to data provided by F. Koechl. Numbers are nominal; no particle losses are considered.

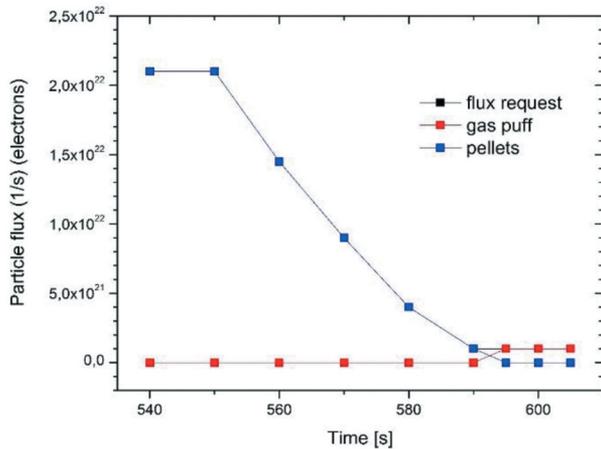


Fig. 8. Development of the particle fluxes for gas injection system and pellet launching system during the ramp-down phase estimated according to data provided by F. Koechl. Numbers are nominal; no particle losses are considered.

modification, divertor buffering, or radiative cooling in the plasma edge as well as the core. Prime candidates for plasma enhancement are nitrogen, which has been proven suitable, and neon, which is a possible candidate as well, despite the fact that this hasn't been fully confirmed yet. For radiative cooling dependent on the prescribed location in the plasma or divertor, noble gases like Ne, Ar, and Xe are preferred.

Just as for fueling purposes, species injected by the gas injection system hardly overcome the separatrix; hence, the delivery efficiency to the plasma core is low. A dedicated assessment will be required for each of these

purposes about whether gas injection is suitable or not. For application in the core, admixing of elements to cryogenic pellets would be an option.

III.B. Design

The main aim for the design of the gas injection system is to provide a precise and fast adjustable mass flow. Furthermore, the flow measurement and control should be reliable and robust to withstand the harsh conditions on a fusion device.

III.B.1. Valve Boxes

The main idea is to separate the on/off (valve) function from the flow adjustment. The gas injection system provides a continuous flow to the run/vent valve box, which switches this flow between straight to the tokamak vacuum vessel or to the tokamak bypass. By doing so, an almost constant gas flow is maintained from the gas distribution system to the DIR loop, either the torus or the tokamak bypass. This valve block is supposed to be robust enough to be installed in the port plug.

Flow control is based on an adjustable orifice and a regulation valve operated in choked flow mode. Alternatively, the flow adjustment could be done by an array of valves having different conductance, for instance, 1/2/4/8/16 ... times the basic conductance. The control valve box (CVB) is allocated to the port cell; see Fig. 9 (Ref. 2).

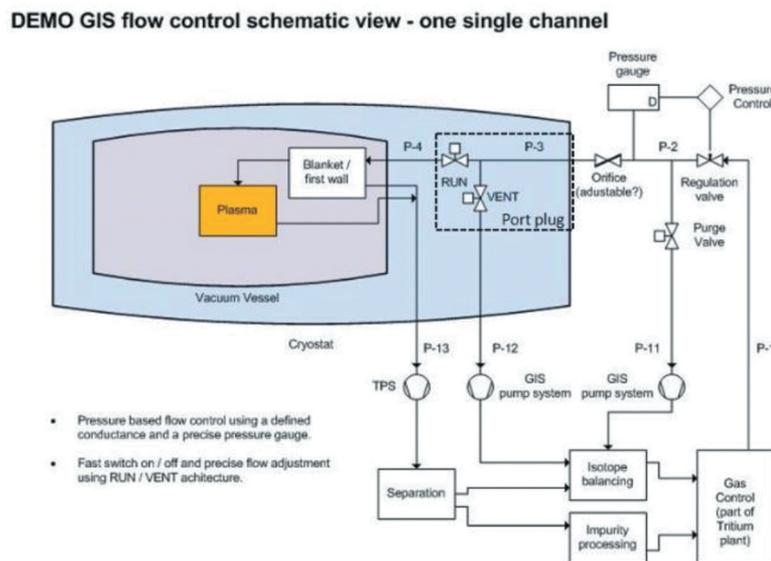


Fig. 9. Functional diagram for one single injection line.² The run/vent valve box will be in the port plug and the CVB in the port cell.

III.B.2. Gas Manifold

The solution that was worked out for ITER is considered suitable for EU-DEMO as well. The manifold consists of a pipe bundle of six tubes attached on the evacuation tube, which has an inner diameter of 54.8 mm. The feed tubes have an inner diameter of 22.4 mm (H₂, D₂) and 13.8 mm (T₂, He, Ne, and Ar). This pipe bundle is covered by an envelope with an outer diameter of 273.1 mm made from two half-shells. The wall thickness is designed to be 4.19 mm. Tee joints can be created without any interference of the tubes among each other either in the horizontal or vertical direction (see Fig. 10). The manifold will be made from SS 316 L to the American Society of Mechanical Engineers (ASME) B36.10/19 standard.²⁶

The manifold connects all components of the gas injection system. A loop architecture is proposed; more detailed engineering is to be carried out in the upcoming conceptual design phase for EU-DEMO.

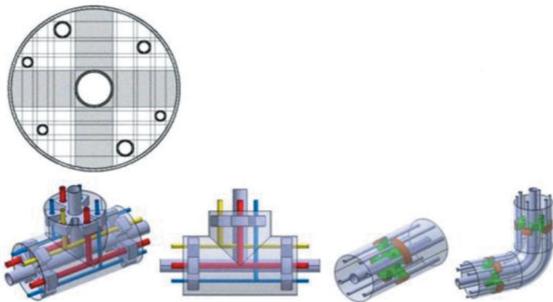


Fig. 10. Cross section and basis structure of gas manifold from Ref. 26.

IV. TRANSITION TO THE CONCEPTUAL DESIGN PHASE

Nowadays, fusion devices are employing a variety of matter injection systems (see Table II). These systems have varying scopes; hence, the technologies and system characteristics are different. Currently, no one of these systems has obtained sufficient maturity to serve for a reactor. A big technology gap is located for pellet injection systems, which is to be closed in the course of the conceptual design phase.

A beneficial matter injection system is designed with a strong focus on the plasma need. The injection geometry defines the speed range, which refers to the acceleration principle. Two speed ranges are present: (1) up to 1200 m/s and (2) up to 3000 m/s. The latter speed range is reserved for double-stage gas guns.

The available speed is not the only criteria. There's also the maximum repetition rate, and more importantly, the speed scatter. The latter has a direct impact on plasma control and should be as small as possible.

The acceleration unit needs pellets in the right shape and quality and in time. Basically, there are two pellet formation principles: ice production by extrusion or using desublimation. The latter is a typical process for pipe guns, hampered by the timescale of the process cycle due to the thermal properties of the material. The extrusion principle is potentially able to provide steady-state ice production.

Early in the upcoming conceptual design phase, a decision for an acceleration technology is required, taking in to account the discussed aspects. Following this decision, the conceptual design phase shall focus on reactor-relevant technology.

It is essential for pellet system operations, and for plasma control purposes as well, that some pellet diagnosis is available. The former is for system conditioning

TABLE II
Summary of System Performance Reported on Current Systems

Type	Speed (m/s)	Scatter (%)	Repetition Rate (Hz)	Remarks
Blower gun	100 to 300	~10	>100	AUG, JET, DIII-D, EAST, KSTAR, W7-X, ITER (designated)
Gas gun (single stage)	1000	>10	10 to 20 (per barrel)	DIII-D, FTU
Gas gun (double stage)	>3000	>10	<1 (per barrel)	DIII-D, Tore Supra
Centrifuge	1200	1	>80	AUG, JET, Tore Supra, JT-60U, JT-60SA (designated)

purposes. The plasma control system needs to get information about whether the pellets arrived on the plasma or not. Pellet diagnosis on today's systems relies on optical methods that are considered difficult to be implemented in any DEMO reactor.

Pellet injections are strong events, creating plasma density step and perhaps some perturbations. The development of “pellet-resilient” diagnoses is a challenge to be addressed in the course of the project with the strong interaction of respective experts.

V. CONCLUSION AND OUTLOOK

The preconceptual design phase has proven that core fueling of the EU-DEMO is possible. It turned out that only “conventional” pellet technology is sufficiently mature and suitable for this purpose. The matter injection systems may potentially also serve for issues like ELM control (if required) or the efficient delivery of most auxiliary gases to the plasma. All investigations were carried out with a strong focus on the plasma need. The properties of today's techniques and their relevance for system performance are discussed. A solution is elaborated on and proposed based on pellets made from an extruded ice rod, accelerated by a centrifuge to a speed up to 1200 m/s, and delivered via curved guiding tubes to the magnetic HFS of the plasma.

An alternative solution would be the injection of pellets at very high speed (~3000 m/s) via a straight guiding tube (DLS). Some technology issues are classifying this solution to be second tier. The main drawbacks are the big speed scatter and the low pellet repetition rates connected to the acceleration principle (propellant gas, double-stage gun) and the unfavorable injection geometry enforced by the EU-DEMO magnets.

Very early in the conceptual design, a decision is required considering whether the alternative solution is able to balance these disadvantages, e.g., by reduced mass loss in the guiding tubes.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014–2018 and 2019–2020 under grant agreement number 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. Raw data were generated at the ASDEX Upgrade facility. Derived data supporting the findings of this study are available from the corresponding author upon reasonable request.

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