A Flexible Pellet Injection System for the Tokamak JT-60SA: The Final Conceptual Design

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Abstract — The research plan of the JT-60SA, a superconducting tokamak device currently under construction, requests a powerful pellet injection system for its particle fueling and edge-localized-mode (ELM) pacing experiments. These investigations, foreseen to answer basic questions with respect to the operation of ITER and a future fusion power plant like DEMO, need pellets with flexible parameters delivered precisely and reliably for control purposes. Here, we present a conceptual design of this system based on classical pellet technology. Analysis showed pellets will show the best performance for fueling and most likely also for ELM pacing when injected from the torus inboard side, despite the limited maximum pellet speed caused by this approach. This is due to constructional constraints rising from the fact the JT-60SA vacuum vessel is already under construction, enforcing inboard injection via a multibend guiding-tube system and limiting the maximum pellet speed to about 470 m/s. To match this boundary condition and fulfill the need for precise control, a centrifuge accelerator has been chosen. Based on the stop cylinder principle and equipped with a double accelerator arm, it can host up to six steady-state ice extruders working simultaneously for pellet production. This way, all system requirements expressed in the research plan can be well covered, providing even some headroom for better flexibility during the planned investigations. Details of our design and the reasoning for the layout chosen are provided in this paper.

Keywords — JT-60SA, tokamak, pellet technology, particle fueling.

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

I. INTRODUCTION

A new superconducting tokamak is currently being built under the Broader Approach Satellite Tokamak Programme run jointly by Europe and Japan, and under the Japanese national program. Already approaching completion, the JT-60SA device is expected to start operation in 2020 (Ref. 1). It will then be at the forefront of the international fusion program, supporting the ITER experimental program as a satellite machine. In addition, it is expected to provide key information for the operational scenario of future DEMO fusion reactors, in particular for a steady-state, advanced performance design option. The startup of operation of such a large experimental device is a challenging enterprise, requiring a broad set of preparation activities that involve among others the elaboration of a research plan2 and conception studies of diagnostics and subsystems, for example, heating, matter injection, and pumping. Many of these activities are carried out in a

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coordinated way by a joint Japan-European Union (EU) JT-60SA Research Unit, in close interaction with the JT-60SA project for the machine construction. One activity of this kind was the conceptual design of the pellet injection system, requested to be elaborated on in a dedicated study within 3 years. The outcome of this study, finalized in 2017, is presented in this paper.

The aim of the study was to find the best possible design for a pellet system covering the requirements formulated in the JT-60SA research plan. However, this design also had to take into account all the boundary conditions arising from the fact that the tokamak facility is already under construction, thus imposing constraints, for example, torus access and any installations inside or close to the vessel. The mission of the JT-60SA endeavor is to support the exploitation of ITER and, by resolving key physics and engineering issues, the design of an EU DEMO reactor. Consequently, the pellet system has been designed for all of the resulting research needs. Two major tasks have been dedicated to the pellet tool managing the injection of cryogenic solid pellets formed from fuel into the plasma: providing the main particle source for the core plasma and edge-localized-mode (ELM) pacing as one of the key techniques considered for ELM mitigation.

Efficient core particle fueling has to be applied for operation at high central densities in long-pulse discharges in ITER- and DEMO-relevant conditions. In ITER and an EU DEMO, operation at core densities close to or even beyond the Greenwald density \( n_{\text{Gw}} \) (Ref. 3) is a must in order to maximize fusion power output. A loss of the demanded high-confinement mode (H-mode) operation takes place when approaching \( n_{\text{Gw}} \) by simple gas fueling. This behavior is attributed to an edge-density limit, which can easily be overcome by deep-particle deposition enforced by pellets.\(^4,5\) Hence, the density profile (or density gradient) needs to be optimized and controlled keeping the core density high while simultaneously preserving edge conditions.

ELMs are intense, short-duration relaxation events occurring in the H-mode regime,\(^6-8\) releasing particles and energy which load plasma-facing components. Scaled up to ITER, such loads would be unacceptable high.\(^9\) ELMs can also play a beneficial role by removing impurities from the plasma.\(^10\) Hence, control of the ELM frequency, and if possible, ELM mitigation will be a key issue in reactor-compatible plasma scenarios. There are several proposed methods for externally triggering or pacing ELMs in order to influence their size and occurrence frequency.\(^11\) One of them is pellet injection, found to work reliably in several devices.\(^12,13\) However, more recently conditions have been observed where pellets failed to achieve ELM control.\(^14\) Thus, the pellet system design has to provide the capacity for investigations in order to clarify the triggering issue and, in case of a positive result, deliver pellets suitable for ELM frequency and size control.

Details of the expected design data of the pellets delivered in order to enable specific physics investigations and engineering capabilities are already provided by the JT-60SA research plan. For the physics goals, the high-density operation in ITER- and DEMO-relevant plasmas, exploration if and how densities above the Greenwald density can be accessed, investigations of the power exhaust by developing radiation layers, particle balance studies, and ELM control have been enlisted. As well, pellets shall be applied for studies on the nonlinearity of the ion and electron heat transport observed from cold/heat pulse propagations. Regarding the density control, pellet fueling experiments will be carried out to demonstrate effective density-control capability in different scenarios. Estimated from a steady-state particle balance analysis (assuming the particle confinement time of the particles fueled is equal to that of the particles fueled by the neutral beam) this will require a pellet particle flux of up to \( 6.4 \times 10^{21} \text{s}^{-1} \). This can be realized, as proposed in the research plan, by injecting of cylindrical pellet with a diameter \( \Omega \) and length \( l \) of both 2.4 mm at a rate of 13 Hz. In the case that the particle confinement time of the pellet-deposited particles is smaller, it is understood a higher pellet particle flux is required. To cover this potential need, an ultimate pellet flux capability of \( 3.0 \times 10^{22} \text{s}^{-1} \) is considered in the research plan, to be shared in this case by up to three individual injectors.

The requested engineering deliverable is to serve as actuator for control on electron density and ELMs within an advanced real-time control scheme. In a staged approach, it has to be commissioned by quantifying the impact in the open loop during the first research phase to prepare for closed-loop control experiments in the second research phase. A real-time frequency control for the plasma density feedback control is planned with one pellet injector delivering the reference pellet size of \( \Omega = l = 2.4 \text{ mm} \) at a maximum injection frequency of 20 Hz. For ELM pace making, a pellet frequency upgrade to 60 Hz is foreseen in the research plan. For studies of the isotope effects on plasma confinement and controllability of isotope ratio, pellets in combination with gas puffing have to actuate for controlling the amount of each species.

Using superconducting toroidal and poloidal field coils, the tokamak device will be capable of confining
break-even-equivalent-class high-temperature deuterium (D) plasmas lasting for a duration of typically 100 s, longer than the timescales characterizing key plasma processes, such as current diffusion and particle recycling. It has been designed to realize a wide range of diverted plasma equilibrium configurations, covering a wide range of different plasma scenarios. Six reference scenarios representing the envisaged operational range of ITER- and DEMO-relevant plasma regimes at the JT-60SA have been selected for the analysis performed in this study. Their basic features are displayed in Table I, a very detailed description is provided in Ref. 2, while Ref. 15 yields a comprehensive overview.

II. STRATEGY

The aim of this study was to perform first a feasibility study and then to develop a system design that can be manufactured with minimized risks but covering all requirements stated in the research plan. It turned out this could be best achieved by a conceptual design composed from one baseline device covering all the essential operational needs but yielding also the option for potential extensions, upgrades, and auxiliary supplements.

Following the recommendation in the research plan and also the decisions of ITER (Ref. 16) and the EU DEMO (Ref. 17), the initial choice for the basic design was to select classical pellet technology. There is a twofold reason for this decision. First, a detailed review of available alternative technologies worth serious consideration showed major shortfalls in all cases; only the classical approach as applied in many fusion devices provides a sufficient and sound base. Apparently, the technology gap between different techniques has widened in recent years. While ITER’s decision significantly boosted efforts for the classical technology, support of alternative approaches has been depleted. And second, evidently by using the same technology as ITER, the JT-60SA will be most suited to identify potential problems and develop relevant solutions.

A sketch of such a classical system is displayed in Fig. 1, showing the setup of the JET high-frequency pellet injection (HFPI) system in a recent configuration capable to launch from two different poloidal positions into the plasma. This system, described in detail in Ref. 18, serves the JET tokamak and has tasks and capabilities close to our desired ones. As highlighted in Fig. 1, classical pellet systems are composed of three main components:

1. **Pellet source:** The pellet source delivering solid fuel with the right size to the acceleration unit. Pellets are formed from gas in the reservoir. This can be done as a batch process or in steady state.

2. **Accelerator:** For the accelerator receiving pellets from the source or cut pellets with the required size from an ice ribbon provided by the source and accelerating them to the preselected speed, several classical accelerator options of different complexity are available offering different operational parameter ranges.

3. **Transfer system:** The transfer system providing the pellet transport to the desired launch position at the plasma boundary, if required by guiding tubes, is possible in case of direct access via free flight.

Usually, multiple diagnosing units are embedded within these main components for controlling the ice/pellet quality and to measure and provide the achieved pellet parameters to the tokamak feedback control and data acquisition systems.

### Table I

Main Parameters of the Six JT-60SA Reference Scenarios*

| Scenario | 1   | 2    | 3    | 4    | 5    | 6    |
|----------|-----|------|------|------|------|------|
| Name     | Inductive | Inductive | High Density | ITER-Like | High-ß Full-CD | High-ß 300 s |
| Configuration | Double Null | Single Null | Single Null | Single Null | Single Null | Single Null |
| $I_p$ (MA) | 5.5 | 5.5 | 5.5 | 3.5 to 4.6 | 2.1 to 2.3 | 2.0 |
| $q_{95}$ | 3.2 | 3.0 | 3.0 | 3.2 to 4.4 | 5.8 to 6.0 | 4.0 |
| $P_{add}$ (MW) | 41 | 41 | 30 | 34 to 37 | 30 to 37 | 13.2 |
| $f_{Gw}$ | 0.5 | 0.5 | 0.8 | 0.8 | 0.85 to 1.0 | 0.39 |
| $\beta_N$ | 3.1 | 3.1 | 2.6 | 2.8 to 3.0 | 4.3 | 3.0 |

*CD = current drive; $I_p$ = plasma current; $q_{95}$ = safety factor at 95% of the poloidal magnetic flux; $P_{add}$ = additional heating power; $f_{Gw}$ = ratio line-averaged electron density/$n_{Gw}$; $\beta_N$ = normalized plasma beta.
To elaborate on the basic layout and to serve system optimization, mainly the expected behavior of an analyzed solution with respect to its particle fueling was taken into account. This is due to the fact the fueling impact of pellets is understood quite well and hence can be modeled reliably. In contrast, there are no proven quantitative models yet at hand for the ELM triggering potential of pellets. Fortunately, experimental investigation strongly indicates solutions selected for their good fueling performance also show the most favorable behavior with respect to their ability for triggering ELMs (Ref. 19). Modeling, at least qualitatively, agrees with this experimental finding.20 This favors for both applications the injection from the torus inboard side rather than launch from the outboard. Inboard injection into hot plasmas, where the pellet ablation cloud is subject to a strong drift force directing into the plasma and increasing the penetration depths, turned out to be more efficient than outboard launch (with the drift pushing pellet particles toward the plasma edge) despite the superior injection conditions (higher available speed, less mass losses) for the outboard launch.21 Hence, we assume the best overall solution for the injection geometry with respect to all applications can be obtained by optimizing with respect to the fueling behavior.

As a matter of course, a differentiation between fueling and ELM pacing is still inevitable with respect to the pellet parameters, which are, apart from the pellet launching location/geometry:

1. material used to produce the pellet
2. the particle content (mass) of the pellet $m_P$
3. speed $v_P$
4. repetition rate $f_P$.

Notably, the repetition rate and mass determine the pellet particle flux $\Gamma_P = f_P \times m_P$, the key actuation parameter for control purposes during operation.

As fueling pellet material, pure D is foreseen for the main operational phase. However, the system will be laid out to handle also pure hydrogen (H) or any mixtures of H/D isotopologues. In addition, it is envisaged to keep also the option to use small amounts of room-temperature gases like nitrogen (N$_2$), neon (Ne), or argon (Ar) to dope the fueling pellets. When keeping the dopant amounts sufficiently low (in the order of 1%) it has been shown a pellet source and accelerator designed for fueling applications can still handle doped ice and pellets,22 enabling an efficient “piggyback” supply of, for example, plasma enhancement gases.23 Pellets dedicated to trigger ELMs will be produced most likely from the same material as the fueling pellets in order to cause as little unwanted fueling side effects as possible.

For the fueling pellet, the mass preset by the research plan acts already as a good indicator. For the optimization of this parameter, size scans have been performed in the modeling of the pellet-particle deposition. The distinct pellet shape has to be adapted to or will be settled by the chosen accelerator. For any gas gun, a cylindrical shape would fit best. In a centrifuge, the shape is essentially irrelevant. In the end, the shape is chosen to get the simplest shape that is the most reliable to fabricate. To provide optimized pacing pellets, the trigger potential has to be granted while minimizing potentially unwanted side effects like unavoidable residual fueling. Hence, here the
pellet mass has to be optimized by reducing it to an amount just sufficient to trigger an ELM while still granting a high delivery reliability. The initial pellet size has to be kept large enough, otherwise pellet losses due to acceleration and transport can compromise the high reliability inevitable for control purposes. Adversely, no modeling tools are yet at hand to predict the pellet-mass threshold for ELM triggering. This threshold can, besides the mass, also depend on the pellet speed and injection location and will differ in different plasma scenarios. Consequently, the system has to provide a distinct flexibility for the available pellet masses in order to adjust this parameter in the experiment, once again, with a pellet shape kept as simple as possible.

For the pellet speed, in all relevant cases it is expected a higher value results in deeper particle deposition and better fueling efficiency. For the pacing application, the impact of the speed is not fully understood. On the one hand, higher speed allowing for deeper penetration was found in some cases helpful; on the other hand, slower pellets causing a stronger local perturbation can surpass the trigger threshold more easily. Thus, for ELM triggering investigations some flexibility of $v_P$ is certainly an advantage. The speed range accessible is essentially preset by the accelerator chosen. Within classical technology, there is a variety of possibilities at hand. One principle relies on momentum transfer from a streaming or expanding gas. In the case where the pellet dimension is smaller than the barrel diameter such a device is dubbed a blower gun. Blower guns work reliably up to very high repetition rates of 100 Hz and beyond in the speed range around 300 m/s. Higher velocities can be achieved by pneumatic gas guns where the pellet acts like a piston in the barrel driven by the expanding gas. Applying light gases like H or helium (He) as propellant, single-stage guns can achieve velocities in excess of 1000 m/s at repetition rates of several tens of Hertz. Pellet speeds in excess of 3000 m/s can be realized by multistage pneumatic guns, where high temperatures and pressures in the reservoir’s final stage are generated by previous stage compressions. For this technique, so far only quite low repetition rates have been achieved. Besides gas guns, mechanical devices relying on centrifugal force acceleration have been applied. For example, the ASDEX Upgrade launcher demonstrated velocities up to 1200 m/s and repetition rates beyond 80 Hz. For the envisioned operation, the speed range up to about 1000 m/s seems to be well covered by the single-stage gas gun or centrifuge option; higher speeds up to about 3000 to 4000 m/s would allow only injection at a rate capable of studying single-pellet effects. Evidently, the accelerator sets the range of available pellet launch speeds while the transfer system can cause restrictions to it. This becomes effectual in particular in case guiding tubes are required—and for the assumed favorable inboard injection they are inevitable. For the pellet transfer through guiding tubes, there is also some relation between pellet mass and maximum transfer speed to be taken into account as discussed in Sec. III in more detail.

With respect to the repetition rates needed, a sound guidance is provided also by the research plan. For fueling needs, $f_P = 20$ Hz is demanded in order to provide some headroom in case it is needed. To drive the ELM frequency up by pellets, it is requested to deliver pacing pellets up to a rate of 60 Hz.

As mentioned before, the injection location and the corresponding transfer system play a major role in the efficiency of pellet fueling and most likely also for ELM triggering. Roughly speaking, the potential of the physics drift effect favoring inboard launch has to be balanced against technology advantages better employable for outboard launch. In a device of the JT-60SA’s size and with respect to the envisioned plasma performance, it is expected the drift effect has to act in favor of the particle deposition, and hence, inboard launch will likely provide the best overall option. Hence, great interest has been put on the design of potential transfer systems allowing for inboard pellet injection. On the other hand, since the JT-60SA is already under construction and essential parts of the torus vessel are already built and in place, stringent boundary conditions and design constraints exist. In particular, access can be granted only through a few available vessel entrance ports and space restrictions apply for the installation of the guiding tubes. From an engineering analysis and assessment, three possible injection-geometry options have been identified. As displayed in Fig. 2, they are outboard, top, and inboard. For both outboard and inboard, at least in principle, a free flight transfer utilizing the full accelerator potential is possible. The inboard option enforces a quite intricate three-dimensional (3-D) guiding-tube installation described in more detail in Ref. 28, imposing significant limitations on $v_P$.

### III. SINGLE-PELLET MODELING-BASED CHOICE FROM AVAILABLE OPTIONS

With the available information on plasma and pellet parameters, an analysis was performed in order to find out the potential performance of the different options.
This approach was based on the investigation of the expected particle-deposition profile calculated for single pellets with given parameters set for every relevant scenario and for any of the considered launch positions. Hence, a set of typical plasma profiles (density, temperature, magnetic configuration, etc.) was taken representing the six scenarios shown in Table I. For each of the three injection options trajectories are determined by the construction-conditioned constraints; it was assumed the pellets follow straight along the initial designated path. Since usually the angular scattering of the pellet trajectories is small, this effect has been neglected.

Operation in D was assumed, the same assumption was made for the pellet material. With a pellet size of $\varnothing = l = 2.4$ mm as defined in the research plan, this yields $m_p = 6.5 \times 10^{20}$ D atoms. Besides this reference case, the option of an oversized pellet with $m_p = 4 \times 10^{21}$ D atoms was analyzed also in order to sound out how larger pellets could help to improve fueling efficiency.

To complete the parameter set, information about the achievable pellet speeds for the different injection configurations was needed. For the outboard launch option, it is assumed free flight injection can be established, and hence, the maximum speed can be the full accelerator potential. Reflecting the typical performance of double-stage gas guns, a range from 2000 to 4000 m/s was taken.$^{26}$

For the inboard guiding tube with multiple bends, in a first step the effective bend radius $R_{eff}$ was estimated. In order to provide redundancy, two separate tubes will be installed: one in section P7 and one in section P12 (the JT-60SA is composed from 18 toroidal sections, labeled P1 through P18). The initial and final sectors of both tubes are identical, just the middle sector is a bit more favorable for the P12 variant. However, these differences are minor and for both inboard options $R_{eff} = 0.4$ m was taken. To determine the maximum (critical) pellet transfer

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Fig. 2. Poloidal cross section of the JT-60SA tokamak with the three launch trajectories considered. Injection from the outboard and top can be achieved, at least in principle, in free flight utilizing the full accelerator potential; for inboard launch an intricate transfer system has to be employed.
speed through we used the empirical AUG calibrated relation:  

\[ v_c = 36.4 \left( \frac{\text{m}}{\text{s}} \right) \sqrt{\frac{R_{\text{eff}}}{l}}, \]

yielding 470 m/s for \( R_{\text{eff}} = 0.4 \) m and \( l = 2.4 \) mm. The relation is based on the assumption that for a pellet sliding along a contour line of radius \( R_{\text{eff}} \) the centrifugal forces are balanced by the critical yield strength \( \sigma_c \). For a cubic pellet with side length \( l \) this yields

\[ v_c = \sqrt{\frac{\sigma_c R}{\rho l}}, \]

with \( \rho \) the pellet density. Taking for D ice at 10 to 12 K, \( \rho = 200 \left( \frac{\text{kg}}{\text{m}^3} \right) \) (Ref. 24) and \( \sigma_c = 0.45 \text{ MPa} \) as maximum yield strength before pellet destruction sets in (necking stress in Fig. 6.6 in Ref. 29), \( \sqrt{\frac{\sigma_c R}{\rho l}} \approx 47.4 \left( \frac{\text{m}}{\text{s}} \right) \) is found. This is close to the value we determined for the looping-type transfer system installed and operated at ASDEX Upgrade for about 20 years with \( R_{\text{eff}} = 1.5 \) m, where for a cubic \( l = 2.0 \) mm D pellet a critical speed of 1000 m/s was found. This somewhat reduced performance is possibly due to an extrusion process not yet fully optimized, and hence, resulting in a somewhat deteriorated ice quality. Possibly, this might be related to the fact material properties are measured from samples better compounded than the pellet ice and could hint for enhancement potential in the way pellets are produced for fusion applications. Nonetheless, the factual achievement was taken into account by reducing \( v_c \) calculated from the material properties by about 1.3 times.

To recheck and further substantiate this calibrated relation, a comparison to data from a couple of well-analyzed transfer systems was performed. The result is shown in Fig. 3, which displays the relation between the effective (or in some cases the minimum) bend radius and the critical pellet speed. Solid lines refer to the relation for four different values of \( l \). The red dot represents the ASDEX Upgrade looping used for the calibration (cubic \( l = 2.0 \) mm pellets), of course fitting exactly to the calculated value. A wide parameter range is covered by the investigations of Combs et al.,\(^{30}\) providing data from different operating devices [Oak Ridge National Laboratory (ORNL) database, vertical black bars and gray area] and the ITER mock-up tests (vertical blue bars). As well, the critical speed observed for the JET HFPI outboard launch guide tube is indicated\(^{31}\) (gray horizontal bar). The EAST high-field side injection line performance for \( O = l = 2.0 \) mm pellets\(^{32}\) (green horizontal bar) is added, too. Finally, the star represents the expected maximum pellet speed to be expected for reference-size pellets launched from the inboard. To sound out if a tighter speed restriction would deteriorate the inboard fueling performance significantly, a safer low-speed option with 200 m/s was also considered. Obviously, the considered launch-speed range for inboard pellet injection is well covered by available accelerator technology.

For the top launch option, free flight injection is possible in principle. However, in reality this might require efforts considered inappropriate. A dedicated technical solution has not yet been worked out. Here, pellet speeds of 470 and 2000 m/s are assumed for the modeling.
though bordering well the range of reasonably possible setups. With the parameter set derived as discussed, ablation and fueling simulations have been carried out by means of the currently most advanced tool, the HPI2 code. The code computes the pellet ablation taking into account thermal ions and electrons and the supra thermal ions generated by the plasma heating systems. It is valid for any considered magnetic and plasma configuration.\textsuperscript{33} The employed model for the plasmoid drift altering the initial ablation profile into the final particle-deposition profile is based on the compensation of the cloud polarization by parallel currents.\textsuperscript{34} For code benchmarking, experimental data from the international pellet ablation database\textsuperscript{35} assembling data from several tokamaks (JET, Tore Supra, DIII-D, FTU, TFTR, ASDEX Upgrade, JT60-U, RTP, and T-10) of different magnetic configurations and auxiliary heating were taken. In order to assess the potential capabilities of the pellet fueling system, code runs have been performed covering the entire range of plausible combinations of injection geometry and pellet speed. Hence, considered cases assume high-speed launch from the outboard but only moderate velocity for the inboard injection. One typical example for such a code run, analyzing the injection of a single pellet into steady target plasma, is shown in Fig. 4. The example displays results for a reference-size pellet ($m_P = 6.5 \times 10^{20}$ D) with a speed of 470 m/s from the inboard into a scenario 2 plasma. Shown in Fig. 4a is the injection configuration with a pellet trajectory intersecting the separatrix at a radial position of $R_V = 1.80$ m at $z = 0.63$ m above mid-plane and tilted by 70 deg with respect to the horizontal mid-plane. In the simulation, a spherical pellet with a diameter of 2.74 mm was assumed. The resulting pellet-particle deposition profile with the maximum position marked versus the normalized plasma radius is plotted in Fig. 4b. In Fig. 4c, the impact of the particle deposition on the electron temperature profile is shown and in Fig. 4d the impact of the particle deposition on the electron density profile is shown, displaying the respective profiles before and immediately after the pellet. Notably, this modeling did not take into account the effect of ELMs potentially triggered by the pellets.

Essential results on pellet-particle deposition for all the six scenarios and pellet characteristics considered reasonable are summarized in Fig. 5. Figure 5a displays the deposition depths of the pellets, with filled dots representing the location of the main maxima and bars the deposition profile extension until 0.1 times this value. In some of the outboard launch cases, the drift directed toward the outward is hindered by the $q = 2$ surface (typically located at $\rho \approx 0.82$); the resulting congestion of the pellet particles leads to a secondary-bump in the deposition profile,

![Fig. 4. Pellet particle ablation and drift simulation with the HPI2 code for scenario 2 in the case of a reference-size pellet ($m_P = 6.5 \times 10^{20}$ D) injected from the inboard with a speed of 470 m/s: (a) injection geometry; (b) pellet-deposition profile versus normalized radius with peak-deposition rate marked; (c) pre- and post-injection electron temperature profiles; and (d) the same for the electron density.](image-url)
significantly smaller than the main peak. The location of
this peak is indicated by the open circles. However, the
magnitude of this effect depends very strongly on the
details of the simulation and was regarded as too dicey
for a dependent reliable fueling performance. Figure 5b
shows the calculated fueling efficiencies $\varepsilon$, the fraction of
pellet particles deposited within the confined plasma inside
the separatrix at the time the pellet is fully ablated. The
missing fraction indicates the amount of prompt losses; a
significant deviation of $\varepsilon$ from unity thus hints at a very
unfavorable fueling performance.

It clearly turned out that the injection configuration is
the most important feature for the fueling characteristics
and that inboard launch provides the best suitable solu-
tion despite its speed restriction and the not fully opti-
mized trajectory with respect to the flux tube geometry.
Fortunately, the speed sensitivity for inboard launch is
modest, hence more severe speed restrictions than
assumed will not cause major performance losses. As
can be seen from the $\varepsilon$ calculated, outboard and top
launch are always hampered by significant instant losses.
Strikingly, the significant advantage of the inboard con-
figuration holds for any scenario considered. It is only the
outboard launch at very high speed that by any chance
reaches a similar performance in cases where the pellet
can reach the $q = 2$ surface. This solution is regarded
worthwhile for physics investigations but thought unfit as
a baseline fueling solution. Injection from the top is not
favorable in any case. Finally, the discrepancy in fueling
efficiency between inboard cases with a rather deep particle
deposition and the situation where the pellet deposits
particles close to the edge will most likely become even
larger under the influence of the ELMs. It is well known
that ELMs causing a transient loss of the edge transport
barrier mainly affect the edge and pedestal region.36
Hence, pellet particles deposited close to the separatrix
will be lost more easily than their counterparts arriving
deeper inside the plasma column. Derogating shallow
deposition much more than deeper profiles, ELMs will
make inboard injection even more favorable than out-
board or top injection.

With the results for any of the six scenarios under
consideration unanimously accounting for inboard launch
to provide the best fueling performance, a well-settled base
for qualifying the expected fueling performance is formed.
Hence, as a main conclusion from the single-pellet model-
ing approach, it was opted to go for the inboard launch as
the prime choice. Here, even in case the estimated transfer
speed of 470 m/s cannot fully be achieved, the best overall
performance in experiments aimed at steady fueling toward
high target densities can be expected. The option for a setup
enabling pellet injection at high speed in free flight from the

![Fig. 5. (a) Particle-deposition depths calculated for different pellet launch sites and speeds for the considered target scenarios. All
assuming D pellets with reference mass ($m_P = 6.5 \times 10^{20}$ atoms) except the case indicated as “Oversize” using $4 \times 10^{21}$ atoms.
Filled dots represent the absolute maxima of the deposition profile; open dots the smaller secondary peaks occurring under some
conditions; and bars denote the deposition profile extension until 0.1 times the maximum value. (b) Calculated fueling efficiencies
($\varepsilon$ = deposited particles inside separatrix at pellet burnout/$m_P$).](image-url)
outboard could yield a possibility for sophisticated physics investigations on pellet and particle transport physics and also foster further technology research and development (R&D). However, it is unlikely to facilitate the full requirements postulated in the research plan. Consequently, the system design worked out in this study was focused on the prime choice—inboard.

IV. DESIGN LAYOUT OF MAIN SYSTEM COMPONENTS

After a start-up of pellet injection experiments with a single system, the research plan finally assigned the full coverage of all requirements to three pellet launchers. Thus, obviously for the initial system, a full simultaneous supply of pellets acting for fueling and pacing applications is not a must. Nevertheless, the presented design for the (first) system is providing the potential to act as the sole pellet device for all needs. Furthermore, this design allows start up in a simple configuration, providing an upgrade toward a flexible multipurpose system. The design proposal presented in Secs. IV.A, IV.B, and IV.C aims to account for all the existing restrictions and boundary conditions while providing a tool able to cover all the needs for the JT-60SA’s demanding physics and engineering tasks. Since this system has to be integrated into a device already under construction, the design started from the transfer system, the component facing the most stringent restrictions, and adopted the other components accordingly.

IV.A. Transfer System

For the system, the inboard launch option has to have the highest priority. The in-vessel part of this track is already fixed, the design drawing is presented in Fig. 6. The challenging character of the solution employing many tube bends is evident; due to this, it is estimated the fueling pellets can be transferred in good order only up to a speed of 470 m/s. Possibly, pellets smaller than the reference size can be used for ELM pacing, which could allow for slightly higher velocities. On the other hand, provisions had to be taken in case reliable transfer can be achieved only at a somewhat lower pellet speed. Correspondingly, to match the technical capabilities of the transfer system adequately, the pellet speed range from 200 to 600 m/s had to be covered. As a matter of course, both possible variants for tube installation have to be implemented for safety redundancy and/or to allow simultaneous injection from different launchers. For the start-up, the P12 variant is more suited while the P7 option provides a back-up solution. As the best advantage for both variants, a nearby vessel access capable for outboard launch will be provided as well. To minimize pellet break-up and mass losses, the overall travelling distance between the accelerator and plasma has to be kept as short as possible. Hence, it is foreseen to place the accelerator inside the torus hall as close to the vessel as possible. An assessment of available sites for launcher installation yielded a total length $L$ of the transfer system of about 16 m. For the start-up phase, and most likely also under

![Fig. 6. Guiding-tube geometry installed inside the JT-60SA vessel for pellet inboard injection. Multiple bends of the guiding tube are expected to impose a limit of about 470 m/s to the maximum injection speed.](image-url)
regular operational conditions, the accelerator will be connected directly to the inboard track. To grant some flexibility, an option will be provided to use a route for outboard injection, too. For the outboard pellet path, due to the restricted pellet speed, the initial part can be a guiding tube as well. Changing between both options can then simply be done by back-fitting the tubes. Even more flexibility can be achieved when allowing switching between tracks within a pellet train. Designs for suitable selectors are available, for example, a four-way selector (three in-vessel guiding-tube lines and a pellet dump) has been used for the JET HFPI (Ref. 31). An even more sophisticated system is currently being developed at ORNL for the ITER pellet system.37 Such systems can manage switching between tracks within less than 1 s.

IV.B. Pellet Source

The technology and design for a source required to deliver pellets steady state or at least for sequences lasting sufficiently long (>100 s) for the size range and with a mass throughput need for the JT-60SA system fortunately is already at hand. Once again, the development of pellet extruders undertaken for the JET HFPI and for the ITER system well match our needs. The extruder built for the JET HFPI demonstrated reliable and persistent pellet delivery already under the harsh conditions of an operating fusion device. Its layout is suitable and demonstrated truly steady-state operation despite JET can operate with pulsed plasma lasting up to several tens of seconds only. It can deliver selectively pellets either for fueling or pacing purposes, but not both simultaneously. Our design is trying to avoid this restriction by employing separate pacing and fueling systems operated in parallel. For the JET HFPI system in fueling mode, cylindrical pellets are delivered with a diameter of 4.0 mm and an adjustable length. Pellets can be formed either by pure H or D, in the latter case $m_P$ can be varied from $2 \times 10^{20}$ to $4 \times 10^{20}$ atoms.31 With a repetition rate of up to 15 Hz it has a pellet flux capability of $6 \times 10^{21}$ s$^{-1}$. All these parameters are very close to the JT-60SA ones, naturally since similarly sized tokamaks need similar fueling capacities. Set into the ELM pacing configuration, cylindrical pellets with diameter 1.2 mm, adjustable length, and thus mass ($m_P = 0.6 \times 10^{20}$ to $1.2 \times 10^{20}$ D) can be launched at up to $f_P = 50$ Hz. Once again, the likely needs for the JT-60SA are closely matched. In this respect, the projected JT-60SA system can benefit from the R&D investments done for the JET HFPI.

For the ITER 1:5 prototype–scale extruder developed at ORNL, the situation is very similar. This unit based on a twin-screw approach as well is a steady-state device capable of handling pellet parameters also in the required range. Furthermore, its design allows for the use of different ice species and even mixtures of different H isotopes.38

In conclusion, devices are already at hand for a pellet source as needed for the JT-60SA pellet system. For our conceptual design, it is envisaged to use several extruders simultaneously in parallel. Every extruder is dedicated to a specific task, for example, fueling, pacing, or eventually other needs. For the fueling extruder, production of cylindrical $\Omega = 2.4$ mm ice is foreseen providing the option to change the pellet length from 1.2 up to 4.8 mm ($l = \Omega/2$ to 2$\Omega$ since pellets with an aspect ratio of less than 2 have been found to be not stable). For $l = \Omega$, a rate of 20 Hz is prescribed. Operation with D ice will be the standard operational scheme, but the option to use H has to be kept as well. For the pacing extruder, the design foresees a fixed $\Omega = l = 1.2$ mm and a rate of up to $50$ Hz. However, the extrusion nozzle has to be laid out for possible easy replacement by one with a different diameter. In case the potential of a single extruder is found insufficient, the concept relies on the possibility to add yet another extruder of the same type for reinforcement. With this approach it is also possible to add an extra extruder dedicated to specific R&D tasks, as for example, the use of ice produced from fuel doped with other species. It is understood our system design approach thus relies on an accelerator capable of receiving pellets simultaneously from different sources delivering pellets at different mass and frequency.

IV.C. Accelerator

To conclude the system design, an adequate accelerator had to be chosen, able to master all the requirements and boundary conditions coming from the source and transfer system. As previously stated, candidate systems have been the blower gun, centrifuge, and single-, double-, or multiple-stage gas guns. The blower gun is disregarded, as the available speed is considered not suitable since it would restrict the operational range even further. The option to use a double- or multiple-stage gas gun could be applied for outboard launching at very high speed. This is a possible setup allowing investigating pellet ablation physics and related transport effects under extraordinary conditions. However, due to the low repetition rate for this technology, it is more adapted to a situation where every pellet performs a
single experiment rather than for steady-state and persisting fueling investigations. Consequently, for the initial pellet system design, this solution was disregarded, too.

This keeps as the only options the single-stage gas gun and the centrifuge. Both techniques have proven able to manage the required pellet parameters. As well, both are equally suited for a pellet system requiring a transfer system. Our decision was to go for the centrifuge solution for three main reasons. The first one is the higher precision of the pellet speed; resulting pellet trains arriving with a regular and more predictable pattern fit better to the feedback control requirements. By comparison, unveiled gas guns can show a launch speed scatter \( \delta v = \Delta v_p / v_p \) (with \( v_p \) the averaged speed and \( \Delta v_p \) the range of launch speed variations) of about 0.1, while for a centrifuge \( \Delta v_p / v_p < 0.005 \) can be achieved. The reason for this is the strong mass dependence of the acceleration force in a gas gun, while there is no such dependence for the centrifuge (details in Sec. V and the Appendix). A moderate scatter of the pellet launch speed can cause a very strong scatter in the frequency of the arriving pellets \( f_p \) after tube transfer. In extreme cases a fast pellet \( (v_p = v_p^+ + \Delta v_p) \) is followed by a slow pellet \( (v_p = v_p^- - \Delta v_p) \) or vice versa:

\[
1/f_p^+ = 1/f_p^- \pm \frac{2L}{v_p^-} \left( \frac{\delta v}{1 - \delta v^2} \right),
\]

with the + case referring to “fast followed by slow” and the − case referring to “slow followed by fast.” The expression becoming negative indicates pellets start even overtaking in the tube. Assuming \( L = 16 \) m and \( v_p^- = 300 \) m/s thus for a gas gun (\( \delta = 0.1 \)) for the ELM pacing \( f_p = 60 \) Hz and \( f_p^+ = 36 \) to 170 Hz and for fueling \( f_p = 20 \) Hz and \( f_p^+ = 16.5 \) to 25.5 Hz, an unacceptably high imprecision would result. In contrast for a centrifuge (\( \delta = 0.005 \)), respective \( f_p^+ \) values of 58 to 62 and 19.8 to 20.2 Hz seem quite acceptable. Furthermore, with a centrifuge \( v_p^- \) can be matched much better to the critical transfer speed. The second reason for choosing the centrifuge is the ability of employing multiple sources for pellet delivery simultaneously, even using extruders producing different size pellets. For example, the former JET centrifuge could host up to six extruders simultaneously.

Third, a centrifuge avoids the loads imposed by the propellant gas employed in a gas gun. Finally, a centrifuge can easily master all reasonable pellet shapes providing some headroom for the optimization of the extruders.

However, the drawbacks related to the centrifuge principle had to be taken into account and handled properly. Due to the revolving mechanics allowing successful pellet launch only at certain times during the cycle, pellet launch at an arbitrary time or at any frequency is not possible. Pellet launch rates must fulfill a synchronization condition with the revolving frequency \( f_C \); \( f_p = M \times f_C / N \) with \( N \) an integer and \( M \) the integer less than or equal to the number of accelerator arms. Since the acceleration force is related to \( f_C \), a relation between \( f_C \) and \( v_p \) exists. Furthermore, changing \( f_C \), and hence \( v_p \), can take place only on a timescale of several minutes. In plasma operation, thus \( v_p \) is essentially fixed for a single discharge, with the alteration taking typically several tens of minutes having to take place between discharges. Hence, the details of the centrifuge layout have to be well matched to the requirements and the envisaged pellet parameter range.

V. OPTIMIZING THE CENTRIFUGE LAUNCHER

In order to optimize the centrifuge layout for the requirements of the JT-60SA, and taking into account the boundary conditions caused by the transfer system and the need for simultaneous pellet delivery from different extruders, a refined design was elaborated based on the experience from previous stop-cylinder centrifuges developed for ASDEX Upgrade, JT-60U (Ref. 42), and JET (Ref. 41). A 3-D sketch of the ASDEX Upgrade system, equipped with a single batch extruder only, is shown in Fig. 7. Our design has been optimized in order to meet the following operational parameters:

Fig. 7. Three-dimensional sketch of the ASDEX Upgrade stop-cylinder centrifuge launcher equipped with a single batch extruder. Due to installation of a single inner acceleration arm, pellets can be accelerated only in one of the two available outer acceleration arms restricting the maximum pellet rate to the centrifuge revolution frequency.
1. pellet speed range 200 to 500 m/s to match the expected inboard speed capabilities
2. 20-Hz rate for the fueling system since such rates have been demonstrated already
3. 50 Hz for the pacing extruder, a value already found hard to achieve for the JET HFPI (Ref. 31).

Like the three reference systems, the JT-60SA centrifuge will run with two outer accelerator arms, but in contrast to them it will have two inner acceleration arms, and hence, will use both outer arms for the acceleration. This allows for a pellet rate of up to twice the revolving frequency. For the start-up configuration, two pellet sources are foreseen, one for fueling and one for pacing purposes. In case needed, it can also be operated either with two fueling or two pacing extruders in order to double the flux and frequency, respectively, for the required task. Finally, it is foreseen to install up to six extruders on the centrifuge vessel in a design like the one used for the JET centrifuge.43 Thus, significantly higher pellet rates and/or higher particle fluxes could be achieved than by a single extruder. As well, this provides the amenity to add a device processing an alternative pellet composition, as for example, H isotope mixtures or admixture to add a device processing an alternative pellet admixture.

Consequently, the centrifuge will be laid out for a maximum of 20/500 = 0.04. Consequently, also \( \Gamma_p \) can be thus adjusted with a final precision only. Disregarding flux changes stemming from pellet speed and mass variations, this is hence ±2% for the fastest pellets and ±5% for the lowest assumed pellet speed of 200 m/s. For the pellet pacing aiming at a rate of 50 Hz, the frequency can be tuned in steps of about 5 Hz (50.0 Hz, 45.4 Hz, 41.7 Hz, ...).

The scheme of a stop-cylinder centrifuge acceleration process is shown in Fig. 8. The upper part of Fig. 8 shows the stop cylinder and the lower part displays the pellet trajectory while sliding on the outer arm as observed in the laboratory frame. Since the pellet path does not depend on the revolution frequency, this trajectory is identical at every \( f_C \) (the dots are plotted for equidistant times). Here, the stop cylinder principle is adapted to the use of two inner arms and the two related outer acceleration arms. The stop cylinder itself is static (but can be adjusted to tune the final pellet flight direction) and the inner and outer arms are fixed on the rotating centrifuge. As is characteristic to the stop-cylinder principle, pellets dropped into the cylinder area are picked up and driven by an inner arm, sliding radially outward until they are stopped by the stop cylinder. At the outlet, the pellets with a nil radial speed component transfer from the inner to the outer arm where final acceleration takes place. At the tip of the outer arm, the pellet leaves with a well-defined exit speed and angle. Due to the large stop-cylinder radius chosen in interaction with a rather high \( f_C \), sufficiently high forces should act on the pellets. Under such conditions, indeed a very low angular dispersion was found at the centrifuge exit.27 In case the angular spread turns out to be too high, a funnel can be inserted in order to guide pellets smoothly into the transfer system. A suitable concept is already available44 that takes advantage of the fact that centrifuge pellets leaving with some angular scatter still follow well-defined trajectories. Shaping the funnel accordingly thus can keep the perpendicular pellet impact speed on the funnel wall sufficiently low and focus all trajectories into the guiding system entrance.

Even more details can be recognized in the upper part of Fig. 8. For the centrifuge hub here a radius of 0.01 m is assumed. The locations of both inner acceleration arms, labeled A and B, are shown at different times displayed in
blue and red (straight lines). To grant successful pellet release at the right position with correct speed and direction, the pellet has to be dropped within the acceptance area. Pellets dropped outside arrive directly at the stop-cylinder outlet, causing misfiring. The two trajectories (curved solid lines) enclosing this “forbidden” area are shown; the area’s size (shaded gray in Fig. 8) depends on the outlet dimension.

For the chosen dimensions of the stop cylinder and outer acceleration arm, the calculated acceleration angle is 139.5 deg and the exit angle is 45.44 deg. The arrow displayed in the lower part of Fig. 8 shows the flight direction of the pellet when leaving the outer arm. Evidently, this flight direction has to point into the guiding tube entrance (or toward the plasma in case of free flight). Therefore, as in all the reference systems, a diagnostic unit for passing pellets is needed to be mounted at the exit of the centrifuge or the entrance of the transfer system, respectively. During the system startup, the fine tuning of the stop cylinder adjusting the final flight direction will be committed by this detector.

VI. CONCEPT VERIFICATION IN A FULL-MODELING APPROACH

To conclude the conceptual design, a showcase check for the layout parameters with respect to fueling was conducted. To do so, a full-modeling approach was made in the context of an analysis of the JT-60SA operational scenarios. For this, the JT-60SA pellet-injection geometry was implemented in the JINTRAC suite of codes (a

Fig. 8. Upper part: Stop cylinder with the two inner acceleration arms A and B (in blue and red at different times) rotating around hub (assumed radius 0.01 m). Trajectories for pellets picked up by an inner arm enclosing the “forbidden” area (shaded gray) for feed in. Pellets inserted inside this small segment are not stopped by the stop cylinder and hence misfired. Pellets inserted elsewhere are stopped at the stop cylinder, leave the cylinder at the outlet with nil radial speed, and undergo a correct acceleration process. Lower part: Pellet path (dots represent equidistant times) on the rotating outer acceleration arm (position at pellet exit in gray) until it leaves in the direction indicated by the arrow. Full outer acceleration angle 139.5 deg; exit angle at the arm tip 45.44 deg.
detailed description is provided in Ref. 45) and used in combination with the HPI2 module. The HPI2 module calculates the pellet impact on the plasma taking into account ablation and $\nabla B$-drift of the cloud. An initial plasma configuration scenario 2 was taken (moderate density inductive H-mode plasma, $I_p = 5.5$ MA and $B_t = 2.25$ T). Keeping the input power constant [24-MW positive neutral beam injection (NBI), 10-MW negative NBI, and 7-MW electron cyclotron resonance heating], a fully predictive simulation was performed using the Bohm/gyro-Bohm transport model. For the code run shown in Fig. 9, the foreseen inboard fueling configuration was adopted with reference-size pellet launch at a speed of 470 m/s. Then, a pellet train was added, starting with a yet low $f_p$ of 3.7 Hz. With $1/f_p$ obviously still in the range of the plasma energy and particle confinement times, the pellet impact on density, temperatures, and confinement remain transient and no significant persistent changes were found. Once quasi-static conditions were achieved, the pellet rate was raised in two steps to finally 11.1 Hz. With the final rate, similar to the value estimated and stated already in the research plan as reasonable, the core density levels out at about $1.3 \times n_{Gw}$. Thus, this modeling confirms the pellet system parameters foreseen can be expected to cover the fueling needs, i.e., to manage the transfer from an initial situation with moderate density to a final one with the core density in a reactor-relevant range.

VII. SUMMARY AND OUTLOOK

A comprehensive overview of the design elaborated for the JT-60SA pellet system, itemized with respect to the three main components, can be found in Table II, which displays the parameters foreseen for the system start-up but also provides information on possible upgrades, extensions, or alterations. At present, the installation of both variants of the inboard guiding tubes is already in progress. As well, places for the launcher installation in the torus hall and access ports for possible outboard injection paths are reserved. A project plan is in preparation, aimed at a detailed component design able to initiate manufacturing or ordering.

Modeling efforts are under way to analyze the stability of the pellet-imposed local perturbations. For example, it is well known pellet deposition modifying density, temperature, and current profiles can trigger the growth of instability. Such instabilities can have a detrimental

![Fig. 9. Modeling of a fueling sequence transferring scenario 2 to scenario 3 (inductive H-mode from moderate to high density). Assuming inboard reference-size pellet injection with $v_p = 470$ m/s, train with increasing $f_p$. The increasing pellet particle flux raises the core density well beyond $n_{Gw}$.](image)
impact on the confinement and hamper fueling efficiency. With the system layout providing sufficient headroom for adapting the pellet parameters accordingly, it is thought capable to handle measures needed to avoid such instabilities. An instructive example has been the avoidance of neoclassical tearing mode instabilities in JET, achieved by tailoring of pellet flux and plasma heating.\textsuperscript{47} In this respect, these stability analyses can aid the efficient planning of the initial fueling experiments once the pellet system has become operational.

### APPENDIX

The acceleration of a pellet on a rotating straight arm can be considered as the motion of a “pearl on a rotating stick” discussed in textbooks on Lagrangian dynamics.\textsuperscript{48} Considered is the acceleration of a pellet with mass $m_P$ on a straight arm, rotating with a constant angular velocity $\omega$. Assuming the motion is within a plane, appropriate choices are the coordinates $r$ for the radial distance and the angle $\phi$. This gives the relations with respect to Cartesian coordinates $x$ and $y$:

\[ x = r \cos \phi \]

and

\[ y = r \sin \phi . \]

Since the pellet is constraint to stay on the arm, we get one equation of constraint:

\[ \phi - \omega t = 0 \]

reducing the 2 deg of freedom to a single one. Applying this rheonome equation of constraint yields for the generalized coordinates:

\[ x(t) = r \cos(\omega t) \]

and

\[ y(t) = r \sin(\omega t) . \]

For the time derivatives we get

\[ \dot{x} = \dot{r} \cos(\omega t) - r \omega \sin(\omega t) \]

\[ \dot{y} = \dot{r} \sin(\omega t) + r \omega \cos(\omega t) . \]
Applying Lagrange's equation

\[ 0 = \frac{d}{dt} \frac{\partial L}{\partial \dot{r}} - \frac{\partial L}{\partial r} = \frac{d}{dt} (m_p \ddot{r}) - m_p r \omega^2, \]

we get the equation of motion

\[ \ddot{r} = \omega^2 r, \]

with the general solution

\[ r(t) = Ae^{\omega t} + Be^{-\omega t} \]

and

\[ \dot{r}(t) = A\omega e^{\omega t} - B\omega e^{-\omega t}. \]

Taking the initial conditions \( r(t_0) = r_0 \) and \( \dot{v}(t_0) = 0 \) yields

\[ r_0 = A + B \]

and

\[ 0 = A - B \rightarrow A = B = \frac{r_0}{2}, \]

\[ r(t) = \frac{r_0}{2} (e^{\omega t} + e^{-\omega t}) = r_0 \cosh(\omega t) \]

and

\[ \dot{r}(t) = \omega r_0 \sinh(\omega t). \]

Since \( r(t) \) can also be expressed as

\[ r(\varphi) = \frac{r_0}{2} (e^\varphi + e^{-\varphi}), \]

the pellet trajectory is not dependent on \( \omega \).

The pellet is moving with steadily increasing acceleration to the outside while its total = kinetic energy continuously grows as

\[ E_{tot}(t) = E_{kin}(t) = \frac{1}{2} m_p (r^2 + r^2 \omega^2) = \frac{1}{2} m_p \]

\[ \times \left\{ \frac{\omega^2 r_0^2}{4} (e^{2\omega t} + e^{-2\omega t} - 2) + \frac{\omega^2 r_0^2}{4} (e^{2\omega t} + e^{-2\omega t} + 2) \right\} \]

\[ = \frac{m_p \omega^2 r_0^2}{2} \cosh(2\omega t) = \frac{m_p \omega^2 r_0^2}{2} \left\{ 1 + 2 \sinh^2(\omega t) \right\}. \]

The acceleration time \( T \) when the pellet arrives at the end of the rotating arm \( R \) is given by

\[ R = r_0 \cosh(\omega T) \]

and hence

\[ T = \frac{\arccosh\left(\frac{R}{r_0}\right)}{\omega}. \]

During \( T \) the arm passes the acceleration angle

\[ \varphi = \frac{360^\circ}{2\pi} \arccosh\left(\frac{R}{r_0}\right). \]

To calculate the final pellet speed \( v_P \) it is helpful to calculate the kinetic pellet energy gained in the frame of the rotating arm when arriving at \( R \):

\[ E_{kin} = \frac{R}{r_0} m_p \dot{r} dr = \frac{R}{r_0} m_p \omega^2 r dr = \frac{m_p \omega^2}{2} (R^2 - r_0^2), \]

yielding for the final radial component of the pellet speed:

\[ v_R = \omega R \sqrt{1 - \left(\frac{r_0}{R}\right)^2} \approx \omega R \left\{ 1 - \left(\frac{r_0}{4R}\right)^2 \right\} \text{ for } R \gg r_0. \]

The perpendicular angular speed equals the speed of the arm tip:

\[ v_\varphi = \omega R, \]

and hence, the pellet speed in the laboratory frame is

\[ v_P = \sqrt{v_R^2 + v_\varphi^2} = \omega R \sqrt{2 - \left(\frac{r_0}{R}\right)^2}. \]

Reversing this relation, \( R \) can be obtained as

\[ R = \frac{1}{\sqrt{2}} \sqrt{\left(\frac{v_P}{\omega}\right)^2 + r_0^2}. \]
For the exit angle of the pellet direction after leaving the arm with respect to the arm it yields

\[ \cot \alpha = \frac{v_R}{v_o} = \sqrt{1 - \left(\frac{r_o}{R}\right)^2}. \]

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References

1. H. SHIRAI et al., Nucl. Fusion, 57, 102002 (2017); https://doi.org/10.1088/1741-4326/aa5d01.
2. “JT-60SA Research Plan 2016;” JT-60SA Research Unit; www.jt60sa.org/pdfs/JT-60SA_Res_Plan.pdf,v3.3 (current as of Feb. 19, 2018).
3. M. GREENWALD et al., Nucl. Fusion, 28, 2199 (1988); https://doi.org/10.1088/0741-3335/28/12/009.
4. P. T. LANG et al., Nucl. Fusion, 52, 023017 (2012); https://doi.org/10.1088/0741-3335/52/2/023017.
5. M. BERNERT et al., Plasma Phys. Control. Fusion, 57, 014038 (2015); https://doi.org/10.1088/0741-3335/57/1/014038.
6. M. KEILHACKER, Plasma Phys. Control. Fusion, 26, 49 (1984); https://doi.org/10.1088/0741-3335/26/1A/035.
7. H. ZOHM, Plasma Phys. Control. Fusion, 38, 105 (1996); https://doi.org/10.1088/0741-3335/38/2/001.
8. K. KAMIYA et al., Plasma Phys. Control. Fusion, 49, S43 (2007); https://doi.org/10.1088/0741-3335/49/7/S03.
9. R. J. HAWRYLUK et al., Nucl. Fusion, 49, 065012 (2009); https://doi.org/10.1088/0029-5515/49/6/065012.
10. A. LOARTE et al., Nucl. Fusion, 54, 033007 (2014); https://doi.org/10.1088/0029-5515/54/3/033007.
11. P. T. LANG et al., Nucl. Fusion, 53, 043004 (2013); https://doi.org/10.1088/0029-5515/53/4/043004.
12. P. T. LANG et al., Nucl. Fusion, 44, 665 (2004); https://doi.org/10.1088/0029-5515/44/5/010.
13. L. R. BAYLOR et al., Phys. Rev. Lett., 110, 245001 (2013); https://doi.org/10.1103/PhysRevLett.110.245001.
14. P. T. LANG et al., Nucl. Fusion, 53, 073010 (2013); https://doi.org/10.1088/0029-5515/53/7/073010.
15. G. GIRUZZI et al., Nucl. Fusion, 57, 085001 (2017); https://doi.org/10.1088/1741-4326/aa7962.
16. L. R. BAYLOR et al., Nucl. Fusion, 47, 443 (2007); https://doi.org/10.1088/0029-5515/47/5/008.
17. P. T. LANG et al., Fusion Eng. Des., 96/97, 123 (2015); https://doi.org/10.1016/j.fusengdes.2015.04.014.
18. A. GERAUD et al., Fusion Eng. Des., 82, 2183 (2007); https://doi.org/10.1016/j.fusengdes.2007.06.036.
19. D. FRIGIONE et al., J. Nucl. Mater., 463, 714 (2015); https://doi.org/10.1016/j.jnucmat.2015.01.048.
20. S. FUTUTANI et al., Nucl. Fusion, 54, 073008 (2014); https://doi.org/10.1088/0029-5515/54/7/073008.
21. P. T. LANG et al., Phys. Rev. Lett., 79, 1487 (1997); https://doi.org/10.1103/PhysRevLett.79.1487.
22. B. PLOECKL et al., Fusion Eng. Des., 96/97, 155 (2015); https://doi.org/10.1016/j.fusengdes.2015.01.006.
23. P. T. LANG et al., “Controlled Fuelling of High Density Scenarios at ASDEX Upgrade in Support of ITER and DEMO,” presented at 42nd EPS Conf., Lisbon, Portugal, June 22–26, 2015.
24. S. COMBS, Rev. Sci. Instrum., 64, 1679 (1993); https://doi.org/10.1063/1.1143995.
25. S. K. COMBS et al., Rev. Sci. Instrum., 56, 1173 (1985); https://doi.org/10.1063/1.1138025.
26. F. BOMBARDA et al., “State of the Art and Perspective of High-Speed Pellet Injection Technology,” 29th SOFT2016, P.4.158 (2016); https://doi.org/10.1016/j.fusengdes.2017.03.162.
27. C. ANDELFINGER et al., Rev. Sci. Instr., 64, 983 (1993); https://doi.org/10.1063/1.1144101.
28. P. T. LANG et al., “Conceptual Design of the JT-60SA Pellet Launching System,” 29th SOFT2016, P.2.19 (2016); https://doi.org/10.1016/j.fusengdes.2017.03.078.
29. P. C. SOURS, Hydrogen Properties for Fusion Energy, University of California Press, Berkeley and Los Angeles, California (1986).
30. S. K. COMBS et al., Fusion Eng. Des., 75–79, 691 (2005); https://doi.org/10.1016/j.fusengdes.2005.06.130.
31. P. T. LANG et al., Nucl. Fusion, 51, 033010 (2011); https://doi.org/10.1088/0029-5515/51/3/033010.
32. C. Z. LI et al., Fusion Eng. Des., 89, 99 (2014); https://doi.org/10.1016/j.fusengdes.2013.12.059.
33. B. PÉGOURIÉ et al., *Plasma Phys. Control. Fusion*, 47, 17 (2005); https://doi.org/10.1088/0741-3335/47/1/002.

34. B. PÉGOURIÉ et al., *Nucl. Fusion*, 47, 44 (2007); https://doi.org/10.1088/0029-5515/47/1/006.

35. L. R. BAYLOR et al., *Nucl. Fusion*, 37, 445 (1997); https://doi.org/10.1088/0029-5515/37/4/012.

36. P. A. SCHNEIDER et al., *Plasma Phys. Control. Fusion*, 77, 014029 (2015); https://doi.org/10.1088/0741-3335/57/1/014029.

37. L. R. BAYLOR, Oak Ridge National Laboratory, Private Communication: Status of Extruder Development (2017).

38. L. DEGITZ, “Pellet Injection Advances to Next Stage in the US,” *ITER NEWSLINE*, 282 (Sep. 24, 2013), ITER Organization.

39. B. PLOECKL et al., *Fusion Eng. Des.*, 86, 1022 (2011); https://doi.org/10.1016/j.fusengdes.2011.02.007.

40. L. D. LANDAU and E. M. LIFSHITZ, *Fluid Mechanics*, Addison-Wesley, Reading, Massachusetts (1959).

41. D. J. WILSON et al., “Recent Developments in Pellet Fuelling at JET,” presented at 20th IEEE/NPSS Symposium on Fusion Engineering, San Diego, California, October 14–17, 2003.

42. K. KIZU et al., *Fusion Eng. Des.*, 58–59, 331 (2001); https://doi.org/10.1016/S0920-3796(01)00310-6.

43. P. T. LANG et al., *Rev. Sci. Instr.*, 71, 3744 (2000); https://doi.org/10.1063/1.1290502.

44. A. LORENZ et al., *Rev. Sci. Instr.*, 71, 3736 (2000); https://doi.org/10.1063/1.1290497.

45. L. GARZOTTI et al., *Nucl. Fusion*, 58, 026029 (2018); https://doi.org/10.1088/1741-4326/aa9e15.

46. M. ERBA et al., *Plasma Phys. Control. Fusion*, 39, 261 (1997); https://doi.org/10.1088/0741-3335/39/2/004.

47. P. T. LANG et al., *Nucl. Fusion*, 42, 388 (2002); https://doi.org/10.1088/0029-5515/42/4/0030.

48. D. A. WELLS, *Theory and Problems of Lagrangian Dynamics*, Schaum Publishing Co., New York (1967).