Different types of cryogenics Pellet injection systems (PIS) for fusion reactor

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Abstract
Fusion reactor is the one of the most capable option for generating the large amount of energy in future. Fusion means joining smaller nuclei (the plural of nucleus) to make a larger nucleus and release energy in the form of neutrons. The sun uses nuclear fusion of hydrogen atoms into helium atoms. This gives off heat and light and other radiation. Hydrogen is used as the fuel in the fusion reactor. We have to inject the solid hydrogen pellet into the tokamak as per the requirement. For injecting the pellet we use the pellet injection system. Pellet injection system (PIS) is the fuel injection system of the fusion reactor.

Keywords: Pellet injection, Comparison of different PIS

I. Introduction
Tokomak is the doughnut shape vessel (fusion reactor) in which the heat energy librates due to the fusion of the hydrogen take place inside the vessel. For this fusion process hydrogen is the fusion fuel. We have to inject hydrogen continuously inside the tokomak for getting heat energy continuously by the fusion process. The pellet injection systems are used to inject the solid hydrogen in the reactor. There are different types of pellet injection systems are available as below:
1) Gas gun type
2) Centrifugal type
3) Rail gun type
4) Extruder type
   i. Piston type
   ii. Single screw
   iii. Double screw

II. Different Pellet injection Systems
B. Plöckl, P.T. Lang (Plöckl, Lang, Jehl, & Prechtl, 2010) In case of a blower gun (and a gas gun as well), acceleration of pellets is due to expanding gas which pushes or drags the pellet. The diameter of the pellet is smaller than the diameter of the barrel and the gas flows around the pellet. Acceleration force transfer follows the force closure principle (frictional connection), hence some slip is present. The thermal impact of the propellant gas influences the pellet as well. Both effects can cause a variation of the velocity and time scatter.

A shuttle in reciprocating motion cuts the ice rod and moves it in one of the two firing positions in front of the barrel. A short propellant gas pulse released by a fast valve accelerates the pellet.

Figure 1 Gun type pellet injection system

B. Plöckl, P.T. Lang (Plöckl, Lang, Jehl, & Prechtl, 2010) In the centrifuge the acceleration is due to the centrifugal force acting on a pellet sliding in the groove of a rotating straight arm. Consequently there is no slip during acceleration. Hence the acceleration of pellets follows the form-closure principle (positive locking) and can be very precisely tuned provided the onset conditions are sufficiently accurate. This requirement is attained by the stop cylinder technique. The generated pellet drops into the stop cylinder that is mounted adjustable but not rotating above the centrifuge.
This stop cylinder ensures an accurate timing for the start of the acceleration since the pellet leaves the stop cylinder at a well defined radial position with zero speed. In the absence of any propellant gas and due to the Leidenfrost effect heat transfer and friction are low. The centrifuge revolution frequency precisely prescribes the pellet velocity (speed scatter at the exit < 0.25%); the repetition rate has to be an integer fraction of centrifuge frequency.

Upon request, the ice rod is shifted by a stepping motor driven mechanical lever; the number of steps determining the pellet length. The pellet is chopped from the rod using an electromechanical cutter.

The ice production is similar to the blower gun using an extrusion cryostat and a storage cryostat. Three different pellet sizes can be selected without any mechanical intervention into the system.

The transfer line guides the pellets to the High Field Side (HFS) of AUG. In order to achieve high pellet velocities a “looping” has been installed, a 17m long transfer line of elliptical shape avoiding changing curvature direction. Due to the Leidenfrost effect and good pumping, friction and the heat transfer are low. The maximum useful transfer velocity is 1000m/s.

### Table 1 Comparison of relevant data

<table>
<thead>
<tr>
<th>System</th>
<th>Pellet velocity [m/s]</th>
<th>Repetition rate [Hz]</th>
<th>Transfer length / time</th>
<th>Time scatter [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUG Centrifuge</td>
<td>1000</td>
<td>62</td>
<td>17m 17ms</td>
<td>± 0.23</td>
</tr>
<tr>
<td>AUG Blower gun</td>
<td>100</td>
<td>60</td>
<td>5m 50ms</td>
<td>± 31</td>
</tr>
<tr>
<td>JET Centrifuge</td>
<td>160</td>
<td>5</td>
<td>12m 75ms</td>
<td>± 2.2</td>
</tr>
<tr>
<td>JET Blower gun</td>
<td>142</td>
<td>10</td>
<td>10m 70ms</td>
<td>± 9</td>
</tr>
</tbody>
</table>

For the ITER application and future steady-state fusion reactors, a feed system capable of providing a continuous supply of frozen isotopic hydrogen is required. A straightforward concept in which multiple extruder units of identical design operate in tandem was described briefly at the 1994 symposium.


While great progress has been made in the area of pellet injector technology at Oak Ridge National Laboratory (ORNL) and around the world during the last decade [1–3], additional research and development are required to meet the fueling needs of the International Thermonuclear Experimental Reactor (ITER) and future fusion reactors. The baseline ITER pellet injector concept is the centrifuge acceleration device. Centrifuge pellet injection systems are currently in operation on ASDEX-U, Tore Supra, and the Joint European Torus (JET). Present devices operate at pellet frequencies of up to 5 to 80 Hz with nominal pellet diameters of 1 to 3 mm. Operation with Pellets >3 mm has yet to be demonstrated with the centrifuge accelerator.
This approach applies a reliable ORNL technology that has been used on many pellet injection systems. The overall reliability of this technology is indicated by the performance record of the three-barrel repeating pneumatic injector, which includes three of the standard ORNL extruder units. Since its construction and initial testing in 1986, this system operated on JET from 1987 to 1992 and on DIII-D since 1994. Over a period of 10 years, the performance and reliability of the extruders have been outstanding; the three extruders have processed an estimated 5 to 10 kg of deuterium ice in that time period without any significant problems or mechanical failures.

S. J. Meitner and L. R. Baylor (S. & L., 2009) work on a twin screw extruder prototype for frozen deuterium pellet production, designed and constructed at Oak Ridge National Laboratory. This one-fifth ITER scale extruder is cooled by a combination of liquid nitrogen, and two cryo-coolers. Separate pre-cooler and liquefier sections reduce the room temperature deuterium gas to a 20K liquid before it is introduced into the extruder. Continuous extrusions in excess of 20 minutes have been made.

Preliminary experiments have shown that initial extrusion start torque can be significant enough to damage the apparatus. The start torque is kept low by keeping a constant torque on the screws while heating the barrel with resistance heaters. Torque levels drop as viscous heating creates a slip layer between the deuterium and the screws.

Experiment characterization tests were conducted at a constant rotation rate and a constant temperature. The extrusion rate increased from 7.4 to 8.6 mm$^3$/s as temperature was increased from 16.7 K to 17.6 K at a set 2 rpm. The extrusion rate increased from 8.6 to 11.5 mm$^3$/s as the rotation rate was increased from 2 to 7 rpm at a constant 17.6 K.

These extrusion rates indicate that material is lost through the gaps in the screws and so a future iteration will be to reduce the gap size and increase the torque limit. Further optimization of the design tests for maximum extrusion rates will be conducted.

I. Viniar, S. Sudo, A. Geraud (Viniar, Sudo, & Geraud, 2001) works on the Pneumatic and centrifugal injectors for steady-state plasma refueling by solid hydrogen, deuterium and tritium pellets have been designed at the PELIN Laboratory to meet requirements.
Based on the screw extrusion concept, recent advances towards the development of a reliable plasma fuelling system for steady-state operation are encouraging. With a high reliability, over 1 million hydrogen and deuterium pellets, 2mm to 3mm in size, have been injected continuously by pneumatic injectors equipped with screw extruders at the repetitive rates of 1 Hz - 15 Hz, during a lot of cycles of duration 100 s ~ 2000 s.

A new hydrogen/deuterium pellet injector capable of injecting small pellets for ELMs mitigation experiments and large pellets for plasma fuelling is in preparation for JET as part of the JET-EP2 programme. This injector is fully ITER relevant apart from tritium aspects.

**Conclusion**

Different types of pellet injection systems are available and they all have their own pros and cons. Now the main requirement of the pellet injection is higher density, continuous injection and high reliability.

From all the PIS available extruder type pellet injection systems are the latest and can inject the pellet continuously with high frequency. From below table we can compare the different pellet injection systems.

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**Figure 8 Schematic of a tritium pellet injector**

**Figure 9 Solid hydrogen rod extruded at 11 K**

**II.10 Schematic drawing of the PELIN pellets injector**
Table 2 Comparison of different PIS

<table>
<thead>
<tr>
<th></th>
<th>Pipe gun type</th>
<th>Piston Extruder</th>
<th>Single Screw Extruder</th>
<th>Twin Screw Extruder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advantages:</td>
<td>simple design</td>
<td>5 Hz pellet production</td>
<td>pellet production with high frequency &gt;95% reliability Continuous production</td>
<td>- Positive pumping. - Low supply pressure. - Increased mass flow. - Low risk of stalling. - Still simple design. - Larger fluid volume with lower shearing at wall.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simple design</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Disadvantages:</td>
<td>very low frequency not continuous less reliability</td>
<td>not continuous</td>
<td>Stalling issues supply pressure high</td>
<td>- High shearing between two screws and screw thread and barrel wall.</td>
</tr>
</tbody>
</table>

From the above table we can say that the Twin screw extruder system is most suitable PIS for the fusion reactor.

References


