§ 1. Development of Repetitive Pellet Injector

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Pellet injection has successfully demonstrated high density operation above $1 \times 10^{20} m^{-3}$ without significant confinement degradation in LHD. In the present injector, however, the number of available pellets is limited to 10 during one plasma discharge since the ice pellet is formed directly in a barrel by "in situ" condensation, which takes a few minutes. A long pulse operation of a high temperature plasma has been already demonstrated for more than 2 minutes. Prolonged discharges exceeding 10^4 seconds are in plan. Therefore a new repetitive fueling pellet injector is required to enable the experimental approach towards steady-state operation in LHD. The new injector adopts the screw extrusion concept, proposed by Mitsubishi Heavy Industry and developed by PELIN Laboratory. Refrigeration is done by two GM cryo-coolers (3 W at 4.2 K in total). Any other cooling media like liquid helium are not used in the system and the cryo-system is completely closed. This concept has realized a high reliability and an easy maintenance. Also the control of temperature is facilitated and the turn-around time of operation and standstill are acceptable. Figure 1 shows the cooling-down and warming-up process of the temperature at the bottom of the extruder. The pellet injection is available 4 hours after the start of cooling down from the room temperature. Also it takes only 1 hour to recover the cryogenic temperature sufficient for the pellet injection from the 6-hour pause of cooling. The temperature is as low as 7 K without pellet formation. Hydrogen is solidified continuously in the cryogenic screw extruder with the maximum rate of 15mg/s. There is no limitation of the operational duration in a technical principle. The solidified hydrogen rod is extruded with a diameter of 2.5mm and consequently the extrusion of 35mm/s is provided. The continuous extrusion of solid hydrogen has been demonstrated for 1000 s and the size of launched pellets was investigated to check the quality of solid hydrogen as a function of formation temperature. When the temperature at the extruding position is less than 11.3 K, the pellet size is maintained stable with small variation. When the temperature increases above 11.8 K, the variation of the size becomes larger, which suggests a deterioration of quality of pellets. Since the cooling capability is sufficient to cope with heat load during solidification and extrusion, the increase of temperature is limited to much less than 1 K (see Fig.2) even at the maximum extrusion speed. Consequently the favorable operational temperature (<11.1k) can be kept in steady-state. A successful technical integration of major elements has led to the completion of a repetitive pellet injector for LHD. Figure 3 shows the typical demonstration of a stable injection of 1000 pellets at 10 Hz. The quality of the pellet is verified by a shadow graph during the 1000 continuous launches. A small temporal change is observed in the early phase, which however can be left out from substantial injection to the plasma if it is not favorable. Typically, a pellet launch reliability of more than 99% was achieved at the propellant gas pressure of 2MPa with only few pellets not passing through the trigger gate at the outlet of the barrel. Although the data of all shots have not been archived, 10000 pellet launches at 10 Hz for 1000 s have been also demonstrated. The fuelled particle by repetitive pellets equivalent to 10 Pam^3/s of hydrogen gas.

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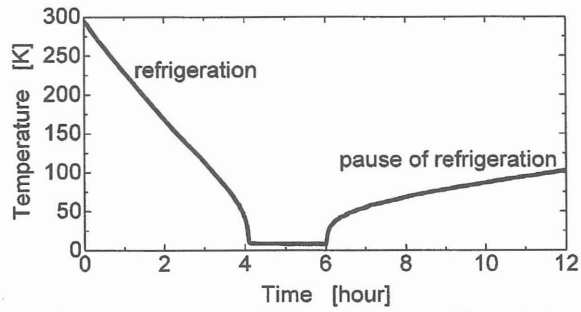

Fig.1 The temperature at the extruding position during the cooling-down and paused phase.

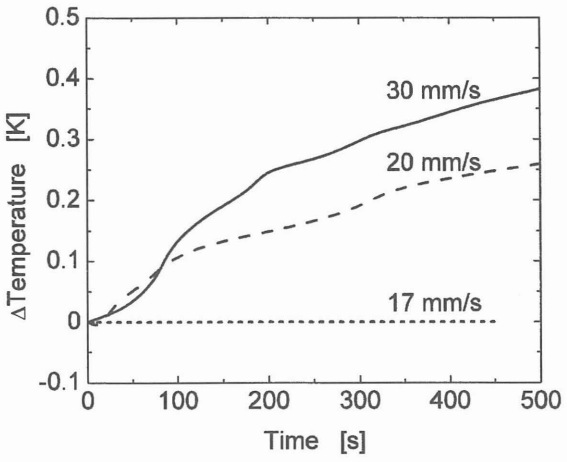

Fig.2 The temperature increase for different extrusion speeds. The base line temperature is 10.5-11 K.

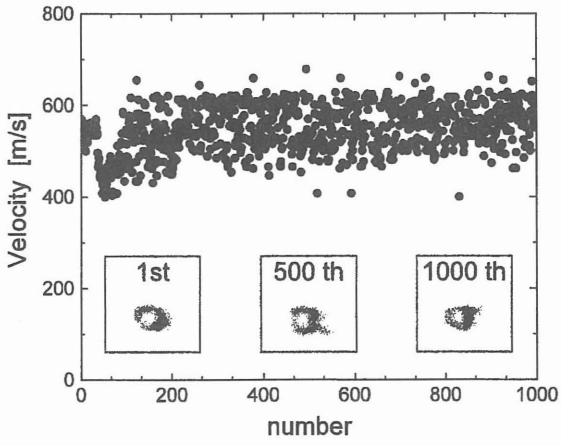

Fig.3 The demonstration of 1000 launches at 10 Hz. The velocity and a typical shadow graph of pellets are shown.