*33rd EPS Conference on Plasma Phys. Rome, 19 - 23 June 2006 ECA Vol.**30I**, P-4.130 (2006)*

# Development of a Cryogenic Variable-Sized Pellet Injector for Pellet Ablation Studies

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Abstract: A pneumatic injector of hydrogen cryogenic pellets with precisely controlled length has been developed. The major elements of this injector are (a) a cylindrical freezing cavity with controllable length which allows the length of a frozen hydrogen pellet formed in situ to be adjusted precisely and continuously from sub-millimeter to a few millimeters and (b) a Gifford-McMahon cryo-cooler which is employed to refrigerate the entire mechanism. After the development and improvement of this injector, the quite successful results have been obtained in terms of hydrogen pellets with the size from 0.5 to 3.0 mm in length.

1. Introduction: From the viewpoint of performance of nuclear fusion plasmas, pellet injection experiments have been actively carried out in many toroidal devices in the sense of the control of density profile, obtaining high density or improved confinement, and diagnostic purposes. A pellet ablation study has been performed as an international cooperation activity, constructing the IPADBASE 1.0 [1]. According to such database or calculations based on the so-called the neutral gas shielding (NGS) model [2], it is known that the penetration depth into hot plasmas is always quite sensitive to the pellet size. Also, an effective or suitable range of the pellet size for certain plasmas is generally very narrow, and this range largely varies depending to each toroidal plasma size. Some computer results of these phenomena obtained from the NGS model using the ABLATE-code of Nakamura [3], particularly in JIPP T-IIU tokamak plasma case, are shown in Fig. 1. Kyushu University variable-sized pellet injector (Kyudai VSPI) is a single-shot pneumatic, pellet carrier disk-type injector equipped with a unique pellet length regulator and a Gifford-McMahon (GM) cryo-cooler [4]. This injector is able to adjust precisely and continuously the length of 1.4-mm-diam cylindrical cryogenic pellets of pure hydrogen ($H_2$) from 0.5 to 3.0 mm as well as to accelerate them to moderate speeds. This pilot research is in development at Kyushu University and is intended for a careful investigation of the following: (i) both NGS predictions about pellet ablation and penetration depth dependences on pellet size and (ii)

suitable pellet length ranges for a deeper penetration depth of the ablating pellet into tokamak plasmas with different volumes, plasma electron temperatures and densities.

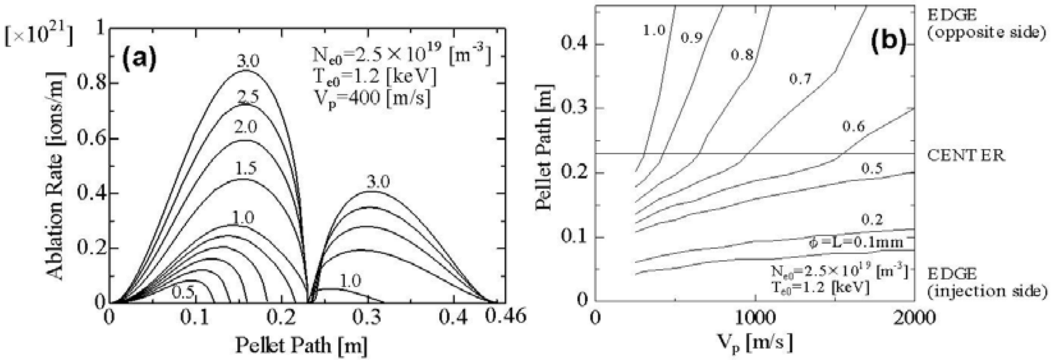


*Fig. 1 – (a) pellet ablation profile with increasing pellet size ranging from 0.5 to 3.0 mm. (b) relationship between the pellet penetration depth and the pellet speed with increasing pellet length ranging from 0.1 to 1 mm (after Ref. 5).*

2. The Kyudai VSPI design and operation: Figure 2 shows a schema of the Kyushu University variable-sized pellet injector which is utilized to produce and launch single solid pellet with controlled length. The injector is inside a $10^{-5}$-Pa vacuum chamber where a vacuum thermal insulation is maintained. A GM cryo-cooler, which is located on the top of that chamber and connected to the injector, is employed (instead of liquid helium) to gradually cool down the injector to cryogenic temperature.

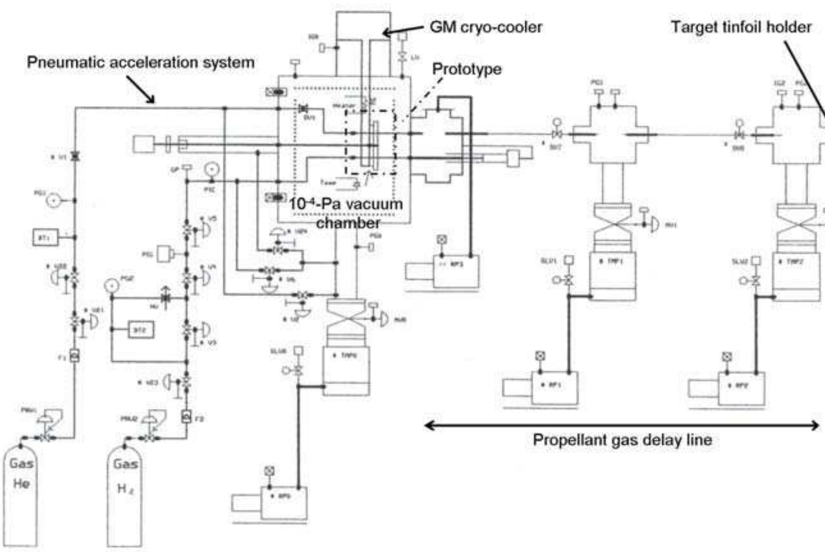


*Fig. 2 – Overall drawing of the Kyushu University variable-sized pellet injector, Kyudai VSPI.*

A pneumatic acceleration system utilizes high pressure helium gas at room temperature to propel the ice pellet out of the mechanism. A propellant gas delay line, which consists of a drift tube partitioned into three separated high vacuum chambers and two fast gate valves, is used to diminish the amount of propellant gas from the injector into the vicinity of injection port. A rotary-type target tinfoil holder, which is located in the injection port, permits both (a) estimation of the scattering angle of the impacting pellets and (b) indirect evaluation of the reproducibility of the injector. The main design elements of the injector are shown in Fig. 3. Basically, it consists of two 1.4-mm-i.d. cylindrical freezing cavities with variable length of 0.5-3.0 mm inside a cool copper pellet carrier disk. Through this mechanism, a single variable-sized ice pellet is pre-formed into one of the freezing cavities for subsequent rotation via the pellet carrier to an acceleration position.

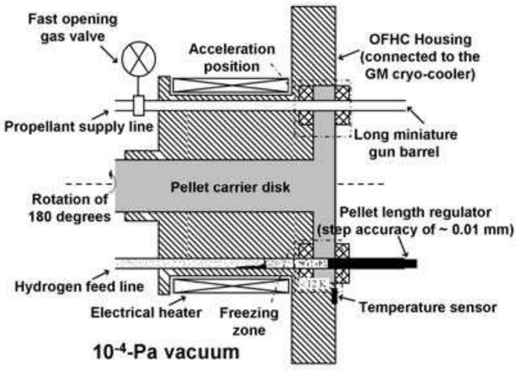


*Fig. 3 – Main design elements of the injector .*

The scheme for producing such ice pellets for the  is as follows: (i) initially the length of the bottom freezing cavity of the pellet carrier is precisely controlled by a pellet length regulator, (ii) room-temperature hydrogen gas at 0.5 bar or so is admitted into the bottom freezing cavity of the pellet carrier (held below the hydrogen triple-point temperature for porous-free ice pellet generation) from the opposite side of the pellet length regulator, (iii) after sufficient freezing time (about 1-3 min) a mm-frozen rod of hydrogen is then formed in situ, (iv) immediately after this pre-fabrication, the $H_2$ gas (re)feeding is held constant without any interruption and the pellet length regulator is pulled to a position outside of the freezing cavity, (v) by means of a 180º rotation of the pellet carrier disk a single variable-sized ice pellet is properly placed between a gun breech and a long gun barrel (acceleration position), (vi) room-temperature helium gas raging 5-20 bar is admitted for 18 ms to propel the frozen pellet out of the freezing cavity and accelerate it in the long gun barrel, and (vii) at last, both propellant and residual hydrogen gases in the mechanism are pumped away. A cycle of 1.5-5 minutes can be repeated again.

3. Results and Discussion (Pellet Length Regulation): After considerations on the $H_2$ affinity of the regulator and on the effects of pressure and flow rate of $H_2$, several improvements in the core structure of the injector and in the procedure of pellet creation have

been carried out, and the quite successful results have been obtained as shown in Fig. 4 (a). The target tinfoil tests indicate that the good ice pellets with controllable length presents a scattering of about 0.3º in the injection port. In order to investigate further more, a 0.18-µs-duration shadowgraph system for estimating the sizes of the pellet formed in situ as well as for verifying the pellet integrity and a digital detection system for measuring the average pellet speed are developed. The latter system will allow us to verify the consistency between the predictive pellet velocities (see Fig. 4(b)), based on the single-stage gas gun acceleration model of Milora and Foster [6], and the exact pellet speed range during pellet launches. In addition, an experimental investigation on angular pellet scattering dependence on both pellet size and speed will be carried out, including a large number of pellet launches.

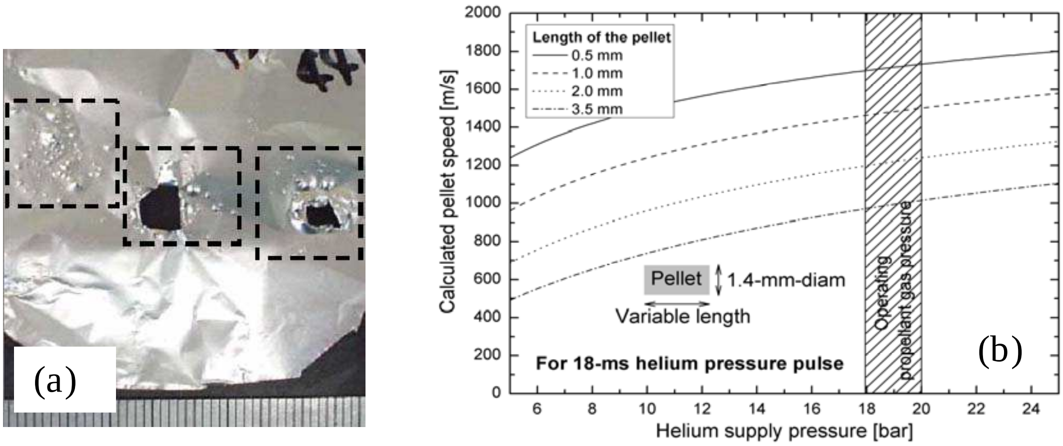


*Fig. 4 – (a) results of the target tinfoil after injection of 2-mm-diam ice pellets. (b) predictive dependence of muzzle speed on the propellant gas pressure with increasing pellet length.*

Acknowledgments: This research is sponsored by the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) and has been carried out as a collaboration research with the National Institute for Fusion Science (NIFS).

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