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# DEVELOPMENT OF A TWO-STAGE LIGHT GAS GUN TO ACCELERATE HYDROGEN PELLETS TO HIGH SPEEDS FOR PLASMA FUELING APPLICATIONS*

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The development of a two-stage light gas gun to accelerate hydrogen isotope pellets to high speeds is under way at Oak Ridge National Laboratory. High velocities (>2 km/s) are desirable for plasma fueling applications, since the faster pellets can penetrate more deeply into large, hot plasmas and deposit atoms of fuel directly in a larger fraction of the plasma volume. In the initial configuration of the two-stage device, a 2.2-l volume ($\leq$55-bar) provides the gas to accelerate a 25.4-mm-diam piston in a 1-m-long pump tube; a burst disk or a fast valve initiates the acceleration process in the first stage. As the piston travels the length of the pump tube, the downstream gas (initially at <1 bar) is compressed (to pressures up to 2600 bar) and thus is driven to high temperature ($\approx$ 5000 K). This provides the driving force for acceleration of a 4-mm pellet in a 1-m-long gun barrel. In preliminary tests using helium as the driver in both stages, 35-mg plastic pellets have been accelerated to speeds as high as 3.8 km/s. Projectiles composed of hydrogen ice will have a mass in the range from 5 to 20 mg ($\rho \approx 0.087$, 0.20, and 0.32 g/cm$^3$ for frozen hydrogen isotopes). However, the use of sabots to encase and protect the cryogenic pellets from the high peak pressures will probably be required to realize speeds of $\approx$3 km/s or greater. The experimental plan includes acceleration of hydrogen isotopes as soon as the gun geometry and operating parameters are optimized; theoretical models are being used to aid in this process. The hardware is being designed to accommodate repetitive operation, which is the objective of this research and is required for future applications.

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# DISCLAIMER

## I. INTRODUCTION

Oak Ridge National Laboratory (ORNL) has been developing pneumatic pellet injectors for about ten years.[1–11] These devices produce and accelerate frozen hydrogen isotope pellets at speeds in the range of 1–2 km/s. The acceleration is accomplished in a single stage by conventional pneumatic gun techniques, in which a reservoir at room temperature provides high-pressure (typically <100-bar) gas via a fast valve[12] to propel hydrogen ice through a gun barrel. A variety of designs have been developed at ORNL, including single-shot (one-pellet) guns,[2,4,7,10] multiple-shot (four- and eight-pellet) guns,[3,8,11] and machine gun (single- and multiple-barrel) types.[5,6,9] These pneumatic-type injectors have been used to inject hydrogen and deuterium pellets into plasmas on numerous tokamak experiments (see, e.g., Refs. 13–17), resulting in improvements of plasma performance. Recently, ORNL used a simple pneumatic gun for the first demonstration of the acceleration of tritium pellets[18] in the Tritium Systems Test Assembly at Los Alamos National Laboratory. Tritium pellet injection is an integral part of the fueling systems planned for fusion experiments and reactors. With recent pellet fueling applications extending to the larger tokamak experiments, such as the Tokamak Fusion Test Reactor[16] (TFTR) and the Joint European Torus[17] (JET), it is clear that higher pellet velocities are desirable (and may be needed) since the faster pellets will penetrate deeper into the larger and hotter plasmas associated with these fusion devices. Toward this goal, advanced technologies to achieve higher pellet velocities (>2 km/s) have been pursued at ORNL for several years.[19,20] Most recently, a research effort has been initiated with the objective of developing a repetitive, two-stage pneumatic light gas gun for plasma fueling applications.

The two-stage pneumatic technique[21] originated during the late 1940s and is currently the leading method for hypervelocity research at the major defense and aerospace facilities. This technique overcomes an intrinsic problem associated with conventional pneumatic guns in attempting to achieve higher muzzle velocities: the speed of sound in the driving gas determines the maximum rate at which the gas can transmit pressure to the projectile, and for conventional guns the driving pressure decreases strongly when the gas velocity in the gun barrel exceeds the sound velocity ($\approx$1.3 and 1.0 km/s for room-temperature hydrogen and helium, respectively). For an ideal gas, the sound velocity is proportional to the square root of the temperature divided by the molecular weight ($c \propto \sqrt{T/M}$). Thus, the choice of light gases for the propellant is obvious. Also, it is apparent that gun performance can be improved by heating the propellant gas to higher temperatures. The two-stage gun system (Fig. 1) accomplishes this by adiabatic compression of the propellant gas in the second stage; in addition, the pump tube pressure automatically increases during the acceleration process. Velocities of up to 10 km/s have been reported[22] for this concept; however, these tests were carried out with very high peak pressures (≈10,000 bar) and relatively strong projectiles (such as plastics). With a more fragile projectile composed of hydrogen ice, experience suggests that driving pressures on the pellet should be limited (probably to <100 bar) to prevent fracturing of the pellet in the gun barrel during the acceleration process. Two research groups in Europe[23,24] are also developing this technique for high-speed injection; in one of these experiments,[24] a deuterium pellet has been accelerated to velocities of 3.4 km/s using a sabot technique to protect the pellet from the high-pressure peaks. The sabots also limited the erosion of the pellet, which becomes an issue at higher velocities. These experiments report peak acceleration limits of 5–6 $\times$ $10^6$ m/s$^2$ for a bare pellet without fracturing. However, this value is somewhat lower than accelerations inferred from the best performance of single-stage guns at ORNL,[5,17] in which levels of $10^7$ m/s$^2$ were indicated.

A simple two-stage light gas gun has been constructed at ORNL to study the acceleration of small, light projectiles to high speeds. A 4-mm-diam pellet size was chosen for these initial tests since it is applicable to large present-day tokamak experiments; in fact, pellet fueling systems on both TFTR and JET are equipped with this pellet size. Thus, the projectile mass of interest is in the range of 5–20 mg ($\rho = 0.087$, 0.20, and 0.32 g/cm$^3$ for hydrogen, deuterium, and tritium ice, respectively). The use of the sabot technique dictates heavier projectiles, depending upon the specific design. The equipment used in this study is described, and initial results with 35-mg plastic pellets are presented. Plans for future work are also discussed.

## II. EQUIPMENT

A schematic of the two-stage pneumatic device used in these studies is shown in Fig. 1. Physical parameters of the gun and operating test ranges are listed in Table I. In the first driving stage, a 2.2-l reservoir provides the gas to accelerate the piston in a 1-m-long pump tube. The downstream gas is compressed as the piston travels down the pump tube and thus driven to high pressure, which propels the projectile in the second driving stage. The projectile does not start to move until the pressure is high enough to overcome the wall shear stress of the tightly fitting pellet ($\approx$100 bar); the pellet is then accelerated through the 1-m-long gun barrel into a vacuum injection line. A burst disk (or a full-flow-type fast valve in some tests) separates the two stages and acts to initiate the acceleration process; the thickness of the burst disk determines the rupture pressure. In a typical test shot, a pellet is loaded through the gun breech into the gun barrel. Next, the pressure in the second stage is adjusted to the desired level ($<$1 bar). Last, the pressure in the first stage is raised to a level high enough to rupture the burst disk ($>$10 bar).

As illustrated in Fig. 1, the pump tube and gun barrel are equipped with instrumentation, including five pressure transducers (two in the pump tube and three in the gun barrel) and a shock accelerometer located at the end of the pump tube. The pressure transducers in the pump tube are located at the start of the tube, directly in front of the piston, and at the tube end. From the data provided by the transducers, the flight time for the piston to travel the 1-m length can be evaluated and the driving pressure in both stages can be monitored. The pressure transducers in the gun barrel track the pressure at three intermediate positions (25, 50, and 96 cm down the barrel). Also, instrumentation located in the vacuum injection line provides velocity and photographic information to document each shot fully. Light barriers through which the pellets pass supply timing data to evaluate accurate pellet speeds. At the end of the injection line, a target plate intercepts the pellets and indicates pellet dispersion and integrity; this also provides timing data for velocity measurements, since it is equipped with a shock accelerometer. A CAMAC data acquisition system is used to record and archive the transient data for each shot. The event takes only about 5 ms, from the time at which the disk ruptures to the time at which the pellet strikes the target plate.

In these tests, different designs and materials for the pistons and pellets were tried; however, most of the experiments were carried out with nylon ($\rho = 1.06$ g/cm$^3$) for the projectile in both stages. The standard pellet for the second stage was 3.9 mm in diameter and 2.8 mm long with a mass of 35 mg. Preliminary tests were performed using a 19.3-mm-diam pump tube; however, significant improvement in gun performance was not observed until a 25.4-mm-diam pump tube was tested. This paper presents results for the larger pump tube. Piston masses ranged from 10 to 22 g, as listed in Table I. The pump tube inner diameter was polished to provide the best possible finish; the clearance between the tube wall and piston was typically 0.025 mm for a new piston.

## III. EXPERIMENTAL RESULTS

The driving force for acceleration of the projectile is determined by the pressure pulse generated at the pump tube exit. The pressure pulse for shot 1111 is shown in Fig. 2; the peak pressure of 2600 bar is the highest value measured in this study. The full width at half-maximum (FWHM) of the pressure pulse is $\approx$50 $\mu$s. Data from a typical high-speed test (shot 1114) are summarized in Table II and shown in Figs. 3 and 4. Helium was used for the driving gas in both stages, with a burst pressure in the first stage of 55 bar and a prefill pressure in the second stage of 0.8 bar. The piston was of the type shown in Fig. 5 and weighed 20.5 g. The piston traveled the 1-m distance of the pump tube in $\approx$3.6 ms, as determined from the information in Fig. 3. The peak pressure (55 bar) at the start of the pump tube corresponds to the time at which the piston passes the first pressure transducer (6274 $\mu$s); the shock accelerometer indicates the time of piston impact at the other end (9868 $\mu$s). The impact occurs at the same time as the peak pressure (2000 bar) as shown in Fig. 4. The pressure transducers in the gun barrel were of limited usefulness for tests in which the piston impacts severely, because they are sensitive to shock. The effect of shock on the instrument output is visible in Fig. 4b; the peak pressure measured at 25 cm down the gun barrel was 293 bar. The noise in the signal is substantial, and it was much worse for the other two downstream locations (not shown), even preventing data interpretation. The speed for this shot was 3.6 km/s. The highest speed recorded in these experiments was 3.8 km/s, and velocities in this range were consistently observed at test parameters similar to those listed in Table II. The target plate from shot 1114 is shown in Fig. 6, which testifies to the significant amount of kinetic energy associated with these light, high-speed projectiles ($\approx$0.25 kJ). A comparison of impact plates for numerous high-speed test shots indicated negligible dispersion of projectiles 1.5 m downstream of the gun muzzle.

Theoretical models have been used to aid in the optimization of the two-stage design and operation. The most extensive of these is a Lagrangian code obtained from the Arnold Engineering Development Center. This two-stage code has the following capabilities: (1) it provides a Lagrangian formulation of the finite difference representation of the one-dimensional differential equations of continuity, motion, and energy; (2) it treats shocks that form in the pump tube and barrel with the artificial viscosity method of von Neumann and Richtmyer,[25] which spreads out shocks due to dissipative effects such as viscosity and heat conduction; (3) it can model either real (variable specific heat) or ideal gases; and (4) it can model nonideal effects, including piston friction and plastic deformation, heat transfer from gas to wall, and smooth-wall or constant factor gas friction. In general, the calculations from the models agree well with the measured pressures in the pump tube during the compression; however, the measured pellet velocities are at least 20% below the predicted speeds. This may be due in part to contamination of the light driving gas in the second stage at the high temperatures (code calculations suggest $T > 5000$ K). As shown in Fig. 5, the piston is severely scorched during the compression. The black sootlike material from this scorching is also dispersed in the driving gas, as indicated by the buildup of coatings on inner surfaces in the gun after several shots. Thus, the average molecular weight of the gas is raised, lowering the "effective" sound speed. Other materials also offer superior mechanical and thermal properties for this application. Even with the nylon material, up to 10 shots could be made with a single piston.

The models do not take into account possible blow-by of gas around the piston. With 0.025-mm gap for a new piston, the flow area between the piston and the tube wall is about 10% of that through the gun barrel. The pistons did show some wear after a shot (≈0.025 mm); successive shots indicated slight additional wear.

In order to obtain high velocities (3 km/s) with the present geometry, it was necessary to drive the piston at high speeds. Code calculations agreed with the measured flight times for the piston in the pump tube and indicated maximum velocities of almost 400 m/s with the piston striking the end of the pump tube at ≈200 m/s. This results in a considerable amount of mechanical shock. The use of a larger tube would allow lower piston speeds, and code calculations suggest that improved performance can be realized while minimizing or possibly eliminating the impact shock. The code calculations also suggest that using hydrogen gas in both driving stages will yield higher pellet speeds at the same operating parameters. This has not been observed in the few tests using hydrogen gas in the second stage. As a safety precaution, most tests have been carried out using helium in both stages. A research group in Italy[23] uses helium in both stages and prefers it to hydrogen for this application. More testing will probably clear up this issue.

In one series of tests, the rupture disk was replaced with a full-flow-type fast valve, and an automatic pellet loading mechanism was installed between the pump tube and the gun barrel. These tests demonstrated that equivalent gun performance could be achieved with this configuration. Thus, these components, when combined with a cryogenic extruder for hydrogen ice, can form the basis for development of a repetitive gun that can perform at rates of ≥1 Hz (with or without sabots).

## IV. CONCLUSIONS AND PLANS

Using a simple two-stage light gas gun, it has been relatively straightforward to accelerate small, light projectiles to speeds of 3.8 km/s. Another series of tests is planned with a larger (50.8-mm-i.d.) pump tube. This configuration offers some distinct advantages. First, the volume of the driving gas is significantly greater (a factor of 4 for the same pump tube length, since the pump tube diameter is doubled), which reduces the drop in driving pressure as the pellet moves down the gun barrel and hence produces higher pellet speeds under similar operating conditions. Second, the larger pump tube will permit slower piston speeds with equivalent or better performance; thus, piston impact can be minimized and probably even avoided by choosing the proper test conditions. After the gun design (geometry and construction materials) and operating parameters of the two-stage pneumatic device are optimized, projectiles composed of hydrogen ice will be accelerated. The sabot technique will probably be required to realize speeds of $\approx$3 km/s or greater. The final objective of this work is the reliable operation of a repetitive two-stage gun at a rate of $\approx$1 Hz or greater.

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Table I. Parameters for two-stage light gas gun

| | |
|---|---|
| First stage | |
| Volume ($cm^3$) | 2250 |
| Length (m) | ≈0.42 |
| Inside diameter (mm) | ≈82 |
| Initial pressure (bar) | 10–55 |
| Second stage | |
| Volume ($cm^3$) | 500 |
| Length (m) | 1 |
| Inside diameter (mm) | 25.4 |
| Initial pressure (bar) | <1 |
| Gun barrel | |
| Length (m) | 1 |
| Inside diameter (mm) | 3.9 |
| Piston mass (g) | 10–22 |

## FIGURE CAPTIONS

Fig. 1. Schematic of two-stage light gas gun.

Fig. 2. Pressure measured at end of pump tube during a high-speed shot.

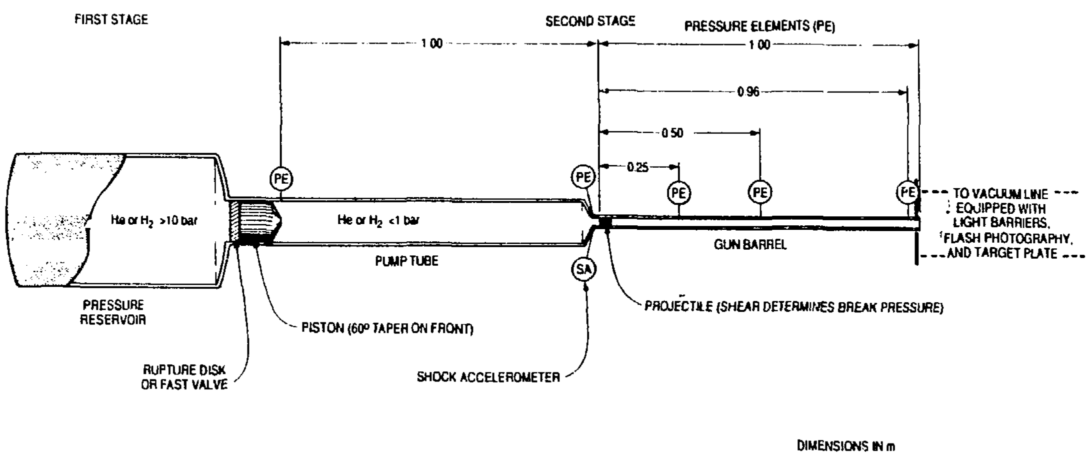
Fig. 3. Data traces for a high-speed shot: (a) pressure measured at end of pump tube, (b) pressure measured 25 cm down barrel, and (c) output of shock accelerometer located at end of pump tube.

Fig. 4. Data traces for a high-speed shot: (a) pressure measured at the start of the pump tube and (b) output of shock accelerometer located at end of pump tube.

Fig. 5. Comparison of piston condition before and after a high-speed shot (nylon material, 25.4 mm in diameter × 41.3 mm long).

Fig. 6. Target plate (4.5 mm thick) after impact of light (35-mg), high-speed (3.6-km/s) nylon projectile (shown on ruler).

ORNL-DWG 88 3279 FED



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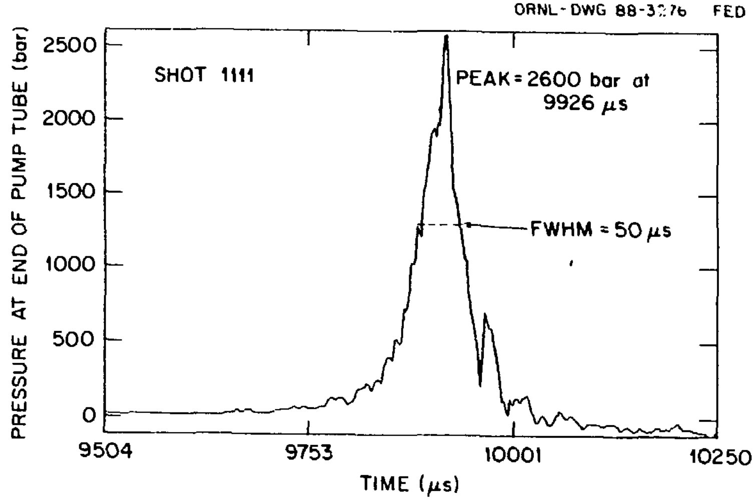
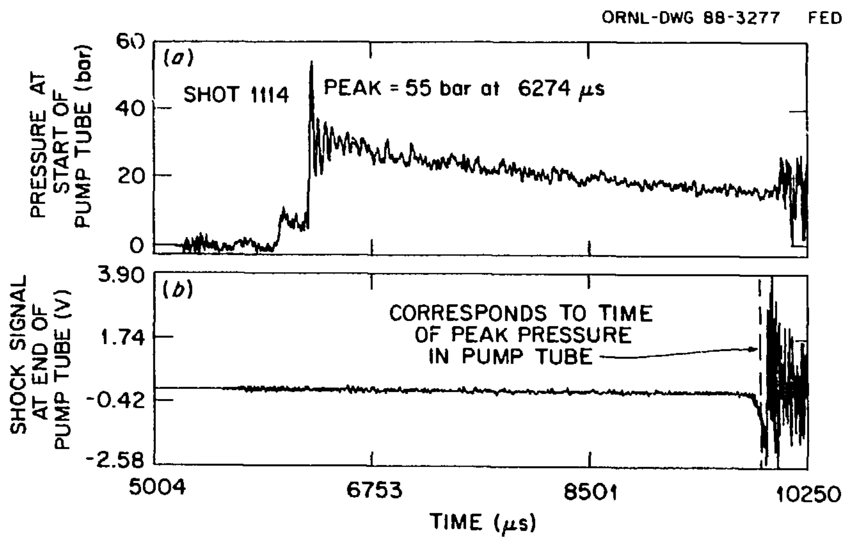
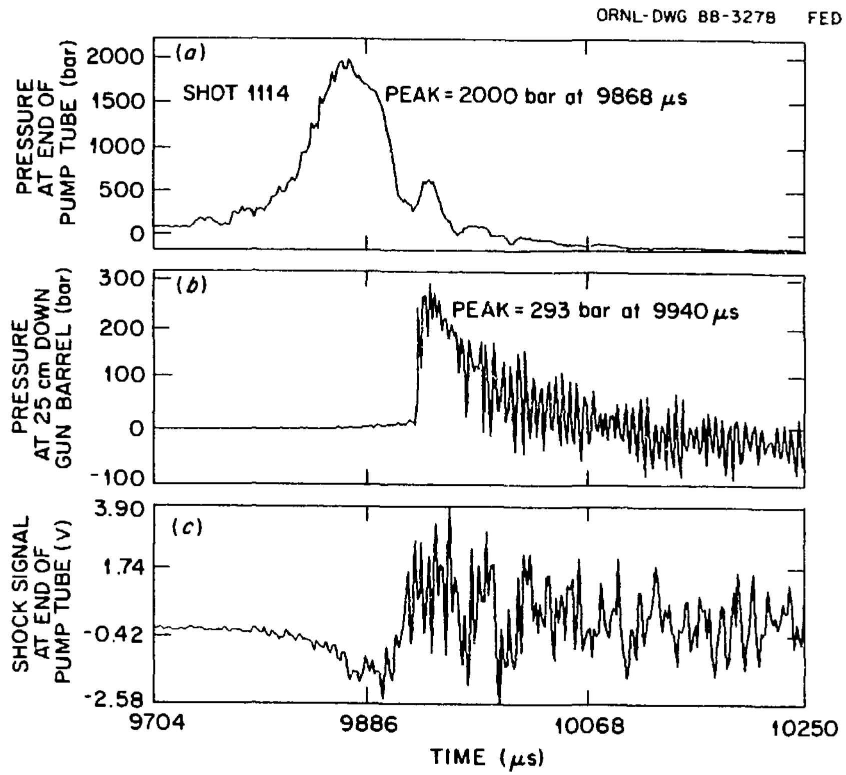



ORNL-DWG 88-3277 FED
(a)
SHOT 1114
PEAK = 55 bar at 6274 μs
PRESSURE AT START OF PUMP TUBE (bar)
60
40
20
0
(b)
CORRESPONDS TO TIME OF PEAK PRESSURE IN PUMP TUBE
SHOCK SIGNAL AT END OF PUMP TUBE (V)
3.90
1.74
-0.42
-2.58
5004
6753
8501
10250
TIME (μs)


ORNL-DWG 88-3278 FED
PRESSURE AT END OF PUMP TUBE (bar)
2000
1500
1000
500
0
(a)
SHOT 1114
PEAK = 2000 bar at 9868 µs
PRESSURE AT 25 cm DOWN GUN BARREL (bar)
300
200
100
0
-100
(b)
PEAK = 293 bar at 9940 µs
SHOCK SIGNAL AT END OF PUMP TUBE (V)
3.90
1.74
-0.42
-2.58
(c)
9704
9886
10068
10250
TIME (µs)