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Proposal of a control scheme for testing a centrifuge-based pellet injection system in DIPAK-PET

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ABSTRACT

The envisaged Pellet Engineering Testbed (PET) in the framework of Direct Internal Recycling Integrated Development Platform Karlsruhe (DIPAK) will provide unique opportunities to advance pellet injection technology and its implementation in the fuel cycle as well as into plasma control of EU-DEMO. This work analyses the parameters for Pellet Launching System (PLS) control according to requirements from plasma control. Main parameter is the particle flux and the related accuracy with respect to amount of flux and arrival time of pellets. Others are addressed as well like dynamic response to setpoint changes and adaptivity of isotope composition of the hydrogen ice. The performance of the PLS is limited by the mass loss in the guiding tubes, both by erosion (applies to any pellet) and loss of an entire pellet, that may apply to only a few pellets, provided a suitable guiding tube geometry is selected depending on the required injection speed. DIPAK-PET has to provide data points in order to enable proper guiding tube design activities based on modelling. A short description of the proposed technical solution for the Pellet Launching System is provided and setup for the Programmable Logic Control (PLC) is suggested comprising a MasterPLC and a dedicated Human Machine Interface (operators' desk). A non-exhaustive proposal of experiments to be performed in DIPAK-PET is listed in order to verify the estimated performance values for the relevant PLS parameters.

1. Short introduction and background of the work

The first European fusion power plant EU-DEMO needs an appropriate fuelling system. Its task is to provide the fuel in right amount, right mixture of hydrogen isotopes and at the right point in time. However, the majority of the provided fuel is not burnt, "just" pumped away helping in keep proper conditions for fusion. That's why it is of great importance to design an efficient system in terms of minimizing the circulating fuel.

A thorough investigation was performed in order to identify suitable technologies for an efficient core fuelling [1]. Cryogenic hydrogen pellet injection was chosen for further studies. Such systems are composed of a pellet source, a pellet acceleration unit and a section with guiding tubes which are guiding the pellet to the plasma in case no free flight is possible. For geometric reasons (injection to the magnetic high field side) the latter is not possible for EU-DEMO using a centrifuge-based system. These pellets are made from a mixture of deuterium and tritium at a ratio about in equal parts in the pellet source.

There are two widely used principles to produce cryogenic pellets made from hydrogen: (i) de-sublimation of gaseous fuel to form a frozen plug inside the gun barrel or (ii) to cut pellets out of an extruded ice rod. Although the former process produces pellets with higher yield stress due to the lower temperature, it is often causing a non-precise starting point for the acceleration and therefore considered not a suitable method for well controlled processes [2].

Simulations on DEMO reference scenarios using FENIX flight simulator have shown strong importance of precise timing of pellet arrival and the consequences of missed out pellets. Hence, the speed scatter of the accelerated pellets is of great importance, as there is a significant distance (~20 m) between the pellet source and the plasma resulting in a corresponding jitter of arrival time. Only centrifuge-based pellet acceleration systems are able to meet the requirements. This is due to the

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form closure acceleration principle [3].

Moreover, missed out pellets are causing severe instabilities in fusion power. Possible countermeasures are relying on safe detection of such events. For this, the knowledge of expected arrival time of the pellet on plasma is a prerequisite to detect a missing pellet arrival.

The need to inject pellets to the magnetic high field side (inboard launch) requires the use of (curved) guiding tubes. Such tubes cause some mass loss for the pellets that are delivered to the plasma, as well as some small fraction of destroyed pellets. These values are depending on the geometrical shape of the guiding tube. The pellet speed may be affected by gas blocking in the guide tube, for example. However, this is considered to be caused by inappropriate design. There are some models available to predict these numbers; however, experimental data are strongly needed in order to assess a possible guiding tube geometry for EU-DEMO [4].

The DIPAK-PET (Direct Internal Recycling Integrated Development Platform Karlsruhe-Pellet Injection Engineering Test Bed) is addressing open points for matter injection by pellets [5].

2. Requirements from plasma control

Besides its principal task to fuel the burning plasma, the fuelling system has potentially additional functionalities: (i) pacing of edge localized modes (ELMs) - if the plasma scenario is associated with such - by injecting a constant rate of small pellets and (ii) providing plasma enhancement gases to the plasma core. The latter is foreseen by injection of pellets made from a mixture of deuterium and tritium with admixture of small amount (a few per cent) of noble gases (e.g. Ne, Ar or Xe). Hence, there are requirements for each of these functionalities coming from the plasma control system. This report is focussed on control issues, further requirements can be found in [3].

2.1. Mass loss in guiding tubes

Cryogenic pellets are sliding on room temperature surfaces on a gas cushion due to the Leidenfrost effect. The amount of evaporated material is depending on pellet size and speed as well as geometrical shape of guiding tube. The cross section of the tube as well as the bending radii and the geometric transitions between them are playing an important role [6,7].

The DIPAK-PET must provide relevant data for proper modelling of mass loss in order to enable proper design engineering activities. Mass loss in the guiding tube has a strong effect on the over-all efficiency of the PLS and therefore affects the fuel cycle performance. It is expected that the mass loss is composed of an almost deterministic mass loss due to erosion on all pellets depending on geometric shape of the guiding tube, pellet speed and injection frequency, and a stochastic component causing loss of some entire pellets. The latter is expected depending mainly on ice quality for a given geometry. A geometry which causes too high forces on the pellets will also drastically increase the number of lost pellets.

The technical effort to investigate different guiding tube geometries is considered to be substantial. However, unavoidable in order to get data points for modelling the DEMO guiding tube efficiency.

2.2. Plasma fuelling

2.2.1. Provide appropriate particle flux (0–100% of maximum throughput)

Basic task of a fuelling system is to provide the right amount of fuel at any time. However, due to the cyclic nature of the centrifuge acceleration system, the launch of a pellet it not possible at any time. There are possible launching slots, defined by the position of the acceleration arm and the time elapsed after the previous pellet production (cutter activity).

Recently, an innovative control scheme was developed on ASDEX Upgrade (AUG) centrifuge-based pellet injection system [8]. Basic idea is to identify possible pellet launching slots. On AUG, there is one launching option per centrifuge revolution provided that the previous pellet production request is more than 12 ms ago. The pellet speed is a function of centrifuge frequency.

This control scheme is proven on AUG, used there in daily operation and foreseen for the JT-60SA PLS as well.

2.2.2. Meet dedicated time window for arrival on plasma

The control system requires an exact prediction of pellet arrival time on plasma. There a two main reasons for this requirement:

(i) Pellet injection causes a significant perturbation on the plasma, resulting e.g. power cut off of ECRH heating systems due to high reflected power on temporal high-density areas. A viable way to avoid such troubles is to switch off the heating system just before the arrival time of the pellet on the plasma and switch it on again after the arrival. This process could be called notching. Repetitive switching off the heating system reduces the average heating power; hence, the duty cycle (ECRH down period/pellet period) must be as low as possible. This requires to minimize the switch off period, but long enough to meet reliably this time span with the pellet arrival on plasma. One single pellet arriving on plasma outside this window causes a power cut off of ECRH. Only a centrifuge acceleration system meets this requirement [9].

(ii) Any missed out pellet causes issues on fusion power control. Hence, a suitable algorithm is required in order to detect such an event as early as possible. One important prerequisite is to determine the time window of the dedicated pellet arrival. This is identical to the window for ERCH notching. Both goals need windows being as short as possible.

2.2.3. Fast reaction on plasma control: counter measures on missed out pellets

There are two stages of detection of a missed-out pellet: (i) pellet not launched and (ii) pellet not arrived at the plasma.

The not launched pellet detection is much earlier than the not arrived pellet, as there is no need to wait for the travel time. A not-launched pellet will not arrive. However, a pellet can be lost during its travel through the guiding tube. Hence, both stages are useful. The control system has to react quickly on both events in a well-defined manner. Most probably by launching as soon as possible an additional pellet (but not limited to). It may be necessary to integrate additional signals to this process, e.g. vacuum pressure in the centrifuge. This is because a not launched pellet could be destroyed in the centrifuge and its sublimated gas must be pumped away.

An additional counter measure for a future EU-DEMO fuelling system could be to switch to a back-up system if there are a few attempts to launch a pellet without effect.

2.2.4. Fast change of particle flux, prompt reaction on change of setpoint

Any change of particle flux setpoint must create a prompt reaction of PLS. The Control system must use the next possible launching slot, even if this may create a slight overshoot in particle flux due to the granularity of system: there is no way to launch just half a pellet. Underlying operational limits (e.g. minimum time distance between two pellets) are integrated in the control scheme.

Rapid setpoint changes are expected rather in ramp-up and ramp down phase than in steady state operation. In the first case, there will be a take over from gas to pellet fuelling at the point, the plasma density is high enough to accept pellets [3].

2.2.5. Adjustment of isotope composition (mimicked by H/D)

The requirement for EU-DEMO is to get a mixture of D:T=50:50 (atoms) with a margin of $+/-5$ % on the plasma. In DIPAK-PET this will be mimicked by the mixture of H_2/D_2., with a fixed composition ratio considering the potentially different mass loss in the guiding tubes for the two species.

The isotope ratio in the pellets dominates the isotope ratio in the plasma. Hence, the development and proper understanding of this actuator is important [10].

2.5. ELM-control

Current plasma scenario for EU-DEMO is aiming to be (almost) ELM-free. However, the need to provide a method to mitigate the ELM magnitude may come back. The fuelling system for EU-DEMO should still consider this purpose and that's why one may include it in the DIPAK-PET as well, although the interaction between pellets and plasma cannot be replicated in DIPAK-PET. The underlying mechanism is to inject small pellets at a high repetition rate (20–60 Hz), each pellet triggers a small ELM and avoid the release of a huge "natural" ELM, causing damage to first wall components by the deposition of a high heat load.

There is a cross talk to the fuelling sources: for technical reasons (the required sub-millimetre size tends to break in the guiding tube), pacing pellets are bigger than required to trigger small ELMs. Hence, there is a contribution to the plasma fuelling as well as big pellets injected for fuelling purposes will trigger an ELM. A dedicated control scheme is developed for JT-60SA in order to consider these side effects [11]. The centrifuge acceleration system provides available pellet launching slots, the control system decides whether to use it and with what kind of pellet: a fuelling or a pacing type one. For this, a priority is to be set. For example, priority is fuelling: the request of both fuelling and ELM pacing functionality is resulting in a launch of a fuelling pellet.

In case the fuelling request is lower than the fuelling contribution caused by ELM pacing pellets this over-fuelling needs to be reported to the control system.

2.6. Plasma enhancements gases

There is a need for EU-DEMO to deal with plasma enhancements gases (PEG), which provide required radiative cooling. For the scrape-off layer (SOL) argon is selected whereas xenon is used for the plasma core [12]. It will not be possible to inject these elements in gaseous state, the efficiency is too low which burdens the fuel cycle components: e.g. pumps and isotope separation systems. Admixing these elements to hydrogen pellets allows the delivery to the requested area with high efficiency [13]. The development of such processes is a goal of DIPAK-PET, results from JT-60SA (however limited to H and D) are expected.

First approach is to admix small amounts of PEG to fuelling pellets. A small amount of admixed gas does not change too much the cryogenic behaviour of the hydrogen matrix and change not much the weight of the pellet. Hence, it can be launched with same accelerator.

Doing so, the contribution to plasma fuelling must be considered for each PEG injection event. A good compromise between sufficient PEG content and cryogenic handling is to be found. This goal will create a lot of effort on pellet source technology (extrusion and pellet production) as well as on centrifuge acceleration system. Nevertheless, for acceleration process by a centrifuge system, the pellet mass does not play a role. Hence, all pellets have same muzzle speed, no matter they are made from pure deuterium, tritium, a mixture of both hydrogen isotopes or with some admixed PEG.

3. Proposed technical solution to meet the requirements

3.1. Extrusion technology: continuous extrusion of hydrogen

The plasma control system will request a value of 0–100 % of maximum particle flux to be injected to the plasma. Hence, the pellet source must be able to provide this maximum particle flux. Production of solid hydrogen using desublimation (e.g. in pipe guns) is considered not useful for fuelling purposes [2].

Hence, the pellet source will consist of a stage to produce hydrogen ice by extrusion with a certain throughput combined with a stage to produce pellets from it. Doing so, pellets are produced on demand, not requested ice is moved to an ice dump, where it is evaporated and pumped back to the fuel cycle. In case of 100 % flux request, the full extruded flow rate is put to the acceleration stage being a pellet. The zero-flux request directs the full throughput to the ice dump.

3.2. Pellet acceleration by a centrifuge system

Precise pellet arrival on the burning plasma is essential for plasma control. This requires a small scatter in muzzle speed which is achievable only by using a form closure accelerating method, e.g. employing a centrifuge launching system. Form closure acceleration has the consequence, that there is no slip. Force closure acceleration has a big speed scatter due to the dependency of pellet mass and the presence of some slip. Hence, any pellet launching system basing on this method (e.g. gas gun) is considered inappropriate.

3.3. Make use of AUG proven pellet control algorithm

The precise arrival prediction of pellets accelerated by a centrifuge is basing on two facts: (i) the form closure acceleration with absence of any slip and mass dependence and (ii) the precise starting point of the acceleration process with no radial speed component, provided by the stop cylinder.

Hence, the centrifuge offers to the control system one or two possible launching slots per revolution. The control algorithm has to decide whether or not to use it considering the actual particle flux request as well as pellet source status. The AUG proven algorithm provides a good basis for EU-DEMO needs, including the option to integrate more than one single pellet source on a centrifuge, see Fig. 1. The required particle flux is communicated to the PLS local controller. For each available launching slot, this value is added to a register and compared to the value of a single pellet. If the required value is bigger than the value of one single pellet, an immediate launch is prompted and the according particle content subtracted from the register [8].

The granularity in particle flux is still present in particular at high flux values. However, the algorithm toggles between the values in a way that the average value meets exactly the required value. This algorithm provides a fast and precise particle flux control actuator.

The JT-60SA developments could serve as blueprint regarding the DIPAK-PET pellet injector control system

3.4. Programmable logic control (PLC)

The PLS proposed for DIPAK-PET consists of pellet source, acceleration system, guiding tube with interface to the target chamber and some diagnostics related to each component, see Fig. 2

Each subsystem is expected to come with its own PLC, providing the option to operate it separately to some extent. This is useful for commissioning and trouble shooting. For this purpose, a Human Machine Interface (HMI) is required for each sub-system.

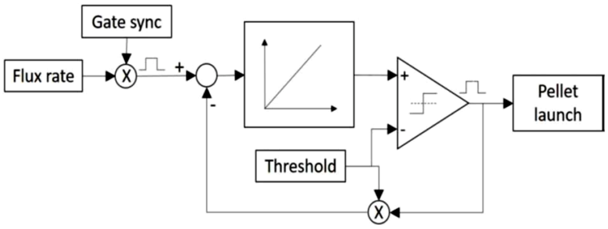

Fig. 1. Control algorithm for precise and fast particle flux control on a centrifuge-based pellet launching system.

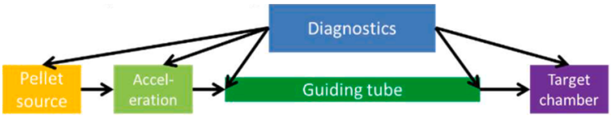

Fig. 2. Components of pellet launching system.

The PLC of these subsystems are connected to the MasterPLC via ProfiNET (Industrial Ethernet). The MasterPLC provides the control of the entire PLS and serves as interface to the DIPAK control system. The operator's desk with HMI is located in the DIPAK-PET control room as well as the CPU of the MasterPLC The Master PLC contains a fast module with a cycle time of less than 1 ms to synchronise the pellet sources and the centrifuge. The CPU of the subsystems may be located close to the system in the experimental hall or at a detached location, to be determined, see Fig. 3.

The MasterPLC is expected to be S7-1500 series. Requirements regarding failure performance of PLC components are to be stated according to DIPAK safety policy.

3.5. Control of vacuum system

The vacuum system of PET is to be implemented into DIPAK environment, see Fig. 4. It provides the required vacuum for the process and has to cover hydrogen safety in normal operation as well as in disturbed one. For this purpose, all components of this system are controlled by PLC.

3.6. Diagnostics and data acquisition

All relevant parameters are to be recorded by the PLC or other appropriate systems using a consistent time stamp for all signals.

Dedicated diagnostic systems are proposed for:

- Video observation systems for ice extrusion in pellet source and pellet movement in stop cylinder or on the way to it
- Pellet speed at centrifuge exit
- Pellet integrity and size at centrifuge exit/guiding tube entrance and at guiding tube exit/target tank entrance

The pellet integrity and size can be observed using shadowgraph method, optionally supported by a microwave cavity, which determines the pellet mass.

Pellet speed is evaluated by using light barriers for the shadowgraph system or evaluating the time of flight between the microwave cavities signals.

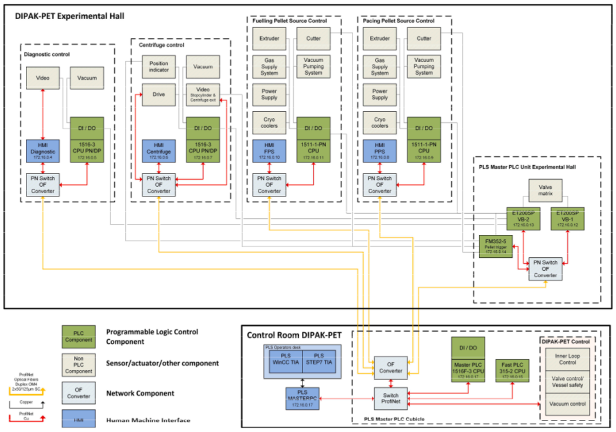

Fig. 3. Proposed block diagram of PLC for pellet launching system in DIPAK-PET.

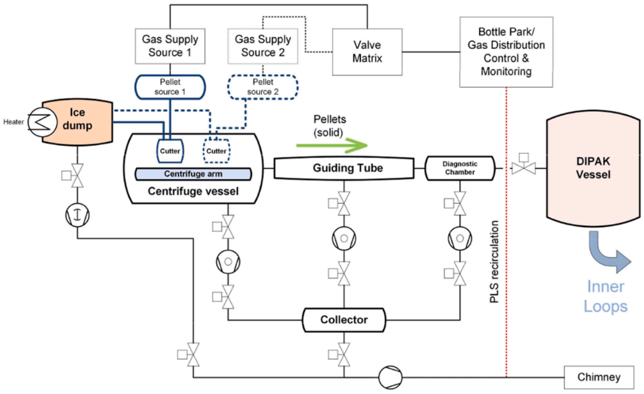

Fig. 4. Proposed block diagram of vacuum system of pellet engineering testbed (PET).

Acoustic systems using microphones are proposed to investigate collisions inside the guiding tube.

Development of diagnostic systems should be addressed as a dedicated task in due time.

3.7. Table of control parameters

Tables 1 and 2 are indicating a set of proposed control parameters.

4. Experiments to verify the performance of proposed solution

Main goal of DIPAK PET is to provide the platform to develop and establish suitable technologies and methods for the EU-DEMO fuel cycle. Hence, it should offer the option for experiments in order to optimize the setup. In the end, the performance of proposed solutions is to be checked by dedicated experiments.

4.1. Establish dedicated constant particle flow

As touched in previous chapter, the centrifuge has a granularity on particle flux adjustment. This is true in particular for high flux values. For example, a centrifuge running at 100 Hz is able to launch a pellet every 10 ms, provided, the pellet sources would do it as well. Using every second launching slot option would give half of the flux: a pellet launched every 20 ms. Every third launch slot provides a 30 ms period and 33 % of maximum flux respectively. The challenge now is to set the correct average particle flow for values above about 30 % of the maximum flow by switching between stages.

The dedicated experiment has to demonstrate that toggling between these periods results in requested particle flux values. Levels for particle flux setpoint are from 70 % up to almost 100 % in particular values non-directly accessible by integer fraction of centrifuge revolution.

Table 1
Proposed list of input control parameters (from DIPAK-PET to PLS).

Name	Description
Operation mode	Pure fuelling mode / pure ELM pacing mode / combined fuelling and pacing mode (BOOL)
Fuelling flux setpoint	Requested fuelling particle flux (0–100 % of max. flux) for fuelling pellet source (REAL)
ELM pacing setpoint	Requested ELM pacing rate (0–100 % of possible rate) (REAL)
Functional priority	Priority definition of fuelling or ELM pacing request (BOOL)
Setpoint isotope fraction	Setpoint of hydrogen isotope fraction (H_2/D_2) (REAL)

Table 2
Proposed list of output control parameters (from PLS to DIPAK-PET).

Name	Description
Source status (op)	Status bits for each pellet source (operation): e.g. at room temperature, ready to resume hydrogen operation, ready to produce pellets, disruption (BOOL)
Source status (conf)	Status bits for each pellet source configuration: e.g. kind of gas (hydrogen isotope/mixture/admixed elements) (BOOL)
Centrifuge status	Status bits for centrifuge system: e.g. accelerating, running at requested speed, run-out, disruption (BOOL)
Pellet speed	Pellet speed derived from centrifuge speed (REAL)
System status	Over-all operational status: e.g. unrestricted/restricted operation (BOOL)
Max. fuelling flux	Maximum particle flux calculated by centrifuge frequency and max. pellet production rate (REAL)
Max. pacing rate	Maximum ELM pacing rate calculated by centrifuge frequency and max. pellet production rate (REAL)
Pellet launched	Confirmation that pellet is launched (one bit for each pellet source) (BOOL)
Over-fuelling alarm	Alarm for over-fuelling: for zero fuelling request at enduring ELM pacing request (BOOL)
Over-fuelling amount	Indication of over-fuelling amount: for zero fuelling request at enduring ELM pacing request (REAL)
Actual isotope fraction	Actual hydrogen isotope fraction value (H_2/D_2) as currently executed by the pellet source (REAL)

4.2. *Demonstrate particle flux ramps*

4.2.1. *Small deviations around a setpoint (e.g. for cw- operation)*

Particle flux ramps to achieve small deviations around a setpoint are expected for steady state operation to balance plasma variations for burn control. The compensation of missed particle flux from a missed-out pellet is expected to cause such small deviations as well. The technical challenge could be associated to the above discussed issue with granularity of time periods between possible launching slots.

The experimental schedule follows the experiments described above (see chapter 4.1). The setpoint is to be shifted by small values and the metric is the time needed for the system to follow such small values and the remaining deviation, if any.

4.2.2. *Strong ramps expected during ramp-up and ramp- down*

Gas puffing is considered not efficient for fuelling purposes. However, it is required for ramp-up and ramp down phases at beginning and end of a plasma pulse.

In terms of plasma fuelling contribution of pellet injection, the penetration depth is the most important value. This value is usually given as a fraction of the minor plasma radius. For suitable fuelling efficiency this must be between 30 % and 10 % of the plasma radius. The penetration depth depends on electron temperature, electron density, pellet mass and pellet speed. As the pellet speed and mass are constant in that case, the penetration depth depends on electron density and temperature. For cold plasmas, the penetration could be 90 % or even more. Penetration depths more than ~50 % are prone to cause plasma instabilities. Values of less than 10 % decrease the fuelling performance, particles are rejected immediately comparable to a gas puff. That's why the target value is between 30 % and 10 %.

During ramp-up, pellet fuelling takes over from gas puffing at values for electron density and temperature resulting in a penetration depth of ~30 %. During this process, these parameters are changing quickly, hence the pellet system must follow this quick setpoint changes.

For ramp-down, the situation is contrary, but gradients are a bit lower. Details can be found elsewhere [3]. Parameters are the deviation of achieved particle flux ramp from the set-point curve.

4.2.3. *Demonstrate cross-talk of pacing and fuelling source*

Any pellet injected to the plasma has a side effect: fuelling pellets may trigger an ELM and pacing pellets fuel the plasma as well. Hence, pellet control system has to consider these effects and to take appropriate measures.

Experimental proofs are:

- Continuous ELM pacing with zero fuelling demand will inevitably lead to over-fuelling due to the fuel content of the pacing pellets. The system must communicate this fact and the corresponding amount of over-fuel flow to the plasma control system.
- Continuous ELM pacing with low fuel demand (~5 %) results in a very different injection rate of fuel and pacing pellets. The system must prioritise the fuelling pellets.
- Continuous ELM pacing with medium fuel demand (~50 %) will result in a very different injection rate of fuelling and pacing pellets. The system must be able to adjust the flow rate accurately.
- Continuous ELM pacing with (almost) full fuel demand still results in a different injection rate of fuelling and pacing pellets. The system must be able to adjust the flow rate accurately.
- During ELM pacing at idle and medium fuel demand (~50 %), the repetition rate of the fuelling pellets is higher than that of the pacing pellets. The system must be able to accurately adjust the flow rate while giving priority to the fuelling pellets.

4.2.4. *Demonstrate reaction on missed out event*

Two cases are of interest: (i) reaction on a pellet failed to be produced or to be launched, detected by the PLS diagnostic system and (ii) reaction on a pellet missed during the travel through the guiding tubes, detected by plasma diagnostic systems, e.g. Mirnow coils.

The experiment is to establish a constant particle flow at high rate, e.g. 90 %. The system gets the signal that a pellet was missed and produces as soon as possible a new one. The relevant parameter is the time span needed until the launch of the new one.

4.3. *Mass loss in guiding tubes*

Important drivers for the mass loss in guiding tubes are the pellet speed, size and quality as well as the geometric shape of the guiding tube [4]. A prerequisite a of successful travel of the pellet through the tube are proper vacuum conditions in order to avoid pellet deterioration due to gas blocking by ablated gas. For this, the resulting pumping capability of the chosen design is of interest. Besides the geometric shape, the surface roughness of the tube is important, to find a reasonable requirement for this is of great importance.

4.3.1. *Experimental setup*

A full mock-up of the DEMO guiding tube geometry is considered too big for DIPAK-PET, see Fig. 5. That's why a segmented investigation is proposed. There are three areas of interest:

- The initial 90° bending section from horizontal to vertical direction
- The (almost) straight segment along the central solenoid
- The final bending which is directing the pellet to the point of injection

As an additional benefit, this approach will provide experimental results for these three different types of geometries. There may be the request to repeat a test with a modified setup in order to verify an optimized geometry. Of course, there is a risk that cumulative effects may be overlooked in this segmented study. These results are important values to benchmark modelling activities [14].

4.3.2. *Modelling activities*

In particular to derive guidelines for the design of the guiding tubes, additional experiments are envisaged. First subject is the influence of pellet temperature on its mechanical properties and the resulting survival probability and mass loss of the pellets along their way to the plasma vessel. The temperature of the pellet is mainly connected to the production process; however, there is some range of suitable extrusion

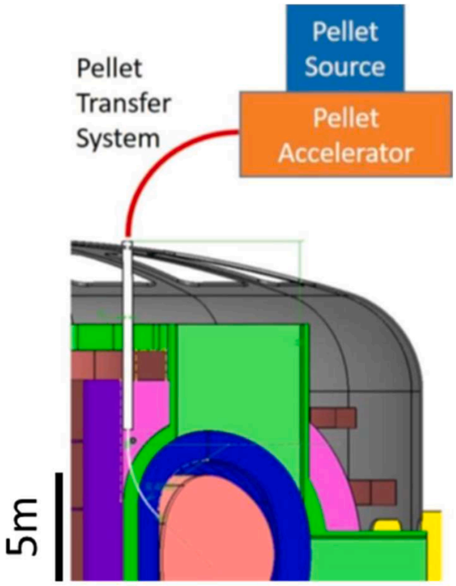

Fig. 5. Pellet guiding tube for centrifuge-based PLS aiming pellet injection to the magnetic high field side of the plasma.

temperature values. The aim is to find out an optimum combination of extrusion temperature, pellet quality and resilience.

Second issue is the type of cross section and material of guiding tube. There are systems in the field using rectangular cross sections as well as circular ones. It is obvious, that the pellet trajectory depends on the type of tube and its dimension. Pellets in circular tubes will move with an additional spin around the main speed direction. Modelling work has to address the type of movement (slipping or bouncing) and reflect the influence of the surface roughness.

The experiments have to provide input for modelling activities, mainly focused on prediction of the forces on the pellet along its way for different geometry [14].

5. Conclusions

The envisaged Pellet Engineering Testbed (PET) in the framework of DIPAK addresses important issues of fuel cycle and pellet technology. A control scheme is proposed basing on requirements of plasma control providing a list of control parameters.

This control scheme includes algorithms developed and verified at ASDEX Upgrade and foreseen to be implemented at JT-60SA.

Moreover, a detailed list of envisaged experiments at DIPAK-PET is provided. This is essential in terms of detailed design of control system, in particular in programming the PLC. The need to examine several guiding tube geometries is motivated. This is to be reflected for the experimental setup.

Modelling activities are launched in order to support the guiding tube geometry investigation. In the end, well justified guidelines are required for the design of the guiding tubes.

CRediT authorship contribution statement

B. Ploeckl: Conceptualization, Formal analysis, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing. **P.T. Lang:** Investigation, Methodology, Writing – original draft, Writing – review & editing. **Th. Giegerich:** Funding acquisition, Methodology, Project administration, Supervision. **E. Geulin:** Formal analysis, Methodology. **B. Pégourié:** Formal analysis, Methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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