Development of a Fast Valve Assisted Mechanical Launcher for Cryogenic Pellets*)

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Plasma fueling and disruption mitigation (DM) are two of the many key aspects in the successful operation of high-temperature fusion devices. Pellets of different gases like hydrogen, its isotopes, neon, and argon solidified at cryogenic temperature are used for fuelling and DM studies. A gas gun-based pellet injector has been developed for the large-size pellet formation and shattering study. Instead of the conventional fast valve injection mechanism, a new technique called mechanical pellet launching system (MPL) has been developed and tested for pellet launching. The MPL is a fast valve-driven pneumatic punch. The advantage of using it over the conventional technique is, the required impulse to dislodge the pellet can be achieved at lower propellant pressure. Before applying to the cryogenic pellets, the MPL has been tested up to 4 MPa pressure on a test bench, and a punch speed of 2 - 12 m/s has been achieved for 0.2 - 4 MPa pressure. The developed MPL has been successfully applied on 6.2 mm $l_p \times 4.2$ mm d_p cylindrical hydrogen pellets. Details of the pellet formation device, MPL system, and experimental results are presented in this paper.

Keywords: pellet injection, gas gun, mechanical launcher, cryogenic pellet, disruption mitigation

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1. Introduction

Plasma fueling and disruption mitigation (DM) are two of the many key aspects in the successful operation of high-temperature fusion devices. Apart from the above, there are also other applications of pellet injection in plasma control and related studies that can be found in the literature [1]. To address these issues, two different techniques such as gas puffing and pellet injection have been widely adopted by the fusion community. While for fuelling a small amount of material injection is required, for the DM process, a massive amount of material injection is necessary. In a large-scale high-temperature plasma, where a hot thick scrape-off layer prevents the penetration of neutral particles, the applicability of the gas-based conventional techniques is questionable. In this regard, pellet injection (of gas species frozen below their triple point temperature) has been proven as a viable technique for fueling and DM in different fusion machines. It is also planned for ITER fueling [2] and disruption mitigation [3] study. For ITER, a pellet size of 28 mm diameter (l_p/d_p = 2.0) has been proposed for the disruption mitigation study. Where l_p and d_p are the length and diameter of the pellet, respectively.

Although various techniques are used for dislodging the pellets from the freezing zone and accelerating it further [4], the gas gun technique is the most promising one. In this technique, a pellet frozen *in-situ* in the gun barrel is injected by using high-pressure propellant gas delivered by a fast-opening valve. Depending on the experimental conditions, the pellet speed varies over a wide range. Apart from fueling, shattered pellets of neon, argon, hydrogen, or a mixture of these gases are used for DM studies. The solid argon and neon pellet materials are too strong that very high pressure is required to dislodge these pellets from the freezing zone. Additionally, higher propellant pressure exerts an extra load on the differential pumping system that is used to restrict the propellant gas flow into the plasma. Alternatively, these solids can also be injected by increasing the freezing zone temperature to a point just below their triple point. However, the vapor pressure of these materials is so high that it can affect the plasma before the pellet reaches the plasma. Keeping all these issues in mind, a fast-opening valve-assisted mechanical pellet launching system (MPL) has been designed to inject cryogenically cooled solid pellets. This paper focuses on the development and testing of the MPL, and its applicability to cryogenic pellets (only solid hydrogen pellets were considered in the experiment). The paper is organized as, the design requirement of the MPL is described in section-2, design details, and characterization study is presented in section-3, its applicability to cryogenic pellets is given in section 4, and finally, the work is summarized in section 5.

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2. Design Requirement

For the shattered pellet injection, a range of pellet sizes has been considered in various tokamaks. Depending on the size of the pellets either a cryocooler or a liquid helium cooling circuit is used to design the cryostat. In the present study, a two-stage GM cryocooler (cooling capacity: 1.5 watts at 4.2 K) is used for the pellet formation study. Considering the available cooling capacity, and other technological challenges, an injector is developed to study the pellet freezing and acceleration process for hydrogen and argon pellets up to size $d_p = 7$ mm and $l_p/d_p = 1.5$ (this ratio is used throughout this paper). However, the present study is performed for a pellet of $d_p = 4.2$ mm, and higher sizes will be considered in future experiments.

Of the different techniques used for pellet formation, the pipe gun technique is the most reliable method. In addition, shattered pellets used in DMS are also formed by using this technique. In the pipe gun, pellets are formed by de-sublimating the gas at the cold region in the gun barrel that is mechanically anchored to a cryogenically cold media. The pellet formed in the gun barrel is injected into the plasma using the helium propellant gas delivered by a fast-opening valve. A multi-stage differential pumping system restricts the flow of propellant gas (moving with the pellet) into the plasma chamber. However, the bonding between the solid pellets and the wall of the pellet freezing barrel for argon and neon pellets is too strong that very high pressure is needed to dislodge and accelerate the pellet. The shear stress of different types of solid pellets can be found in Ref. [5]. To inject these pellets, a specialized valve having very high operating pressure and throughput is required. With the increase in pressure, the requirement for additional pumping also increases. For this kind of requirement, a solenoid-based punch mechanism [6] can be suitable. However, it needs a power supply having sufficient current to generate the required actuation force. Keeping all these in mind a fast-valve (readily available) driven MPL has been designed and developed. The first-hand requirement for the MPL is to dislodge the pellet from the barrel wall. The breakaway pressure (P_b) of a pellet can be calculated using the relation:

$$P_b = 4\sigma(l_p/d_p). \tag{1}$$

Here, σ is the shear stress of the pellet area in contact with the barrel wall. Using P_b, the impact kinetic energy threshold (E_{th}) needed to dislodge different size pellets from the freezing zone was calculated. The punching head speed (V_{pn}) of the MPL has been calculated using E_{th}. At first, the calculations were performed for Argon pellets and verified with the reported values in Ref. [7]. The results are shown in Fig. 1. In this figure, the filled circles and the dashed line indicate the E_{th} and V_{pn}, respectively. For a 12.5 mm diameter argon pellet having pellet-barrel wall contact area (A_{con}) 7.4 cm^2, the reported V_{pn} (for punch weight = 0.032 kg) and E_{th} are 25 m/s and ~ 10 J, respectively. These values are indicated by the filled green circle in the inset figure. Following calculations and keeping E_{th} constant, the V_{pn} required by the newly developed MPL (punch weight = 0.052 kg) for different size argon pellets is shown by the dash-dot-dot line. As shown in the figure, the required V_{pn} for an argon pellet of $d_p = 7$ mm ($A_{con} = 2.31$ cm^2) is estimated to be ~ 12 m/s. The shaded area in the inset picture represents the designed operation range of the MPL. In the following sections, a detailed design of the MPL and the test bench operation results are presented.

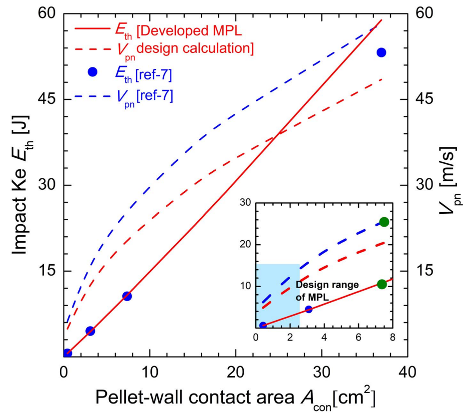

Fig. 1 Impact kinetic energy threshold, E_{th}, and the punch head speed V_{pn} for Argon pellets of different pellet-barrel wall contact areas (A_{con}). The filled circles and the dashed line represents E_{th} and V_{pn}, respectively (matched with data in Ref. [7]). The calculated E_{th} and V_{pn} needed to dislodge the pellet for the developed MPL are shown by the solid line and the dash-dot-dot line, respectively. The shaded area in the inset picture represents the proposed operation range of the MPL.

3. Design Details and Characterization of MPL

The MPL works by the combined operation of a fast-opening valve and a pneumatic punch head. Figure 2 shows the schematic of the fast valve-punch-barrel interface. The working principle of the MPL is: high-pressure helium propellant gas from the fast-opening valve fills the punch head cylinder cavity and accelerates the disk connected to it in the forward direction. The volume of the cavity at the breach of the punch disk is nearly equal to the volume of the fast valve gas chamber. The fast opening valve is PELIN make and can be operated to a pressure of 10 MPa or higher. The full stroke length of the punch is ~ 30 mm. As shown in Fig. 2, there is minimal clearance between the punch disk and the associated volume to restrict the gas leak around the disk towards the barrel. With pressure, the punch disk moves forward and enters the gas bypass chamber at ~ 20 mm stroke length. A spring is used to hold the punch head and retract it to its starting position. The solid length of the spring has been decided such that

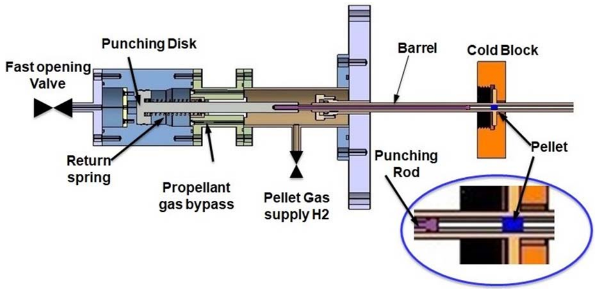

Fig. 2 Image shows the working principle of the MPL along with its sub-parts including the fast valve, pneumatic punch head, and the pellet freezing barrel.

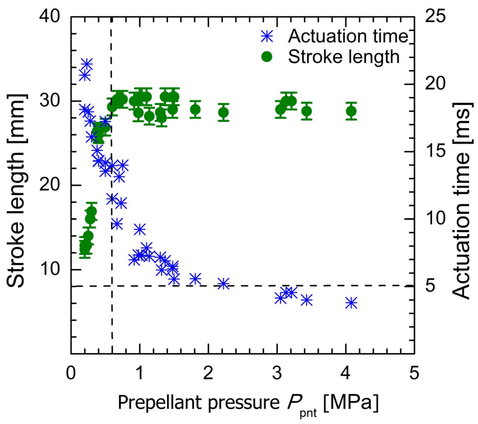

Fig. 3 Variation of the stroke length and the actuation time of MPL punch head with different propellant pressure.

the disk stops just before hitting the wall of the punch, and it retards back to its original position from this point. Adequate provision has been made on the punch disk stem to replace the punch rod according to the pellet size. The weight of the punching rod arrangement used in this paper is ~ 0.052 kg.

The performance of the MPL was tested before being applied to pellet freezing experiments. The punching device is tested up to a propellant pressure (P_{pnt}) of 4 MPa. In this experiment, the fast valve opening duration was set at 2 ms. A high-speed camera (Phantom V1210) was used to measure the speed of the MPL punch head. In the first step, the movement of the punch head is tested. Figure 3 shows the maximum punching length and the total actuation time of the punch. It can be observed that for a P_{pnt} < 0.6 MPa, the stroke length varies linearly with the pressure, and thereafter it achieves the maximum stroke length. Similarly, for P_{pnt} < 1.2 MPa the actuation time of the punch falls linearly, and after that, it saturates around ~ 5 ms. The error bars refer to ± 7 pixels measurement error that corresponds to a length of 1 mm.

In the experiment, it has been measured that the punch head achieves its maximum speed within 20 - 25 mm of stroke length. This length matches well with the design; where the punch head enters the gas bypass cavity. As the pressure starts to decrease at this point, a further increase in V_{pn} ceases. Therefore, the distance between the pellet base and the punch head has to be considered to achieve a maximum energy transfer from the punch. Figure 4 shows the variation of the punch head speed with P_{pnt}. The solid circles indicate the maximum speed of the punch achieved typically within 20 - 25 mm stroke length (for P_{pnt} > 0.6 MPa). From these discussions, it can be concluded that the developed MPL can provide sufficient energy to inject pellets formed at cryogenic temperatures.

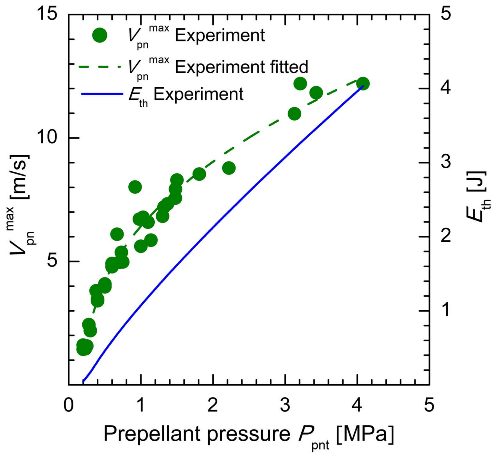

Fig. 4 Maximum speed (V_{pn}^{max}) and associated E_{th} achieved by the MPL punch head as a function of the propellant pressure in the test bench experiment.

4. Pellet Injector Device and Application of MPL

Although the MPL is developed to launch pellets for hydrogen, argon, and neon pellets, current experiments have been performed for the hydrogen pellets only. The injector design is similar to the injector developed earlier [8]. It has a cryostat for pellet freezing and a three-stage differential pumping system for restricting the propellant gas flow from the injector. A gas feed system capable of handling pressure up to 10 MPa is installed in the injector. A GM-type cryocooler having a cooling capacity of 1.5 W at 4.2 K has been used to achieve the desired cooling for the pellet formation. The pellet freezing barrel is attached to the 2nd stage of the cryocooler through a copper block. The cold block is enclosed by a copper radiation shield which minimizes the radiation heat load on it. The cryostat is operated at a vacuum level of $< 5 \times 10^{-4}$ Pa to minimize the connective load on the pellet freezing block. The temperature on the cold block and at various points on the barrel is measured using Lakeshore make DT-670 silicon diodes. This sensor has a temperature measurement range of 1.5 to 500 K, (accuracy ± 40 mk at 4.2 K). The temperature achieved on the cold head and the pellet formation block is 4.5 K and 5.0 K, respectively. During pellet freezing, the temperature on the cold block increases marginally by 0.5 K. A mass flow meter having a full-scale flow rate of 0.17 $Pa.m^3/s$ has been used for the pellet formation process. The high-speed camera mentioned in the previous section is used to diagnose the injected pellet.

Experiments were carried out on 4.2 mm $d_p \times 6.2$ mm l_p ($A_{con} = 0.83\,cm^2$) cylindrical hydrogen pellets. The shear stress of solid hydrogen as reported in Ref. [4] is 0.35 MPa at 4.2 K. Using equation (1), the breakaway pressure for a hydrogen pellet of $l_p/d_p = 1.5$ is calculated to be 2.1 MPa. This pressure corresponds to an impact energy of 0.35 J. To check the strength of th freezing pellet, launching experiments were first carried out using a fast-opening solenoid valve only (without the MPL). The solenoid valve was operated for ~ 2 ms opening duration, and high-pressure helium propellant gas (~ 2.5 MPa) was introduced in the barrel to dislodge and accelerate the pellet. This pressure closely matches with the estimated value considering the shear stress of the hydrogen ice. Subsequently, the feasibility of launching the hydrogen ice pellets using the MPL was studied. The punch head strikes the pellet base at a stroke length of ~ 12 mm. The capability of the MPL has been tested for a propellant pressure range of 0.3 to 1.6 MPa. The transition pressure range for pellet launching by MPL is found to be 0.4 - 0.6 MPa. For $P_{pnt} <$ 0.4 MPa, the launcher couldn't able to inject the pellet, and within the pressure transition range, the pellet occasionally launched. As shown in Fig. 4, $P_{pnt} = 0.5$ MPa corresponds to $V_{pn} \sim 4$ m/s and the associated E_{th} is ~ 0.41 J. This energy is in close agreement with the energy needed to dislodge the pellet mentioned earlier. Therefore, the use of MPL has reduced the propellant pressure required to dislodge the pellet from the freezing zone. The pellet speed (V_p) varies from 80 to 140 m/s for a propellant pressure of 0.4 to 1.6 MPa. More than 100 pellets were fired in the experiment. It is worth mentioning that the pellet speed obtained at these pressure using the MPL is lower than the V_p obtained using the fast-opening valve only. Since the intrinsic idea behind the current work is dislodging the pellet from the freezing zone, its acceleration to a higher speed has not been studied at present. This study will be performed in the future. From the images, the pellet sizes were measured to have dimensions of (5.9 ± 0.3) mm $l_p \times (4 \pm 0.3)$ mm d_p.

Pellet images were taken at differential pumping chambers. Figure 5 shows the image of two different pellets acquired at the first (left image, $P_{pnt} = 1.12$ MPa, $V_p =$ 110 m/s) and at the third expansion chambers (right image, $P_{pnt} = 0.72$ MPa, $V_p = 90$ m/s), respectively. In the experiment, it has been observed that shards are present around the pellet while exiting the barrel. The fragments increase when pellets are formed at lower mass flow rates. Similarly, it decreases for pellets formed at higher mass flow rates. This effect may be due to the formation of snow

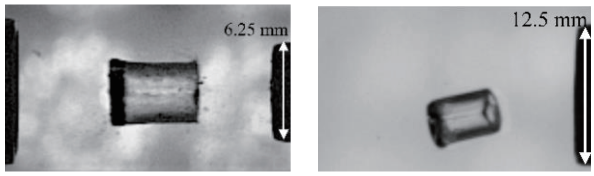

Fig. 5 Image of two different hydrogen pellets, (left image) $P_{pnt} = 1.12$ MPa, $V_p = 110$ m/s at the barrel exit, and (right image) $P_{pnt} = 0.72$ MPa, $V_p = 90$ m/s, at the 3rd differential pumping chamber.

inside the barrel surface. At the starting phase of pellet freezing, the heat load from lower throughput pellet freezing gas is lesser in comparison to the higher throughput gas, which leads to rapid de-sublimation and formation of snowy dust on the barrel's inner wall. In addition, it is also observed that the pellets formed at low mass flow rates require a marginally higher punch speed to dislodge from the freezing zone as compared to the pellets formed at higher mass flow rates. These observations will be investigated further. In the future, the MPL will be tested for other pellet materials like argon and neon.

5. Summary

A fast valve-assisted MPL has been developed to inject frozen pellets of gases like hydrogen, argon, etc. This device is designed to launch pellets up to 7.0 mm d_p ($l_p/d_p = 1.5$) from the gun barrel. The developed MPL is tested on a 4.2 mm d_p hydrogen pellet. In the test bench operation, the MPL piston head attained the design speed of 12 m/s for a propellant pressure of 4 MPa. This device has been tested on solid hydrogen pellets. In the experiment, it is found that a minimum pressure of ~ 0.5 MPa is needed by the punch to dislodge the pellet, and the V_p varies from 80 to 140 m/s for a propellant pressure of 0.4 to 1.6 MPa. The energy equivalent to the propellant pressure matches well with the values reported in the literature. The application of this device significantly reduces the propellant gas pressure needed to dislodge the pellet from the freezing zone, and hence the gas load on the differential pumping system. In the future, the usefulness of this device will be tested for larger-size pellets of hydrogen, argon, neon, etc. Also, pellet launching at higher speed will be studied.

[1] S.K. Combs *et al.*, Fusion Sci. Technol. **73**, 4, 493 (2018).
[2] L.R. Baylor *et al.*, Phys. Plasmas **12**, 056103 (2005).
[3] L.R. Baylor *et al.*, Nucl. Fusion **59**, 066008 (2019).
[4] S.K. Combs, *et al.*, Rev. Sci. Instrum. **64**, 1679 (1993).
[5] T.E. Gebhart *et al.*, Fusion Sci. Technol. **77**, 7 (2021).
[6] J. Mishra *et al.*, Rev. Sci. Instrum. **82**, 023505 (2011).
[7] T.E. Gebhart *et al.*, Fusion Sci. Technol. **75**, 8 (2019).
[8] J. Mishra *et al.*, Fusion Eng. Des. **138**, 332 (2019).