CONF-940843--14

Pellet Injector Research and Development at ORNL*

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Oak Ridge National Laboratory has been developing pellet injectors for plasma fueling experiments on magnetic confinement devices for more than 15 years. Recent major applications of the ORNL development program include (i) a tritium-compatible four-shot pneumatic injector for the Tokamak Fusion Test Reactor, (ii) a centrifuge pellet injector for the Tore Supra tokamak, and most recently (iii) a three-barrel repeating pneumatic injector for the DIII-D tokamak. In addition to applications, ORNL is developing advanced technologies, including high-speed pellet injectors, tritium injectors, and long-pulse pellet feed systems. The high-speed research involves a collaboration between ORNL and ENEA-Frascati in the development of a repeating two-stage light gas gun based on an extrusion-type pellet feed system. Construction of a new tritium-compatible, extruder-based repeating pneumatic injector (8-mm-diam) is complete and will replace the pipe gun in the original tritium proof-of-principle experiment. The development of a steady-state feed system in which three standard extruders operate in tandem is under way. These research and development activities are relevant to the International Thermonuclear Experimental Reactor and are briefly described in this paper.

1. Introduction

A variety of pellet injector designs have been developed at Oak Ridge National Laboratory (ORNL) and applied on experimental fusion devices in the United States and Europe [1–3]. With these systems, pellets (1 to 6 mm in nominal diameter) composed of hydrogen isotopes are formed and accelerated to speeds of ~1 to 2 km/s for injection into tokamak plasmas. In this paper, we briefly describe some recent research and development activities at ORNL, including (i) three development applications on large experimental fusion devices, (ii) a high-velocity repeating pellet injector, (iii) a tritium proof-of-principle (TPOP) experiment, and (iv) a steady-state extruder feed system.

2. DEVELOPMENT APPLICATIONS

2.1 TFTR Tritium-Compatible Four-Shot Pellet Injector

The latest ORNL pellet injection system provided for the Tokamak Fusion Test Reactor (TFTR) (previous systems installed in 1985 and 1986) is a tritium-compatible, four-shot pipe-gun configuration with three single-stage guns and a two-stage light gas gun driver. This system is a modification of the TFTR eight-shot pneumatic pellet injector [4] that operated on the tokamak from 1986 to 1991. The upgraded injector [5–7] is equipped with 1-m-long gun barrels, two with a 3.4-mm ID and two with a 4.0-mm ID. The three standard guns have been operated reliably at pellet speeds of up to 1.5 to 1.7 km/s (deuterium pellets). The two-stage gun can provide the high-pressure, high-temperature gas required to accelerate pellets to the 2- to 3-km/s range (2.8 km/s recorded in deuterium tests at ORNL). The size of individual pellets can be varied using techniques demonstrated in the TPOP experiment to freeze different amounts of hydrogen ice. The injector was installed on TFTR in 1992 and has been used in plasma-fueling experiments. The present experimental plan includes deuterium injection experiments in support of TFTR deuterium-tritium (D-T) experiments.

2.2 Tore Supra Centrifuge Injector

As part of an international collaboration with the Commissariat à l'Energie Atomique, ORNL supplied a centrifuge pellet injector to the Tore Supra tokamak in 1989 and continues to participate in the experiments [8,9]. With the present configuration, the centrifuge has the capability of injecting up to 100 deuterium pellets into a single plasma discharge. Up to 10 pellets per second can be injected at speeds from 0.5 to 0.8 km/s, with sizes ranging from 3 to 10 torr•L per pellet [$(2–7) \times 10^{20}$

*Based on work performed at Oak Ridge National Laboratory, managed for the U.S. Department of Energy under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

atoms per pellet]. Pellets are formed and injected into the centrifuge accelerator with the Zamboni-like pellet fabricator. With a similar system at ORNL, techniques are under experimental investigation with the objective of improving the pellet reproducibility and the pellet delivery reliability to the plasma. To accommodate extended pulse lengths of Tore Supra, another development objective is to increase the number of pellets that can be provided for a single machine pulse; alternative feed systems will be evaluated and could be retrofitted to the existing centrifuge accelerator. The current experimental program that is under way combines repetitive pellet fueling with an ergodic divertor and pump limiters to establish and study long-pulse plasmas in which the pellet fuel source is in balance with the active particle exhaust.

2.3 DIII-D Three-Barrel Repeating Pneumatic Injector

The three-barrel repeating pneumatic injector that was previously used on the Joint European Torus (JET) [10–12] from 1987 to 1992 has been modified and installed on DIII-D. For the JET application, the device was equipped with gun-barrel diameters of 2.7, 4.0, and 6.0 mm and capable of repetitive operation (5, 2.5, and 1 Hz, respectively, for each pellet size) under quasi-steady-state conditions (>10 s). In this long-pulse fueling device, three separate cryogenic extruders are used to provide continuous streams of frozen hydrogen isotopes to the gun sections, where individual pellets are repetitively formed, chambered, and accelerated. For the DIII-D application, the 6-mm gun was replaced by one with a 1.8-mm-ID gun barrel and corresponding mechanisms. Because JET did not use a conventional delivery system with guide tubes and differential pumping, the injector was also equipped with such a system, including the pellet diagnostics required for measuring pellet parameters. The installation on DIII-D is shown schematically in Fig. 1. The three guns have been qualified with helium propellant and deuterium pellets at velocities of ~1 km/s. The small gun was operated at up to 10 Hz for a pulse length of 15 s. This performance represents the smallest pellet size and highest repetition rate demonstrated with an ORNL repeating pneumatic pellet injector.

The injector equipped with gun bores of 1.8, 2.7, and 4.0 mm (nominally 3×10^{20}, 9×10^{20}, and 3×10^{21} D^0 atoms per pellet) will be used in future plasma fueling experiments on DIII-D. By using the pellet injector in conjunction with the DIII-D pumped divertor, pellet fueling experiments will be performed in which the fuel particle throughput is balanced by the particle exhaust rate. A major objective of the experimental program will be to demonstrate a greater degree of control of the plasma density level and the shape of the plasma density profile than previously achieved under quasi-steady-state conditions.

3. HIGH-SPEED REPEATING PELLET INJECTOR

In the ORNL/Frascati collaboration, an ORNL deuterium extruder (equipped with pellet-chambering mechanism and gun barrel) and a small ENEA-Frascati

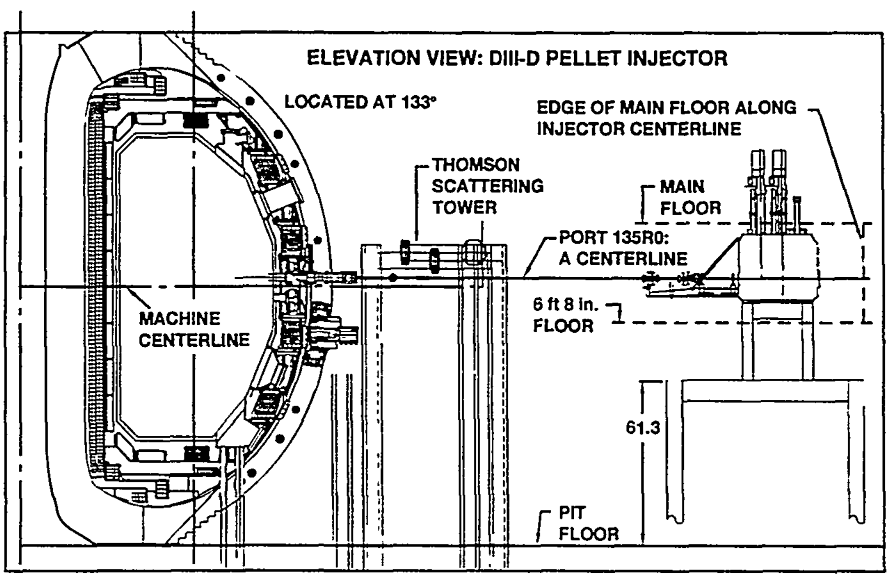

Figure 1. Schematic of three-barrel injector installation on DIII-D.

two-stage gun have been combined to demonstrate and study repetitive operation with bare deuterium ice [13, 14]. The test objectives include operation at pellet frequencies of up to ~1 Hz and speeds in the range of 2 to 3 km/s. In tests at ORNL, pellet speeds of up to 2.55 km/s have been achieved with nominal 2.7-mm-diam deuterium pellets. The data from two experimental campaigns are shown in Fig. 2; the pellet speed is plotted against the maximum breech pressure. During the first set of experiments, it was found that the low pellet release pressure (~5 bar) of the repeating device made it difficult to achieve speeds >2 km/s. Also, the scatter in the data from the first campaign was very large. On the basis of these results, techniques were developed to (i) prevent the pellets from accelerating until the pressure burst from the two-stage gun driver is delivered and (ii) tailor the shape of the pressure pulse for optimal pellet acceleration. For the second set of experiments, the improvement in performance was dramatic, as shown in Fig. 2, with pellets consistently launched at speeds in the 2.0- to 2.5-km/s range. In addition, the high speeds are obtained with much lower breech pressures than for the first set of experiments, and the data scatter is greatly reduced. Most of the experiments have concentrated on optimization of single shots; however, results from limited testing in the repeating mode (0.2 to 0.5 Hz) have also been encouraging, with no significant degradation observed in the pellet speeds at equivalent breech pressures. The higher pellet speeds are about twice that available with conventional repeating pellet injectors (single-stage light gas guns and centrifuges).

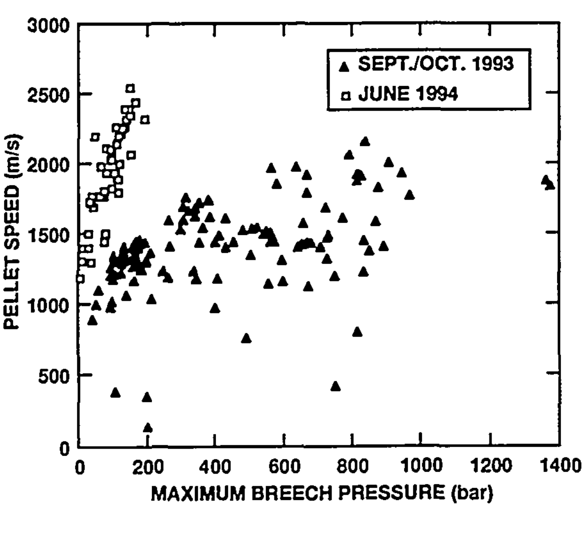

Figure 2. Experimental data from a repeating two-stage light light gas gun (ORNL/Frascati collaboration)

4. TPOP EXPERIMENT

The TPOP experiment was operated in the period 1988–1989 to demonstrate the basic scientific feasibility of production and pneumatic acceleration of tritium pellets for fueling future fusion reactors [15,16]. The experiment, designed and built at ORNL, was installed and operated by ORNL personnel in the Tritium Systems Test Assembly (TSTA) at Los Alamos National Laboratory. Hundreds of 4-mm-diam pellets composed of deuterium, tritium, and mixtures of D-T were made and accelerated in this device; speeds of up to 1.4 km/s were recorded. Over 100 kCi of tritium was processed through the experiment without incident. The gun for this first phase of the TPOP program was based on the pneumatic pipe-gun concept, in which pellets are formed in situ in the barrel and accelerated with high-pressure gas. In phase II of this experiment, the pipe gun will be replaced with a repeating pneumatic pellet injector similar to the design used for the three-barrel injector recently installed on DIII-D. The repetitive device will produce and accelerate 8-mm-diam pellets (twice the diameter of the original TPOP pellets), and the projected maximum repetition rate is ~1 Hz. The 8-mm size will be the largest pellet used in an injector (6-mm-diam pellets were previously used on JET) and is relevant for ITER fueling.

The new TPOP injector will be qualified in deuterium tests at ORNL before installation at TSTA, where it will be housed in a glove box. A schematic of the TPOP-II equipment is shown in Fig. 3. Much larger D-T throughputs are required for TPOP-II than for the original pipe-gun experiment; the baseline approach will include recycling of extruder and injection line exhaust streams to maximize experimental tests within TSTA

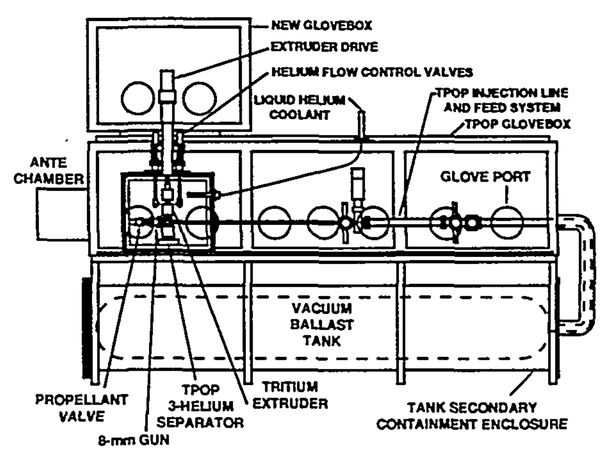

Figure 3. Schematic of TPOP II experiment.

constraints of tritium supply rate and exhaust gas storage. In operation at TSTA, the repeating pneumatic injector will be thoroughly tested with tritium and D-T mixtures.

5. STEADY-STATE EXTRUDER FEED SYSTEM

For the proposed ITER application and future steady-state fusion reactors, a feed system capable of providing a continuous supply of frozen hydrogen is required. At ORNL, a straightforward technique in which multiple extruder units of identical design operate in tandem is being developed. This approach makes use of a reliable ORNL technology, which is illustrated in Fig. 4. A prototype that is under construction should be able to provide a continuous source of hydrogen ice for steady-state operation. In the illustration, it is shown feeding a repeating pneumatic injector; however, the steady-state extruder feed system should be compatible with any acceleration scheme. A transition piece that accepts the three individual feeds and outputs a single feed is the key component that must be developed for this design. Three standard ORNL extruders will be used for the prototype with each containing ~4 cm^3 of solid deuterium, for a total maximum inventory of ~12 cm^3.

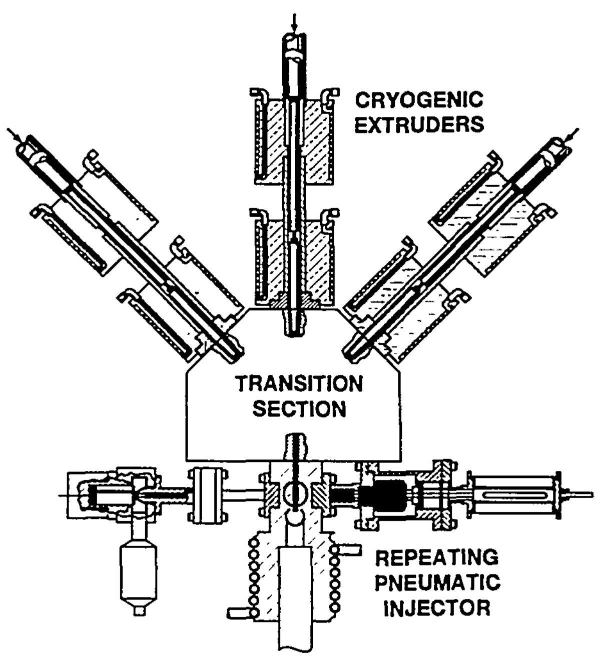

Figure 4. Schematic of steady-state extruder feed system; three standard extruders operate in tandem to provide a continuous source of frozen hydrogen.

This equipment should be adequate to demonstrate steady-state feed rates required for pellet injector operation at frequencies of up to several hertz and pellet sizes in the 2- to 6-mm range. Preliminary designs in which the extruder volume is doubled have been carried out, and these units can be employed in a second phase of the development to accommodate larger throughput rates. The prototype steady-state extruder feed system could also be used on present long-pulse tokamaks such as Tore Supra and JET to increase the effective fueling duration.

REFERENCES

1. S. L. Milora, *J. Fusion Energy* 1 (1981) 15.
2. S. L. Milora, *J. Vac. Sci. Technol. A* 5 (1989) 325.
3. S. K. Combs, *Rev. Sci. Instrum.* 67 (1993) 1679.
4. S. K. Combs et al., *Rev. Sci. Instrum.* 58 (1987) 1195.
5. M. J. Gouge et al., *Fusion Technology* 21 (1992) 1665.
6. G. W. Barnes et al., *Fusion Technology* 21 (1992) 1662.
7. S. L. Milora et al., in: *Fusion Technology 1992: Proc. 17th Symposium, Rome, 14–18 September 1992* (North-Holland, Amsterdam), Vol. I, p. 579.
8. C. A. Foster et al., in: *Proc. of the IAEA Technical Meeting on Pellet Injection and Toroidal Confinement, Gut Ising, Federal Republic of Germany, 24–26 October 1988* (International Atomic Energy Agency, IAEA-TECDOC-534, 1989) p. 275.
9. C. A. Foster et al., in: *Fusion Technology 1992: Proc. 17th Symposium, Rome, 14–18 September 1992* (North-Holland, Amsterdam), Vol. I, p. 496.
10. S. L. Milora et al., in: *Proc.12th Symposium on Fusion Engineering, Monterey, CA, 12–16 October 1987* (IEEE New York, 1987), Vol. 2, p. 784.
11. S. K. Combs et al., *J. Vac. Sci. Technol.* A6(3) (1988) 1901.
12. S. K. Combs et al., *Rev. Sci. Instrum.* 60 (1989) 2697.
13. A. Frattolillo et al., in: *Fusion Technology 1992: Proc. 17th Symposium, Rome, 14–18 September 1992* (North-Holland, Amsterdam), Vol. I, p. 500.
14. S. K. Combs et al., in: *Proc.15th Symposium on Fusion Engineering, Hyannis, MA, 11–15 October 1993* (IEEE New York, 1993), Vol. 2, p. 583.
15. P. W. Fisher et al., *J. Vac. Sci. Technol. A* 7 (1989) 938.
16. P. W. Fisher, *Fusion Technology* 21 (1992) 794.