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ABSTRACT.

Three innovative repetitive and multi-barrel deuterium ice pellet injectors have been designed for plasma investigations in fusion facilities.

The pellet injector for JET has capability to inject small pellets (variable volumes within 1–2 mm^3) at frequency up to 67 Hz and velocities 80–200m/s for ELM (edge localised modes) control and large pellets (volume within 35–70mm^3) at frequency up to 15Hz and velocities 100-300m/s for plasma fueling. A new extrusion nozzle has been designed and tested to improve the extrusion stability and injection reliability.

The pellet injector for HL–2A has a piston type extruder with a variable cross-section. It allows pushing out deuterium ice rod from the extruder at velocity up to 100m/s and injecting a limited number of pellets 1.3mm diameter and variable length in the range 1.3–1.7mm at frequency up to 30Hz for plasma fueling.

The pellet injector for fueling of a facility with theta pinch plasma is capable to inject one pellet with variable length from 5 to 15mm and diameter 1 mm with extremely low velocity of about 40–50m/s, followed by eleven pellets with variable length from 1 to 3mm and diameter 0.9mm at velocities 100–200m/s. A novel gas valve with in-built punch mechanism has been developed to simplify the injector design.

Design and distinguishing features of these three injectors are presented.

1. INTRODUCTION

Injection of deuterium ice pellets is one of the best techniques for fusion plasma fueling. It is also promising method for ELM mitigation. As a part of the programme JET EP2 in support of ITER, a repetitive pellet injector has been designed and put in operation on JET in 2008. The injector has been equipped with a screw extruder similar to those that earlier demonstrated excellent performances on LHD [1] and TORE-SUPRA [2]. To provide variable volumes of pellets a nozzle having two small and one large channels for continuous solid ice ribbons fabrication has been installed in the extruder outlet. However, during injector commissioning on JET plasma, the extrusion stability was often deteriorated during simultaneous ice extrusion through two channels and corrections were necessary. The injector design, overpatching and performance are described in section 2.

A new technique of pellet fabrication at frequency up to 30Hz in a repetitive injector with a piston type extruder has been developed for plasma fueling of HL-2A tokamak. The pellet injector design and parameters are presented in section 3.

A twelve-barrel pellet injector has been developed for a theta pinch plasma facility installed at Tri Alpha Energy, Inc. (USA). As for others multi-barrel injectors, pellets are fabricated by means of gas condensation inside pellet generator cells cooled by a cryorefrigerator and accelerated with propellant gas. To reach pellet velocity lower than 100m/s which was not achievable even with a punch mechanism [3], a new technique of pellet acceleration as well as a novel gas valve have been applied in the injector presented in section 4.

2. PELLET INJECTOR FOR JET

Operating specification of the JET pellet injector includes the following main requirements: unlimited number of small (variable volumes within 1–2mm^3) and large (variable volumes within 35–70 mm^3) pellets of deuterium or hydrogen ice should be injected at frequencies up to 60Hz and 15Hz at velocities 50–200m/s and 100–500m/s for small and large pellets, respectively, with reliability 98%. The required parameters are close to the future ITER pellet injector characteristics. Unlimited number of pellets to be injected can be provided with the screw extruder technology developed earlier for LHD [4] and TORE-SUPRA [5] facilities.

The injector design, shown schematically in Fig.1, is a main component of a complete injection system installed at JET late 2007 [6]. It consists of vacuum and diagnostic chambers equipped with a screw extruder and a cooling system, with a pellet fabrication and acceleration system, and with a pellet-in-flight diagnostics. The extruder with a hydrogen liquefier is surrounded by a thermal insulating screen. A heat exchanger installed above the screen consists of two long tubes made of oxygen-free copper bent as a cylinder and covered with an insulating film. A helium flow regulator is inserted into the vacuum chamber and connected to the heat exchanger. Four thermal sensors and heaters are used for temperature regulation and measurement near the extruder nozzle, extruder inlet, liquefier and thermal screen. A visual chamber is welded to the bottom of the extruder. The exhaust pipe line connects the visual chamber with buffer chambers and vacuum pumping system. Parts of pellet fabrication and acceleration system are inserted into the visual chamber.

The requested pellet injection frequency up to 60Hz is difficult to provide using one outlet channel of the screw extruder, because the extrusion velocity is usually too slow (less than 50mm/s) [7]. Therefore, the extruder has been equipped with a nozzle having three channels with rectangular cross-section: two for simultaneous extrusion of small ribbons and one for large ribbon. A pellet size regulator can change the cross section of the channels and therefore ice ribbons can have variable sizes, namely: 2.8–5.6mm with constant 4 mm width from large channel and 0.9–1.8mm with 1.2mm width for small channels. The size regulator closes either the large channel or the two small channels, so one large or two small ice ribbons can be extruded in a moment. A set of electromagnetic cutters operating in turn is used to form pellets from ice ribbons. The cutters push formed pellets into barrels where they are accelerated by short pulses of propellant gas (helium) coming from gas valves.

During operation gaseous deuterium at a pressure of 0.1–0.13MPa is continuously supplied into the extruder through the heat exchanger. The helium flow regulator and heaters stabilize the temperature of the extruder at a level of 15K for deuterium ice formation. The extruder's screw is rotated by a motor installed on the top flange of the vacuum chamber. Solid deuterium moves along the helical channel of the screw. Ice is gradually compressed and pushed out continuously through the channels in the extruder nozzle into the visual chamber. Electromagnetic cutter cuts out a part of the extruded ice ribbon and transports the pellet thus formed into the barrel. Approximately 5ms after the pellet formation, the gas valve supplies compressed helium (0.1–0.2MPa) into the barrel. The gas accelerates the pellet and ejects it into the diagnostic chamber. The pellet intersects two light barriers, which yield signals allowing measurement of the pellet velocity and initiate a flash recorded by a video camera. The pellet moves through guide tubes to plasma; the propellant gas is removed by the vacuum pumping system, and the injection cycle repeats.

The results of more than 100000 pellets injected during the injector commissioning on target phase at JET in 2008 complied with specification parameters for large pellets. The results, presented in Fig.2 for 20s injection cycle, were achieved with pellets having medium length: 1.4mm for small and 4 mm for large pellets, respectively. Results are shown in term of reliability (number of unbroken pellets seen on the photo station at the injector exit / number of requested pellets) as a function of the pellet injection frequency for large and small pellets and for hydrogen and deuterium ice for different pellet velocities. Large hydrogen and deuterium pellets were injected with high reliability over 98% for medium volumes and velocities. For all range of large pellets volumes and velocities the reliability was equal to 93–95%.

These local test sequences were triggered manually waiting for a stable extrusion. However, significant extrusion instability appeared when ice was pushed out through both small extruder channels simultaneously. If the extrusion velocity is increased in one channel, the heat release and temperature of ice in this channel are also increased, the ice viscosity is reduced and that lead to increased extrusion velocity. During this process the ice becomes less and less compressed and finally can not be pushed out through the channel. The extrusion is interrupted. On the contrary, in case of velocity reduction in one channel, the heat release and temperature are also reduced, the ice viscosity is increased and that lead to further reduction of the extrusion velocity up to stopping. During the following commissioning on plasma phase in 2009, triggers came from the JET control system at random times with respect to the extrusion start order and it became obvious that reliability of small pellets injection was not acceptable likely due to this extrusion instability.

Successful extrusion from both channels simultaneously requests identical conditions for both channels which are difficult to create and maintain. To overcome this instability of ice flow through the two small channels a new extruder nozzle has been developed. The nozzle has one channel with rectangular cross section for all operation modes with small and large pellets. Large pellets are formed in the same way as in previous design. Small pellets are fabricated from two extruded ice ribbons which are separated from one ribbon by a special moveable blade as shown in Fig.3. The two ribbons are directed through two channels where pellets can be formed as in previous design. The modified nozzle has been tested and no instability has been observed during 30 minutes continuous extrusion of two ice ribbons.

The tests of the JET injector equipped with this modified nozzle will start early 2011 after the 2010 JET shut down termination. A complete testing will be undertaken in order to understand and overcome a general degradation of the performance observed during the 2009 campaign.

3. HL-2A PELLET INJECTOR

The injector for plasma fueling of HL-2A tokamak is capable to inject in one cycle up to 33 pellets of 1.3mm diameter and variable length within 1.3-1.7mm at frequency up to 30Hz with velocities

100–450m/s. The injector design is shown schematically in Fig.4. It consists of a vacuum chamber with a piston type extruder connected to a cryorefrigerator (not shown in Fig.4), a linear motor with variable speed connected to the extruder piston, a pellet size regulator, a cutter, a gas valve and a diagnostic chamber.

Extrusion velocity of solid deuterium ice is limited, therefore a new design of a piston type extruder has been proposed to provide the fabrication of ice ribbon and its movement with velocity of about 100mm/s acceptable for pellets production and injection at 30Hz. The extruder and piston have variable cross section as shown in Fig.5. In position 1 deuterium gas is admitted into the extruder cooled by the cryorefrigerator down to 8K. The piston moves down at velocity 1–2 mm/s to position 2 and press the frozen gas forming deuterium ice which is extruded through a long extruder nozzle. The end of the thin part of the piston comes to the nozzle inlet by the end of the extrusion stage. In the same position the thick part of the piston comes to the beginning of the wide section of the extruder chamber. The edge of the pellet size regulator can be moved into the nozzle inlet to change the thickness of the ice ribbon from 1.3 to 1.7mm thereby setting the pellet length. In injection mode a powerful heater wound around the extruder is switched on and solid deuterium ice becomes very soft like a Bingham liquid [8] for a less than 200ms. The piston is moved down by the linear motor at speed of about 100mm/s almost without resistance, because the melted ice flows around the piston in the wide section of the extruder. The end of thin part of the piston pushes out the solid ice ribbon from the nozzle. One of extruded ice ribbon is shown in Fig.6. The cutter moves along the barrel thereby cut off a section of the extruded ice ribbon forming a pellet. Simultaneously the gas valve is opened and propellant gas is supplied into the barrel, causing the acceleration of the formed pellet. Propellant gas and pellet flies into the diagnostic chamber, where the pellet size, shape and velocity are registered. One pellet snapshot in two perpendicular directions is shown in Fig.6. The pellet cutter is returned to the initial position, and the cycle is repeated.

4. TAE PELLET INJECTOR

The pellet injector is capable to inject first deuterium pellet of 1mm diameter with variable length from 5 to 15 mm at velocity of about 50m/s. After that up to 11 pellets of 0.9mm diameter with variable length within 1-3mm are available for injection at velocities within 100–250m/s with 0–100ms time interval between shots.

The injector design is shown schematically in Fig.7. Twelve barrels with copper cells are connected to the copper ring with a central crosspiece which is attached to a cryorefrigerator head. Deuterium gas is admitted into all barrels simultaneously and is frozen in the cells forming pellets. Technology of good quality pellets fabrication is described in [9]. A helium propellant gas provides reliable injection at velocities over 500m/s because a pressure over 1MPa is necessary to break away the frozen pellet from barrel walls. A new gas valve with a punch mechanism, which releases a pellet from barrel walls and causes velocity reduction, is shown schematically in Fig.8. A plunger was moved by an electromagnetic coil. A puncher nozzle made of a thin-wall tube, which is attached to the plunger, moved a frozen pellet from the pellet formation cell. The puncher also picked up a sleeve with a gasket which opened a channel with pressurized propellant gas. Gas penetrated into ducts in the sleeve and the puncher and accelerated the pellet in the barrel. Springs returned the puncher and the plunger in the initial position and the channel with propellant gas was closed by the gasket also. Nevertheless, pellet velocities were over 100 m/s after the puncher action only, even without propellant gas. To reduce a pellet velocity from the first barrel a heater (8W power) has been wound around the first pellet formation cell. The heater was triggered just before injection start for several seconds. After preheating, first pellets velocities were reduced to 35–50m/s. One of pellets accelerated with preheating technique from the first barrel is shown in Fig.9. Preheating does not effect on following pellets injection within 1 s after the first pellet acceleration. So, preheating is an effective technique for pellet velocity reduction in multi-barrel injectors.

CONCLUSION

The presented pellet injectors completed a list of 10 injectors and pellet generators built by PELIN for fusion facilities in Russia, Japan, France, USA, UK and China for the last 12 years. Each apparatus developed by PELIN was innovative and allowed significant contributions to the worldwide fusion programme in the pellet injection domain.

ACKNOWLEDGMENTS

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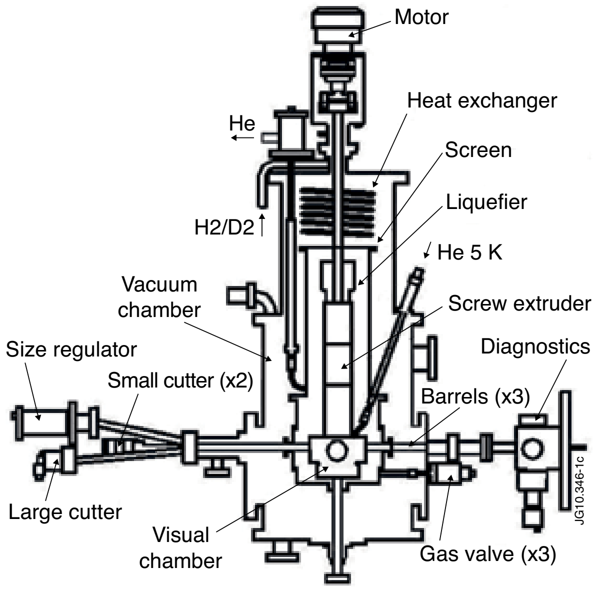

Figure 1: A schematic drawing of the JET pellet injector.

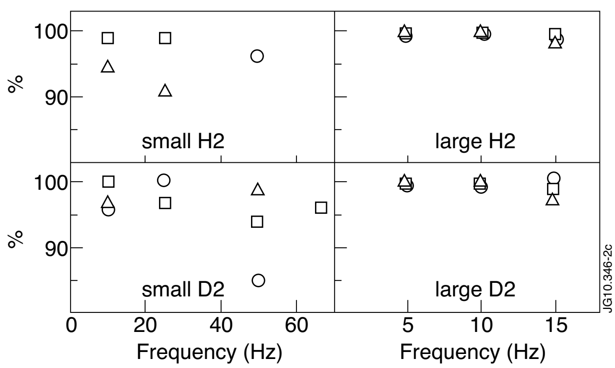

Figure 2: Results of injection on target for small (1.6 mm^3) and large (50mm^3) hydrogen (top) and deuterium (bottom) pellets. Velocities 80 and 100m/s (circles), 100 and 200m/s (square), 200 and 300m/s (triangle) for small and large pellets, respectively.

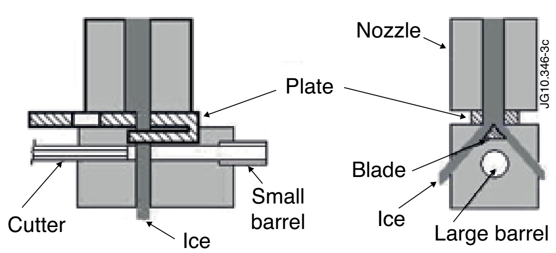

Figure 3: A schematic diagram of the modified extruder nozzle with the movable blade.

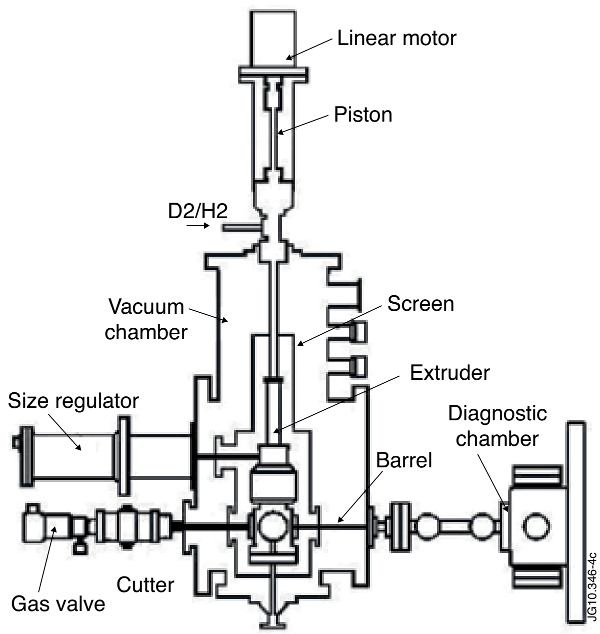

Figure 4: A schematic diagram of the HL-2A pellet injector.

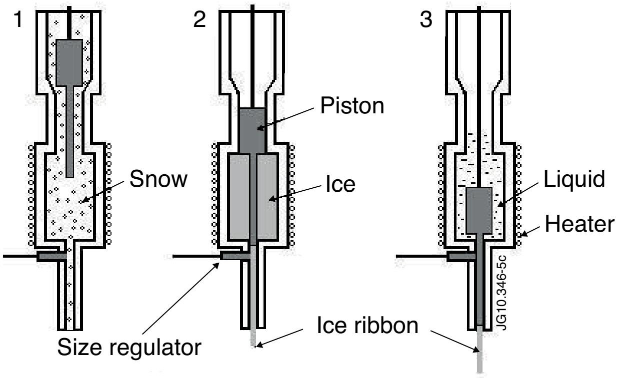

Figure 5: A schematic diagram of the extruder of HL-2A pellet injector.

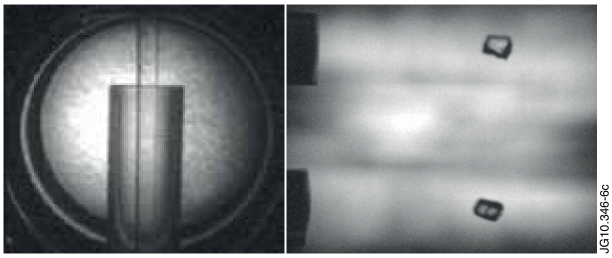

Figure 6: Deuterium ice ribbon (left) and a pellet-in-flight (right) in HL-2A pellet injector.

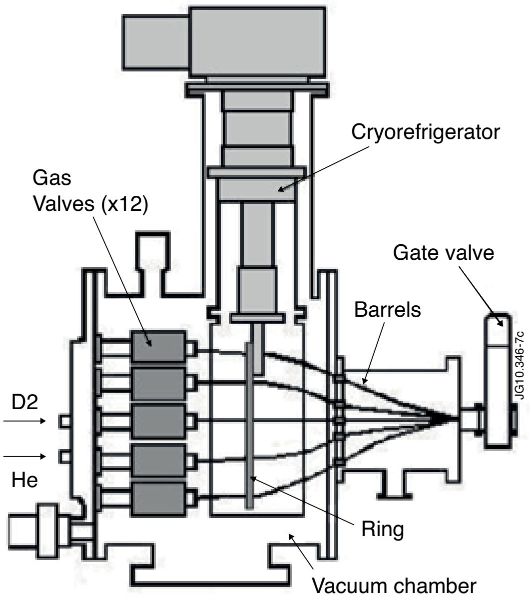

Figure 7: A schematic diagram of the TAE pellet injector.

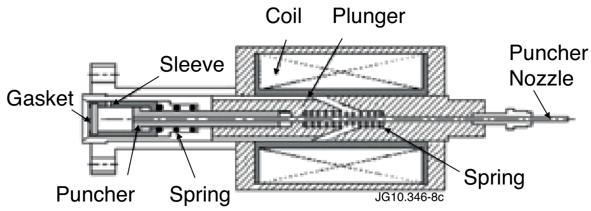

Figure 8: A gas valve with in-built punch mechanism.

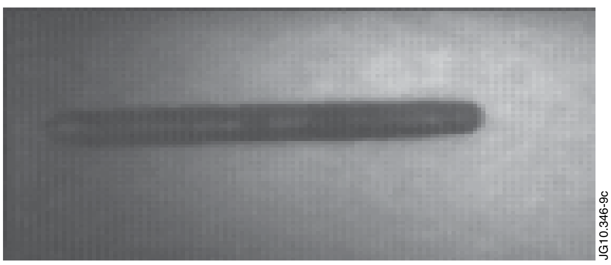

Figure 9: Deuterium pellet of 1 mm diameter and 12mm length traveling at 36m/s.