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Pellet injector development at ORNL*

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Oak Ridge National Laboratory (ORNL) has been developing pellet injection systems for plasma fueling experiments on magnetic fusion confinement devices for about 20 years. Recently, the development has focused on meeting the complex fueling needs of the International Thermonuclear Experimental Reactor (ITER) and future reactors. The proposed ITER fueling system will use a combination of deuterium-tritium (D-T) gas puffing and pellet injection to achieve and maintain ignited plasmas. The pellet injection system will have to provide D-T fueling for much longer pulse lengths (up to ~1000 s) than present-day applications (typically limited to less than several seconds). In this paper, we describe the ongoing pellet injector development activities at ORNL, including the following three in direct support of ITER: (1) an improved pellet feed system for the centrifuge injector, (2) a steady-state extruder feed system, and (3) tritium extruder technology. In addition to the major activities, a repeating two-stage light gas gun for high-speed pellet injection (~2.5 km/s) has been developed in a collaboration with ENEA Frascati; also, the production of impurity pellets (Ne, Ar, and Kr) has been demonstrated using the DIII-D and Tokamak Fusion Test Reactor pneumatic pellet injection systems.

1. INTRODUCTION

While great progress has been made in the area of pellet injector technology at Oak Ridge National Laboratory (ORNL) and around the world during the last decade [1–3], additional research and development are required to meet the fueling needs of the International Thermonuclear Experimental Reactor (ITER) and future fusion reactors [4,5]. The base-line ITER pellet injector concept is the centrifuge acceleration device. Centrifuge pellet injection systems are currently in operation on ASDEX-U, Tore Supra, and the Joint European Torus (JET). Present devices operate at pellet frequencies of up to 5 to 80 Hz with nominal pellet diameters of 1 to 3 mm (Fig. 1). Operation with pellets >3 mm has yet to be demonstrated with the centrifuge accelerator. When compared with light gas guns, the main advantage is that there is no driver propellant gas to handle, process, and recover. Presently, the single-stage light gas gun is the alternate/backup acceleration technique for ITER. Pneumatic injectors have demonstrated the reliability [6] approaching that needed for ITER and the larger pellet sizes (up to 8-mm diam) that may be needed for efficient and flexible operation on ITER (Fig. 1). Repetition rates of up to 10 Hz from a single gun have recently been achieved [7], and multiple guns can be operated sequentially to attain

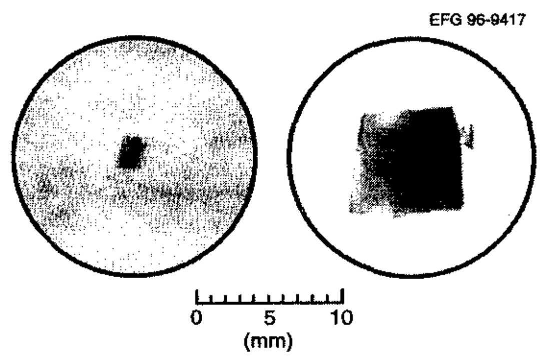

Figure 1. Photographs of small deuterium pellet (left) from centrifuge injector and large tritium pellet (right) from TPOP-II repeating pneumatic injector.

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any practical pellet frequency. While the extra gas load is a disadvantage with gas gun acceleration, the technology is readily available to handle the problem. With some of these issues unresolved and given the complementary capability of the two acceleration methods, it is planned to keep both centrifuge and pneumatic acceleration options viable for ITER. The major activities described in this paper are key steps toward the development of a prototype pellet injector for ITER.

2. IMPROVED PELLET FEED SYSTEM FOR CENTRIFUGE INJECTOR

An existing centrifuge accelerator facility at ORNL [8] provides a test bed for experimental investigations and hardware development. A standard ORNL extruder and a new pellet punch mechanism have been fitted to the centrifuge accelerator facility (Fig. 2). The new, punch-type pellet feed device is close coupled to the arbor and completely adjustable, including the capability to change pellet lengths remotely in 0.2-mm increments over the 1.6- to 2.8-mm range. The operation is illustrated in Fig. 3, which shows the extruded deuterium ice ribbon and the punch that produces the pellet and directs it toward the entrance slot of the arbor. The key component in the new feed is the pellet punch, and it can operate at frequencies of up to 20 Hz and greater. However, the limiting factor is the rate at which hydrogen ice of satisfactory quality can be provided to the cutting section. The

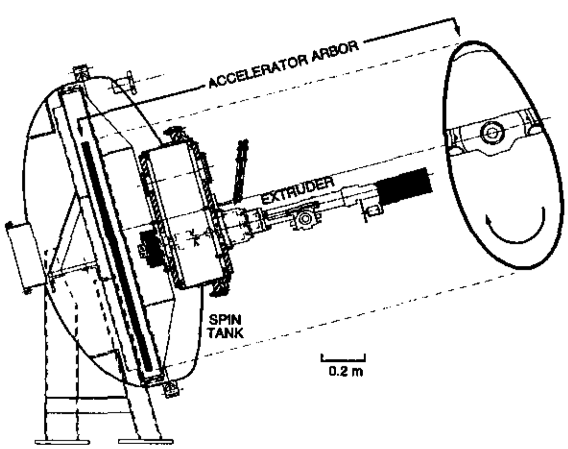

Figure 2. Side elevation view of ORNL centrifuge pellet injector with new extruder pellet feed system.

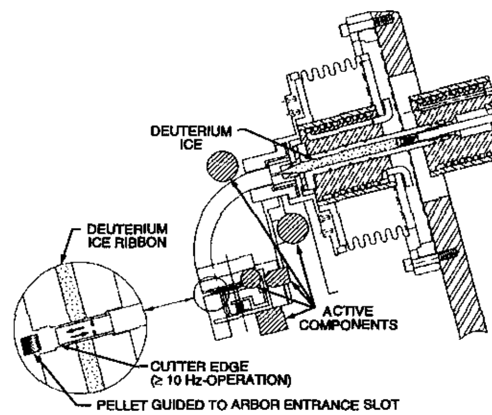

Figure 3. Close-up view of extruder feed and pellet punch components (punching of pellets is illustrated).

key advantage of the new system is the flexibility incorporated in the design of the components. Four stepping motors allow the punch to be precisely positioned relative to the arbor entrance slot. Position of individual components can be adjusted during operation to affect the actual pellet orientation relative to the arbor.

Deuterium testing is being carried out to optimize system performance and reliability with a goal of retrofitting this feed and punch system to the Tore Supra centrifuge injector previously provided by ORNL. To date, the feed system has produced ~1000 cylindrical pellets (nominally 2.3-mm diam by 1.6-mm long) at repetition rates of up to 10 Hz in a single sequence (Fig. 1). With a rotational arbor speed of 50 Hz, the pellets have been accelerated to speeds of ~450 m/s with a high fraction of intact pellets exiting the guide tube from the spin tank. While the shortest pellet length has been used in most of the tests, experiments indicate that all lengths are functional. The extrusion nozzle can be replaced for different pellet diameters, and some successful tests have been carried out with one of 3.2-mm diam.

3. STEADY-STATE EXTRUDER FEED SYSTEM

For the ITER application and future steady-state fusion reactors, a feed system capable of providing a continuous supply of frozen isotopic hydrogen is required. A straightforward concept in which multiple extruder units of identical design operate in tandem was described briefly at the 1994 symposium [9]. This approach applies a reliable ORNL technology [10,11] that has been used on many pellet injection systems. The overall reliability of this technology is indicated by the performance record of the three-barrel repeating pneumatic injector [6,12], which includes three of the standard ORNL extruder units. Since its construction and initial testing in 1986, this system operated on JET from 1987 to 1992 and on DIII-D since 1994. Over a period of 10 years, the performance and reliability of the extruders have been outstanding; the three extruders have processed an estimated 5 to 10 kg of deuterium ice in that time period without any significant problems or mechanical failures.

A prototype consisting of three extruder units is under construction and should be capable of demonstrating steady-state operation at frequencies of up to several hertz (or greater) and pellet sizes in the 2- to 8-mm range. Instead of using the standard ORNL extruder design for this application, units have been fabricated in which the volume of ice is doubled, which gives ~8 cm^3 of solid ice available per unit (Fig. 4). The only significant change is that the inner diameter of the reservoirs and interconnecting tubing has been increased from 1.0 to 1.4 cm. A single extruder unit of the new design has been set up and tested in a vacuum test chamber with deuterium, and in the initial experiments standard operation was observed. A transition section that accepts the three individual feeds and outputs a single feed is the key new component that must be developed for this concept. This component will allow a smooth transition when switching between extruder feeds.

A control scheme that could easily handle up to six extruder units has already been developed and makes use of a personal computer and the graphical interface/control software LabView.

4. TRITIUM EXTRUDER TECHNOLOGY

The hardware and plans for the second phase of the Tritium-Proof-of-Principle (TPOP-II) experiment were described briefly at the 1994 Symposium [9].

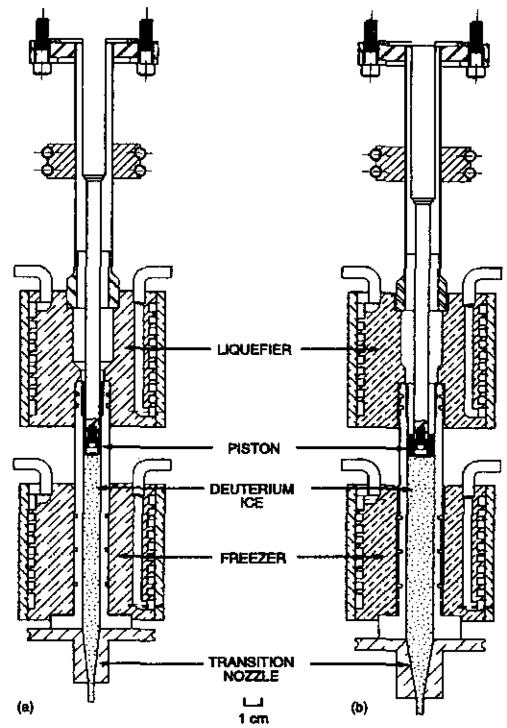

Figure 4. Designs of (a) standard ORNL extruder and (b) new version with twice the ice volume.

The repeating, single-stage pneumatic injector has a piston-driven mechanical extruder and is designed to extrude and accelerate isotopic hydrogen pellets sized for the ITER device. In initial tests with deuterium feed at ORNL, up to 13 pellets were extruded at rates up to 1 Hz and accelerated to speeds of ~1 km/s (Fig. 5). The pellets, typically 7.4-mm diam and 7 to 11 mm in length, are the largest pellets produced in the fusion program to date. These pellets represent about a 5 to 10% density perturbation to ITER-sized plasmas. In a series of successful experiments with TPOP-II at Los Alamos National Laboratory, solid tritium has been extruded, and the equipment has been used to

Figure 5. Photographs of a sequence of deuterium pellets from TPOP-II injector (8-mm bore); pellets fired at 0.5 Hz and ~1 km/s.

produce repetitive tritium (Fig. 1) and deuterium-tritium (D-T) pellets [13].

5. OTHER ACTIVITIES

5.1. High-Speed Pellet Injector Research

An experiment to demonstrate the feasibility of a repetitive pneumatic pellet injector at 1 Hz in the velocity range of 2 to 3 km/s was carried out in a collaboration between ORNL and ENEA Frascati, in the context of a cooperative agreement between the U.S. Department of Energy and EURATOM-ENEA Association. The experiments [14] have been performed on an ORNL test facility that is equipped with an extruder feed system/repeating pneumatic injector, and ENEA-Frascati provided the small two-stage light gas gun system. The latest series of experiments, the third joint campaign in 3 years, was completed in May 1995. Both the operation and performance of the equipment were improved, and the original objectives of the collaboration were met. Figure 6 shows the results of many single pellet and repetitive pellet sequences with deuterium ice and hydrogen propellant; muzzle velocities of 2.5 km/s have been attained at repetiton rates of 1 Hz. Based on the excellent results, some future follow-up work is planned.

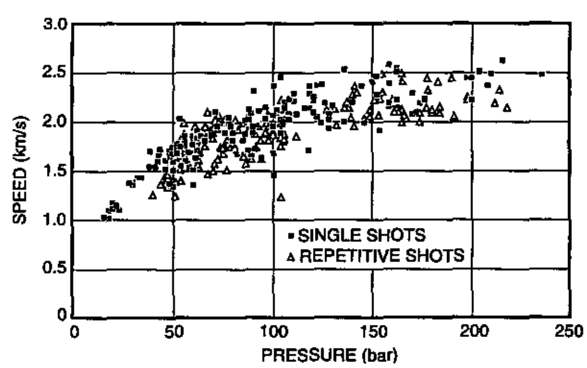

Figure 6. Muzzle velocity of deuterium pellets as function of peak breech pressure for repeating two-stage pneumatic injector (2.7-mm bore).

5.2. Impurity Pellets

The production of impurity pellets (Ne, Ar, and Kr) has been demonstrated using ORNL pneumatic pellet injection systems. Initially, a repeating pneumatic injector in the laboratory was used to demonstrate the extrusion of neon ice and acceleration of neon pellets with both single-stage and two-stage light gas guns (speeds of up to ~700 and 1740 m/s, respectively) [15]. The production of impurity pellets has since been demonstrated using the DIII-D and TFTR pneumatic pellet injection systems; such pellets have been used in experiments to optimize edge plasma/divertor conditions and evaluate rapid plasma shutdown capability for mitigation of the effects of a major plasma disruption.

REFERENCES

1. S. L. Milora, J. Fusion Energy 1 (1981) 15.
2. S. K. Combs, Rev. Sci. Instrum. 64 (1993) 1679.
3. S. L. Milora, W. A. Houlberg, L. L. Lengyel, and V. Mertens, Nuclear Fusion 35 (1995) 657.
4. M. J. Gouge et al., Fusion Eng. Des. 19 (1992) 53.
5. M. J. Gouge et al., Fusion Tech. 28 (1995) 1644.
6. S. K. Combs et al., Rev. Sci. Instrum. 60 (1989) 2697.
7. S. K. Combs, C. R. Foust, and S. L. Milora, Rev. Sci. Instrum. 66 (1995) 2736.
8. C. A. Foster et al., in: Fusion Technology 1992: Proc. 17th Symposium, Rome, 14–18 September 1992 (North-Holland, Amsterdam), Vol. I, p. 496.
9. S. K. Combs et al., in: Fusion Technology 1994, Proc. 18th Symposium, Karlsruhe, Germany, 22–26 August 1994 (North-Holland, Amsterdam), Vol. I, p. 637.
10. C. A. Foster, J. Vac. Sci. Technol. A1 (1983) 952.
11. S. K. Combs et al., Rev. Sci. Instrum. 56 (1985) 1173.
12. S. K. Combs et al., J. Vac. Sci. Technol. A6(3) (1988) 1901.
13. P. W. Fisher and M. J. Gouge, Fusion Tech. 28 (1995) 603.
14. A. Frattolillo et al., Rev. Sci. Instrum. 67 (1996) 1834.
15. S. K. Combs et al., Rev. Sci. Instrum. 67 (1996) 837.