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# Recent High-Speed Ballistics Experiments at ORNL*

S. K. Combs, M. J. Gouge, L. R. Baylor, P. W. Fisher, C. A. Foster,
C. R. Foust, S. L. Milora, and A. L. Qualls

Oak Ridge National Laboratory
P.O. Box 2009
Oak Ridge, TN 37831-8071
USA

Oak Ridge National Laboratory (ORNL) has been developing pellet injectors for plasma fueling experiments on magnetic confinement devices for almost 20 years. With these devices, pellets (1 to 8 mm in diameter) composed of hydrogen isotopes are formed (at temperatures <20 K) and typically accelerated to speeds of ~1.0 to 2.0 km/s for injection into plasmas of experimental fusion devices. A variety of pellet injector designs have been developed at ORNL, including repeating pneumatic injectors (single- and multiple-barrel light gas guns) that can inject up to hundreds of pellets for long-pulse plasma operation. The repeating pneumatic injectors are of particular importance because long-pulse fueling is required for present large experimental fusion devices, with steady-state operation the objective for future fusion reactors. In this paper, recent advancements in the development of repeating pneumatic injectors are described, including (1) a small-bore (1.8-mm), high-firing-rate (10-Hz) version of a single-stage light gas gun; (2) a repeating single-stage light gas gun for 8-mm-diam tritium pellets; (3) a repeating two-stage light gas gun for operation at higher pellet velocities; and (4) a steady-state hydrogen extruder feed system.



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## DISCLAIMER

## INTRODUCTION

Pellet injection represents a unique application of high-speed acceleration techniques because of the properties of the hydrogen ice that constitutes the pellets. Some important properties of the hydrogen isotopes ($H_2$, $D_2$, and $T_2$) for pellet injection are shown in Table I. Gouge[1] briefly discussed these properties relative to pellet acceleration at last year's Aeroballistic Range Association (ARA) Meeting; this subject, as well as other general information on pellet injection, is covered in some detail in the review papers by Combs[2] and Milora.[3] The basic single-stage light gas has been used with great success over the past decade in accelerating single and repetitive hydrogen pellets of diameter from 1 to 6 mm. In general, the reliability of repeating single-stage injectors is approaching the level required for reactor applications (e.g., Ref. 4). Recent advancements in the repeating pneumatic injector technology at the Oak Ridge National Laboratory (ORNL) are described here.

**Table I. Properties of hydrogen isotopes**

| Isotope | Molecular weight (g/mol) | Critical-point temperature (K) | Triple-point temperature (K) | Triple-point pressure (bar) | Solid parameters | |
|---|---|---|---|---|---|---|
| | | | | | Density ($g/cm^3$) | Ultimate yield strength[a] (bar) |
| $H_2$ | 2.016 | 33.2 | 13.9 | 0.072 | 0.087 | 0.7–3.5[b] |
| $D_2$ | 4.028 | 38.3 | 18.7 | 0.172 | 0.20 | 2.1–5.3[c] |
| $T_2$ | 6.032 | 40.4 | 20.6 | 0.216 | 0.32 | 10.3,[d] 11.7[e] |

[a]Reported strengths for hydrogen and deuterium at 8 K are 2.4 and 4.4 bar, respectively. Tritium strength is estimated from breakaway pressures for tritium pellets in pipe-gun experiments.
[b]For temperatures ranging from 12.0 to 4.2 K.
[c]For temperatures ranging from 16.4 to 4.2 K.
[d]At 8.0 K (average of two data points).
[e]At 9.0 K.

## 1. SMALL-BORE, HIGH-FIRING-RATE INJECTOR

The three-barrel repeating pneumatic injector (Fig. 1) that was previously used on the Joint European Torus (JET) [4–6] from 1987 to 1992 has been modified and installed on the DIII-D tokamak. 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. The operation of a cryogenic extruder/gun unit is depicted in Fig. 2. 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 diagnostics required for measuring pellet parameters. The installation on DIII-D is shown schematically in Fig. 3. The three single-stage guns have been qualified with helium propellant and deuterium pellets at

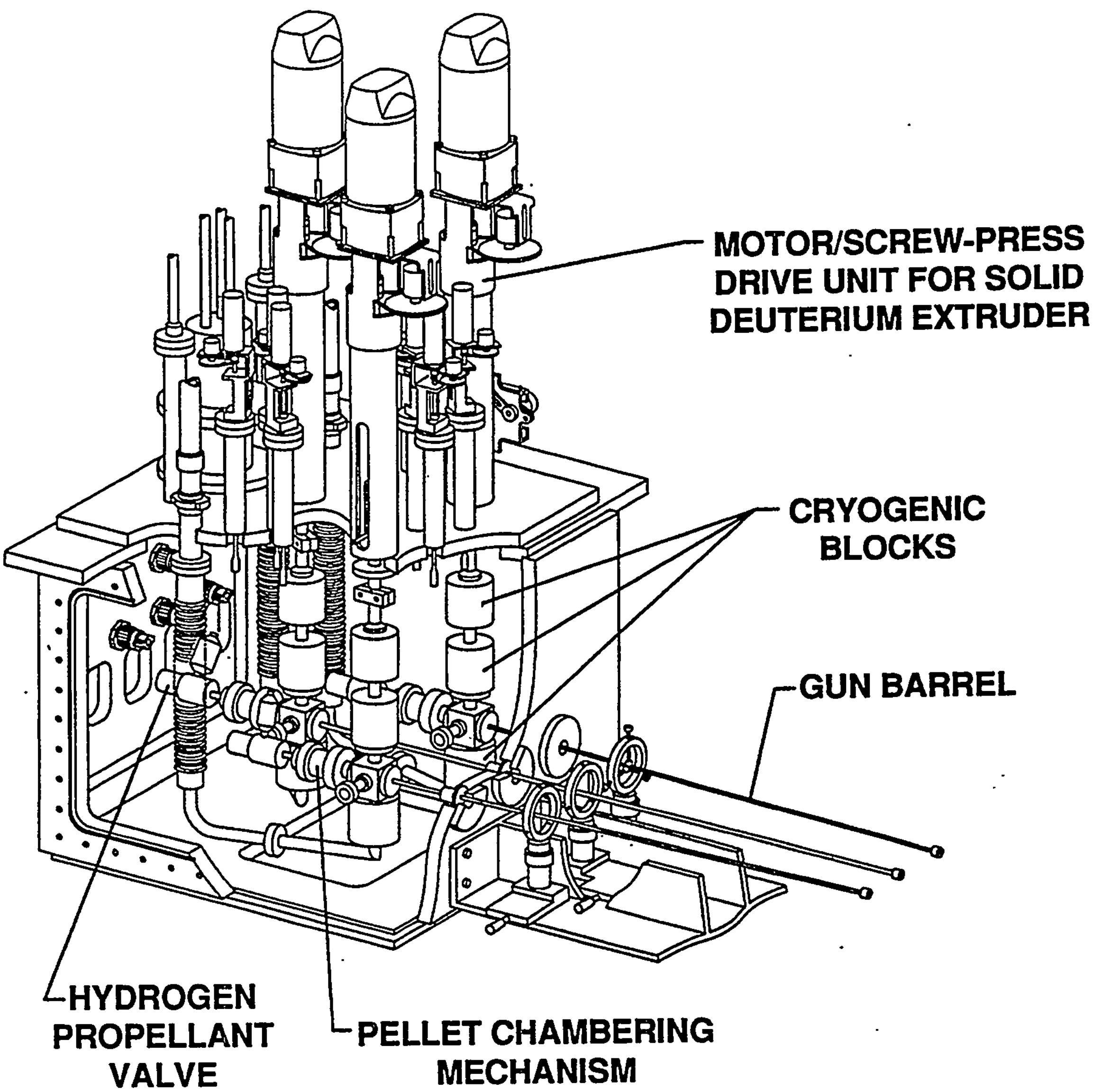


Fig. 1 Three-barrel repeating pneumatic pellet injector

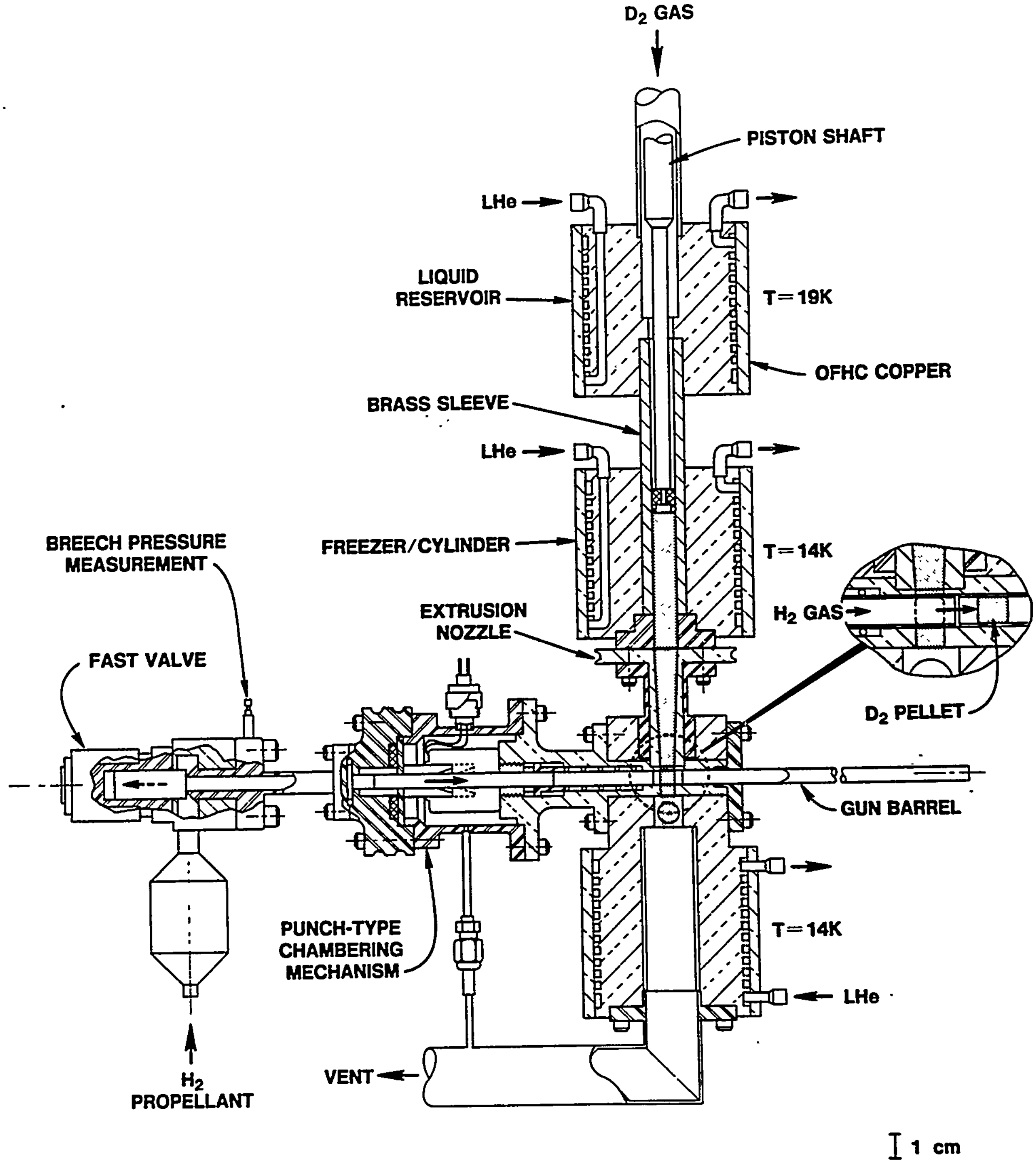


Fig. 2. Schematic of cryogenic extruder and gun assembly for repeating pneumatic injector

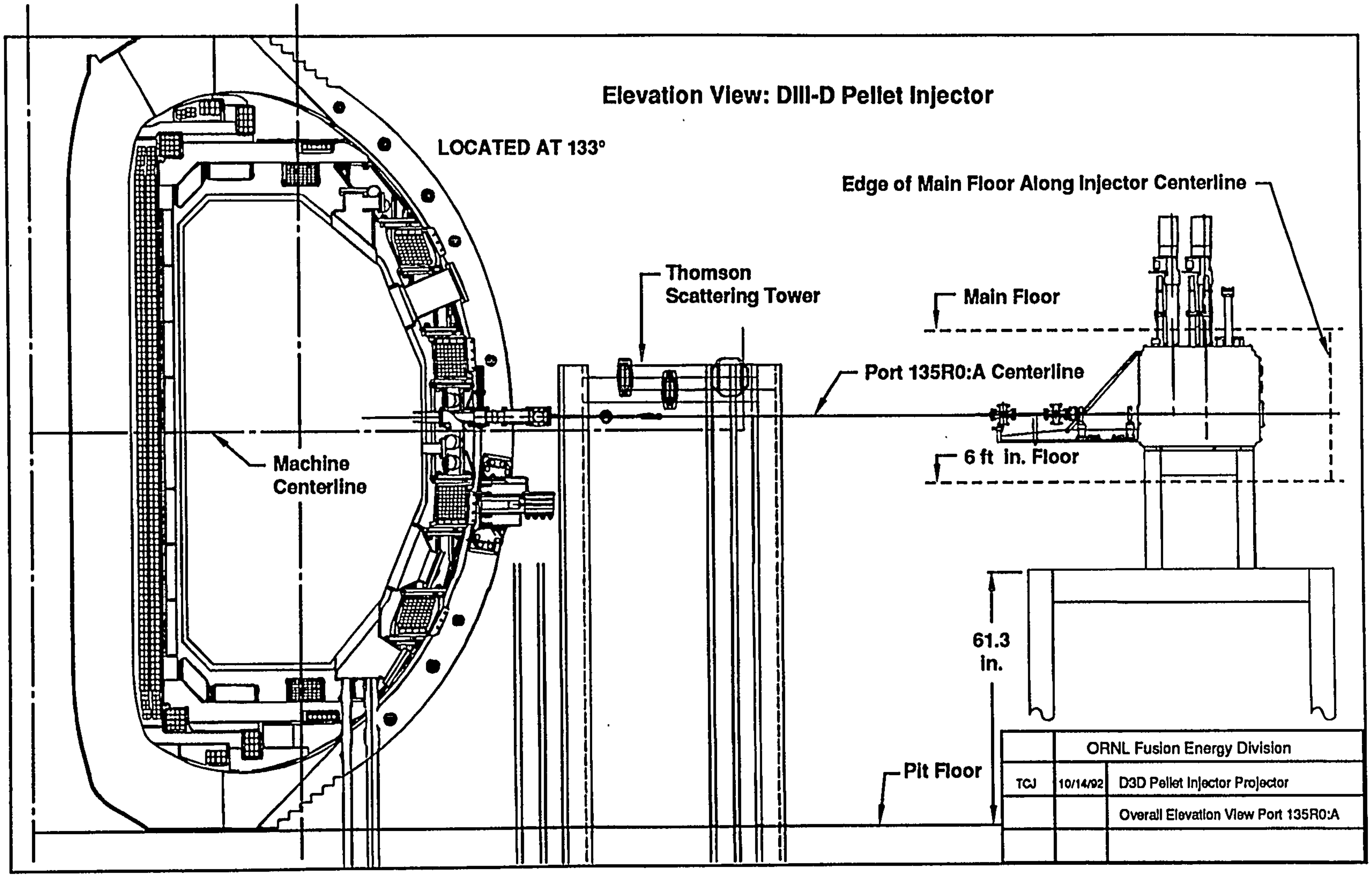


Fig. 3. Schematic of three-barrel injector installation on DIII-D

velocities of ~1 km/s. The small gun was operated at up to 10 Hz for a pulse length of 15 s (Fig. 4). 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 $3 \times 10^{20}$, $9 \times 10^{20}$, and $3 \times 10^{21}$ $D^0$ 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.

## 2. TRITIUM PROOF-OF-PRINCIPLE INJECTOR, PHASE II

As part of the International Thermonuclear Engineering Reactor (ITER)[7] plasma fueling development program, ORNL has fabricated a pellet injection system to test the mechanical and thermal properties of extruded tritium. This repeating, single-stage, pneumatic injector, called tritium-proof-of-principle, Phase II (TPOP-II) pellet injector, has a piston-driven mechanical extruder and is designed to extrude hydrogen pellets sized for the ITER device. The TPOP-II program has the following development goals: (1) evaluate the feasibility of extruding tritium and deuterium-tritium (D-T) mixtures for use in future pellet injection systems; (2) determine the mechanical and thermal properties of tritium and D-T extrusions; (3) integrate, test, and evaluate the extruder in a repeating, single-stage light gas gun sized for the ITER application (pellet diameter ~ 7 to 8 mm); (4) evaluate options for recycling propellant and extruder exhaust gas; and (5) evaluate operation and reliability of ITER prototypical fueling systems in an environment of significant tritium inventory requiring secondary and room containment systems.

An earlier ORNL tritium pellet injector experiment[8,9] (1988–89) at the Tritium Systems Test Assembly (TSTA) at Los Alamos National Laboratory established the basic scientific feasibility of production and pneumatic acceleration of tritium pellets for fueling future fusion reactors. This earlier experiment, TPOP-I, used a single-stage light gas gun in which single 4-mm-diam pellets were formed in-situ in the barrel and accelerated with high-pressure gas. Over 100 kCi of tritium was processed through the experiment without incident. In Phase II of this experiment, the pipe gun has been replaced with a repeating pneumatic pellet injector similar to the design of the three-barrel injector used on JET and recently installed on DIII-D. A schematic of the TPOP-II equipment as it will appear during operations at TSTA is shown in Fig. 5. The single-stage repeating pneumatic injector, guard vacuum enclosure, vacuum injection line, and gas handling system are housed in a lexan/aluminum glovebox for secondary tritium containment. This is the same glovebox that was used in the original TPOP experiment. A glovebox extension has been added above one end of the TPOP glovebox to contain the tritium extruder, which is too tall to fit in the original glovebox. Below the glovebox is a ~600-L ballast volume to maintain pressure in the injection line below 30 mbar during pellet production runs. In addition to the standard components shown in Fig. 2, this injector includes a $^3He$ separator that removes the $^3He$ byproduct from the tritium radioactive decay from the incoming tritium supply gas stream. With very few exceptions, tritium-wetted surfaces are all metal (usually stainless steel). All interfaces between the glovebox and TSTA (tritium, deuterium, nitrogen, helium, electrical,


Fig. 4. Photographs of a 150-pellet sequence from the repeating pneumatic pellet injector; deuterium pellets of nominal 1.8-mm diameter are shown exiting a guide tube (5.3-mm ID by 9.5-mm OD), and the gun operated at a firing rate of 10 Hz and pellet velocities of ~1 km/s: (a) pellets 1–72 and (b) pellets 73–150

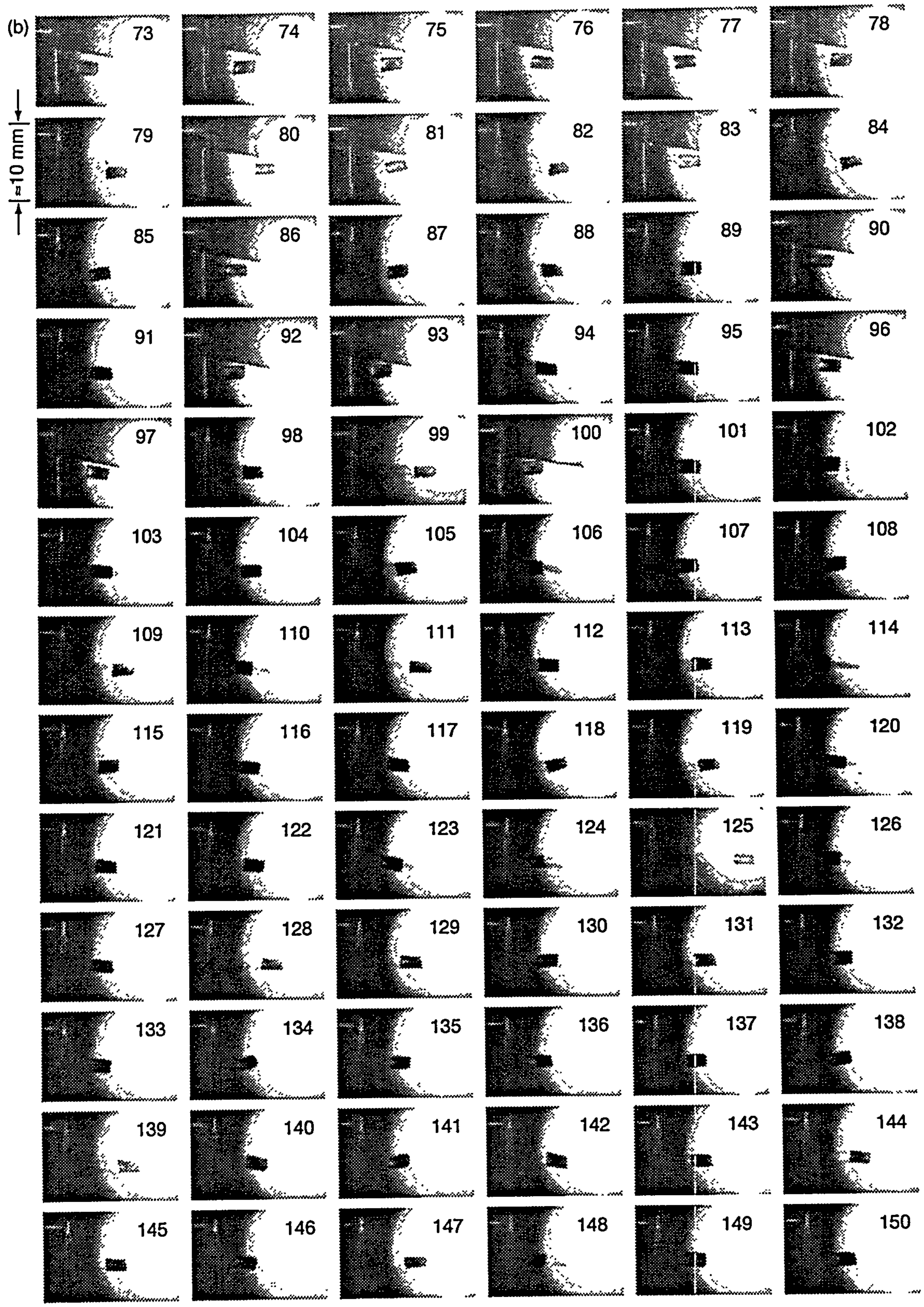


Fig. 4. (Continued)

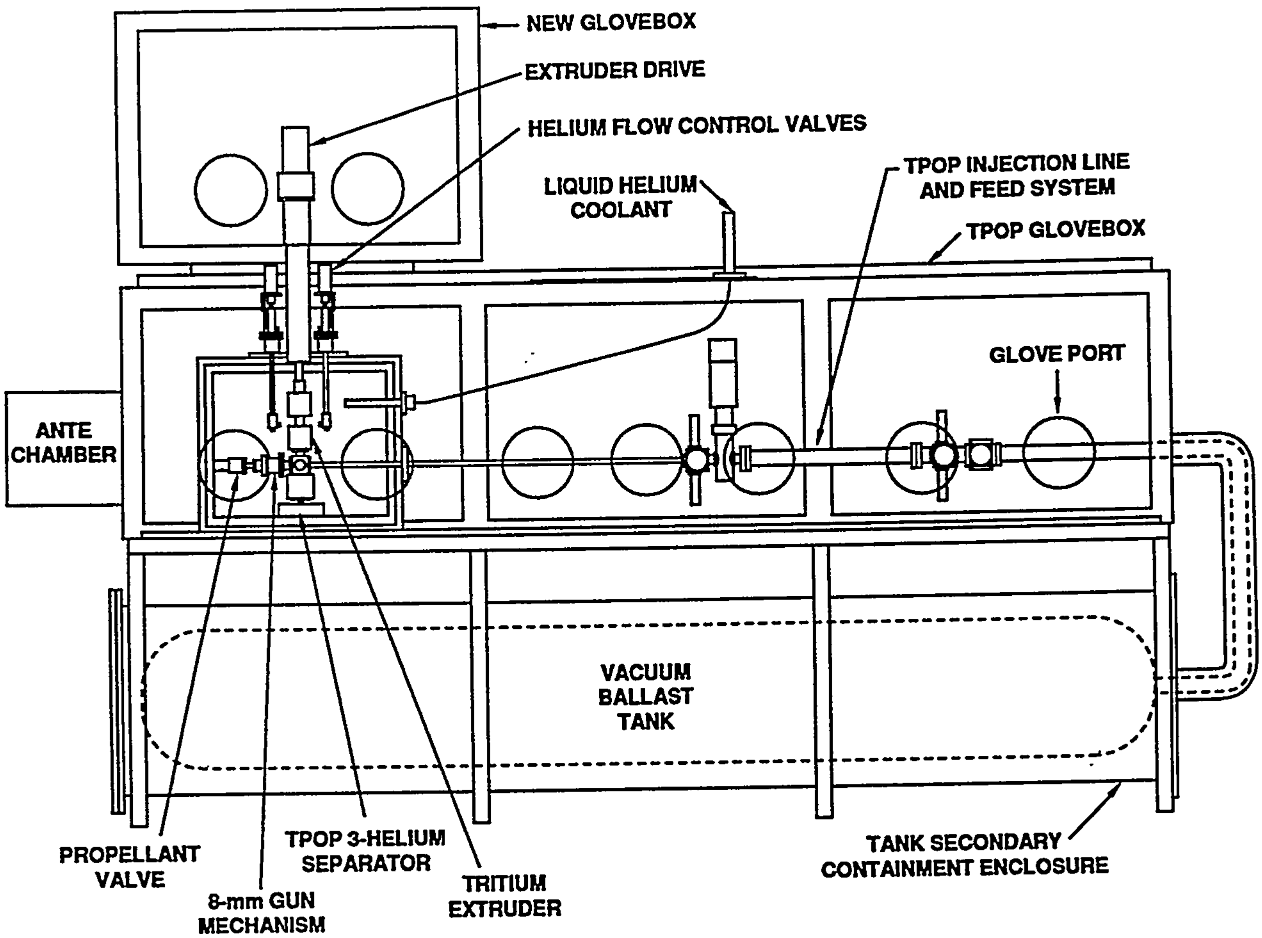


Fig. 5. Schematic of TPOP -II pellet injector (repeating single-stage light gas gun in glovebox for tritium pellet operations)

control, vacuum connections, etc.) are through panels in the top of the glovebox. High-speed data acquisition and fast control functions will be accomplished through a MicroVAX II computer and CAMAC digitizing and timing modules.

Much larger D-T throughputs are anticipated for TPOP-II than were required in the earlier TPOP experiments; the baseline approach will include recycling of extruder and injection line exhaust gas streams to maximize experimental output within TSTA constraints of tritium supply rate and D-T gas storage. It is planned to use deuterium propellant gas at TSTA that will mix with the D-T pellet exhaust from the injection line to allow subsequent tests with leaner (in tritium) D-T feed.

In initial tests with deuterium feed at ORNL, up to seven pellets have been extruded at rates up to 0.5 Hz and accelerated to speeds of order 1.0 to 1.1 km/s, using hydrogen propellant gas at a supply pressure of 65 bar. The pellets (one of which is shown in Fig. 6) are typically 7.4 mm in diameter and 11 mm in length and are the largest cryogenic pellets produced by the fusion program to date. This pellet represents about a 10% density perturbation to ITER. Hydrogen pellets will be used in ITER to sustain the fusion power in the plasma core and may be crucial in reducing first-wall tritium inventories by a process called isotopic fueling in which tritium-rich pellets fuel the burning plasma core and deuterium gas fuels the edge. TPOP-II will continue deuterium testing at ORNL for the next several months and then will be installed at TSTA for testing with D-T and tritium feed in 1995.

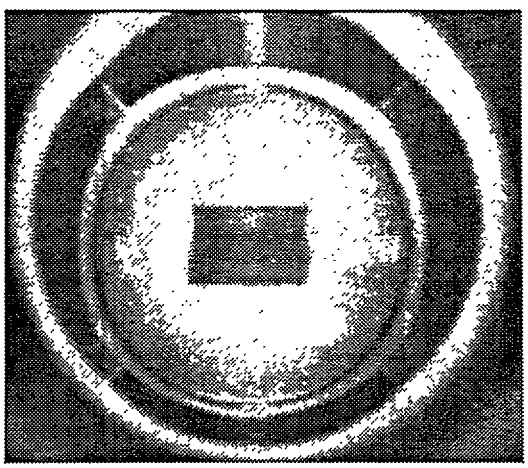

Fig. 6. Photograph of 7.4-mm-diam by 11-mm-long deuterium pellet at a speed of ~1.1 km/s

## 3. REPEATING TWO-STAGE LIGHT GAS GUN DEVELOPMENT

At the 1991 ARA Meeting, the development of a repetitive two-stage light gas gun was described[10] with the objective of demonstrating the feasibility of using the concept for steady-state fueling. In that study, 4-mm-diam plastic pellets were fired at 1 Hz and 3 km/s, using a standard two-stage configuration applicable for pellet injection (for pulse lengths of 10 s, limited by the data acquisition system). The second phase of the high-speed research[11–13] involves a collaboration between ORNL and Ente per Le Nuove Tecnologie L'Energia E L'Ambiente (ENEA)-Frascati in the development of a repeating two-stage light gas gun based on an extrusion-type pellet feed system. This activity is being carried out in the framework of a collaborative agreement between the U.S. Department of Energy and the European Atomic Energy Community. In the ORNL/Frascati collaboration, an ORNL deuterium extruder (equipped with pellet-chambering mechanism and gun barrel) and a small ENEA-Frascati two-stage gun have been combined to demonstrate and study repetitive operation with bare deuterium ice. A schematic of the repeating two-stage injector is shown in Fig. 7. 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. 8; 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 (1) prevent the pellets from accelerating until the pressure burst from the two-stage gun driver is delivered and (2) 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. 8, 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).

## 4. STEADY-STATE EXTRUDER FEED SYSTEM

For fueling of 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 uses a reliable ORNL technology and is illustrated in Fig. 9. 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 $cm^3$. This equipment should be adequate to demonstrate steady-state feed rates required for pellet injector

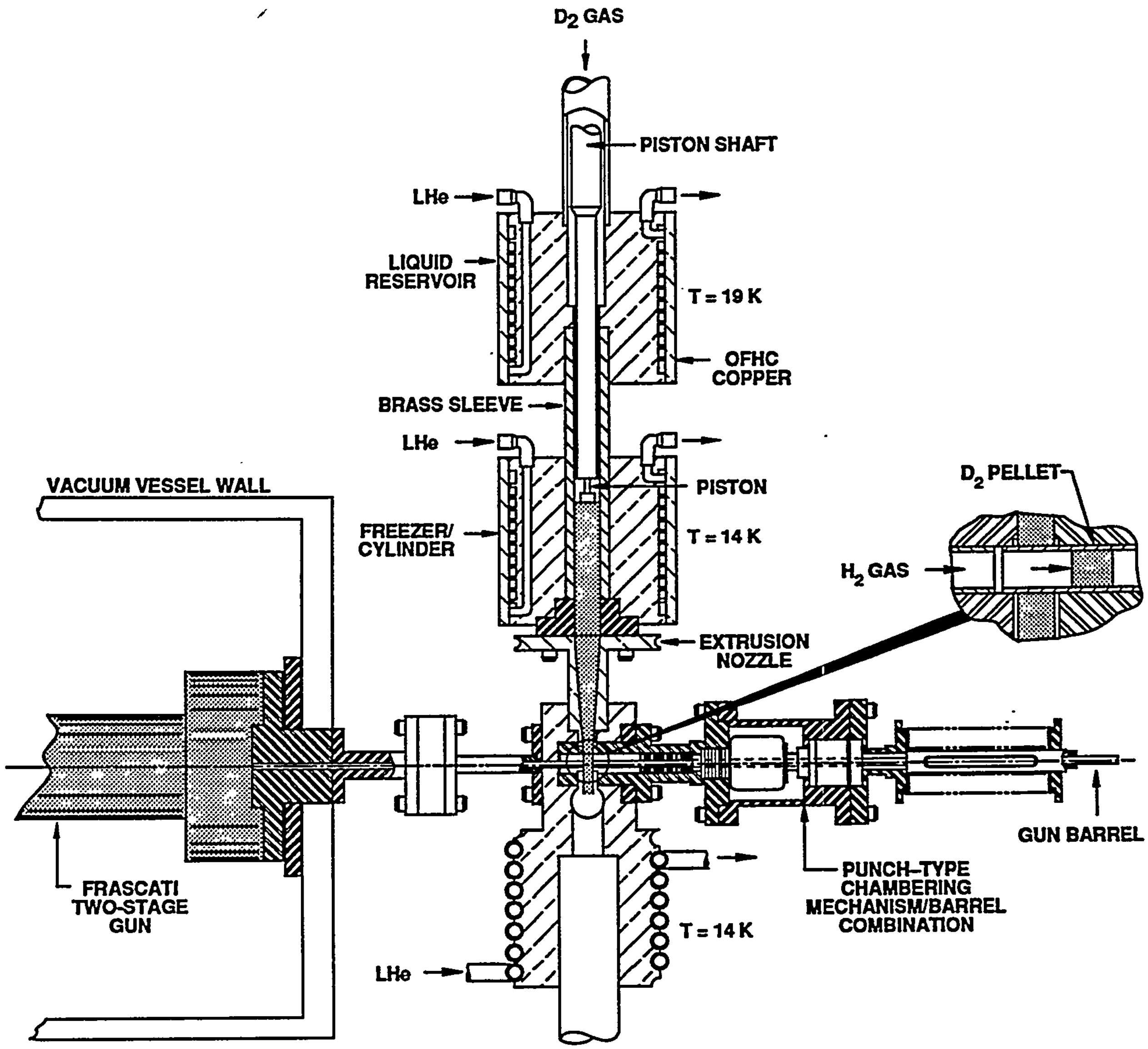


Fig. 7. Schematic of ORNL/Frascati repeating two-stage light gas gun

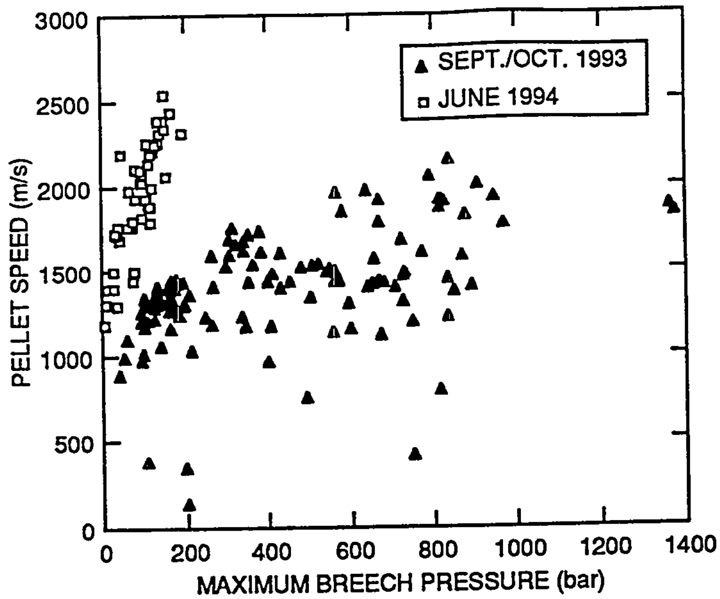


Fig. 8. Experimental data from repeating two-stage light gas gun (2.7-mm bore); pellet muzzle velocity as a function of peak breech pressure

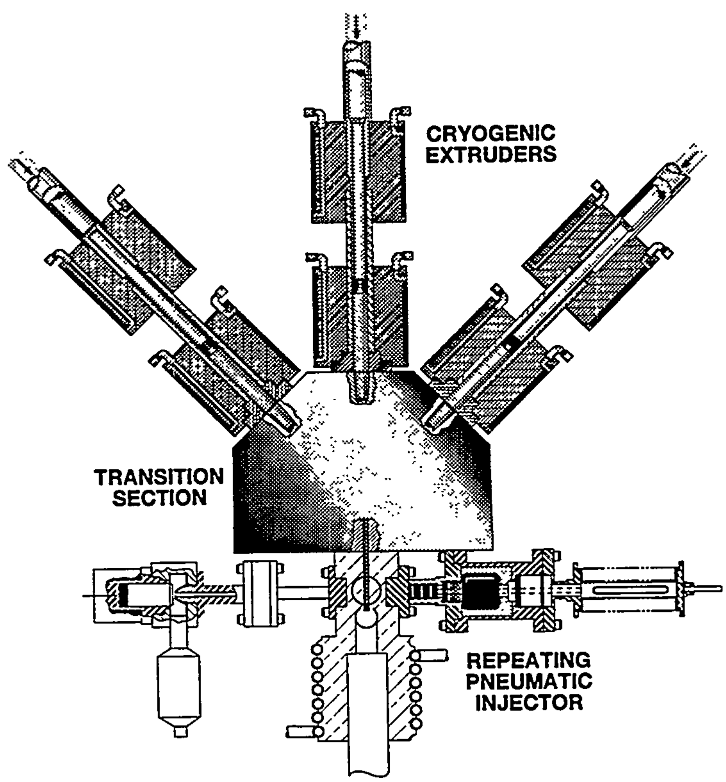


Fig. 9. Schematic of steady-state extruder feed system; three standard extruders operate in tandem to provide a continuous source of frozen hydrogen

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 to increase the effective fueling duration.

## REFERENCES


1. M. J. Gouge et al., "Ballistic Considerations for Small-Caliber, Low-Density Projectiles," presented at the 44th Aeroballistic Range Association Meeting, Munich, Germany, September 13–17, 1993.
2. S. K. Combs, *Rev. Sci. Instrum.* **67** (1993), 1679.
3. S. L. Milora, *J. Vac. Sci. Technol.* **A5** (1989), 325.
4. S. K. Combs et al., *Rev. Sci. Instrum.* **60** (1989), 2697.
5. 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.
6. S. K. Combs et al., *J. Vac. Sci. Technol.* **A6(3)** (1988), 1901.
7. M. J. Gouge et al., *Fus. Eng. Des.* **19(1)**, (July 1992) 53–72 .
8. P. W. Fisher et al., *J. Vac. Sci. Technol.* **A7** (1989), 938.
9. P. W. Fisher, *Fus. Tech.* **21** (1992), 794.
10. S. K. Combs et al., "Repetitive Small-Bore Two-Stage Light Gas Gun," presented at the 42nd Aeroballistic Range Association Meeting, Gleneg, South Australia, October 22–25, 1991.
11. A. Frattolillo et al., in: *Fus. Tech. 1992: Proc. 17th Symposium, Rome, 14–18 September 1992* (North-Holland, Amsterdam), Vol. I, p. 500.
12. 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.
13. S. K. Combs et al., "Pellet Injector Research and Development at ORNL," presented at 18th Symposium on Fusion Technology, 22–26 August 1994, Karlsruhe, Germany (proceedings to be published).