CONF-9010227--2

DE91 002635

Fueling of Magnetically Confined Plasmas by Single- and Two-Stage Repeating Pneumatic Pellet Injectors

M. J. Gouge, S. K. Combs, C. R. Foust, and S. L. Milora

Oak Ridge National Laboratory, P.O. Box 2009, Oak Ridge, Tennessee, 37831-8071, United States of America

Advanced plasma fueling systems for magnetic fusion confinement experiments are under development at Oak Ridge National Laboratory (ORNL). The general approach is that of producing and accelerating frozen hydrogenic pellets to speeds in the kilometer-per-second range using single shot and repetitive pneumatic (light-gas gun) pellet injectors. The millimeter-to-centimeter size pellets enter the plasma and continuously ablate because of the plasma electron heat flux, depositing fuel atoms along the pellet trajectory. This fueling method allows direct fueling in the interior of the hot plasma and is more efficient than the alternative method of injecting room temperature fuel gas at the wall of the plasma vacuum chamber. Single-stage pneumatic injectors based on the light-gas gun concept have provided hydrogenic fuel pellets in the speed range of 1-2 km/s in single-shot injector designs. Repetition rates up to 5 Hz have been demonstrated in repetitive injector designs. Future fusion reactor-scale devices may need higher pellet velocities because of the larger plasma size and higher plasma temperatures. Repetitive two-stage pneumatic injectors are under development at ORNL to provide long-pulse plasma fueling in the 3-5 km/s speed range. Recently, a repeating, two-stage light-gas gun achieved repetitive operation at 1 Hz with speeds in the range of 2-3 km/s.

I. INTRODUCTION AND FUELING CRITERIA

Most of the material in this section is from a recent review article [1] on the technology of hydrogen pellet injection. The first and most widely used method of fueling magnetically confined plasmas is by introducing a controlled puff of room temperature gas beyond the plasma edge using fast piezoelectric valves. This technology is well developed, and its inherent simplicity has lead to widespread use, although it has the limitation of allowing the fuel source at only one location. In the last decade, high-speed injection of frozen macroscopic (millimeter size) pellets of the isotopes of hydrogen has become the leading technology for fueling magnetically

* Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems Inc.

confined plasmas for controlled thermonuclear fusion research. The process of plasma fueling by this approach has been demonstrated conclusively on a number of toroidal magnetic confinement configurations, including tokamaks, stellarators, and reversed field pinches. Other related effects, such as beneficial improvements in energy confinement properties which have also been observed experimentally on several confinement devices, are generally associated with modifications in the plasma density and/or temperature radial profiles as a result of the fueling or particle deposition profiles. Peaking of the plasma density profile is accomplished in present experiments as the fuel pellet traveling at a high speed (>1 km/s) penetrates the plasma column and deposits fuel preferentially in the hotter, denser central plasma regions where the evaporation rate of the hydrogenic ice is highest.

The pellet fueling requirements of present and future magnetic confinement devices depend upon the specific plasma parameters (the electron temperature and density, which govern the evaporation rate at the pellet surface) and the device physical and operating characteristics (the experiment pulse length, the plasma volume, the type of plasma limiter, etc.). With respect to pellet speed, it is desirable that the pellet have sufficient speed to penetrate a significant fraction of the distance to the magnetic axis (center of the plasma). This requirement is linked to the evaporation rate of hydrogenic ice in a magnetized plasma.

Several theoretical models have been proposed to describe this process; the model that is most often found to be in agreement with the experimental measurements of pellet penetration is the Neutral Gas Shielding Model. According to this model, the surface of the pellet reacts to the intense plasma heat flux by expelling molecular hydrogen gas at a sufficiently high rate to partially shield the surface from the external plasma heat flux (see Figure 1). The ablation rate is most sensitive to the electron temperature, and higher temperatures imply shorter pellet lifetimes and consequently higher pellet speeds to penetrate a given plasma size. This can be offset by using pellets of larger size; this technique is frequently used to obtain central penetration in higher temperature laboratory plasmas. However, large pellets impose large perturbations on the plasma density, and, although increments in excess of 100% have been demonstrated, 20 to 30% global perturbations are more desirable from plasma stability considerations. The pellet size follows from this increment, the known plasma volume, and the desired density level. For a hypothetical fusion reactor operating at an average electron density of 1.4×10^{20} m^{-3} and a central temperature of 20 keV, a 30% fuel charge would correspond to a pellet radius of 4 mm. A tritium pellet of this size that penetrates to the center of such a plasma would evaporate in about 60 ms; consequently, pellet speeds in the range of 20 km/s would be required to penetrate a 1.2-m minor radius discharge. In large laboratory plasmas with present state-of-the-art injectors operating at ~1.5 km/s, central penetration typically occurs for peak temperatures on the order of 2.5 keV. Although the Neutral Gas Shielding Model has been benchmarked in this lower temperature range, velocity projections based on extrapolation to the 20-keV reactor regimes should be considered only as approximate.

Other shielding mechanisms, such as the development of a region of high-pressure plasma near the pellet surface which diverts magnetic field lines away from the pellet, are predicted to increase the pellet lifetime by as much as 30% and thereby reduce the velocity requirement proportionately. At this point, it is not clear that pellet penetration to or near the magnetic axis is necessary or even desirable; and pellet speeds in the few kilometer-per-second range may be sufficient for providing plasma fueling beyond the plasma edge region.

The remaining fueling requirement is the pellet injection frequency, which is related to the rate at which the plasma must be replenished; this depends on the intrinsic plasma particle replacement time in the plasma and the net plasma exhaust rate. The former is roughly proportional to the plasma volume, and the latter is dependent on the plasma limiter configuration (material limiter, pump limiter, magnetic divertor). Small plasma devices with plasma volumes in the range of a few cubic meters typically require pellet injection frequencies as high as 10-30 Hz to maintain the plasma density at steady state levels. Larger devices such as the Joint European Torus (JET) whose plasma volume exceeds 100 m^3, require injection frequencies in the 1-5 Hz range; and injection rates in the range of one to several hertz will likely satisfy the requirements for future fusion reactors.

II. SINGLE -STAGE LIGHT-GAS GUNS

A gas gun operates on the principle that a projectile confined laterally in a tube or gun barrel will experience an acceleration when subjected to an applied pressure imbalance. When the fluid that supplies the driving force is a compressible gas, the projectile can be accelerated to high speed as the internal energy of the gas is converted in the expansion process to kinetic energy of the projectile.

The performance of the basic single-stage light-gas gun can be modeled analytically [2] by assuming that the pellet accelerates in an infinite tube of constant cross section. The motion of the pellet is then governed by the propagation of simple rarefaction waves into the high-pressure medium. Neglecting nonideal effects such as friction at the projectile-barrel interface, heat transfer, and gas viscosity, the pellet velocity U(t) at time t after the sudden application of the gas at pressure P_0 is given by

$$U(t) = \frac{2C_0}{\gamma - 1}\left\{1 - \left[1 + \frac{(\gamma+1)\,A_p}{2M\,C_0}\,P_0\,t\right]^{-(\gamma-1)/(\gamma+1)}\right\},$$

where C_0 is the propellant gas sound speed, γ is the ratio of specific heats, M is the projectile mass, and A_p is the projectile base area. This result illustrates several important points concerning the acceleration of the hydrogen isotopes. First, high performance is possible with relatively low accelerating forces (pressures) since the projectile mass per unit area is small. Secondly, a high sound speed is required for high-speed operation; this favors low-molecular-weight gases and high temperature. A study of the effect on performance due to different mass and temperature propellant gases was performed by Schuresko et al. [3], who found that warm hydrogen at 400 K provided about a 30% improvement relative to room temperature helium. Other studies of propellant gas heating have not been conclusive. The effect of pellet mass was studied by Combs et al. [4]. The results of this study are that the performance with deuterium pellets is reduced by about 15% relative to the less dense hydrogen pellets. Recent experiments with tritium pellets performed by Fisher et al. [5] show a similar reduction relative to the deuterium pellet data (see Figure 2).

The data of Figure 2 and results from other studies [6] generally agree with the predictions of the ideal gun theory presented above to within 80% [7]. The saturation in velocity shown in the figure which occurs at about 2 km/s is due to the fact that the pellet is traveling at speeds greater than the local sound speed. At velocities above $\sim 1.5\ C_0$, pressure pulses emanating from the breech of the gun cannot propagate quickly enough in the cold gas that fills the barrel; consequently, the pressure at the base of the pellet, which is responsible for the acceleration, is reduced substantially below the breech pressure P_0. For this reason, single-stage light-gas guns operating with hydrogen pellets are generally limited to pellet speeds slightly in excess of 2 km/s. As described in the next section, this limitation is overcome in two-stage light-gas guns, where higher accelerations are maintained by increasing the temperature of the propellant by rapid adiabatic compression of the gas at the breech.

An analysis of the performance of single-stage light-gas guns has been carried out using two methods:

1. Numerical calculations using a Lagrangian finite-difference code [7].
2. Generic light-gas gun curves developed by A. E. Seigel [8].

The generic, dimensionless curves developed by Seigel were developed using both the method of characteristics and an early Lagrangian code with no losses. A more recent Lagrangian finite-difference code [9] has the following capabilities for modelling either single-stage or two-stage light-gas guns:

- Lagrangian formulation of the finite difference representation of the one-dimensional differential equations of continuity, motion, and energy.
- Shocks that form in the pump tube and barrel are treated by the artificial viscosity method of von Neumann and Richtmyer, which spreads out shocks due to dissipative effects such as viscosity and heat conduction.
- The code can model either real (variable specific heat) or ideal gases.
- Nonideal effects can be included:
  - piston friction and plastic deformation,
  - heat transfer from gas to wall, and
  - smooth wall or constant factor gas friction.

When the code was used in the single-stage pneumatic mode to model Tritium Procf of Principle (TPOP) injector data, best agreement was obtained using the ideal gas equation of state with gas friction (see Figure 3). Runs made with the two-stage version of the code show gas friction to be the dominant nonideal effect, with heat transfer and piston friction accounting for only 10-20% of the energy loss relative to that due to gas friction. This conclusion agrees with recent theoretical work at the RISO National Laboratory in Denmark, as discussed in reference 7.

At ORNL the initial single-stage pneumatic pellet injectors were single-shot design, although later units had multiple barrels and the ability to chamber up to four pellets. More recent development efforts have produced a reliable repetitive pneumatic gun design. The pellet feed in a repetitive pneumatic gun is generally accomplished with cryogenic extruders that are capable of moving solid hydrogenic feed material at a sufficiently high rate of speed (~5 cm/s) to provide a "real-time" pellet feed system. The apparatus shown in Figure 4 is an example of a repeating pneumatic injector [4] that is capable of delivering pellets continuously at rates of up to 5 Hz. The injector developed for the JET [10,11] tokamak features three units of 2.7-mm, 4-mm and 6-mm diam in a common vacuum enclosure (Figure 5). This versatile device consists of three independent machine-gun-like mechanisms that operate at cryogenic temperatures (14-20 K). Individual high-speed extruders provide a continuous supply of solid deuterium to each gun assembly, where a reciprocating electromagnetically driven breech-side cutting mechanism (punch tube) forms and chambers cylindrical pellets from the extrusion. Deuterium pellets are then accelerated in the gun barrels to velocities ≤1.5 km/s, with controlled amounts of compressed hydrogen gas delivered by fast electromagnetic valves (see Figure 4). The ORNL version of this valve develops full pressure within 300 ms and has operated with a supply pressure of 240 bar. Each gun is capable of operating (individually or simultaneously) at the design repetition rate for 15-s duration pulses (limited only by the capacity of the extruder feed system). The extruder section consists of a liquid reservoir positioned above a cylindrical freezing chamber, which is fitted at its outlet with a tapered copper extrusion nozzle. A programmable motor-driven screw press activates a piston that moves vertically inside the cylindrical bore of the freezing chamber where the solid deuterium charge is located. The extrusion nozzle, which terminates just above the chambering mechanism position, provides a smooth transition from the 10.5-mm cylindrical extruder bore to a rectangular-like cross section whose length is larger than the punch tube diameter and whose width determines the length of the pellet. Present deuterium extruders typically operate at ~14 K, where the shear strength of the ice is low enough to prevent excessive piston forces at high extrusion rates.

III. TWO-STAGE LIGHT-GAS GUNS

Recently, ORNL began developing a two-stage light-gas gun [12,13] to accelerate pellets to high speeds. The basic single-stage light-gas gun is limited in performance by the sound speed of the room temperature propellant gas to about 2 km/s. To overcome this limitation, the two-stage gun relies on a piston moving at high speeds (100-400 m/s) in a cylinder (pump tube) to adiabatically compress the propellant gas (He or H) to high pressure and temperature in a chamber located at the gun breech. In the current configuration of the two-stage device (Figure 6), a 2.2-L volume (pressure, <120 bar) provides the gas to accelerate a 25.4-mm-diam plastic piston in a 1-m-long pump tube. A specially designed pneumatically-operated fast valve initiates the acceleration process in the first stage. As the piston travels the length of the pump tube, the downstream gas (initially at <1 bar) is compressed and thus is driven to high temperatures. By carefully choosing the initial conditions, the piston can be made to approach the cylinder head to within a few millimeters or less before it stops and reverses direction. This results in a near adiabatic compression of the second-stage gas, and pressures much higher than the first-stage reservoir pressure (up to 4000-6000 bar) and high temperatures (of the order 2000-8000 K, depending on the gas type) will be generated. This provides the driving force for acceleration of a 4-mm-diam pellet in a 1-m-long gun barrel.

Because of its higher temperature capability, the two-stage gun can be designed to more closely approximate the ideal constant base pressure gun, which, as its name implies, provides a uniform acceleration along the gun barrel. In earlier tests that used helium gas as the driver in both stages and a burst disk between the two stages, 35-mg plastic pellets were accelerated to speeds as high as 4.5 km/s (see Table 1). More recently, bare deuterium pellets formed in a pipe gun geometry have been accelerated to speeds near 2.9 km/s using the pneumatic valve between the first and second stages (Table 1). Theoretical modeling [7] of these experiments with a one-dimensional Lagrangian hydrodynamics code has identified gas friction in the pump tube and small-diameter barrel to be the dominant loss mechanism.

The use of sabots to encase and protect the cryogenic pellets from the high peak pressures (accelerations) will be required to realize speeds above about 3 km/s; speeds above 4 km/s have been achieved by encasing the pellet in a sabot [14]. The speeds of bare hydrogenic pellets have also been limited by a progressive reduction in the pellet diameter thought to be due to erosion by the gun barrel wall which becomes important at speeds of 2 km/s and above [14,15]. With sabots, the pellet can also be protected from the effects of erosion. Sabots that separate from the pellet after it exits the muzzle are being developed at ORNL and in Europe.

This technology at ORNL is being developed for long pulse to continuous fueling of future fusion reactor-scale devices. Piston lifetimes have exceeded several hundred experimental shots, and recently the two-stage light-gas gun has been operated in a repetitive mode. A repeating pneumatically operated valve between the first and second stages and a magazine-type plastic pellet loading mechanism were used in these initial multishot experiments. A pressure/vacuum ballasting system was implemented for recharging the 0.5-L second stage between shots, and a PLC-based control system linked to a Camac-based data acquisition system was developed. The two-stage injector has been operated in bursts of several to 10 pellets at repetition rates in the range 0.7 to 1 Hz and at pellet speeds of 2-3 km/s. Figure 7 shows a data sequence of 10 pellets at 1 Hz and a velocity of 2 km/s. The upper plot shows initial pressure behind the piston. The uniformity of this pressure resulted in nearly identical velocities for pellets 2-10. The lower plot shows an impact signal on the target from a shock transducer.

IV. CONCLUSIONS

The technology of pellet fueling systems operating in the speed range of up to 1-2 km/s with single-stage pneumatic injectors is well developed. Deuterium pellet injection systems based on the conventional gas gun concepts have been employed in plasma fueling experiments on numerous toroidal confinement devices. Repetitive single-stage pneumatic injection systems have been developed and operate reliably. A two-stage light-gas gun has been developed which can accelerate bare deuterium pellets to near 3 km/s and saboted pellets to speeds over 4 km/s. Initial experiments with a repeating two-stage light-gas gun have demonstrated operation at 1 Hz for a 10-pellet sequence of plastic pellets.

ACKNOWLEDGMENTS

This research was sponsored by the Office of Fusion Energy, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

REFERENCES

1. S. L. Milora, *J. Vac. Sci. Technol. A* **7**, 925 (1989).
2. L. D. Landau and E. M. Lifshitz, *Fluid Mechanics*, Pergamon Press, London, 1959.
3. D. D. Schuresko, S. L. Milora, J. T. Hogan, C. A. Foster, and S. K. Combs, *J. Vac. Sci. Technol. A* **1**, 959 (1983).
4. S. K. Combs, S. L. Milora, C. R. Foust, C. A. Foster, and D. D. Schuresko, *Rev. Sci. Instrum.* **56**, 1173 (1985).
5. P. W. Fisher, M. L. Bauer, L. R. Baylor, et al., *J. Vac. Sci. Technol. A* **7**, 938 (1989).
6. J. Lafferanderie et. al., *Fusion Technol. 1986*, (Proc 14th Symp., Avignon, France, Sept. 8-12,1986), Vol.2, p. 1367.
7. M. J. Gouge, S. K. Combs. P. W. Fisher, and S. L. Milora, *Rev. Sci. Instrum.* **60**, 570 (1989).
8. A. E. Seigel, *The Theory of High Speed Guns*, AGARDograph-91, 1965.
9. J. Dewitt, Arnold Engineering Development Center, Tullahoma, TN, personal communication.
10. S. K. Combs, S. L. Milora, L. R. Baylor, C. R. Foust, F. E. Gethers, and D. O. Sparks, *J. Vac. Sci. Technol. A* **6** , 1901 (1988).
11. S. K. Combs, T. C. Jernigan, L. R. Baylor, S. L. Milora, and C. R. Foust, *Rev. Sci. Instrum.* **60** , 2697 (1989).
12. S. K. Combs, S. L. Milora, C. R. Foust, M. J. Gouge, D. T. Fehling, and D. O. Sparks, *J. Vac. Sci. Technol. A* **7**, 963 (1989).
13. S. K. Combs, C. R. Foust, M. J. Gouge, and S. L. Milora, *J. Vac. Sci. Technol. A* **8**, 1814 (1990).
14. K. Sonneberg et al., in *Proceedings of the 12th Symposium on Fusion Engineering, Monterey, California, October 1987*, Vol. 2, p. 1207.
15. A. Reggiori, G. Riva, G. Daminelli, A. Frattolillo, L. Martinis, and F. Scaramuzzi, *J. Vac. Sci. Technol. A* **7**, 959 (1989).

Table 1. Experimental data for test shots and results from gas dynamics model (Values in parentheses are inputs to or results from code calculations)

	Shot number					
	1210	5041	5064	5088	5089	5165
Projectile	Nylon	Deuterium	Deuterium	Deuterium	Deuterium	LiH
Temperature	295 K	10 K	10 K	10 K	10 K	295 K
Projectile mass (mg)	35	— (10)	— (10)	— (10)	— (10)	26
Piston mass (g)	19.6	25.5	25.5	25.5	25.5	51.0[d]
First-stage pressure[a] (bar)	72.0 (51.7)[b]	13.8 (13.8)[b]	39.9 (34.8)[b]	38.3 (34.8)[b]	42.0 (34.8)[b]	66.4 (81.1)[b]
Second-stage pressure (bar)	0.8	0.8	0.8	0.8	0.8	0.8
Peak pump tube pressure (bar)	3670[c] (4690)	— (180)	— (1600)	— (1600)	— (1600)	— (3350)
Piston travel time (ms)	3.20 (3.24)	8.20 (8.00)	5.10 (4.85)	4.90 (4.85)	5.10 (4.85)	5.15 (5.14)
Maximum piston speed (m/s)	— (391)	— (152)	— (265)	— (265)	— (265)	— (269)
Peak pellet acceleration (m/s^2)	— (5.6×10^7)	— (4.3×10^6)	— (6.7×10^6)	— (6.7×10^6)	— (6.7×10^6)	— (2.3×10^7)
Pellet velocity (km/s)	4.50 (4.88)	1.60 (1.63)	2.60 (2.75)	2.70 (2.75)	2.85 (2.75)	4.20 (4.00)

[a]This is not the reservoir pressure but the maximum pressure estimated from the output of the transducer located at the upstream end of the pump tube.
[b]First-stage pressure for the code calculation; it was adjusted so that the calculated piston travel time closely matched the experimentally measured value; for shots 5064, 5088, and 5089, the same pressure was used, so the code results are the same.
[c]Flat profile of pressure pulse at peak on this shot suggested that instrument or data acquisition may have missed maximum value.
[d]Two 25.5-g pistons were used in pump tube for this shot; it was modeled as a single piston.

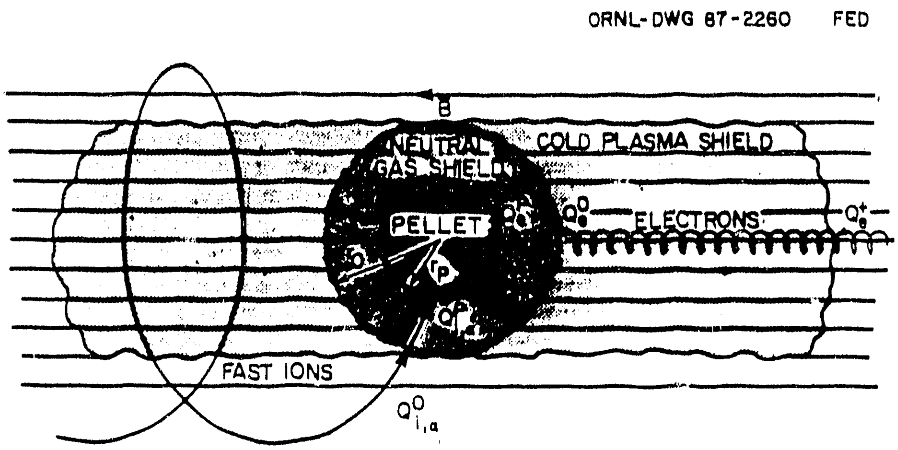

Figure 1 Pellet ablation and shielding mechanism

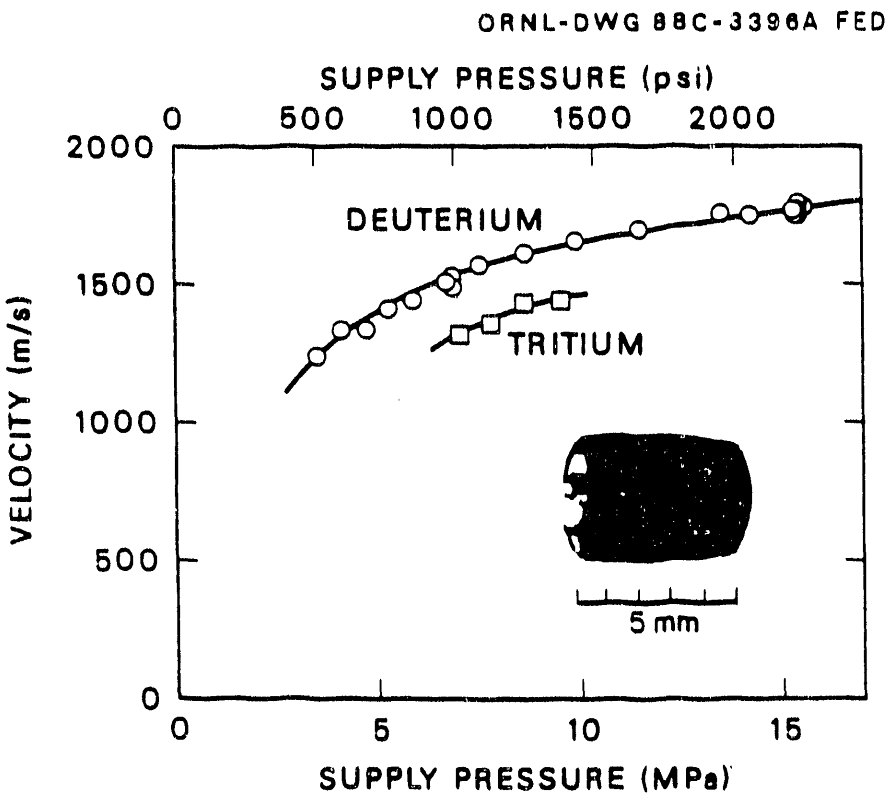

Figure 2 Pellet velocity vs supply pressure for deuterium and tritium pellets

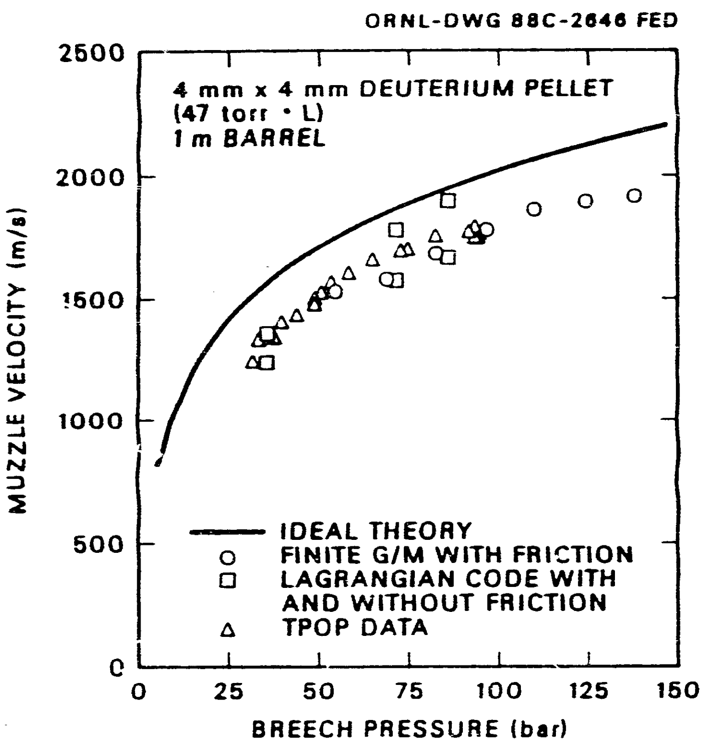

Figure 3 Deuterium pellet velocity data and theoretical results

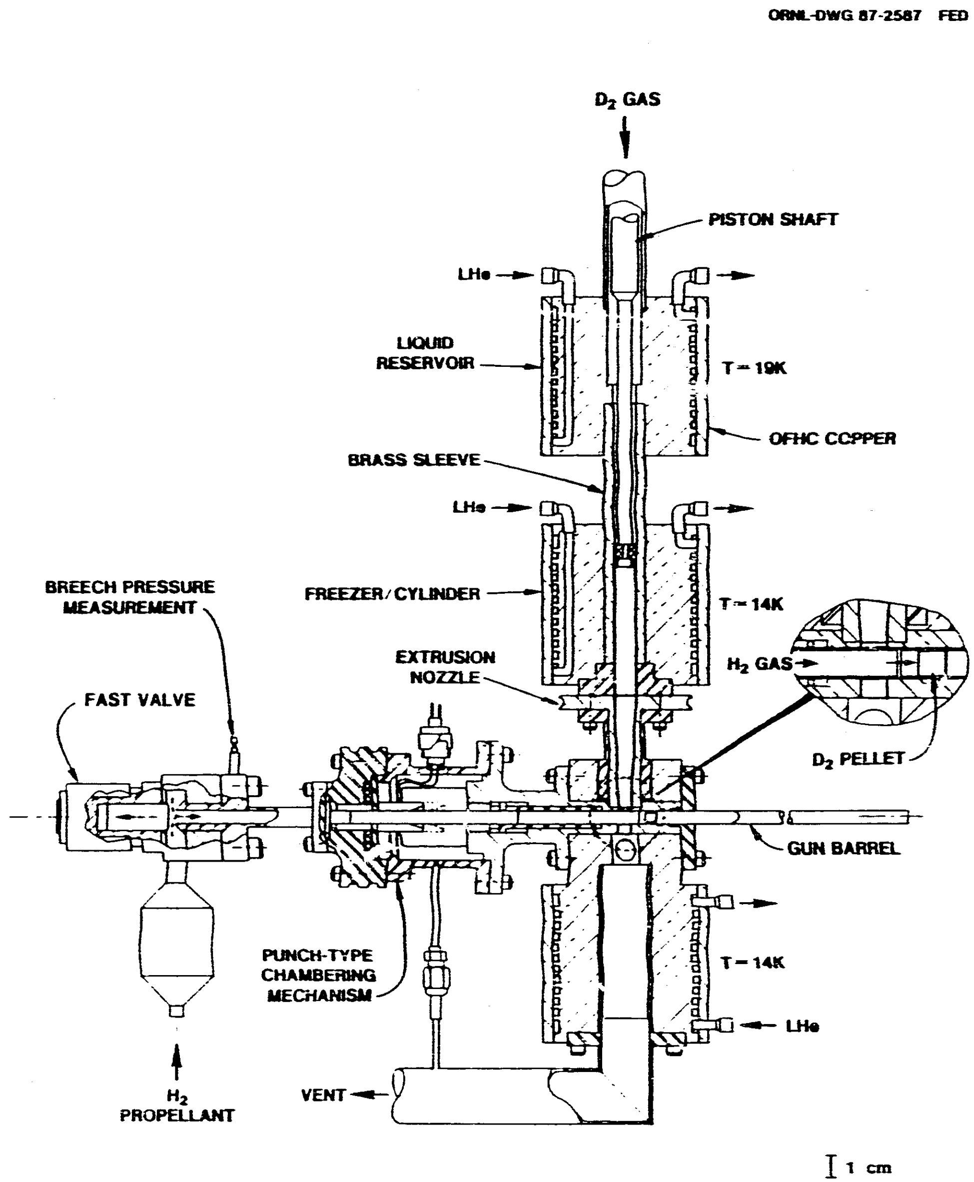

Figure 4 Schematic of an ORNL repeating pneumatic injector

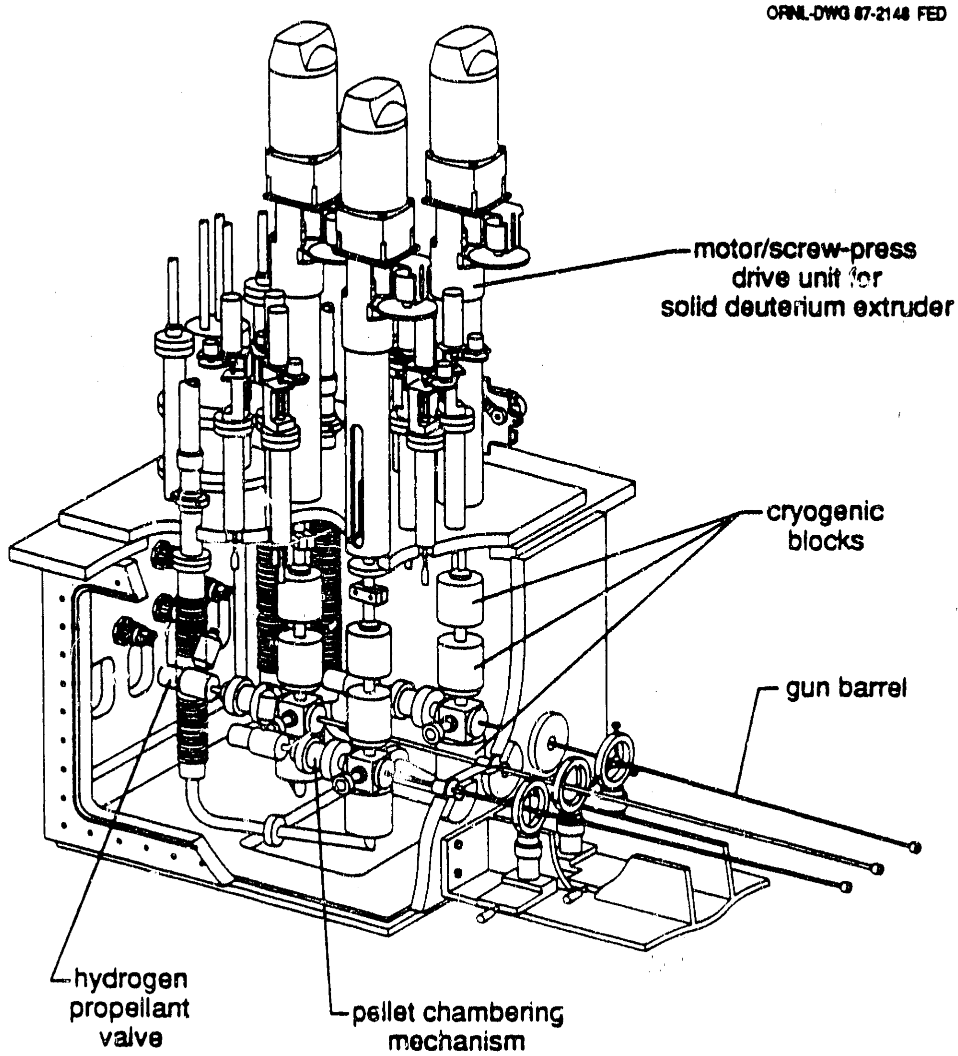

Figure 5 Schematic of the ORNL repeating pneumatic pellet injector installed on JET

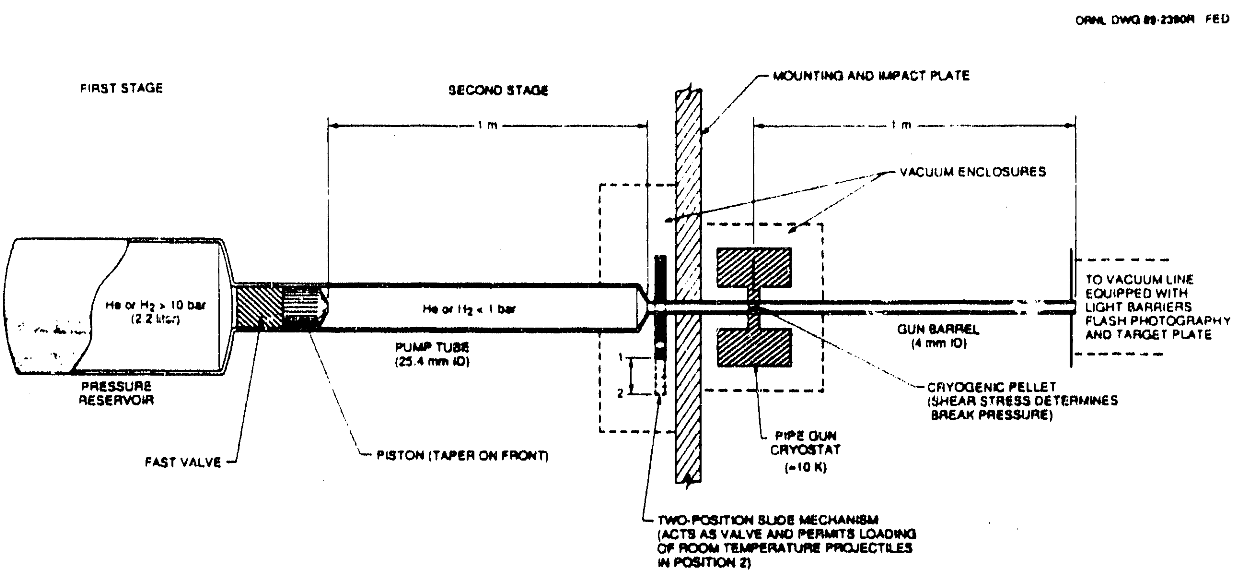

Figure 6 Schematic of ORNL two-stage light-gas gun

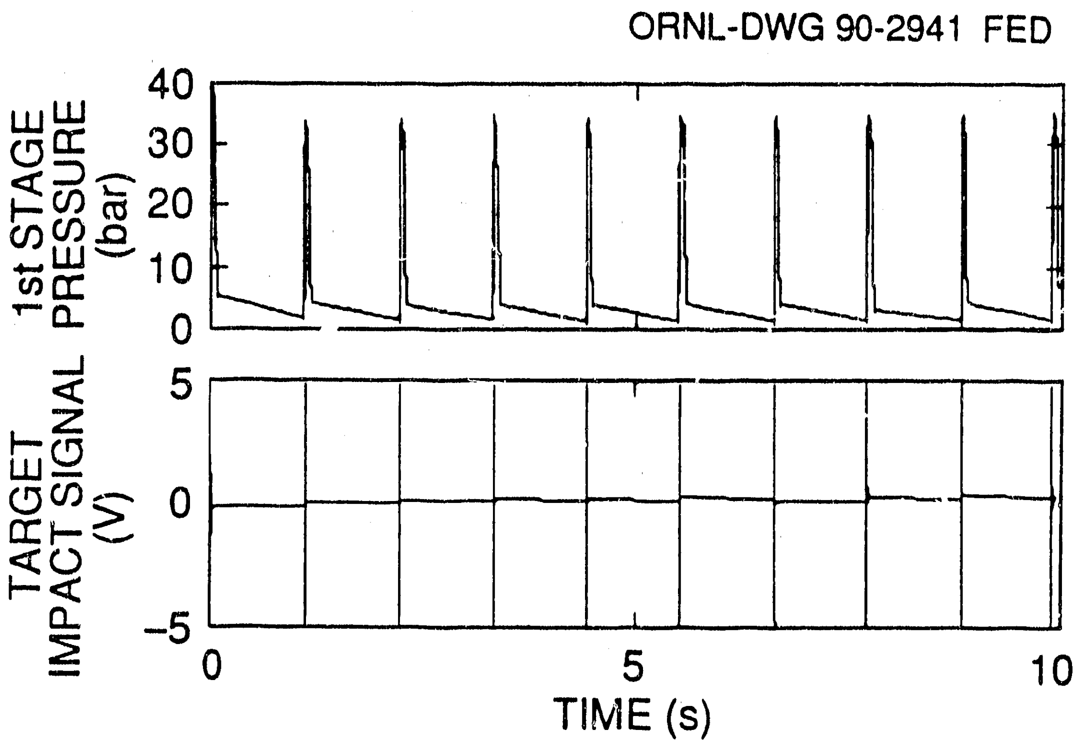

Figure 7 Repetitive data from ORNL two-stage light-gas gun

END

DATE FILMED

12 / 05 / 90